Navigating the New Arctic: Insights into Ship Activities, Ice Modeling, and Stakeholder Engagement in the U.S. Arctic Waters

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ABSTRACT

In this paper, we focus on investigating ship activities in the United States' Arctic waters and developing new viscoelastic materials that can mimic specific ice behavior. This is a significant challenge, and we discuss potential positive outcomes and how the acquired knowledge can contribute to understanding ice behavior in Arctic and Sub-Arctic regions. We first define ice and ship statistics, providing a foundational understanding of potential ice-ship interactions. We then describe the development of thought experiments for wave-ice interactions and the creation of a numerical environment for modeling purposes. This step is crucial for simulating various scenarios related to ice and wave dynamics, ultimately contributing to the design of ships capable of navigating safely in diverse Arctic conditions. Finally, stakeholder and community engagement is addressed, recognizing the importance of involving local perspectives and insights to ensure practical, socially responsible, and effective solutions.

INTRODUCTION

Climate change and the extent of retreating ice have led to the Arctic becoming an ever-increasing area of interest for the maritime industry and governments (Berkman et al., 2020). The loss of sea ice has the potential to change climate patterns and create harsh environmental conditions in the polar regions, which creates extra challenges for marine structures. For example, drifting sea ice may collide with a structure and cause ice-induced vibrations (IIV) (Gedikli et al., 2019), cause damage to a ship's hull (Suyuthi et al., 2013), or have a substantial impact on Arctic coasts, rendering them physically susceptible to erosion, inundation, along with infrastructure and settlement destruction caused by ocean water (Barnhart et al., 2014). As a result, ships and offshore and coastal structures in the Arctic must be designed to be safe for people and environmentally friendly while also being cost-effective. However, our ability to describe and model the Arctic regions compared to non-Arctic regions is limited, so we need a holistic approach that includes developing new materials to mimic ice behavior while incorporating local perspectives and insights for socially responsible and effective solutions.

In order to look forward to the potential of the future of Arctic and ice-structure interactions (ISI), it is essential first to understand the context of the past. The Alaskan waters have a long history of supporting various marine trades, which has been historically monitored using the Automatic Identification System (AIS). AIS is a VHF-based system that transmits ship identification information, vessel characteristics, current navigational information, and voyage information. Prior research has shown that AIS data can be used to study ice navigation, where it has been utilized for route optimization in ice-covered waters, modeling emissions from Arctic shipping, and analyzing winter navigation accidents in the Baltic Sea (Kotovirta et al., 2009; Valdez Banda et al., 2016; Winther et al., 2014).

The AIS data alone is insufficient to show the complete picture; environmental data is also needed to fully understand Arctic maritime operations. The remote nature of most of the Alaskan maritime communities makes in-situ data coverage impractical to rely on. Satellite-based remote sensing techniques, such as those used by the Copernicus satellite system, have enabled us to collect large amounts of sea ice data, including information on ice extent, thickness, and concentration. By combining AIS data with sea ice data from the Copernicus missions, we can better understand vessel behavior in challenging navigational conditions and support the safe and sustainable maritime operations in Alaskan waters (Peel et al., 2023).

Building upon this understanding, studying complex ISI in the marginal ice zone, where most ships and offshore structures operate in the Arctic, involves addressing challenges in accurately modeling the behavior of ice. Numerical simulations face limitations with current ice models. The use of more complex ice materials, such as those considering viscoelastic properties, has been proposed to enhance accuracy in depicting the interaction between waves and ice (Sree et al., 2020). Solitary ice floes have been mathematically modeled to bend with ocean waves, supporting the use of flexible and viscoelastic material properties in wave modeling (Meylan & Squire, 1994). A wave-based model for the marginal ice zone, including a floe breaking parameterization, has also been developed by treating ice as both a flexible and rigid material, emphasizing the importance of material flexibility in accurately representing ice floe behavior in waves (Dumont et al., 2011). The comparison of idealized simulations using three-dimensional formulations for wave-ice interactions for flexible ice floes emphasizes the importance of considering flexible material properties when modeling wave-ice interactions (Perrie et al., 2022). This is supported by the preference for field observations or modal analyses, which show that larger ice floes are subject to more significant flexure-induced stresses or strains. In contrast, smaller floes will likely move with waves with slight bending, highlighting the importance of considering ice floe size and flexibility in wave interactions (Li, Gedikli, Lubbad, et al., 2020; Li et al., 2021).

