Forecasting Waves-in-ice for Arctic Operators

a report by

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The heroic age of polar exploration documents anecdotally how ocean surface waves change as they enter a region of ocean covered with sea ice. Evidence suggests that the indigenous dwellers of the Arctic were also aware that the intensity of waves diminishes as they travel further into the ice cover. Since those times, considerable effort has been put into understanding this physical phenomenon, and to a lesser extent, how sea ice itself is affected and altered by waves. The latter effects are of special interest because global warming is expected to increase the destructive impact of waves on the Arctic sea-ice cover.[1–6] When pummeled and broken up by waves, sea ice melts more easily to become less compact and more compliant. This in turn boosts the ability of the penetrating waves to destroy the weakened sea-ice mass that remains, a positive feedback that could accelerate the loss of ice during summer. Understanding, simulating and monitoring wave–ice interactions in the marginal ice zone (MIZ) – the part of the ice cover that interacts with the open ice-free ocean[7–10] – is the focus of Waves-in-ice Forecasting for Arctic Operators (WIFAR), a project funded by the Research Council of Norway and Total E & P Norge through the Programme for Optimal Management of Petroleum Resources (called PETROMAKS) for the period 2010–2013. WIFAR is co-ordinated by the Nansen Environmental and Remote Sensing Center (NERSC), Norway.

In a geophysical context, this research is motivated by the crucial importance of sea ice in regulating atmosphere–ocean fluxes, its effect on spatially integrated albedo and its capacity to create plumes of deep saline water during freezing that have a major influence on the circulation of the world's oceans. Notwithstanding this, the topic has become immensely important to industries involved in offshore exploration and production in ice-infested seas, where waves are a constant operational hazard. The presence of sea ice can, depending on wave conditions, protect or threaten structures, and help or complicate platform evacuation. Waves can propagate long distances into the ice and, therefore, a wave event is hard to predict from local weather conditions. Planning for safe operations thus requires sea-ice forecasting systems to take waves into account.

Wave–Ice Interactions

Ocean waves are affected variously depending on the nature of the sea ice encountered. Normally, the MIZ is a congeries of separate floes and cakes a few metres across near the ice edge that delineates the open sea from pack ice (see *Figure 1*). The MIZ can be identified from satellite images (see *Figure 1*), but no automatic algorithm is yet available to objectively identify it. In the Fram Strait, ice vortices forced by surface ocean currents highlight the relatively weak resistance of the ice to large-scale forces compared with ice in the central pack. The change in the dynamical regime of the ice is explained by waves. As waves penetrate the ice pack, they are scattered by ice floes and gradually lose energy with distance travelled. Wave energy attenuation is thus highly dependent on the number of floes encountered. However, the floe size distribution is mainly determined by the waves and generally increases with distance into the sea ice.[11] Near the ice edge, waves are sufficiently powerful to fracture and sometimes pulverise local ice into a slurry. A little further in, they can usually break up floes, but, when a certain distance is reached, the waves have become sufficiently weakened that they no longer regulate size. While scattering is the main mechanism operating to remove energy from the waves, other mechanisms such as ice inelasticity, collisions between floes, turbulence and viscous damping in the water also contribute to energy loss. Beyond the zone of fracture, the ice cover ordinarily becomes quasi-continuous. Ice floes are much larger although they may still be punctuated by cracks, pressure ridges and separated by leads. Scattering continues to occur from these heterogeneities but, because these features are less frequent, the other mechanisms can dominate. Activities planned during the course of the WIFAR project aim to measure, quantify and parameterise these processes to improve monitoring and forecasting capabilities in the MIZ. To do this, field experiments are planned to help validate models and parameterisations, but also to design future wave-monitoring systems in seasonally ice-covered areas. *Figure 2* provides an overview of WIFAR activities.

