

The influence of ocean waves on Antarctic sea-ice albedo and seasonal melting, and potential coupled physical- and biological feedbacks

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30 **Abstract.** Identifying the full suite of processes that drive the rapid-melting of Antarctic sea ice each summer is crucial to improving the currently-poor ability of contemporary models to accurately simulate the climatological retreat phase of Antarctica'sthe annual sea-ice cycle. This is crucialcritical to 1) understanding, modelling and attributing observed trends and recent high-variabilityabrupt changes in sea-ice extent,coverage and to projecting-2) the more robust prediction of future sea-
35 ice conditions and impacts-accurately. To date, the rapid-annual retreat of Antaretic sea-ice each spring-summer has been largely attributed to-. This paper identifies wave-driven processes that can accelerate the seasonal melting of sea ice both in the marginal ice zone (MIZ) and in open-water areas within the interior sea-ice zone (SIZ). It builds on the long-held view that seasonal Antarctic sea-ice ablation is primarily driven by ice-floe lateral and basal melting of ice floes, enhanced in the MIZ by wave-induced breakup of largeice floes. Here, based on observations and modelling, we propose, by demonstrating, that ocean waves play important additional roles in generating previously-neglected surface and interior melting, by removing

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40 snow from small floes, flooding them, and pulverising them into slush. Results here show a resultant (termed “wave melting”) via three sets of processes: “wave flooding”, “wave pulverisation”, and “wave greening” (involving algal proliferation in wave-modified ice). Based on existing observations and simple one-dimensional modelling, these wave processes are estimated reduction in to reduce ice albedo by 0.38–0.54, that increases melting by compared to snow-covered ice, resulting in vertical melt-rate enhancements of 0.9–5.2 cm day⁻¹ at 60–70°S compared to a snow-covered floe of first year ice, and depending on surface type, wave flooding coverage, latitude and ice density. Rapid proliferation of algae within and on the high light and high nutrient environment of the wave-modified ice reduces the albedo by a further 0.1 to increase the melt-rate enhancement⁻¹, with biological effects amplifying this to 1.1–6.1 cm day⁻¹. Melting is further accelerated by a wave-induced ice-albedo feedback mechanism, similar to that associated with Arctic melt ponds but involving seawater rather than freshwater. This⁻¹. The study also identifies five positive feedback is strengthened by ice-algal greening. Floe thinning and weakening by wave melting initiate additional dynamic-thermodynamic and sub-feedback mechanisms that likely accelerate the ice melting further. It addresses a gap in current climate and Earth system models, which account for wave effects on floe-size distributions but overlook these coupled wave-driven dynamic, thermodynamic and biological processes that may contribute to explaining why and how Antarctic sea ice can melt back so rapidly each summer. An intention of this preliminary study is to stimulate further targeted investigation aimed at quantifying the role of wave melting in the annual sea-ice cycle – as well as the contribution of wave greening to primary production in the sea-ice zone and its role in key biogeochemical processes that feed back to climate. The work has implications for planetary albedo, global climate feedbacks by increasing the likelihood of both wave flooding and flexural breakup, leading to further floe melting. Wave melting, marine ecosystems, and the associated physical-biological feedbacks will likely increase in importance in a predicted stormier accuracy of future sea-ice, and warmer climate projections in an increasingly stormy Southern Ocean, and will also become more prevalent in as well as a changing Arctic. There are implications for global weather and climate, the health of the ocean and its ecosystems, fisheries, ice-shelf stability and sea-level rise, atmospheric and oceanic biogeochemistry, and human activities.

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1 Introduction

1.1 Motivation and contribution aims

Each year from late austral spring through summer, the Southern Ocean encircling Antarctica undergoes a remarkable large-scale transformation with the areal retreat of its sea-ice zone (SIZ) from ~18–20 x 10⁶ km² in September to ~2–4 x 10⁶ km² in February. The retreat largely occurs over just a 3-month period (November through January), whereas the autumn–winter advance phase lasts for 7 months (Comiso et al., 2017a). By comparison, the annual cycle of Arctic sea ice is approximately symmetrical (i.e., 6 months advance and 6 months retreat), reflecting the different geographical setting and processes occurring there (Parkinson, 2014; Maksym, 2019). To date, the rapid annual retreat of Antarctic sea ice has been largely attributed to lateral and basal – rather than surface and interior – melting of its constituent ice floes (Eayrs et al., 2019a,b2019). The classical view is that this is driven by: (a) solar heating in leads (open-water gaps) between floes (Gordon, 1981) and within polynyas

(Massom et al., 2003) that is related to the ~~seasonal cycle (upturn) in springtime increase of~~ incident solar radiation (Roach et al., 2022); and (b) upwelling of relatively warm deep waters in certain regions (Gordon, 1981). Moreover, melting in the Antarctic marginal ice zone (MIZ) has been identified as making the largest contribution to the mean annual ice retreat across the entire Southern Ocean (Kimura et al., 2022), ~~pointing to the need to better understand the climatological processes driving seasonal melting there.~~ The Antarctic MIZ is the tens- to hundreds of kilometres-wide region (Fraser et al., ~~subm.)in review~~) closest to the open ocean where the ice floes are ~~regularly~~ influenced by ocean surface waves (Wadhams, 1986; Bennetts et al., 2024), which break up larger floes and prevent smaller floes ~~and paneakes~~ from consolidating.

Here, and based on *in situ* observations, remote sensing and first-principle modelling calculations, we ~~introduce~~~~propose~~ ~~an~~ additional ~~and previously-unconsidered climatological factors~~~~factor~~ that ~~contribute to the rapid annual retreat~~~~drives seasonal melting~~ of the Antarctic ~~SIZ~~~~sea ice each late spring-summer~~ and which will likely increase in importance in a predicted stormier Southern Ocean (Young et al., 2020), as well as becoming more prevalent in a changing Arctic. ~~These are the multiple roles of ocean waves in driving snow saturation and/or removal, creating seawater ponding and substantially decreasing the ice albedo, leading to surface and interior melting of small floes (while also contributing to basal and lateral melting)—both in the MIZ and the entire SIZ, i.e., adjacent to large open-water areas (leads and polynyas) and during deep swell penetration events.—Where present, snow~~This is the role of ocean waves in decreasing the sea-ice albedo and in driving surface and interior melting, which we term “*wave melting*”, by 1) flooding ice floes (“*wave flooding*”) and 2) mechanically grinding down the ice and its snow cover into “*wave slush*” and brash ice (“*wave pulverisation*”). ~~In addition, we propose that wave-flooding and wave-pulverisation processes create optimal habitat for enhanced ice algal production, and that the resultant darkening of the ice and wave ponds due to increased chlorophyll content (which we term “*wave greening*”) further decreases the ice albedo, which increases the wave-melting rate. Moreover, we hypothesise that wave melting is additionally accelerated by three coupled positive feedbacks – which we term the “*wave-driven ice-albedo feedback*”, the “*wave flooding-ice melting feedback*” and the “*wave flooding-floe fragmentation feedback*” – and that these are amplified by two biological-physical sub-feedbacks involving wave greening. We further propose that wave melting occurs not only over areas of the MIZ but also within the interior SIZ when long-period swell penetrates deeply into the SIZ (cf., Liu and Mollo-Christensen, 1988) and adjacent to large open-water areas (leads and polynyas) with wind waves.~~

~~Where snow is present, it~~ inhibits/delays sea-ice melt (Eicken et al., 1995) by virtue of its high albedo compared to bare sea ice (Perovich, 1996; Brandt et al., 2005; Zatko and Warren, 2015) and its low thermal conductivity (Sturm and Massom, 2017). The snow cover strongly reflects incoming solar radiation and decreases its absorption by, and ~~transmittance~~~~transmission~~ into and through, the underlying ice (Grenfell and Maykut, 1977; Grenfell and Perovich, 2004; Nicolaus et al., 2010). Moreover, snow buffers the ice below from air-temperature increases, including those associated with the frequent passage of storms, even in winter ~~in the MIZ, e.g., Massom et al. (1997).~~ Therefore, waves dramatically alter the surface energy budget year round and the seasonal sea-ice melt rate, primarily by removing the snow cover to reduce the ice albedo and increase ice

105 exposure to warm air temperatures, but also by overwashing floes with warm seawater at the relatively-low latitudes attained by the MIZ (Massom et al., 1997).

110 We introduce the term *wave flooding* to encompass the processes of wave-induced seawater inundation, ponding and snow removal/modification. We also highlight a process that we call *wave pulverisation*, which is the breakdown of floes in the MIZ by their grinding together by incoming swells (see Massom et al., 2006). This process is distinct from flexural fracturing (cf., Squire et al., 1995), and also contributes to a wider reduction in surface albedo and an increase in melt rate (compared to snow-covered floes). We introduce the term *wave melting* to refer to the combined contributions of wave flooding and pulverisation to the melting of the floe surface, the floe interior, and pulverised slush. We also propose that wave flooding and pulverisation processes lead to a proliferation of ice algae, which further decreases the ice albedo to enhance the surface and interior melting. Moreover, we propose that the wave flooding processes invoke a positive ice albedo feedback similar to that associated with freshwater melt ponds (cf., Perovich et al., 2003; Perovich and Richter-Menge, 2009; Perovich et al., 2009) which form extensively on Arctic sea ice in summer (Fetterer and Untersteiner, 1998) from air temperature-driven snow melt and the pooling of the meltwater in surface depressions (Petrich et al., 2012) — albeit on different spatial and temporal scales but which also accelerate melting through spring-summer. We put forward that this *wave-driven ice albedo feedback* is amplified by the algal greening (ice darkening), and that this further accelerates melting in concert with two other wave-driven positive feedback mechanisms. These are a *wave flooding-ice melting feedback* and a *wave flooding floe fragmentation feedback*.

125 The premise of this paper is that waves can dramatically alter the surface energy budget year round and drive surface melting of sea ice in summer – primarily by removing or substantially modifying the snow cover and/or pulverising the snow and ice to reduce the ice albedo, but also by directly exposing the ice surface to warm air temperatures and overwashing by warm seawater as summer progresses. The overall aims are 1) to show that previously-unconsidered wave-driven processes, feedbacks and effects could be significant – not only in the MIZ but also within the interior SIZ – and are therefore worthy of further investigation, and 2) to encourage and make recommendations for future research activities. Specific aims are: 1) to make a preliminary estimate of the effect of waves on the daily vertical melt rate of a single localised ice floe (and/or area of wave-pulverised slush) as a function of latitude and time in the Antarctic SIZ in summer, by changing the ice albedo in the surface radiation energy budget; and 2) to introduce feedbacks that may accelerate wave melting. Regional to pan-Antarctic quantification of wave melting and associated feedbacks is not attempted in this initial study due to current lack of requisite observations, but is recommended as a high priority requiring targeted observations, analysis and modelling (see Sect. 6).

1.2 Context

135 To date, and in contrast to the Arctic (e.g., Tsamados et al., 2015), floe-surface melting and interior melting and their as well as the possibility of associated ice-albedo and related feedbacks have remained been largely neglected as climatological factors contributing to the rapid annual retreat of climatological seasonal melting of the Antarctic SIZ. This neglect is based on the

dual premise that Antarctic sea ice largely retains its high-albedo and insulative snow cover into summer (Massom et al., 2001; Eayrs et al., 2019) while also lacking Arctic-like freshwater melt ponds (Andreas and Ackley, 1982; Drinkwater and Liu, 2000); ~~that form from air-temperature-driven snow melt and pooling of the meltwater in surface depressions (Petrich et al., 2012). The general lack of surface melt ponds on Antarctic sea ice,~~ apart from a few isolated observations (e.g. Takahashi, 1960; Corkill et al., 2023). ~~The general lack of surface melt ponds on Antarctic sea ice,~~ has been attributed to the radiative and turbulent surface heat fluxes occurring there (Vihma et al., 2009). Complete synoptic-scale snow-melt episodes do occur at lower latitudes due to extreme air-temperature increases and even rainfall associated with the passage of storms, including in winter in the MIZ, but those events tend to be somewhat localised and short-lived/ephemeral (Massom et al., 1997).

Given these factors, the generally-used conceptual model for the broad climatological annual retreat of Antarctic sea ice is that each late-spring and summer, wind-driven Ekman divergence (Gordon and Taylor, 1975) associated with a twice-yearly deepening and poleward contraction of the circumpolar trough of sea-level pressure known as the Semi-Annual Oscillation (van Loon, 1967; Eayrs et al., 2019) pushes ice floes northwards into warmer waters where they melt. In addition, the ice divergence creates ~~dark (low-albedo)~~ leads between floes that strongly absorb incoming solar radiation (Gordon, 1981; Enomoto and Ohmura, 1990). With the seasonal upturn in insolation following the September equinox (Roach et al., 2022), solar heating of the ocean's mixed layer then drives both lateral and basal melting of the floes (Maykut and Perovich, 1987). This further activates a positive "ocean-ice albedo feedback" (Nihashi and Cavalieri, 2006) related to the large difference in albedo between sea ice and open water, whereby solar heating in leads enhances lateral melt of floes and increases the open-water area ~~(decreases the ice concentration),~~ to further enhance ice melt and so on in an amplifying cycle (Ebert and Curry, 1993; Curry et al., 1995; Ohshima and Nihashi, 2005; Kashiwase et al., 2017).

Currently, ocean waves are largely considered to influence sea-ice melting only in terms of their important role in fracturing the MIZ ice cover into smaller floes (cf., Wadhams, 1986; Squire, 2007; Kohout et al., 2016). Small floes are more mobile and have a larger perimeter per unit area (Maykut and Perovich, 1987; Toyota et al., 2006) compared to larger floes, leading to relatively larger rates of lateral melting (Steele, 1992; Asplin et al., 2012; 2014; Perovich and Jones, 2014; Kohout et al., 2014) and basal melting (Horvat and Tziperman, 2018). Sea-ice and climate models now include the influence of waves on floe-size distributions (e.g., Bennetts et al., 2017; Roach et al., 2019; Bateson et al., 2020) – but not the role of waves in driving coupled ~~dynamic-thermodynamic processes involving year-round~~ flooding, snow removal, pulverisation and albedo reduction that lead to seasonal surface and interior melting of small wave-fragmented floes and wave-pulverised slush, as proposed here.

1.3 Significance

There is strong motivation to identify, understand and model the ~~complex-atmosphere-ice-ocean-interaction~~ climatological processes and feedback mechanisms responsible for driving the mean rapid retreat phase of Antarctica's annual Antarctic sea-ice eyelemelt, including the role of within the MIZ (Saiki et al., 2021). Such process knowledge is crucial 1) to addressing/rectify the current inability of contemporary models to accurately reproduce the rate and magnitude of the mean

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170 ~~annual sea-ice seasonal~~ retreat phase observed in the satellite record ~~accurately since 1979~~ (cf., Eayrs et al., 2019; Roach et al., 2020), ~~towards attributing 2) to attribute~~ observed Antarctic sea-ice trends and variability, and ~~providing 3) to provide~~ more-
confident future projections (e.g., Notz and Bitz, 2017; Maksym, 2019; NAS, 2017; Roach et al., 2020). This priority need is
underpinned by mounting concern over recent ~~abrupt~~ Antarctic sea-ice loss and its serious implications for ~~Antarctic the region~~
and the Earth system (Kennicutt et al., 2014; Massom et al., 2018; Meredith et al., 2019; ~~Abram et al., 2025~~). Since 2012,
Antarctic sea-ice coverage has unexpectedly switched to a state of high variability (Turner and Comiso, 2017; ~~Hobbs et al.,~~
~~2024~~), with record high sea-ice extents in 2012–2014 (Reid and Massom, 2015) plummeting to record lows since 2016 – and
175 with the biggest deficit occurring not only in the spring–summer melt period (Parkinson, 2019) but also in autumn–winter in
2023 ~~through the present~~ (Reid et al., 2024) ~~and 2024~~ (Reid et al., in ~~press~~ 2025). ~~There has also been a change to increased~~
~~regional coherence in the pattern of sea-ice loss which is anomalous in the long-term record~~ (Hobbs et al., 2024).

