Spectral modelling of ice-induced wave decay: implementation of a viscoelastic theory in WAVEWATCH III

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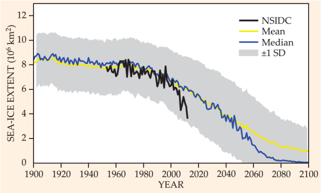
Contents

1. Introduction

Satellite records clearly revealed the continuous decline of the Arctic sea ice extent and thickness over the past several decades (e.g., Maslanik et al. 2007, 2011).

The contemporary climate models, however, generally fail to capture such rapid loss of the Arctic ice cover (e.g., Stroeve et al. 2012, Overland et al. 2013).



Decline of SIE (Jeffries et al. 2013)

Effects of waves on sea ice

- the fracture and breakup of ice by strong waves (e.g., Doble & Bidlot 2013; Collins et al. 2015)
- positive wave-ice feedback (Thomson and Rogers 2014): ice retreat → H_s increase → ice retreat

1. Introduction

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How to quantify the impacts of waves on ice

1. how much wave energy penetrates into the ice field (H_s)
2. how long the attenuation scales of these incident wave energy are (α)
3. . . .

> A spectral wave model with reasonable parameterizations of the influences of ice on waves, particularly the *ice-induced wave decay*

2. Previous work on Wave-Ice Interaction

2.1 Spectral Wave Modeling in Ice-free Waters

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The radiative transfer equation (RTE) for **WAVEWATCH III** (WW3):

$$\frac{\partial N}{\partial t} + \nabla \cdot \dot{\vec{x}} N + \frac{\partial}{\partial \sigma} \dot{\sigma} N + \frac{\partial}{\partial \theta} \dot{\theta} N = \frac{\mathcal{S}_{\mathcal{T}}}{\sigma},$$

$$\mathcal{S}_{\mathcal{T}} = S_{in} (+S_{swl}) + S_{ds} + S_{nl} + \cdots,$$

$$\sigma^2 = gk \tanh(kd),$$

- S_{in} wind input (e.g., Janssen 1991, Donelan et al. 2006)
- S_{ds} whitecapping dissipation (e.g., Komen et al. 1984, Babanin 2011)
- S_{nl} four-wave interaction (Hasselmann 1962)
- S_{swl} Swell dissipation (e.g., Ardhuin et al. 2010, Babanin 2011)
- $\cdots$ See Young (1999), Holthuijsen (2007) and Cavaleri et al. (2007) for more details.

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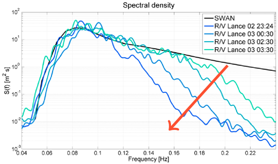
When ocean waves impinge on ice floes or ice packs:

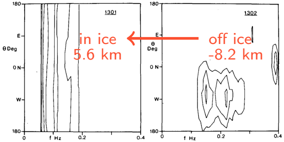
1. wave energy decays exponentially with distance (e.g. Wadhams et al. 1986, 1988; Meylan et al., 2014), according to (α in m^{-1})

$$\frac{1}{F(f,x)}\frac{\mathrm{d}F(f,x)}{\mathrm{d}x} = -\alpha(f,\mathcal{I}),$$

2. dispersion relation may differ significantly from that for linear wave theory (e.g., Collins et al. 2016)
3. directional properties of the wave fields are also modified (e.g., Wadhams et al., 1988; Sutherland & Gascard, 2016)



Low-pass filter (Collins et al. 2015)



Spread effect (Wadhams et al. 1986)

2. Previous work on Wave-Ice Interaction

2.3 Introducing Ice Effects into RTE

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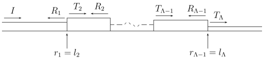
The RHS of RTE can be modified as (Masson and Leblond 1989)

$$\mathcal{S}_{\mathcal{T}} = (1 - \mathcal{C}_{\mathcal{I}}) \cdot (S_{in} + S_{ds}) + S_{nl} + S_{ice} + \cdots ,$$

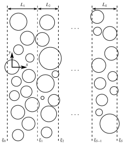
where $\mathcal{C}_{\mathcal{I}}$ is ice concentration. [Further reading: Polnikov & Lavrenov (2007), Rogers et al. (2016).]