To build a more comprehensive understanding of ice interactions with ships and offshore structures in the Arctic, particularly in Alaskan waters, it is also necessary to explore stakeholder and local community maritime experiences. As an integral part of the overall Navigating New Arctic, National Science Foundation (NNA-NSF) Arctic Sea ice research, our team is actively engaging stakeholders, working to build community partnerships, and conducting a stakeholder survey analysis to gather vital anecdotal information about the local experiences with sea ice interactions along the Far North and Western Alaska coastline regions. Our research into understanding the behavior of ice using viscoelastic materials to create an objective framework based on statistical modeling, which could potentially provide a more accurate measure of the potential interactions between drifting Arctic Sea ice floes and marine vessels, requires critical stakeholder support and local knowledge of the region. Collaborative partnerships with local stakeholders and communities better inform the research with their feedback, providing a pathway for sharing local indigenous knowledge and coordinating research efforts in the future.

SHIP OPERATIONS IN THE CHANGING ALASKA

In this section, we present a framework that links the ship AIS data with the Copernicus Sea ice data to visually represent possible interactions between ice and ships. The AIS and Copernicus data were spatially limited to the latitudes 53º to 75º North and longitudes 180º to 120º West. Since the AIS data continuously updates, a minimum Speed Over Ground (SOG) filter was set at 3 knots to only include the active vessels. This framework utilizes 28 UTM Grid Zones, 7 horizontal longitudinal zones, each 6º wide, and 4 vertical latitude zones, each 8º tall (see Figure 1). This framework also functions primarily by assessing whether there is maritime activity and ice concentration exceeding the threshold within the designated zone. If such conditions are met, it identifies the nearest point in terms of space and time for each AIS data point and verifies if it surpasses the ice limit. See Peel et al. (2023) for a more thorough explanation of the framework.

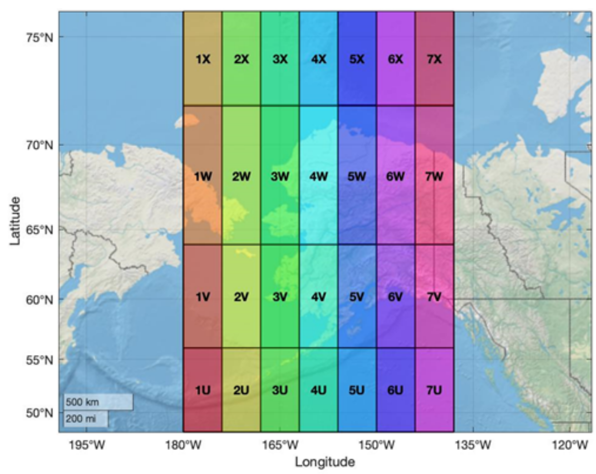

Figure 1. A visual depiction of the UTM Zones utilized in the framework and their color coding.

Figure 2 depicts the graphical representation of the results obtained from running the framework at a 60% limit for ice contraction. The top row, (a) and (b) plots, in Figure 2 shows the number of unique ships identified by the framework, with the right plot (b) showing which UTM zones they were operating in and the left plot (a) showing the types of ships that were identified. It should be noted that the total number of ships, shown monthly on the Zone plot, can be higher than the total number of unique ships operating that month, as a ship can be counted as unique in different Zones in the same month. The bottom row of plots in Figure 2 shows the monthly vessel activity both spatially, in the right plot (d), and by industry in the left plot (c). The plots showing the industry breakdown on the left half of the figure (a and c) help illustrate the evolution of the data. The data prior to 2015 was stored as geodatabase files by Longitudinal zone in monthly blocks, while post-2015, the data was stored as daily .csv files. The .csv files stored the data together instead of by different layers, making it easier to read, more reliable, and easier to verify. The shift in data quality can be seen in the frequency of the number of vessels listed as NA and other, before and after 2015. The number of ships and their frequency starts to steadily increase after 2016, which coincides with the US Coast Guard instituting more stringent AIS requirements for vessels that year, which sped the general trend of voluntary AIS adoption stemming from the technology becoming cheaper and more effective in maritime industries. Conversely, the spike seen in 2012 appears to be driven by environmental factors. Most potential ice interactions during the spike were experienced in the lower latitude V Zones as opposed to the higher latitude W interactions seen later after the more widespread AIS adoption. Note that the same framework was applied at different ice concentration levels, but we are unable to present the details here due to page limitations. 593 locations have been identified in the Alaskan waters where a moving ship was present. All 593 locations were utilized to estimate the thickness of the ice, as explained below.

