



Research paper

Controlled weakening of model ice: Replicating the mechanical response of summer-warmed sea ice in laboratories and test basins[☆]

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ARTICLE INFO

Dataset link: <https://doi.org/10.5281/zenodo.0744917>

Keywords:

Arctic sea ice
Model sea ice
Model tests
Sea ice physics
Ice mechanics
Ice-structure interaction
Warming trends
Climate-informed engineering
Flexural strength
Elastic modulus

ABSTRACT

This study examines how the mechanical properties of model ice can be tuned to approximate the weakening of natural sea ice as it warms during summer. The work is motivated by satellite-derived observations and projections indicating that warm-ice conditions in the Arctic are increasing.

The observed warming trend, coupled with the seasonal timing of Arctic shipping activities, challenges the traditional focus on winter conditions in model tests and suggests that incorporating weaker ice is increasingly relevant to ship-ice interaction and ship design. Laboratory tests for ship-performance optimization are often a crucial intermediate step toward implementation in the final maritime application. To provide a broader range of test conditions, we explore methods to adjust two key parameters – the elastic modulus and flexural strength – in model ice under laboratory conditions. The overarching goal is to establish a testing regime capable of representing selected summertime sea-ice properties.

Experiments conducted at the Hamburg Ship Model Basin demonstrate that surface treatment of columnar model ice with saturated sodium chloride solution effectively reduces its flexural strength by 71 %. Furthermore, we investigate how variations in the amount of applied solution influence mechanical properties, highlighting differing sensitivities of elastic modulus and flexural strength to modifications of the ice surface layer.

1. Introduction

The retreat of sea ice due to climate change is widely recognized; however, alongside this evident decline, the physical properties of the remaining sea ice also undergo significant alterations. These changes – such as variations in thickness, temperature, salinity, porosity, and lifespan – are crucial factors that determine mechanical strength and must therefore be integrated into engineering considerations. Incorporating such climate-informed considerations ensures that infrastructure, maritime operations, and safety protocols remain robust and efficient amid evolving sea ice conditions, also from the perspective of performance and resource efficiency. In this study, we present an assessment of ongoing and future changes in sea ice temperature, a key parameter that controls mechanical properties. We investigate how modifying the thin granular surface layer of an otherwise columnar model ice enables us to adjust its mechanical properties and transition them into a new, stable state. This process exemplifies a review and adaptation process of a historically developed model ice recipe in test basins, intending to

expand its applicability to account for the changing physical properties of polar and subpolar sea ice environments.

1.1. The loss of winter ice temperatures

Since 1979, the Arctic sea ice cover extent has declined markedly, by approximately -12.8 ± 2.3 % decade⁻¹ in September and -3.5 % decade⁻¹ to 4.1 % decade⁻¹ over the entire annual cycle (Gulev et al., 2021). More specifically, Notz and Stroeve (2016) reports an approximately linear relationship between September sea-ice area and greenhouse-gas forcing, with a sensitivity of -3 ± 0.3 square meters of September sea-ice area per metric ton of CO₂ emission. This has led to a reduction in sea ice area between the 1980s and 2010s from 6.23 million km² to 3.76 million km² in summer and 14.52 million km² to 13.42 million km² in winter. Concurrently, the melting of most multi-year ice and the transition to a seasonal ice regime – dominated by first- and second-year ice – have reduced average ice thickness by 2.0 m between early submarine

[☆] This article is part of a Special issue entitled: 'OE_ITTC Journal' published in Ocean Engineering.

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data in 1958 and CryoSat-2 in 2017, leaving 1.0 m average sea ice thickness at the end of the Arctic melt-season (Kwok, 2018). Thinner ice is less effective as an insulator, allowing more heat exchange between the warmer ocean and the extremely cold Arctic atmosphere. This has led to a corresponding increase in ice temperatures, which, on average, have risen in parallel with these changes in all months of the year (Fig. 1). These trends are supported by satellite observations (DMI, 2026) and are reflected in sea ice components within global climate models (CMIP6) (Eyring et al., 2016; Notz et al., 2016).

To estimate, very generally, the conditions in the Arctic across seasons, we examine the ice temperature averaged across all spatial dimensions as an indicator of large-scale change under the moderate SSP2-4.5 and SSP3-7.0 shared socioeconomic pathway emission scenarios (O'Neill et al., 2017). Compared with the more extreme scenarios SSP1-2.6 or SSP5-8.5, which are more unlikely to occur under current policy settings (Hausfather, 2025), we assume that these more moderate greenhouse gas emission pathways are best suited to project future Arctic sea-ice evolution. For consistency between model outputs and satellite observations, we approximate the mean ice temperature by averaging the ice bottom temperature (-1.8°C) and the simulated or observed ice surface temperature (IST), which represents the ice skin temperature or, when present, the snow cover temperature. This approach simplifies the analysis by neglecting differences in thermal conductivity between snow and ice; however, it enables a qualitative assessment, including satellite data that lack detailed layer-thickness information. It is important to note that this approximation may yield too-cold ice temperatures during seasons with thicker snow cover, whereas in summer, when snow is thin or absent, the associated errors are expected to be smaller.

The isotherms in Fig. 1 mark the course of seasonal transition temperatures from 1950 in the CMIP6 model mean data. They highlight an ongoing decline of traditional winter sea-ice conditions. This indicates a shift towards Arctic conditions where ice temperatures rarely fall below the levels historically observed during early spring or autumn. This trend aligns well with satellite-derived surface temperature observations starting in the 1980-ies. Generally, the duration of spring warming phases, during which sea ice is warming up, remains similar; however, warm conditions increasingly extend into late autumn. The overall warming trend, as reflected in sea ice temperatures, corresponds to a loss of cold seasons that began 50 years ago and has since accelerated.

This warming, together with the prevailing traffic patterns of much greater distances sailed in High Arctic Waters during the summer months – when ice contact is still possible – and a general reduced traffic in winter months (Sander and Mikkelsen, 2025), necessitates a paradigm shift. Continuing to focus on winter conditions alone means focusing solely on the worst-case ice load scenario. Instead, efficiency-optimization strategies should also account for summer conditions and future warming ice conditions to optimize operational performance and resource use. This requires understanding how warming affects sea ice mechanical properties.

1.2. How warming affects mechanical sea ice properties

When seawater cools below its freezing point, which is typically around -1.8°C in the Arctic Ocean, ice crystals nucleate and gradually consolidate into a dense freshwater ice matrix interspersed with brine inclusions, forming pockets and channels. The dissolved sea salts concentrate within these inclusions, lowering their freezing point and preventing the brine from solidifying. Consequently, sea ice remains a multiphase system with a characteristic bulk salinity.

Any change in sea ice temperature triggers a phase adjustment to maintain thermodynamic equilibrium, leading to variations in the solid and liquid fractions within the ice. The relationship between the brine salinity (S_{br} in ppt) and temperature (T in $^\circ\text{C}$) for typical seawater is approximated by Vancoppenolle et al. (2019):

$$S_{br,SW}(T) = -18.7T - 0.519T^2 - 0.00535T^3 \quad (1)$$

and for pure sodium-chloride (NaCl) in water solutions (Notz, 2005, based on data from Weast, 1971) by:

$$S_{br,NaCl}(T) = -17.6T - 0.389T^2 - 0.00362T^3. \quad (2)$$

Both relationships are approximately linear near the melting point and can thus be effectively represented using linear fits:

$$S_{br,SW}(T)|_{T>-5^\circ\text{C}} = -T/0.05411 [\text{ppt } ^\circ\text{C}^{-1}] \quad (3)$$

$$S_{br,NaCl}(T)|_{T>-5^\circ\text{C}} = -T/0.0598 [\text{ppt } ^\circ\text{C}^{-1}] \quad (4)$$

(based on Assur, 1958, and data from Weast, 1971).

Below these temperatures, the brine salinity–temperature curve gradually flattens. Hence, at lower temperatures, substantial temperature shifts are needed for small changes in brine salinity. Conversely, near the melting point, large phase transitions are required to maintain thermodynamic equilibrium with small temperature changes, leading to greater variations in the multiphase composition of ice at warmer temperatures.

Processes such as gravity drainage during the growth and warming phases, as well as surface-melt-induced flushing of the brine network, act to reduce brine salinity and thereby decrease the overall salt content within the ice (Notz and Worster, 2009). Generally, older and colder sea ice exhibits a higher solid ice fraction. Additionally, small inclusions within the ice can be present, including gases, precipitated minerals, or salt crystals at temperatures below their eutectic points.

The microscale physical and mechanical properties of sea ice are inherently linked (Schulson and Duval, 2009). Under typical open-ocean freezing conditions, characterized by the turbulent movement of nucleating ice crystals, these crystals initially consolidate in random orientations, forming an isotropic, granular ice layer (Weeks and Ackley, 1986). As freezing continues, conglomeration ice develops below the granular layer, creating a thick, columnar ice structure with vertically elongated ice crystals. The orderly alignment of these columnar ice crystals renders the ice anisotropic at the crystal-lattice level, with weaker bonds along their c -axis, facilitating vertically oriented fractures (Weeks and Ackley, 1986). When summer melt sets in, which in the Arctic typically involves surface melting, this anisotropy is further enhanced as the isotropic granular surface layer diminishes. Additionally, the ice is interspersed with slender vertical brine pockets and channels, which weaken the ice compared to freshwater ice. Elevated temperatures, especially in younger, saltier ice, therefore also influence sea ice strength through internal phase changes and through the general response of the pure ice matrix, leading to weakening of the ice cover under warming conditions.

