

Theory, modelling and observations of marginal ice zone dynamics: multidisciplinary perspectives and outlooks

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Introduction



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Theory, modelling and observations of marginal ice zone dynamics: multidisciplinary perspectives and outlooks

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The marginal ice zone (MIZ) is the dynamic interface between the open ocean and sea ice-covered ocean. It is characterized by interactions between surface gravity waves and granular ice covers consisting of relatively small, thin chunks of sea ice known as floes. This structure gives the MIZ markedly different properties to the thicker, quasi-continuous ice cover of the inner pack that waves do not reach, strongly influencing various atmosphere–ocean fluxes, especially the heat flux. The MIZ is a significant component of contemporary sea ice covers in both the Antarctic, where the ice cover is surrounded by the Southern Ocean and its fierce storms, and the Arctic, where the MIZ now occupies vast expanses in areas that were perennial only a decade or two ago. The trend towards the MIZ is set to accelerate, as it reinforces positive feedbacks weakening the ice cover. Therefore,

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understanding the complex, multiple-scale dynamics of the MIZ is essential to understanding how sea ice is evolving and to predicting its future.

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

The profound physical transformations to Arctic [1] and Antarctic [2] sea ice covers caused by climate change have driven an explosion in research activity on the marginal ice zone (MIZ), particularly the dynamic (and thermodynamic) feedback processes occurring in the region. Fundamental research questions are being addressed, such as the rate at which the MIZ ice cover attenuates ocean waves, the threshold for waves to break up consolidated ice covers, the typical floe size distributions encountered in the MIZ and the dynamic response of the granular ice cover to forcing from winds and currents. The field of MIZ dynamics is moving rapidly due to advances across a range of physical, mathematical, earth and engineering sciences, often revolving around large multi-national research programmes and experimental campaigns. Progress is beginning to translate into predictions of the MIZ’s role in the response of sea ice to warming temperatures and its impact on other components of the atmosphere–ice–ocean–land feedback system.

After approximately a decade of sustained advances in MIZ dynamics, the current theme issue brings together many of the most prominent research communities involved to showcase the state of the art in theory, modelling and observations. Beyond presenting the latest research advances, the theme issue places emphasis on communicating important new findings to the broader research community and highlighting the critical role of the MIZ in the Earth system. Moreover, the theme issue aims to delineate pathways for the field to create more significant impact and improve understanding of climate change, noting that MIZ researchers are demonstrating strong commitment to integrate MIZ-specific physics into relevant components of Earth-system models used by influential scientific bodies, such as the International Panel on Climate Change.

The theme issue is dedicated to the career of Prof. Vernon Squire following his retirement in 2020. Squire was a leading member of the University of Cambridge’s Scott Polar Research Institute (SPRI) team that conducted pioneering Arctic MIZ experiments in the 1970s and 1980s [3] and participated in large international experiments [4,5], during an era in which the Arctic Ocean was a potential battleground for the reigning superpowers. As part of the SPRI team, Squire helped develop seminal theories for wave attenuation in the MIZ [6] and wave-induced ice breakup [7], alongside cognate work on iceberg dynamics [8], loads imposed on floating ice by vehicles [9] and more. He moved to the University of Otago, New Zealand, in 1987, where he stayed for the remainder of his career, leading a small but productive research team in the Department of Mathematics and Statistics, which was largely responsible for carrying the field of MIZ dynamics forward until the early 2010s, and (directly or indirectly) spawned many members of the present research community. His team is best known for developing the theories of wave–ice interactions that underpin the present state of the art, but were also active in remote sensing [10] and laboratory experimental modelling [11,12], both of which have become active research areas. Squire wrote two highly cited review articles during this period, *Of Ocean Waves and Sea Ice* [13] and *Of Ocean Waves and Sea Ice Revisited* [14], which communicated the field to a broad audience in his hallmark engaging and (to appropriate one of his favourite words) mellifluous writing style. He came into the recent research boom recognized as one of the most prominent figures in MIZ dynamics and has been influential in the rapid development of the field through his involvement in international programmes, such as the Norwegian-led *Waves in Ice Forecasting for Arctic Operators* [15] and the US-led *Sea State and Boundary Layer Physics of the Emerging Arctic Ocean* [16], co-organizing the *Mathematics of Sea Ice Phenomena* research programme at the Isaac Newton Institute [17], and promoting the progress of the field through perspectives and review articles [18], including a third instalment in the *Of Ocean Waves and Sea Ice* series [19]. The guest editors and authors express their appreciation for his enthusiasm and mentorship, and are delighted to offer the theme issue to celebrate his contributions. Prof. Squire is actively involved

in the theme issue as the author of a preface [20] and a synopsis of the research presented in the theme issue that includes directions for future interdisciplinary research [21].

