Spectral modelling of ice-induced wave decay: implementation of dissipative ice theories in WAVEWATCH III

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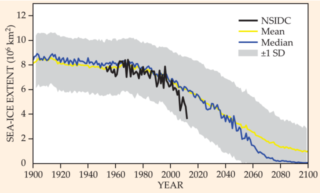
1. Introduction

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
- wave-induced mixing (e.g., Qiao et al. 2004, Babanin 2011, ch. 9, Cavaleri et al. 2012)

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 far these wave energy could travel into the ice field (α)
3. among others

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

2. Previous Works on Wave-Ice Interactions

2.1 Spectral Wave Modeling in Ice-free Waters

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

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

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

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

- S_{in} wind input (e.g., Janssen 1991, Tolman & Chalikov 1996, Donelan et al. 2006)
- S_{ds} whitecapping dissipation (e.g., Komen et al. 1984, Babanin 2011)
- S_{nl} resonant four-wave interactions (Hasselmann 1962)
- $\cdots$ see Young (1999), Holthuijsen (2007) and Cavaleri et al. (2007, 2018) for more details.

2. Previous Works on Wave-Ice Interactions

2.2 Ice effects on Waves

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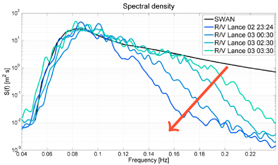
When ocean waves impinge on ice floes/packs:

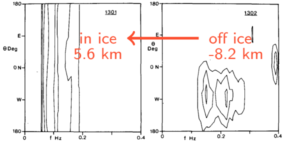
1. wave energy decays exponentially with distance (e.g. Wadhams et al. 1986, 1988; Meylan et al., 2014), according to (α in m^{-1})

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

2. dispersion relation may differ significantly from that for the open-water, linear wave theory (e.g., Collins et al. 2016)
   - however, open-water dispersion relation may hold up to 0.3 Hz (Sutherland & Rabault 2016, Collins et al. 2018)
3. directionality 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 due to scattering (Wadhams et al. 1986)

2. Previous Works on Wave-Ice Interactions

2.3 Introducing Ice Effects into RTE

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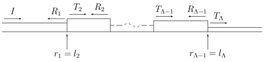
The RHS of RTE can be modified as (Masson and Leblond 1989)

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

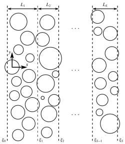
where C_I is ice concentration. [Further reading: Polnikov & Lavrenov (2007), Rogers et al. (2016)].

The physical processes related to S_{ice}

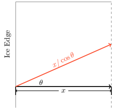
1. the conservative scattering process (e.g.,Wadhams et al. 1986, Kohout and Meylan 2008, Montiel et al., 2016);
2. dissipative processes: creep hysteresis losses (Wadhams 1973), viscous effects (e.g., Weber 1987; Liu and Mollo-Christensen 1988, Keller 1998), overwash near the floes front (Toffoli et al. 2015), floe collisions and breakup (Collins et al. 2015), sea ice turbulence (Voermans et al. 2019), etc.



2D scattering (Kohout and Meylan 2008)



3D scattering (Montiel et al., 2016)



Path length effect (Wadhams et al. 1986)

2. Previous Works on Wave-Ice Interactions

2.3 Introducing Ice Effects into RTE

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

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

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

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

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

- S_{ice}^ϑ scattering-induced amplification of wave energy along other directions ($\vartheta \neq \theta$)
- S_{ice}^s scattering-induced attenuation of forward-going wave energy
- S_{ice}^d wave attenuation caused by dissipative processes;
- 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 dissipation-related attenuation rate.
- $\mathcal{B}$ Binary parameter [0, 1]

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2.4 Previous Studies on Parameterization of S_{ice}

Previous works on the parameterization of S_{ice} (S^{ϑ}_{ice}, S^{s}_{ice}, S^{d}_{ice}) in wave and ice models and the corresponding theories.