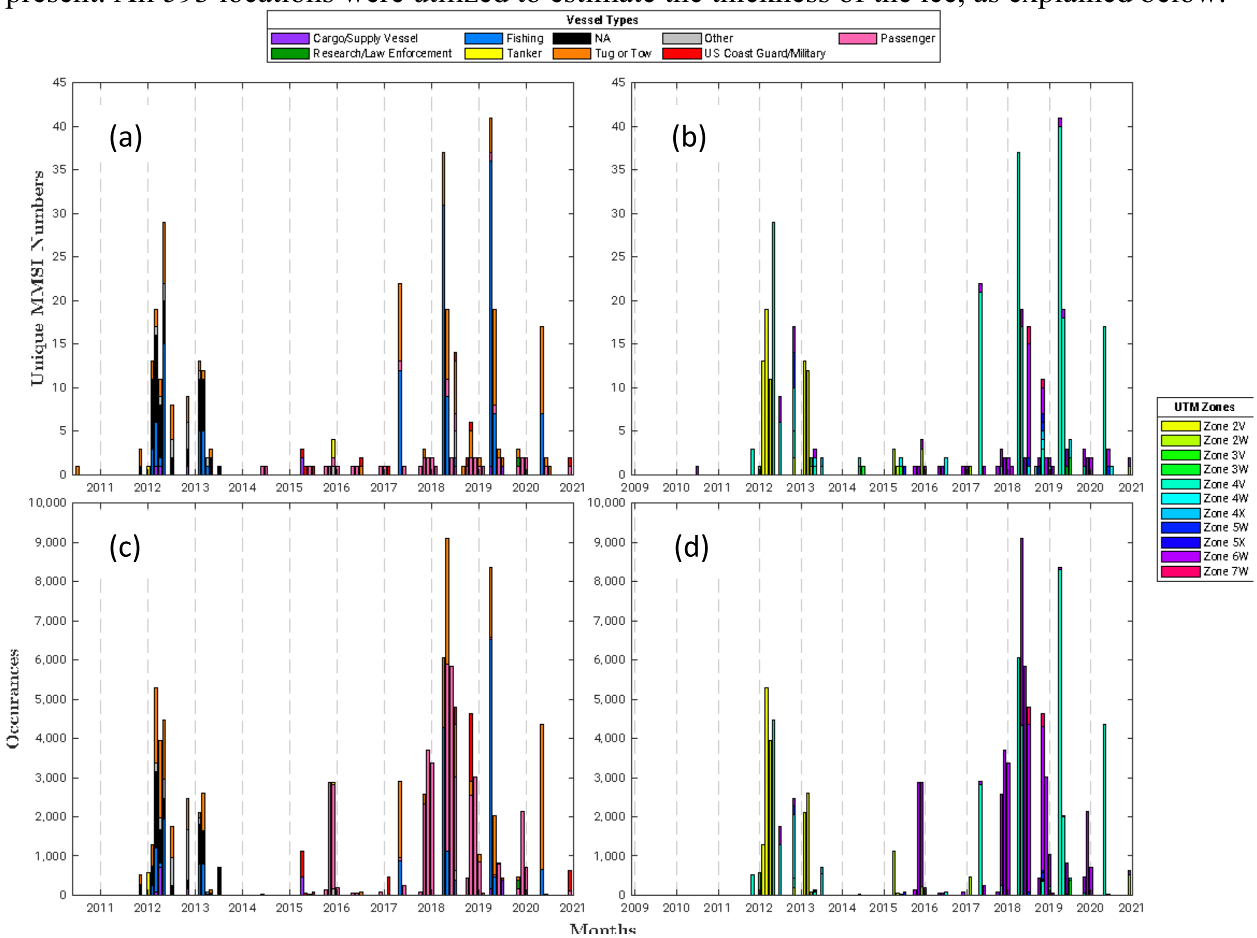

Figure 2. The framework results at ice concentration above 60% (a) number of unique ships of each vessel type per month (b) spatial distribution of the ships per month (c) number of occurrences for each vessel type per month (d) spatial distribution of the vessel activity per month.

ICE THICKNESS ESTIMATION

Accurate ice thickness estimation is critical for safe ship and offshore operations in cold environments for piloting vessels through areas with thinner ice, avoiding collision risks, and planning successful routes. It adds to the structural integrity of offshore structures by ensuring that they are built to resist the forces exerted by changing ice conditions. Moreover, ice thickness data is critical for optimizing operational planning, resource allocation, and risk management, allowing shipping companies and offshore operators to make informed decisions. It also plays an important role in icebreaking operations, environmental impact assessment, and emergency response planning, ultimately improving the safety, efficiency, and environmental sustainability of activities in challenging icy environments (Kujala et al., 2019; Høyland et al., 2021).