The unanticipated ~~rapidity and abruptness~~, magnitude ~~and spatial coherence~~ of this apparent regime ~~changes~~ shift raises concerns
around potential acceleration of future Antarctic sea-ice loss in response to resultant changes in albedo and the surface energy
180 budget (Riihelä et al., 2021) and activation and amplification of sea ice-related albedo feedback mechanisms (cf., Goosse et al., 2018). At the same time, a change in the albedo of the Antarctic SIZ (~~including the ice itself~~) has the potential to amplify
high-latitude climate warming in the Southern Hemisphere, as it has in the Arctic (Manabe and Stouffer 1980; Meehl
and Washington, 1990; Holland and Bitz, 2003; Screen and Simmonds, 2010). Model analyses by Goosse et al. (2023) highlight
the key ~~role~~ importance of albedo in the annual Antarctic sea-ice cycle and as a prime target for process understanding and
185 model development. Here, we provide mechanisms (~~wave flooding, pulverisation and greening~~) ~~for determining and~~
~~modifying that modify~~ the surface albedo, as well as the thickness distributions and volume of the sea ice and its snow cover –
all of which are major unknowns in the global climate system ~~and which~~ severely compromise modelling ~~performance~~ and
predictive capability (Maksym et al., 2012; Webster et al., 2018).

190 ~~While this study is limited in terms of coordinated large-scale observations of wave flooding and melting across the Antarctic~~
~~MIZ and SIZ, the synthesis of available observations given here is timely and presents a new paradigm in our understanding~~
~~of factors controlling the seasonal retreat/melt phase of Antarctic sea ice. Our aim is fourfold:~~

- 195 ~~(1) to stimulate targeted cross-disciplinary observations of the wave-related surface melt processes and feedbacks we~~
~~describe, towards quantification of current unknowns relating to their distribution and characteristics in space and time;~~
- ~~(2) to encourage further testing of the new hypotheses presented here, not only in the Antarctic but also in the Arctic;~~
- ~~(3) to encourage investigation of the contribution of wave flooding and wave melting to primary production and key~~
~~biogeochemical processes in the SIZ, and to the ocean biological carbon pump and the uptake of atmospheric CO₂ by the~~
~~ocean; and~~

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(4) to encourage incorporation and analysis of wave flooding and resultant wave melting processes and feedbacks in climate and Earth system models and sensitivity studies, in order to help address the critical key deficiencies in model prediction outlined above.

Given the current lack of requisite data, this study does not attempt a detailed quantitative evaluation of the characteristics and effects of wave flooding and wave pulverisation and the spatio-temporal coverage and overall magnitude of wave melting and its contribution to the annual sea-ice cycle. The primary contribution of this work is on making a first estimate of the effect of wave flooding and wave pulverisation on the daily melt rate of an idealised ice floe (and/or area of wave pulverised slush) in the Antarctic SIZ in summer by changing the ice albedo (α) in the surface radiation energy budget. The overall aim is to show that the effect could be significant, and is therefore worthy of further investigation by targeted fieldwork and modelling.

2 Data and techniques

2.1 Observations

Wave-melting phenomena and processes are identified [here](#) based on shipborne observations and photographs acquired from multiple voyages across the Antarctic SIZ, particularly the MIZ, and from the literature (e.g., Ackley, 1985; Massom, 1991; Ackley and Sullivan, 1994; Massom et al., 1997, 1998, 1999, 2001, 2006). As no direct measurements are available for albedos of wave-flooded and wave-pulverised ice, we use proxy estimates of albedos [for](#) the different [wave-affected](#) surface types derived from measurements made from ships and helicopters, as described in [Section 3.2](#) below. Daily sea-ice [concentrations](#) for calculating the distance to the ice edge (Sect. 3.1.2) [and the latitude of ice within the MIZ](#) (Sect. 3.3) are based on [daily](#) satellite passive-microwave ice-concentration data dating back to 1979 (Cavalieri et al. 1996, updated yearly). The sea-ice edge is delineated by the 15% ice-concentration isoline.

2.2 Computing radiative transfer and [wave-driven melt-rate enhancement](#)

Here, we consider the effect of wave flooding and wave pulverisation [on](#) only [on](#) the shortwave [rather than longwave](#) properties of an ice floe/area of wave slush, which is to reduce the sea-ice albedo. The longwave (infrared) emissivities of snow, ice and water are all close to 100% (Warren, 1982, 2019), so the only longwave effect of wave flooding is to increase the longwave emission slightly by increasing the surface temperature of the ice [floe](#), bringing it up to $\sim 0^\circ\text{C}$.

Our computation starts with the daily-average incident solar flux at the top of the atmosphere, F_{TOA} (in W/m^2), and then [multiplies](#) it by the atmospheric transmittance over Antarctic sea ice, τ_a , to obtain the solar flux at the surface (F_{sfc} , in W/m^2) as

$$F_{sfc} = \tau_a F_{TOA}. \quad (1)$$

Following Fitzpatrick and Warren (2005; FW05), and as τ_a is not directly available, we take two steps to obtain F_{sfc} . We first obtain the transmittance, τ_{clr} , for clear sky (shown in Fig. 7 of FW05 as a linear fit versus solar zenith angle θ_z), such that

$$\tau_{clr} = 1.03 - 0.0046 \theta, \quad (2)$$

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with θ in degrees. Then we apply the “cloud radiative forcing” CRF as a correction, to obtain F_{sfc} as

$$230 \quad F_{sfc} = \tau_{clr} F_{TOA} + CRF_d, \quad (3)$$

where CRF_d is the downward shortwave cloud radiative forcing in W/m^2 (measured by FW05 and plotted in their Fig. 10), which is a negative quantity, indicating that clouds reduce the downward solar flux at the surface.

We estimate the albedo change (decrease), $\Delta\alpha$, caused by wave flooding of a snow-covered floe of wave pulverisation to be

$$\Delta\alpha = \alpha_s - \alpha_w, \quad (4)$$

235 where α_s is the albedo of a snow-covered floe of first-year ice (FYI) (e.g., floe marked D in Fig. 1e), and α_w is the albedo of a wave-overwashed floe (e.g., floes marked A flooded and B in Fig. 1a), a wave-ponded floe (e.g., labelled C and E in Fig. 1e) /or wave-pulverised slush (e.g., Fig. 1i) ice. Multiplying F_{sfc} by $\Delta\alpha$ gives the wave-washing radiative forcing, RF_w , of wave-flooded or wave-pulverised ice as

$$RF_w = \Delta\alpha F_{sfc}, \quad (5)$$

240 which is in units of $W m^{-2}$. Equation (5) holds for a single idealised sea-ice slab; or an idealised small area of (unconsolidated) wave slush at a given latitude and day of year. Due to current lack of important spatio-temporal information e.g., on the extent and fractional coverages of the different wave-flooded types and wave-pulverised slush ice, it is beyond the scope of this study to estimate regional averages of radiative forcing ($RF_{w,avg}$) as a function of latitude, longitude and month. Our aim is simply to show that wave flooding and wave pulverisation could enhance seasonal sea-ice melting – arguing that it is worthy of further investigation.

245 To obtain regional averages of radiative forcing, $RF_{w,avg}$, we would multiply RF_w by the ice concentration, C , and the fraction of floe area affected by wave flooding, f_w , to give:

$$RF_{w,avg} = C f_w RF_w = C f_w \Delta\alpha F_{sfc} \quad (6)$$

250 This calculation could be refined by using the frequency distributions of (a) ice concentration, (b) solar zenith angles, (c) cloud thicknesses, and (d) the fractional coverages of the different wave-washing types, to get $RF_{w,avg}$ as a function of latitude, longitude and month, i.e., similar to Eq. (8) of Fitzpatrick and Warren (2007). However, that refinement is also beyond the scope of this study, the aim of which is simply to show that wave flooding and wave pulverisation could enhance sea-ice melting, arguing that it is worthy of further investigation.

255 To estimate the change in melt rate of sea ice the idealised wave-flooded small floe and/or area of wave slush due to the radiative forcing, i.e., the wave-driven melt-rate enhancement, we divide the radiative forcing (Eq. 5) by the sea-ice density, $\rho = 905 \text{ kg m}^{-3}$ (Fang et al., 2022), and the latent heat of fusion, $L = 334 \text{ J g}^{-1}$ (Fang et al., 2022), to obtain

$$dh/dt = RF_w / (\rho L), \quad (76)$$

where h is the sea-ice thickness and t is time.

3 Results

3.1 Wave flooding and wave melting processes

Based on available observations, we identify six the following coupled dynamic-thermodynamic (and biological)-wave-driven processes driven by waves that operate year round and increase surface and interior melting of small floes (typically <5 m diameter) that are the product of wave breakup of larger floes. Five of these processes, *wave overwashing*, *wave buffeting* and associated *wave ponding*, *wave deformation ponding* and *wave compression flooding*, involve partial or complete snow removal and/or snow wetting and inundation of the ice surface with seawater, plus (in the case of wave ponding) seawater pooling on the ice. Further, we propose *wave pulverisation* as a sixth wave-induced process that contributes contribute to Antarctic seasonal sea-ice melting by mechanically wave melting, with open circles denoting sub-processes and dashes sub-sub-processes:

- Wave Flooding (physical seawater-inundation processes)

- Wave overwashing

- Wave ponding

- Wave-buffeting ponding

- Wave-deformation ponding

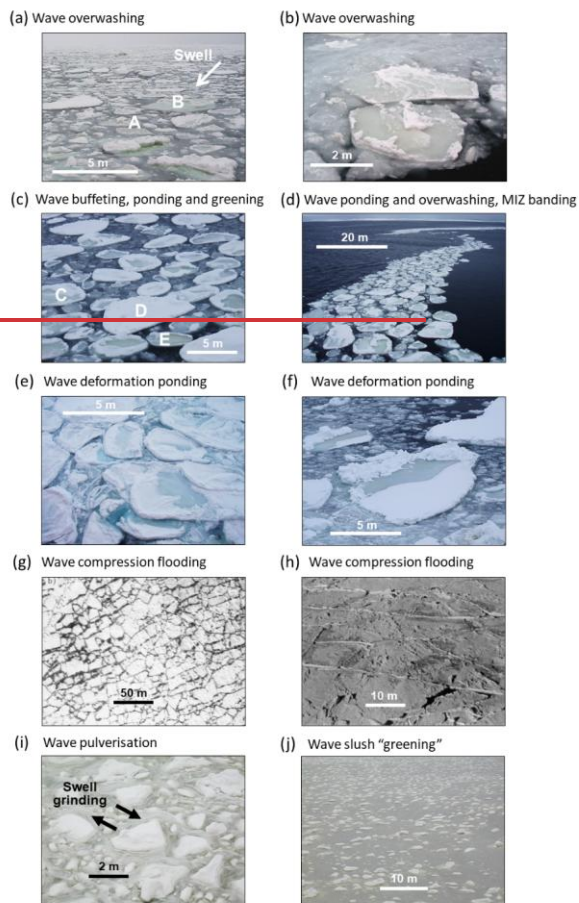
- Wave-compression flooding

- Wave Pulverisation (mechanical grinding down small of floes and fragments of brash ice into a combined slurry of ice and snow wave slush, which melts more rapidly. We term this *wave slush*. An additional (seventh) process—*wave greening*—involves and brash ice)

- Wave churning

- Wave Greening (algal proliferation and ice/wave-pond darkening of the ice due to increased algal growth in surface wave ponds, the interior of the snow-free ice, and wave-pulverised slush, in turn increasing light absorption and ice melt (cf., Zeebe et al., 1991).)

Example images are shown in Fig. 1, with schematic representationrepresentations of wave-fracturing, wave-flooding and, wave-pulverisation processes and wave greening in Fig. 2. The images are all from the in Fig. 1a-f and 1h are oblique views taken from the Australian icebreaker *RSV Aurora Australis* during experiments in the East Antarctic sector in late austral winter to early spring, apart from while the wave-pulverisation and wave-slush images (Fig. 1i, j) which are from were acquired from the US icebreaker *RSV Nathaniel B Palmer* in the Bellingshausen Sea. All are oblique views from during the ship (the *RSV Aurora Australis*), apart from Fig. late-austral spring. Figure 1g which is a larger vertical aerial image view of wave-compression flooding from an aerial camera on a helicopter of the scene shown in Fig. 1h.



290 **Figure 1: Photographic examples of wave flooding and wave pulverisation processes, with estimates of ice thickness (h_i) and surface**
water depth (h_w): a-b) wave overwashing ($h_i \sim 100$ cm, $h_w \sim 1.5$ cm); c) wave buffeting, wave ponding and wave greening ($h_i \sim 70$ cm,
 $h_w \sim 5$ cm); d) marginal ice zone banding with wave ponding and wave overwashing ($h_i \sim 50-70$ cm, $h_w \sim 5$ cm); e-f) wave deformation
ponding ($h_i \sim 70-100$ m, $h_w \sim 5-20$ cm); g-h) wave compression flooding from aerial photography and from the surface ($h_i \sim 70$ m); i)
295 wave pulverisation (wave slush thickness $\sim 0.50-1.00$ m), with black arrows denoting wave churning; and j) wave slush greening
(wave slush thickness $\sim 0.5-1.0$ m).

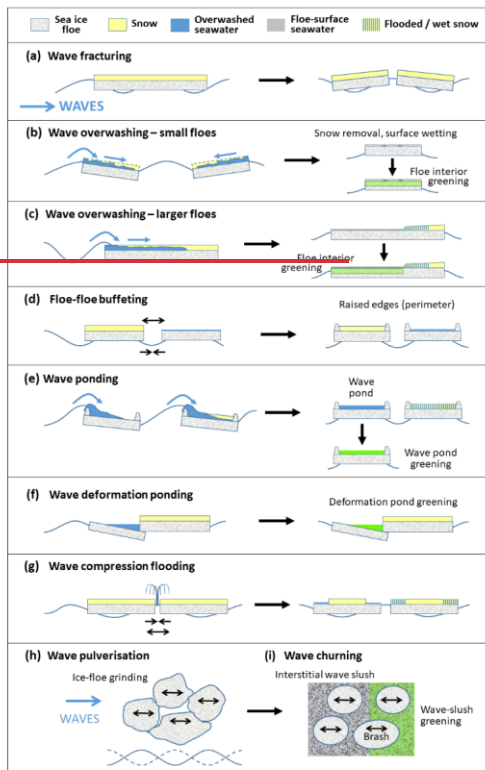


Figure 2: Schematic representation of a) wave fracturing; b-c) wave overwashing; d) wave buffeting; e) wave ponding; f) wave deformation ponding; g) wave compression flooding; h) wave pulverisation; and i) wave churning. Representative images b-i are shown in Fig. 1.

Wave-flooding processes are not to be confused with flooding due to floe-surface submergence under the weight of overlying snow (Wadhams et al., 1987; Massom et al., 2001). This latter style of flooding is widespread across the Antarctic SIZ (Eicken et al., 1994; Maksym and Markus, 2008), but it seldom results in complete snow removal and exposed ponding because only the lowest part of the snowpack is flooded (Massom et al., 2001).

