Waves – ice interactions

Comité de thèse 4 mai 2017

Guillaume Boutin

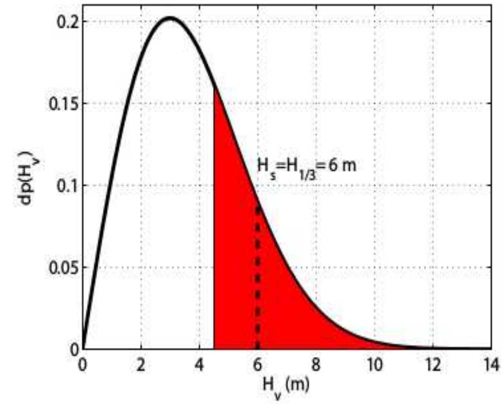
PhD student

Laboratoire d'Océanographie Physique et Spatiale, CNRS/Ifremer/UBO/IRD, Brest, France

Supervisors :
Fabrice Ardhuin
Fanny Girard-Ardhuin

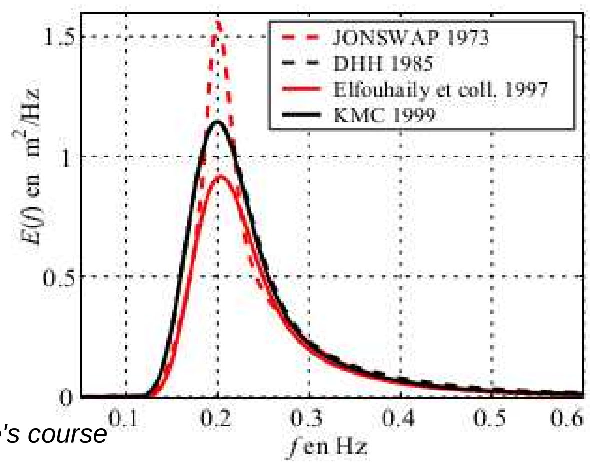
Generalities

- **Waves are random → Statistics**



The great wave of Kanagawa, Hokusai

- **Parameters : Hs, Tp...**
- **Spectra , frequency & directions**



Graphs from Fabrice's course

Wavewatch III : Presentation

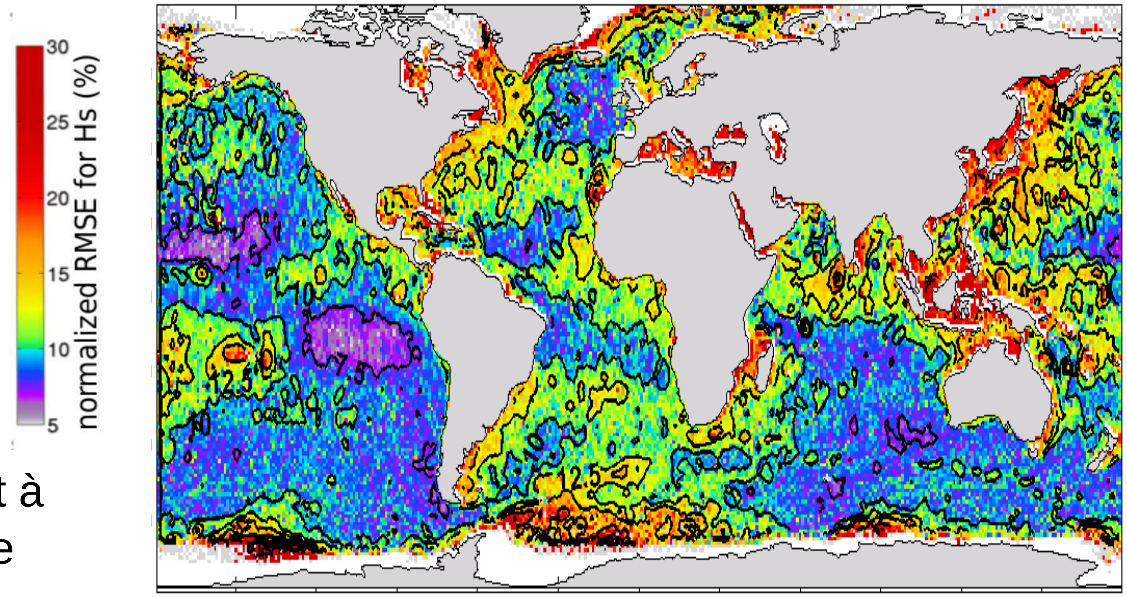
Un modèle spectral de vagues

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

Sources and sinks

Action advection

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



Des grandes incertitudes demeurent à hautes latitudes → présence de glace

Adding ice in Wavewatch III

Why ?

- 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
- LOPS is involved in two projects aiming at improving our understanding of wave-ice interactions

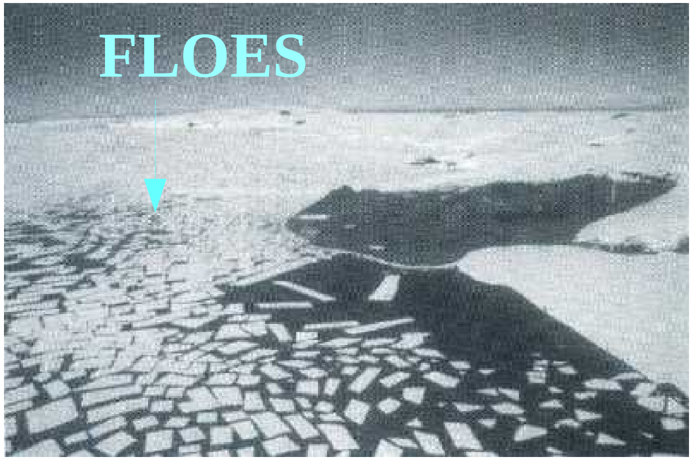
SWARP

ARCTIC SEA STATE 2015 OFFICE OF NAVAL RESEARCH

On wave / ice interactions

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)



Cape Royds, Antarctica, in 1995. Photograph : Antarctica New Zealand. (Langhorne et al., 1998)

The Marginal Ice Zone (MIZ)

The interface between open water and fully ice covered ocean

Different processes:

- Mechanical : fracture (waves, shear...), ridging
- Thermodynamical (melt, freeze…)
- Advection

modify

MIZ properties :

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

(Toyota et al., 2011)

Waves / ice interaction in polar areas

I) Adding ice in a spectral wave model

1) Theory

2) Results

1st year

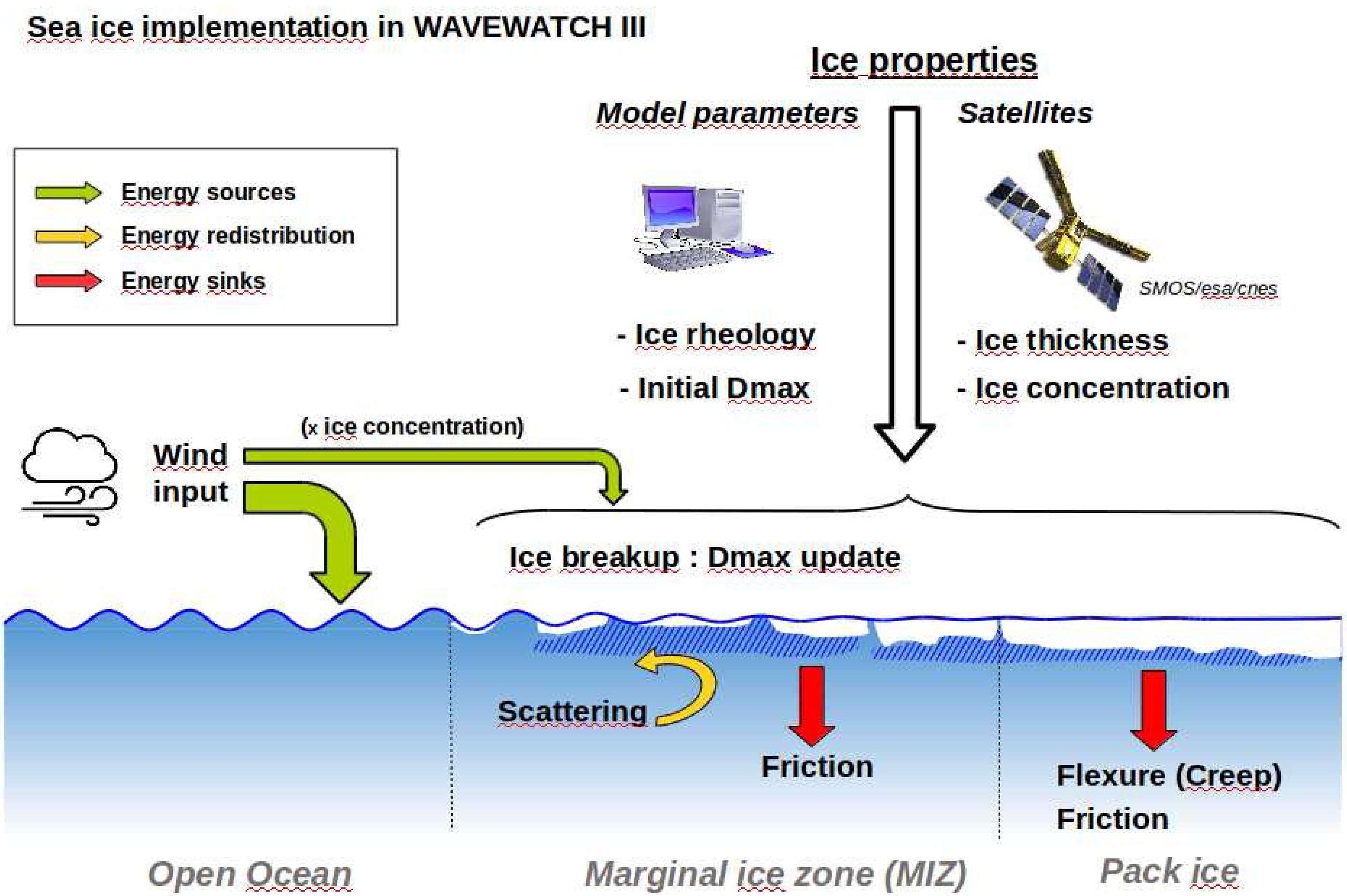
II) Coupling an ice model with a wave model to investigate waves in ice impact

