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Discussion

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Author for correspondence:
Vernon A. Squire
e-mail: vernon.squire@otago.ac.nz

A prognosticative synopsis of contemporary marginal ice zone research

Vernon A. Squire

Department of Mathematics and Statistics, University of Otago, PO Box 56, Dunedin 9016, New Zealand

VAS, 0000-0002-5570-3446

Commentary narrated in this theme issue is recast to contextualize the diverse themes presented into a forward-looking conversation that synthesizes, debates opportunities for multidisciplinary advances and highlights topics that deserve enduring sharpened attention. Research oriented towards foundational elements of the marginal ice zone that relates to three unifying topic subclasses—namely (i) wave propagation through sea ice, (ii) floe size distributions and (iii) ice dynamics and break-up—and is encapsulated in mini-reviews provided by Thomson, Horvat and Dumont is revisited to distill it into a blueprint for the future guided by the cutting-edge, present-day knowledge documented herein by leading practitioners in the field. Six threads are signalled as imperative for prospective research, each with a bearing on Arctic and Antarctic sea-ice canopies in which the propensity for marginal ice zones to coexist with pack ice is greater as a result of global climate change reducing sea-ice resilience while increasing the prevalence and forcefulness of injurious storm winds and waves.

This article is part of the theme issue 'Theory, modelling and observations of marginal ice zone dynamics: multidisciplinary perspectives and outlooks'.

1. Introduction

I have compiled three reviews since 1995 [1–3] which relate to a defining aspect of the conjunct focus of this volume, namely the marginal ice zone (MIZ). The global warming that the Earth is currently experiencing has meant that [1,2] are outdated and that even [3], published in 2020, is already non-current

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because of the profound effects experienced by the polar and subpolar seas due to the increased frequency and intensity of storms triggering higher wind speeds that have stimulated a more aggressive ocean wave climate. As a result, the Arctic sea-ice cover, for example, has dramatically reduced in extent and area over the past two decades or so, with a concomitant greater prevalence of dynamic MIZ-like morphologies arising on account of wave action.

The outermost approximately 200 km of sea ice of the Southern Ocean surrounding the Antarctic continent, on the other hand, has historically customarily been designated an MIZ. This is attributable to the substantial fetches in the oceans north of the ice edge, which repeatedly proliferate ocean swells of unparalleled ferocity that inhibit the formation of consolidated pack ice until the waves travelling through the sea ice are weakened sufficiently that they can no longer do damage and limit floe size. Hitherto, the devastating effects of climate change on sea ice have been less obvious in the Antarctic; the trend in Antarctic sea-ice extent and area is nearly flat, although there appears to be slightly less ice in 2022 at the time of writing. Nevertheless, large-scale variations make the trend very noisy, and whether the morphology of the sea ice within the trend, e.g. MIZ width, is changing is unknown. As the frequency of extreme weather events increases, the ocean waves that are stimulated are expected to be more destructive, with the result that the MIZ will extend farther from the edge into the ice interior.

2. A prospective synopsis

Rather than stratifying my article into the sections delineated earlier in this volume, I have chosen to single out a number of topical strands of contemporary MIZ research which I consider to be pivotal for the future of the field.

(a) Defining the MIZ

It probably seems quite remarkable to the unenlightened reader that numerous research programmes have been conducted over the past 40 years or so focused overwhelmingly on the MIZ, yet science is still arguing over its definition. Acronyms typically epitomize international campaigns, such as MIZEX, LIMEX, parts of CEAREX, SIZEX, GSP, WWSP and PIPERS, but humbler projects in the Greenland, Bering and Barents Seas have also produced valuable insights into the dynamics of numerous MIZs. The recent *Marginal Ice Zone (MIZ) Program* [4] and *Sea State and Boundary Layer Physics of the Emerging Arctic Ocean Program* [5] supplement our knowledge base further. So there is no lack of material, especially when remote sensing is also undertaken. The definition provided in the preface to this volume, ‘the part of the seasonal ice zone where waves, swells and other open ocean processes affect the sea ice’, is fine as it stands, but it lacks pragmatic specificity. How, for example, do we determine where the interior boundary of the MIZ is located from an overflying aircraft, from space or, indeed, from a ship? Passive microwave radiometers point us to using concentration as the basis for a possible definition, while floe size or even floe shape could be appropriate for remote-sensing instruments with greater spatial resolution such as synthetic aperture radars (SARs); or perhaps ocean wave height is suitable on the basis that spaceborne lasers such as those aboard ICESat-2 can detect the waves gradually diminishing as they traverse the sea ice [6]. Does it matter? Unfortunately, it does matter because the width of the MIZ, i.e. the distance from the ice edge to the interior consolidated pack ice, is different for different definitions.