Most research on the effect of environmental parameters on the mechanical properties of sea ice has focused on winter sea ice (Timco and Weeks, 2010), and empirical insights from warm conditions are very limited (e.g. Karulina et al., 2019). Recent machine-learning-driven approaches re-investigated, more generally, the parameters affecting sea-ice strength using available measurement data, independent of ice age. The studies were performed by Kellner et al. (2019, 2022) for compressive strength and Buil et al. (2022) for flexural strength. Excluding parameters that are property-specific, such as the strain rate for compressive strength, the studies showcased the importance of temperature, loading direction, salinity, ice type, porosity, and volume in affecting the mechanical properties of ice. Recent measurements in the Arctic during summer voyages focused on creating better insight into the vertically resolved material composition of sea ice (von Bock und Polach and Kubiczek, 2025). Example profiles of summer sea ice, including measurements of salinity, temperature, and flexural strength, are displayed in Fig. 2. Flexural strength was tested on disks cut from core specimens. These results, derived from particularly small disk specimens, contain a scale effect (see von Bock und Polach and Kubiczek, 2025). We therefore illustrate them normalized to assess the distribution over depth. Transferring them to a cantilever beam would result in a flexural strength of around 200 kPa (von Bock und Polach and

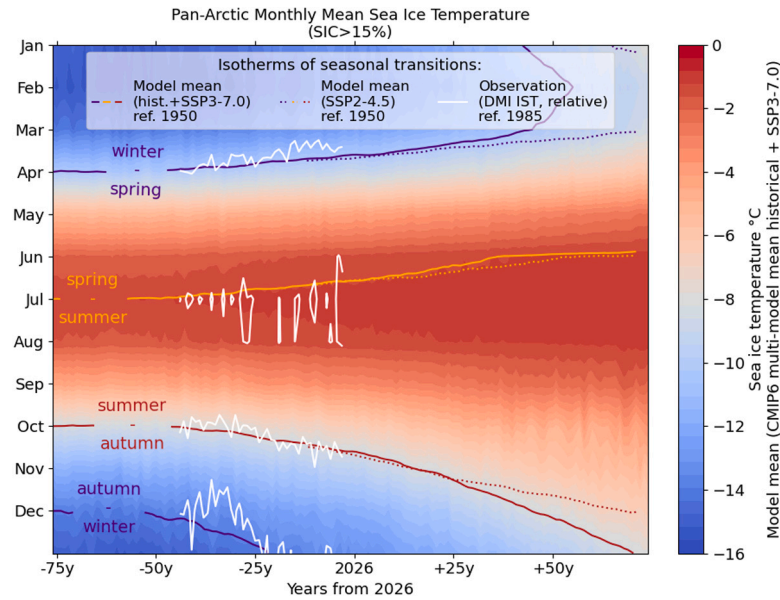


Fig. 1. Hovmoller-diagram of seasonal average sea-ice temperature evolution 1950 to 2100. The background color shows the pan-Arctic, multi-model average sea ice temperature simulated by CMIP6 climate models under the SSP3-7.0 emission scenario (see [Appendix A](#) for a list of included models). The temperature is linearly averaged from the surface and bottom temperatures and weighted by the grid cell's sea ice area. Only grid cells with sea ice concentration larger than 15 % were included. The lines show the isotherms of seasonal transitions in the model data (black, reference temperatures: 1950) and the DMI sea-ice surface temperature satellite product (white, reference temperatures: 1980) ([DMI, 2026](#)). The observed isotherms show the relative evolution and do not correspond to the absolute modeled values.

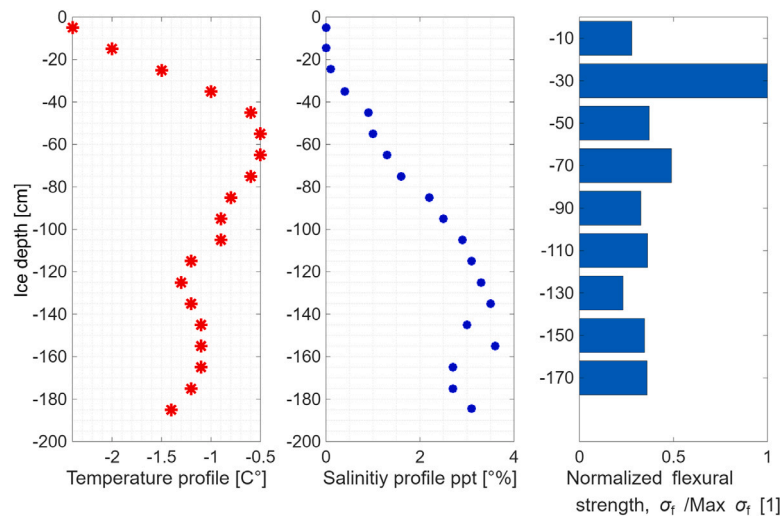


Fig. 2. Properties of Arctic sea ice in September 2024 ([von Bock und Polach and Kubiczek, 2025](#)): temperature distribution (left), salinity profile (center), and normalized flexural strength from disk tests (right).

[Kubiczek, 2025](#)). These measurements were taken in mid-September 2024 in the Arctic and are considered to reflect a value close to the lower threshold for flexural strength. Another experimental campaign by [Karulina et al. \(2019\)](#) at the end of April 2013 in Svalbard measured flexural strength values between 130 kPa and 370 kPa, with ratios of elastic modulus and flexural strength E/σ_f from 2600 to 6000. The referred ice in [Karulina et al. \(2019\)](#) may not classify as summer ice, but rather as decayed and tempered first-year ice, but the mechanical properties are considered in a similar range. Similar values for the flexural strength were measured during a RV *Polarstern* expedition in May 1984 ([Hoffmann, 1985](#)). [Fig. 2](#) shows clearly that the cold, fresh top layer, with temperatures still about -2°C below the freezing point

of freshwater, was the strongest in the entire ice column compared to the warmer, saltier ice beneath it. After further warming, we expect the ice to become equally weak throughout its entire column; however, we lack the measurement data to study these processes further.

Interestingly, unpublished data from industrial sea trials suggest that the power required by ships to break through or maneuver in sea ice does not decrease proportionally with ice flexural strength; instead, measurements taken with the same ship in different seasons of the year indicate that the attainable speed at maximum power in first-year level ice with lower salinity (brackish water) and higher flexural strength can be as high or in some cases even higher than the attainable speed in sea ice with lower flexural strength and same thickness. This

discrepancy, together with the lack of comprehensive data, underscores the need for a better understanding of summer sea ice properties and their physical–mechanical interactions.

1.3. Ship optimization in model basins

Ship model testing has a long-standing tradition in naval architecture. It remains a well-established tool in the design and assessment of vessels, both in open water and ice conditions. There is still no numerical model available for the performance assessment of ships in ice that provides insights equivalent to those from state-of-the-art ice model tests.

Ice model testing began in the late 1950s at the Russian Arctic and Antarctic Institute (AARI) in St. Petersburg. Until today, nine active ice model test basins exist, which all use different model ice in terms of production and grain structure as well as additives or dopants to adjust the mechanical properties of the ice (von Bock und Polach et al., 2019). “Model ice” refers here to ice grown in a laboratory, with specific properties designed for testing.

In ice model testing, Cauchy and Froude similitude govern the scaling of parameters based on geometric scaling (ITTC, 2021). This means that if model length scales L_m , such as the ship length or the ice thickness, are scaled according to Eq. (5) relative to full scale L_f , also pressures and stresses can be converted by the scaling factor λ . More information on the scaling of model tests is found in Vance (1975), Schwarz (1977), Zufelt and Ettema (1996), von Bock und Polach et al. (2019, 2020).

$$\frac{L_f}{L_m} = \lambda \quad (5)$$

Schwarz (1977) postulated that the non-dimensional ratio of elastic modulus and flexural strength E/σ_f in full-scale and model-scale should be identical to assure sufficient stiffness of the model ice. In von Bock und Polach (2015), von Bock und Polach et al. (2019) it was demonstrated that the model exhibits not only elastic deformation until failure, but rather holds a small elastic domain and a large plastic domain. The ratio between the two prevailing elastic moduli was defined as *non-linearity*, which was found to be independent of the ice and additive types.

At HSVA, open water model tests have been conducted since 1913, with the first ice-related tests commencing in 1958. Subsequently, new ice testing facilities were constructed in 1972 and 1985 (Evers, 2017), with the latest being HSVA's 72 × 10 m large ice model basin (LIMB), where tests for this project were performed. Confidence in model-scale ice testing at HSVA and its agreement with full-scale ship performance is supported by an ever-growing database of sea-trial data accumulated over decades. Since natural sea ice rarely occurs in large, uniform patches under typical sea-trial conditions, the controlled uniformity of model ice and previous model tests provide valuable benchmarks during initial ship design and for complementing later sea-trial results.

The accurate estimation of a ship's required installed power – ensuring it can efficiently and profitably carry out its intended transport or operational duties – is essential for ship designers, operators, and shipowners. Physical model tests enable direct observation and measurement of phenomena that may be difficult to capture solely through numerical simulations. They support the optimization of hull designs and propulsion systems and help validate and improve computational models, ultimately contributing to safe, efficient, and reliable ship operation.

1.4. Model sea-ice at the HSVA model test basin

The primary goal of model ice preparation is to ensure that the model ice behavior in interaction with ships or structures accurately represents that of natural sea ice at a reduced geometric scale, while conforming to fundamental scaling laws such as Froude and Cauchy

scaling. To achieve this, the material characteristics of model ice do not fully reproduce all physical properties and their vertical stratification of natural sea ice at small scales.

Two main types of aqueous model sea ice are utilized in testing facilities. Fine-grained ice is typically produced by continuous spraying from above, building the so-called laboratory “ice sheet” from the bottom upward. Columnar ice, in contrast, is created by first applying a fine-grained seed layer, from which crystals grow downward, emulating the natural formation processes of sea ice. To achieve a proportional reduction in strength, water dopants¹ are added.