The main body of the theme issue is divided into three focus topics that encapsulate current trends in multidisciplinary MIZ-dynamics research. Each topic opens with a mini-review that introduces the topic and highlights implications for other areas of science, followed by three to four research articles that collectively cover the latest activity in theory, modelling and observations within the topic area. Focus topic I is on wave propagation in the MIZ: the mini-review by Thomson [22] highlights debates in the community on whether wave scattering or viscous dissipation dominates wave attenuation in the MIZ and the potential coastal impacts of waves with a weakened sea ice buffer; Shen [23] compares the leading theories for wave propagation in the MIZ; Toffoli *et al.* [24] analyse experimental laboratory models of irregular wave interactions with artificial floes, focusing on nonlinear interaction processes; Waseda *et al.* [25] present multiple-platform field observations of waves and ice in the MIZ; and Perrie *et al.* [26] implement a new source term for wave–ice interactions in a numerical wave forecasting model. Focus topic II is on floe size distributions: the mini-review by Horvat [27] summarizes the history of floe size distribution (FSD) observations and models, and discusses the climate-scale impacts of the MIZ FSD; Montiel & Mokus [28] provide new theoretical support for lognormal FSDs in the MIZ; Hwang & Wang [29] use satellite observations in a region of the Arctic MIZ to study the FSD life-cycle; and Cooper *et al.* [30] compare *in situ* wave observations with outputs from coupled wave and sea ice models, in which the sea ice model contains a recently developed FSD sub-model. Focus topic III is on ice dynamics and breakup: the mini-review by Dumont [31] gives an overview of the current state of the art in the area; Herman [32] uses discrete-element simulations to conduct a theoretical analysis of the MIZ rheology; Boutin *et al.* [33] compare MIZ extents from a coupled wave–ice numerical model involving a rheology sub-model to satellite observations; and Auclair *et al.* [34] use a numerical model to investigate the effects of wind and wave radiative stresses on ice dynamics. The theme issue closes with two future-facing articles: the first is the above-mentioned synopsis by Squire [21]; and the second article is by the guest editors [35] and generates visions for the future of the field and pathways to create impact in the broader science community, e.g. impacts on climate science.

Data accessibility. This article has no additional data.

Authors' contributions. L.G.B.: writing—original draft; C.M.B.: writing—review and editing; D.L.F.: writing—review and editing; A.L.K.: writing—review and editing; M.H.M.: writing—review and editing. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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References

1. Stroeve J, Notz D. 2018 Changing state of Arctic sea ice across all seasons. *Environ. Res. Lett.* **13**, 103001. (doi:10.1088/1748-9326/aade56)
2. Eayrs C, Li X, Raphael MN, Holland DM. 2021 Rapid decline in Antarctic sea ice in recent years hints at future change. *Nat. Geosci.* **14**, 460–464. (doi:10.1038/s41561-021-00768-3)

