Ocean waves in sea ice: dependence of dissipation on ice thickness for coupled wave modeling

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Outline

- Slides 3-23 - Dissipation of waves by sea ice
- Slides 24-31 - Ambient noise from breaking waves

Background: empirical parameterizations

We have implemented empirical/parametric forms of the spectral dissipation by sea ice in the two most commonly-used phase-averaged wave models:

- WAVEWATCH III: Collins and Rogers (2017), Rogers et al. (2018a,b)
- SWAN: Rogers (2019), Rogers (2021)

SWAN and WW3* are able to read in two "field variables" related to ice :

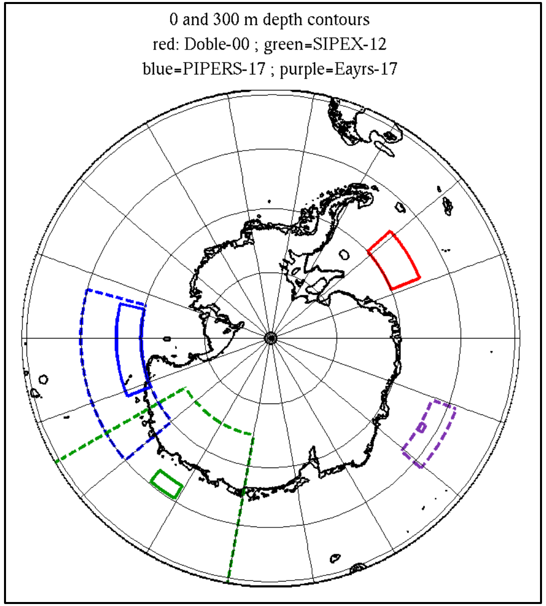
1. Ice fraction, a_{ice}
2. Ice thickness, h_{ice}

*WW3 includes other variables too

Prior Literature

Wave-ice interaction in the southern hemisphere

- Early work by Robin 1959+.
- Important work by Doble and others 2000+.
- Kohout and Meylan: 2012+
- Eayrs and others: 2017
- Kohout and others: 2017 (this study)
- Ardhuin et al.: 2018 (GRL 2020)
- Voermans and others (2020) (landfast ice) (TC 2021)



Pioneer: Robin (PTRSL 1963)

WAVE PROPAGATION THROUGH FIELDS OF PACK ICE

By G. de Q. Robin
Scott Polar Research Institute, Cambridge

(*Communicated by G. E. R. Deacon, F.R.S.—Received* 18 *May* 1962)

- Weddell Sea 1959-1960
- Ship-borne measurements
- Detailed information, but difficult to interpret, due to myopia characteristic of the era
- Finding: for longer waves (T>11 s), dissipation is primarily controlled by wavelength and ice thickness

Phil. Trans. A, volume 255, *plate* 3

Figure 2. Small ice floes from navigating bridge at lat. 67·4° S, on return voyage, estimated at 0·5 to 0·75 m thick, 5 to 20 m diameter (see table 1).

Applications of this dataset

Wave data collected from deployments during the "PIPERS" cruise, April-June 2017, *R/V Palmer*, to/from Ross Sea

- Kohout et al. (A. Glaciology 2020). Focus is on dissipation of total wave energy, i.e. significant waveheight; "geometric method" used to estimate dissipation.
- Rogers et al. (CRST 2021). Focus is on frequency dependence of dissipation, and correlation with other variables (e.g. ice thickness); "inversion method" used to estimate dissipation.
- Rogers et al. (NRL report, 2021); Yu et al. (CRST 2022). Focus is on parameterization of dissipation that depends on frequency **plus ice thickness**.

Field experiment overview

Fig. 1. An image taken from the *R/V Nathaniel B. Palmer* of the deployment of WIIOS B21 at 03:50 on 21st April 2017 at 69.1715833 S and 171.8200167 E.

Table 1. WIIOS deployments for PIPERS-17: Only buoys in eastern grouping with 500 or more data records are included. Notation: h_{ice}, d_{ice}, a_{ice} are ice thickness, floe size, and concentration respectively. Buoys are given here in order of deployment, from south to north. Note that the sizes of the floes on which the buoys are deployed are not known generally. Floes may have broken after deployment, and some buoys far from the ice edge were actually deployed on the continuous ice and became "buoys on floes" later.

		floe upon which the buoy is deployed		most prevalent ice near the buoy, from nearest ASPeCt record			# of spectra	init. dist. from ice edge (km)
Buoy #	Buoy ID	h_{ice} (cm)	d_{ice} (m)	a_{ice}	h_{ice} (cm)	d_{ice} (m)		
14	A-34*	54	N/A (cont. ice)	100%	50	100-500	509	244
5	B-25	60	100	100%	60, 75	20-100	1349	175
6	B-26	70	20	100%	30	20-100	1746	153
7	B-27	36	40	50%	30	20-100	1830	151
9	B-29	50	40	100%	20	<20 (cake)	1668	133
10	B-30	75	20	100%	30	20-100	2052	118

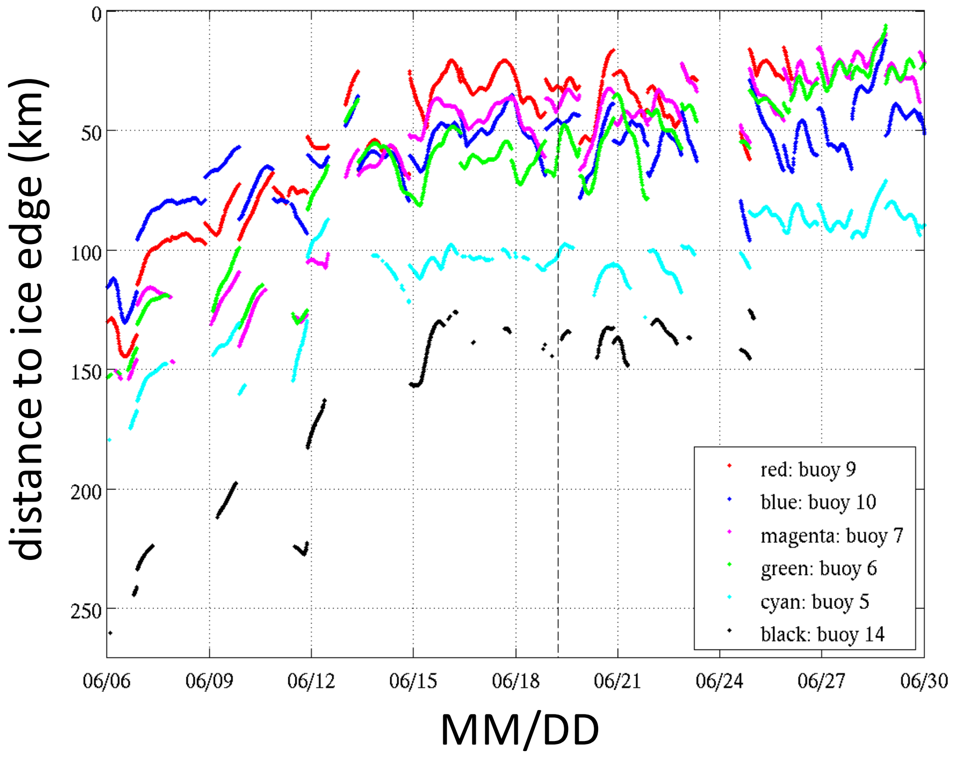
Table from Rogers et al. (2021)

Photo from Kohout et al. (2020)

Buoy positions 6 to 30 June 2017

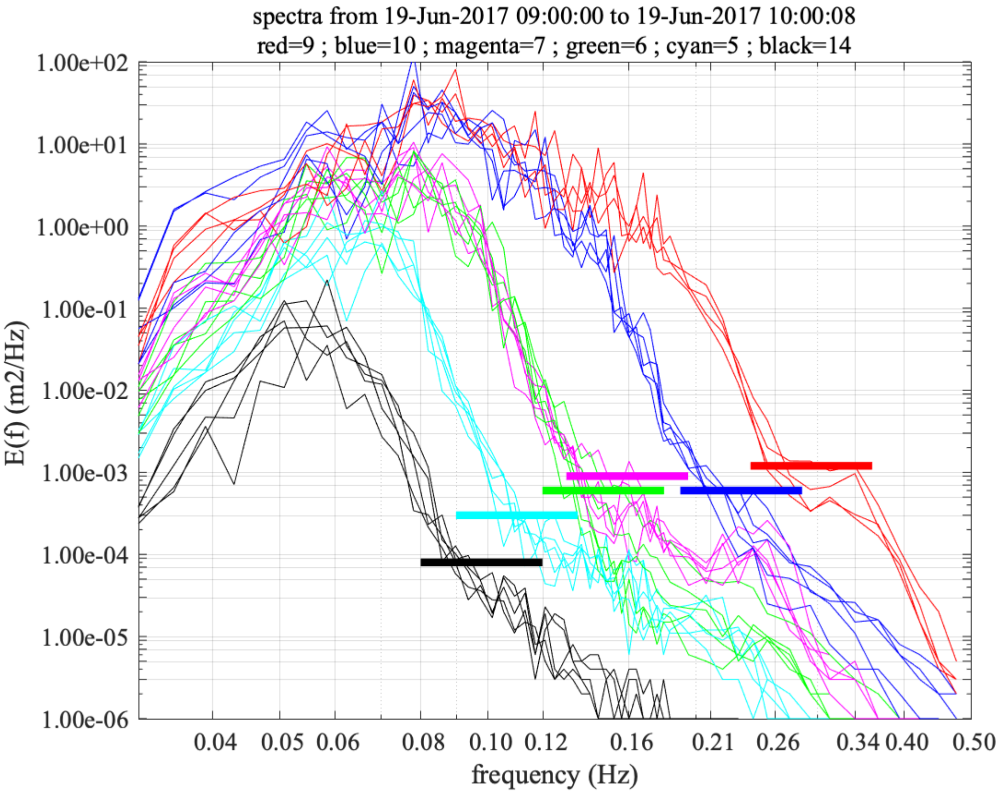
Shown: buoy positions, relative to the ice edge, over the 24-day study period.

