REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 12/31/2019	**2. REPORT TYPE** Final Technical Report	**3. DATES COVERED** *(From - To)* 08/01/2017 - 12/31/2019

4. TITLE AND SUBTITLE Analysis of field data for wave ice interaction in the Arctic marginal ice zone	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER N00014-17-1-2862
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Shen, H.H.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Clarkson University 8 Clarkson Ave Potsdam NY 13676-1401	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 N Randolph Street Suite 1425 Arlington VA 22203-1995	**10. SPONSOR/MONITOR'S ACRONYM(S)** ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

There are two goals in this project. One is to extend the data analysis to a region north of the Sikuliaq 2015 track, covering the pack ice zone, to determine the viscoelastic model parameters. The other is to combine the two dominant modes in the mode swap zone to obtain a smoothly varying wave speed and attenuation in the entire parameter space. This will remove the need to choose only one mode currently adopted in WW3, so that contribution of equally important two modes in the mode swap zone may both be accounted for. An updated module to be implemented in WW3 will be completed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Hayley H. Shen
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	6	315-268-6614

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contract Number: N000141712862
Title: Analysis of field data for wave ice interaction in the Arctic marginal ice zone
Duration: 2017-08-01 to 2019-12-31
Principal Investigator: Hayley H. Shen, Department of Civil and Environmental Engineering, Clarkson University, Potsdam NY USA, hhshen@clarkson.edu

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ABSTRACT

This is the final report of N000141712862 "Analysis of field data for wave ice interaction in the Arctic marginal ice zone", a continuation of N000141310294 "An integrative wave model in the marginal ice zone based on a rheological parameterization". The long-term goal of both the present and the previous projects are to enhance wave forecasting models such as WAVEWATCH III® (WW3) so that they can predict the marginal ice zone (MIZ) wave conditions in the present and future Arctic seas. In project N000141310294, we completed the theory and delivered the resulting numerical code to the Naval Research Laboratory (NRL). This model is now one of the ice switches (IC3) implemented in WW3. We then used data from the SeaState and Boundary Layer Program (https://www.onr.navy.mil/en/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/arctic-global-prediction/Sea-State-DRI) to calibrate the two parameters in IC3 for ice covers predominantly populated with pancake ice. These results have been disseminated in 17 journal papers, 27 conference papers and abstracts, 1 book chapter, and 2 PhD theses. Details may be found in the final report of that project. In the present project, we improved the numerical procedure for the viscoelastic model to handle the mode switch zone. The resulting code (IC3+) delivered to NRL is smooth over the entire parameter space. Calibration of the two parameters in the viscoelastic model has also been extended to the pack ice zone further into the MIZ. This calibration is made possible based on SAR data from Sentinel-1A provided by Justin Stopa. Laboratory and numerical studies of wave propagating through an array of rectangular ice floes have been carried out to determine the equivalent elasticity for floe aggregates, thus provide a physical basis for the elastic aspect of the theory. The viscous aspect affects wave dissipation caused by many floe-scale processes including floe-floe collisions, hysteresis in floe flexing, hydrodynamic drag, and overwash. A numerical simulation has been conducted to reproduce the laboratory results. In this simulation many dissipation mechanisms are included. The results show that multiple parameterizations may reproduce the same wave attenuation. Hence model validation will require simultaneous measurements of all potential dissipative processes. Publications from this project include 13 journal papers (11 published, 2 under revision), 1 book chapter (under revision), and 5 conference papers/abstracts. Details are listed in the publications section.

Major objectives:

There are two major objectives in this project.

1. Extend the data analysis to a region north of the Sikuliaq track covering the pack ice zone, to determine the corresponding viscoelastic model parameters. The viscoelastic model was developed with a general ice cover in mind. Hence, it is necessary to expand the study beyond the grease/pancake ice zone covered by the buoys in the

2015 field campaign. More ambitiously, through doing so, we can develop a road map to expand the work to all ice types and other theoretical models.