Articles [7,8] address this topic, the latter specifically comparing the MIZ width predicted by the state-of-the-art, coupled wave–sea-ice model neXtSIM-WAVEWATCH III with ICESat-2 laser wave data [9], which is further reconciled against an MIZ width based on floe size obtained from satellite altimetry and one based on concentration. Mindful that the model has parameters which can be optimally tuned, the agreements obtained are promising, but, while the rationale undergirding [9] is to establish whether the neXtSIM-WAVEWATCH III model can reproduce observations, it is evident that the question of definition remains unanswered and that greater

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clarity about how MIZ width should be defined is a pressing practicality of contemporary polar oceans research.

(b) Floe size distribution

Formulating a generic equation for the floe size distribution (FSD) is not a new problem [10–17], with many independent studies concluding that a power law, i.e. a Pareto distribution, provides a good fit to data, recognizing that the power which defines the slope can change over the span of floe sizes present because different physical processes are involved in creating and maintaining the distribution. Notwithstanding these determinations and the empirical evidence that motivates them, there has been a resurgence of interest recently in quantifying FSD shape that in some cases challenges the power-law conjecture on the basis of theoretical arguments, a sounder application of statistical tests or the plentitude of power index values identified for the MIZ. FSD is recognized as a determinative ingredient of coupled ocean-wave–sea-ice models of the MIZ, so it is important that an accurate distribution of floe sizes is used and that the physics describing how FSD mutates due to wave-induced flexural and collisional break-up and melting, for example, is accurate. The present volume has three relevant papers: [18] is concerned with modelling, [19] discusses a broken power-law distribution in the context of the physics that creates it, and [20] argues for a lognormal FSD instead of a power law. The informative mini-review by Horvat [21], who re-examines the history and current state of FSD observations and modelling, argues that further high-temporal-resolution investigations of the FSD are needed, e.g. under the action of ocean waves. This is because of the pivotal role sea ice plays in Earth system science, where large-scale coupled models are now only just beginning to be able to expedite wave–ice feedbacks, and in ecology, where breaking up the sea-ice canopy invariably decreases the concentration which encourages phytoplankton blooms in summer by allowing increased ingress of sunlight into the ocean.

In sum, therefore, while FSD is currently quantified empirically, its centrality to future sea-ice research at large—but especially to coupled climate models that strive to include the effects of ocean waves in the MIZ and multidisciplinary ecological studies—is such that we need to understand in substantially greater detail how an FSD is created and changes in time as a result of geophysical processes such as fracturing and buffeting by ocean waves and lateral melting. Most of the observations to date are limited to a snapshot in time taken at some point in a continuous process that causes an FSD to evolve. We need to know how this occurs.

(c) Dispersion, spreading and attenuation parametrization

Ocean waves entering an ice field, whether an MIZ or a more aggregated ice cover such as fast ice or continuous pack ice, are radically affected by the sea ice both directly due to its physical attributes and indirectly as a result of ongoing interactions between the ice sheet(s) and the ocean beneath. It is well known from observations, for example, that an incoming wave train is incompletely transmitted at the ice edge on entry to the MIZ [22,23], that it suffers attenuation and frequency-dependent directional spreading as it traverses the MIZ [23–27] and that wave dispersion does not seem to be majorly affected by the ice floes in MIZs [28], although more consolidated, thicker sea ice may have an effect at low to modest periods [29]. Of these three phenomena, it is attenuation that is currently attracting the most attention, undoubtedly because of its immediate relevance to the goal of introducing waves into coupled sea-ice models and sea ice into wave forecasting models such as WAVEWATCH III® [30]. Because ocean waves propagating in the MIZ are mainly influenced by gravity, any change to dispersion is inconsequential, and changes to directionality, e.g. refraction and spreading, while fascinating, are secondary to how wave height reduces as the waves proceed farther into the MIZ. So, despite the considerable corpus of work on wave attenuation in sea ice (see e.g. [1–3]), there is still more work to do. Arguably this is partly because of a dearth of *in situ* data, but ironically it is also because two potential sources of attenuation exist: conservative, which redistributes the energy spatially but does not remove it from the wave field, and dissipative. The former source has attracted greater theoretical study to date because it is mathematically more fascinating and is broader in scope than just MIZs. Yet it is likely that the latter, somewhat prosaic, source of energy loss dominates in most situations [27,31], necessitating theories and parametrizations that account for the damping experienced by the waves [32,33].