1) Objectives

2) Discussion

Work in progress

Summary


Sea ice implementation in WAVEWATCH III
Ice properties
Model parameters
Satellites
Energy sources
Energy redistribution
Energy sinks
SMOS/esa/cnes
- Ice rheology
- Initial Dmax
- Ice thickness
- Ice concentration
(x ice concentration)
Wind
input
Ice breakup : Dmax update
Scattering
Friction
Flexure (Creep)
Friction
Open Ocean
Marginal ice zone (MIZ)
Pack ice

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 critical strain , σ_c

Limits

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

Y and σ_c have been modified from empirical results :

$$Y^* = Y_0(1 - 3.51\nu_b) - 1GPa$$

$$\sigma_c = \sigma_0 e^{-5,88\sqrt{\nu_b}}$$

With :

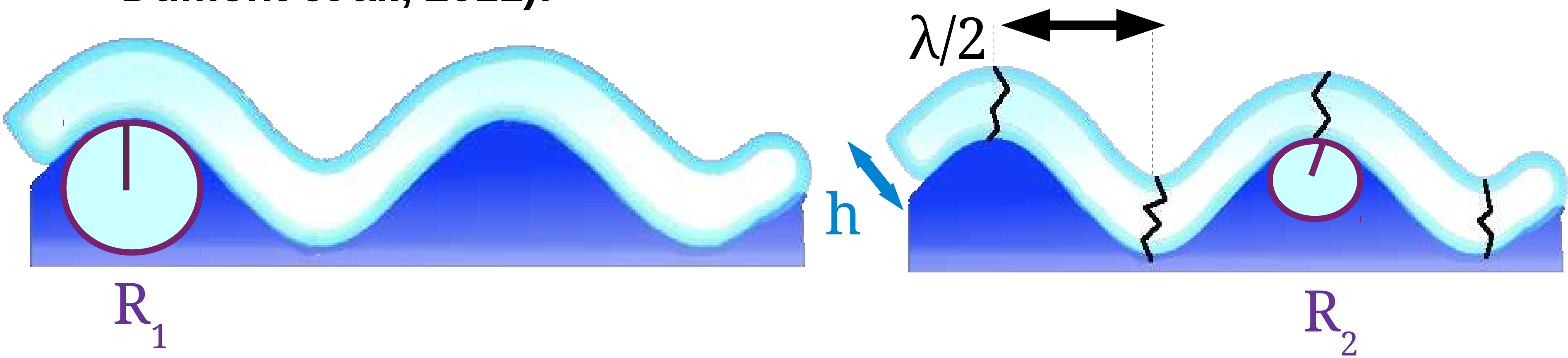
σ_0, Y_0 : Nominal values

ν_b : brine volume fraction

$-1GPa$: delayed elasticity

The MIZ in WW3

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



ε_c: critical strain for a thin elastic plate.

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

New floes have a max. diameter (Dmax) equal to λ/2

The MIZ in WW3

Floe Size Distribution (Totoya et al, 2011):

- The FSD follows a power law : $N(D) \approx D^{-\gamma}$
- Once γ is known, the full distribution can be determined if we set limit values :

$$D_{min} \;\&\; D_{max} \longrightarrow D_{mean} = f(D_{max}, D_{min}, \gamma)$$

This adds two conditions for breaking the floes :

1st Criterion : $\underbrace{\frac{\lambda}{2} \geqslant D_{min}}$ and $\underbrace{\frac{\lambda}{2} \leqslant D_{max}}$

Does not affect scattering

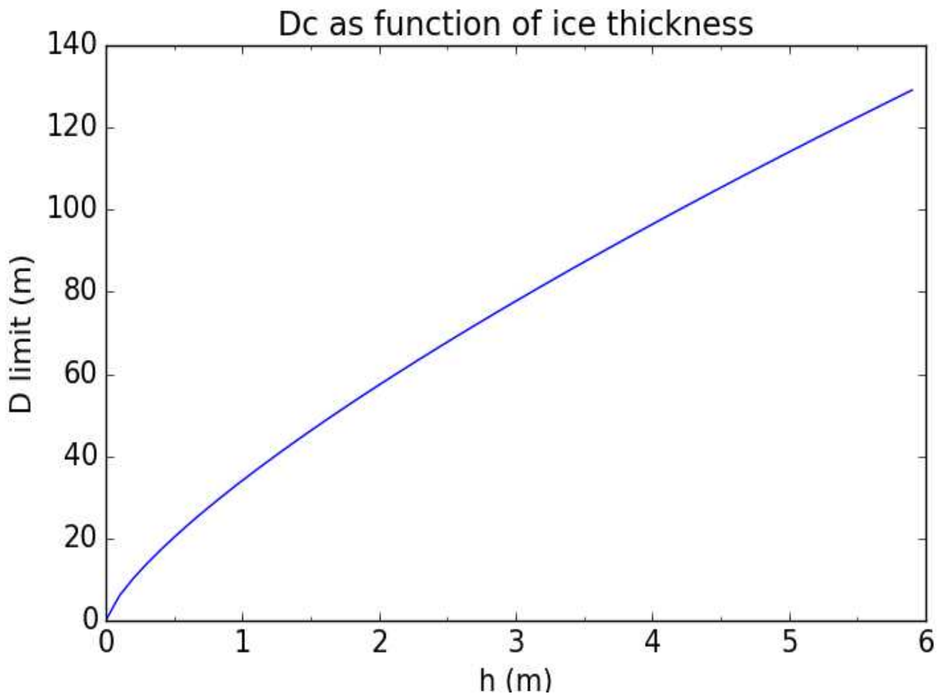
Well... Waves do not make floes greater than they are

The MIZ in WW3

Small and thick floes don't bend : Flexural failure limit (Mellor, 1986) :