2. Combine the two dominant modes in the mode swap zone in this viscoelastic model to obtain a smoothly varying wave speed and attenuation in the entire parameter space, so to remove the need to choose only one mode currently adopted in switch IC3 for WW3. In this way, contributions of equally important two modes in the mode swap zone may both be accounted for. Although only minor changes result in this modification, it is technically more complete. The above is on model building. On the fundamental physics side, derivation of an equivalent elasticity for ice covers consist of discrete floes also needs to be established.

Accomplishments:

Directional wave spectra from Sentinel-1A images obtained from Justin Stopa have been analyzed to obtain the wave attenuation in the pack ice zone. They show an order of magnitude difference in the viscoelastic parameters for this type of ice than for the grease/pancake ice (see Figures 1 and 2 in Results Dissemination). A manuscript will appear in The Cryosphere for the pack ice analysis. Combined results for grease/pancake ice and pack ice will appear in the Proceeding of the 25th IAHR Ice Symposium. The technique developed can be applied to other ice types and different wave-in-ice models.

The IC3+ code that combines both dominant modes in the mode swap zone from the viscoelastic model has been completed and delivered to the WAVEWATCHIII® group at NRL for testing.

Laboratory and numerical simulation data analysis for wave propagation through an array of discrete rectangular floes is completed. We have obtained a formula that relates the equivalent elasticity to floe size, thickness, and the intrinsic elasticity of ice. Initial tests of this formula against field and laboratory conditions show that it can be used to determine the equivalent elasticity of an ice field consisting discrete floes. Once generalized to a three-dimensional case with circular floes, we may be able to estimate the equivalent elastic properties of a fragmented ice cover from the floe size distribution obtained through remote sensing images.

Results Dissemination

Details of the results are listed in the Publications section. Out of those results, the most important is the completed viscoelastic model for predicting ice effects on wave propagation in the MIZ. The derived dispersion relation from this model is (Wang and Shen, 2010, doi:10.1029/2009JC005591):

$$\sigma^2 - Qgk \tanh kH = 0 \qquad (1)$$

where

$$Q = 1 + \frac{\rho_{ice}}{\rho_{water}} \frac{(g^2k^2 - N^4 - 16k^6a^2v_e^4)S_kS_a - 8k^3av_e^2N^2(C_kC_a - 1)}{gk(4k^3av_e^2S_kC_a + N^2S_aC_k - gkS_kS_a)} \qquad (2)$$

In which, H is water depth, $\sigma = 2\pi f$ is the angular frequency, ρ_{ice} and ρ_{water} are the densities of ice and water, respectively, $k = k_r + ik_i$ is a complex wavenumber, h is the ice thickness, $a^2 = k^2 - \frac{i\sigma}{\nu_e}$, $S_k = \sinh kh$, $S_a = \sinh ah$, $C_k = \cosh kh$, $C_a = \cosh ah$, $N = \sigma + 2ik^2\nu_e$, and $\nu_e = \nu + \frac{iG}{\rho_{ice}\sigma}$. The equivalent shear modulus G and kinematic viscosity ν in this model are to be calibrated. These two parameters are envisioned to combine many sub-scale physical processes. In this project, the most important final product is the calibrated parameters G and ν for different types of ice covers. The completed model may then be used to calculate the complex wavenumber k. The real part k_r is used to obtain the wave group velocity $c_g = d\sigma/dk_r$. The imaginary part k_i is used to obtain the wave dissipation $S_{ice} = C2c_gk_iE$ in the governing equation for WW3:

$$\frac{\partial E}{\partial t} + \frac{\partial c_g E}{\partial x} = (1 - C)(S_{in} + S_{ds}) + S_{nl} + S_{ice} \tag{3}$$

where E is the power spectral density, C is the ice concentration, S_{in} is wind input, S_{ds} represents damping through wave breaking and swell dissipation, S_{nl} is the energy transfer due to nonlinear interactions among spectral components. Without knowing the values of the viscoelastic parameters, the above model cannot be used for wave forecasting. In this project,. we have combined results of its predecessor N000141310294 "An integrative wave model in the marginal ice zone based on a rheological parameterization" focusing on the grease/pancake ice and the present project N000141712862 "Analysis of field data for wave ice interaction in the Arctic marginal ice zone" focusing on the pack ice further from the ice edge. The parameters G and ν for both ice types are obtained. Figure 1 shows a Landsat 8 image which depicts both ice types. These Landsat 8 images are powerful for evaluating the ice cover morphology. They are however limited by the cloud cover. We could not find a clear Landsat 8 image that overlapped with our dataset shown in Figure 2.

