Artic Sea Ice and Ocean Waves: Understanding a Complex Relationship

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Scientia

ARTIC SEA ICE AND OCEAN WAVES: UNDERSTANDING A COMPLEX RELATIONSHIP

As the global temperature rises, we are already seeing worrying changes to ice conditions in the Arctic. Using computational modelling, scientists are trying to predict exactly how these changes may affect other areas of Earth's ice-ocean-atmosphere system. The relationship between sea ice and ocean waves is only beginning to become better understood: waves control the type of ice that forms, and the knowledge of various types of ice can be used in wave forecasting. **Dr Hayley Shen** of Clarkson University is part of an international research team that is developing and improving models to advance our understanding of wave-ice relationships.

Earth as a System

When we think about Earth, we think of a green and blue planet, with white clouds and icy poles. But what does this represent? Our planet is a series of environments: a liquid ocean, gaseous atmosphere, landmasses and ice at the north and south poles. These environments are all interconnected, creating a delicate system wherein a slight change to one affects the others.

The oceans hold over 95% of Earth's water, so it is unsurprising that they play a leading role in determining the behaviour of other environments. The relationship between Earth's oceans, ice and atmosphere is complex, and one where scientists are seeing rapid changes as the global temperature rises.

Changes to Arctic ice coverage are a key indicator of our changing climate, and the impacts of reduced ice cover are still being identified. Taking measurements in the Arctic is challenging due to the extreme conditions, so for a long time, scientists relied on limited observations and theoretical modelling to understand the ice-ocean-atmosphere system.

Modelling the Earth

Climate and Earth system modellers use mathematics to represent each part of a system and its variables – for example, the ocean and its surface temperature – to study how they interact. Modelling can reveal how changes in one component of a system can cause changes in others, and identify feedback loops. Models can be entirely based on theory, be driven by scientific data, or use a combination of both. Because data collection is challenging in extreme environments, Arctic scientists rely on theory-based models that they can calibrate with data from observations and laboratory experiments.

Dr Hayley Shen of Clarkson University in New York models the relationships between the ocean and polar sea ice. She is particularly interested in the mutual impact of ocean waves and Arctic ice cover, and has been establishing a model that can ultimately be used to help forecast waves in areas of ocean that are covered by ice.

A Theoretical Framework

In the ocean, wind disturbs the water and drives surface waves, often for hundreds of miles. Dr Shen and her team focus on how waves change as they move through a body of water covered with ice and how new ice growth is affected by the wave conditions. Scientists have been trying to create accurate models of how waves move through ice-covered water for many years. One of the key challenges is mathematically describing the properties of the ice itself. Ice covers are not uniform flat sheets. Instead, they are collections of many individual, packed together 'floes', or semi-continuous plates with cracks and ridges. An ice cover varies in thickness, concentration and type. Its temperature and salinity can significantly change how it flexes in ocean waves. No single model can fit all of these variations present in the polar seas. The goal for scientists is to find the simplest model that can explain most of what is being observed in nature.

Dr Shen and her colleagues began developing a new wave-ice model in 2001. They knew that different types

of waves cause different types of ice to form during periods of ice growth. One prominent type of ice grown in waves is pancake ice – circular ice pieces ranging from centimetres to metres across. They developed a theoretical framework that describes the formation or absence of pancake ice, and discovered that the size of ice pieces depends on the wave amplitude and the distance between wave crests. The team was able to identify this key relationship between waves and ice formation, but they needed to support their theoretical framework with data. These data have been collected in laboratories using wave tanks and from field experiments.

Over the past three decades, scientists have been studying ice formation using wave tanks, which range in size from 4 to 70 metres in length. 'In the past 20-year period, we have used a number of facilities at the US Army Cold Regions Research and Engineering Laboratory and Germany's Hamburg Ship Research Basin with various sizes,' explains Dr Shen. 'Because of their different sizes, a range of wave frequencies could be tested, where smaller tanks were for high frequency short waves and the larger ones for low frequency long waves.'

In these wave tank studies, they used underwater pressure sensors to measure the wave characteristics while they studied the ice that formed on the surface of the water under different conditions. The team discovered that in choppy seas where waves were short, only small pieces of pancake ice could develop, while in mild conditions larger pancakes formed. These are very similar conditions to those found around the edges of the Arctic Ocean. This work helped to clarify the idea that the type of ocean waves, in addition to the freezing conditions, controlled the size of ice pieces that formed.

Developing the Model

Next, the team developed a viscoelastic model that built on their theoretical framework to describe how waves propagate into ice-covered water. Since the 1970s, there have been increasing numbers of wave-ice models that apply different mathematical descriptions to ice covers, depending on the type of ice. The lack of a universally applicable model means that wave-ice modelling has captured only small snapshots of the whole relationship and cannot perfectly describe what is observed in nature.