Study	S^{ϑ}_{ice}	S^{s}_{ice}	S^{d}_{ice}	Ice Properties
Masson and Leblond (1989) Perrie and Hu (1996)	Masson and Leblond (1989)	Masson and Leblond (1989)	Masson and Leblond (1989)	C_I, h_i, D_F, η
Meylan et al. (1997)	Meylan and Squire (1996)	Meylan and Squire (1996)	Meylan et al. (1997)	C_I, h_i, D_F, η
Dumont et al. (2011)	/	Kohout and Meylan (2008)	/	C_I, h_i, D_F
Doble and Bidlot (2013)	/	Kohout and Meylan (2008)	Kohout et al. (2011)	C_I, D_F, η
Williams et al. (2013)	/	Bennetts and Squire (2012)	Robinson and Palmer (1990)	C_I, h_i, D_F, η
Rogers and Orzech (2013)	/	/	Liu and Mollo-Christensen (1988)	C_I, h_i, η
Rogers and Zieger (2014) Rogers et al. (2016)	/	/	Wang and Shen (2010)	C_I, h_i, G, η
Collins and Rogers (2017)	/	Horvat and Tziperman (2015)	Meylan et al. (2014) Kohout et al. (2014) Doble et al. (2015)	C_I, h_i, η
Boutin et al. (2018)	Meylan and Masson (2006)	Bennetts and Squire (2012)	Wadhams (1973) Liu and Mollo-Christensen (1988) Boutin et al. (2018)	C_I, h_i, D_F, C_P

1. neglect S^{ϑ}_{ice} when necessary (e.g., when scattering is thought unimportant or directional info. is unavailable)
2. scattering theory (S^{s}_{ice} w/o S^{ϑ}_{ice}) alone → underestimation of the attenuation of long waves
3. under certain ice conditions, some standalone dissipative theories (e.g., Liu and Mollo-Christensen 1988, Wang and Shen 2010) work reasonably well
4. advect wave packets with c_g from the linear wave theory

3. Dissipative ice theories

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Ignoring the scattering effect, we focus on the **dissipative ice theories** only in this study. Consequently, S_{ice} is simplified as

$$C_I S_{ice} = C_I S_{ice}^d = -C_I \cdot c_{g0} \alpha_d(\omega; \vec{x}, t) F(\omega, \theta; \vec{x}, t),$$

C_I ice concentration

c_{g0} ice-free group velocity [assuming that the ice-induced change in c_g is not significant, at least for long waves (e.g., Sutherland and Rabaul 2016; Collins et al. 2018)]

α_d dissipation-related attenuation rates

3. Dissipative ice theories

Three dissipative (two *viscoelastic* and one *viscous*) ice theories have been selected and implemented in WW3 as **IC5**:

2.4.5 S_{ice}: Damping by sea ice (Mosig et al.)

Switch:	IC5
Origination:	U. of Otago MATLAB code
Provided by:	Q. Liu, E. Rogers, A. Babanin

WW3 manual (v6.07)

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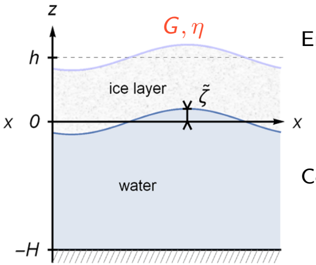
The sketch of the viscoelastic (VE) models (Mosig et al. 2015):



Empirical rheological params.:

- G: shear modulus (Pa)
- η: viscosity ($m^2\ s^{-1}$ or $kg\ m^{-2}\ s^{-1}$)

Complex wavenumber:

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

Under this framework, the dispersion relation is modified as

$$\boxed{Qg\kappa \tanh(\kappa d) - \omega^2 = 0}$$

where ω is radian frequency, d is water depth.

3. Dissipative ice theories

Viscoelastic models: EFS and RP

The extended Fox and Squire model (EFS)

$$Q_{EFS} = \frac{(G - i\omega\rho_i\eta)h_i^3}{6\rho_w g}(1+\nu)\kappa^4 - \frac{\rho_i h_i \omega^2}{\rho_w g} + 1,$$

The Robinson and Palmer model (RP)

$$Q_{RP} = \frac{G h_i^3}{6\rho_w g}(1+\nu)\kappa^4 - \frac{\rho_i h_i \omega^2}{\rho_w g} + 1 - i\frac{\omega\eta}{\rho_w g},$$

where ρ_w (ρ_i) is the density of water (ice), h_i the ice cover thickness, $\nu \simeq 0.3$ the Poisson ratio of sea ice, η in m^2 s^{-1} (EFS) or kg m^{-2} s^{-1} (RP).

Due to their high similarity, the dispersions for the EFS and RP models could be essentially solved by a single solver (Newton-Raphson iterations).