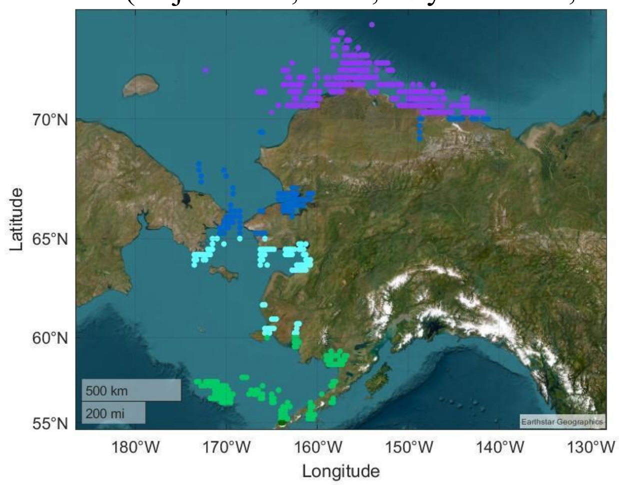

Figure 3. The locations of color-coded ice thickness time series in Alaskan waters.

In this work, we are particularly interested in the ice thickness values around the Alaska region as shown in Figure 3. The ice thickness between 2009 and 2020 was estimated based on the local air temperature values pulled from the ERA5 reanalysis downloaded from the Copernicus Database. The air temperature data has a spatial distribution of $0.25^o \times 0.25^o$ and an hourly temporal distribution. The identified locations for the potential ice-ship interactions discussed in the previous section were compared to the spatial distribution for the air temperatures until 593 points were identified as areas of interest. A daily mean air temperature time series was found in each identified location. The ice thickness was determined by coupling two models based on air temperature, one for ice growth and the other for ice melting (see Equation 1&2). The ice growth model was based on a solved Stefan's Law using Freezing Degree Days (FDD) (Seidou et al., 2006). The ice melting model used was a Positive Degree Day (PDD) Model that equated the volume of water melted to a loss of ice thickness using the ice density (Wake & Marshall, 2015). For the ice growth model, the FDD was calculated using the freezing point of Seawater -1.8°C (Timco & Frederking, 1996) while the PDD was calculated using a melting point of 0°C. This method leaves a buffer zone where neither ice growth nor melts around the freezing point, which was necessary after some observed drift in the generated interannual ice thickness time series.

$$h_f = \sqrt{{h_i}^2 + .0014FDD} \qquad Air\,Temp \leq -1.8°\text{C} \tag{1}$$

$$h_f = h_i - .008\frac{\rho_{water}}{\rho_{ice}}PDD \qquad Air\,Temp > 0°\text{C} \tag{2}$$

where h_i represents initial ice thickness, h_f represents final ice thickness, ρ_{water} is density of water and ρ_{ice} is the density of ice. Figure 4 illustrates a cumulative plot of the daily ice thickness time series generated from air temperature data from 2009 and 2020 in the region. It shows that the daily ice thickness time series generated by this method is consistent and, therefore, relatively conservative on the actual ice thickness values (with a lack of significant interannual variability).

As shown in the left image of Figure 4, this method produces a consistent daily time series of ice thickness, indicating a conservative estimate of actual ice thickness values and low interannual variability. This method is especially useful for level ice scenarios and is mostly used in operational contexts with lower ice concentrations. In these regions, vessels focus on identifying minimum ice thicknesses rather than experiencing maximum potential thicknesses. Figure 3 shows variable locations with potential ice-ship interactions, while Figure 4's right image shows a well-distributed range of ice thicknesses across air temperatures. These findings affirm the success of the instituted buffer and indicate a higher prevalence of multiyear ice in the higher latitudes.