In HSVA's LIMB, the standard model ice is columnar ice grown from water doped with 7‰ sodium chloride (NaCl). At the start of the model ice sheet production, the water is at its freezing temperature, and the ambient air temperature is typically at around −20 °C, depending on the configuration. Ice that has already formed during cooling is transferred to a defrosting basin, followed immediately by spraying a seeding layer. This process creates a granular surface layer approximately a few millimeters thick, beneath which the desired congelation ice develops (Fig. 3). The ice grows at about 2 mm h^{−1} and the thickness of the final laboratory-grown level ice sheet typically ranges from 10 mm to 80 mm. To mitigate the artificially high density of this layer at small scales and imitate higher porosity, micro-bubbling techniques are employed. This modification also favors a more brittle failure mode, similar to that of natural sea ice. As a side effect, the entrapped air bubbles make the ice appear white and opaque, which facilitates visual observation during testing. To finely tune the ice's mechanical properties – particularly its flexural strength – the temperature sensitivity of ice near the freezing point is exploited. The ice is tempered to closely match the intended full-scale strength (also referred to as thermal conditioning of the ice), ensuring that its mechanical behavior accurately reflects real-world conditions.

The model ice used in tests at HSVA, along with the predictions based on these tests, was carefully calibrated to represent colder, and consequently stronger, first-year winter ice at full scale. Depending slightly on ice thickness, the minimum achievable flexural strength through tempering is approximately 15 kPa. Further reductions in strength using this approach are generally not feasible, as the model ice becomes thermally unstable when its temperature approaches the melting point. Such instability would make model testing unmanageable, as it would hinder precise control over the ice's mechanical properties. Furthermore, at this point, flexural failure can no longer be clearly defined, as the over-tempered model ice loses its structural integrity and essentially flows under the applied load rather than exhibiting a distinct flexural failure. This study, therefore, explores methods to modify (columnar-) model ice – like the one produced in HSVA's large ice model basin – to reduce its flexural strength while keeping its structural integrity. The goal is to develop ice conditions for bending-dominated ice failure that better represent summer sea ice while maintaining sufficient stability over time to conduct reliable model tests. Accordingly, we focus on developing a method to adjust the properties of an ice sheet, rather than producing a fixed set of absolute values, since these ultimately depend on the intended, scalable test conditions, including the model size and the ice thickness.

2. Methods

Modification procedures for model-sea ice were developed within the interdisciplinary HamburgIceLab network, taking full advantage of differently sized and equipped sea ice laboratories for initial small-scale testing and subsequent model-scale implementation.

Initial experimental-style testing was conducted in the University of Hamburg's ice laboratory, which features a 1 m³ water tank housed

¹ Common dopants are sodium chloride (NaCl), ethanol, urea, and a combination of ethylene glycol, aliphatic detergent, and sugar.

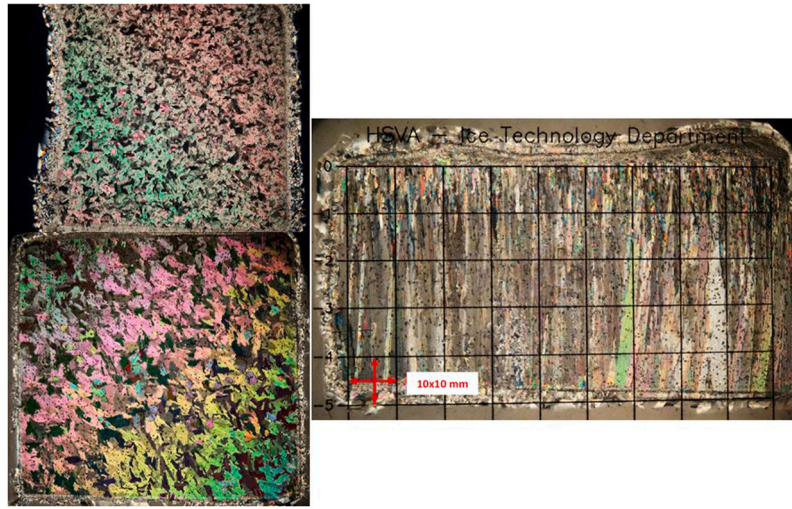


Fig. 3. Horizontal (left) and vertical (right) thin sections of HSVA's model ice with visible micro air bubbles. The top left shows the surface layer, and the bottom left shows the columnar ice.

Table 1

Overview of model-ice sheets in the HSVA LIMB, including ice thickness h_i , tempering time $t_{\text{tempering}}$, air temperature during ice growth T_{cooling} , ice temperature T_{ice} , water temperature T_{water} , as well as flexural strength σ_f and modulus of elasticity E of the ice after tempering. Model ice sheet Nr. II exhibited a thickness exceeding the typical thickness range due to an experimental opportunity arising from a specific use case that was conducted in parallel.

Model ice sheet	h_i [mm]	$t_{\text{tempering}}$ [hours]	T_{cooling} [°C]	T_{ice} [°C]	T_{water} [°C]	σ_f [kPa]	E [MPa]
Nr. I	57	20	−19	−	−0.3	36.7	9.5
Nr. II	90	10	−19	−	−0.4	145.5	8.8
Nr. III	34	10	−20	−1	−0.4	46.5	6.3

within a cooling chamber. This setup offers high flexibility for small-scale, efficient, and reproducible experiments. It is equipped with a range of physical measurement tools to monitor and control boundary conditions affecting the ice. As part of this study, we implemented a setup to measure flexural strength and elastic modulus in the lab, following the International Towing Tank Conference (ITTC) guidelines as closely as possible, despite the limited extent of the available ice surface. Promising modifications identified at the University of Hamburg were then transferred to HSVA's LIMB for scale-up implementation and testing. In this chapter, we further describe the measurement principles based on ITTC recommendations and detail the experimental setup used at HSVA LIMB.

2.1. Experiment overview

We produced three model ice sheets in the LIMB, each subjected to different modification procedures for testing. We here provide a brief overview of the fundamental physical and mechanical properties of these different thick ice sheets, serving as a reference for the subsequent test analyses (Table 1). All ice sheets were produced using the previously described model-ice recipe and were grown from a 7‰ NaCl solution in water.

2.2. Measurement techniques

The study focuses on assessing the impact of our modifications on the flexural strength and elastic modulus, two key parameters in characterizing model sea ice in test basins for bending-dominated icebreaking tests. We used in situ methods to measure flexural strength σ_f and elastic modulus E . We complemented these measurements with numerical simulations when measuring elastic moduli was not feasible due to design constraints. The experimental setup for determining the mechanical properties is depicted in Fig. 4. It incorporates several recent advancements in automation that enable reliable comparability

and a high measurement frequency, both of which were essential for our various test areas. The setup comprises an S2M load cell manufactured by HBM with a nominal load of 200 N and an accuracy of $\pm 0.02\%$ of full scale, a routing machine equipped with a milling head of 8 mm diameter, and a positioning device enabling controlled translational motion in three degrees of freedom (x, y, and z).

2.2.1. Flexural strength measurements

The flexural strength σ_f is determined in situ using cantilever beam tests. The automated routing machine cuts samples with dimensions of $6 \times 2.5 \times 1 \cdot h_i$ as recommended by ITTC guidelines (ITTC, 2024). These aspect ratios allow the determination of flexural strength based on Bernoulli's linear beam theory. A piston applies a downward displacement 30 mm from the outer edge, with the load cell measuring the force. For each beam, the distance l_b between the location of load application and fracture, the dimensions b and h_i of the idealized cross section of the fracture surface, and the fracture load F_{Peak} , extracted from the recorded force–displacement curves, are assessed. The flexural strength is then calculated according to Bernoulli beam theory by Eq. (6) following the ITTC recommendations.

$$\sigma_f = \frac{6F_{\text{Peak}}l_b}{bh_i^2} \quad (6)$$

2.2.2. Elastic modulus measurements

The elastic modulus E in this study is determined by in-situ measurements of elastic displacement δ , assuming the applicability of the theory of infinite plate bending on an elastic foundation. A displacement-controlled piston equipped with a pin-jointed contact area of 0.01 m^2 was attached to the load cell measuring the reaction force F . After carefully establishing contact between the piston and the ice surface, the piston displaces the ice sheet vertically downward in five equidistant increments, held for 10 s each, until a maximum deflection of the ice sheet corresponding to 8% of its thickness h_i is reached. Subsequently,

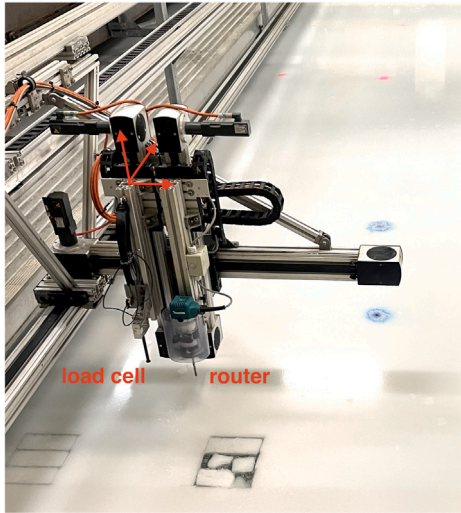


Fig. 4. Image of the recent measurement setup in the HSVA LIMB. The load cell and router are attached to a positioning device with three degrees of translational freedom (shown with red arrows). In the foreground, two previous cantilever beam test fields are visible, each with three individual beams, the right one with broken beams after manual thickness measurements. Sprayed markers on the ice were used to mark the test fields for different modifications.

the same displacement levels are applied in reverse order to evaluate the loading–unloading response. The Poisson’s ratio ν for model ice was taken as 0.33 (Schulson and Renshaw, 2022), gravitational acceleration g as 9.81 m s^{-2} , and tank water density ρ was measured at 1005.5 kg m^{-3} . The applicable formula for deriving E from these measurements in accordance with ITTC recommendations is given in Eq. (7).

$$E = \frac{3}{16} \frac{1 - \nu^2}{wh_i^3} \left(\frac{F}{\delta} \right)^2 \quad (7)$$

with $w = g\rho$

While being one of the standard methods according to ITTC, it has been shown under natural conditions that – probably due to differences in strain and strain rate – comparable tests of the strain modulus of elasticity can yield values that are 4 to 5 times higher than those determined acoustically (see, e.g., Karulina et al., 2019).