Like the table in a previous slide, we only show the 6 buoys which have more than 500 records (spectra)



Example spectra

Energy spectra from the six buoys during the period of 0900 to 1000 UTC 19 June 2017. The same color scheme is used as in prior slide, with red/blue being nearer the ice edge and cyan/black being farther into the ice. The thick horizontal lines indicate energy levels below which the tail is visibly “propped up”, presumably by instrument noise. See Thomson et al. (JGR 2021).



Methods for estimating dissipation

Geometric method

- Computes differences in spectra between two buoys
- If buoys are aligned with wave direction and directional spread is zero, calculation is straightforward. Not generally true.
- Cheng et al. (2017) use include cos(θ) in calculations to remedy this, but such rigor is uncommon.
- If both buoys are placed on ice, then the dissipation near ice edge cannot be represented.

Inversion method

- Uses only one buoy spectrum at a time.
- Finds dissipation rate which permits model (WW3) to match buoy spectrum, Rogers et al. (JGR 2016).
- Strength: automatically includes a number of things that are ignored by other approach.
- Weakness: requires that model is otherwise accurate: all model-data mismatch is addressed via “dissipation by ice”, but it could be due to errors in wind, ice concentration, other source terms, etc.

A review of pros/cons of each method is reviewed in preliminary/longer version of this paper: http://arxiv.org/abs/2006.04978

PIPERS deployment, north of Ross Sea

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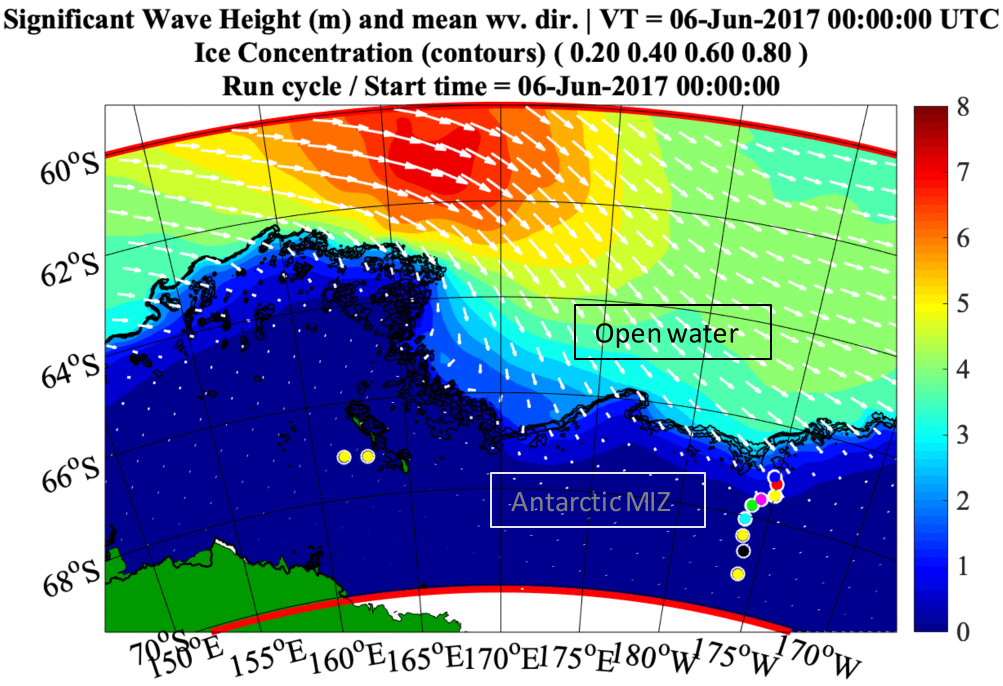
Rogers, W.E., M.H. Meylan, A.L. Kohout, 2021. Estimates of spectral wave attenuation in Antarctic sea ice, using model/data inversion, *Cold Reg. Sci. Technol.*, 13 pp. https://doi.org/10.1016/j.coldregions.2020.103198

colors: waveheight
arrows: wave direction
contours: ice fraction
circles: buoy locations

Animation:
WW3 simulation, 3 km resolution: ice concentration taken from AMSR2, winds are from NAVGEM, and boundary conditions from global WW3



Frequency dependence of dissipation by sea ice is estimated using model/data inversion.

The employed dataset is of extraordinary size (9477 spectra), computed from buoys deployed on the ice.

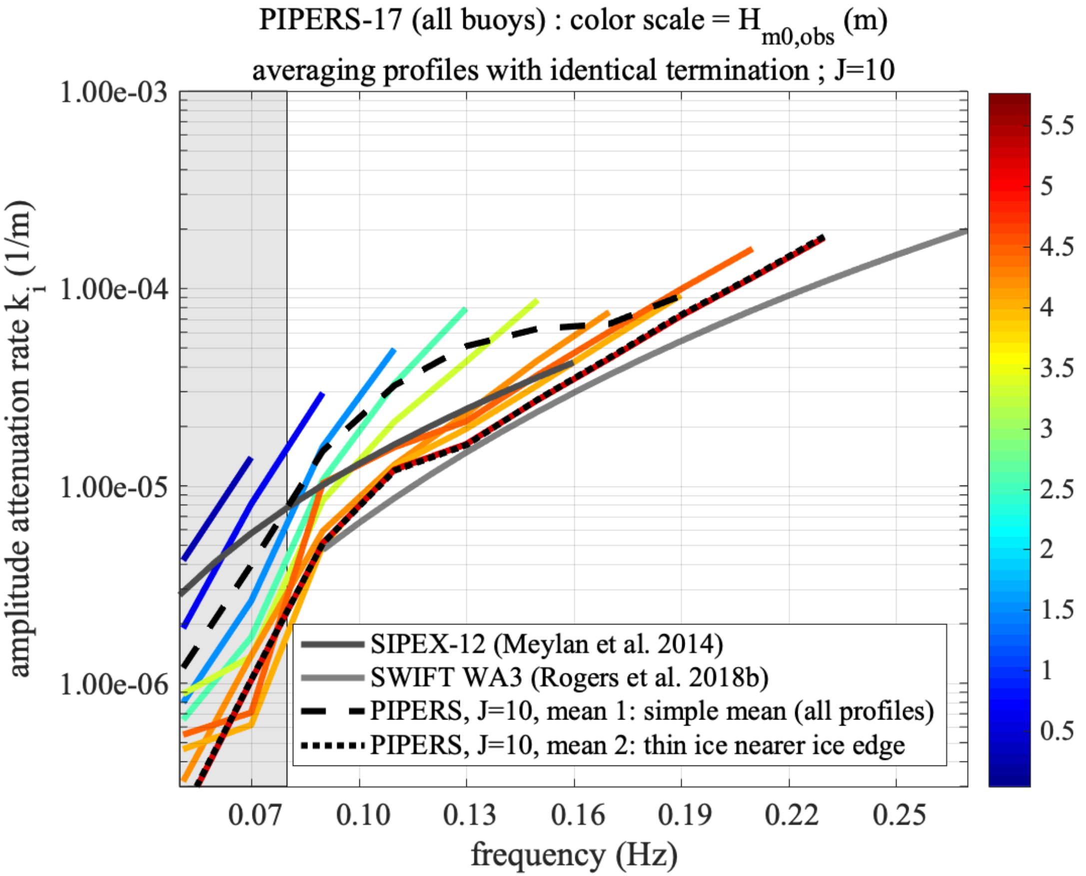
Results

Figure: Dissipation rate vs. frequency, estimated using the model-data inversion with a conservative anti-noise algorithm.

Evaluating correlation with significant waveheight

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

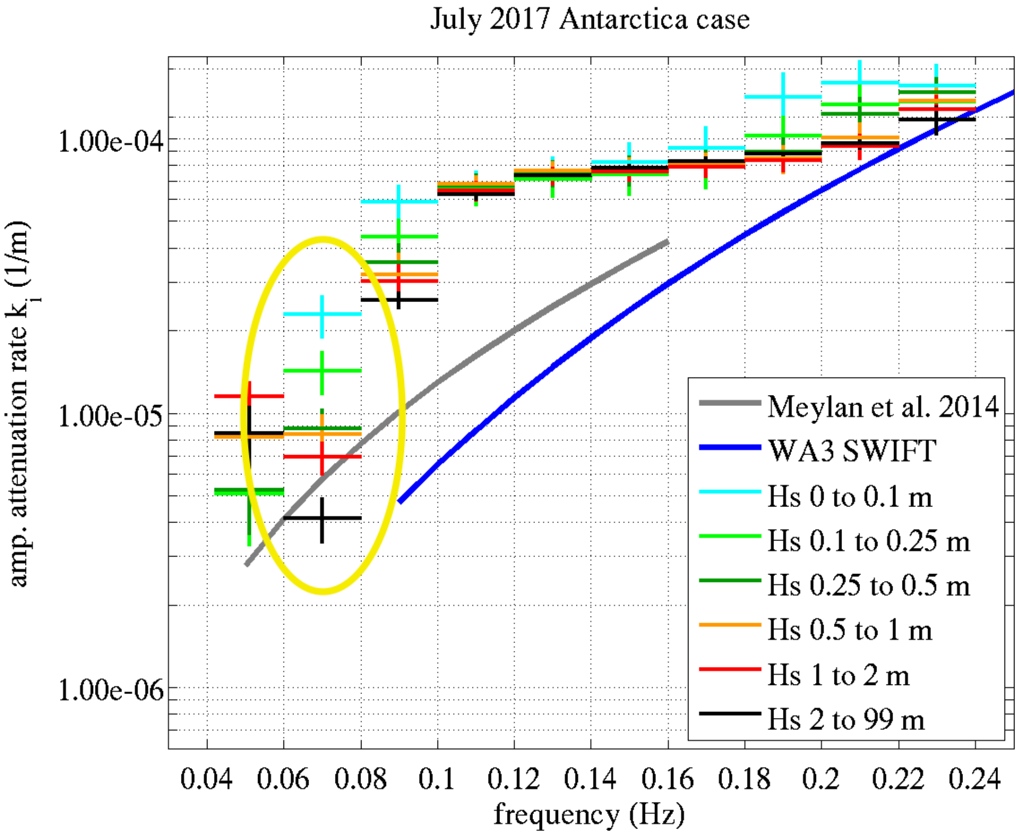
S_{ice} : temporal dissipation rate of energy.
k_i : spatial exponential dissipation rate of wave amplitude.
C_g : group velocity
E : energy density



Results from a similar field experiment

Colored crosses in this figure: this is another inversion, but this time I use data collected by Clare Eayrs, July 2017, north of Queen Maud Land, longitude ~Africa.