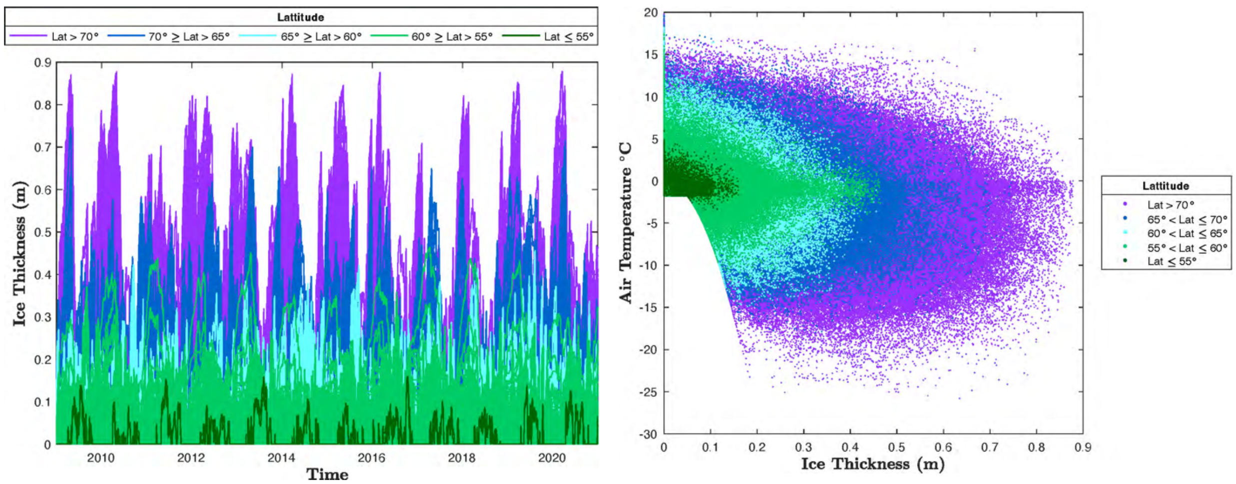

Figure 4. Left image: A cumulative plot of the daily ice thickness time series generated from air temperature data from 2009 to 2020 in areas of interest around Alaskan waters. Right image: Air temperature vs. Ice thickness at locations of interest in Alaskan waters from 2009 to 2020.

The local air temperature-based ice thickness estimation method is computationally efficient and useful for preliminary assessments in areas with lower ice concentrations. The method is most accurate for stationary ice masses like landfast ice due to fixed spatial air temperature locations. This limitation emphasizes the need to consider operational context and ice conditions when using the method. However, determining minimum ice thickness aligns with operational priorities in regions with lower ice concentrations, improving ship and offshore safety. An effective buffer zone improves ice thickness time series reliability. Finally, while the method provides a valuable approach, further refinement and validation may be required for diverse operational requirements and environmental dynamics in various Arctic regions.

HYDROELASTIC RESPONSE OF FLEXIBLE PLATES

This section investigates the combined effects of material properties and hydrodynamics on wave absorption for floating flexible plates. The scalability issues with ice led to the idea of finding a material similar to ice that mimics the properties of viscoelastic ice sheets and the behavior of ice under different wave conditions. For this purpose, an experimental setup was designed to better understand the mechanics of ice sheets' wave-induced flexural motion using viscoelastic materials similar to the ice-wave interaction experiments of Li et al. (2021). The accuracy of the experimental study was compared to the results of a 10-cases in FSI analysis performed with the ICFD solver in LS-DYNA using the finite element method.

Physical and Numerical Experiments: Two flexible floating plates with the same dimensions (length 76.2cm, width 15cm, thickness 0.5cm) and different elastic properties were produced consisting of silicone rubber and modified with different filler materials. The density of the two sheets is similar to that of ice ($\sim 900\ kg/m^3$). Tensile testing was used to determine the modulus of elasticity. The experimental setup consists of a wave tank with a piston-type wave generator for generating regular waves, a beach-shaped wave absorber, and four wave gauges, as shown in left image in Figure 5. To study plate-wave propagation, two wave gauges were placed in front of and two behind the test area to measure wave elevation. A GoPro recorded the plate's motion at 60Hz for motion analysis. Mooring lines limited the plate's x-motion to keep it in place for motion tracking and mimic the ice experiments (Li et al., 2021; Behnen et al., 2022). The plates' width matches the wave tank's, limiting plate movement (quasi 2D).

An analysis was conducted to examine the impact of various wave conditions on flexible plates. This investigation resulted in 20 separate trials, as depicted in Table 1. The five distinct wave period scenarios were also conducted without a plate to normalize the transmission coefficients. Each experiment was performed with a four-minute interval between each trial to ensure that the water in the tank remained in its initial state for each experiment.

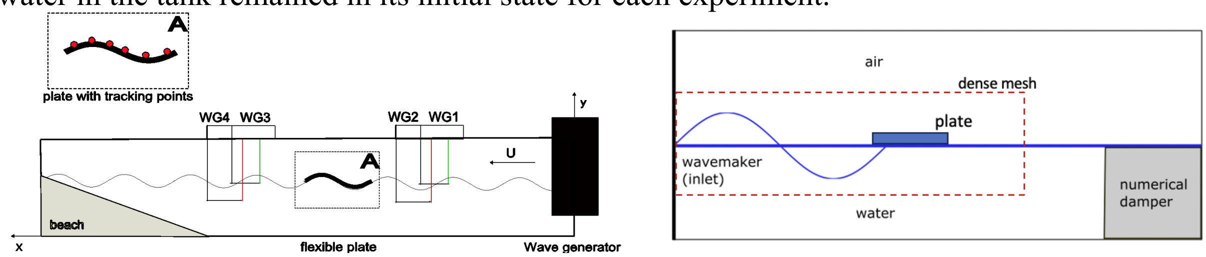

Figure 5. Left image: Experimental sketch. Right image: Sketch of the numerical model.