The physical processes related to S_{ice}

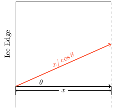
- the conservative scattering process (e.g.,Wadhams et al. 1986, Kohout and Meylan 2008, Montiel et al., 2016);
- dissipative processes: creep hysteresis losses (Wadhams 1973), viscous effects (e.g., Weber 1987; Liu and Mollo-Christensen 1988, Keller 1998), overwash near the floes front (Toffoli et al. 2015), floe collisions and breakup (Collins et al. 2015), etc.



2D scattering (Kohout and Meylan 2008)



3D scattering (Montiel et al., 2016)



Path length effect (Wadhams et al. 1986)

2. Previous work on Wave-Ice Interaction

2.3 Introducing Ice Effects into RTE

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Parameterization of S_{ice} (Meylan and Masson 2006; Zhao and Shen 2016):

$$S_{ice} = \mathcal{B}_{\vartheta} S_{ice}^{\vartheta} + \mathcal{B}_s S_{ice}^{s} + \mathcal{B}_d S_{ice}^{d},$$

$$S_{ice}^{\vartheta}(\sigma, \theta; \vec{x}, t) = \mathcal{C}_{\mathcal{I}} \cdot c_g \int_0^{2\pi} \mathcal{S}_{\mathcal{K}}(\sigma, \theta, \vartheta; \vec{x}, t) F(\sigma, \vartheta; \vec{x}, t) \mathrm{d}\vartheta,$$

$$S_{ice}^{s}(\sigma, \theta; \vec{x}, t) = -\mathcal{C}_{\mathcal{I}} \cdot c_g \alpha_s(\sigma, \theta; \vec{x}, t) F(\sigma, \theta; \vec{x}, t),$$

$$S_{ice}^{d}(\sigma, \theta; \vec{x}, t) = -\mathcal{C}_{\mathcal{I}} \cdot c_g \alpha_d(\sigma, \theta; \vec{x}, t) F(\sigma, \theta; \vec{x}, t),$$

- S_{ice}^{ϑ} wave amplification by scattering of waves incident in other directions (ϑ);
- S_{ice}^{s} wave attenuation by scattering of wave incident in the θ direction;
- S_{ice}^{d} wave attenuation caused by dissipative processes;
- $\mathcal{S}_{\mathcal{K}}$ scattering kernel;
- α_s The scattering-induced attenuation rate [i) $= \int_0^{2\pi} \mathcal{S}_{\mathcal{K}}(\sigma, \vartheta, \theta; \vec{x}, t) \mathrm{d}\vartheta$), ii) approximated from 2D scattering model];
- α_d The the dissipation-related attenuation rate.
- $\mathcal{B}$ Binary parameter [0, 1]

2. Previous work on Wave-Ice Interaction

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2.4 Previous Studies on Parameterization of S_{ice}

Previous work on the parameterization of S_{ice} ($S_{ice}^{\vartheta}, S_{ice}^{s}, S_{ice}^{d}$) in wave and ice models, and the corresponding theories.

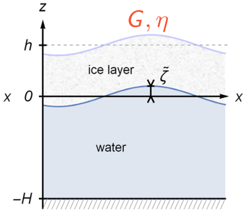
Study	S_{ice}^{ϑ}	S_{ice}^{s}	S_{ice}^{d}	Ice Properties
Masson and Leblond (1989) Perrie and Hu (1996)	Masson and Leblond (1989)	Masson and Leblond (1989)	Masson and Leblond (1989)	$\mathcal{C_I}, h_i, \mathcal{D_F}, \widetilde{\alpha_d}$
Meylan et al. (1997)	Meylan and Squire (1996)	Meylan and Squire (1996)	Meylan et al. (1997)	$\mathcal{C_I}, h_i, \mathcal{D_F}, \widetilde{\alpha_d}$
Dumont et al. (2011)	/	Kohout and Meylan (2008)	/	$\mathcal{C_I}, h_i, \mathcal{D_F}$
Doble and Bidlot (2013)	/	Kohout and Meylan (2008)	Kohout et al. (2011)	$\mathcal{C_I}, \mathcal{D_F}, \eta$
Williams et al. (2013)	/	Bennetts and Squire (2012)	Robinson and Palmer (1990)	$\mathcal{C_I}, h_i, \mathcal{D_F}, \eta$
Rogers and Orzech (2013)	/	/	Liu and Mollo-Christensen (1988)	$\mathcal{C_I}, h_i, \eta$
Rogers and Zieger (2014) Rogers et al. (2016)	/	/	Wang and Shen (2010)	$\mathcal{C_I}, h_i, G, \eta$
Ardhuin et al. (2017)	Meylan and Masson (2006)	Kohout and Meylan (2008)	Wadhams (1973)	$\mathcal{C_I}, h_i, \mathcal{D_F}, \mathcal{C_P}$