2.2.3. Elastic modulus numerical reconstruction

Determining the elastic modulus based on plate bending experiments (see Eq. (7)) requires a significant amount of intact and similarly treated ice around it, as it is based on the infinite plate theory (ITTC, 2021). This was not always feasible for all test fields.

We therefore added stiffness parameters with a finite element model based on the force–displacement curves measured during the cantilever beam experiments. The method is analogous to the model described and used in von Bock und Polach et al. (2021, 2023), including geometric adjustments. Fig. 5 displays the start and end points for the simulation from a cantilever beam experiment.

The model configuration consists of 8-noded solid elements (Fig. 6). No shell elements are used, as shear deformations in thickness directions tend to be significant. The material model is linear elastic, with the nominal elastic modulus adjusted to maintain compliance with the global deformation. Consequently, neither ice failure nor stress analysis is included; it is used only to determine a representative stiffness of the ice until a certain deformation is reached. The model includes the adjacent parent ice sheet to include the vertical root displacement. The size of the parent ice sheet ensures that the boundary conditions are not disturbing the beam deflection (see also von Bock und Polach, 2015).

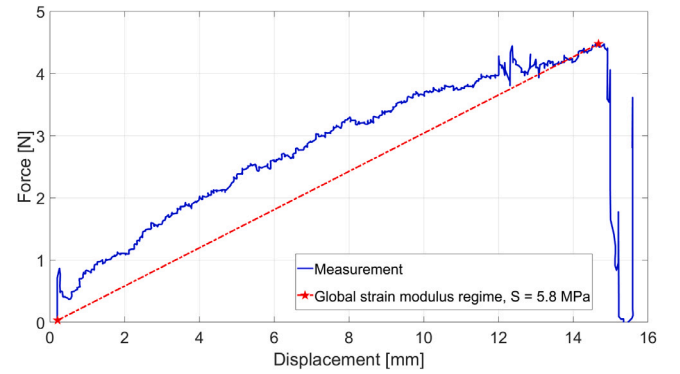


Fig. 5. Exemplary force–displacement curve of a cantilever beam test with selected start and end points for the simulation.

Furthermore, the hydrostatic effects of the water underneath are modeled using nonlinear springs. The springs account for the linear increase in buoyancy force until the top of the beam is submerged, at which point surface flooding commences. From this point on, the buoyancy force no longer increases due to the pressure from the flooded topside. This is an idealization, as flooding might not occur instantaneously due to surface tension (von Bock und Polach, 2015). The spring forces on the nodes account for the beam area and the number of nodes. The model has a resolution of five elements over the full ice thickness, yielding a converged result (von Bock und Polach et al., 2023). The modeling approach is described in more detail in von Bock und Polach et al. (2023) and von Bock und Polach et al. (2021).

Ultimately, the stiffness is determined by an iterative optimization algorithm that minimizes the difference between the measured and simulated displacements. The here selected acceptance criterion was a difference of 0.1% between simulated and measured displacement.

Fig. 7 displays a comparison of the elastic moduli determined by the plate bending method and the simulations. It must be acknowledged that even among three cantilever beams next to each other, the flexural strength may vary by up to 15% due to natural variation in the ice. Therefore, the agreement in Fig. 7 is accepted as satisfactory (see also von Bock und Polach et al., 2021).

3. Modifying model sea-ice to simulate weaker ice conditions

This study aims to investigate methods to weaken columnar model ice to better represent summer sea ice conditions in model test basins. We focus on approaches beyond overall tempering of the model ice, aiming to achieve stable, controllable conditions, even at temperatures close to melting. In the following sections, we present tests examining the layer structure of the current model ice, analyze the mechanical properties of the modified ice, and evaluate these results in the context of typical key figures for model sea ice—such as the ratio between elastic modulus and flexural strength that describes the brittleness of the ice.

In columnar model ice, we hypothesize that the few millimeter-thin surface layer contributes disproportionately to the mechanical properties of the model ice, thereby increasing its flexural strength. Therefore, we investigate whether manipulating this surface layer – either by (partially) destroying or disrupting it – weakens the model ice and allows us to simulate summer sea ice conditions in model tests better. The larger columnar layer beneath should remain mostly intact to preserve properties such as thickness and density, to preserve, e.g., ice floe dynamics during breaking. This approach of targeting the surface layer closely mimics natural processes, as it is the strong granular surface of sea ice that melts first during the Arctic summer.

Various methods were tested to weaken or remove the surface layer, considering their applicability to large-scale model test basins, reproducibility, and effectiveness in altering mechanical properties

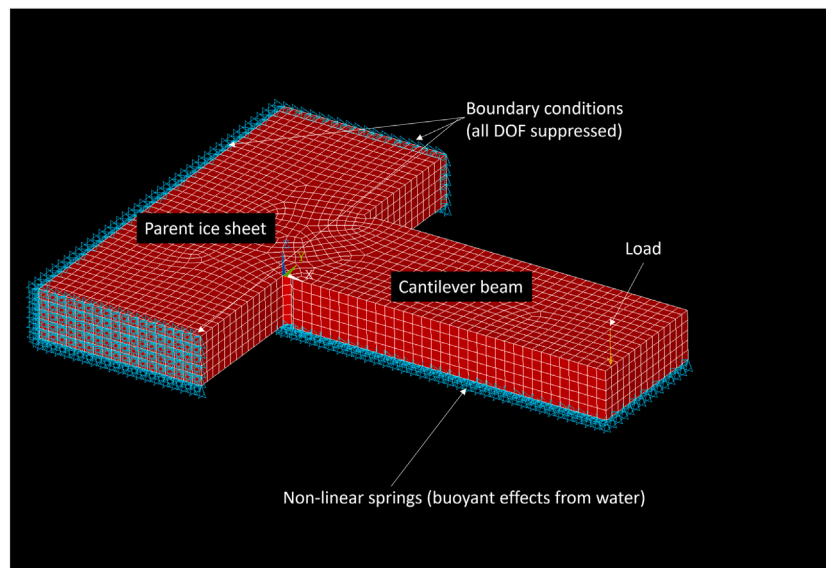


Fig. 6. The finite element model with radii at the transition between beam and root, the parent ice sheet, the boundary conditions, the nonlinear springs, and the applied load (yellow arrow).

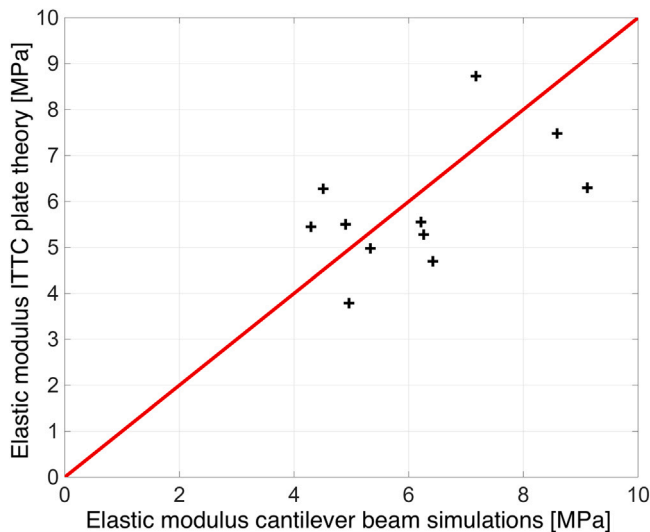


Fig. 7. Comparison of the elastic moduli determined by plate deflection and reconstructed from cantilever beam tests using the numerical simulation.

relative to standard model ice. We included mechanical, thermal, and thermohaline techniques in our experiments:

1. Disrupting the integrity of the top layer and the freezing process by incorporating styrofoam beads into the freshly sprayed top layer
2. Breaking or dicing the almost finished ice sheet and allowing it to refreeze or consolidate prior to tempering.
3. Multidirectional scratching of the top layer of the final ice sheet
4. Melting away the top layer of the final ice sheet with directed heat
5. Melting away the top layer of the final ice sheet with sprinkling pure NaCl or spraying a saturated NaCl aqueous solution

In the initial phase, the different methods were tested side by side on a single ice sheet with an average thickness of 57 mm, ensuring direct comparability (Fig. 8). Based on the results, the most promising method – NaCl treatment – was then further tested in multiple configurations on

two additional ice sheets with thicknesses of 90 mm and 34 mm (Table 1).

We also hypothesize that sublimation at the ice–air interface could be an effective method for removing the surface layer, as sublimation rates of up to 1 cm week^{-1} have been observed in the small UHH ice chamber, driven by effective drying of the ventilated air. However, implementing sublimation in the large LIMB would require significant modifications to the cooling infrastructure and was therefore outside the scope of this study.