Numerous field observations suggest that a simple low-order power law with a power index n that is dependent on ice conditions consistently appears to describe how the amplitude attenuation coefficient k_i varies with wave frequency ω; e.g. see fig. 2 of [34]. Unfortunately, to the best of my knowledge, no dissipative model has convincingly reproduced this proportionality to date, and it may be that a homogeneous linear model will never accurately reproduce what is observed. Furthermore, the link between sea-ice morphology, e.g. FSD, ice type, topography and rheology, and the power index n has not been made. Accordingly, although the power law $k_\mathrm{i} \propto \omega^n$ is a step in the right direction, considerably more work needs to be done before a generic parametrization for the profusion of ice conditions that exist in MIZs can be reliably assembled. While empirically driven, it should account for the energy lost to the ocean via several fluid-dynamical mechanisms, e.g. under ice turbulence, basal friction, collisions between ice floes and, in principle, ice inelasticity, although this is likely to be negligible in most circumstances. There is also an elephant in the room that needs to be accommodated, namely evidence that wind waves can be generated within the MIZ [18] and that during summer these can induce lateral melting of ice floes—especially when their widths are less than about 30 m [35]. Current parametrizations are helpfully investigating how to assimilate waves into coupled sea-ice models, but the parametrizations used to express how ocean waves attenuate in the MIZ are based on linear viscoelasticity, are only part of the story or are implausible physically [8,18,32,33,36]. I stress that this is not meant to be a criticism, as the inclusion of ocean waves in a sea-ice model is a massive undertaking, especially when the sea ice is being modified through break-up as is done in some studies. Rather, I am intimating that an obligatory topic for future MIZ research is the development of a physically defensible parametrization of the attenuation of waves in the MIZ that includes dissipation and scattering, the latter phenomenon being included where refraction or spreading is expected to occur. The advent of global climate change, with its higher incidence of storms that produce more frequent and angrier seas, increases the urgency of this work if climate models are to reflect Nature accurately.

(d) Data collection

The paucity of physical data with which to test models and supply key parameters has been mentioned on several occasions. These data can be provided by transitory experiments or longer-term monitoring campaigns conducted in the field, i.e. within the polar seas, or in the laboratory where greater controls can be enforced but other challenges such as scaling exist. While early *in situ* observational programmes such as MIZEX, LIMEX, parts of CEAREX, SIZEX, GSP and WWSP, and other projects produced pertinent measurements to study the MIZ, the datasets are short-lived snapshots that sample unique configurations of particular MIZs and ocean wave spectra. These data are certainly incredibly useful, but their value is limited to the environment that prevailed at the time and qualitative reasoning in regard to other circumstances. Moreover, superannuated instrumentation was primitive in comparison to what is available today, such as inertial measurement units, *in situ* microprocessors, satellite communication systems that allow meaningful quantities of data to be recorded remotely, high-resolution imagers on aircraft and satellites, interferometric SAR and subsurface moorings with upward-looking Doppler profilers for acoustic surface tracking, to name but a few. Nevertheless, oceanographic fieldwork in the polar oceans is not cheap and, because regional meteorology can be fickle, successful outcomes are not guaranteed.

It is speculated that remote sensing from satellites will be the predominant resource for collecting data about the MIZ in the future, especially in regard to wave–ice interactions, and that this will be supplemented by high-resolution, targeted remote sensing from aircraft, episodic surface truth when practicable and financeable, and laboratory experiments primarily to gain informative qualitative insights. The value of SAR measurements from space has already been well demonstrated in [37], while laboratory experiments using artificial, i.e. plastic, ice floes such as those described by Toffoli *et al.* [38] provide a valuable perspective on the subtleties of how waves and floating bodies interact that can be extrapolated to Nature, e.g. nonlinear behaviour such as overwashing and the ramifications of irregular waves. A small number of experiments could be done in freezable wave flumes such as the ice tank at the Hamburg Ship Model Basin, especially work related to sea-ice slurries and pancake ice.

Recognizing the immense repercussions of climate change for the polar and subpolar regions, the determinative propositions are that current datasets are inadequate, that more data are required and that improvements in technology are such that it makes most sense for satellites to do much of the heavy lifting.

(e) MIZ rheology

The majority of early rheological work relating to the deformation of sea-ice fields dates back to AIDJEX (Arctic Ice Dynamics Joint Experiment), which took place in the early to mid-1970s. Soon after this was followed by Hibler's seminal paper [39], where Arctic sea ice was treated as a viscous compressible fluid defined by two nonlinear bulk and shear viscosities such that the stress state lies on an elliptical yield curve with a no-stress condition applying for pure divergence. Over the intervening years, Hibler's rheology has been fine-tuned in various ways, but it has always had less applicability to the MIZ as it was intended to represent how consolidated (as opposed to dispersed) sea ice deforms on a basin-wide scale at 125 km resolution; the fundamental assumption of continuity breaks down if the grid resolution approaches the floe scale. Notably, some contemporary large-scale sea-ice models have attempted to represent how MIZs progressively distort at small scales towards a realistic ice state on long time scales by invoking cumulative brittle deformation, e.g. the Bingham–Maxwell constitutive model and Maxwell elasto-brittle rheology used in [8,40] with the Lagrangian neXtSIM-WAVEWATCH III coupled ocean-wave–sea-ice model.