To sum up:

- neglect S_{ice}^{ϑ} when necessary
- scattering theory (S_{ice}^{s} with/without S_{ice}^{ϑ}) alone $\rightarrow$ underestimation of the attenuation of long waves
- under certain ice conditions, some standalone dissipative theories (e.g., Liu and Mollo-Christensen 1988, Wang and Shen 2010) work reasonably well
- advect wave packets with c_g from the linear wave theory

3. FS Viscoelastic (VE) Ice Layer Model

The sketch of the viscoelastic models:



Rheological params.:

- G: shear modulus (Pa)
- η: viscosity (m^2 s^{-1})
- $G_\eta = G - i\sigma\rho_i\eta$

Complex wavenumber:

- $\kappa = k_r + ik_i$
- $k_i = \alpha/2$

The WS VE models (Wang and Shen 2010):

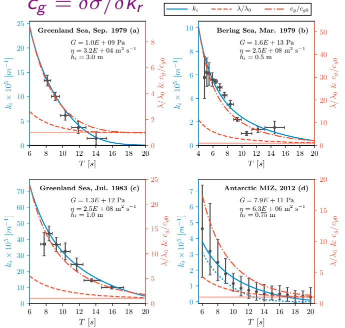
- **IC3** in WW3;
- good performance but difficult to solve numerically
- more than one root of geophysical relevance
- Rogers & Zieger (2014), Li et al. (2015), Mosig et al. (2015), Rogers et al. (2016)

The FS model & its dispersion relation (Mosig et al. 2015):

$$Qg\kappa\tanh(\kappa d) - \sigma^2 = 0,$$

$$Q = \frac{G_\eta h_i^3}{6\rho_w g}(1+\nu)\kappa^4 - \frac{\rho_i h_i \sigma^2}{\rho_w g} + 1,$$

$c_g = \delta\sigma/\delta k_r$



k_i, λ/λ_0 & c_g/c_{g0} vs T.

3. FS Viscoelastic (VE) Ice Layer Model

Implementation of the FS model in WW3

S_{ice} is simply parameterized as

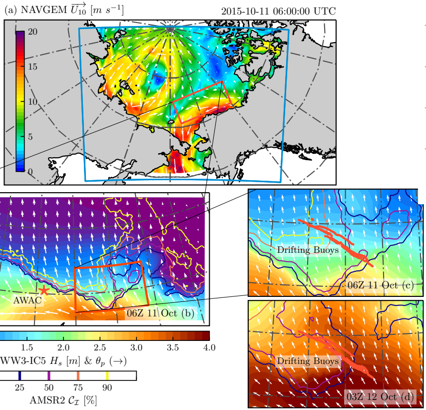
$$S_{ice} = S^{d}_{ice} = -2\mathcal{C}_{\mathcal{I}} \cdot c_g k_i(\sigma; \vec{x}, t) F(\sigma, \theta; \vec{x}, t). \qquad (1)$$

1. still use the ice-free group velocity c_{g0} to advect wave packets;
2. no complementary scattering terms used at this stage (i.e., $\mathcal{B}_{\vartheta} = \mathcal{B}_s = 0$);
3. implemented as **IC5** in WW3.

4. Numerical Simulations of Waves in Ice

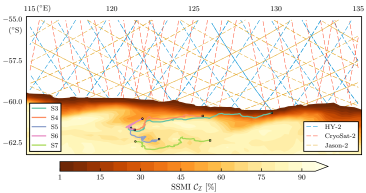
Two case studies

R/V Sikuliaq Cruise 2015 ($h_i = 0.15$ m)



Four-day storm event, Oct 2015 (Rogers et al. 2016, Wadhams and Thomson 2015)

SIPEX II Voyage 2012 ($h_i = 0.75$ m)



∼20-day obs. of waves in ice (Sep/Oct) (Kohout et al. 2014)

- Sikuliaq: 2-curvilinear-grid system
- SIPEX: traditional lon-lat grid

4. Numerical Simulations of Waves in Ice

Sensitivity of H_s on other source terms

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S_{in}, S_{ds} and S_{nl} (S_{other}) are customarily neglected by field experimentalists and ice modellers (e.g., Wadhams et al. 1986, 1988; Squire and Montiel 2016, among others).