This is from the cruise reported in Vichi et al. (2019) and Alberello et al. (2019).

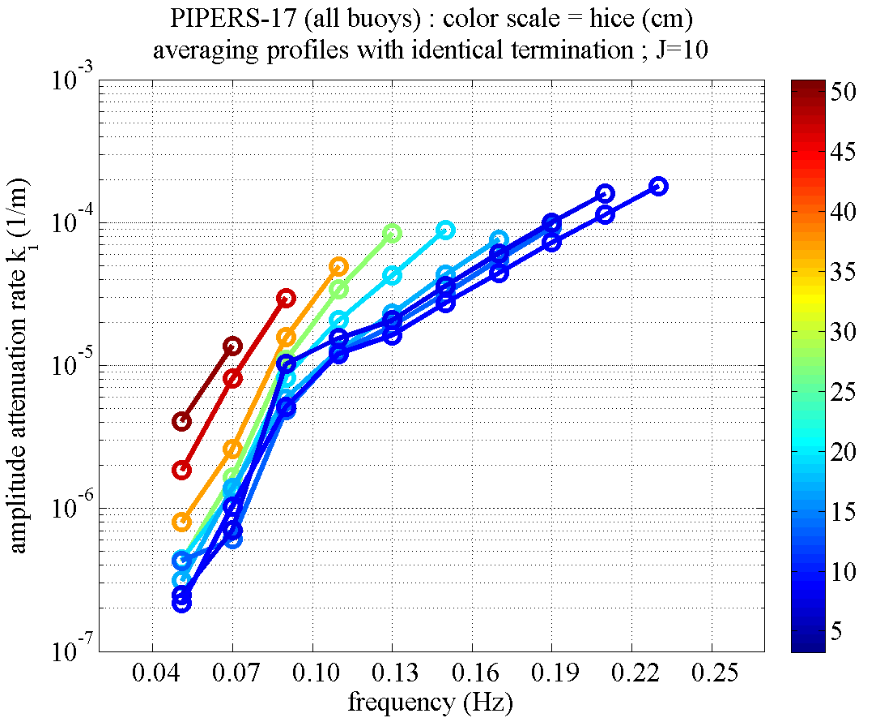


PIPERS deployment, north of Ross Sea

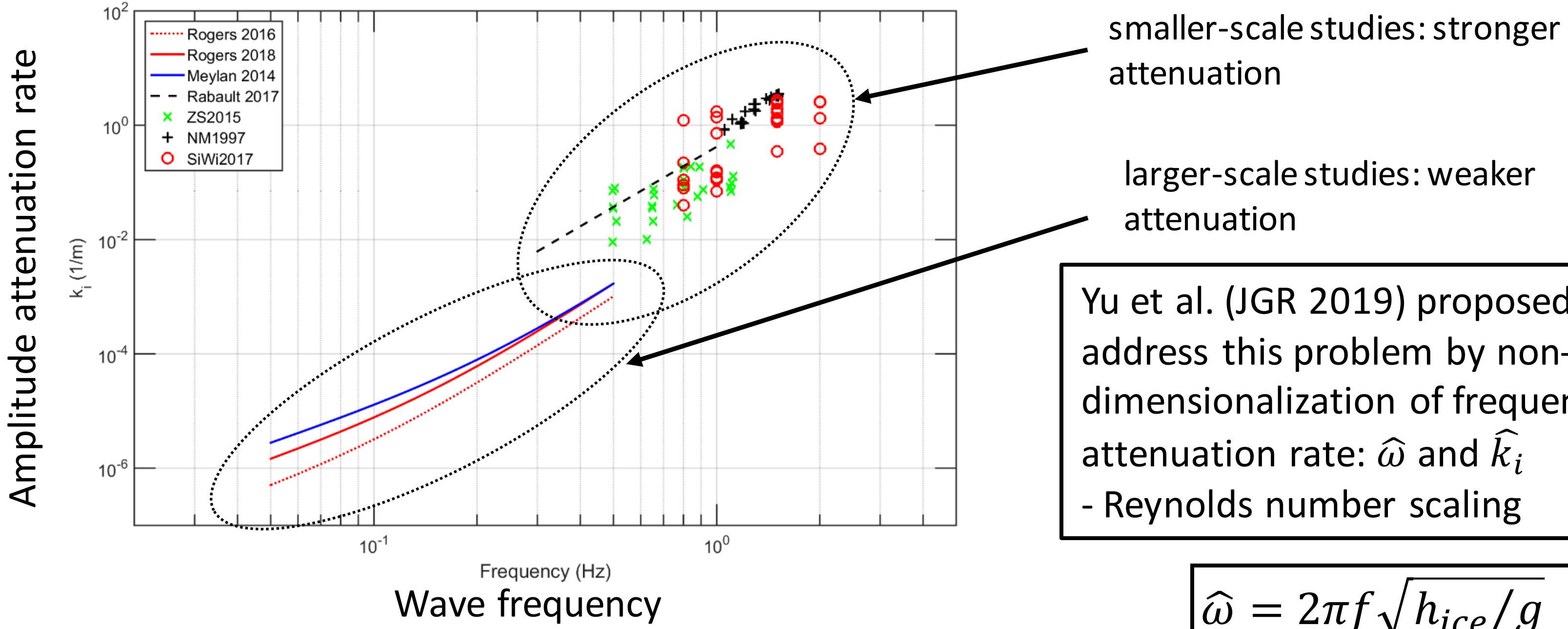
Rogers, W.E., M.H. Meylan, A.L. Kohout, 2021. Estimates of spectral wave attenuation in Antarctic sea ice, using model/data inversion, *Cold Reg. Sci. Technol.*, 13 pp. https://doi.org/10.1016/j.coldregions.2020.103198

Figure: Dissipation rate vs. frequency, estimated using the model-data inversion with a conservative anti-noise algorithm. Ice thickness is evaluated here.

- Dissipation rate in thinner ice is found to be well represented using frequency to a power of three to four.
- The positive correlation between ice thickness and dissipation rate can potentially be exploited for <u>operational</u> predictive models.



Apparent discrepancy in literature



Yu et al. (JGR 2019) proposed to address this problem by non-dimensionalization of frequency and attenuation rate: $\widehat{\omega}$ and $\widehat{k_i}$

- Reynolds number scaling

$$\widehat{\omega} = 2\pi f \sqrt{h_{ice}/g}$$

$$\widehat{k_i} = k_i h_{ice}$$

Reconciling laboratory and field data

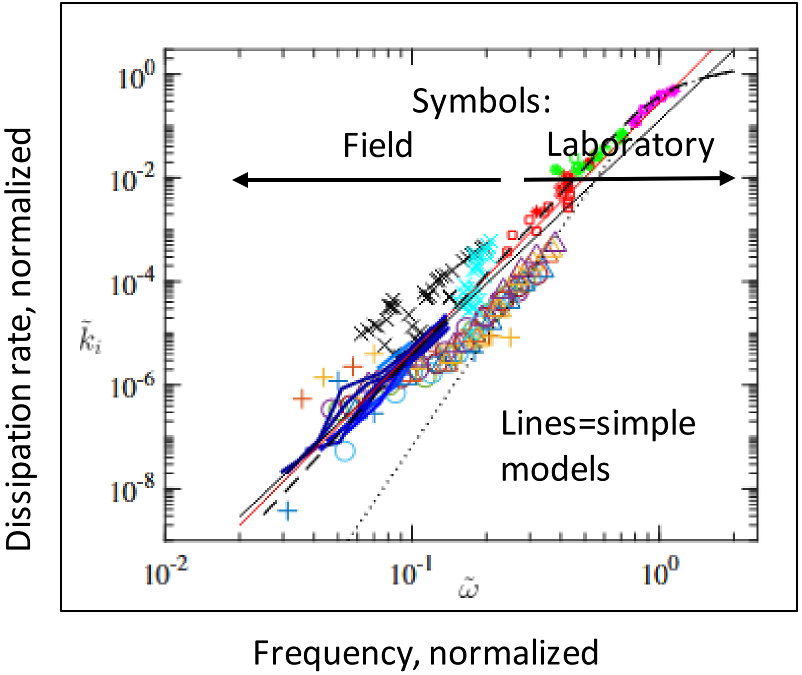
From Yu et al. (2022, J. Mar. Sci. Eng.)

- This figure is similar to Rogers et al (2021 report) and Yu et al. (CRST 2022), with minor update.