3. Dissipative ice theories

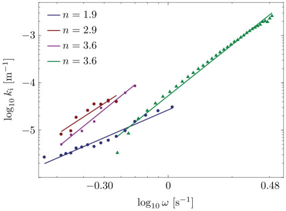
The 3^{rd} viscous model: M2

Meylan et al. (2018) suggested that

under the assumption of weak attenuation (e.g., small G, η and long waves)

$$k_i^{EFS} \overset{\propto}{\sim} \eta h_i^3 \omega^{11}, \quad k_i^{RP} \approx \frac{\eta}{\rho_w g^2}\omega^3$$

Field measurements (e.g., Meylan et al. 2014; Cheng et al. 2017) favor a power law $k_i \propto \omega^n$ with $n \in [2, 4]$.



At low attenuation regime,

1. k_i of the EFS model is too sensitive to ω
2. k_i of the RP model shows no dependence on h_i

Model with Order 3 power law (M2)

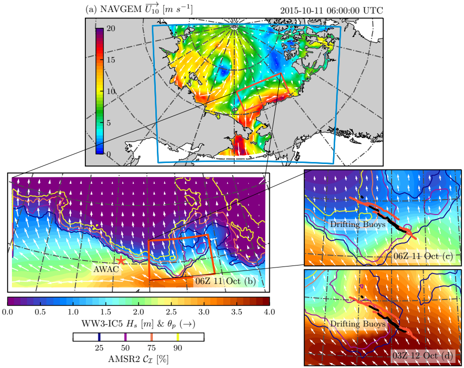
$$k_i^{M2} = \frac{\eta h_i}{\rho_w g^2}\omega^3, \quad (\eta \text{ in kg m}^{-3}\text{s}^{-1})$$

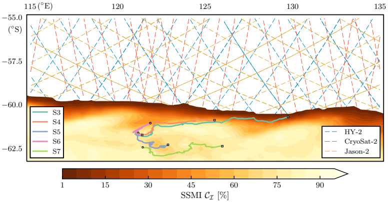
4. Numerical Simulations of Waves in Ice

Two case studies

R/V Sikuliaq Cruise 2015 (Arctic)

SIPEX II Voyage 2012 (Antarctic)





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

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

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

5. Results & Discussions

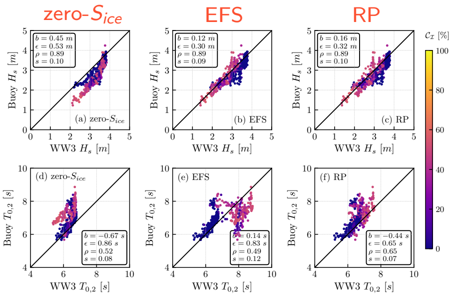
Optimal rheological parameters (G, η) used to fit observations in two selected cases.

Case	Model	h_i (m)	G (Pa)	η	b_{zi}	b_f	b_{zo}	R_I (%)
Sikuliaq	EFS	0.15	**1.0**	$\mathbf{3.2 \times 10^4}$	0.45	0.12	0.06	18
	RP		**1.0**	**2.0**		0.16	0.05	38
	M2		/	**14.0**		0.16	0.05	38
SIPEX	EFS	0.75	$\mathbf{4.0 \times 10^{10}}$	$\mathbf{1.6 \times 10^5}$	1.36	0.00	-0.02	1
	RP		**1.0**	**2.6**		0.01	0.00	1
	M2		/	**4.0**		-0.03	-0.04	1

1. Recall that $k_i^{M2} = \frac{\eta h_i}{\rho_w g^2}\omega^3$ and that at low attenuation regime (e.g., small G, η), $k_i^{RP} \approx \frac{\eta}{\rho_w g^2}\omega^3$, it is immediately clear that for low G and constant h_i, the RP and M2 models will yield very close results given that $\eta^{RP} \simeq \eta^{M2} h_i$.
2. Therefore, unless otherwise necessary, we will show results from one of the RP and M2 models only for limiting the number of plots.

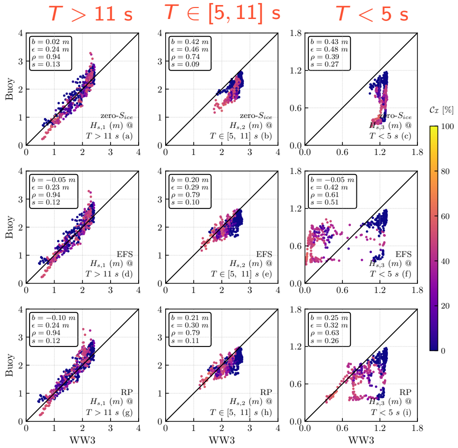
5. Results & Discussions

5.1 R/V Sikuliaq Cruise 2015



Comparison of (top) H_s and (bottom) $T_{0,2}$.