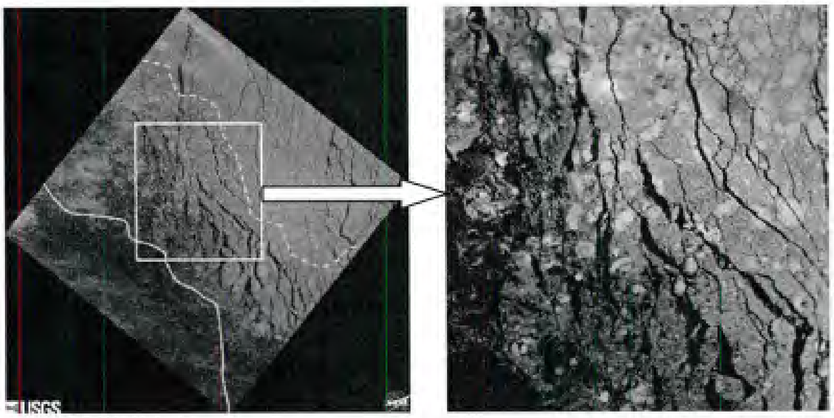

Figure 1. LANDSAT8 image on 20 September 2014. (LC80820052014263_Path82.jpg), centered around 77°03N, 145°34.5W. (Left) Full image. (Right) Enlarged rectangle in the full image. Solid line: 50% ice concentration contour ~30km from the center location. Dash line: 80% ice concentration. There is no in-situ information on the ice type. Left of the solid line it is mostly likely grease/pancake ice and to the right pack ice. Within the rectangular sub-region there is a clear combination of diffused ice, floe aggregates, and semi-continuous cover populated with leads.

The following figure provides a quick glimpse of the key results from this project. The data points represented by circles are the calibrated parameters G and ν for the viscoelastic ice model, labelled as IC3 in WAVEWATCHIII® for two types of ice covers: grease/pancake and pack ice. The color bars show their values. The pack ice is further divided into two zones: before and after the first appearance of leads (FAL). Before the FAL the ice cover is an aggregate of ice fragments. After the FAL the ice cover is semi-continuous populated with leads.