$$\widehat{\omega} = 2\pi f \sqrt{h_{ice}/g}$$

$$\widehat{k_i} = k_i h_{ice}$$

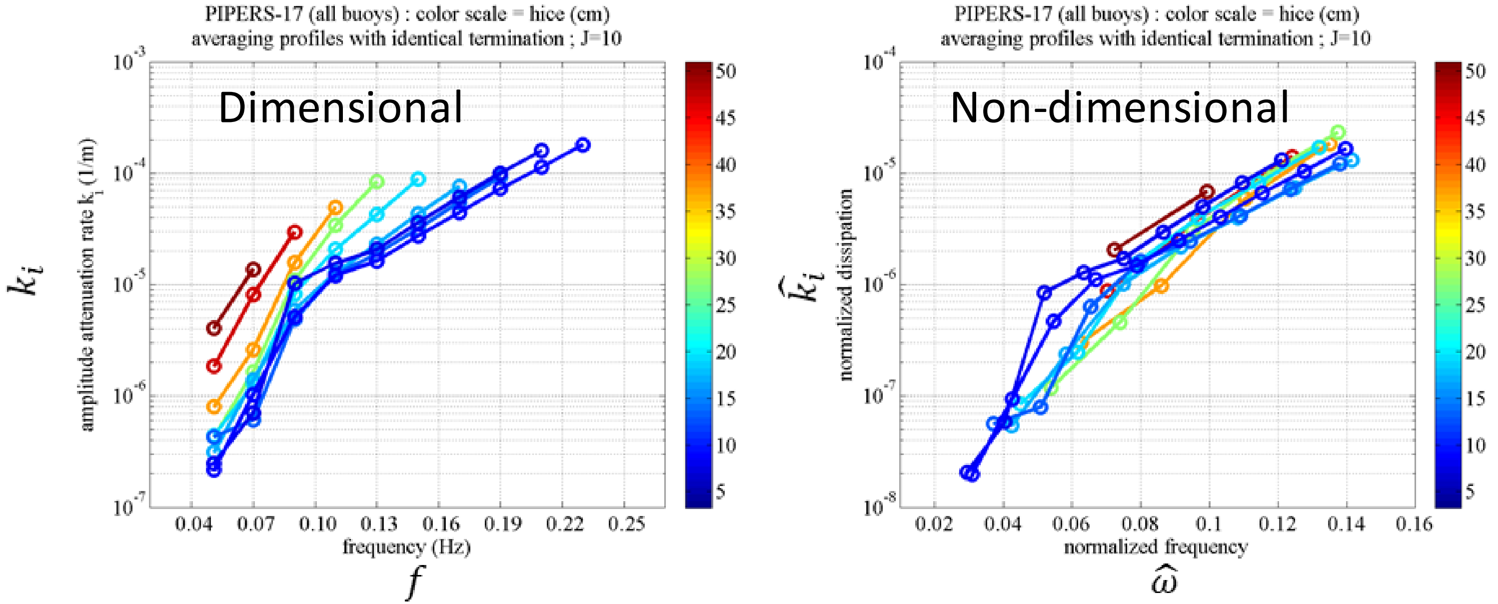
Figure 5. Comparison of modeled wave attenuation with data. The field data at lower $\tilde{\omega}$: PIPERS dataset (bluish line segments joining the data points) with co-located satellite ice thickness (see [13,34] for details); Arctic 'Sea State' dataset (larger symbols +, ○, △ with various colors); two datasets for the Weddell Sea (larger symbols × with color black and cyan). See [17] for h associated with the 'Sea State' and Weddell Sea data. The smaller symbols at higher $\tilde{\omega}$ (> 0.2) are the lab datasets with documented ice thickness: green, three tests in [29]; blue, two tests in [28]; magenta, two tests in [27].



Scale collapse

Rogers, W.E., J. Yu, D.W. Wang, 2021. Incorporating dependencies on ice thickness in empirical parameterizations of wave dissipation by sea ice, *Technical Report*, NRL/OT/7320-21-5145, 35 pp., https://www7320.nrlssc.navy.mil/pubs.php

Application of Yu et al. (JGR 2019) normalization to PIPERS estimates results in significant scale collapse.



Yu et al. (JGR 2019) non-dimensionalization, as applied by Rogers et al. (2021 rep.) and Yu et al. (CRST 2022)

Yu et al. (JGR 2019) :

$\widehat{k_i} = k_i h_{ice}$ and $\widehat{\omega} = 2\pi f \sqrt{h_{ice}/g}$.

Method:

1. Take non-dimensionalization from Yu et al., $\widehat{k_i}$ and $\widehat{\omega}$
2. Assume form $\widehat{k_i} = C_Y \widehat{\omega}^n$

Now make it dimensional again (algebra)

We find: $m = n/2 - 1$

So $k_i = C_{hf} h_{ice}^{n/2-1} f^n$

Naïve formula: $k_i = C_{hf} h_{ice}^m f^n$

Our formula (more constrained):

$k_i = C_{hf} h_{ice}^{n/2-1} f^n$

Examples:

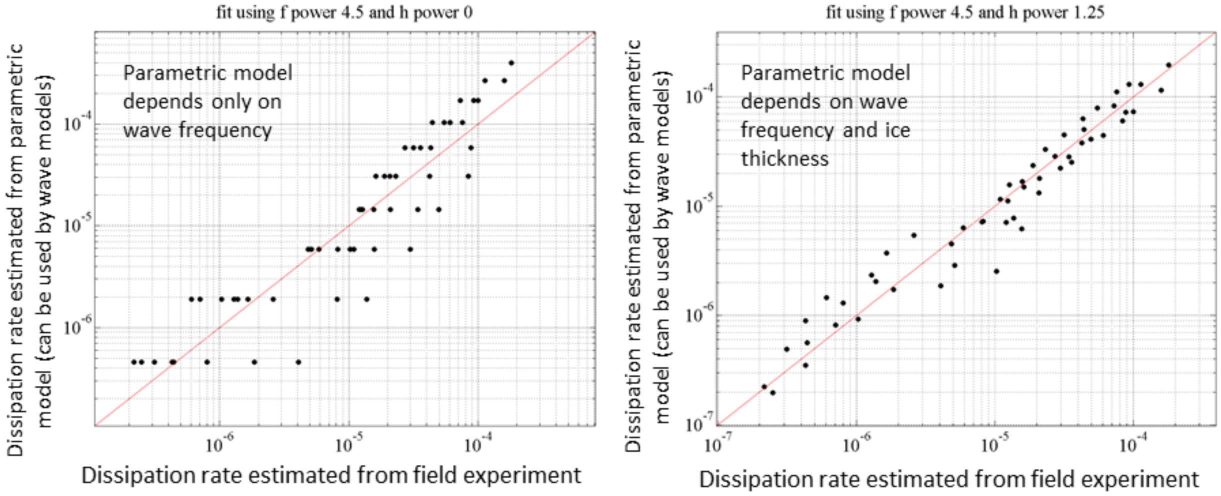
1. $k_i = C_{hf} h_{ice}^1 f^4$
2. $k_i = C_{hf} h_{ice}^{1.25} f^{4.5}$

New parametric model

Rogers, W.E., J. Yu, D.W. Wang, 2021. Incorporating dependencies on ice thickness in empirical parameterizations of wave dissipation by sea ice, *Technical Report*, NRL/OT/7320-21-5145, 35 pp., https://www7320.nrlssc.navy.mil/pubs.php

Normalization can be combined with power-fit to create a new parametric model.

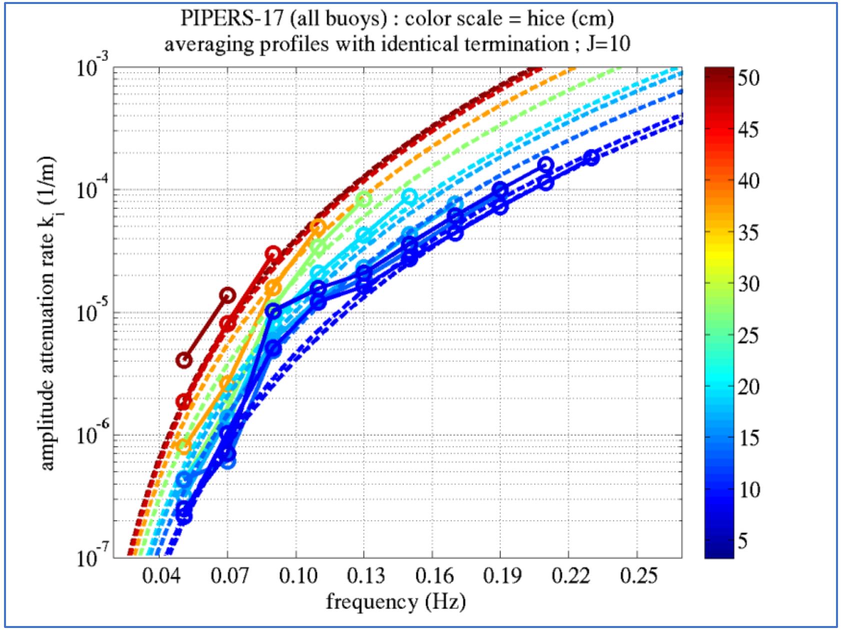
This new parametric model has much lower scatter than a power-fit using frequency only.



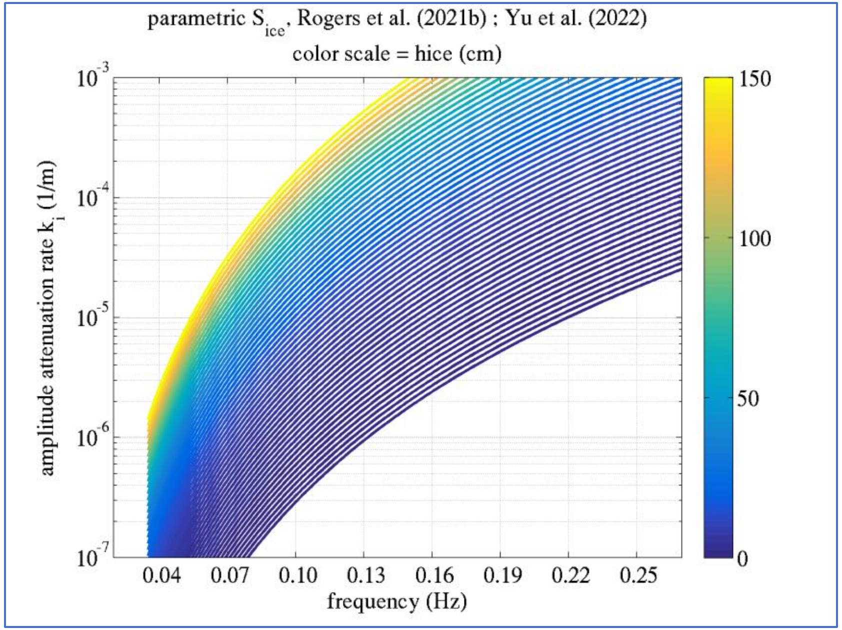
This is one of three new parametric models with ice thickness dependence that we implemented in SWAN now (in public release 41.31AB) and now has been ported to our “IC4” routine in WW3 (development branch maintained by NCEP on github as “IC4M9”).

New parametric model

Fitting to PIPERS-17 inferred dissipation rates



Parametric model w/extrapolation to higher/lower h_{ice}



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Summary

Approach:
{Yu et al. (2019) non-dimensionalization} + {monomial power fit}
= {new empirical/parametric formula for dissipation by sea ice that depends on wave frequency and ice thickness, $k_i = C_{hf} f^n h_{ice}^{n/2-1}$}.