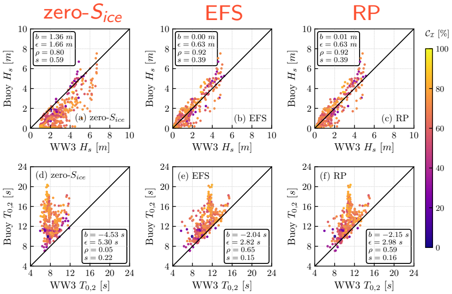
1. the zero-S_{ice} simul. clearly over(under)-estimates H_s ($T_{0,2}$) and severely overpredicts high-frequency energy ($H_{s,3}$)
2. for moderate C_I, the EFS significantly under(over)-estimates $H_{s,3}$ ($T_{0,2}$)
3. the RP (M2) model performs better than the EFS.



Comparison of partial wave height $H_{s,i}$: (top) zero-S_{ice}, (middle) EFS and (bottom) RP.

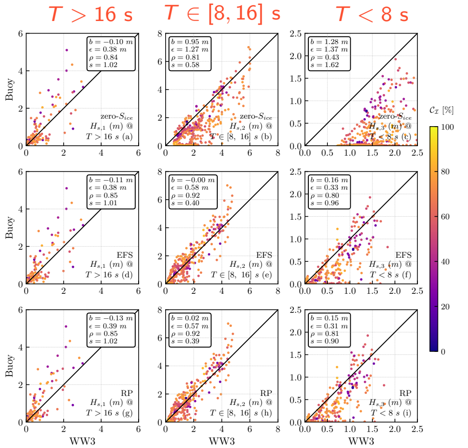
5. Results & Discussions

5.2 SIPEX II Voyage 2012



Comparison of (top) H_s and (bottom) $T_{0,2}$.

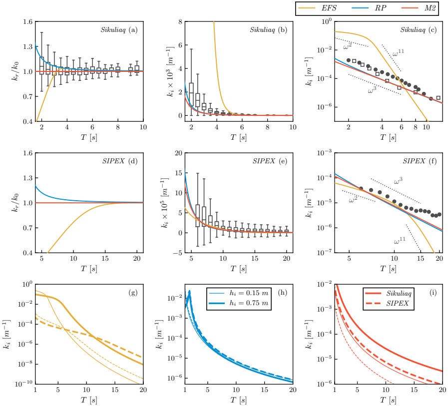
1. Similarly, the zero-S_{ice} simul. clearly over(under)-estimates H_s ($T_{0,2}$) and severely overpredicts high-frequency energy ($H_{s,3}$)
2. the EFS and RP (M2) models perform comparably well at all three frequency bands.



Comparison of partial wave height $H_{s,i}$: (top) zero-S_{ice}, (middle) EFS and (bottom) RP.

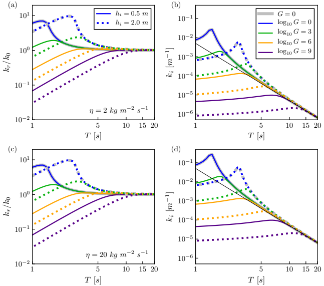
5. Results & Discussions

5.3 Wavenumber k_r and attenuation rate k_i



Close inspection of k_r and k_i estimated by three models: (top) Sikuliaq, (middle) SIPEX and (bottom) dependence of k_i on ice thickness h_i. Boxs and markers denote field observations.

1. Both the RP (low attenuative regime) and M2 models favor $k_i \propto \omega^3$ (as prescribed by the equations), consistent with measurements
2. the EFS model shows two different power laws: $k_i \underset{\sim}{\propto} \omega^2$ ($k_i \propto \omega^{11}$) for short (long) waves
3. The RP shows observation-consistent k_r in the Sikuliaq case



Further exploration of features of the RP model: thin black line for low attenuative approx..