Discrete element models (DEMs) where the elements represent actual floes are the most obvious way to proceed for the MIZ, anticipating that continuum models represent an average of discrete behaviour—an assertion that is not obviously true and needs to be corroborated. To my mind, some of the most exciting work relating to MIZ rheology has been completed by Herman [41] and Feltham [42]. In her paper in this compilation, Herman has applied granular flow theory to a polydispersed MIZ with a tapered power-law FSD using her DESIgn model [43]. Floe shape has not yet been taken into account, but Herman's earlier paper [43] successfully partially parametrized ocean wave action within the constraint of a two-dimensional model by introducing an oscillating current and the stresses arising from flexural moments acting on the sea ice when surface waves are present. While DEMs have not yet achieved the justified reputability of [39] for large-scale quasi-continuous sea-ice sheets, they have the potential to do so with a concentrated effort by the modelling community.

(f) A fully coupled Earth system model with waves

A little after the Nansen Centre was established in 1986 by Professor Ola M. Johannessen at the Geophysical Institute, University of Bergen, the reflexion and transmission coefficients for ocean waves impinging on a floating ice sheet were calculated by Fox and Squire [44]. Coming soon after MIZEX and fully appreciating that dissipation would also be present in the real world, to my mind this was the first stage of being able to incorporate waves into large-scale sea-ice models, but at the time this was not regarded as high-priority science. Inexplicably, it was argued that the MIZ, and wave-induced effects especially, was a local phenomenon nestled close to the ice edge. Now, with the advent of climate warming, the impact of ocean waves has increased and recognition that it is a major causal element in the establishment and evolution of MIZs, which are also now more pervasive, has been accepted. Accordingly, and capitalizing on the increasing resolution of operational forecasting models, the past decade has witnessed the development of several basin-scale, coupled sea-ice models that have begun to append a contribution from ocean waves, with several papers appearing within this issue [7,8,18,36]. Reciprocally, NOAA's most recent community wave-modelling framework, WAVEWATCH III® [30], includes trial parametrizations of wave attenuation in ice fields. Unquestionably, this work is at an exciting early stage, acknowledging that §2c identifies the attenuation of waves in sea ice as an area of current and future research, but the step towards fully coupled AOGCMs (atmosphere–ocean general circulation models) and, potentially, Earth system models remains a worthy challenge as MIZs proliferate in the polar seas because of the increased storminess and weaker sea ice caused by global climate change.

3. Conclusion

Several foci have been singled out in this synopsis as being scientifically expedient to future MIZ research:

(a) Resolving the question of how to define an MIZ, i.e. by concentration, floe size or a metric associated with the action of ocean waves.
(b) Continued work to confirm a universal statistical law to represent the FSD for a generic ice field. Should a Pareto power-law distribution, a broken power-law distribution, a lognormal distribution or some other probability distribution be used? And how does the FSD evolve as a result of the causative physics, i.e. ice melting and wave-induced pummelling and fracture?
(c) The development of a robust parametrization involving both conservative scattering and dissipative fluid dynamics—which will undoubtedly be non-Newtonian for some types of sea-ice cover—to describe how ocean waves disperse, spread and attenuate as they propagate into and within MIZs. While energy loss through dissipation will outweigh the reapportionment of the incident wave trains by scattering in most cases, e.g. notably in the proximity of the ice edge [22], there will be types of sea ice or locations within the MIZ where it is anticipated that this is not the case [33].
(d) Data collection, both in the field and in the laboratory, with the former, in particular, making increased use of modern technology and remote sensing by aircraft and satellites.
(e) The development of a sea-ice rheology that better represents the MIZ under various circumstances for the multifarious stresses that act upon it. This will be by means of a granular, discrete element model [42,43] or, in some settings, as an aggregated continuum that parametrizes how the MIZ deforms as a whole, e.g. the Maxwell elasto-brittle [45] or the brittle Bingham–Maxwell rheologies [40] referred to by Boutin *et al.* in this volume [8].
(f) The continuation and furtherance of current work on coupled ocean-wave–sea-ice models towards the development of fully coupled climate models and, ultimately, Earth system models that include the impact of ocean waves—either directly or implicitly via the after-effects of waves on the ice cover— acknowledging the formidable computational challenges involved at this time.

Data accessibility. The source of any data reported is stated in the text. Access can be facilitated through V.A.S. if the data are not publicly available.
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