3.1. Mechanical manipulation

As the first approach to mechanically manipulating the top layer, we manually applied styrofoam beads in a single layer immediately after the seeding process. The concept was that these beads would partially replace the top layer but, due to their low strength and stiffness, would not contribute significantly to the final ice sheet's mechanical strength. Following a successful preliminary test in the small tank at the University of Hamburg, this labor-intensive method was implemented on approximately 12 m^2 of the first test ice sheet at HSVA. However, the synchronization with the seeding process – intended to distribute the beads immediately after spraying the initial layer, but managed only after the first layer had solidified – prevented the beads from integrating into the top layer as planned. This actually led to an inverse impact of the beads, causing a much thicker fresh top layer of 3 mm to 4 mm after ice growth. The insulating effect of the styrofoam probably kept the ice warmer, thereby amplifying desalination during growth. Additionally, the strong insulating effect of the styrofoam hindered ice growth by 41% in comparison to the surrounding ice sheet. The elastic modulus and flexural strength in the modified area were similar to those in the reference areas (Fig. 9).

The second concept involved disrupting the uniformity of the top layer by manually breaking the almost finished ice sheet into roughly cube-sized pieces, which were then randomly repositioned and refrozen to form a continuous ice sheet, similar to a refrozen brash ice channel. This process aimed to increase the number of salt inclusions within the ice, as saltwater would refreeze in the gaps between the cubes. This approach was tested once over an area of $6 \times 6 \text{ m}$. While effective at reducing flexural strength and elastic modulus by approximately two-thirds, it resulted in a very rough ice surface. This variability raises concerns about the mechanical properties and repeatability of

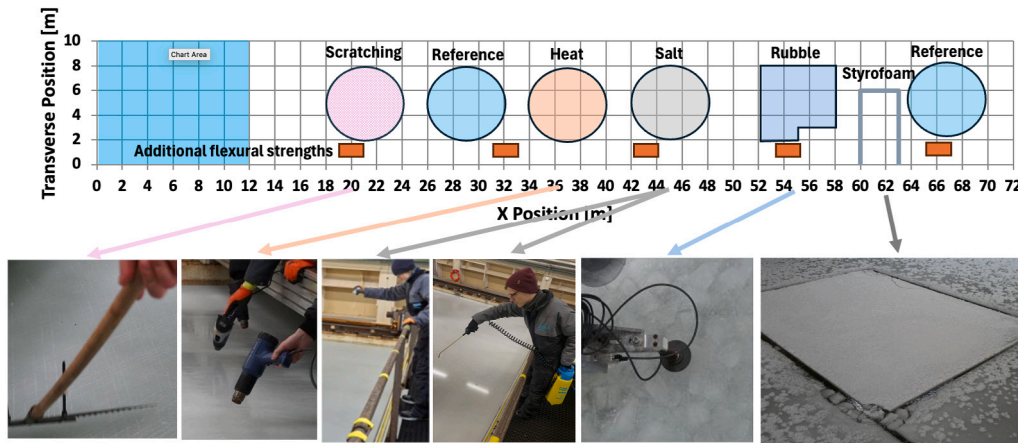


Fig. 8. Overview of a typical setup of the conducted experiments in the HSVA LIMB with pictures of the different modification methods. The upper panel shows a top view of the tank and its separation into different study areas during experiment I, large enough to measure both flexural strength with cantilever beam tests and elastic modulus by plate deflection. Areas are prepared from a mobile platform to avoid disturbing the ice in any way during preparation.

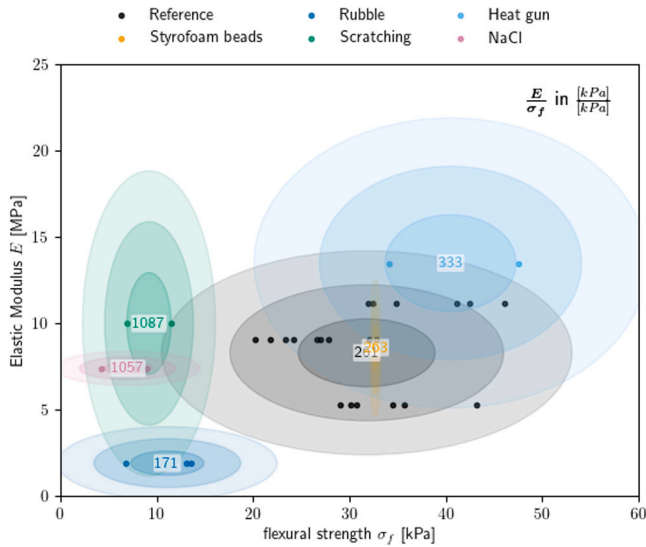


Fig. 9. Bivariate distribution of E vs. σ_{flex} for each experimental category (values in model scale). Colored points represent individual samples. Ellipses indicate the Gaussian approximation of each category based on the precomputed mean and standard deviations (1σ , 2σ , 3σ levels) of the samples. The numbers in the center provide the stiffness-to-strength ratio E/σ_f .

this approach, making it less suitable for controlled model-testing conditions.

For the third approach, the surface layer was scratched in multiple directions over an area of 6×6 m. A manually applied linear pattern at approximately 120° rotational intervals was initially deemed sufficient to avoid stipulating unnatural fracture patterns in bending failure. Although this method effectively reduced the ice's strength, it still introduced pronounced linear fracture lines (Fig. 10), which are not representative of natural fracture behavior and could compromise the realism and consistency of the mechanical response. The ice's elastic modulus was similar to the reference values.

3.2. Thermal manipulation

Another approach to remove the overly load-bearing top layer involved targeted melting with heat guns. The intention was for the meltwater to drain through existing channels in the columnar layer, ideally leaving only the underlying columnar ice intact. An area of

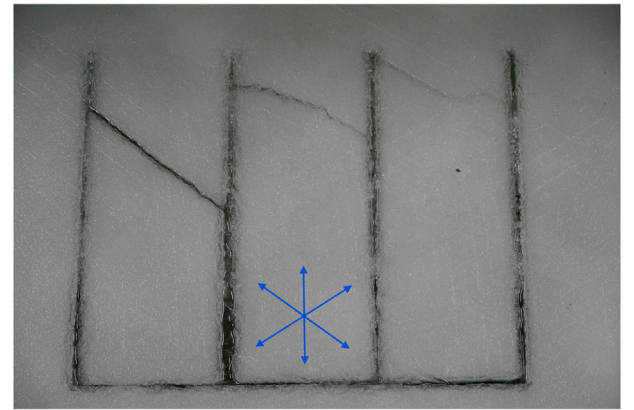


Fig. 10. Beams for flexural strength measurement of scratched ice after failure, with scratching directions indicated by blue arrows. The failure patterns closely align with the scratch directions.

6×6 m was manually prepared for subsequent measurements of the elastic modulus and flexural strength. However, the results revealed an unintended adverse effect: a significant increase in overall flexural strength (Fig. 9). This was likely caused by rapid refreezing of the surface meltwater into the pore spaces of the underlying ice, leading to a welding-like effect (Schulson and Renshaw, 2022) that increased the flexural strength and made it less representative of natural summer conditions.

3.3. Thermohaline manipulation

The third group of methods aimed to modify the ice's properties through thermohaline processes, achieved by distributing salt on top of the existing model ice. These techniques are based on the fact that small-scale melting and freezing processes between brine inclusions and ice crystals maintain a balance between salinity and temperature within the ice. When salt is applied to the ice surface, it induces localized melting that dilutes the brine until it returns to the equilibrium state. Salt successfully reduced the flexural strength on the comparison ice sheet (Nr. I) by more than two-thirds (Fig. 9).

Given this positive outcome and comparatively practical applicability, we focused on the thermohaline melting from here on and further tested different application methods, including sprinkling pure, dry NaCl onto the ice and spraying a saturated 263 g kg^{-1} NaCl aqueous

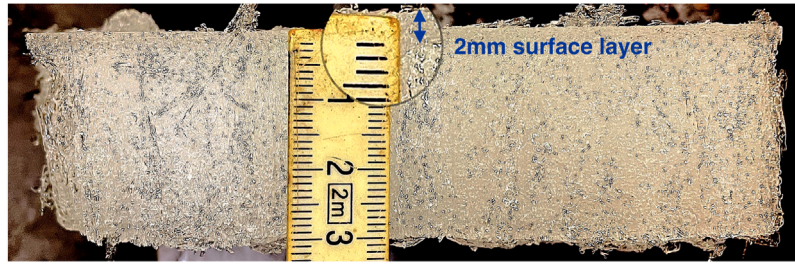


Fig. 11. Side view of the model ice of ice sheet Nr. III at one of the reference sites. The image is color- and contrast-adjusted for better visibility of the granular surface layer and the columnar crystals below. The magnifier details the upper millimeters.

solution. Two dedicated ice sheets (Nr. II and III) were used to quantify the temporal stability of the elastic modulus and flexural strength, as well as the impact of multiple salt amounts, each with a defined thickness of the melted layer. In the following, we first introduce the concept used to determine this layer, then present the results from the mechanical measurements.

3.3.1. Surface melt capacity SMC

Distributing salt, pure or dissolved, on the ice, turns ice into melt-water until diluting and temperature changes restore thermohaline equilibrium. Since we are primarily interested in the amount of potential surface melt dependent on the amount of distributed salt in this engineering case, we introduce the surface melt capacity SMC in mm as a predictor of this dependency.