5. Results & Discussions

5.4 Impact of other source terms S_{other}

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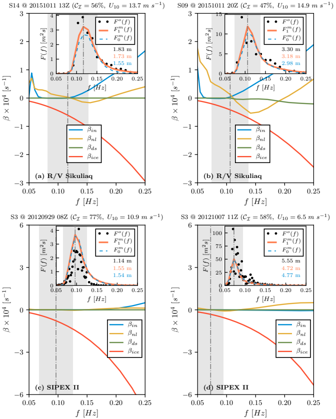
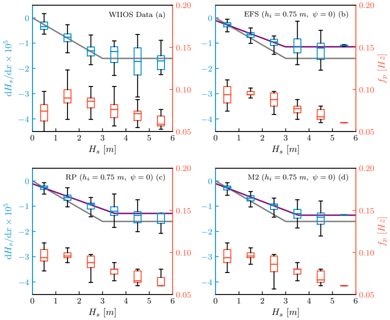
It can be inferred from model results that

- Sikuliaq: S_{other} could be as about 40% important as S_{ice}
- SIPEX: S_{other} may be discarded without noticeable loss in the model accuracy



Growth rate $\beta = S_{xx}/F$ vs f: (top) Sikuliaq, (bottom) SIPEX according to the full RP simul.

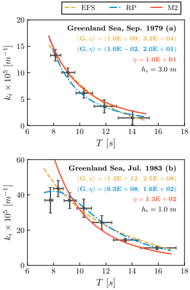


$\mathrm{d}H_s/\mathrm{d}x$ (blue) and f_p (red) as a function of H_s: (a) observations (Kohout et al. 2014), (b-d) zero-S_{other} simul. according to the EFS, RP and M2 models.

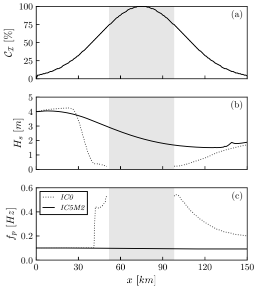
5. Results & Discussions

5.5 Limitations and Operational Forecast

1. The three dissipative ice models are intuitively appealing but practically difficult
   - a MIZ composed of thousands of ice floes, pancake ice and frazil present at different sizes is mapped onto a modified dispersion relation with one/two characterizing parameters (G, η) only
   - operational applications require a priori knowledge of (G, η) which is, unfortunately, unavailable yet at present.
   - the EFS-favored (G, η) sometimes may be unphysically large (left figure below).
2. Operational forecast: the M2 model with predefined viscosity η $[\mathcal{O}(1)]$
   - the M2 model (observation-consistent k_i power law with proper dependence on ice thickness h_i) degrades as a fixed k_i profile — interim solution only
   - Similar fixed k_i profile has been applied routinely in the global and regional wave forecasts at the U.S. Naval Research Laboratory (Rogers et al. 2018a).



Fit IC5 to more historical observations.



A steady JONSWAP spectrum propagates into ice cover

IC0: partial-blocking approach used in most of operational wave models

IC5M2 with predefined η provides continuous evolution of wave event.

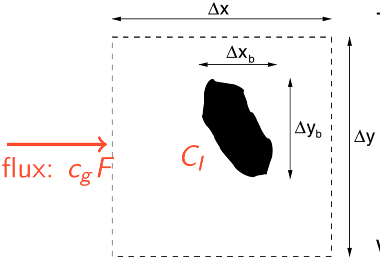
6. Conclusions

1. A brief review of previous works on the parameterizations of S_{ice}
2. Implementation of the EFS/RP/M2 model in WW3
3. Two case studies in MIZs
4. Limitations of the selected ice models and operational forecast

Thank you !

Appendix: Operational wave forecast

How is ice utilized in operational wave forecast models (IC0)?



Chawla & Tolman (2008)

The transparency of a cell boundary α_b:

$$\alpha_b = \begin{cases} 1 & \text{for } C_I < c_0 \\ \frac{c_1 - C_I}{c_1 - c_0} & C_I \in [c_0, c_1] \\ 0 & \text{for } C_I > c_1 \end{cases},$$

where $c_0 = 0.25$ and $c_1 = 0.75$. Thus, energy flux: $c_g F \rightarrow \alpha_b c_g F$ (Tolman 2003)

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 (Li et al. 2015).

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

$$\begin{aligned} \mathcal{S}_{\mathcal{T}} &= \Psi \cdot [(1 - C_I) \cdot (S_{in} + S_{ds}) + S_{nl}] + S_{ice}, \\ &= \Psi \cdot S_{other} + S_{ice}, \end{aligned}$$

where the binary switch Ψ is given by

$$\Psi = \begin{cases} 1 & \text{for } C_I = 0 \\ \psi & \text{for } C_I > 0 \end{cases}.$$

$\psi = 1$ full utilization of S_{other}

$\psi = 0$ switch off S_{other} in ice-infested seas