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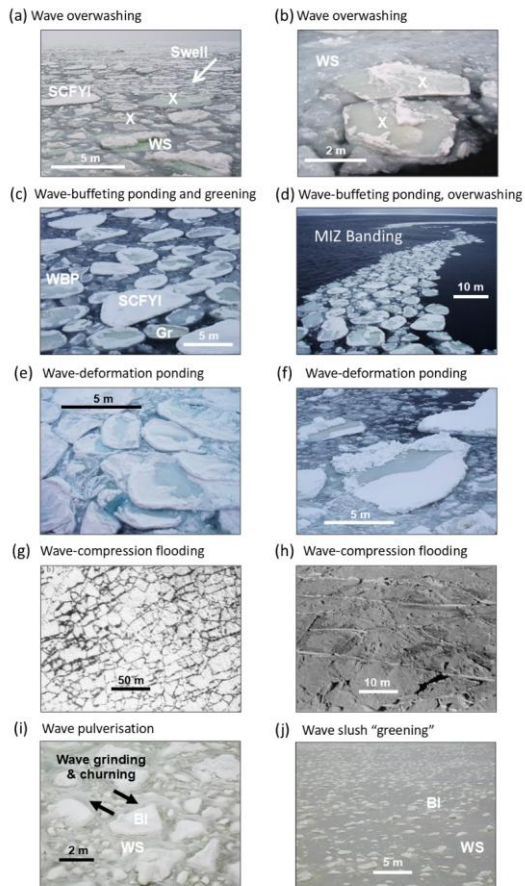


Figure 1: Photographic examples of wave flooding, wave pulverisation and wave greening, with estimates of ice thickness (h_i) and sea-ice surface water (wave pond) depth (h_w) from the ship: a–b) wave overwashing ($h_i \sim 100$ cm, $h_w \sim 1\text{--}5$ cm); c) wave-buffeting ponding and wave greening ($h_i \sim 70$ cm, $h_w \sim 5$ cm); d) marginal ice zone (MIZ) banding with wave-buffeting ponding and wave overwashing ($h_i \sim 50\text{--}70$ cm, $h_w \sim 5\text{--}5$ cm); e–f) wave-deformation ponding ($h_i \sim 70\text{--}100$ m, $h_w \sim 5\text{--}20$ cm); g–h) wave-compression flooding from aerial photography and from the surface, respectively ($h_i \sim 70$ m); i) wave pulverisation (wave-slush thickness $\sim 0.50\text{--}100$ m), with black arrows denoting wave grinding and wave churning; and j) wave-slush greening (wave-slush thickness $\sim 0.5\text{--}1.0$ m).

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m). X indicates wave-overwashed ice; SCFYI is snow-covered first-year ice; WS is wave slush; WBP is wave-buffeting pond; Gr is greening; and BI is brash ice.

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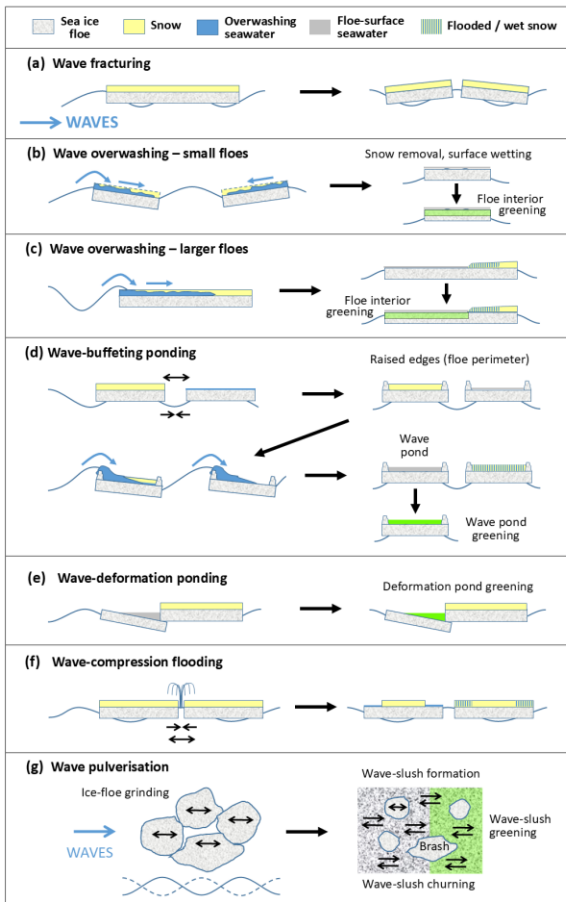


Figure 2: Schematic representation of a) wave fracturing; b-c) wave overwashing for large and small floes, respectively, and greening; d) wave-buffeting ponding and greening; e) wave-deformation ponding and greening; f) wave-compression flooding; g) wave pulverisation leading to wave-slush formation and wave churning. Representative images of b-g are shown in Fig. 1.

320 3.1.1 Wave overwashing

Wave overwashing is a widespread phenomenon and process in the outer MIZs in both the Antarctic MIZ (Massom et al., 1997; 1998), as well as and the outer Arctic MIZ (Massom, 1991), where it typically affects small floes (<5 m diameter) that are themselves the product of wave-driven fracturing of larger floes. Floes smaller than or comparable to the prevailing wavelengths ~~move~~ tilt with the incoming waves but slightly out-of-phase with them, such that overwashing is generated at the leading and trailing floe edges as they pitch below the ocean surface (Skene et al., 2015; Toffoli et al., 2015; Dolatshah et al., 2018; Nelli et al., 2020). This causes seawater to flow (wash) back and forth across their surfaces (e.g., floes marked X in Fig. 1a,b; and Fig. 1b; and Fig. 2b), where it can either push the snow cover into the water and/or turn it into a slush layer on the floe surface. In contrast, floes larger than the prevailing wavelengths, and directly exposed to open water, are overwashed by waves breaking over their leading edge and onto the floe surface (Passerotti et al., 2022; Fig. 2c). Wave overwashing can also ~~thrust~~ thrust sea-ice blocks onto the surfaces (margins) of small floes, to weigh down that part of the floe, decrease the local floe's freeboard and increase the likelihood of further overwashing and flooding (see Sect. 3.1.32 below).

Wave overwashing is not restricted to the MIZ, as; it also affects floes adjacent to large open-water areas, i.e., leads and polynyas, as observed for example in the Weddell Sea (Massom et al., 1997) and the East Antarctic sector (Massom et al., 1998). This is due to the prevalence of wind waves there, generated by katabatic winds in coastal regions, e.g., within polynyas (cf., Ackley et al., 2022; Herman and Bradtke, 2024) and the frequent passage of storms across the wider SIZ (cf., Godfred-Spenning and Simmonds, 1996; Uotila et al., 2011). For example, Ackley et al. (2022) observed significant wave heights exceeding in excess of 2m in the Terra Nova Bay Polynya (Ross Sea) in May. Large leads are a prevalent feature within the Antarctic SIZ (Dubey et al., 2025) due to its largely-divergent nature with the frequent passage of storms (Worby et al., 1998), with lead widths of up to 6500 m observed in the Weddell Sea by Muchow et al. (2020), and there is also widespread distribution of while recurrent and persistent coastal and polynyas are widely distributed around Antarctica along with fewer open-ocean polynyas (Barber and Massom, 2007).

335 3.1.2 Wave buffeting/ponding

We further propose that the ponding of seawater on ice-floe surfaces can occur by a set of ice-deformation processes driven not only by winds and currents but also by ocean waves ("wave ponding ~~Wave~~"). By one sub-process that we term "wave buffeting-is", the constant collision, jostling and rotation of small floes (typically <5m across) driven by incoming waves, which rounds off their angular edges and creates decimetre-scale raised rims (e.g., floe marked WBP in Fig. 1c; Fig. 2d). Where these rims form around the entire floe perimeter, (which is often the case), they act as mini-ice levées that entrap and retain seawater introduced onto the surface by wave overwashing (Fig. 2e,2d) and/or via the upward movement of seawater through the ice if it is permeable (cf., Golden et al., 1998) and has a negative freeboard. We term ~~these~~ this sub-class of saline wave ponds wave-buffeting ponds. Such ~~Although wave ponds in some ways resemble seasonal Arctic melt ponds, they are saline rather than freshwater (low salinity) and occur year-round, i.e., they are~~

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not confined to the summer melt season and form faster than Arctic melt ponds (cf., Lüthje et al., 2006; Webster et al., 2022). Wave pond formation is also likely influenced by the effect of the additional mass of rim ice and rafted ice blocks in modifying the floe isostasy and decreasing the floe freeboard. Wave ponds can be maintained by constant wave overwashing, but they can also freeze and accumulate a snow cover in the cold season and where wave energy dies down.

In the typical example shown in Fig. 1c, the scene-wave-buffeting ponding is visually estimated to cover about one third of surface area of the small floes, which comprise approximately 10% about 65% of the image scene (the remaining 35% being a mix of open water and 25% combined brash ice and wave slush ice-by-area, with flooding/ponding covering about one third of the remaining coverage of small ice floes; see Section 3.1.4 for discussion of wave slush). This example, from 11 October 2007 at -62.5° S and 123.7° E, is about 25 km south of the ice edge as demarcated by the 15% sea-ice concentration isoline. Another example in Fig. 1d shows extensive coverage of wave-buffeting ponding in an ice-edge band, fields of which are a ubiquitous feature of the MIZ (cf., Ishida and Ohshima, 2009). They may extend the spatial and temporal influence of wave melting; this is covered in Sect. 4.2.

3.1.3 Wave deformation ponding

Surface ponding seawater inundation and snow removal can also occur where incoming waves drive convergence and deformation in the interaction and deformation of small floes sea-ice field and push floe surfaces below sea level, leading to “wave-deformation ponding” where there is connection to the underlying ocean (cf., Massom et al., 1997, 1998). The localised replacement of snow cover with saline water in pools up to a few metres across (Fig. 1e,f; Fig. 2f). In this case, this second sub-process of wave ponding can occur where waves force drive the over-rafting of small floes and/or the mechanical pile-up of ice rubble and/or pressure ridging (on their surfaces (cf., Dai et al., 2004; Bennetts and Williams, 2015; Sutherland and Dumont, 2018), which can depress part of the floe); an example is given in Fig. 1e, with a schematic depiction in Fig. 2e. Wave-deformation ponding can also occur where wave-driven fracturing of a floe adjacent to an existing pressure ridge can place the surface below sea level of the resultant smaller floe out of isostatic balance due to the weight of the ridged ice (that was originally spread over a larger floe) – leading to seawater ponding when there is connection to the underlying ocean (partial submergence, seawater flooding and ponding as the new floe readjusts (cf., Ackley, 1985; Ackley and Sullivan, 1994). An example is shown in Fig. 1f. Flooded areas caused by pressure-ridge loading have been termed surface-saline ponds by Ackley and Sullivan (1994), but we retain the Massom et al., 1997, 1998). We term this wave-deformation ponding. Wave-deformation ponds here as surface-saline ponds can also occur in the interior SIZ due to sea-ice convergence and deformation driven by winds and ocean currents. Deformation-type ponds have been observed to cover ~5–10% of the total surface area of the sea-ice floes about 200 km poleward of the ice edge and in winter, in both the northwestern Weddell Sea (Massom et al., 1997), the western Weddell Sea (Ackley and Sullivan, 1994) and the western Pacific Ocean sector (Massom et al., 1998). Henceforth and for the purposes of investigating their impact on ice albedo and wave melting, wave-buffeting ponds and wave-deformation ponds are collectively referred to as wave ponds. Although wave ponds in some ways resemble seasonal Arctic

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385 melt ponds, they are saline rather than freshwater (low salinity) and occur year-round, i.e., they are not confined to the summer
melt season and form faster than Arctic melt ponds (cf., Lüthje et al., 2006; Webster et al., 2022). ~~In addition, wave-induced~~
~~fracturing of larger floes near an existing pressure ridge can place the adjacent ice surface out of isostatic balance due to the~~
~~weight of the ridge, leading to submergence, flooding and ponding of the resultant smaller floe as it readjusts (Aekley and~~
~~Sullivan, 1994).~~ ~~In the Weddell Sea, such ponding can be prevalent in the outer 200 km of the SIZ, and in the highly deformed~~
~~ice in the western outflow region of the Weddell Gyre, i.e., 40–60°W (Aekley and Sullivan, 1994).~~ ~~Flooded areas caused by~~
390 ~~pressure ridge loading have been termed *surface saline ponds* by Aekley and Sullivan (1994).~~ ~~Similar ponds also occur even~~
~~deeper into the SIZ, due to deformational processes not related to waves, e.g., convergence in the ice field causing surface~~
~~depression and ice cracking adjacent to pressure ridges (Aekley, 1985; Massom et al., 1997).~~

~~3.1.4~~

~~3.1.3~~ Wave-compression flooding

395 Under certain circumstances, long-period swells penetrate more deeply into the Antarctic SIZ, i.e., hundreds of kms in from
the ice edge (Liu and Mollo-Christensen, 1988; Nose et al., 2023; ~~cf.,~~ Morris et al., 1998; Worby et al., 1998; Kohout et al.,
2014). In addition to potentially driving wave-deformation ponding, deep swell penetration can lead to wave-compression
flooding in extensive areas of consolidated and undeformed FYI (Massom et al., 1999). By this process (Fig. 2g2f) and in the
400 through-cutting breaks (cracks) in large FYI floes of uniform thickness- (estimated ~0.7 m). These cracks opened and then
closed a few seconds later with the passage of each wave crest and trough, leading to compression of seawater between the
two converging ice plates (Massom et al., 1999). This resulted in the "squirting" of seawater onto the surface of the newly-
created, small angular floes around their perimeter (Worby et al., 1998). Analysis of aerial photographs along the 139° 15' E
405 the ice edge (Massom et al., 1999). This process wetted and darkened an estimated 20% of the surface of 100%-concentration
sea ice (seen as a greying of the snow cover adjacent to the cracks, determined from the aerial photos). ~~While the~~ The frequency
of such wave-compression flooding events is unknown, ~~they may occasionally cause flooding of floes deep in the SIZ,~~
~~irrespective of season.~~

~~3.1.54~~ Wave pulverisation

410 While there has been emphasis on the role of waves in the flexural breakup of larger floes into smaller floes in the MIZ (e.g.,
Kohout et al., 2014), we here highlight an additional widespread, yet largely neglected, wave-driven process in floe breakdown
and melting. This is the lateral grinding together ~~of and~~ mechanical pulverisation of small floes by incoming swells (Fig.
2h2g), resulting in the mechanical pulverisation of the floes and their snow cover into an agglomeration of 1) small brash-ice
fragments that are easily flooded by waves and 2) an unconsolidated slushy mix of wave-slush pulverised ice and brash
415 fragments snow (Massom et al., 2006); ~~that we term "wave slush"~~. In the colder months, this wave slush is likely supplemented

by, and potentially enhances, frazil-ice formation. Wave pulverisation is distinct from the flexural fracturing of floes by waves, which decreases their size as depicted in Fig. 2a (cf., Squire, 2007), and we propose here that it contributes to a wider reduction in surface albedo and an increase in melt rate (compared to snow-covered floes).

In an October 2001 observation from the Bellingshausen Sea (Fig. 1i), persistent north-westerly winds compacted the MIZSIZ against the western Antarctic Peninsula, while a 2–3 m north-westerly swell mechanically ground-down pulverised the ice cover within the highly-compact MIZ over a distance of tens of kilometres in from a linear ice edge (Massom et al., 2006). This created a continuous (100% cover) but unconsolidated agglomeration of brash ice fragments (<~1 m across) separated by an interstitial slurry of and unconsolidated wave slush ice that which was constantly churned and reworked by the incoming swells, by a sub-process that we term “wave churning”. Interstitial wave slush ice and brash ice also occur between larger contiguous floes in such wave-affected areas, as in the examples of wave overwashing marked (WS and ponding given BI respectively) in FigFigs. 1a-b and Fig- 1c-d, respectively.