The numerical aspect of this study relies on analyzing the hydrodynamic (not shown) and mechanical behavior of a floating, flexible ice floe in regular waves using the ICFD method in commercial software LS-DYNA (Behnen et al., 2022). The software uses a simplified mathematical model based on the Navier-Stokes equation, which describes the behavior of fluids. The used FSI algorithm solved the fluid numerically with a CFD solver and the structure with a FEM solver. The limitation of the plate motion allows the use of a 2D environment for the numerical model based on the layout of the wave tank shown in the right image in Figure 5, which outlines the essential components and fluid boundary. Based on the second-order Stokes wave theory, the inlet serves as the numerical wave generator. The flexible plate sheet, represented as a 2D plate, is composed of shell elements and uses an elastic material type to represent elastic behavior. A convergence study was conducted for a numerical wave tank simulation to determine the optimal mesh size and time step for reliable results. The choice of mesh size aimed at ensuring stable wave propagation within the investigated area of the wave tank, avoiding issues such as wave attenuation or abnormal amplitude increases. A comprehensive examination involving different CFL (Courant-Friedrichs-Lewy) numbers was conducted to optimize the time step. The CFL number, representing the ratio of the distance a signal travels in one-time step to the spatial resolution of the grid, was varied to assess its impact on simulation stability. The optimum CFL value was defined as 0.4, at which the wave propagation in the wave tank was stable, and no instability occurred, consistent with observations by Tavakoli (2022).

Table 1. Experimental test matrix.

Case	Elastic modulus [MPa]	Wave period [s]	Wave amplitude [m]
1	2	0.7-1.1	0.01
2	2	0.7-1.1	0.015
3	0.3	0.7-1.1	0.01
4	0.3	0.7-1.1	0.015

Results of flexible plate experiments and numerical simulations: The recorded wave elevation of the wave gauges was used to determine the wave transmission coefficient where the wave transmission coefficient K_T is the ratio of transmitted wave amplitude, A_T, to incoming wave amplitude, A_I ($K_T = A_T/A_I$). The right image in Figure 6 shows this transmission coefficient, normalized with the transmission coefficient from the experiments without a plate, plotted against the wave period for the various cases. The graph demonstrates a noticeable correlation: as the wave period decreases, the transmission coefficient also decreases, indicating a greater energy loss in the wave, which is in line with the experiments of Li et al. (2020). It also shows that the wave gauge observations in the simulations correlate well with those in the experiment, indicating that the wave amplitude is decreasing; hence, there is an energy loss.

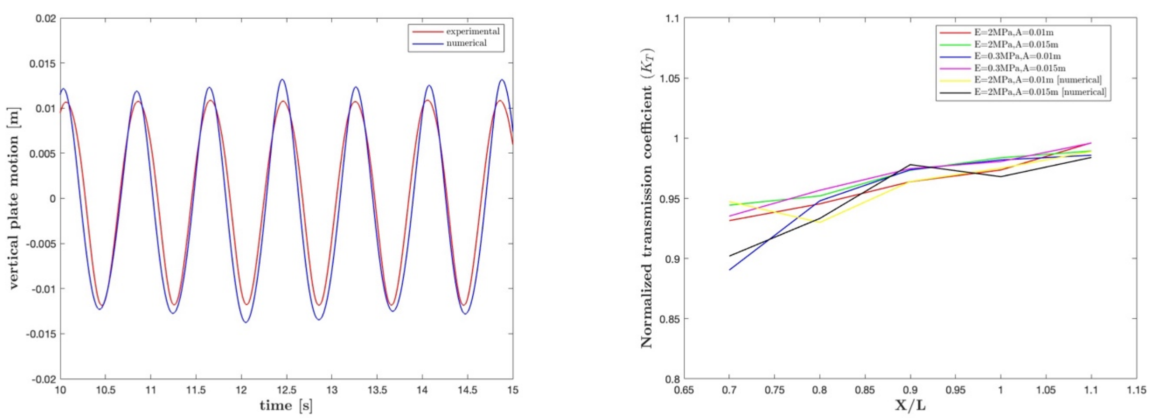

Figure 6. Left Image: Vertical plate motion for the experiments (blue) and the numerical simulation (red) (T=0.9s, A=0.015m, E=2MPa). Right Image: Wave transmission coefficient (the numerical results of the material with E=0.3 MPa have not been displayed to avoid clutter).

The motion analysis is performed using ProAnalyst software, and frequency response reveals a single dominant frequency in the plate motion, which is equal to the wave frequency, and no nonlinearities in the system are visible in the phase portraits (not shown). As a result, the plate precisely follows the wave motion, and the system can be considered linear. The left image in Figure 6 shows a validation case showing plate motion in the experiment and numerical simulation correlated well. The plate follows the waves in the simulation and has one dominant frequency.