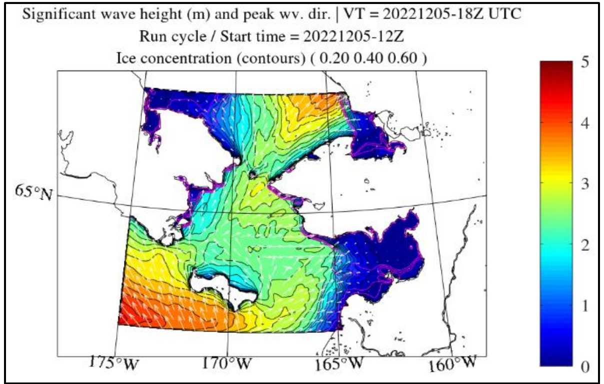
- Applied to dataset of Rogers et al. (2021), used to calibrate the formula, the formula performs well: we get much less scatter than if ice thickness is not used in formula, SI=0.063→0.038
- Applied to independent datasets, results are mixed.
- Question: Could inconsistent methods of estimating dissipation be the main issue?

Implementation in COAMPS system

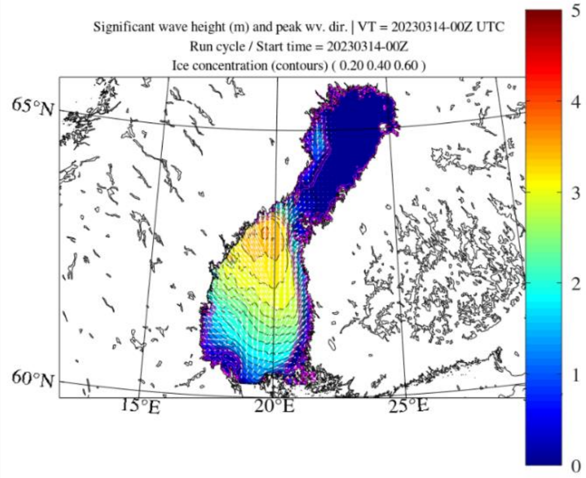
- COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System) is the US Navy's propriety regional coupled modeling system, e.g., Smith et al. (OM 2013) ; Doyle et al. (TOS 2014)
- The new dissipation by sea ice routines have been implemented in the system and are available for 2-way coupled modeling using either WW3 or SWAN, coupled to mesoscale models:
  - Ocean model: NCOM (Navy Coastal Ocean Model)
  - Ice model: CICE (Community ice code)
  - Atmosphere: "COAMPS-atmosphere"
- However, COAMPS also allows uncoupled modeling: software derives forcing from global models: HYCOM, CICE, NAVGEM

Implementation in COAMPS system (e.g. Smith et al. OM 2013 ; Doyle et al. TOS 2014)

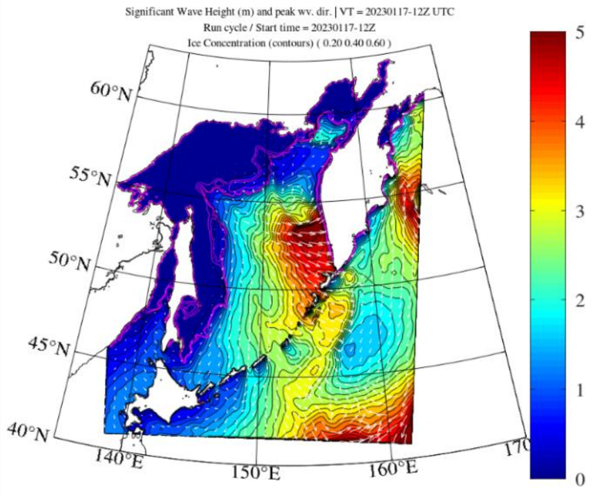
COAMPS in non-coupled mode: Three demo cycling systems with wave models using new S_{ice} parameterization, with boundary forcing, and ocn/ice/atm forcing from files.



SWAN output example: Bering Strait, Dec. 5, 2022. (Boundary forcing from global WW3)



SWAN output example : Gulf of Bothnia, Mar. 14, 2023.

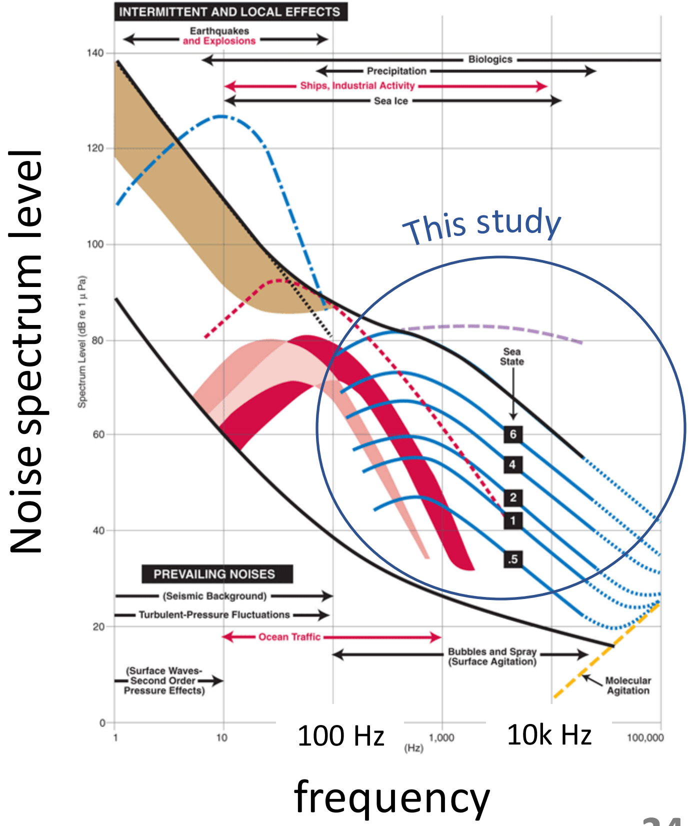


WW3 output example : Sea of Okhotsk, Jan. 1, 2023. (Boundary forcing from global WW3)

Colors: SWH in meters
The **magenta** lines are ice concentration contours
Arrows indicate dominant wave direction

Ambient noise from breaking waves

- Ambient noise (AN) is produced by shipping, biology, wind (waves), sea ice, and rain. We focus on the wind (waves) AN here.
- So-called "wind noise" is produced by bubbles from breaking waves.
- This noise correlates fairly well with wind speed (in the mean). Empirical relations such as Wenz curves (figure) exploit this correlation.



Limits of Prevailing Noise
Wind-Dependent Bubble and Spray Noise
Heavy Precipitation
Heavy Traffic Noise
Thermal Noise
Earth Quakes and Explosions
Low-Frequency Very-Shallow-Water Wind
Usual Traffic Noise-Shallow
Usual Traffic Noise-Deep

Wenz curves from https://dosits.org/science/sounds-in-the-sea/what-are-common-underwater-sounds/

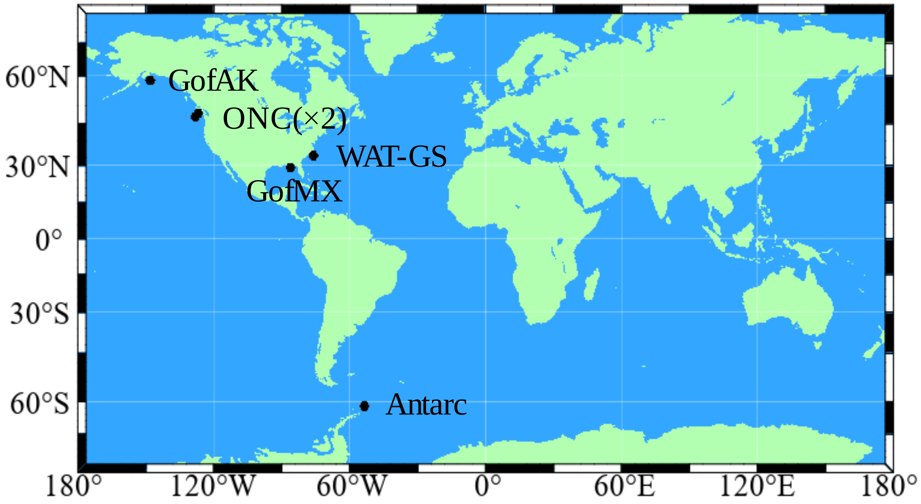
Ambient noise study

"Utility of ocean wave parameters for improving predictions of ambient noise", E. Rogers, L. Fialkowski, D. Brooker, G. Panteleev, J. Fialkowski
Submitted for review; a pdf is here:
https://doi.org/10.48550/arXiv.2403.18728