Flexural failure can occur if : $D_{floes} > D_c$

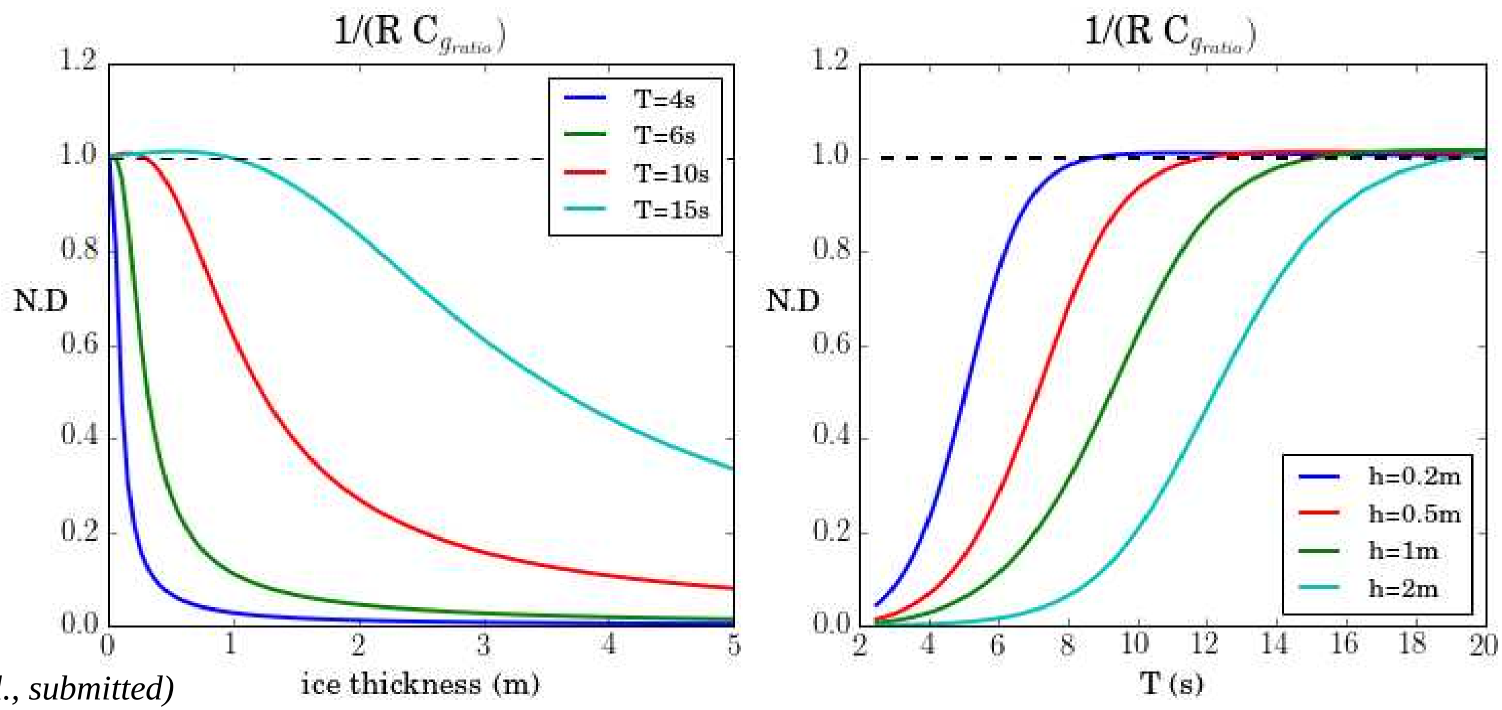
$$D_c = \left(\frac{\pi^4 Y^* h^3}{48 \rho g (1 - \nu^2)} \right)^{1/4}$$



Conservation of the energy flux

Wadhams (1973)

Energy flux conservation : $C_g \frac{a^2}{2} = C_{g,i} R \frac{a_i^2}{2}$. $R = 1 + \frac{4Y^* h^3 \pi^4}{3\rho g \lambda_{ice}^4 (1-\nu^2)}$

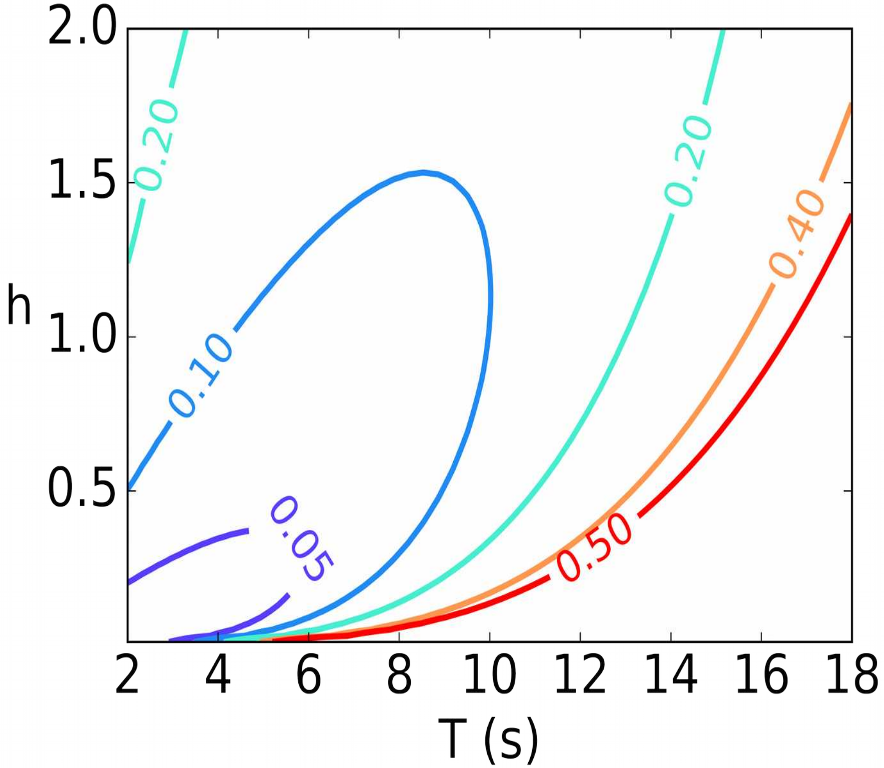


(Boutin et al., submitted)

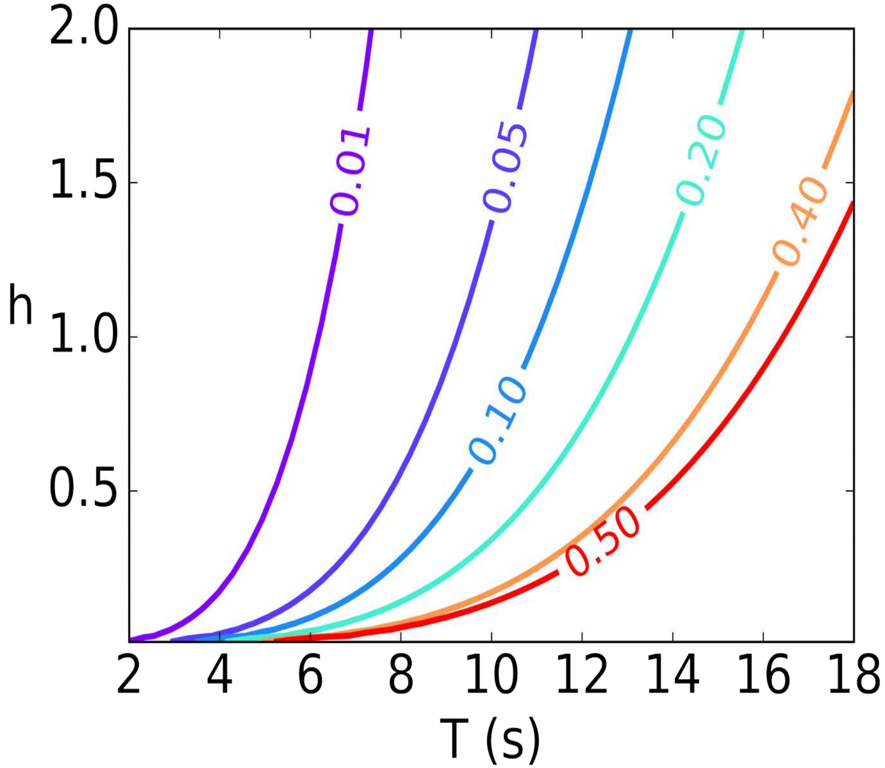
➡ Has to be taken into account for breaking and attenuation

Conservation of the energy flux

With conservation:



Without:



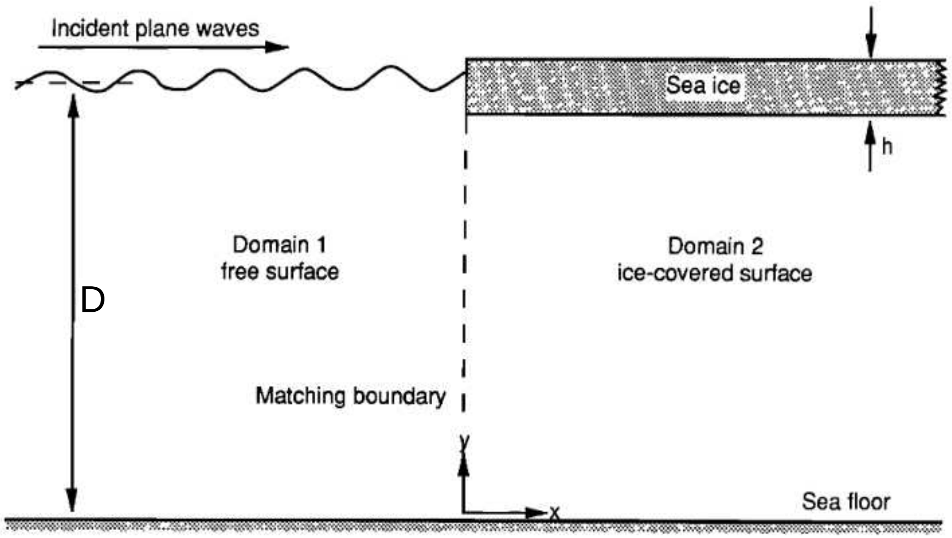
Hs min. necessary to break the ice

(Boutin et al., submitted)