As we focus on the top layer that partially forms within the seeding process, for which pure freshwater is used, we approximate the ice as purely fresh and impermeable, thus hindering vertical brine seepage. This allows us to derive SMC through the first-order approximation of thermohaline equilibrium melting:

$$SMC_{sol. NaCl} = \frac{m_{SAS}}{A \cdot \rho_{ice}} \cdot \frac{S_{SAS} - S_{brine}(T_{ice})}{S_{brine}(T_{ice})} \cdot 1000 \frac{\text{mm}}{\text{m}} \quad (8)$$

for a distributed saturated NaCl aqueous solution with mass m_{SAS} in kg on an ice area A in m^2 , and

$$SMC_{dry NaCl} = \frac{m_{salt}}{A \cdot \rho_{ice}} \cdot \frac{1 - S_{brine}(T_{ice}) \cdot 10^{-3} \frac{\text{kg}}{\text{g}}}{S_{brine}(T_{ice}) \cdot 10^{-3} \frac{\text{kg}}{\text{g}}} \cdot 1000 \frac{\text{mm}}{\text{m}} \quad (9)$$

for pure salt with mass m_{salt} in kg distributed on the HSVA model ice. $S_{SAS} = 263 \text{ g kg}^{-1}$ is the salinity of a saturated NaCl aqueous solution at -1°C (estimated from the values in Haynes (2016)) and $\rho_{ice} = 923 \text{ kg m}^{-3}$ the density of the solid ice. Assuming that heat fluxes with the surroundings supply the energy needed for melting while keeping the ice bulk temperature T_{ice} constant, we estimate the equilibrium salinity from the brine salinity at the surrounding ice temperature $S_{brine}(T_{ice})$ using Eq. (3). The melting capacity formula then provides an approximation of the amount of salt that must be distributed on the ice surface at a given ice temperature to melt a specified surface-layer thickness SMC . Continuous measurements of ice temperature after salt application to the ice surface indicated that a 1 h response time was sufficient for the initial temperature changes to dissipate. We used this flattening as an indicator that the system had returned to equilibrium and as a minimum waiting time before measurements. As shown later, the assumption of impermeability only hold through until the surface layer was melted away, thus inhibiting further melting for larger SMC , as the brine solution drained the ice.

3.3.2. Decreasing surface layer thickness

The sprayed surface layer of ice sheet Nr. III was approximately 2 mm thick (Fig. 11). To test how the mechanical properties of the ice change with decreasing surface-layer thickness, we treated this ice sheet with varying amounts of saturated NaCl aqueous solution and dry salt to investigate the dependency between SMC and mechanical

properties, as well as to compare the impact and applicability of solution versus dry salt. The setup included a total of 17 rectangular areas with different salt quantities and 11 unaltered reference areas (Table 2). Smaller areas were designated for direct flexural strength measurements via cantilever tests at varying salt levels, while larger areas facilitated comparative assessments across multiple similarly treated fields. These larger sections also served to determine elastic moduli in situ using the plate deflection method, alongside flexural testing. The arrangement of the different small areas was chosen randomly to avoid errors by local gradients in the model ice sheet. For salt application, the saturated NaCl solution was sprayed using a spray gun to ensure uniform horizontal distribution, whereas dry salt was sprinkled with a large sieve. The spraying method proved more successful in achieving homogeneous coverage in our trials and caused an immediate change in surface appearance from glossy to matte, highlighting the direct effect of the salt on the surface layer (Fig. 15). Salt application via sprinkling often left visible linear tracks on the ice.

3.3.3. Changes in flexural strength

The modified model ice still exhibited a distinct failure point in most beam tests, enabling us to determine its flexural strength. In the small areas, we observe an immediate thermohaline impact on ice flexural strength within 1 h of application, as compared to the reference fields (Fig. 12a). Within the range of the lowest tested $SMCs$, from 0.3 mm to 2 mm, the flexural strength of the model ice decreases by up to two-thirds, reaching as low as -67% of the reference values. A simple gradient of $\Delta\sigma_f/\Delta SMC = -39.2\% \text{ mm}^{-1}$ explains 58% of variability during the decline. However, achieving a homogeneous distribution of the solution still proved challenging at these low amounts. This difficulty could introduce errors in the initial gradient, since the intended SMC may not precisely reflect the local distribution at the location where we measured the beams. For higher SMC values, reduction in flexural strength plateaued at around -71% , unaffected by further changes in SMC ($R^2 = 0.14$), indicating that the surface layer had melted completely. Visual inspection revealed the formation of vertically continuous drainage channels through the ice, likely causing the residual solution to drain after melting the impermeable surface layer. The underlying columnar ice retained a bulk flexural strength of about 11.6 kPa. Using Cauchy-scaling from 34 mm model ice thickness to 1 m full-scale sea ice implies an illustrative reduction in flexural strength from 1268 kPa to 341 kPa in natural sea ice between our reference and the modified ice. However, the exact resulting values depend on the specific model scale and target ice thickness; therefore, these numbers should not be interpreted as absolute. In general, any increase above $SMC > 2 \text{ mm}$ appears ineffective. Hence, applying a salt amount corresponding to an SMC smaller than the surface layer thickness weakens the ice, whereas amounts above this threshold do not produce further noticeable reductions in flexural strength.

While generally following similar patterns, measurements on the larger areas exhibited greater variability in flexural strength (gray dots in Fig. 12a), likely due to above-average variations in the ice sheet. These variations may have resulted from the timing of our experiments,

Table 2

Overview of test areas for studying the thermohaline impact of salt application on model ice on its mechanical properties on ice sheet Nr. III (mechanical measurements are provided in model scale). Salt was applied in two states: dry salt (DS) and saturated aqueous solution (SAS). In addition to the average value per group, the standard deviation for each sample group is provided. Sample groups consisted of three cantilever beams for flexural strength measurements per area. The elastic modulus E was derived numerically from the same three cantilever beams per area or, in the large areas, from one elastic displacement measurement per area. Values colored in red imply that these averages contain cantilever beams whose post-failure dimensions do not comply with ITTC standards. This can occur if the beams are broken too short or if their dimensions are slightly incorrect due to local deviations in ice thickness.

State	number of areas	SMC [mm]	Amount SAS [kg m^{-2}]	Amount pure salt [kg m^{-2}]	Flexural strength $\sigma_f \pm \text{std}$ [kPa]	Elastic modulus $E \pm \text{std}$ [MPa]
Small areas of 2 m^2						numerical E :
Ref.	8	–	–	–	46.3 ± 9.8	4.0 ± 1.8
SAS	1	0.3	0.019	0.005	42.6 ± 10.1	6.9 ± 1.0
SAS	1	0.6	0.038	0.010	21.0 ± 2.0	10.4 ± 2.4
SAS	1	1	0.063	0.017	18.4 ± 1.3	17.1 ± 1.1
SAS	1	2	0.125	0.033	15.6 ± 3.0	15.1 ± 8.2
SAS	1	3.24	0.203	0.053	14.0 ± 1.9	5.7 ± 0.5
SAS	1	4	0.251	0.066	9.2 ± 1.1	5.7 ± 0.6
SAS	1	6	0.376	0.099	11.6 ± 2.6	5.2 ± 0.5
SAS	1	10	0.627	0.165	12.0 ± 2.1	6.0 ± 0.4
Large areas of 9 m^2						measured E :
Ref.	3	–	–	–	48.0 ± 2.7	5.7 ± 1.4
SAS	3	0.6	0.038	0.010	27.3 ± 8.8	8.1 ± 2.7
DS	1	1	–	0.017	10.1 ± 0.9	4.8
SAS	3	2	0.125	0.033	22.8 ± 11.6	7.4 ± 2.4
DS	1	2	–	0.033	13.4 ± 0.5	5.7
SAS	1	3.24	0.203	0.053	10.9 ± 0.3	6.8

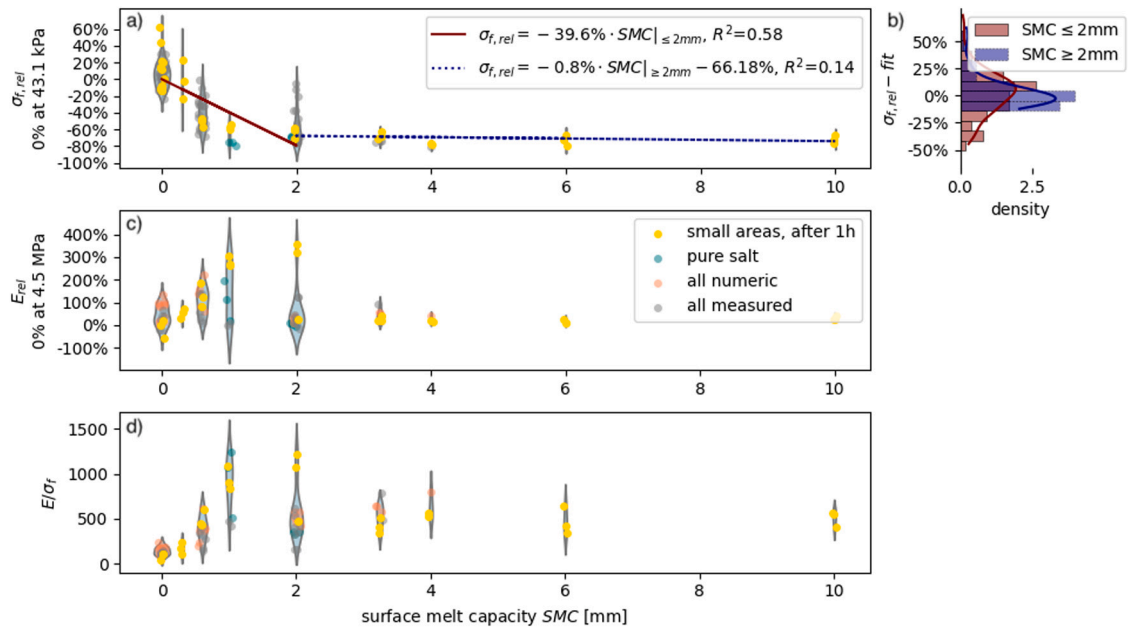


Fig. 12. Changes in flexural strength caused by thermohaline melting of the model ice surface with salt. Panel (a) shows all measurements (gray dots) of flexural strength dependent on the surface melt capacity (SMC) of the distributed salt. Tests with dry salt (blue dots) and saturated solution on the small areas (golden) are highlighted. Background violins indicate the distribution of all measured points. Panel (b) shows the residuals of all gray measured points after linear regression of the decline (red) and the level part (blue). Panels (c) and (d) include the relative changes in the measured (gray) and numerically reconstructed (coral) elastic modulus E and the absolute values of the brittleness ratio E/σ_f . The reference values for relative changes (i.e., the absolute values at 0%) are the median values of the corresponding untreated reference fields in model scale.

which had to be arranged directly after an extended revision break. At this stage, several ice sheets are typically prepared to recalibrate the ice preparation before industry projects are carried out.