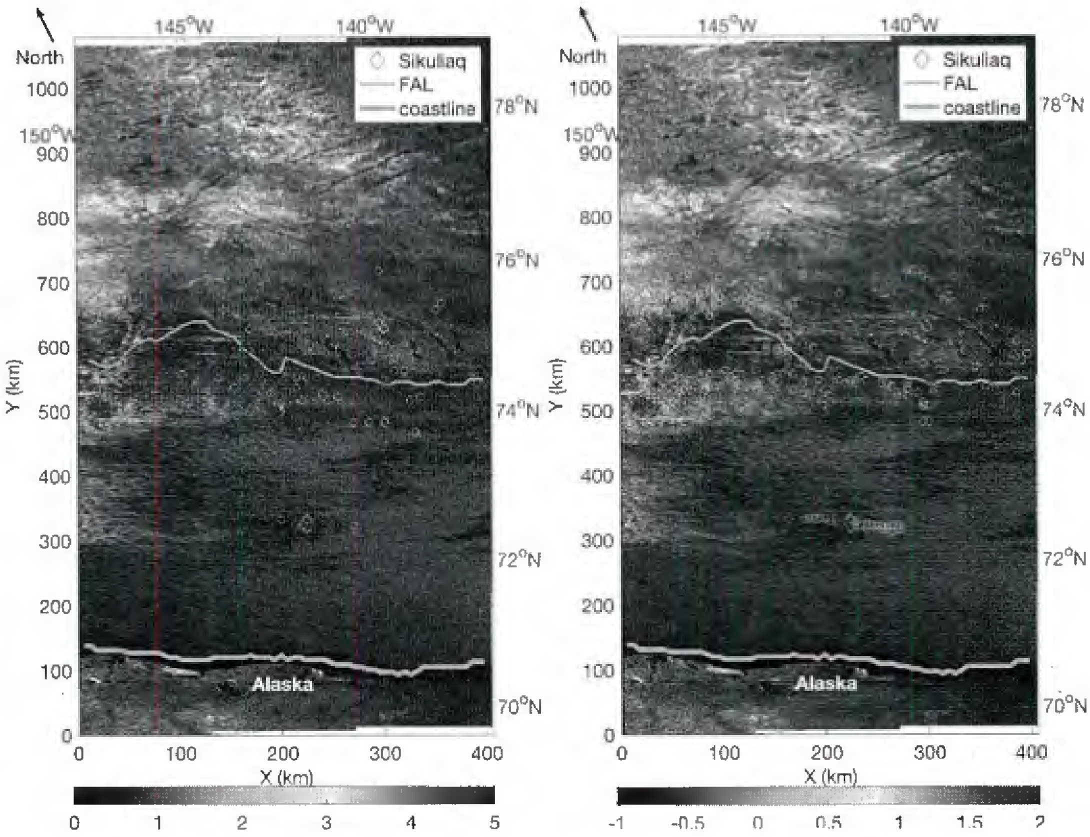

Figure 2. (Left) $\log_{10} G$ and (right) $\log_{10} \nu$. Both shown by circles with the color bars indicating their values. The cluster around 72°N is from the buoys deployed in grease/pancake ice zone near the ice edge. Those above 74°N are from SAR images obtained in the pack ice zone. The cyan-color line marks the first appearance of leads (FAL). North to FAL the ice cover is semi-continuous distributed with leads. South of FAL the ice cover is an aggregate of ice fragments. The underlying images is the SAR image from Sentinel-1A that provided the wave spectra data used in this project. Wave data used for this calibration are from two sources. The buoy data are explained in Thomson et al. (2018, https://doi.org/10.1002/2018JC013766). They were obtained from 10-13, October 2015. The SAR data are explained in Stopa et al. (2018, https://doi.org/10.1029/2018JC013791) obtained around 16:50 UTC on 12 October 2015. This figure summarizes the result of combining data and theory to calibrate a wave-in-ice model IC3 for WW3 applications. The same technique may be used to calibrate other models based on different theories. The completed models may then be tested to determine their capability for wave forecasts.

Publications:

A. Journal articles

Published:

1. Liu, D., Tsarau, A., Guan, C., and Shen, H.H. (2020) Comparison of ice and wind-wave modules in WAVEWATCHIII® in the Barents Sea, Cold Reg. Sci. Tech. https://doi.org/10.1016/j.coldregions.2020.103008
2. Herman, A., Cheng, S., Shen, H.H. (2019) Wave energy attenuation in fields of colliding ice floes – Part 1: Discrete-element modelling of dissipation due to ice–water drag. The Cryosphere, 13, 2887-2900, doi: 10.5194/tc-13-2887-2019.
3. Herman, A., Cheng, S., Shen, H.H. (2019) Wave energy attenuation in fields of colliding ice floes – Part 2: A laboratory case study. The Cryosphere, 13, 2901-2914, doi: 10.5194/tc-13-2901-2019.
4. Voermans, J.J., Babanin, A.V., Thomson, J., Smith, M.M., and H.H. Shen (2019) Wave attenuation by sea ice turbulence, GRL, doi:10.1029/2019GL082945.
5. Cheng, S., Tsarau, A., Evers, K.-U., and Shen, H.H. (2019) A laboratory and numerical study of floe size effect on wave propagation through ice covers, J. Geophys. Res. – Oceans. doi: 10.1029/2018JC014094.
6. Shen, H.H.. (2019) Modelling ocean waves in ice-covered seas, Applied Ocean Res. 83:30-36, https://doi.org/10.1016/j.apor.2018.12.009.
7. Sree, D. K. K., Law, A. W.-K., and Shen, H.H. (2018) An experimental study on gravity waves through a floating viscoelastic cover, Cold Regions of Science and Technology, https://doi.org/10.1016/j.coldregions.2018.08.013.
8. Zhao, X., and Shen, H.H. (2018) A three-layer viscoelastic model with eddy viscosity effect for flexural-gravity wave propagation through ice covers, Ocean Modelling, 151:15-23, https://doi.org/10.1016/j.ocemod.2018.08.007.
9. De Santi, F., De Carolis, G., Olla, O., Doble, M., Cheng, S., Shen, H.H., and Thomson, J. (2018) On the ocean wave attenuation rate in grease-pancake ice, a comparison of viscous layer propagation models with field data. J. Geophys. Res. – Oceans. doi: 10.1029/2018JC013865.
10. Mandal, S., Law, A. W.-K., and Shen, H.H. (2018) Wave interaction with circular ice ridge embedded in level ice, Cold Regions of Science and Technology, 155:90-99. https://doi.org/10.1016/j.coldregions.2018.06.011.
11. Thomson, J., Ackley, S., Girard-Ardhuin, F., Ardhuin, F., Babanin, A., Boutin, G., Brozena, J., Cheng, S., Collins, C., Doble, M., Fairall, C., Guest, P., Gebhardt, C., Gemmrich, J., Graber, H.C., Holt, B., Lehner, S., Lund, B., Meylan, M.H., Maksym, T., Montiel, F., Perrie, W., Persson, O. Rainville, L., Rogers, W.E., Shen, H., Shen, H., Squire, V., Stammerjohn, S., Stopa, J., Smith, M.M., Sutherland, P., Wadhams, P. (2018) Overview of the Arctic sea state and boundary layer physics program. J. Geophys. Res. – Oceans. doi:10.1002/2018JC013766.

Under revision:

12. Sree, D., Law, A. W.-K., and Shen, H.H. An experimental study on gravity wave through a segmented floating viscoelastic cover. Applied Ocean Research.

13. Cheng, S., Stopa, J., Ardhuin, F., and Shen, H.H. Spectral attenuation of ocean wave and its application in calibrating two viscoelastic models for pack ice. The Cryosphere.

B. Book Chapter

Shen, HH (2020) Wave-in-Ice Models and Experimental Observations, Proceedings of IUTAM Symposium on Physics and Mechanics of Sea Ice, Aalto University, Finland, under revision.

C. Conference papers and abstracts

1. Sree, D., Law, A.W.-K., and Shen, H.H. (2020) An experimental study on surface wave propagation along segmented floating viscoelastic covers. Proc. 25th IAHR International Symposium on Ice. Trondheim, June 14-18, 2020.
2. Shen, H.H., Ackley, S.F., Shen, H.T., and Yue, C. (2020) Modeling new ice formation under the influence of ocean waves. Proc. 25th IAHR International Symposium on Ice. Trondheim, June 14-18, 2020.
3. Cheng, S., Stopa, J., Ardhuin, F., and Shen, H.H. (2020) Calibrating viscoelastic wave-in-ice models for different types of sea ice covers. Proc. 25th IAHR International Symposium on Ice. Trondheim, June 14-18, 2020.
4. Shen, H.H. (2019) Wave-in-Ice Models and Experimental Observations, Invited speaker for IUTAM Symposium on Physics and Mechanics of Sea Ice, Aalto University, Finland – http://aalto.fi/iutam2019
5. Shen, H.H. and Cheng, S. (2018) Physics, mathematics, and reality of some viscoelastic wave-in-ice models. 2018 SIAM Conf. Nonlinear Waves Coherent Structures, June 11-13, 2018, Anaheim, CA.