Wave propagation in ice covered sea

Classical

$$
\left\{
\begin{array}{ll}
\Delta \phi = 0 & \\
\dfrac{\partial \phi}{\partial y} = 0 & y = -D \\
\dfrac{\partial \phi}{\partial y} = \dfrac{\partial \xi}{\partial t} & y = 0 \\
p = -\rho g \xi - \dfrac{\partial \phi}{\partial t} & y = 0
\end{array}
\right.
$$



Fox and Squire, 1990

With ice

$$
\left\{ (L\partial_x^4 + \rho_{ice} h \partial_t^2)\eta_{ice} = p \qquad y = 0 \right.
$$

With : $L = Y^* h^3 / 12(1 - \nu^2)$

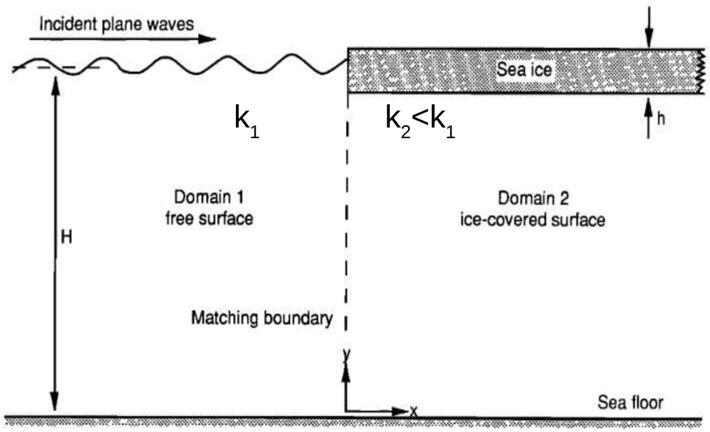
Thin plate, Euler-Bernoulli hypothesis

No dissipation in this relation

Computation of λ_i → Only used in source terms (attenuation & breaking)

Scattering

Change in wavelength → Reflection & Transmission → **Scattering**



Fox and Squire, 1990

In most papers, scattering is assumed to be the main mechanism for wave attenuation in the MIZ

Exponential attenuation observed : $E \propto e^{-\alpha N_{floes}}$

(Wadhams, 1975)

$$N_{floes} = \frac{x \times C}{D_{mean}}$$

In WW3, we chose to redistribute energy **isotropically**.

Floes that do not bend do not contribute much : Dmin = f(λ)

We set : $D_{min} = 0.3\lambda$

Friction

Stopa et al. (2016) :

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

Liu and Mollo-Cristensen (1989)

$$\alpha_v = -k\sqrt{\nu_m \sigma / 2}$$

Grant and Madsen (1979)
(for bottom friction)

$$\alpha_t = -f_e(u_{orb}/g)$$

$w = w(Re)$ **Depends on Reynolds number**

Does not depend on floe size (and not much on ice thickness)

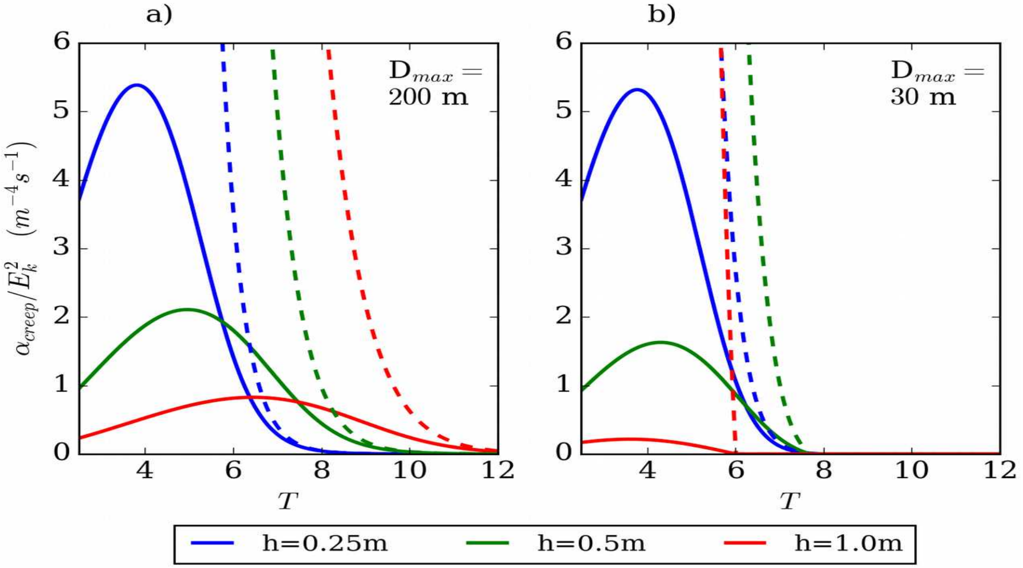
Creep

(Wadhams, 1973)

Hypothesis : Ice is viscous, it absorbs energy from the waves at a constant rate
Physically : during loading, micro-craks appear an propagate in sea ice.

- **Very strong ice thickness / wave frequency dependency**
- **Once ice is broken, no reason to have creep anymore...**

It exists a value of $\frac{\lambda}{D_{max}}$ at which creep starts to decrease : 0.3