In the region of the small areas, the ice sheet appeared visually more homogeneous, and the clear trends, despite the random distribution of measurement areas, make the results more reliable.

Applying the salt dissolved in a saturated aqueous solution proved noticeably easier than applying dry salt. Comparing results from both methods revealed no obvious difference in their effects. A small deviation observed at $SMC = 1 \text{ mm}$ can be attributed to an uneven distribution of dry salt, resulting in higher local salt concentrations at the measurement site.

The thermohaline treatment alters the model ice surface and therefore potentially affects failure modes of the ice, which would impact ship–ice interaction in intended model tests. While studying the microscale failure processes was out of the scope for this study, we compared cantilever beams after breaking to detect differences in beam shapes and crack propagation paths. Fig. 13 shows two beam groups of three beams each for reference conditions and with a surface treatment of $SMC = 3.2 \text{ mm}$. Breakage occurred preferably as intended between the endpoints at the fixed end of the pre-sawn beams. Deviations from this optimal case occurred for both test cases, thus highlighting that a constant deviation in the failure patterns dependent on the surface treatment was not detectable.

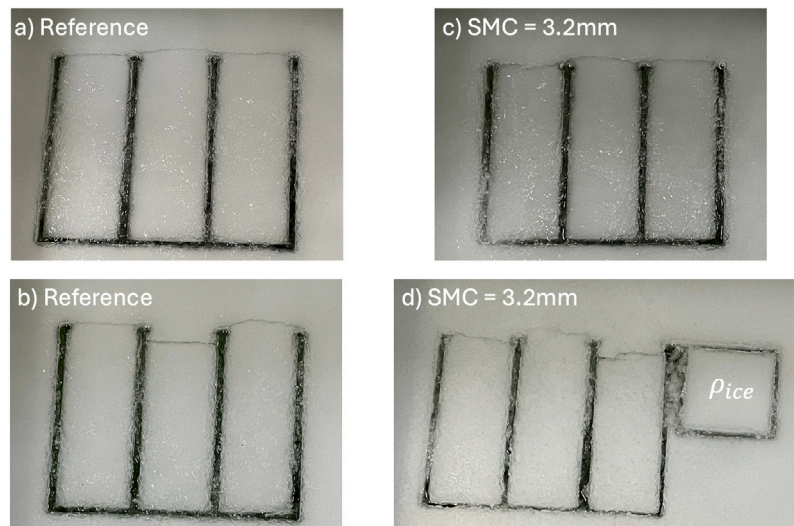


Fig. 13. Cantilever beams used for flexural strength measurement of reference (a and b) and modified ice (c and d, $SMC = 3.2\text{ mm}$) after failure showing the variability of crack pattern at the fixed end of the beams. The additional square in (d) was an ice sample cut for density measurements.

3.3.4. Changes in elastic modulus

In contrast to the reduction in flexural strength of the model ice, the elastic modulus increased inconclusively with increasing $SMC < 2\text{ mm}$ by more than 100% and beyond this threshold, returned to initial values, plateauing at 5.5 MPa (Fig. 12c). The general trend is similar across the differently treated surfaces and is evident in both measured and simulated values. In general, all elastic modulus values from the differently treated areas with $SMC \leq 2\text{ mm}$ show a very large spread, including possible outliers and already a range of -100% to 100% in the reference fields. The elastic moduli derived from the cantilever beam tests in the small fields at $SMC \geq 2\text{ mm}$, however, showed smaller variations and indicate that there was no large change, neither decrease nor increase, between before and after melting away the entire surface layer.

3.3.5. Changes in stiffness

The non-dimensional ratio of elastic modulus to flexural strength, E/σ_f , describes the relationship between material stiffness and strength and is expected to be above 2000 for first-year sea ice, but also for decayed first-year ice (Karulina et al., 2019). In the case of summer ice, the relationship and, therewith, the exact target values are unknown. Based on recent field data in von Bock und Polach and Kubiczek (2025), the ratio may be lower, but this remains to be confirmed. In our experiments, the relationship appears to be dominated by the strong σ_f decline in the model ice, causing even slightly higher values than the reference and therefore rendering the ice more brittle (Fig. 12d), while at the same time losing strength in general. The only investigated method in our series that reduced the ratio was the rubble ice modification on ice sheet Nr. I ($E/\sigma_f = 171$ vs. $E/\sigma_f = 261$ on the reference fields). It was steered by a strong decline in elastic modulus (Fig. 9).

3.3.6. Temporal stability

For the modified model ice to be practically useful, its temporal stability must be comparable to that of the regular model ice, as represented by the reference areas. Model tests at HSVA typically last between 4 h to 8 h. We assessed this stability by comparing the flexural strength of small areas at 1 h and 6 h after salt application on ice sheet Nr. III (Fig. 14a) and the elastic modulus after 2 h and 6 h on ice sheet Nr. II (Fig. 14b). While simple linear regression suggests a very slow decline in flexural strength and elastic modulus over time – similar between reference and test areas – none of the regressions were statistically significant, with all valid R^2 values below 0.5 (note that

the elastic modulus evolution for the area treated with salt is derived from only two measurement points). Temporal variation is within small bounds compared to spatial differences. On this basis, we consider the impact of time on the property change to be small – after the mentioned 1 h initial reaction time – and exceeded by spatially distributed inherent local property variation.

4. Discussion and concluding remarks

This study aimed to explore and evaluate various methods for weakening columnar model ice to better simulate summer sea ice conditions suitable for bending-dominated ice failure in laboratory settings, thereby laying the groundwork for new standard definitions. Our approach included mechanical, thermal, and thermohaline methods, each with distinct effects and practical considerations. All methods focused on altering the sprayed surface layer, which is initially necessary as nuclei for the regular congelation ice to grow below. Mechanical methods, such as surface-layer disruption via scratching or breaking, caused an immediate reduction in flexural strength, confirming that the surface layer governs the flexural strength of the model ice. However, these method demonstrated limited applicability and repeatability, potentially compromising the integrity of model tests. Melting of the surface layer caused consolidation below, leading to even stronger ice. The use of styrofoam beads, although initially promising, paradoxically produced a thicker surface layer after transfer into the HSVA LIMB, increasing ice strength. In terms of ease of use and maintaining the facilities clean, we can report that, despite the failure, this was a positive outcome, leading us to pursue other approaches.

The thermohaline method – applying saturated salt solutions – focused on removing the surface layer without other impacts and resulted in a more consistent and effective weakening of the ice within a short time frame of 1 h, and therefore appears promising for creating temporarily weakened, summer-like ice conditions in the laboratory. After spraying sufficient salt to melt the entire surface layer, we observed a -71% reduction in flexural strength, consistent with the intended simulation of summer conditions, where surface melting and warming lead to weaker ice. Unfortunately, there is no field data available to compare this reduction, in which the immediate effect of warming on sea-ice strength was directly measured. To still provide a sense of the order of magnitude of our observed reduction, we estimate the decrease in natural sea ice using a strongly simplified extrapolation based on the flexural strength-to-brine-volume approximation by Timco and Weeks (2010). Following this, the brine volume change estimated with Eq. (1)

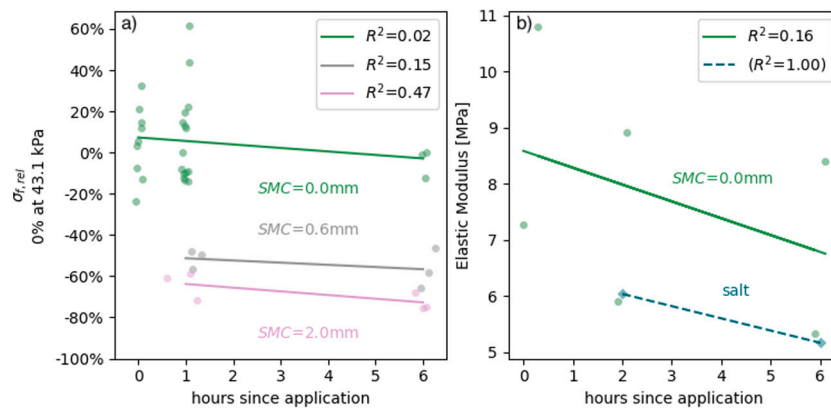


Fig. 14. Temporal changes of mechanical properties over experiment days. The temporal evolution of flexural strength at the small measurement areas on ice sheet Nr. III is included in panel (a) for different SMC s, together with linear regression lines and the coefficient of determination R^2 , which emphasizes a large spread in the data. Similarly, data of the temporal change of the elastic modulus during ice sheet Nr. II is shown in (b).

in sea ice with a constant bulk salinity of 3 g kg^{-1} that warms from -15°C to -2°C would lead to a flexural strength decrease by -62% from 827 kPa to 317 kPa . While this approach simplifies many sea-ice physical processes, such as porosity increase and desalination, it still provides an order-of-magnitude estimate based on the brine volume increase at a commonly observed sea-ice salinity. Our modifications to the model ice are thus probably in a similar range as the effect of summer warming in natural sea ice.