Challenge of Measuring Waves in the Marginal Ice Zone

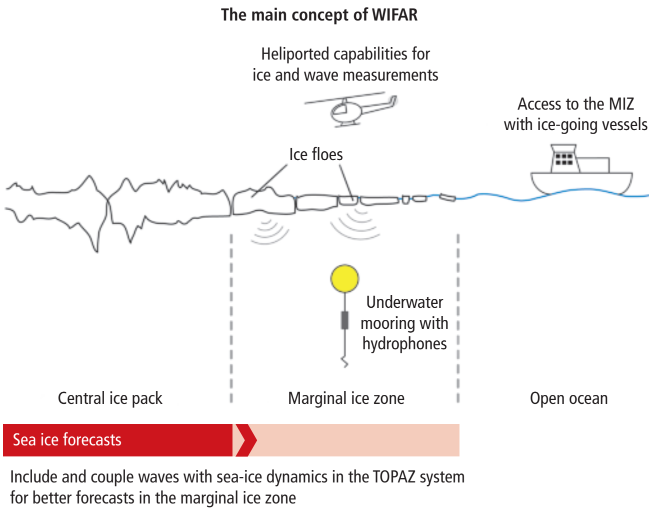
In previous research projects, tilt-metres and accelerometers were integrated into ice buoys placed on top of ice floes to measure tiny vibrations and flexural movements in the ice several hundreds of kilometres into the ice pack for several months.[10] However, small amplitude waves in the interior Arctic are not our concern in WIFAR. Our focus is the measurement of waves in the MIZ, which cause the individual floes to crush, heave, roll and even break up. In the highly energetic MIZ, it is nearly impossible to keep ice buoys stable on a particular ice floe for long-term measurements. Correspondingly, there is no observation system of waves in the MIZ.

Passive Acoustics

In response to the deformation, collision and break up of ice floes due to waves, acoustic noise is generated in the ocean.[12,13] The interaction of swell with sea ice is clearly observed on spectrograms obtained by sonobuoys. These buoys were dropped from a Norwegian P3 aircraft in the outer part of the MIZ in the Barents and the Greenland Sea.[12] As part of the WIFAR project, the ambient noise caused by waves in ice is being monitored at a fixed location (see *Figure 3*) for a period of two consecutive years by an Autonomous Acoustic Logger (AAL) serving a two-metre long vertical array of four equally spaced hydrophones. This system has been jointly designed and developed by NERSC and Naxys AS for the WIFAR project. The AAL is also integrated into an acoustic tomography system installed in the Fram Strait as part of the ACOBAR project,[14] which is also coordinated by NERSC, and allows the navigation of gliders under the ice.

Figure 1: The Marginal Ice Zone as Seen by the Synthetic Aperture Radar From the ENVISAT Satellite (Left, European Space Agency) and From a Ship (Right, GFD License 1.2)

Figure 2: Waves-in-ice Forecasting for Arctic Operators Will Carry Out Field Experiments in the Marginal Ice Zone of the Fram Strait and the Barents Sea



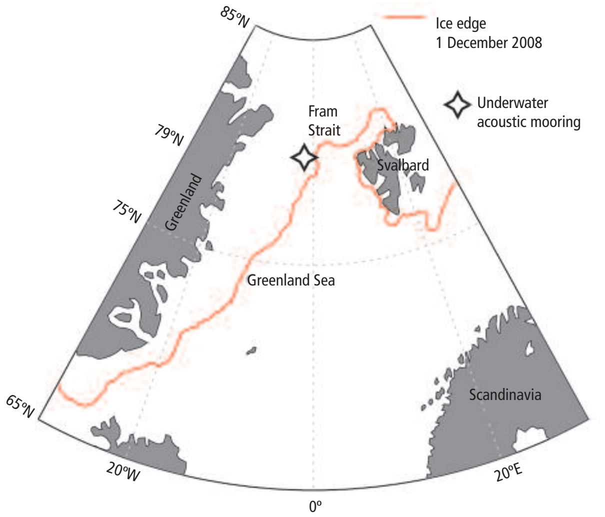
Underwater moorings will monitor the ambient noise of various ice conditions over at least one complete annual cycle. In combination with ship-based or heliported ice and wave measurements, these data will not only be used for model development and validation, but also for the design of waves-in-ice monitoring systems in the future. WIFAR = Waves-in-ice Forecasting for Arctic Operators; MIZ = marginal ice zone.