However, S_{nl} (and S_{in}) may be important, particularly for large, storm-generated waves ($H_s > 3$ m) (Li et al. 2015).

Further sensitivity studies of simulated H_s to S_{other}:

$$\mathcal{S}_{\mathcal{T}} = \Psi_{in}(1 - \mathcal{C}_{\mathcal{I}}) \cdot S_{in} + \Psi_{ds}(1 - \mathcal{C}_{\mathcal{I}}) \cdot S_{ds} + \Psi_{nl} S_{nl} + S_{ice},$$

where the binary switch Ψ is given by

$$\Psi = \begin{cases} 1 & \text{for } \mathcal{C}_{\mathcal{I}} = 0 \\ \psi & \text{for } \mathcal{C}_{\mathcal{I}} > 0 \end{cases}. \tag{2}$$

$\psi = 1$ (or $\psi_{in} = \psi_{ds} = \psi_{nl} = 1$) — full utilization of S_{other};
$\psi = 0$ (or $\psi_{in} = \psi_{ds} = \psi_{nl} = 0$) — switch off S_{other} in ice-infested seas

5. Results & Discussions

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For each case, we present results from 3 different simulations:

full simulation : $\psi = 1$, non-zero[†] h_i (optimal G and η minimize the RMSE of simulated H_s)[‡]

zero-S_{other} simulation : $\psi = 0$ and the same h_i

zero-S_{ice} simulation : $\psi = 1$, $h_i = 0$ m

[†] $h_i = 0.15,\ 0.75$ m for the Sikuliaq and SIPEX cases, respectively

[‡] typically requires $\mathcal{O}(10^2)$ model runs

5. Results & Discussions

5.1 R/V Sikuliaq Cruise 2015

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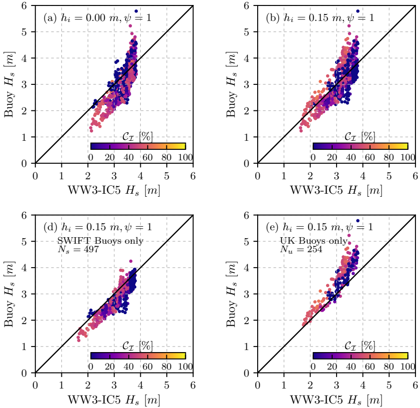

a) zero-S_{ice} simul.

b) full simul.

c) zero-S_{other} simul.

d) full/SWIFT only

e) full/UK only

Case	ψ	h_i [m]	N	$b^\dagger$ [m]	ε [m]	ρ	SI
Sikuliaq Cruise 2015	1	0.00	751	0.21	0.51	0.82	0.15
$G = 10^7$ Pa	—	**0.15**	—	**0.01**	**0.45**	**0.79**	**0.14**
$\eta = 4 \times 10^3$ m^2 s^{-1}	0	—	—	-0.09	0.48	0.76	0.15

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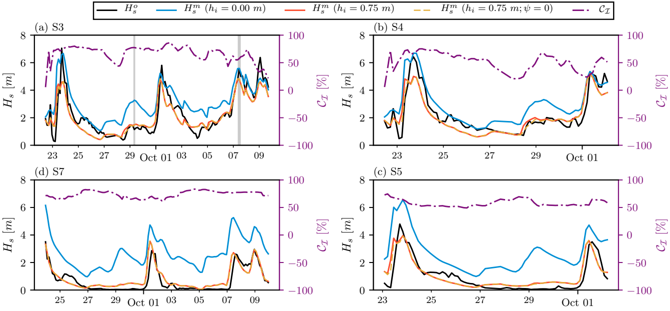

obs / zero-S_{ice} simul. / full simul. / zero-S_{other} simul. / $\mathcal{C}_\mathcal{I}$