3.1.6 3.1.5 Wave greening

We propose that wave flooding and wave pulverisation and associated snow removal also drive the rapid create an ideal habitat for proliferation of ice algae within wave ponds (see.g., floe Emarked Gr in Fig. 1c) and/or in the snow-free ice column (particularly in late spring–summer) – and that this wave greening (darkening due to high chlorophyll and other algal pigment content) intensifies the sea-ice melt rate enhancement by further reducing reduces the ice albedo (see Sects. 3.2 and 3.3). Light attenuation by snow is a major limiter of ice-algal growth (Arrigo et al., 2014), and snow-cover removal by waves increases the exposure of low-light-adapted algae to substantially higher amounts levels of photosynthetically-active radiation to potentially enhance primary production within the wave-flooded ice. Wave flooding likely also introduces biogenic material and nutrients onto floe surfaces, where they are retained in wave ponds and/or continually replenished by wave flooding overwashing. While no direct measurements of wave-pond habitats (“floe-oases”) are yet available, limited observations of have shown similar surface-saline deformation ponds show that they cant support high algal biomass (chlorophyll content) (Kottmeier and Sullivan, 1990; Ackley and Sullivan, 1994; Garrison et al., 2003; Arrigo et al., 2014) and act as mini oases of high primary production within ice-covered areas. This greening and darkening of wave-(and deformation) ponds contrasts with Arctic freshwater meltponds, which generally contain low algal biomass due to low nutrient concentrations (Arrigo et al., 2014).

In the case of the wave pulverisation depicted, and in the example from the Bellingshausen Sea MIZ in October 2001 shown in Fig. 1i and Fig. 2i,j, the mechanical grinding and churning together of the ice floes and resultant release of ice algae contained within it created an extensive area of unconsolidated agglomeration of green wave slush/frazil-ice slurry interspersed with and brash-ice fragments <1 m across, that was constantly churned and mixed by the incoming swells (Fig. 2g). This exposed the ice algae to significantly higher light and nutrient levels than in a snow-covered floe, leading to an intense “intra-ice algal

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bloom” in October”, i.e., unusually early in the sunlit season and relatively far south at ~65°S and also undetectable in satellite ocean-colour data (Massom et al., 2006).

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3.2 Wave modification of sea-ice albedo

To our knowledge, spectral albedo has not yet been directly measured for wave-flooded and wave-pulverised ice (and their wave-greened equivalents). For this initial study, we therefore use surrogate estimates of spectral albedo based on measurements from ships and helicopters for multiple types of Antarctic sea ice, both bare and snow-covered, that we consider to have similar albedos to the wave-affected ice types. Brandt et al. (2005) and Zatko and Warren (2015) summarise the measured albedo values, where spectral values are integrated over wavelength (weighted by the solar spectral flux) to obtain band-average albedos for narrow- and broad-bands, and for both clear and cloudy skies. Here we use averages over the entire solar spectrum (290–3000 nm wavelengths), which we call “broadband albedo” (Table 1a). We list the albedos for cloudy sky rather than clear sky, as they are the most relevant to the Antarctic SIZ, given that average cloud coverage there exceeds 80% in spring–summer (Warren et al., 1988; Fitzpatrick and Warren, 2007). Immediately apparent is the strong sensitivity of sea-ice albedo to even a thin layer of snow. Snow, with snow-free FYI floes that are <0.7 m and >0.7 m thick have having average broadband albedos which are 0.3 less than their snow-covered counterparts, respectively. (Table 1). Therefore, snow removal (e.g., by waves) is of crucial importance in terms of its effect on the radiation energy budget and the seasonal melt rate of sea ice.

Table 1a.

Surface type	Albedo range	Average albedo
Open water	0.06–0.07	0.07
First-year ice (<0.7 m), bare	0.41–0.49	0.45
First-year ice (<0.7 m) with 2–4 cm snow	0.70–0.78	0.74
First-year ice (>0.7 m), bare	0.50–0.58	0.54
First-year ice (>0.7 m) with >3 cm snow	0.82–0.87	0.84
Wave-pulverised ice plus pancake ice, one case only (Allison et al., 1993 Figure 12)	0.68	=
Snow slush (average and range of 4 cases)	0.35–0.59	0.46

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Table 1b.

470 **Table 1. Broadband albedos for open water, bare ice, snow-covered ice and snow slush measured in the Antarctic SSIZ, under a cloudy sky (Brandt et al., 2005; Zatko and Warren, 2015) and used as the basis of surrogate estimates of broadband albedos of the different wave-flooded and wave-pulverised types in Table 2.**

Wave-affected surface type	<i>A</i> type	Photos in Figure 1	Albedo range	Average albedo	$\Delta\alpha$
Overwashed first-year ice	A	a, b	0.35–0.59	0.46	0.38
Wave-compression flooded		g, h			
Wave-pulverised slush		i			
Wave-pulverised slush – green	B	j	0.25–0.49	0.36	0.48
Wave-buffeting pond	C	c, d	0.2–0.4	0.3	0.54
Wave-deformation pond		e, f			
Wave pond, bare ice* – green	D	c	0.1–0.3	0.2	0.64

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475 **Table 1. Broadband2. Surrogate estimates of broadband albedos for surface types in the Antarctic SSIZ, under a cloudy sky: (a) measured for open water, bare for the four broad albedo classes of wave-affected sea ice, snow-covered; (A) wave-overwashed FYI, wave-compression flooded ice, and wave slush (Brandt et al., 2005; Zatko; (B) wave slush darkened by wave greening; (C) wave ponds; and Warren, 2015); (D) wave ponds and (b) estimated for wave-flooded and wave-pulverised sea-ice types, and albedo difference/reduction ($\Delta\alpha$) compared to first-year ice >0.7 m thick with a >3 cm snow cover. *Bare ice refers to wave-overwashed/or *wave-overwashed ice with no snow cover.**

480 Albedo has not been measured for wave-flooded or wave-pulverised ice floes, excepting Allison et al. (1993) who reported an albedo of 0.68 for a mixture of pancake ice, nilas and brash ice. However, that albedo value depends on the relative amounts of the three ice types present, so we do not use it in our calculations. Instead, we use Zatko and Warren (2015)'s measured albedo for four cases of slush formed by snow blowing into a lead in the Antarctic SIZ, as a surrogate for wave slush ice formed by wave pulverisation processes (Fig. 1i), wave compression-flooded ice (Fig. 1g,h) and wave-overwashed FYI (Fig. 1a,b), based on their similar appearance.

485 To represent wave ponds (Fig. 1e,d) and wave deformation ponds (Fig. 1e,f), we use albedos measured on Arctic melt ponds with similar appearance (Light et al., 2022). Most Arctic melt-ponds are darker than Antarctic wave ponds, because melt ponds overlay waterlogged ice (the snow is long-gone) whereas wave ponds are typically brighter as they consist of slush or water over relatively bright ice. However, many Arctic melt ponds do resemble the wave ponds shown in Fig. 1c–f, and those melt ponds are the ones we use as surrogates. The surrogate broadband albedo values for the different wave-affected surface types are given in Table 1b2. Table 1b2 also includes surrogate albedo estimates for wave-ponded, bare and wave-pulverised ice types modified by wave greening. In the absence of direct measurements and for the purpose of this initial study, the

greening is estimated (assumed) to ~~reduced~~darken the ice, reducing the albedos of these types by an additional 0.1 compared to their “non-green” counterparts.

We compare these surrogate average broadband albedo values with that observed for non-wave greened thick FYI with ~~thickness >0.7 m and a snow layer >3 cm thick cover~~ ($\alpha = 0.84$) to determine the ~~change~~ (decrease) in average broadband albedo ($\Delta\alpha$) for the four different wave-affected ~~surfacealbedo-type categories (classes A–D given in Table 2). Values of $\Delta\alpha$ are: 0.38. Thick FYI with a snow cover is chosen as the reference/baseline for~~ overwashed FYI, wave compression flooded ice, and wave pulverised slush; 0.48 for wave pulverised slush (green); 0.54 for wave ponds and wave deformation ponds; and 0.64 for wave pond or bare ice that are greened. As outlined in Sect. 2.2 (Eqs. 4–6) ~~thesethis~~ this initial study as it has the highest albedo (Table 1). Estimated values of $\Delta\alpha$ then are given in Table 2, and range from 0.38 to 0.64.

These values of $\Delta\alpha$ form the basis for our first crude estimate approximation of the resultant increases in the daily vertical melt rates of the wave-affected ice types surface-type classes in the Antarctic SIZ in summer due to wave flooding and wave pulverisation, and melting, compared to a snow-covered FYI floe (Sect. 3.3 below). More detailed analysis of the influence of wave melting on larger regional to pan-Antarctic scales, and as a function of time of year, is not attempted due to current lack of key large-scale information on the spatio-temporal coverage of wave flooding and wave pulverisation – but is recommended as priority future work when observations become available (see Sect. 6).

3.3 Enhancement Wave enhancement of seasonal sea-ice melting caused by vertical melt rate

We first compute the wave flooding and wave pulverisation

~~Here we consider driven enhancement in vertical melt rate (dh/dt) based on the radiative effects of both wave flooding of a single idealised snow-covered floe and wave pulverisation that creates wave slush, in order to compute the increase in the vertical melt rate of wave flooded and wave pulverised ice compared to a snow-covered FYI floe. We term this “wave induced melt rate enhancement” (see Sect. 2.2). For illustration, we work through an example representing approximately the midpoint of the austral melt season for the approximate middle latitude of the SIZ, namely and wave pulverisation on the December solstice (the approximate midpoint of the austral-summer melt season) and for single parcels of ice at 65°S. We (a representative latitude of the MIZ for much of East Antarctica and the Ross Sea at that time of year). In order to illustrate the technique and the magnitude of the effect, we initially focus on Type A (wave-overwashed ice, wave compression-flooded FYI and wave pulverised slush), where $\Delta\alpha = 0.38$ (Table 1b), and take f_w (the fraction of floe area affected by wave flooding) to be 1.0. For this example: 2).~~

(1) On the December solstice at 65°S, the downward shortwave (SW) flux at the top of the atmosphere ($F_{\downarrow 0A}$) is 510 W m^{-2} (Fig. 2.7 of Hartmann, 2016). This corresponds to an effective daily average solar zenith angle of 68° (solar constant is 1360 W m^{-2} ; $\cos^{-1}(510/1360) = 68^\circ$).

(2) For solar zenith angle 68°, we get the downward SW at the surface, $F_{\downarrow sc}$, as described in Sect. 2.2. The corresponding atmospheric transmittance over sea ice is $t_a = 0.52$, so $F_{\downarrow sc} = 0.52 \times 510 = 264 \text{ W m}^{-2}$.

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~~(3)~~ Referring back to Eq. (5), the radiative forcing caused by wave flooding (RF_w) is then:

525 $RF_w = \Delta\alpha F_{sfc} = 0.38 \times 264 = \sim 100 \text{ W m}^{-2}$.

~~(4) To get regional averages, we would multiply RF_w by the ice concentration (C) and the fraction of floe surfaces that are wave flooded or the area of ice that is wave pulverised (f_w) (see Eq. 6 in Sect. 2.2). However, as we are dealing with~~
~~For an idealised fully-flooded single floe (snow-free sea-ice slab) or idealised mass (a small area) of wave slush, C~~
~~is both the fraction of ice area affected (f_w) and the ice concentration (C) are taken here to be 1.0, and we can compute~~
530 the melt-rate enhancement by Eq. (76) (Sect. 2.2).

~~For In this example at 65°S and where $f_w = 1.0$, the estimated wave-driven enhancement in vertical melt rate case, dh/dt for~~
~~wave flooded ice and wave slush (compared to snow-covered FYI) is $\approx 2.9 \text{ cm day}^{-1}$.~~

We next carry out a broader sensitivity analysis of wave-driven the relative enhancements in daily melt rates (dh/dt) for the four different wave-affected classes whereof wave-modified (-darkened) ice surfaces A-D given in Table 2 (with albedo reductions $\Delta\alpha$ is = 0.38, 0.48, 0.54, 0.64) and 0.64, as a function of: 1) for three wave-flooding and/or wave-slush coverage fractions (f_w , with values of = 0.33 and 0.5 in addition to 1.0 derived from, based on visual inspection of photographs acquired from icebreakers (Fig. 1a-j); 2) latitude; and 3) time of year from 1a-j)), over November through January (the main period of annual sea-ice retreat). The estimated melt-rate enhancement values and as a function of latitude. Results for 60°S to 65°S and 70°S, i.e., the zone typically covered by sea ice at some time during the annual retreat phase (e.g., Massom et al., 2013), are plotted in Fig. 3, while 3. These results and values for the wider latitudinal range of 55–75°S are shown given in the Appendix in Tables A1A–1C. Over the range of latitudes examined, A1C show that wave-enhanced rates of vertical ice melt melting steadily build up through late austral spring (November). Not surprisingly, the lower the , and that they generally increase with decreasing latitude, the higher the melt-rate enhancement, and there is strong dependence on f_w , i.e., the greater the and increasing fraction of a floe surface that is wave flooded or the area of ice that is wave pulverised, the higher the melt-rate enhancement coverage. In all cases, the melt-rate enhancement values of dh/dt converge towards a broad annual seasonal peak around the December solstice, before slowly decreasing through January (mid-summer).