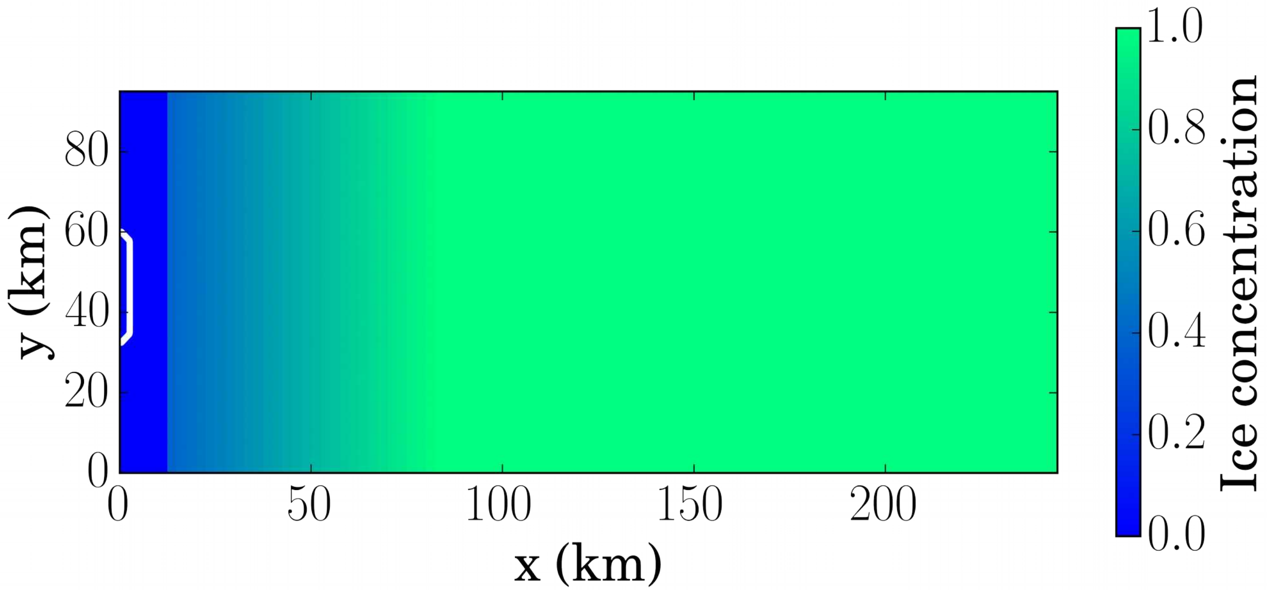


Creep is 0 for $\lambda > 3.33Dmax$

and is « full » for $\lambda < D_{max}$

Tests Set-up

Waves with Hs =3m radiate from the western border



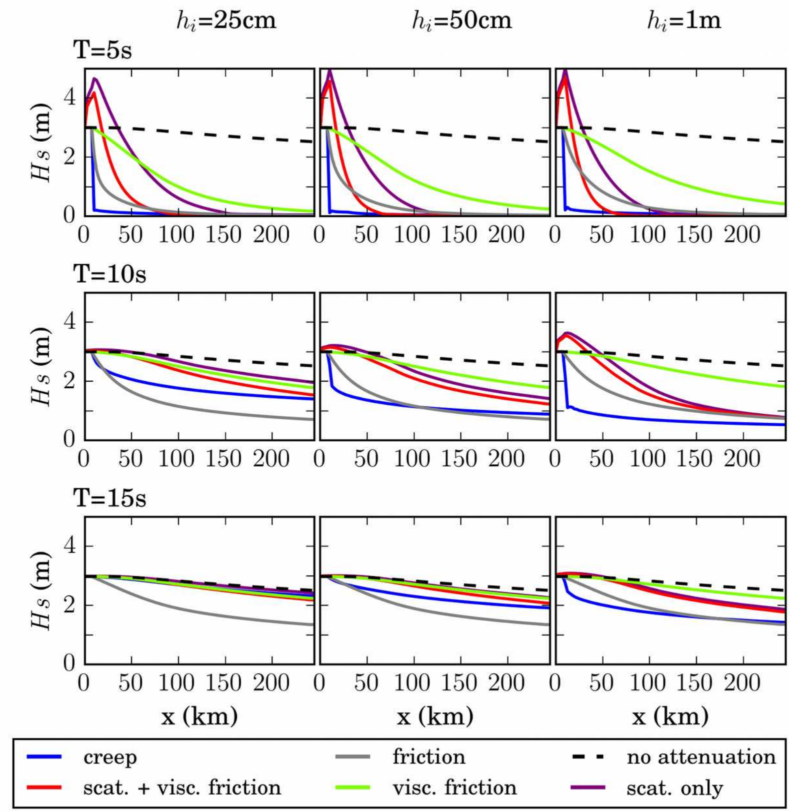
Ice concentration roughly represents a realistic MIZ

Ice thickness is constant

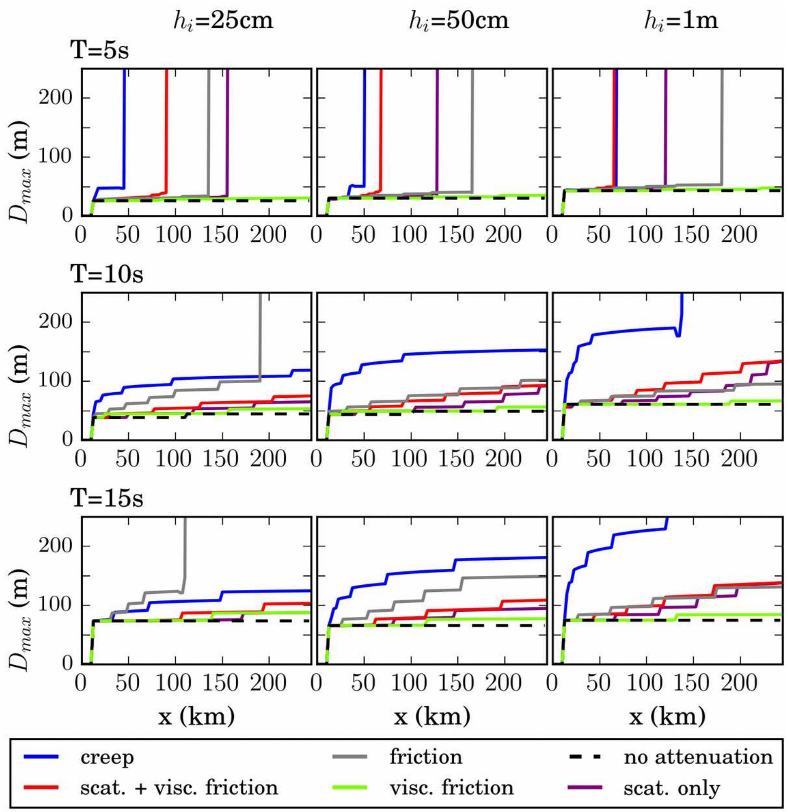
Floes are initially unbroken (Dmax=1000m)

Adding ice in WW3 : Results (Academic Tests)

Hs



Dmax



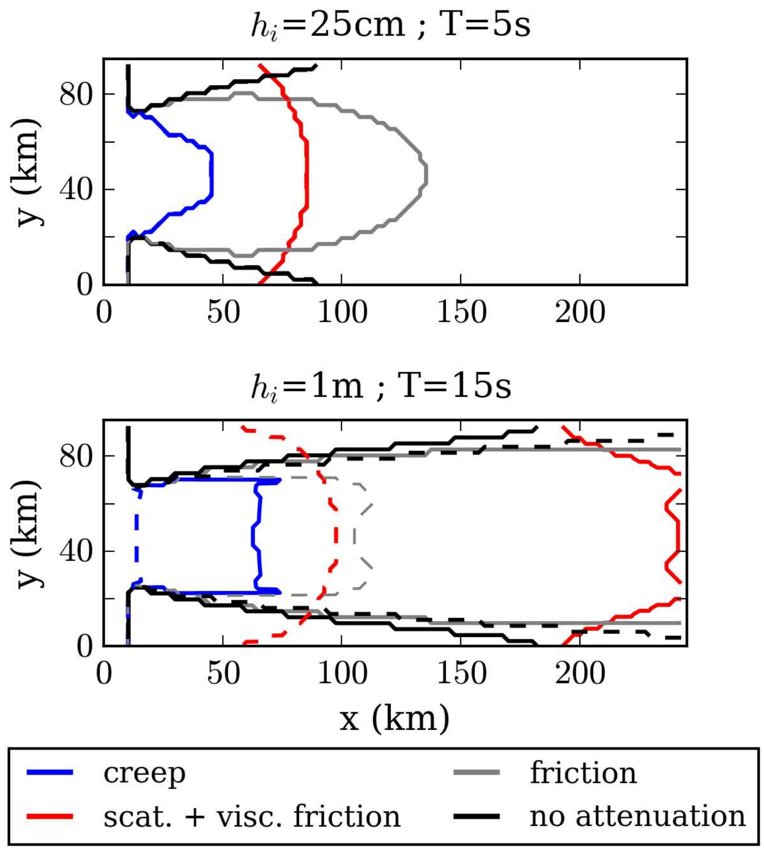
Creep is VERY frequency/thickness dependent

(Boutin et al., submitted)

Scattering can increase wave height at the ice edge

Tests Results

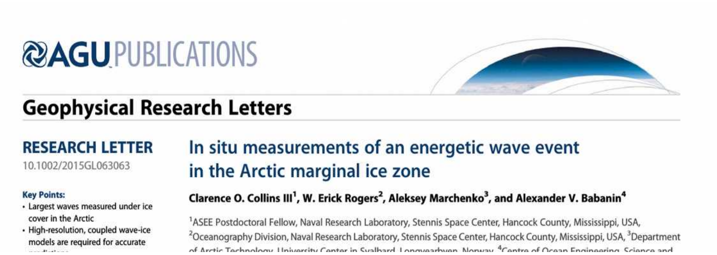
Effect of scattering : increase of the spread



(Boutin et al., submitted)

Academic tests with realistic forcing

Collins et al. (2015)


AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063063

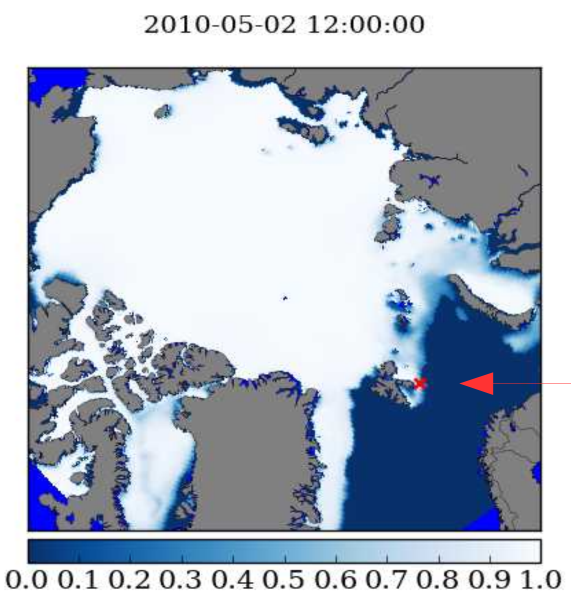
In situ measurements of an energetic wave event in the Arctic marginal ice zone