Case	ψ	h_i [m]	N	$b^\dagger$ [m]	ε [m]	ρ	SI
SIPEX II Voyage 2012	1	0.00	400	1.35	1.65	0.80	0.59
$G = 4 \times 10^{10}$ Pa	—	**0.75**	—	**0.00**	**0.67**	**0.91**	**0.41**
$\eta = 1.6 \times 10^5$ m^2 s^{-1}	0	—	—	-0.04	0.62	0.93	0.38

5. Results & Discussions

5.3 Impact of other source terms S_{other}

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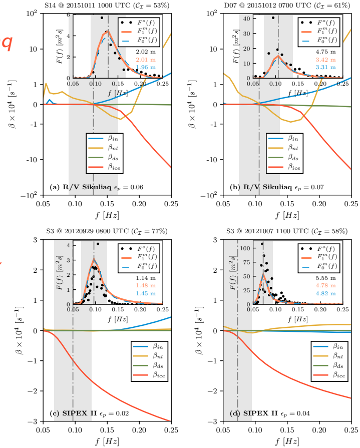
Based on the ε, it can be inferred that

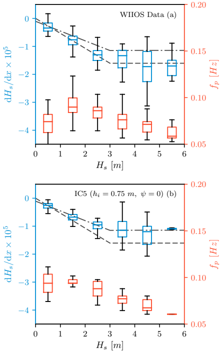
- Sikuliaq: S_{other} could be half as important as S_{ice}
- SIPEX: S_{other} may be discarded without noticeable loss in the model accuracy

Sikuliaq

SIPEX



Growth rate $\beta = S_{xx}/F$ vs f



SIPEX Obs.

Kohout et al. (2014)

dashed line

SIPEX

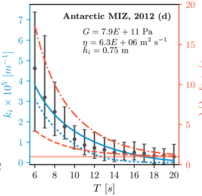
zero-S_{other} simul.

dash-dotted line

Box-and-whisker plots of dH_s/dx and f_p (red box with black whiskers), as a function of H_s.

5. Results & Discussions

5.3 Impact of other source terms S_{other}



Based on the ε, it can be inferred that

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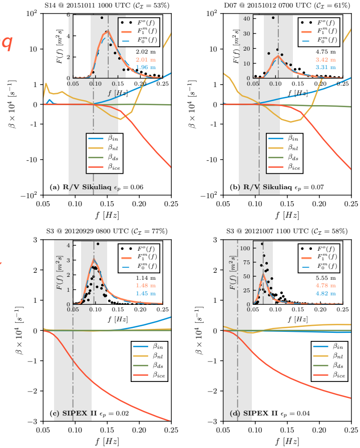
Sikuliaq

SIPEX



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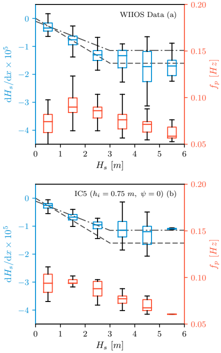

SIPEX Obs.

Kohout et al. (2014)

dashed line

SIPEX

zero-S_{other} simul.

dash-dotted line

Box-and-whisker plots of dH_s/dx and f_p (red box with black whiskers), as a function of H_s.

5. Results & Discussions

5.4 Limitations of the FS model

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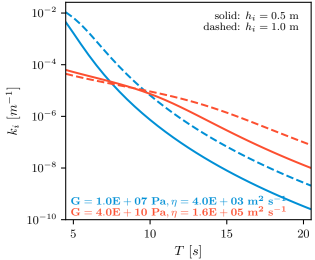
- Originally designed for *continuous shore fast ice* (Fox and Squire 1994), later extended in Mosig et al. (2015) by adding viscous effect → never intended to be used for *a dynamic marginal ice zone (MIZ)*.
- Highly simplified and totally empirical parameterization, and the two tuning rheological parameters G and η do not necessarily related to the physical properties of sea ice.
- A less intuitive feature: for some typically-large values of the shear modulus G, k_i does not vary monotonically with h_i.



6. Conclusions

1. A brief review of the previous work on the parameterizations of S_{ice}
2. Implementation of the FS model in WW3
3. Two case studies in MIZs
4. Sensitivity studies of simulated H_s to S_{ice} and S_{other}
5. Explanation of the linear decay of $\mathrm{d}H_s/\mathrm{d}x$ for large waves ($H_s > 3$ m) as reported in Kohout et al. (2014)
6. Limitations of the FS model

Thank you !