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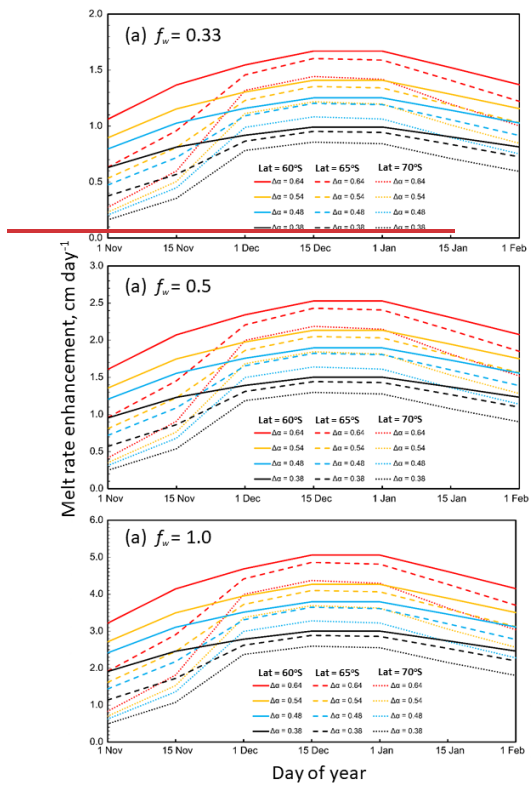
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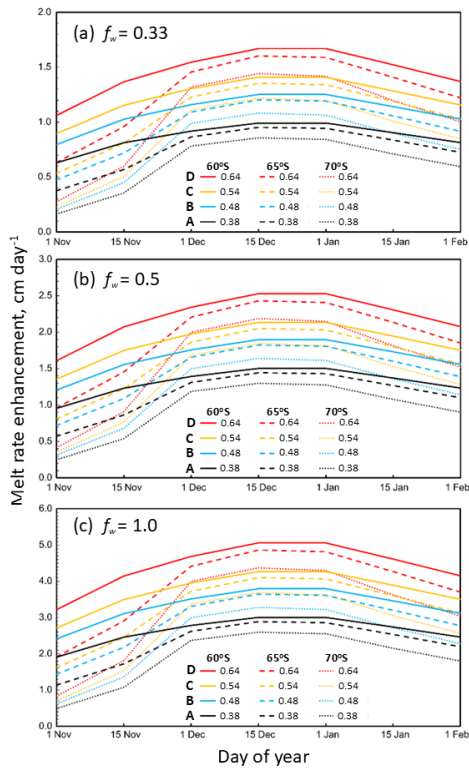
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550 **Figure 3: Plots of Wave-driven sea-ice melt-rate enhancement based on albedo change (dh/dt) showing substantial increases in vertical melting ($\sim 0.2\text{--}5\text{ cm day}^{-1}$ extra) caused by albedo reduction ($\Delta\alpha$) related due to different types of wave flooding and/or wave pulverisation, as a function of latitude (60°S , 65°S and 70°S), time of year t . Results are shown for three coverage fractions ($f_w = 0.33, 0.5, 1.0$) and four surface darkening scenarios (see Table 2) marked A–D in the legend ($\Delta\alpha = 0.38\text{--}0.64$) across Antarctic latitudes 60°S – 70°S) during November through January), and for sea ice of density 905 kg m^{-3} . For a) $f_w = 0.33$; b) $f_w = 0.5$; and c) $f_w = 1.0$. Note the different scales on the y axes. Coincident estimated values of wave-driven melt-rate enhancement for 55°S – 75°S are given in Tables A1A–A1C.**

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Annual summer Estimated values of annual maximum wave-induced melt rate enhancement values (on 15 December) for the four wave-affected ice-surface type categories, as a function of latitude (60°S, 65°S and 70°S) and f_w (0.33, 0.5 and 1.0), coverage fraction scenarios for three latitudes are given in Table 23. For ice-surface types A and C which are unaffected by algae, these range from 0.9 cm day⁻¹ (for type A at 70°S where $f_w = 0.33$) to 4.3 cm day⁻¹ (type C at 60°S where $f_w = 1.0$). Algal greening increases the wave-induced melt rate enhancement by between 0.2 and 0.8 cm day⁻¹. In all cases, melt rate enhancement triples when f_w increases from 0.33 to 1.0, and doubles when f_w increases from 0.5 to 1.0. Moreover and for any given wave-affected ice-surface type, there is, in general, a slight decrease in the wave-driven melt rate enhancement dh/dt with increasing latitude south (Tables A1A–A1C and Fig. 3), which is greatest in late austral spring (November) compared to summer. Sea-ice coverage south of 70°S is largely confined to the Weddell, Amundsen and Ross seas, whereas sea ice across East Antarctica mainly occurs equatorward of 67°S (Massom et al., 2013). The highest melt-rate enhancements are at 55°S (Tables A1A–A1C), but sea ice usually attains that latitude only in the eastern limb of the Weddell Gyre at ~5–25°E and parts of East Antarctica around ~80°E, and only in winter through October (cf., Massom et al., 2013; Comiso et al., 2017a).

Wave-affected surface type	Latitude 60° S			Latitude 65° S			Latitude 70° S		
	$f_w = 0.33$	$f_w = 0.5$	$f_w = 1.0$	$f_w = 0.33$	$f_w = 0.5$	$f_w = 1.0$	$f_w = 0.33$	$f_w = 0.5$	$f_w = 1.0$
A ($\Delta\alpha = 0.38$)	1.0	1.5	3.0	1.0	1.4	2.9	0.9	1.3	2.6
B ($\Delta\alpha = 0.48$)	1.3	1.9	3.8	1.2	1.8	3.6	1.1	1.6	3.3
C ($\Delta\alpha = 0.54$)	1.4	2.1	4.3	1.4	2.1	4.1	1.2	1.8	3.7
D ($\Delta\alpha = 0.64$)	1.7	2.5	5.1	1.6	2.4	4.9	1.4	2.2	4.4

Table 2. Annual3. Estimated annual maximum wave-induced driven sea-ice vertical melt rate enhancement dh/dt (in cm day⁻¹) on 15 December, for the four wave-affected ice-surface type categories classes A–D (see Table 1b), as a function of latitude (60°S, 65°S and 70°S) and ice parcel affected ($f_w = 0.33, 0.5$ and 1.0), and three latitudes. Type A is wave-overwashed FYI, wave-compression flooded ice, and/or wave-pulverised slush; B is green wave-pulverised slush—green; C is wave pond, and/or wave-deformation pond; and D is green wave pond, and/or green bare ice—green. Sea-ice density = 905 kg m⁻³.

The wave-induced melt rate enhancement values shown in Table 23 are for sea ice with fixed density 905 kg m⁻³ (see Eq. 76), which is taken here to be an approximation for a cold FYI floe under cold conditions. Although the densities of the four wave-affected ice-surface types are unknown, but they may be lower than 905 kg m⁻³—particularly for wave-slush, but also for the other wave-affected surface types shown in Fig. 1—and progressively become even lower as wave-induced surface and internal ice, and are likely to decrease through late-spring and summer as melting progresses and ice permeability and porosity increase through late-spring and summer. This would be the case if the pore spaces are filled with air, but the density

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would increase if the pores filled with water. Given these ~~factors and current unknowns/uncertainties~~, we now investigate the effect of lowering ice density on ~~wave-induced melt rate enhancement~~ dh/dt , using a value of 750 kg m^{-3} measured in Lützow-Holm Bay in East Antarctica by Urabe and Inoue (1988). Results ~~are shown~~ in Table 3. ~~These indicate~~ ~~4~~ ~~show that decreasing~~ ~~the ice density increases the~~ melt-rate ~~enhancements in the range of~~ ~~1~~ ~~enhancement by an extra~~ ~~0 to~~ ~~1~~ ~~cm day⁻¹~~ compared to ice with density 905 kg m^{-3} , pushing dh/dt up to ~~1.0–6.1~~ cm day^{-1} (again depending on surface type, latitude, f_w , and greening), ~~i.e., an increase of between 0.1 and 1.0 cm day⁻¹ compared to ice with density 905 kg m⁻³.~~

Wave-affected surface type	Latitude 60° S			Latitude 65° S			Latitude 70° S		
	$f_w \equiv 0.33$	$f_w \equiv 0.5$	$f_w \equiv 1.0$	$f_w \equiv 0.33$	$f_w \equiv 0.5$	$f_w \equiv 1.0$	$f_w \equiv 0.33$	$f_w \equiv 0.5$	$f_w \equiv 1.0$
A –A ($\Delta\alpha = 0.38$)	1.2	1.8	3.6	1.1	1.7	3.5	1.0	1.6	3.1
B –A ($\Delta\alpha = 0.48$)	1.5	2.3	4.6	1.5	2.2	4.4	1.3	2.0	4.0
C –A ($\Delta\alpha = 0.54$)	1.7	2.6	5.2	1.6	2.5	4.9	1.5	2.2	4.5
D –A ($\Delta\alpha = 0.64$)	2.0	3.1	6.1	1.9	2.9	5.9	1.7	2.6	5.3

Table 3. Annual maximum wave-induced sea-ice melt rate enhancement (in cm day^{-1}), on 15 December, for the four wave-affected ice-surface-type categories (see Table 1b), as a function of latitude (60°S, 65°S and 70°S) and f_w (0.33, 0.5 and 1.0). Type A is wave-overwashed FYI, wave-compression flooded ice, and/or wave-pulverised slush; B is wave-pulverised slush—green; C is wave pond, and/or wave-deformation pond; and D is wave pond, or bare ice—green. Sea-ice density = 750 kg m^{-3} .

4 Discussion

4.1 Melt enhancement by wave ~~Table 4. Same as Table 3, but for sea-ice density = 750 kg m^{-3} .~~

3.4 Potential positive feedback mechanisms that amplify wave melting

We propose that ~~wave-flooding and wave-pulverisation~~

Our results indicate that wave flooding and pulverisation exert a strong influence on the vertical melt rate of affected areas of the Antarctic SIZ in summer, and highlight the need for detailed large-scale measurements, *in situ* observations, mapping and numerical modelling. We highlight that wave-flooded and wave-pulverised regions of the outer MIZ will have little or no snow cover during the summer melt season. This also applies to sea ice immediately adjacent to polynyas and large leads within the interior SIZ (due to the occurrence of wind waves there), but contrasts with other areas of the interior SIZ, where snow cover may persist during summer (Massom et al., 2001). Depending on the wave process type, it is estimated that wave

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flooding and wave pulverisation reduce the albedo of typical FYI >0.7 m thick by 0.38–0.54, or by 0.28–0.44 for <0.7 m thick ice, where the reductions are compared to snow-covered ice (Table 1). These values increase by an estimated 0.1 to 0.48–0.64 and 0.38–0.54, respectively, due to rapid greening of the ice (again driven by wave flooding and wave pulverisation).

610 These large albedo reductions substantially increase the absorption of solar radiation by the wave-affected floes and wave slush as insolation increases following the September equinox, and within the annual window of most Antarctic sea ice melting, i.e., November–December–January. At its mid-December maximum and depending on (i) wave-affected surface type, (ii) fraction of the floe/surface affected, (iii) latitude (over the range 60–70°S) and (iv) ice density (here 750 or 905 kg m⁻³), the estimated increase in vertical melting due to wave flooding and/or wave pulverisation and compared to snow-covered
615 FYI ranges from 0.9 cm day⁻¹ to 5.2 cm day⁻¹ (Tables 1 and 2). This range of wave-induced melt-rate enhancement increases to 1.1 cm day⁻¹ to 6.1 cm day⁻¹ for wave-affected surface types darkened by algae. Note that these estimates of melt-rate enhancement are instantaneous, and do not consider non-linear feedbacks over time that result from the increased melt driven by wave processes (see Sect. 4.3). Estimating additional melt-rate enhancements due to activate a suite of three physical dynamic-thermodynamic positive feedback mechanisms amplified by two biological-physical sub-feedbacks, depicted
620 schematically in Figures 4 and 5. We argue that these feedbacks should be added to the inventory of feedbacks listed by Goose et al. (2018). Determining the strengths of these feedbacks is a challenge outside the scope of this paper, but is worthy of; our purpose here is to introduce them so as to stimulate their investigation. Another factor that may further enhance ice interior melting is the absorption of incoming solar radiation by ice algae proliferating in the wave-affected ice habitat, due to their pigmentation (cf., Zeebe et al., 1991).

625 Our computation indicates that, all else being equal, albedo reduction by wave flooding or wave pulverisation (and wave greening) could cause a 1 m thick floe or mass of wave slush to absorb enough additional solar energy to melt away in just one month—although again this rate may accelerate over time due to melt-related non-linear feedbacks outlined below (Sect. 4.3). This wave-induced surface melting is with targeted observations and modelling, in addition to, and supplements, ice-floe lateral and basal melting (not and in combination with the more-generally-considered here). While there is large
630 uncertainty in these first approximation estimates due to lack of observations, they indicate a strong need to investigate wave-melting processes towards their inclusion in sea-ice, climate and Earth-system models ocean-ice albedo feedback.

3.4.1 Wave-driven ice-albedo feedback

635 Firstly, we hypothesise that wave-driven reductions in albedo will activate a positive sea ice-albedo feedback (Fig. 4) similar to that associated with melt ponds on Arctic sea ice in summer (cf., Curry et al., 1995; Perovich et al., 2009), albeit on different spatial and temporal scales and involving saline wave ponds, wave-washed bare ice and/or wave slush rather than freshwater accumulations formed in floe-surface depressions from melted snow cover. By this “wave-driven ice-albedo feedback”, the instantaneous decrease in the albedo of a snow-covered floe caused by the initial wave flooding and/or pulverisation

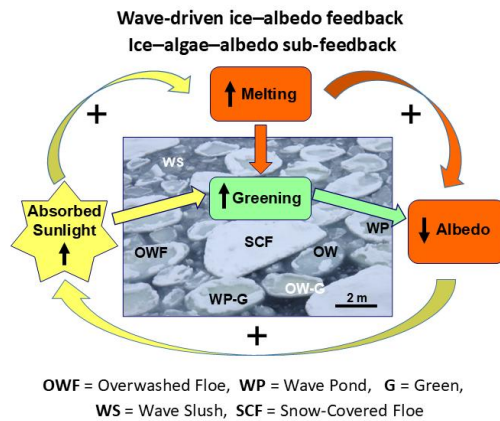
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substantially increases the absorption of solar radiation, leading to additional surface and interior melting, which further reduces the ice albedo to then cause additional enhancement of the vertical melt rate, and so on.



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Figure 4: Schematic representation of wave-driven sea ice–albedo feedback, strengthened by wave greening and an embedded ice–algae–albedo sub-feedback. Black up arrows denote an increase, and black down arrows a decrease.

3.4.2 Wave greening sub-feedbacks

645

We further hypothesise that the wave-driven ice–albedo feedback is strengthened in places by two sub-feedbacks associated with wave greening. Firstly, we propose that algal darkening of the ice and/or wave ponds activates what we term an “ice–algae–albedo sub-feedback” (Fig. 4), whereby the extra decrease in albedo caused by the onset of wave greening (see Sect. 3.2 and Table 2) further increases the absorption of solar radiation and therefore the vertical melt rate. This melting results in greater light availability for photosynthesis, causing ice algae to proliferate, which further darkens the ice – again an amplifying cycle. We further hypothesise that the two albedo-based feedbacks described above increase the porosity and permeability of affected ice floes as summer progresses, and that this could stimulate additional ice–algal growth and darkening by increasing nutrient replenishment and transport of algae upwards through the more permeable ice column to higher light conditions, to further increase the melt rate and generate additional algal proliferation – and so on. This would entail a positive “algae–ice permeability sub-feedback” that further amplifies the ice–algae–albedo sub-feedback. In addition, micro-scale melting around dark algal cells due to their conversion to heat of the enhanced shortwave radiation transmitted (cf., Zeebe et al., 1996) could

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655 further increase the ice permeability over time and enhance both the algae–ice permeability sub-feedback and the ice–algae–albedo sub-feedback.

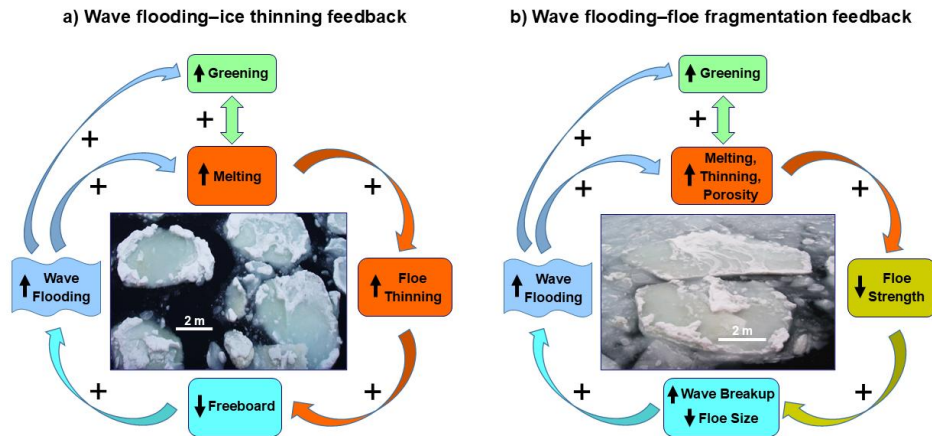
3.4.3 Wave flooding–ice thinning feedback

660 We further propose that wave-driven thinning lowers the freeboard (surface height above sea level) of small floes, which increases their susceptibility to additional wave overwashing and wave ponding. This then increases the wave melting (see Sect. 3.3 and 4.1), leading to further thinning and lowering of the floe freeboard, in an amplifying cycle that we term a “wave flooding–ice thinning feedback” (Fig. 5a). The arrow signifying a positive relationship between increased wave flooding and melting shown in Figure 5a includes, and is enhanced by, the wave-driven ice-albedo feedback (Fig. 4) – with the inclusion of the greening box indicating the further enhancement driven in places by the algae-related sub-feedbacks.