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

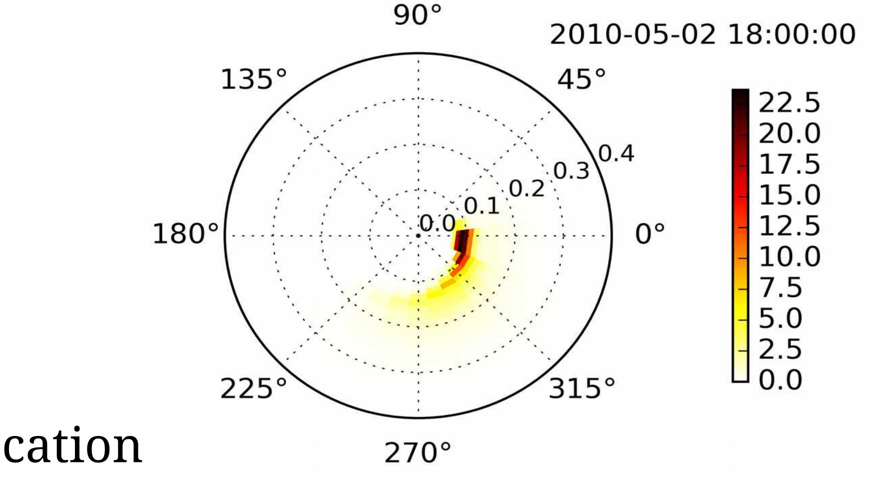
[1]ASEE Postdoctoral Fellow, Naval Research Laboratory, Stennis Space Center, Hancock County, Mississippi, USA, [2]Oceanography Division, Naval Research Laboratory, Stennis Space Center, Hancock County, Mississippi, USA, [3]Department

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

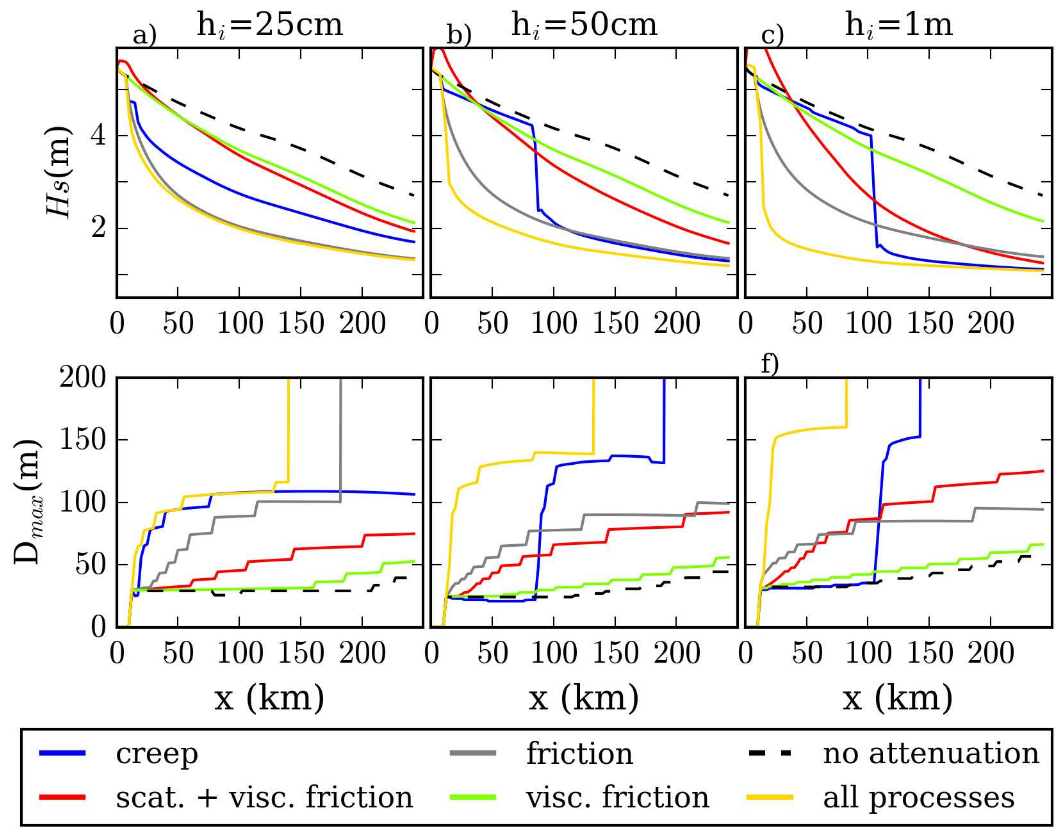


Ship location



Ice thickness : 50-60cm

Academic tests with realistic forcing



(Boutin et al., submitted)

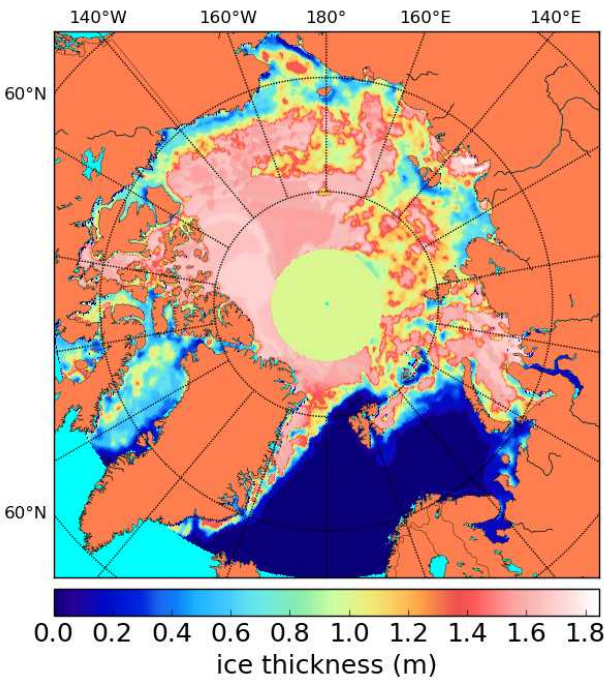
Only creep repdroduces the observations.

How to get ice thickness and concentration

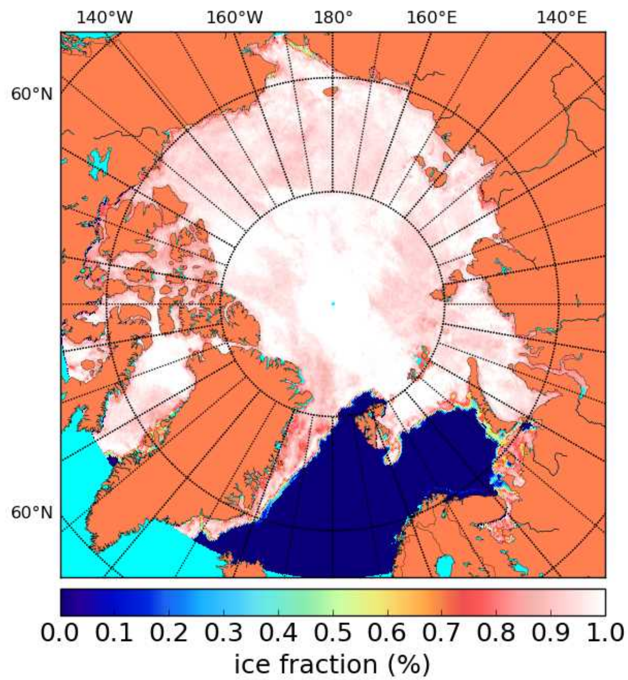
Satellite data forcing :

SSM/I : daily data from 1992

Ice thickness from SMOS



Ice concentration from SSM/I



SMOS : daily data from 2011
BUT only from october to april

Problems !

Missing year / month !
Use of TOPAZ reanalysis

High uncertainties, hole over 85°N !
Use of Cryosat-2 / SMOS merged product

Ice forcing on 2015-02-02 03:00:00 GMT

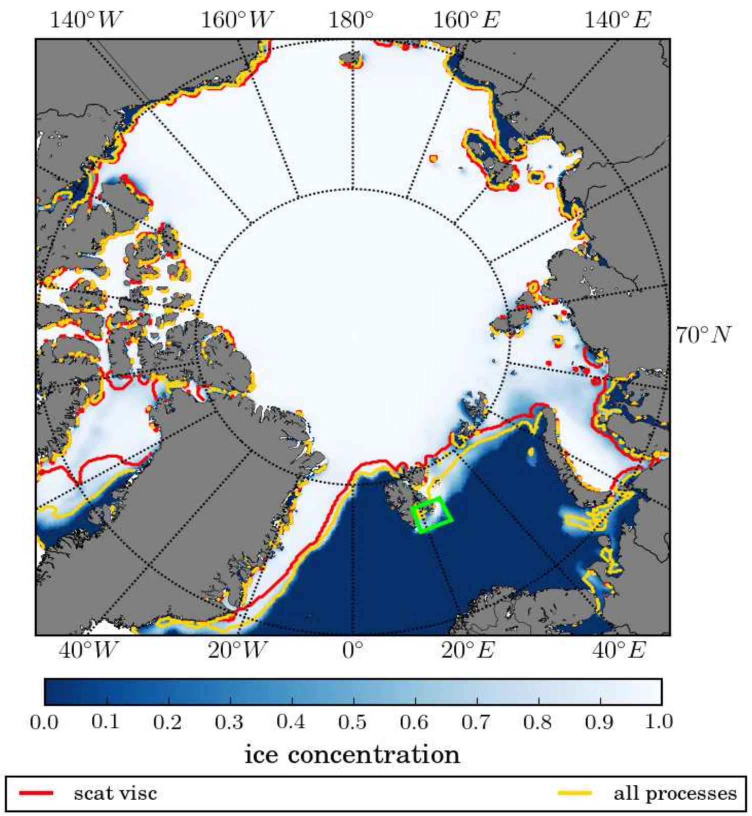
Arctic configuration

How to define the MIZ ?