3. Squire VA, Moore SM. 1980 Direct measurement of the attenuation of ocean waves by pack ice. *Nature* **283**, 365–368. (doi:10.1038/283365a0)
4. Wadhams P. 1985 The marginal ice zone experiment (MIZEX) 1984: Scott Polar Research Institute participation. *Polar Rec.* **22**, 505–510. (doi:10.1017/S0032247400005957)
5. Rottier P. 1989 SPRI participation in the winter marginal ice zone experiment, MIZEX-87. *Polar Rec.* **25**, 33–36. (doi:10.1017/S0032247400009955)
6. Wadhams P, Squire VA, Goodman DJ, Cowan AM, Moore SC. 1988 The attenuation rates of ocean waves in the marginal ice zone. *J. Geophys. Res.* **93**, 6799. (doi:10.1029/JC093iC06p06799)
7. Squire VA. 1984 How waves break up inshore fast ice. *Polar Rec.* **22**, 281–285. (doi:10.1017/S0032247400005404)
8. Kristensen M, Squire VA, Moore SC. 1982 Tabular icebergs in ocean waves. *Nature* **297**, 669–671. (doi:10.1038/297669a0)
9. Squire V, Robinson W, Langhorne P, Haskell T. 1988 Vehicles and aircraft on floating ice. *Nature* **333**, 159–161. (doi:10.1038/333159a0)
10. Drinkwater M, Squire V. 1989 C-band SAR observations of marginal ice zone rheology in the Labrador Sea. *IEEE Trans. Geosci. Remote Sens.* **27**, 522–534. (doi:10.1109/TGRS.1989.35935)
11. Montiel F, Bonnefoy F, Ferrant P, Bennetts LG, Squire VA, Marsault P. 2013 Hydroelastic response of floating elastic discs to regular waves. Part 1. Wave basin experiments. *J. Fluid Mech.* **723**, 604–628. (doi:10.1017/jfm.2013.123)
12. Montiel F, Bennetts LG, Squire VA, Bonnefoy F, Ferrant P. 2013 Hydroelastic response of floating elastic discs to regular waves. Part 2. Modal analysis. *J. Fluid Mech.* **723**, 629–652. (doi:10.1017/jfm.2013.124)
13. Squire VA, Dugan JP, Wadhams P, Rottier PJ, Liu AK. 1995 Of ocean waves and sea ice. *Ann. Rev. Fluid Mech.* **27**, 115–168. (doi:10.1146/annurev.fl.27.010195.000555)
14. Squire VA. 2007 Of ocean waves and sea-ice revisited. *Cold Reg. Sci. Technol.* **49**, 110–133. (doi:10.1016/j.coldregions.2007.04.007)
15. Squire VA, Williams TD, Bennetts LG. 2013 Better operational forecasting for contemporary Arctic via ocean wave integration. *Int. J. Offshore Polar Eng.* **23**, 8.
16. Thomson J *et al.* 2018 Overview of the Arctic sea state and boundary layer physics program. *J. Geophys. Res.: Oceans* **123**, 8674–8687. (doi:10.1002/2018JC013766)
17. Smith F, Korobkin A, Parau E, Feltham D, Squire V. 2018 Modelling of sea-ice phenomena. *Phil. Trans. R. Soc. A* **376**, 20180157. (doi:10.1098/rsta.2018.0157)
18. Squire VA. 2011 Past, present and impendent hydroelastic challenges in the polar and subpolar seas. *Phil. Trans. R. Soc. A* **369**, 2813–2831. (doi:10.1098/rsta.2011.0093)
19. Squire VA. 2020 Ocean wave interactions with sea ice: a reappraisal. *Annu. Rev. Fluid Mech.* **52**, 37–60. (doi:10.1146/annurev-fluid-010719-060301)
20. Squire VA. 2022 Marginal ice zone dynamics. *Phil. Trans. R. Soc. A* **380**, 20210266. (doi:10.1098/rsta.2021.0266)
21. Squire VA. 2022 A prognosticative synopsis of contemporary marginal ice zone research. *Phil. Trans. R. Soc. A* **380**, 20220094. (doi:10.1098/rsta.2022.0094)
22. Thomson J. 2022 Wave propagation in the marginal ice zone: connections and feedback mechanisms within the air-ice-ocean system. *Phil. Trans. R. Soc. A* **380**, 20210251. (doi:10.1098/rsta.2021.0251)
23. Shen HH. 2022 Wave-in-ice: theoretical bases and field observations. *Phil. Trans. R. Soc. A* **380**, 20210254. (doi:10.1098/rsta.2021.0254)
24. Toffoli A, Pitt JPA, Alberello A, Bennetts LG. 2022 Modelling attenuation of irregular wave fields by artificial ice floes in the laboratory. *Phil. Trans. R. Soc. A* **380**, 20210255. (doi:10.1098/rsta.2021.0255)
25. Waseda T, Alberello A, Nose T, Toyota T, Kodaira T, Fujiwara Y. 2022 Observation of anomalous spectral downshifting of waves in the Okhotsk Sea Marginal Ice Zone. *Phil. Trans. R. Soc. A* **380**, 20210256. (doi:10.1098/rsta.2021.0256)
26. Perrie W, Meylan MH, Toulany B, Casey MP. 2022 Modelling wave-ice interactions in three dimensions in the marginal ice zone. *Phil. Trans. R. Soc. A* **380**, 20210263. (doi:10.1098/rsta.2021.0263)
27. Horvat C. 2022 Floes, the marginal ice zone and coupled wave-sea-ice feedbacks. *Phil. Trans. R. Soc. A* **380**, 20210252. (doi:10.1098/rsta.2021.0252)

28. Montiel F, Mokus N. 2022 Theoretical framework for the emergent floe size distribution in the marginal ice zone: the case for log-normality. *Phil. Trans. R. Soc. A* **380**, 20210257. (doi:10.1098/rsta.2021.0257)
29. Hwang B, Wang Y. 2022 Multi-scale satellite observation of Arctic sea ice: a new insight into the life cycle of the floe size distribution. *Phil. Trans. R. Soc. A* **380**, 20210259. (doi:10.1098/rsta.2021.0259)
30. Cooper VT, Roach LA, Thomson J, Brenner SD, Smith MM, Meylan MH, Bitz CM. 2022 Wind waves in sea ice of the western Arctic and a global coupled wave-ice model. *Phil. Trans. R. Soc. A* **380**, 20210258. (doi:10.1098/rsta.2021.0258)
31. Dumont D. 2022 Marginal ice zone dynamics: history, definitions and research perspectives. *Phil. Trans. R. Soc. A* **380**, 20210253. (doi:10.1098/rsta.2021.0253)
32. Herman A. 2022 Granular effects in sea ice rheology in the marginal ice zone. *Phil. Trans. R. Soc. A* **380**, 20210260. (doi:10.1098/rsta.2021.0260)
33. Boutin G, Williams T, Horvat C, Brodeau L. 2022 Modelling the Arctic wave-affected marginal ice zone: a comparison with ICESat-2 observations. *Phil. Trans. R. Soc. A* **380**, 20210262. (doi:10.1098/rsta.2021.0262)
34. Auclair J-P, Dumont D, Lemieux J-F, Ritchie H. 2022 A model study of convergent dynamics in the marginal ice zone. *Phil. Trans. R. Soc. A* **380**, 20210261. (doi:10.1098/rsta.2021.0261)
35. Bennetts LG, Bitz CM, Feltham DL, Kohout AL, Meylan MH. 2022 Marginal ice zone dynamics: future perspectives and pathways. *Phil. Trans. R. Soc. A* **380**, 20210267. (doi:10.1098/rsta.2021.0267)