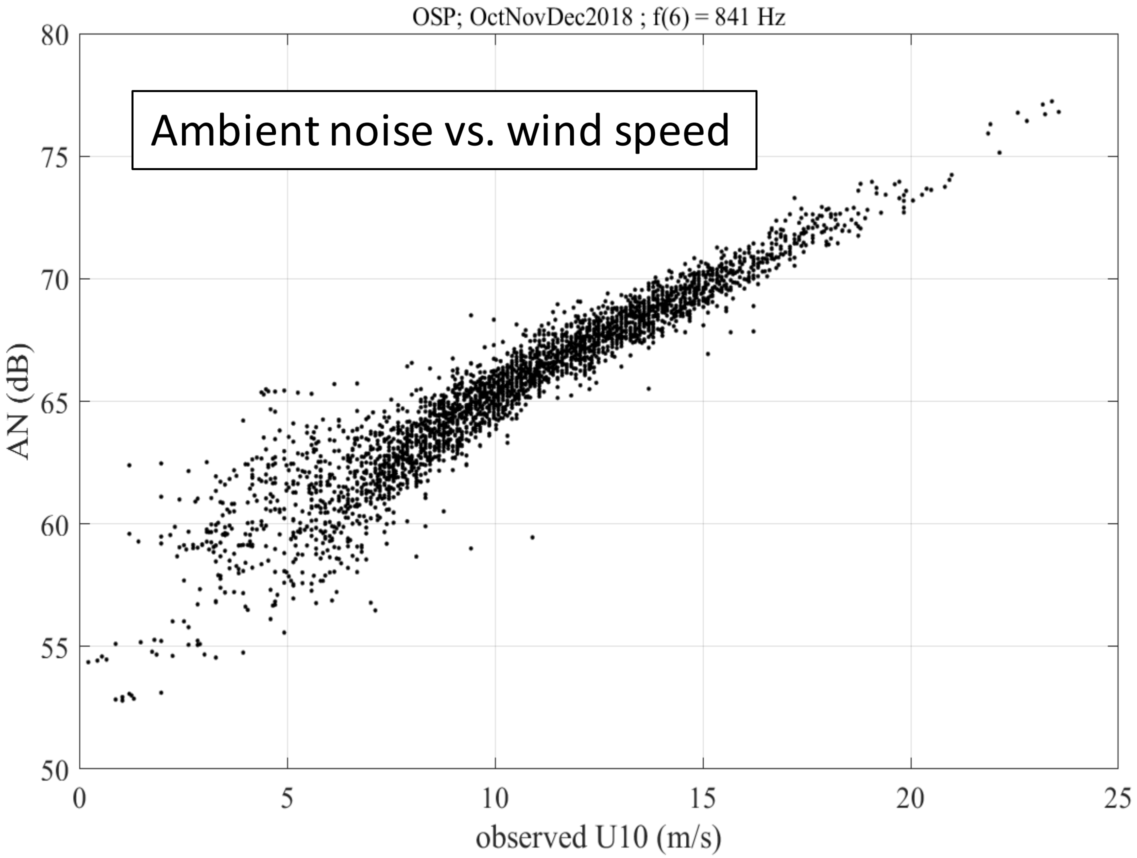
Objectives:
- Quantify correlation between ambient noise and wave state, *independent of mutual correlation with wind speed*.
- Quantify benefit of including wave state in prediction of ambient noise, relative to a prediction using only wind speed.

Method: Hydrophone measurements of ambient noise, co-located with model-derived wave parameters.

six hydrophone locations



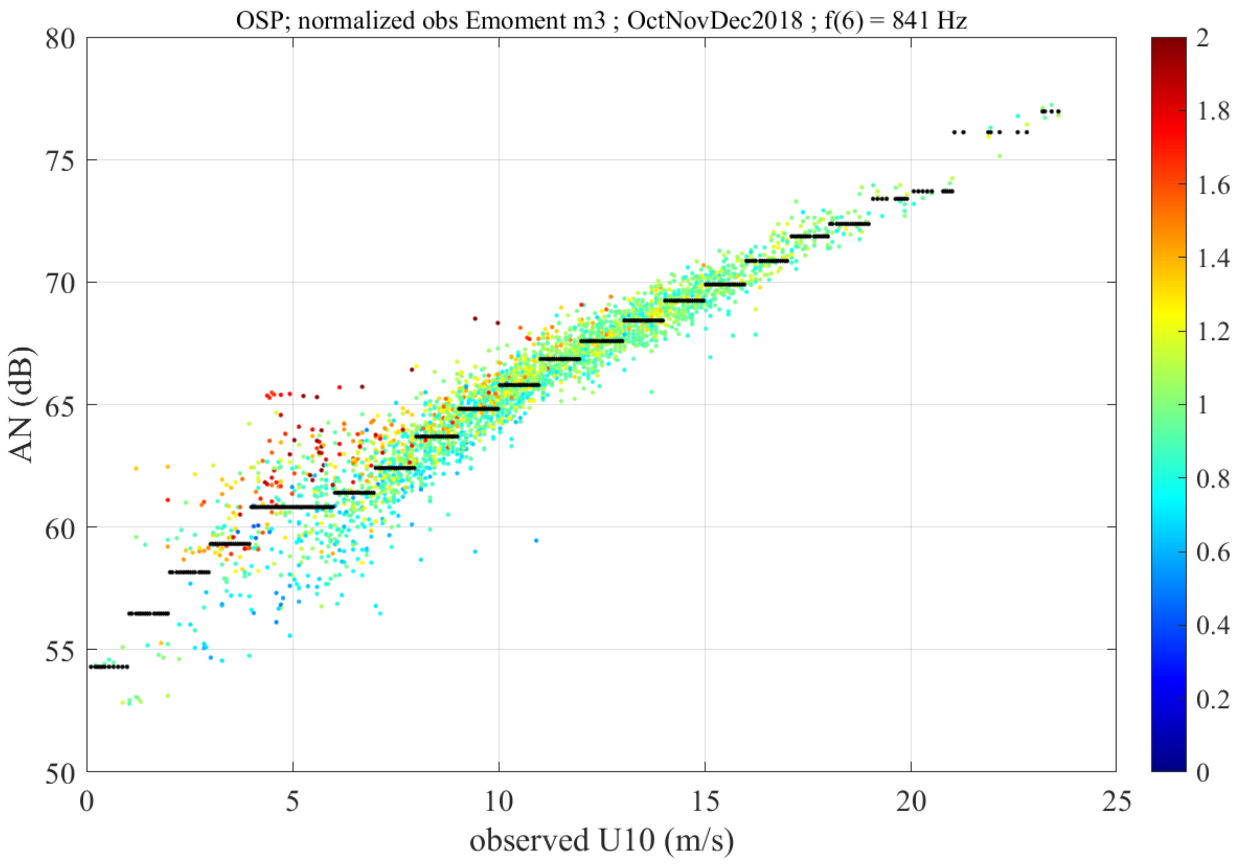
Using wind & wave obs at Ocean Station Papa.
Single frequency (841 Hz)



Scatter suggests (for this frequency/location/time):

- U_{10} alone is a good predictor of AN, at U_{10}>10 m/s
- There is room for improvement at U_{10}<10 m/s

Using wind & wave obs at Ocean Station Papa. Single frequency (841 Hz), wave parameter "m_3"



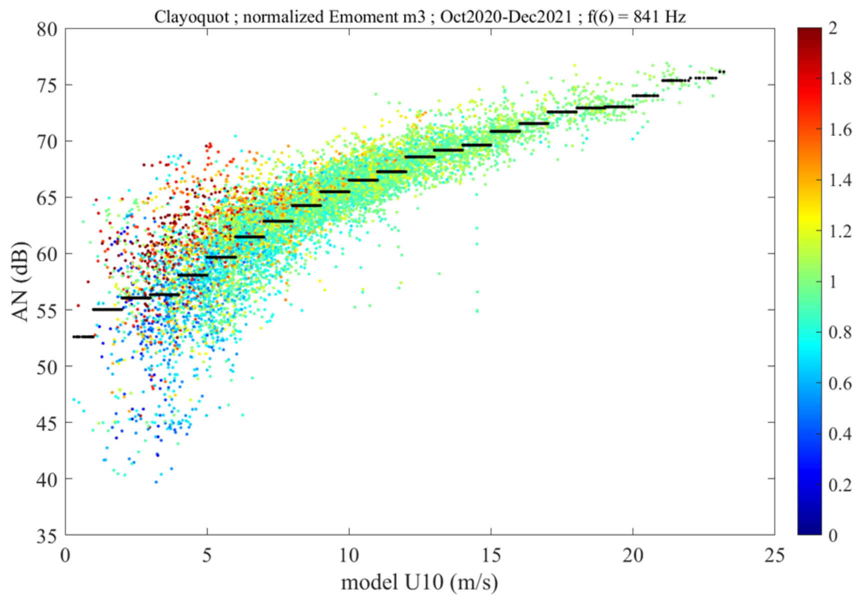
- Black horizontal lines indicate mean m_3 of that wind speed bin
- Color is m_3 after being normalized by mean m_3
- This suggests, for $U_{10}<10$ m/s, that sea state is a fair predictor of error in the wind-only model. This implies that wave parameter can improve AN prediction.

Ambient noise study

"Utility of ocean wave parameters for improving predictions of ambient noise", E. Rogers, L. Fialkowski, et al. Submitted for review; a pdf is here: https://doi.org/10.48550/arXiv.2403.18728

Conclusions:

- Likely, the wave process which leads to ambient noise (wave breaking, bubbles) reaches "mature state" more quickly than, e.g. wave height, consistent with some expectations for $S_{ds}(f)$.
- Correlation study indicates clear correlation of AN with wave parameters, independent of mutual correlation with wind. This "residual correlation" is rarely more than 0.4.
- Multilinear regression: there is consistent/robust improvement by including wave parameters in prediction (vs. wind speed alone). However, it is modest, e.g. 0.1-0.25 dB in the RMSE.



Multilinear Regression: Methods

- Each frequency bin is addressed separately (i.e. different frequency, different fit).
- Each location is addressed separately (i.e. different location, different fit).
- Observational data used for calibration is not used for evaluation
  - ~67% of time series used for calibration
  - ~33% of time series used for evaluation
- We tested three methods of fitting, all of form AN=term1+term2+..., but here we apply two and take the better of the two (during training):
  1. Linear fit: 'term' is 'coefficient × wave_parameter'
  2. Log fit: 'term' is 'coefficient × log10(wave_parameter)' (this is the traditional method for fitting to wind speed)