3.4.4 Wave flooding–ice thinning feedback

665 We propose that the combined thinning and increase in the porosity of wave-flooded floes would reduce their mechanical strength, i.e., their resistance to compressive and flexural failure (cf., Eicken et al., 1991; Timco and Weeks, 2010), making them more susceptible to further fragmentation by wave flexure into smaller floes which are themselves more susceptible to wave flooding. This results in a “wave flooding–floe fragmentation feedback” (Fig. 5b). This feedback is based on the positive relationship between the strength of a sea-ice “slab” and its thickness (Chai et al., 2021), and the negative relationship between sea-ice strength and porosity (Timco and Weeks, 2010; Wang et al., 2022; Mellor, 1986; Eicken et al., 1991). At the same time, it is influenced by, and contributes to, the wave flooding–ice thinning feedback, and is coupled to the other feedbacks described above.

670 The wave flooding–floe fragmentation feedback would also enhance the ocean–ice albedo feedback (cf., Nihashi and Cavalieri, 2006), by helping to create smaller floes that are more mobile than large floes and have a larger perimeter per unit area, promoting lateral and basal melting in summer. The increased mobility of these smaller floes may also increase their likelihood of drifting northwards under Ekman divergence driven by winds and/or ocean eddies (cf., Auger et al., 2023), i.e., into warmer and wavier waters.



680 **Figure 5: Schematic representations of a) wave flooding–ice thinning feedback, and b) wave flooding–floe fragmentation feedback, both strengthened by positive feedbacks with wave greening as shown. Black up arrows denote an increase, and black down arrows a decrease.**

685 4 Discussion

Although outside the scope of this initial study, it is likely that wave flooding and wave pulverisation processes further contribute to seasonal sea ice melting in two additional ways, and that a third process affects the exact location of the melting in the floe, i.e., whether it occurs in the ice interior or instead on the floe base and sides. First, wave overwashing and flooding likely make a direct contribution to ice surface melting where the sea surface temperature (SST) rises above -0°C in summer (sea ice has a lower salinity than seawater, which freezes at about -1.8°C). This would be the case for small floes swept northwards from the pack ice zone into warmer waters by wind driven Ekman divergence and/or ocean eddies, including within bands.

690 Second, removal of the insulating snow buffer by waves directly exposes bare floe surfaces and/or wave slush to air temperatures above 0°C as summer progresses. More ephemeral and localised/regional surface melting also occurs in other seasons in the MIZ due to episodic incursions of warm (above freezing) air temperatures associated with the passage of storms; e.g., even in winter at the relatively low latitudes attained by the MIZ (Massom et al., 1997), with wave flooding and snow removal again facilitating such melting.

A third factor is the transmission of solar radiation through the ice. This transmission is small for snow-covered floes, but is significant for wave-overwashed bare ice, wave-ponded ice and wave slush. **4.1 Wave-driven enhancement of sea-ice melting**
Our initial results – based on limited point observations and simple one-dimensional modelling of a single floe or parcel of wave slush – indicate that the flooding and pulverisation of sea-ice floes by waves can influence the solar energy budget of parts of the sea-ice zone. Removal or wetting of snow, seawater ponding and creation of wave slush are estimated to reduce the albedo of an original floe of snow-covered first-year ice by as much as 0.54. This causes a large increase in the absorption of solar radiation by the ice in spring through summer, enhancing the vertical melt-rate by an extra 0.9–4.3 cm day⁻¹ compared to a snow-covered first-year floe and depending on the fraction of ice area flooded/pulverised, latitude and time of year. We hypothesise that this wave-driven enhancement of surface and interior melting, supplements the conventionally-considered lateral and basal melting.

Concurrently, wave-flooding and -pulverisation processes, and resultant snow removal, should produce suitable high-light and high-nutrient habitats for low light-adapted ice algae within the ice column, wave slush and wave ponds. We speculate that this enhanced primary production would further decrease the albedo by 0.1, to push $\Delta\alpha$ to 0.64. This would increase the vertical melt-rate enhancement to 1.1–5.1 cm day⁻¹, meaning that wave melting amplified by wave greening could completely melt a 1 m-thick slab of wave-flooded ice in just 20 days (assuming no other contributing factors). The melt-rate enhancement increases to up to 6.1 cm day⁻¹ if the floe density is assumed to be lower at 750 kg m⁻³, as found in some measurements. In addition, the melt-rate enhancement of unconsolidated wave slush could be even greater, given the much smaller particles of ice involved and their constant churning and continual contact with warming seawater by passing waves.

While this preliminary study is limited to instantaneous modelling of daily wave-melting only, we propose that our initial estimates of the melt-rate enhancements are probably underestimates, because of five coupled positive feedbacks and sub-feedbacks that link physical to biological processes. In addition, the intensified transmittance of solar radiation through wave-flooded and wave-ponded ice “skylights” could heat the ocean mixed layer (cf., Nicolaus et al., 2010), enhancing the basal and lateral melting of floes – as is the case for melt ponds in the Arctic (Inoue et al., 2008). Although no Antarctic measurements are available, Arctic observations show that freshwater melt ponds there increase the amount of shortwave radiation transmitted through the ice in summer by up to about a factor of four (Nicolaus et al., 2012; Light et al., 2015). Arctic melt-pond transmittance attains values of 0.5 compared to ~0.2 for bare ice and ~0.0–0.1 for snow-covered ice (Perovich, 2005), leading to melt rates under ponds that are 2–3 times higher than they are for bare ice (Fetterer and Untersteiner, 1998). While Arctic-like melt ponds are extremely rare on Antarctic sea ice, wave ponds form a pseudo-year-round equivalent in that they act as mini “skylights” that preferentially transmit solar radiation and heat to the floe interior and underlying mixed layer. Increased transmittance of solar radiation through wave flooding might be a key driver for the onset of phytoplankton growth in the ice-covered Southern Ocean (cf., Hague and Viehi, 2021).

Another factor highlighted by this study is that the mechanical break-down of floes in the MIZ occurs not only by wave-driven flexural fracture (Williams et al., 2013) but also by the wave-induced pulverisation of floes and their snow cover into icy slush

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730 ~~and small brash-ice fragments (There are two other ways in which wave-flooding and wave-pulverisation processes may contribute to surface melting in summer. First, wave overwashing would directly cause surface melting of small floes swept northwards from the pack-ice zone into warmer waters. Second, removal of the insulating snow buffer by waves directly exposes bare floe surfaces and/or wave slush to direct melting by air temperatures above 0°C as summer progresses.~~

735 ~~Massom et al., 2006). As a result, low albedo wave slush can form a significant proportion of the sea ice cover in the outer MIZ, as shown in Fig. 11j. This scenario challenges the commonly held view that the MIZ is simply a collection of wave-fractured small floes that decrease in size with increasing proximity to the ice edge (open ocean) and are either closely packed or separated by open water (depending on wind direction) — with implications for modelling the seasonal meltback of the ice cover. Moreover, it is likely that unconsolidated fields of wave slush particles and brash-ice fragments are susceptible to particularly rapid seasonal melting due to their small size and their direct contact with wave-induced pulsations of warm seawater in summer — with this melt enhancement being increased by algal greening (Massom et al., 2006).~~

740 ~~4.2 Spatio~~Large-scale spatio-temporal influence of wave flooding, greening and melting

745 ~~Due to the current lack of observations, we have not attempted to quantify the overall areal occurrence and influence of wave melting. Despite this caveat, there are a number of key factors to consider, that point to wave melting likely making a substantial~~significant ~~contribution to driving the melt phase of Antarctica's rapid climatological annual sea-ice seasonal retreat phase~~cycle ~~when combined and integrated over the entire SIZ. Not least is the vast circumpolar extent of the MIZ (Brouwer et al., 2022; Day et al., 2024) and its constant interaction with both large ocean swells (cf., Young et al., 2020) and wind waves locally generated by intense cyclones (Vichi et al., 2019; Alberello et al., 2022).~~

750 ~~Wave melting is not confined to the MIZ. It also occurs more deeply within the SIZ, due to the presence there of large leads and both coastal and offshore polynyas (cf., Barber and Massom, 2007) that are affected by wind waves. It is again likely that the influence of wind-wave driven melting in the interior pack increases as open water areas within the SIZ expand and remain ice-free as the melt season progresses (cf., Massom et al., 2003). We apply the term "rotting from within" to the large-scale seasonal melting of the interior and coastal SIZ (after Massom et al., 2003). In addition, deep-swell penetration events can drive wave flooding in the interior Antarctic pack. In an example from the Weddell Sea in winter 1986, a series of waves of 18 s period and 1 m amplitude were observed to break up the ice (concentration 90% and average thickness 0.8 m) and cause active rafting and ridging at 560 km in from the ice edge (Liu and Mollo-Christensen, 1988). Also, wave-compression flooding has been observed in the compact inner pack ice zone up to 360 km south of the East Antarctic sea-ice edge, e.g., Fig. 1g,h (also, cf., Massom et al., 1999).~~

760 ~~For compact ice-edge zones, e.g., due to compacted by on-ice winds (e.g., Massom et al., 2008) with a high concentration of FYI floes,~~ attenuation of incoming wave energy by the high-concentration ice cover (e.g., Squire 2020) is likely to limit wave overwashing and wave pulverisation to a relatively short distance in from the ice edge (Pitt et al., 2022). However, the Antarctic ice-edge zone is typically more diffuse (e.g., see Fig. 1 of Massom and Stammerjohn, 2010) due to the frequent

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765 passage of storms (cf., Simmonds et al., 2003) and the occurrence of ocean eddies ~~there~~ (cf., Auger et al., 2023; see also Fig. 9 of Massom et al., 1999) ~~— including in late spring through summer. For the ice-edge zone.~~ In particular, the areal influence of wave ~~flooding, wave pulverisation, wave greening and resultant wave-melting~~ — and the feedbacks and sub-feedbacks proposed in Section 3.4 — is likely to be substantially extended in late spring through summer by the widespread occurrence of ~~extensive fields of elongated bands of floes that peel driven by off-ice winds~~ away from the main SIZ and ~~are separated by areas of open water into more open-ocean conditions, where they wave-fracture into smaller floes~~ (Comiso et al., 1992; Wadhams, 2000; Ishida and Ohshima, 2009). ~~Reported widths of Antarctic ice-edge band zones range) that are more susceptible to wave overwashing (snow removal) and wave ponding. Such bands, which are separated by open water, can be a few tens of metres to kilometres wide and can extend over zones ranging~~ from about 100 km (Saiki and Mitsudera, 2016) to 770 >300 km (Massom and Stammerjohn, 2010). The ~~percentage coverage fraction of ice surface covered by~~ wave overwashing and ponding ~~is (i.e., f_w) can be~~ particularly high in ~~such ice-edge~~ bands, e.g., ~50–60% in the narrow band in Fig. 1d.

In addition, we hypothesise that seasonal wave-melting is not confined to the MIZ, but that it also occurs within the interior Antarctic SIZ due to 1) the presence there of extensive open-water areas in the form of large leads (cf., Dubey et al., 2025) and both coastal and offshore polynyas (cf., Barber and Massom, 2007) and 2) the occurrence of deep swell penetration events. 775 Under the first scenario proposed, locally-generated wind waves drive localised ice flooding, pulverisation and greening around the lead and polynya margins (see Sect. 3.1.1), with the resultant wave melting increasing as the melt season progresses and the open-water areas expand rather than freeze over, to potentially contribute to the seasonal meltback of the sea-ice zone from within (cf., Massom et al., 2003). Secondly and under certain circumstances, it is possible that the propagation of swells deep into the pack drives wave flooding there. In the Weddell Sea in winter 1986, a series of waves of 18-s period and 1-m 780 amplitude were observed to break up the ice (concentration 90% and average thickness 0.8 m) and cause active rafting and ridging at 560 km in from the ice edge (Liu and Mollo-Christensen, 1988). Also, wave-compression flooding (Sect. 3.1.3) has been observed in the compact inner East Antarctic SIZ up to 360 km south of the satellite-derived sea-ice edge, e.g., Fig. 1g,h (also, cf., Massom et al., 1999). More observations are required to validate the occurrence of wave melting in leads and polynyas within the interior SIZ and to determine its contribution to the observed seasonal meltback of the Antarctic SIZ, as observed from space within certain regions (cf., Massom et al., 2003). 785 Two other factors

Another factor that likely enhance/enhances the areal occurrence and influence of wave flooding and wave-melting around Antarctica. Firstly, is the nature of the sea-ice cover itself. Antarctic first-year and younger floes are relatively thin and typically have a near-zero or negative freeboard (Worby et al., 1998; see also Fig. 1b). Secondly, the wave flooding processes themselves can directly contribute to lowering the freeboard (and increasing wave overwashing) by changing the floe isostasy via (i) the creation of raised rims by wave buffeting (Fig. 1e,d; Fig. 2d), (ii) wave driven deformation processes (see Sect. 3.1.3 and Fig. 1e,f), and (iii) the additional weight of pooled seawater (Fig. 1e,f) due in large part to the weight of the overlying snow cover (Massom et al., 2001). As such, they are naturally vulnerable to wave overwashing and wave ponding (see Fig. 1a–f), although large waves will also overwash floes with higher freeboard. 790

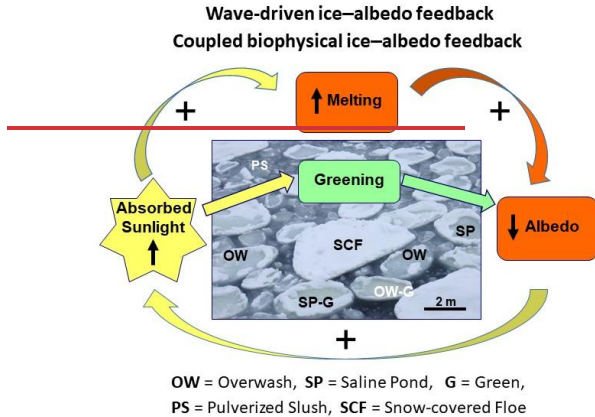
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4.3 Positive feedback mechanisms

795 We propose that wave flooding and pulverisation processes activate three coupled dynamic–thermodynamic positive feedback mechanisms that likely accelerate the rate of ice melt, and also an embedded fourth coupled physical–biological feedback involving the impact of ice algal pigments (chlorophyll and also accessory photosynthetic and non-photosynthetic algal pigments) on the ice albedo. These feedback mechanisms, which are depicted schematically in Fig. 4–6, have been largely unconsidered to date (cf., Goosse et al., 2018), but merit further investigation towards their inclusion in sea-ice and climate models. All four mechanisms are closely linked and operate in concert, as discussed below.