STAKEHOLDER ENGAGEMENT AND SURVEY

Stakeholder Management Plan – Stakeholder Identification & Engagement: As a first step towards effective stakeholder engagement, survey analysis, and communication, it is important to establish a stakeholder management plan focused on identifying stakeholders, along with planning and implementing stakeholder management, which includes continued communication with stakeholders. Identifying stakeholders for this research includes understanding the initial geographical areas where our sea ice research focuses, which in this case includes Alaska and Alaska's Far North and Western coastlines.

Key stakeholders not only live but also conduct maritime operations within the Far North and Western coastline regions. The initial stakeholders this research identifies who operate within these industries include maritime transportation (shipping, barging and tugging operations, and cruise or charter services), fishing, construction, and other maritime industries. Along with these maritime industry stakeholders, additional stakeholders this research identifies include local residents (personal recreational activities and subsistence hunting and fishing), environmental groups, research or academic groups, state and federal organizations, and the military.

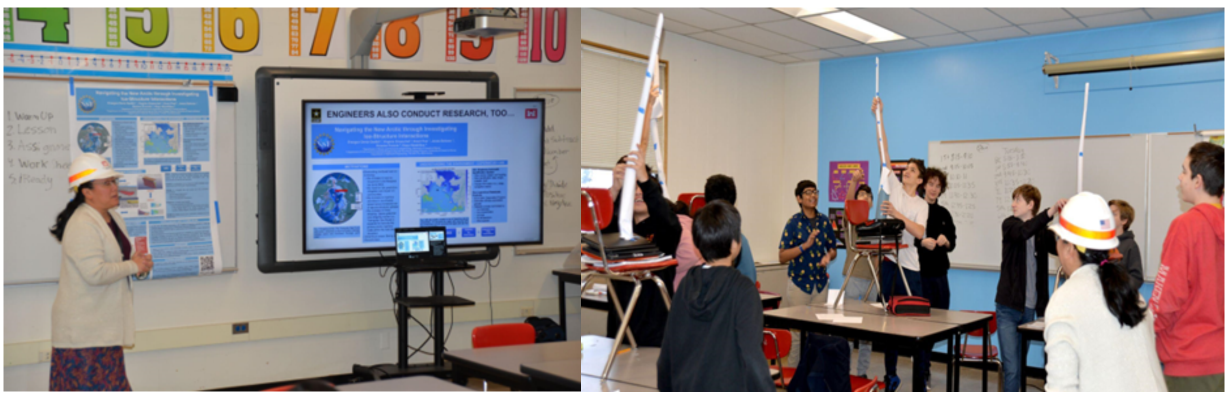

Figure 7. Community Outreach. Virginia Groeschel presenting sea ice research to students at Romig Middle School's STEM Fair in Anchorage, Alaska, Feb 23, 2023 during National Engineers Week statewide events (photo courtesy of USACE, Alaska District, 2023).

Local residents, who comprise stakeholders within this research area, are from 30 coastal village communities along Alaska's Far North coastline, which include Kaktovik, Alpine, Nuiqsut, Utqiagvik, Atqasuk, and Wainwright. Along Alaska's Western coastline, local resident communities also within this research area include Point Hope, Kivalina, Kotzebue, Deering, Shishmaref, Diomede Island, Brevig Mission, Nome, Elim, Savoonga, Gambell, Koyuk, White Mountain, Shaktoolik, Unalakleet, Scammon Bay, Hooper Bay, Mekoryuk, Tununak, Nightmute, and Chefornak among other coastline communities. These communities represent 36 Native Alaskan tribal groups and four Native Corporations, including Arctic Slope Regional Corp., Calista Corp., NANA Regional Corp., and Bering Straits Native Corp. Within the maritime industry, vessels actively operating in designated ice-infested research zones (Figure 1) are also included in the stakeholder register, or identified stakeholder list. As part of the stakeholder engagement process, the telecommunications industry is identified as experiencing interactions with sea ice along this region, which is an ongoing discussion to engage more stakeholders.

Once initial stakeholders are identified, the next step is to engage stakeholders and establish community research partnerships to support the NNA-NSF mission for inclusive and collaborative research. The goal is to promote mutual sharing of culturally appropriate information with indigenous cultures, their knowledge systems, and research needs, as well as share and facilitate connections among other NNA researchers and communities across Alaska. Stakeholder engagement also promotes education and outreach activities for local students and educators.