Moreover, the surface melt capacity (SMC) concept proved useful as a predictor for thermohaline surface melt smaller than the seeded surface layer of the model ice. Applying salt amounts exceeding the surface layer thickness did not further weaken the ice significantly as it drained through the underlying permeable columnar ice layer.

While flexural strength was successfully reduced by thermohaline melting of the surface layer, the elastic modulus remained rather constant. Above all, it showed huge inherent local variation in both the directly measured and simulated values across the entire ice sheet. Variations were much larger than on a typical ice sheet, indicating that in this specific case, the postponed recalibration after previous maintenance work on the LIMB technical facilities may have had an aftereffect, especially in the large measurement areas of our third ice sheet.

The different responses of flexural strength and elastic modulus following the removal of the granular surface layer reflect distinct mechanisms governing failure and elastic response, as well as the mechanical impact of the surface layer, which is a fundamental component of the model ice manufacturing process itself. In bending, failure is initiated at the outermost layers, where stresses are maximal, rendering flexural strength highly sensitive to near-interface properties. This sensitivity is further amplified by the asymmetry between tensile and compressive behavior in ice, with tensile strength significantly lower than compressive strength; as a result, failure in downward bending is typically governed by tensile cracking at the surface. The seeded, granular surface layer likely constitutes a relatively strong and flaw-resistant zone, and its thermohaline melting exposes weaker underlying ice, promoting earlier crack initiation and reduced strength. In contrast, the elastic modulus represents the bulk, pre-failure response. It is governed by the integrated stiffness across the entire ice depth, making it comparatively insensitive to the thin surface layer, which does not substantially affect overall stiffness. The only case in which we achieved major changes in the elastic modulus occurred after the complete vertical restructuring within the rubble ice field. This observed behavior of σ_f and E is consistent with principles of sandwich structure mechanics and demonstrates the complex composite structure of the model ice and, potentially, of natural ice as well, as field measurements from von Bock und Polach and Kubiczek (2025) highlight a similar vertical stratification of mechanical properties.

In summer, the flexural strength and the elastic modulus of the Arctic ice are significantly reduced (von Bock und Polach and Kubiczek, 2025) compared to first-year ice in winter (Timco and Weeks, 2010). This reduction also affects the ratio of E and σ_f . While this dimensionless ratio is expected to be at least 2000 for first-year ice in winter (Schwarz, 1977), its exact behavior in summer remains unclear. Based on the values reported in Karulina et al. (2019), ratios larger than 2000 may still be expected for decayed first-year ice, which could be considered an upper threshold. Measurements in von Bock und Polach and Kubiczek (2025) suggest a decrease in the ratio toward summer, reaching values of about 500. Comparing our measurements between untreated reference areas and modified areas, we did not unambiguously match this trend. However, in absolute numbers, we still observed ratios within this range after weakening the ice (Figs. 9 and 12c). We expect that lower ratios of E/σ_f may be generated as well when the bulk model ice is impacted more strongly, leading to a reduction in its elastic modulus, for example through increased bubbling during formation. Such a lower E/σ_f ratio in summer may lead to an amplified ride-up of the ship (Schwarz, 1977) and increased vessel motions, resulting in additional resistance components (von Bock und Polach and Ehlers, 2011; von Bock und Polach, 2016). However, further investigation is required to quantify the contribution of vertical motions to the added resistance in the context of reduced flexural strength, and to determine how the ratio behaves in natural sea ice.

Our results demonstrate a promising proof of concept for adjusting the physical and mechanical properties of model ice to better mimic weakening effects in summer sea ice conditions for failure-dominated icebreaking tests. To establish a definitive ITTC recommendation for model summer sea ice based on these findings, further refinement and development are required. This includes enhancing the homogeneity and automation of spraying techniques and developing an accurate predictive system for the progressive strength degradation during partial surface-layer melting. The number of measurements taken so far has not been large enough for this purpose, given the empirical nature of model ice experiments. In the next step, we will collect measurements of further model ice properties like surface friction in contact with ship hulls and run model tests in the modified ice. Validation using sea-trial data will eventually be essential. This includes comparisons of physical and mechanical ice properties, identifying the elasto-plastic behavior of summer sea ice (from force-displacement curves of cantilever beam tests and thrust-displacement tests at zero speed at a ship's bow), measuring ship motions and performance, and collecting visual observations that enable us to substantiate the phenomenological similarity of the ship-ice interaction and the associated ice failure. The implications of the changing E/σ_f ratio of the modified ice compared to the standard ice need to be further addressed in future work. We also encourage insights and data sharing

from other test basins employing different types of model ice. We here focused exclusively on post-seeding methods, while alternative methods could also include influencing model ice crystal structure in the initial stage, as e.g., demonstrated by [Ziemer \(2018\)](#) who used increased turbulent motion to produce model ice with improved mechanical properties for tests with vertically sided structures at which the ice experiences crushing-dominated failure. During our project, we observed that mechanical field measurements from summer sea ice are generally very sparse. Previous studies, such as [Timco and Weeks \(2010\)](#), even note that their equations with increased brine volumes are not representative of actual ice in summer conditions, as they focus on brine volume rather than porosity. Given the anticipated impacts of climate change, we strongly recommend prioritizing research into the mechanical properties of summer sea ice to improve model accuracy and predictive capabilities.

CRedit authorship contribution statement

N. Fuchs: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **F. von Bock und Polach:** Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis. **P. Buil:** Writing – original draft, Methodology, Investigation, Formal analysis. **S.M. Isay:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **D. Notz:** Writing – review & editing, Methodology, Funding acquisition. **L. Nupnau:** Writing – review & editing, Methodology, Investigation, Formal analysis. **N. Reimer:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **L. Schoepflin:** Writing – review & editing, Methodology, Investigation, Conceptualization. **T. Zorn:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization.

Research data

This study has been conducted using E.U. Copernicus Marine Service Information: <https://doi.org/10.48670/moi-00123>, and with CMIP6 model data accessed from ESGF via the DKRZ using the Python Code

provided under https://github.com/nielsfuchs/CMIP6_and_satellite_SMiLLA.

Processed measurement data from the Ice Sheets at the HSVA are available on Zenodo via <https://doi.org/10.5281/zenodo.20744917> ([Fuchs et al., 2026](#)).

Funding sources

This research was conducted within the BMFTR-funded project SMiLLA 03DPS1278A/03DPS1278B. Publication costs are covered by DEAL.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: HSVA provides testing services in model ice to external customers. The method presented here may form part of these services in the future. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

N.F. and L.N. acknowledge funding from the German Federal Ministry of Research, Technology and Space under the project SMiLLA, grant 03DPS1278A. HSVA personnel acknowledge funding from the German Federal Ministry of Research, Technology and Space under the project SMiLLA, grant 03DPS1278B. We thank the HSVA tank crew for their professional support in conducting all experiments, as well as Susie Brunier and Arved Lattekamp for their support in experiment preparation and manual observations.

Appendix A. Overview of included CMIP6 models in the multi-model temperature mean

The multi-model mean shown in [Fig. 1](#) was constructed from a temporal (monthly), spatial (Arctic Ocean >60°N, all grid cells with sea-ice concentration $SIC > 15\%$) and weighted (with sea-ice area SIA per grid cell) average of the sea-ice surface temperature variable $sitemptop$ in the CMIP6-member models listed in [Table A.3](#).

Table A.3
Overview of included CMIP6 models.

Model	Realization	Forcings
ACCESS-CM2	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
BCC-CSM2-MR	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
CAMS-CSM1-0	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
CESM2-WACCM	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
CESM2	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
CIESM	r1i1p1f1	historical, SSP2-4.5
CMCC-CM2-SR5	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
CNRM-CM6-1-HR	r1i1p1f2	historical, SSP2-4.5, SSP3-7.0
CNRM-CM6-1	r1i1p1f2	historical, SSP2-4.5, SSP3-7.0
CNRM-ESM2-1	r1i1p1f2	historical, SSP2-4.5
CanESM5-CanOE	r1i1p2f1	historical, SSP2-4.5, SSP3-7.0
CanESM5	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
EC-Earth3-CC	r1i1p1f1	historical, SSP2-4.5
EC-Earth3-AerChem	r1i1p1f1	historical, SSP3-7.0
EC-Earth3-Veg-LR	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
EC-Earth3-Veg	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
EC-Earth3	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
FGOALS-F3-L	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
FIO-ESM-2-0	r1i1p1f1	historical, SSP2-4.5
GFDL-CM4	r1i1p1f1	historical, SSP2-4.5
GFDL-ESM4	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
IPSL-CM6A-LR	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
KIOST-ESM	r1i1p1f1	historical, SSP2-4.5
MIROC6	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
MRI-ESM2-0	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
NESM3	r1i1p1f1	historical, SSP2-4.5
NorESM2-LM	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0
NorESM2-MM	r1i1p1f1	historical, SSP2-4.5, SSP3-7.0



Fig. 15. Oblique view of the small measurement areas on ice sheet No. III after surface modification. The extent of the areas was marked on the ice with colored chalk spray. A change in surface appearance from glossy (intact surface layer: surroundings and quadratic reference areas) to matte (thermohaline-melted surface layer: elongated areas) is evident.

Appendix B. The model ice surface appearance in comparison

See Fig. 15.

Data availability

Processed measurement data from the Ice Sheets at the HSVA are available on Zenodo via <https://doi.org/10.5281/zenodo.20744917> (Fuchs et al., 2026).

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