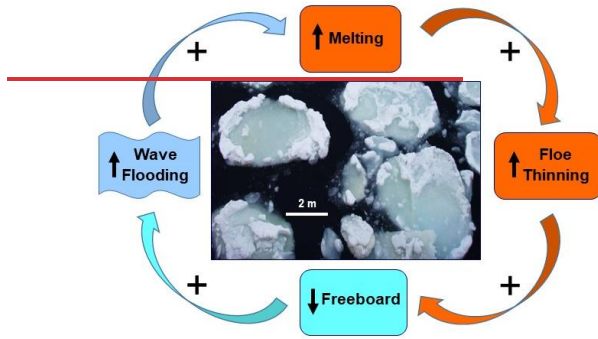
800 Firstly, the wave-induced reduction in ice surface albedo activates a positive sea-ice albedo feedback (Fig. 4) similar/equivalent to that associated with freshwater melt ponds on Arctic sea ice in summer (cf., Curry et al., 1995; Perovich et al., 2009), but in this case involving saline wave ponds, wave-washed bare ice and/or wave-pulverised slush and brash ice fragments. By this mechanism, the wave-driven decrease in ice surface albedo increases the absorption of solar radiation and melting, which further reduces the ice albedo, leading to enhanced melting—an amplifying cycle. We also propose that this *wave-driven ice albedo feedback* is strengthened in places by the additional decrease in albedo associated with the rapid proliferation of ice algae in the high-light and high-nutrient environment of (i) wave-modified floe surfaces (including saline wave ponds) and/or interiors and (ii) wave slush. This greening (increased ice algal pigment content) further enhances the melting of wave-flooded floes and wave slush and represents a *coupled biophysical ice albedo feedback* or *ice-algae albedo*
805 *feedback* (Fig. 4). At the same time, heating of the ocean mixed layer by shortwave radiation transmitted through wave-flooded and wave-ponded ice skylights likely amplifies the open-water–sea-ice feedback associated with solar heating in leads (cf., Nihashi and Ohshima, 2001), as is the case for melt ponds in the Arctic (Inoue et al., 2008).



815 **Figure 4: Schematic representation of wave-driven sea ice albedo feedback, intensified by floe greening, i.e., an embedded-coupled biophysical ice-albedo feedback. Up arrows denote an increase, and down arrows a decrease.**

820 We also propose that the thinning of small floes by wave melting decreases their freeboard, to increase their susceptibility to further flooding by overwashing and deformation ponding (due to increased rafting with the thinner ice) thereby increasing the melt rate enhancement due to wave flooding (see Sect. 3.3 and 4.1), and so on (Fig. 5). This entails a *wave flooding–ice melting feedback*. Concurrently, wave melting also likely increases the ice porosity and permeability. The thinning and increase in ice porosity would together reduce the mechanical strength of floes, i.e., their resistance to compressive and flexural failure (cf., Eicken et al., 1991; Timco and Weeks, 2010), making them more susceptible/vulnerable to further fragmentation by wave flexure into smaller floes—to increase wave flooding and wave melting, leading to further thinning and overwashing, and so on. This represents a *wave flooding–floe fragmentation/breakup feedback* (Fig. 6). This feedback is based on the positive relationship between the strength of a sea ice “slab” and its thickness (Chai et al., 2021) and the negative relationship between strength and porosity (Timco and Weeks, 2010; Wang et al., 2022; Mellor, 1986; Eicken et al., 1991). Moreover, smaller floes are more mobile and more likely to peel away in bands and/or drift northwards and away from the main pack under Ekman divergence driven by the prevailing westerly winds and/or ocean eddies (cf., Auger et al., 2023), i.e., into warmer waters where they rapidly melt.

Wave flooding–ice melting feedback



830 Figure 5: Schematic representation of wave flooding–ice melting feedback. Up arrows denote an increase, and down arrows a decrease.

Wave flooding–floe fragmentation feedback

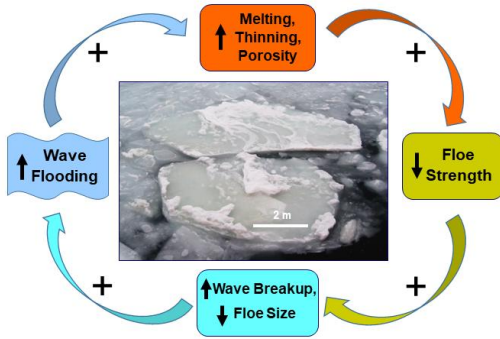


Figure 6: Schematic representation of wave flooding–floe fragmentation feedback. Up arrows denote an increase, and down arrows a decrease.

835 The wave-driven *ice-algae-albedo* feedback is likely intensified by an increase in ice porosity and permeability due to increased absorption and transmittance of solar radiation, and its conversion to heat, by algae embedded in the ice structure (cf., Zeebe

et al., 1996). This would then stimulate additional ice-algal growth by facilitating nutrient replenishment and algal transport through the more permeable ice column — to further enhance the coupled biophysical ice-albedo feedback. At the same time, the algae permeability sub-feedback and wave-induced greening likely intensify the wave flooding-floe fragmentation feedback, by further decreasing the mechanical strength of the small floes (cf., Eicken et al., 1991). These feedbacks also enhance the ocean-ice albedo feedback (i.e., floe lateral and basal melting, cf., Nihashi and Cavalieri, 2006) by creating smaller floes that are more mobile than large floes and have a larger perimeter per unit area. Any decrease in sea-ice density due to wave flooding, wave pulverisation and wave greening would increase the sea-ice melt rate (dh/dt) due to radiative forcing (see Eq. 7).

845 5 Conclusions and outlook

~~We In this preliminary study, we have built on expanded upon the classical picture of seasonal that late spring-summer melting of Antarctic sea ice each October to February due to occurs by lateral and basal melting which are accelerated by a positive ocean-ice albedo feedback (e.g., Horvat, 2022) accentuated by the wave-driven breakup of floes in the MIZ. We have provided — by providing evidence that waves also drive a suite of previously rapid ice surface (and interior) melting that has been neglected coupled dynamic thermodynamic processes (termed to date. We propose that wave flooding and wave pulverisation) that remove the thermal and optical buffer provided by snow cover and/or mechanically grind down floes into wave slush and also create optimal habitat for proliferation of ice algae (wave greening) — not only in the MIZ but also in the interior SIZ where wind waves prevail. These.~~

855 5.1 Albedo reduction

855 With simple one-dimensional modelling based on proxy estimates, particularly measurements of slush albedo, we show that the wave-driven processes reduce the reduction in sea-ice albedo is as much as 0.54, and enhancing the vertical melt-rate by up to an estimated 0.54 extra 4.3 cm day⁻¹ (compared to a snow-covered ice, thereby increasing the absorption of solar radiation by first-year floe). We also propose that wave greening decreases the ice and generating (previously neglected) rapid surface and interior melting of both floes and wave slush (previously neglected) in summer. This albedo by an additional melting is amplified by an estimated additional decrease of 0.1 in ice albedo due to a combined reduction of 0.64, to a proliferation of ice algae (greening) in amplify the high light and high nutrient sea-ice habitats created by wave-driven melt enhancement to as much as 5.1 cm day⁻¹, and as much as 6.1 cm day⁻¹ if the floe density is taken to be 750 kg m⁻³ (rather than 905 kg m⁻³). Not only this, but we also propose that wave flooding and wave pulverisation and greening activate five coupled positive feedbacks and sub-feedbacks that further accelerate the melt-rate enhancement as summer progresses.

865 Further, we propose that wave flooding and wave pulverisation activate four previously unconsidered coupled dynamic thermodynamic positive feedbacks that link sea-ice physics to biology — and that these feedbacks likely result in additional acceleration of seasonal sea-ice melting to contribute to the rapid climatological melt phase of Antarctica's annual sea-ice cycle. In the warm season, the increase in through-ice transmittance of solar radiation due to the wave flooding, wave

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pulverisation and wave greening also likely contributes to heating the ocean mixed layer (cf., Nicolaus et al., 2010). This would further enhance basal and lateral melting (due to absorption of sunlight in leads and polynyas), to strengthen the more generally considered open-ocean ice albedo feedback (cf., Goosse et al., 2018). The complex wave melting feedbacks and non-linear relationships identified in this study require and warrant further analysis towards their inclusion in models, as they have implications for 1) accelerating sea-ice loss while also enhancing climate warming, 2) attributing observed recent high variability, and 3) predicting future climate, sea-ice conditions and impacts. Also worthy of investigation is the effect of wave melting on freshwater input into the ocean, with implications for upper-ocean stratification that may enhance ice formation—and potential feedbacks involved.

Ice-edge bands have been considered to influence the seasonal evolution of the MIZ, e.g., in the Arctic (Martin et al., 1983), by increasing the open-water area within the pack and promoting rapid lateral and basal melting of floes within the outer MIZ (Saiki and Mitsudera, 2016). To this, we add the influence of wave melting processes on floes within the bands themselves, and hypothesize that bands (and ice-edge ocean eddies) play an important role in extending the spatial domain of wave melting influence—including smaller bands such as that in Fig. 1d. More work is required to investigate and quantify this factor, and to determine how banding distribution, composition (floe size) and processes interact with waves, and how bands respond to changing wind and wave conditions under a warming climate—and how this will influence wave flooding and melting.

By generating elevated concentrations of ice algae compared to snow-covered floes, wave flooding and wave pulverisation contribute to another positive feedback involving sea-ice biological and biogeochemical cycles. In spring–summer, ice algae (and phytoplankton blooms in the ocean as the ice melts back in summer) produce dimethylsulfoniopropionate, a precursor of the gas dimethyl sulfide, which gets oxidised in the atmosphere to form sulfate particles which in turn serve as cloud-condensation nuclei. Clouds formed in this way then influence the surface radiation and energy balances (Tison et al., 2017) and precipitation—to affect sea-ice conditions and algal production, and so on (cf., Charlson et al., 1987; Wang et al., 2018).

The complex relationships between wave flooding, wave melting and wave pulverisation, coupled physical–biological–biogeochemical processes and cloud physics are outside the scope of this paper, but again require and warrant detailed investigation with targeted cross-disciplinary observations and modelling that we hope are stimulated by this paper.

Wave-flooded floes and wave slush form “mini-oases” and hotspots respectively for enhanced primary productivity. This results in extensive intra-ice algal blooms relatively early in the season compared to open-ocean phytoplankton blooms, and that are undetected in satellite ocean-colour datasets (Massom et al., 2006). Wave flooding and wave pulverisation also likely contribute to supporting active algal communities and elevated chlorophyll concentrations in low-light-level months before the September equinox, including those observed in the winter Antarctic MIZ (cf., Louw et al., 2022) when the ice reaches relatively low latitudes of $\sim 57^{\circ}\text{S}$ – 60°S in places. Given these factors, we hypothesise that wave flooding and wave pulverisation make previously neglected contributions to: 1) overall year-round primary production within the Antarctic SIZ (cf., Saenz and Arrigo, 2014; Dalman et al., 2025) including the MIZ (cf., Taylor et al., 2013); 2) phytoplankton blooms under sea-ice (cf., Hague and Vichy, 2021; Horvat et al., 2022); and 3) phytoplankton blooms in late spring through summer both seaward of the

ice edge as it retreats (Massom et al., 2006; cf., Arrigo et al., 2014; Ito et al., 2025) and within polynyas (cf., Arrigo and van Dijken, 2003). This has implications for the uptake by the Southern Ocean of anthropogenic carbon from the atmosphere, the biological carbon pump (Henley et al., 2020), and the ocean's moderation of **5.2 Wave ponding**

905 ~~climate warming (cf., Frölicher et al., 2015). At the same time, wave flooding and wave pulverisation likely increase the release of algae and biogenic material into the upper ocean and its availability for under-ice pelagic grazers in the MIZ year round and at the receding ice edge in late spring-summer, which then support higher trophic levels (Massom et al., 2006).~~

On the small scale, it is likely that wave flooding and melting processes substantially modify the microstructure and mechanical properties of sea ice floes, by progressively increasing the sea ice porosity and permeability, decreasing its density and changing its salinity, brine volume and temperature (cf., Golden et al., 1998). In terms of computations of melt rate enhancement (see Eq. 7), the densities of wave flooded, wave pulverised and wave greened ice—and their evolution as the melt season progresses—represent a major current unknown, and may be lower than the densities of 905 kg m^{-3} and even 750 kg m^{-3} used in Eq. (7). This factor, in concert with the additional vertical melt rate enhancements by the four newly proposed positive feedback mechanisms driven by wave flooding and wave pulverization, means that the melt rate enhancement estimates provided here may in fact be underestimates. An additional unknown, outside the scope of this analysis, is the magnitude of the contribution of wave flooding to ice floe lateral and basal melting, and the associated ocean ice albedo feedback (cf., Nihashi and Cavalieri, 2006).

915 ~~Wave flooding and wave pulverisation also have implications for the retrieval of sea ice concentration (and extent) from satellite passive microwave brightness temperature data (Massom et al., 1999; and cf., Comiso et al., 1992 and Ivanova et al., 2015). For example, the ice covers shown in Fig. 1a, Fig. 1g and Fig. 1i have a 100% concentration, but this value is likely to be substantially underestimated in satellite passive microwave products as the microwave emissivity of flooded ice and/or wave slush is intermediate between that of snow-covered dry ice and open water (cf., Comiso and Steffen, 2001). In addition, wave flooding and wave pulverisation have implications for the accurate estimation of both sea ice and snow cover thickness from satellite radar and laser altimeter measurements (cf., Kacimi and Kwok, 2020), and are factors that need accounting for (certainly in Antarctica's extensive circumpolar MIZ).~~

925 ~~In the Arctic, there has been strong recognition of the need for explicit treatment of melt ponds in climate and Earth system models (e.g., Taylor and Feltham, 2004; Flocco et al., 2010; Tsamados et al., 2015; Webster et al., 2022), in order to simulate both Earth's radiation balance (Maslanik et al., 2007; Perovich et al., 2008; Nicolaus et al., 2010) and the strength of the ice-albedo feedback (Curry et al., 1995, 2001; Tschudi et al., 2008). This Results presented here suggest that the same recognition and parameterisation in models is required for wave-washed/overwashed floes, saline wave ponds and wave-pulverised slush and wave greening and associated feedbacks in the Antarctic (and the Arctic), all modulated by additional albedo changes due to associated ice-algal greening—albeit on a smaller scale given the lower proportional coverage compared to summer melt ponds in the Arctic. However, there are fundamental differences. Unlike Arctic melt ponding that only occurs in the melt~~

935 ~~season, wave-flooding and wave-pulverisation processes and associated snow removal~~(in the Antarctic and the Arctic) are
not limited to the warm season but rather occur year-round. ~~They exert year-round~~Although wave-melting processes may
influence ~~on the energy budget and mass balance~~a small proportion of the overall SIZ, ~~and at the start of the melt season, the~~
940 ~~proportion affected is likely to increase as the SIZ recedes through summer.~~ Wave melting also ~~have~~has implications for the
ocean freshwater budget and upper-ocean buoyancy and stratification, ~~which would feed back to influence sea-ice formation~~
~~and melt.~~

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940 5.3 The MIZ

Given the factors highlighted in this paper, it is likely that wave-melting processes contribute to: 1) the observed predominant
role of the MIZ in driving overall mean annual sea-ice retreat around Antarctica (cf., Kimura et al., 2022); and 2) the observed
close spatio-temporal correspondence between (trends in) significant wave height and circum-Antarctic sea-ice extent and
annual retreat identified by Kohout et al. (2014). Our initial findings further support the assertion that the Antarctic SIZ is
945 vulnerable to increased storminess (Kohout et al., 2014), but adding wave flooding and greening and associated feedbacks as
processes that need to be considered in addition to the generally-considered wave fragmentation of floes. Moreover, we
highlight that the mechanical breakdown of floes in the MIZ occurs not only by wave-driven flexural fracture (Williams et al.,
2013) but also by the wave-driven pulverisation of floes and their snow cover into wave slush (see Sect. 3.1.4). As a result,
950 low-albedo wave slush between small floes and brash ice may form a significant proportion of the sea-ice cover in the outer
MIZ, as shown locally in Fig. 1i,j, although this is again yet to be established and quantified on the large-scale.
Notwithstanding this caveat, the new paradigm challenges the commonly-held view that the MIZ in late spring-summer is
simply a collection of wave-fractured small (snow-covered) floes that decrease in size with increasing proximity to the ice
edge (open ocean) and are either closely packed or separated by open water (depending on wind direction). Another unknown
955 factor worthy of investigation is that unconsolidated fields of wave-slush particles (and small brash-ice fragments) are
susceptible to particularly rapid seasonal melting (compared to floes) due to their small size and their direct contact with wave-
driven pulsations of warm seawater (wave churning) in summer – with this melt enhancement of wave slush again being
increased by wave greening (cf., Massom et al., 2006), (2014). We support their assertion that Antarctic sea-ice is vulnerable
to increased storminess, and add wave flooding, greening, pulverisation and melting to wave fragmentation as key processes
affecting sea-ice seasonal melting. Moreover, while our focus has been on Antarctic sea-ice, wave flooding, wave
960 pulverisation and wave-melting processes and associated feedback mechanisms also apply to the Arctic (e.g., Massom, 1991)
– and to not only marginal seas but also the central Arctic Ocean where wave-ice interaction processes occur.