We are currently involved in six community research partnerships across five maritime and regional industries (Table 2). To inform our community partners and stakeholders, we are engaging more community research partners and offering in-person presentations of our research status. In addition to community partnerships, NNA-NSF targets community outreach. As part of the U.S. Army Corps of Engineers (USACE), Alaska District's group STEM activity sessions, a member of our research team presented this Arctic sea ice research to students ages 12 to 14 at Romig Middle School on February 23, 2023, during the annual National Engineers Week celebration in Anchorage, Alaska. The event included several hands-on STEM activities (Figure 7).

Table 2. Community Research Partnerships.

Community Research Partner	Industry
U.S. Army Corps of Engineers (USACE) Engineer Research & Development, Cold Regions Research and Engineering Laboratory (ERDC-CRREL)	Military, Research
Carlile Transportation	Shipping
Arctic Slope Regional Corporation (ASRC)	Construction, Engineering
Kilokak, Inc. (Sam & Doreece Mutch)	Fishing
Willow Netishen, Tugboat Captain	Towing
Kurtis Hansen, Tugboat Captain/Port Engineer	Towing

Stakeholder Survey & Analysis*:* The next step after identifying and engaging stakeholders is to prepare a survey to collect stakeholder anecdotal and observational data and then analyze their responses. The online stakeholders survey is located at www.fsilab.org.

Several variables are essential for survey analysis and risk assessment. Understanding the local physical environment can reveal risks in Arctic operations that would be difficult to identify without firsthand experience navigating in sea ice. Figure 8 shows a stakeholder analysis and risk assessment workflow that compiles survey responses and could incorporate follow-up interviews for operational information. Preparing a risk management plan helps identify impacts (positive and negative) and stakeholders' interests, expectations, and needs for safe marine navigational system research. Identifying risks and Enterprise Environmental Factors, which indicate factors that can affect the research but are outside the researcher's control, is the next stage of the assessment. Creating and conducting the survey is where stakeholder responses are gathered. The stakeholder survey, or questionnaire, is already prepared, and the stakeholder survey is currently underway. However, engaging larger numbers of stakeholders to take the survey is a challenge. Once the information is compiled, a survey analysis and risk assessment can be performed using qualitative, quantitative, and sensitivity analyses. Mitigating and controlling risks is the next step, where potential follow-up with stakeholders may be needed to understand existing interactions further in order to understand how to develop and implement a risk response, track a risk that has been identified, and monitor any continuing residual risks. There would also need to be a strategy on how to translate the risk assessment results to provide insights into the research.

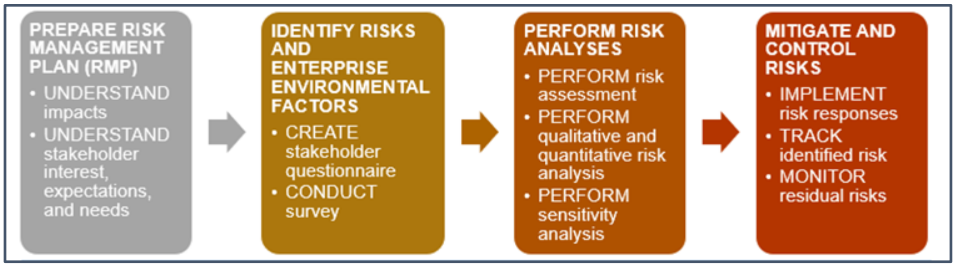

Figure 8. Stakeholder Survey Analysis & Risk Assessment Workflow.

CONCLUSION

In this paper, we address the critical challenges posed by changing Arctic conditions, particularly in Alaskan waters, and focus on understanding and mitigating the impacts of ice on ships and offshore operations. The study is structured into three main parts: defining ice and ship statistics, developing experiments and numerical models for wave-ice interactions, and engaging stakeholders and communities. We first explore the historical context of Alaskan waters using AIS data, supplemented by Copernicus satellite data, to better understand vessel behavior in ice-covered conditions between 2009-2020. The integration of environmental data enhances the overall comprehension of Arctic maritime operations. Later, we investigate the dynamics of several viscoelastic materials that mimic specific ice behaviors. The results indicate a correlation between wave period and transmission coefficients, providing valuable insights into energy transfer mechanisms. Stakeholder engagement and community partnerships are integral components of the research, recognizing the importance of local perspectives and knowledge. We identify key stakeholders in maritime industries and local communities, fostering collaborations through community research partnerships. The stakeholder survey and analysis seek to capture anecdotal information and operational insights, contributing to a comprehensive risk management plan. In conclusion, this research advances our understanding of potential ISI in the Arctic and Sub-Arctic regions and emphasizes the importance of community engagement for socially responsible and effective solutions. The combination of numerical modeling, experimental studies, and stakeholder involvement positions this work at the forefront of efforts to enhance the safety and sustainability of ship and offshore operations in the dynamically changing Arctic environment.

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