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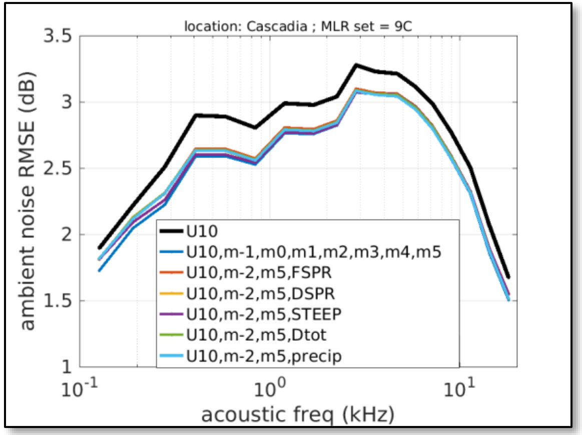
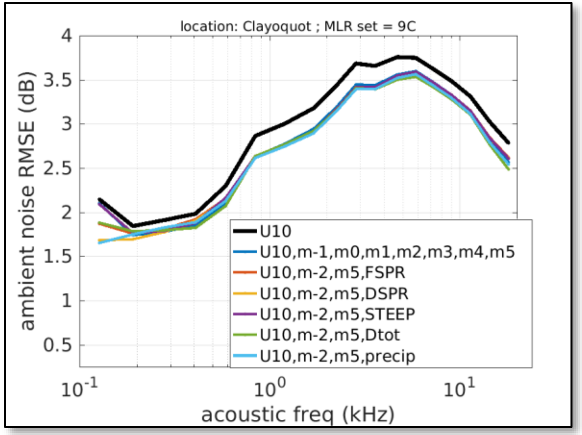
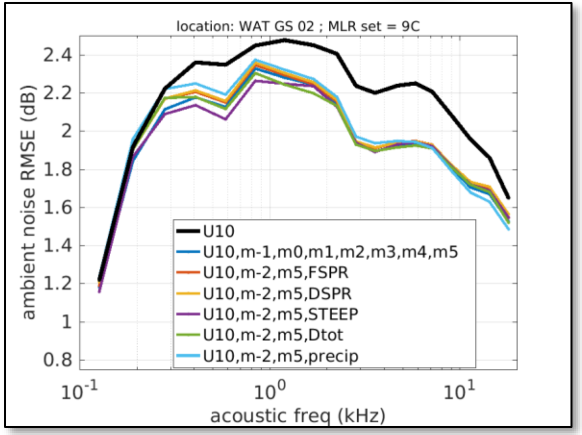
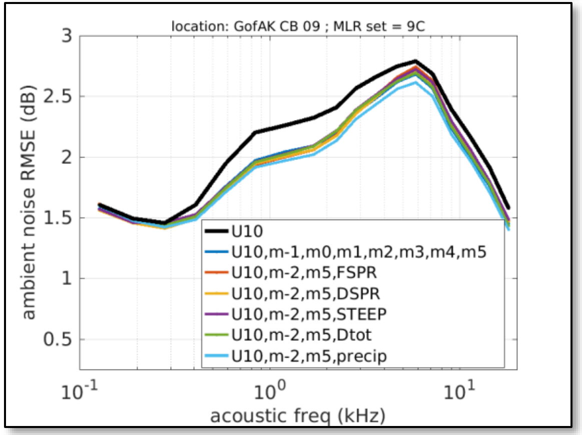
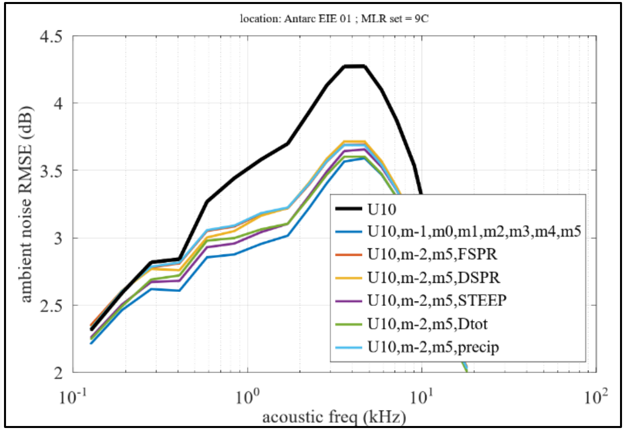
Ambient noise study: Results from multilinear regression at six locations

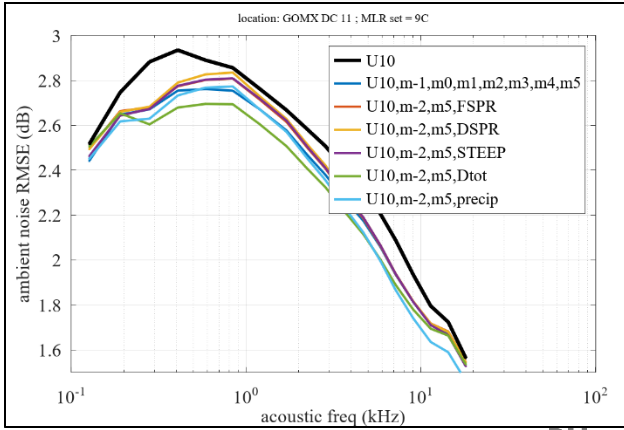












‘Antarc’ hydrophones of ‘HARP’ dataset

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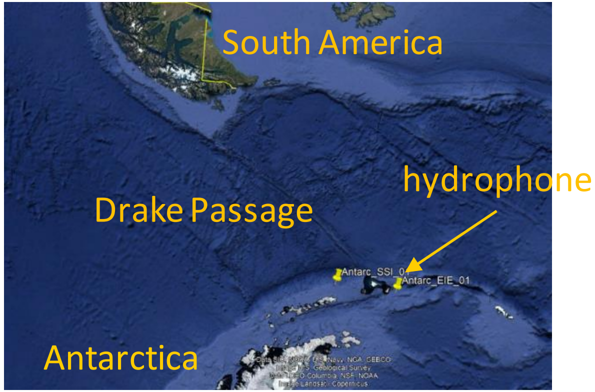
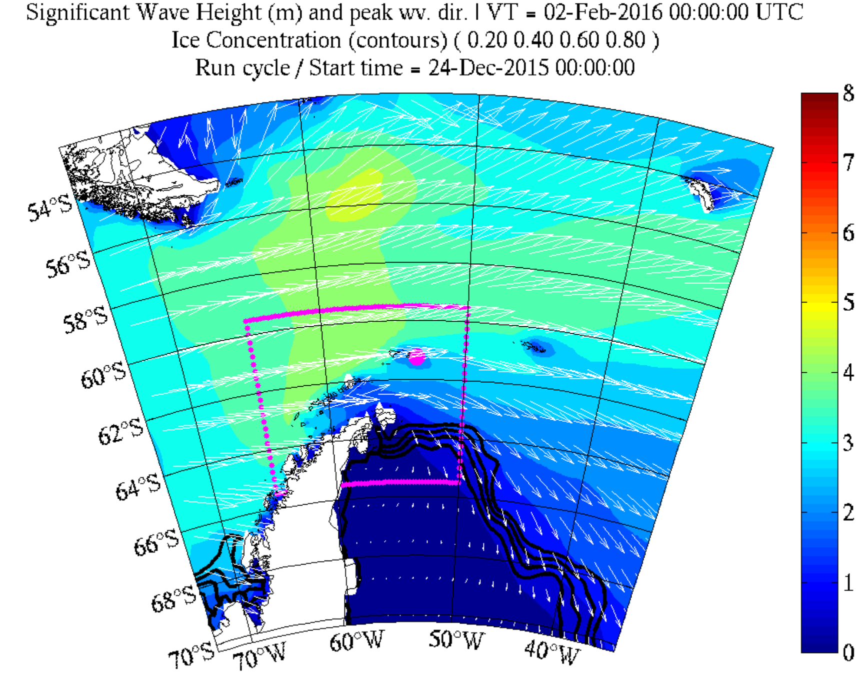
Hildebrand et al. (JASA 2021) : enormous dataset (more than one hundred cumulative years) from many hydrophones. “HARP” dataset, from UCSD, Scripps I.O.

Time period of colocation: Feb. 2 to Nov. 30, 2016. (SWAN nested in WW3)





WW3 results shown. Black contours indicate ice fraction. Hydrophone is at or near ice for much of the hindcast duration.

The End

Thank you for your attention
Thanks to ECWMF

Extra slides

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Ice noise

JASA ARTICLE

Analysis of under-ice ambient noise characteristics of Gakkel Ridge in the Arctic

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ABSTRACT:

This paper presents an analysis of the under-ice acoustic data and environmental parameters measured over a three-month period from August 31 to November 28, 2021, within the area of the Gakkel Ridge in the Arctic. After "spikes" caused by micro-level events are removed, the distribution of the retained under-ice noise related to macro-level events can be described satisfactorily by a Gaussian distribution, as verified by Q–Q plots and kurtosis/skewness analysis. We use sliding window analysis to deal with the features of under-ice ambient noise and model the data by Gaussian interpolation. This shows that the ambient noise level over the low-frequency range (10–100 Hz) is comparatively flat at about 60 dB; with the frequency increases from 100 to 2560 Hz, the ANL decreased to about 40 dB. We then introduce canonical correlation analysis (CCA) to analyze the potential relation between environmental forcing and the under-ice noise level. The results of CCA indicate that the seawater parameters (including temperature, salinity, and sound velocity) close to the ice–water interface have the greatest influence on the under-ice noise level among all environmental parameters recorded in the air, sea-ice, and seawater. Additionally, the under-ice noise level forced by the environment does not exhibit any particular frequency dependence.

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I. INTRODUCTION

Given the accelerated melting of sea-ice caused by global warming, and the consequent opening of sea routes (Huang *et al.*, 2017; Lajeunesse, 2012; Solli *et al.*, 2013), there has been increased interest in underwater acoustic investigations of the Arctic Ocean. As one of the most important topics in such investigations, the study of under-ice ambient noise and its modeling, characteristics, and generation mechanisms has attracted considerable attention, providing important reference values for underwater acoustic detection, communication, and navigation in the Arctic (Pajala *et al.*, 2021; Schmidt and Schneider, 2016; Tian *et al.*, 2019).

Due to the widespread ice coverage, underwater ambient noise in the Arctic differs from that in ice-free areas. The corresponding research began in the 1960s with several pioneering studies (Greene and Buck, 1964; Macpherson, 1962; Milne and Ganton, 1964) of the under-ice ambient noise in the Arctic Ocean. After Ganton and Milne made their initial investigation (Ganton and Milne, 1965), numerous studies examined the relation between environmental factors and under-ice noise levels. The distinguishing feature of underwater noise in the Arctic Ocean is the generation of high-frequency (kHz) noise stemming from thermal-induced ice cracking. The relation of this feature with air temperature has been studied in depth (Milne, 1972). Greene and Buck (1979) studied the influence of atmospheric pressure gradients on the ambient noise level in the Beaufort Sea, and found a correlation coefficient of greater than 0.5 at frequencies from 0 to 32 Hz. Makris and Dyer (1986) found that under-ice noise levels below 100 Hz are related to wind speed.