The entire tomographic, including the AAL, was deployed in September 2010 and will be recovered in the summer of 2012. During these two years, the AAL will record five minutes of ambient noise every three hours. Under the action of waves, currents and winds, the ice edge in the vicinity of the mooring can easily move more than 10 kilometres in a day. As a result, ambient noise will be recorded for a wide variety of wave and ice conditions, from compact ice pack to open ocean. Quite uniquely, ambient noise data will add to model output from wave models and satellite data to allow the study of the spatial variability of the wave field in the Fram Strait through the seasons.

Model Integration

Although intermittent in intensity, there have been efforts to try to understand wave–ice interactions for over a century. However, the mathematical and computational tools necessary to obtain physically viable solutions of wave propagation in inhomogeneous media such as sea ice have only appeared during the past decade. We are now at the point where wave transmission across significant swathes of Arctic quasi-continuous ice can be computed[15,16] and where 3D scattering by realistic ice floes in the MIZ can be accurately simulated.[17,18] At present, operational wave models do not simulate wave propagation into

Figure 3: The Fram Strait – the Location of the First Field Experiment in Summer 2010



The star symbol indicates where the acoustic system was deployed. The ambient noise will be recorded for two consecutive years under various ice conditions.

ice-covered areas. Moreover, operational sea-ice models do not include wave effects, even though they have a marked influence on sea-ice dynamics and morphology in the MIZ. The WIFAR project plans to do just that: to assimilate the omnipresent effects of penetrating ocean waves, allowing waves to dissipate properly through the actions of scattering and other mechanisms; to break up ice floes systematically and, in this way, reconfigure regional ice morphology; and to interact with the ice rheology used to describe the continuum behaviour of the sea ice field. The converse, namely to discover how the incoming wave spectrum moves through the ice pack and is altered by it, will also be possible. This should enable, for example, the wave-induced, potentially destructive momentum of ice floes to be calculated at any location. Recently, a method to synthesise waves-in-ice mathematical models and sea-ice numerical models has been devised with encouraging results.[19] It uses the latest waves-in-ice propagation model results to compute wave attenuation, given the ice conditions and the incident wave spectrum obtained from current operational models. A novel yet simple parameterisation for floe breaking is derived and used to determine whether or not the sea ice will be fragmented by waves, and the final size distribution. The size distribution is assumed to obey a power law, with the scale invariance of fractals.[20] The composite model ultimately provides information about the floe size that can be used to alter sea-ice dynamical and thermodynamical properties. When applied to a 1D representation of the Fram Strait along 79°N, the width of the MIZ obtained with this model corresponds well with observations from satellite images. For the first time, we can contemplate embedding wave–ice interactions into an operational ice–ocean model or even an oceanic general circulation model for forecasting purposes.

Towards an Improved Forecasting System of the Marginal Ice Zone

Based on the work accomplished so far, the WIFAR project promises to deliver an improved operational forecasting system that will hopefully be helpful in planning offshore operations in or near the hazardous MIZ. This will involve not only the simulation of waves and sea-ice variables, but also defining risk indexes associated with waves in ice. This effort will build on the existing system known as Towards an Operational Prediction system for the North Atlantic European coastal Zones (TOPAZ)[21] (http://topaz.nersc.no), the MyOcean[22] Arctic monitoring and forecasting system. TOPAZ is based on a Hybrid Coordinate Ocean Model (HYCOM) configured on a grid with a horizontal resolution of 12km and forced by atmospheric variables obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). With the contribution of WIFAR, TOPAZ will become a unique tool for predicting wave and sea-ice conditions in the MIZ. However, adequate forecast accuracy and relevance will necessitate a sustained validation effort and the vital feedback of Arctic operators – those who will face both the danger and the beauty of waves invigorating the ice canopy. For more information, go to http://msc.nersc.no and visit the WIFAR page. ■

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