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

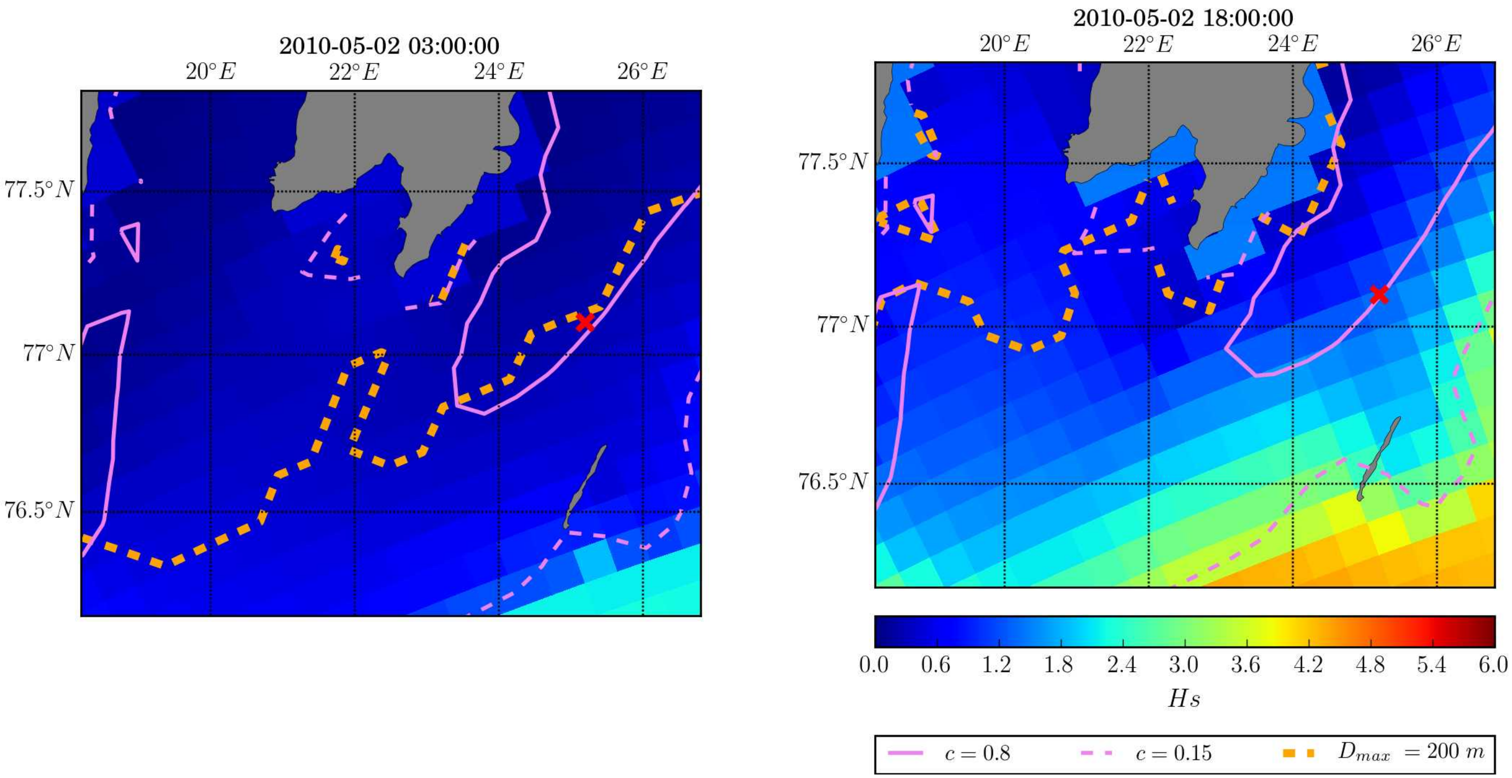
To note: Creep cannot be used « alone » !

Values are in agreement with orders of magnitude expected



Arctic configuration

Collins case with all processes



Break-up occurs but waves are attenuated too much

Limits

Ice types :

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

ONR campaign on Sikuliak

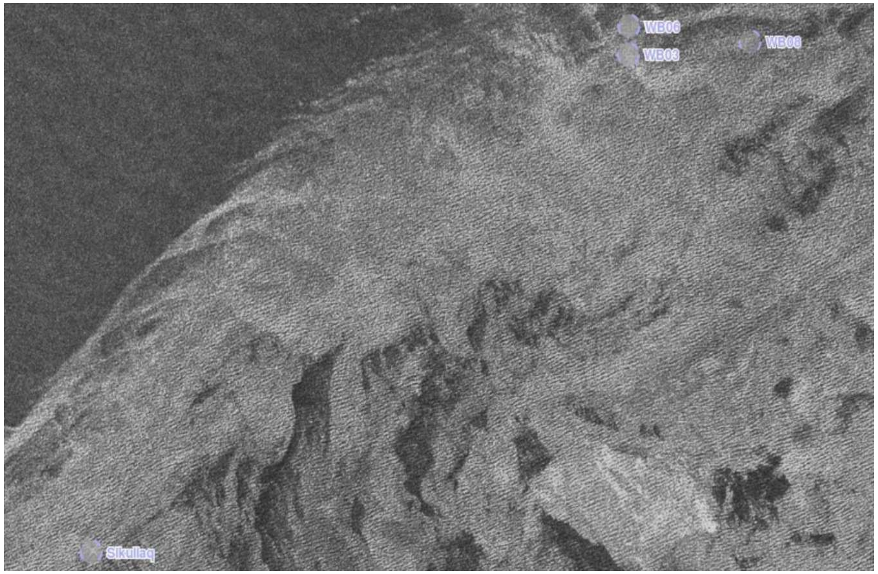
Broken floes :

What do they become after being broken ?

.

Validation :

SAR, buoys...



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

It's the end of the first part

The article was submitted last february → waiting for reviews

By the way, my life as a phd student was also made of :

- formation sessions (communication, ethic...)
- management of a small group of M2 students
- Scientific mediation with my lab.
- Participation to various meetings and to AGU
- Visits et visitors (NOC, UCL, LOCEAN)

Coupling with an ice model : LIM3

- To see how much waves do push the ice (radiative stress)
- What do the broken floes become ?
- Effect of breaking the floes on lateral melting

And find a case study with waves associated with ice decline

Coupling with an ice model : LIM3 (in short)

LIM 3 is an ice model, part of NEMO

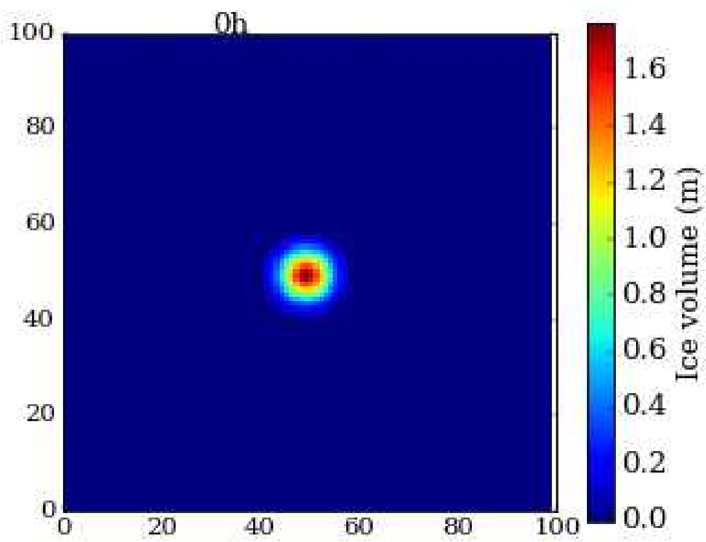
- Ice is divided into different categories depending on thickness.
- advection due to winds and ocean currents
- Ice rheology with internal stress, but without tensile stress
- Various thermodynamic effects

Coupling with an ice model : LIM3

Pushing the ice

Radiative stress (Longuet-Higgins)

When a wave encounters a floating object → Drift force in the direction of the wave



$$\rho_i h \frac{D\mathbf{u}}{Dt} = \nabla \cdot (\boldsymbol{\sigma} h) - \nabla P + \tau_a + \tau_o + \tau_{w,i}$$

(Williams et al., 2017)

Waves from west
Hs=3m,
Tp=6s
pendant 22h

Looks like it works

Coupling with an ice model : LIM3

Advecting the floes

Not as simple as we thought

First idea : Advection of a number of floes (bad idea) (Williams et al., 2017)

Idea from last friday : Division of the floes in categories depending on Dmax
(Horvat et al.,2015 ; Zhang et al. 2015)

Melting the floes

Keep coherence between the two models.