Other than the abovementioned atmospheric factors, environmental forcing from ice and water affects the under-ice ambient noise level in an even more direct manner. Zakarauskas *et al.* (1990) and Greening and Zakarauskas (1992) found that, in the low-frequency range (0–200 Hz), ice cracking, ice fracturing, ice ridging, ice shearing, and ice vibration all affect the under-ice noise. In the Arctic marginal ice area, a main source of the under-ice ambient noise is the interaction of sea-ice, sea waves, mesoscale vortices, and internal waves (Chen, 1988). Such observations are supported by a number of studies showing that the under-ice ambient noise level is closely related to the sea-ice concentration and marginal ice condition (Diachok and Winokur, 1974; Johannessen *et al.*, 2003; Makris and Dyer, 1991).

More recently, Roth *et al.* (2012) analyzed the monthly average noise level of the Chukchi Sea continental slope

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Spectral description of conservation of wave action used in wave models (varies by model)

Governing equation: $$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c}N = \frac{S}{\sigma}$$

Primary source/sink terms in deep water: $$S = S_{in} + S_{ds} + S_{nl4}$$

c = propagation speed
σ = relative radial wave frequency
Θ = wave direction

$$S_{ds} = S_{br} + S_{bot} + S_{ice}$$

$N = N(\sigma, \theta, \vec{x}, t)$ [spectral density of wave action, the variable that is being solved for]

$S = S(\sigma, \theta, \vec{x}, t)$ [spectral description of source/sink terms]

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$$S_{ds} = S_{br} + S_{bot} + S_{ice}$$

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

C_g is group velocity

E is energy density

k_i is spatial exponential dissipation rate of wave amplitude.

S_{ice} is temporal dissipation rate of energy.

Yu et al. (JGR 2019)

Yu et al. (JGR 2019) propose a non-dimensionalization,
$\widehat{k_i} = k_i h_{ice}$ and $\widehat{\omega} = 2\pi f \sqrt{h_{ice}/g}$.

"Using the thickness *h* of the ice layer as the scale for length, we define the dimensionless frequency and wavenumber"

"When the normalization is applied to laboratory and field measurements, scale collapse of different data sets is observed, suggesting the relevance of the scaling. The reduction of data scattering in the dimensionless plane is advantageous for identifying the generalized trend, and comparing with theories."

"Other scalings, yet to be proposed, are certainly possible
and may be superior."

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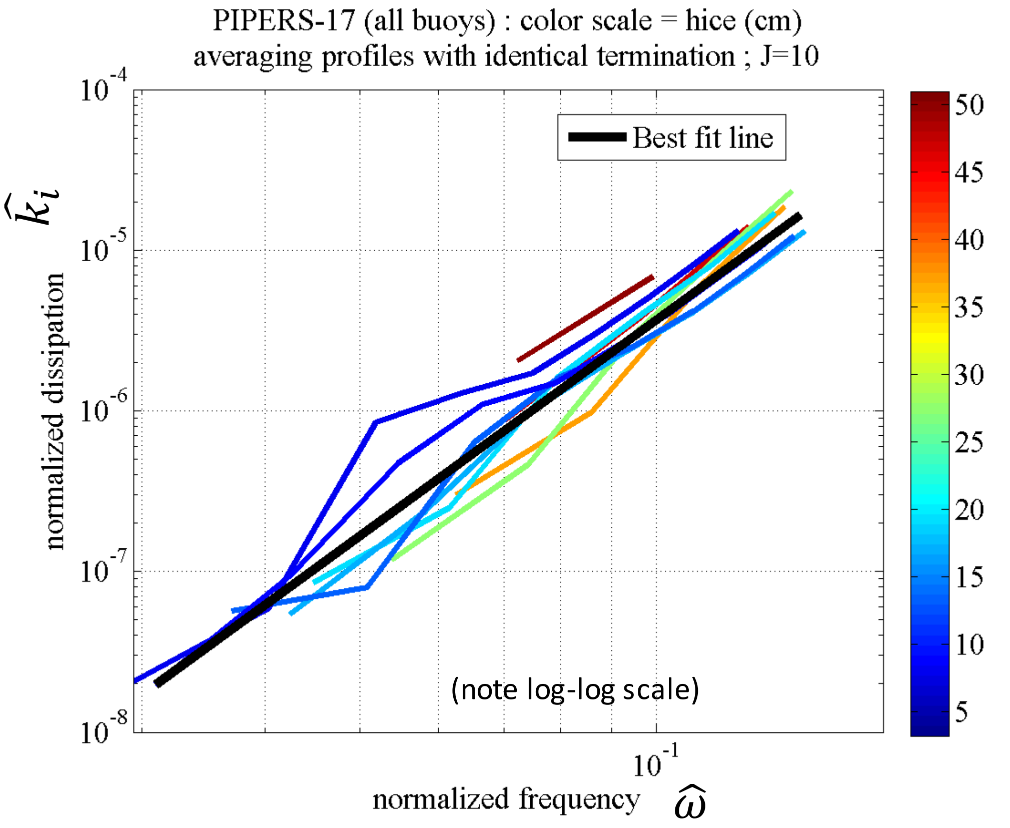
Approach, including h_{ice} : Yu et al. + power fit

Normalized space (figure at right):
Our line gives $n = 4.46$, and we round to $n = 4.5$.

Dimensional space:

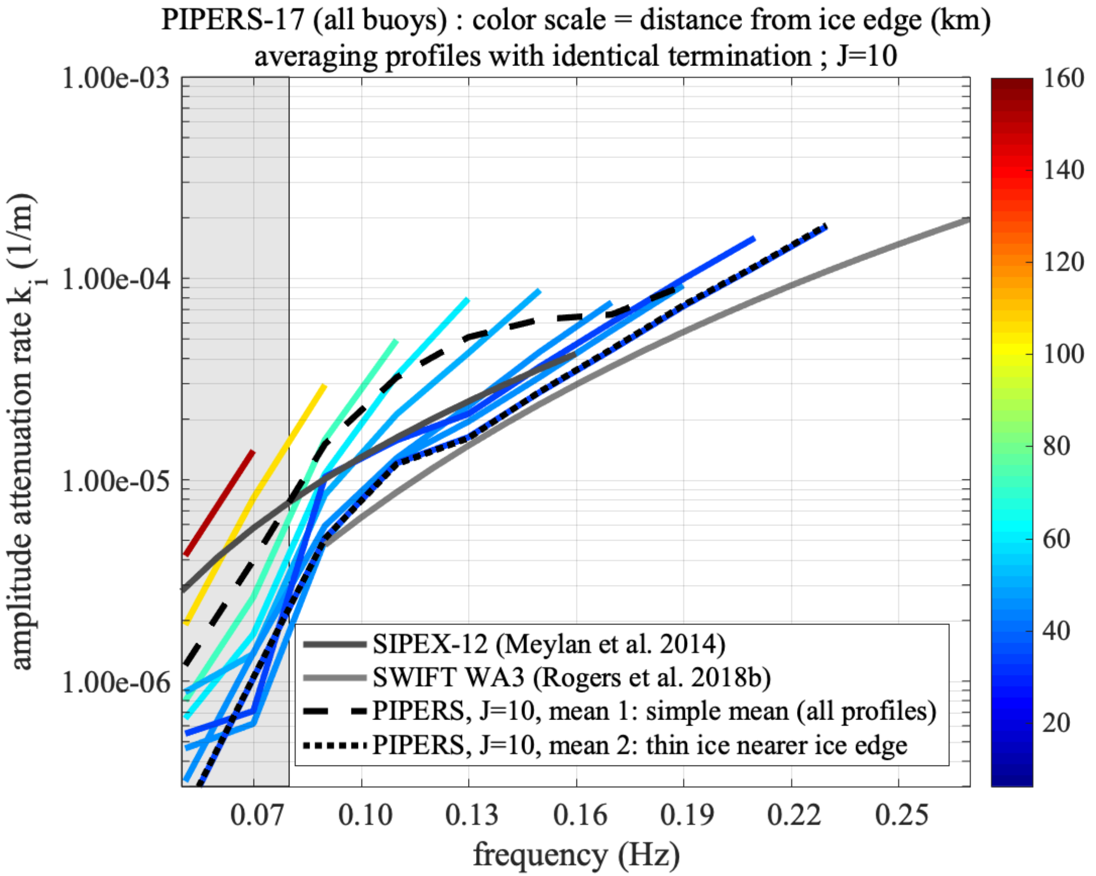
$$k_i = C_{hf} h_{ice}^{1.25} f^{4.5}$$

Calibrate for zero bias of $\log(k_i)$.
That gives $C_{hf} = 2.9$ (with SI units).



Results

Evaluating correlation with distance from ice edge.



Manuscripts about this dataset

Kohout, A.L., Smith, M., Roach, L.A., Williams, G., Montiel, F., Williams, M.J.M., 2020. Observations of exponential wave attenuation in Antarctic sea ice during the PIPERS campaign. Annals of Glaciology, 1–14. https://doi.org/10.1017/aog.2020.36

This introduces the field study and presents estimates of dissipation rate using what I call the "geometric method" and dissipation rate is primarily computed in terms of total energy. Uses entire dataset.

Rogers, W.E., M. Meylan, A. Kohout, 2021: Estimates of spectral wave attenuation in Antarctic sea ice, using model/data inversion, *Cold Regions Science and Technology*, 13 pp., https://doi.org/10.1016/j.coldregions.2020.103198

This is the paper presented here. It uses what I call the "inversion method". Dissipation rate is computed as a function of frequency (spectral). Focuses on ~40% of dataset.

Field experiment overview

- Region: Southern Ocean north of the Ross Sea
- Motion sensors (“buoys”) were deployed on the ice during the ingress and egress of the R/V Palmer to the Ross Sea, part of the “PIPERS” field experiment
- Ingress: 21-22 April 2017, “western” deployment, 4 buoys, last surviving buoys reports to 6 July
- Egress: 30 May to 3 June 2017, “eastern” deployment (by ~470 km), 10 buoys, last surviving buoy reports to 26 July.

This study focuses on buoys from the second (outgoing) deployment, 6 to 30 June. We use 9,477 spectra, or 41% of the full dataset (23,206). These 24 days include all large wave events (H_{m0}>3 m) from the full dataset.

anti-noise algorithm