Viscoelasticity describes the property of materials that have both viscous and elastic characteristics when they are deformed. A viscous material, such as honey, is frictional when it deforms and thus consumes energy. When a viscous material deforms it cannot regain its shape, while an elastic material will return to its original shape after the force is removed. Pure elastic materials do not consume energy when they deform. Many natural materials are both viscous and elastic, such as a soft bread dough or paint. An ice cube may not be easily envisioned as viscoelastic, but polar ice, comprising an enormous collection of individual pieces covering hundreds of miles, may be visualised as a material that deforms under a wave's undulation, and which returns to its original form while consuming energy simultaneously.

The team's model bridged the gap between the previous models that

attempted to describe wave-ice relationships as either purely elastic or purely viscous, and provides a tool for modellers to identify the parameters for wave propagation in polar seas. These parameters are variables, depending on many environmental conditions such as the type of ice cover, air temperature or wave height, that are required by the model to make predictions. Scientists can often estimate parameters based on collected data, although this is limited in the case of polar research.

What are the Next Steps?

The Arctic Ocean is becoming more open, allowing wind to create bigger and longer waves. These waves change the formation of ice cover and reshape existing ice covers to create a much more complicated environment. This means that sea-ice models need to incorporate accurate representations of the interactions between waves and ice to better describe the changes.

The parameters of Dr Shen's model (elasticity and viscosity) must be properly calibrated in order to provide the most accurate simulations. The best way to calibrate a model is to apply it to real data in the field. This means scientists can compare the predictions that their model suggests with what occurs in nature. By adjusting the model parameters, these predictions will change. The best-fit parameters are then used for applications. Calibration is common in many scientific models that have too many factors to be individually resolved, such as weather forecasting.

Dr Shen was part of an interdisciplinary and international group of researchers working on the SeaState and Boundary Layer Physics Project from 2012 until 2017. This investigation was driven by the US Navy, whose key aim was to understand environmental changes to the Arctic sea ice. The team collected huge amounts of data from the marginal ice zone during autumn of 2015, including temperature, wave measurements, ice data and weather information. They dropped buoys into the ocean to collect wave measurements, including data on their height and direction, combined with wind speed and direction measurements. The more measurements that are made, the more information modellers can incorporate into their wave-ice models to make them as accurate as possible.

Forecasting Waves

The key unknowns in Dr Shen's model had been the viscous and elastic parameters of the ice, but these could be determined through calibrating the model using the measured data. The team validated the model by incorporating it into the WAVEWATCH 3 model. This is a large, global wave-forecasting model that predicts wave conditions around the world, such as wave height and direction, using wind and ice concentration and thickness data.

The team used their viscoelastic wave-ice model as part of the larger model to forecast an area over the Beaufort Sea, which is a marginal area of the Arctic Ocean. They compared their calibrated model results with measured data from the region, and found that their model was a good match for locations where pancake ice dominates. Expanding the model to other ice types requires calibration with additional data.

Outlooks for Future Wave-ice Models

Dr Shen has been thrilled with the results of her team's research so far. 'From being overwhelmed with the complexity of polar ice covers and the vast ocean that interacts with them, to getting a handle on how to make reasonable estimates of wave conditions for navigation, it has been an enlightening experience,' she says.

So, what does the future bring for wave-ice interaction modelling? We know that the Arctic Ocean is losing its covering of ice, and its marginal zones where coverage fluctuates are becoming increasingly dynamic. As well as driving further climate changes through a reduced albedo effect, this has increasing impacts on shipping and offshore operations, making accurate predictions of wave behaviour and sea ice coverage even more important.

Even though there may never be a perfect, single wave-ice theory, the team hopes that as more environmental data becomes available, they can continue to fine-tune their model for other types of ice covering, helping to forecast and understand the changes we can expect as rising global temperatures drive further changes to Earth's climate.

Meet the researcher

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Dr Hayley Shen is Professor Emeritus at Clarkson University's Department of Civil and Environmental Engineering in New York. She holds two PhD qualifications in Applied Mathematics and Engineering Sciences. Her key areas of research are sea-ice dynamics as well as granular materials, and she enjoys opportunities to work on cross-disciplinary collaboration projects. Dr Shen has taught a variety of courses to both undergraduates and graduates, with an emphasis on applying mathematical results to physical interpretations. She has also provided mentoring and enrichment programs to under-represented students in STEM fields. She feels most fortunate for the experience to observe and make sense of Nature through the research projects she has undertaken, and through working with many amazing colleagues and students.

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