Freezing the floes

Well, we were told not to try without a very good idea...

Case study

To quantify the impact of waves relatively to other processes :

A «good» case shoud combine :

- Waves
- Ice decline
- No fast freeze-up
- Data available for validation

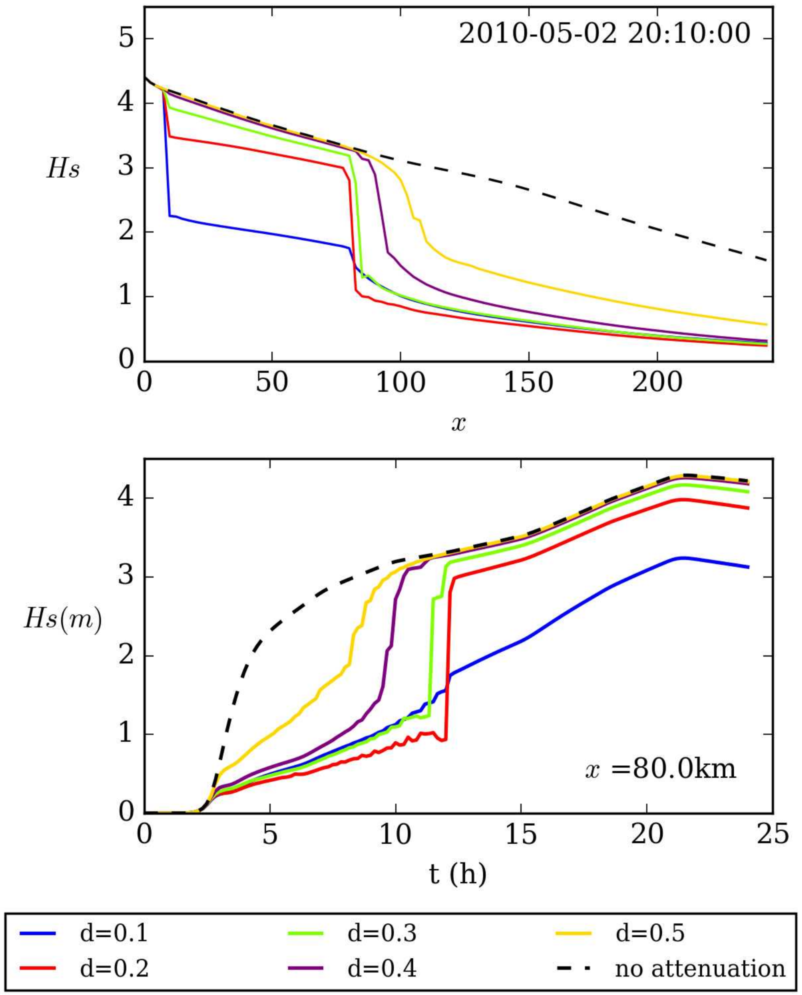
The « Great Storm of 2012 », storms in fall 2006.

Thank you for your attention !

Using the Academic case with real. forcing

Tuning for creep floe parameter :

- Transition which lasts for 1h
- No waves from 3-4m waves



The MIZ in WW3

Floe size distribution (Totoya et al, 2011):

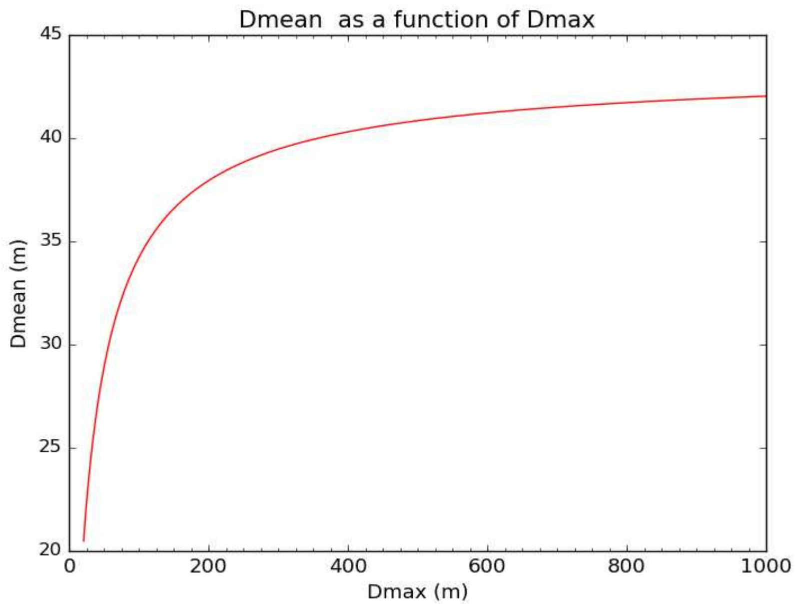
It is assumed that $\gamma = 2 + \log_{\xi}(f)$

f Is the probability that a floe breaks , set to 0.9

We need to know the average value of floes diameter.

For a power-law :

$$\overline{D} = \frac{\gamma}{\gamma - 1} \times \frac{D_{max}^{-\gamma+1} - D_{min}^{-\gamma+1}}{D_{max}^{-\gamma} - D_{min}^{-\gamma}}$$



Dmin = 20m (Kohout and Meylan, 2008)

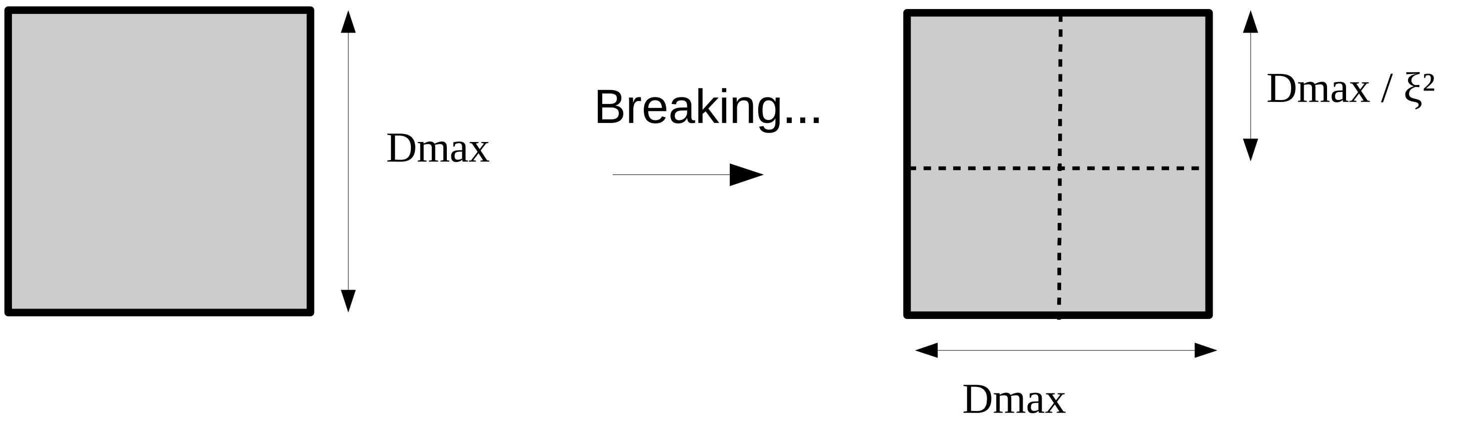
The MIZ in WW3

Floe size distribution (Totoya et al, 2011):

The FSD is driven by the waves :

Initially, I have one big squared floe :

After breaking, I have ξ new floes :
(we set ξ=2)



So, I can have up to M fragmentation : $M = log_{\xi}(\frac{D_{max}}{D_{min}})$