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Wave floodingIce-edge bands have been considered to influence the seasonal ablation of the MIZ, e.g., in the Arctic (Martin
et al., 1983), by increasing the open-water area within the pack and by enhancing wave-driven flexural breakup of the ice into
smaller floes, which promotes rapid lateral and basal melting of floes within the outer MIZ (Saiki and Mitsudera, 2016). To
965 this, we add the influence of wave melting processes on floes within the bands themselves, and hypothesise that bands (and
ice-edge ocean eddies) extend the spatial domain of wave-melting influence – including smaller bands such as that in Fig. 1d.

5.1 Biology

Another factor highlighted here is that wave greening contributes to: 1) overall primary production within the Antarctic SIZ (cf., Saenz and Arrigo, 2014; Dalman et al., 2025) including the MIZ (cf., Taylor et al., 2013); and 2) phytoplankton blooms seaward of the ice edge as it retreats (Massom et al., 2006; cf., Arrigo et al., 2014; Ito et al., 2025) and within polynyas (cf., Arrigo and van Dijken, 2003) in late-spring through summer. While we have proposed that snow-free wave-flooded floes and wave-pulverised slush fields form hotspot habitats for intra-ice algal proliferation and blooms in spring-summer, they also potentially support active communities of low-light-adapted algae and elevated chlorophyll concentrations before the September equinox, and even in winter in the Antarctic MIZ (cf., Louw et al., 2022) when the ice reaches relatively-low latitudes of ~57°S–60°S in places. Neither are detectable in satellite ocean-colour imagery and therefore remain unquantified (cf., Massom et al., 2006). Moreover, transmittance of shortwave radiation through skylights in wave-flooded floe and wave-slush likely facilitate under-ice blooms (cf., Hague and Vichy, 2021; Horvat et al., 2022), i.e., indirect wave greening. At the same time, wave melting and wave pulverisation likely increase the release of algae and other biogenic material into the upper ocean and its availability for under-ice pelagic grazers in the MIZ year round and at the receding ice edge in late spring-summer, to support high concentrations of higher trophic levels there (Massom et al., 2006).

5.5 Carbon and clouds

Wave greening would additionally contribute to key biogeochemical processes – with implications for marine ecosystems, properties of the Southern Ocean, and weather and climate – including 1) the uptake by the Southern Ocean of anthropogenic carbon from the atmosphere to help moderate climate warming (cf., Frölicher et al., 2015); 2) the marine biological carbon pump (Henley et al., 2020); and 3) ice-algal production of cloud-condensation nuclei (Mallet et al., 2025). Clouds formed in this way then influence the surface radiation and energy balances (Tison et al., 2017) and precipitation – to affect sea-ice conditions and algal production, and so on in a possible feedback (cf., Charlson et al., 1987; Wang et al., 2018).

5.5 Remote sensing

Another influence of wave flooding and wave pulverisation requiring investigation and quantification is on the accuracy of sea-ice concentration (and extent) retrievals from satellite passive-microwave brightness temperature data in wave-flooded and -pulverised areas (Massom et al., 1999; and cf., Comiso et al., 1992 and Ivanova et al., 2015). For example, the scenes shown in Figures 1a, 1g and 1i have ice covers with 100% concentration, but this value is likely to be substantially underestimated in standard satellite passive-microwave sea-ice concentration products from the MIZ (and year-round) as the microwave emissivity of flooded ice and/or wave slush is intermediate between that of cold first-year ice with a dry snow cover and open water (cf., Comiso and Steffen, 2001). This ice-concentration estimate has implications for the analysis of sea-ice extent and area. In addition, wave flooding and wave pulverisation, and their likely effects on ice density and snow-cover properties, need accounting for in the estimation of both sea-ice and snow-cover thickness from satellite radar and laser altimeter measurements in the MIZ and adjacent to large leads and polynyas (cf., Kacimi and Kwok, 2020).

5.7 The Arctic as well

1000 While our focus has been on Antarctic sea ice, these wave processes and feedbacks also apply to the Arctic (e.g., Massom,
1991) – and not only to marginal seas but also to the central Arctic Ocean where wave-ice interaction processes occur (cf.,
Squire et al., 2009). In the Northern Hemisphere, loss of sea-ice coverage (particularly in summer, e.g., Comiso et al., 2017b)
has exposed the Arctic Ocean to more swells (Thomson and Rogers, 2014), to increase the likelihood of more extensive wave
flooding and pulverisation there. Around Antarctica, wave melting and wave greening may already be intensifying, given
1005 observed increases in recent decades in: (i) cyclones at high southern latitudes related to a poleward shift in storm tracks (IPCC,
2014), and (ii) both wave height and near-surface wind speed over the Southern Ocean adjacent to the SIZ (Young and Ribal,
2019; Morim et al., 2019; 2019). In the Northern Hemisphere, loss of sea-ice coverage (particularly in summer, e.g., Comiso
et al., 2017b) has exposed the Arctic Ocean to more swells (Thomson and Rogers, 2014) to increase the likelihood of more
extensive wave flooding, pulverisation and melting there.

5.8 The future

Looking to the future and for Antarctica, wave flooding, wave-pulverisation, greening and wave-melting processes—in harness
with the associated feedbacks identified above—have the potential to will likely increase in their areal extent and influence in
coming decades, given predicted further increases in wind speed and wave height across the high-latitude Southern Ocean
(Casas-Prat et al., 2024). This intensification would contribute to changing Antarctic sea-ice formation and melt rates, and the
1015 thickness and properties of the ice and its snow cover (cf., Webster et al., 2018). In turn, these changes have major implications
for) and melt rates but potentially also ice formation rates – to impact the seasonality and extent and seasonal duration of
the both seasonal pack-ice zone (cf., Stammerjohn et al., 2012) and the coastal fast-ice zone (cf., Fraser et al., 2023); planetary
albedo and Earth's surface energy and heat budgets (cf., Riihelä et al., 2021), with a decrease). This would in albedo due to
wave-driven snow loss and sea-ice modification (and loss) amplifying the positive contribution to the climate feedback at high
1020 southern latitudes (cf., Williams et al., 2023); turn affect: oceanic and atmospheric interactions, properties and circulation, and
the ocean and global freshwater budget (cf., Haumann et al., 2016; Meredith and Brandon, 2017; Smith et al., 2017; England
et al., 2018); low-latitude and global weather and climate (cf., England et al., 2020; Ayres et al., 2022); the stability of the
Antarctic ice shelves, ice-sheet mass loss and sea-level rise (cf., Massom et al., 2018; Teder et al., in press); primary production
both within and under the ice, habitat quality, krill and food-web energetics, and marine ecosystem2025); marine ecosystem
1025 structure and function, health and biodiversity (cf., Massom and Stammerjohn, 2010; Ducklow et al., 2013; Meredith et al.,
2019); the critical capacity of the Southern Ocean to take up atmospheric carbon and to moderate anthropogenic climate change
(cf., Williams et al., 2023), while also influencing ocean acidification (cf., Nissen et al., 2024); and important other
biogeochemical processes that feed back into the climate system (cf., Vancoppenolle et al., 2013). These potential scenarios
underline the need to better understand wave melting and greening processes towards their inclusion in Earth system models.

6 Recommendations for needed measurements and follow-on work

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1035 ~~As stated in the Introduction, the~~The new ~~paradigms~~paradigm presented here ~~are~~is based on limited observations and simple modelling. ~~only, with sensitivity analysis of daily wave-driven vertical melt-rate enhancement (dh/dt) of a single floe and/or parcel of wave slush as a function of latitude, time in summer and proportion of the ice surface affected.~~ An important next step is to carry out targeted measurements, both large-scale and small-scale, ~~combined with high-resolution modelling~~ in order to quantify and more fully understand wave flooding, wave pulverisation, wave greening and wave melting – and ~~the associated feedbacks identified~~their overall regional and pan-Antarctic influence – as a function of space and time, and their relationship to wave and ice conditions, including floe size; ~~ice type and thickness~~; distance from the ice edge; ~~ice type and thickness~~; concentration (C) and banding. Obtaining estimates of these quantities and of f_w and C in Eq. 6, and their seasonal and spatial variations, is challenging, given the scale and dynamism of the environment involved. It will require coordinated use of autonomous technologies – such as ship-borne stereo camera systems (e.g., Alberello et al., 2022); ~~and arrays of~~ wave and ice mass-balance buoys, and drone remote sensing including hyperspectral sensors to detect and quantify ~~wave~~ greening – extended in space and time using satellite ~~high-resolution~~ remote sensing (e.g., ~~ultra-high-resolution~~) and combined with novel altimetric measurement of wave penetration distances into the SIZ ~~that may be able to detect deep swell-penetration~~ (e.g., Brouwer et al., 2022; Fraser et al., in prep.); ~~Ship~~review). Additional unknowns in need of measurement and modelling include: ~~1) the properties and wave-melting behaviour of wave slush; and 2) the extra contribution of wave flooding to enhancing ice-floe lateral and basal melting and its associated ocean-ice albedo feedback (cf., Nihashi and Cavalieri, 2006).~~

1040 ~~More work is required to investigate, model and quantify the role of ice-edge banding (and eddies) in wave flooding, pulverisation, greening and melting, and to determine how banding distribution, composition (floe size and wave slush proportion) and processes interact with waves, and how bands respond to changing wind and wave conditions. Also in need of quantification is direct influence of wave overwashing on surface melting where bands (and ocean eddies) isolate floes from the main pack and transport them equatorward into warmer waters.~~

1050 ~~Targeted ship-based- and in situ~~ spectral radiation measurements are needed for the albedo and transmittance of the different wave-affected surfaces, including the effect of algal greening on albedo. Also needed are coincident detailed *in situ* observations ~~and sampling~~ of the ~~following and their evolution in space and time:~~

- 1055 • ~~the thickness, morphology, density, salinity and brine volume, temperature~~ and micro-structural properties (e.g., porosity and permeability) of wave-flooded floes and wave-pulverised-ice slush, and ~~the depth and characteristics of wave ponds;~~
- their algal pigment content and ~~community~~ composition, primary production and nutrients; and
- 1060 • ~~their role in key biogeochemical processes within and under the SIZ (cf., Henley et al., 2020), and notably the ocean biological carbon pump and the uptake of atmospheric CO₂ by the ocean (cf., Hauck et al., 2015) and the production by ice algae of climate-active sulphur-compound gases by wave-affected ice. (cf., Trevena and Jones, 2006).~~

In parallel, ~~dedicated~~targeted modelling efforts are required to synthesise the observations and carry out ~~detailed~~sensitivity analyses. ~~There is compelling need, to work on including these important~~determine the contribution of wave-melting processes

1065 ~~and to the rapid overall melt phase of Antarctica's annual sea-ice cycle. For the modelling, a particular challenge will be to~~
~~parameterise the coupled feedbacks in coupled-described here, and to quantify their role in accelerating wave melting under a~~
~~range of sea-ice and wave conditions. The ultimate aim is to encourage inclusion of wave-melting processes and feedbacks in~~
~~coupled climate and Earth system models, as a crucial step towards 1) the more accurate simulation of the climatological~~
~~annual cycle of Antarctic sea ice and its current state, and; 2) attributing observed recent high variability in the Southern Ocean~~
~~sea-ice system; and 3) more robust predictions of the future fate of both polar sea-ice systems and the wider Earth system.~~

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1070 7 Appendix A. Additional Tables – See separate pdf file

8 Code availability

To be provided.

9 Data availability

1075 To be provided.

10 Author contribution

1080 RAM conceptualised the study and carried out the visual observations of the wave processes and phenomena. SGW, BL and DKP provided albedo data; and surrogate albedo values; SGW designed the surface radiation energy budget calculation; PAR developed the model code and ran the model, and provided the model output and Fig. 3; and RAM and, PAR and SGW analysed the output. LGB, MHM, AT and GP provided expert input on wave-ice interaction; PU, SPO, PAR, ~~PGS~~ and ~~PHPGS~~ on sea-ice modelling; KMM, PGS and PW on sea-ice algae; and ADF, PW, SC and MF on remote sensing. RAM prepared the manuscript with contributions from all co-authors.

11 Competing interests

~~The~~KMM is a member of the editorial board of The Cryosphere. ~~The other~~ authors declare that they have no conflict of interest.

1085 12 Acknowledgements

1090 RM is very grateful to the Australian, US and German Antarctic programs and the masters and crews of the icebreakers RVs *Aurora Australis*, *Nathaniel B Palmer* and *Polarstern*, and to Drs Ray Smith and Sharon Stammerjohn for enabling his participation in the US National Science Foundation Palmer LTER program. SGW thanks the Institute for Marine and Antarctic Studies (IMAS) for their hospitality during visits to Hobart to work on this paper. We gratefully acknowledge the US National Snow and Ice Data Center for the satellite sea-ice concentration data used in this study. We sincerely thank two anonymous reviewers for their detailed, insightful and highly-constructive reviews which have substantially strengthened the paper, and also thank the editor Dr Stephen Howell.

13 Financial support

This work was funded by, and contributes to, Australian Antarctic Science Projects 189, 741, 4073, 4116, 4123, 4298, 4625 and 4635. For RM and KM, this work was supported by the Australian Antarctic Division (AAD), the Australian Government's Australian Antarctic Program Partnership (AAPP), and the Australian Research Council Special Research Initiative the Australian Centre for Excellence in Antarctic Science (Project Number SR200100008). LGB is funded by the Australian Research Council (FT190100404, DP240100325). PU is funded by the EU Horizon 2020 PolarRES project (grant number 101003590) and by the Research Council of Finland (grant number 364876). For DKP, this work was supported by US NA24OARX431G0018 and US NSF-OPP-2138785. BL gratefully acknowledges financial support from ONR (N00014-23-1-2484) and NSF (ARCSS 2138787 and Arctic Natural Sciences 2143547). AT acknowledges support from the Australian Research Council (LE220100103, DP240100325). ADF is supported by the Australian Research Council (FT230100234, LP170101090, LE220100103 and DP240100325). PW's contribution is funded by AAPP, ACEAS and the Australian Research Council's Special Research Initiative for Antarctic Gateway Partnership (Project ID SR140300001). SC is funded by the AAD, AAPP and International Space Science Institute team grant #501.

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