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Small-scale sea ice features revealed by the Pan-Arctic 500 m Ultra-High resolution Sea Ice–Ocean Coupled Model on an Exascale Supercomputer

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Main text

The past two decades witnessed the most rapid decline of Arctic sea ice in recorded history. Compared to pre-2006 conditions, summer sea ice extent has diminished by over 50%, and 35% of the sea ice volume was lost. The Arctic is transitioning into a new normal[1] characterized by a smaller summer ice cover and thinner winter ice. This transformation has attracted substantial attention, not only for scientific research but also because of the emerging socioeconomic opportunities in maritime accessibility.

The small-scale sea ice features like leads and ridges (jointly referred to as linear kinematic features, LKFs) that determine safe shipping passage, remain poorly resolved in current operational forecast systems (res. ~3km). Physically, multifractal sea ice processes, mesoscale oceanic processes, and the coupling between ocean and sea ice are not well studied. Because there are not enough observations and the horizontal resolution of most current models is too low. Many parameterizations, particularly in the sea ice component of model for the Coupled Model Intercomparison Project (CMIP), are often implemented without explicitly representing all the physical processes, or there is no in-depth validation against observations or a solid foundation in model physics. Therefore, to develop the 'Digital Twin' of the Arctic Ocean, resolving the mesoscale and sub-mesoscale processes in the ocean and enabling fine-scale processes in the sea ice including lead formation, floe fragmentation, and ridge dynamics, we configure a state-of-the-art, ultra-high-resolution (finer than 1 km) sea ice–ocean coupled model.

The Quest for Resolution: The Multifractal Nature of Sea Ice and the Eddy-Rich Ocean

The Arctic coupled ice-ocean system presents a unique challenge for numerical modeling due to its inherently multiscale dynamics, e.g., fractal sea ice and turbulent ocean processes. A key limitation arises from the Rossby radius of deformation, which reduces to 2–15 km in the Arctic as a result of stratification, planetary rotation, and many shallow water regions. This necessitates horizontal resolutions finer than 1 km to explicitly resolve mesoscale processes. Yet even at these scales, emergent phenomena driven by nonlinear interactions such as ice fracture cascades, eddy-driven turbulence, frontal processes, deep convection etc. reveal an endless hierarchy of complexity, challenging the very concept of "sufficient resolution" in polar ocean simulations[2].

Satellite-derived deformation fields and model simulations reveal Arctic sea ice as a scale-invariant system, with strain rate spectra exhibiting a persistent slope for the spatial scale above 10km. This power-law behavior is a symptom of the multifractal nature of sea ice, manifested as discrete features (e.g., ice floes, leads, and ridges), shaped by shear and compression in reaction to winds and currents. Eulerian continuum models typically parameterize these processes using the viscous-plastic rheology or other variants. The validations of these parameterization have been conducted against the synthetic aperture radar (SAR) imagery at large scales. Their capacity to replicate observed scaling laws at kilometer-scale resolutions remains unclear. Ice-tracker observations indicate a breakdown in scaling invariance at these scales, raising questions about the limits of current modeling approaches—specifically, where is the methodological 'frontier' and can existing strategies reliably reach it.

Ultra-high-resolution modeling is essential for investigating these unknowns in polar regions, but it ~~still~~ faces a computational scaling crisis. In discrete element sea ice models, each doubling of resolution often requires a 4.2-fold increase in computational resources to preserve statistical accuracy. For Eulerian frameworks, implicit solvers in ice dynamics necessitate solving large sparse matrices— during wintertime a computational cost comparable to full 3D ocean integration. The elastic-viscous-plastic method avoids this through explicit time stepping, but the solutions depend critically on sub-cycling time steps. Small numbers of sub-cycles are criticized for not converging to the physical solution. Beyond the solver challenge, high-resolution simulations also grapple with high I/O burdens, stringent time-step constraints, and the need to reconcile parameterizations developed for large-scale situations with coarse resolutions.

The pan-Arctic Ultra-High-Resolution Sea Ice–Ocean Coupled Model on China’s domestic heterogeneous many-core exascale supercomputer

A pan-Arctic ultra-high resolution sea ice-ocean coupled model is configured based on the Massachusetts Institute of Technology general circulation model[3] and has been substantially refactored and improved to adapt to the exascale computing system Sunway. The model's Pacific open boundary is positioned north of the Okhotsk Sea, away from the Aleutian Islands, and the Atlantic open boundary is set north of the Strait of Gibraltar (Figure 1a). It operates on a three-dimensional grid comprising approximately 15.1 billion points, with around 9 billion wet points. The horizontal grid spacings range from 391 m (minimum) to 641 m (maximum), resulting in a mean of 589 m, and is therefore nominally referred to as 500 m resolution in this study. To the authors' knowledge, it is the first model covering the whole pan-Arctic region with resolution to such level.

The sea ice component[4] shares the same grid as the ocean model, enabling direct coupling at each grid point. For sea ice thermodynamics, a zero-heat-capacity model is employed, while sea ice dynamics uses the viscous-plastic rheology. After discretization, the highly nonlinear sea ice momentum equations are solved using the Picard iteration with the linearized system solved by a tridiagonal solver combined with a line successive relaxation method[5]. The nonlinear loop is iterated 10 times, with each iteration allowing a maximum of 500 steps.

The heterogeneous many-core computer Sunway has a unique design both in hardware and software[6], which makes it necessary to refactor the model code for a high performance computation. We use the secondary parallelization feature that, similar to GPU-based approaches, significantly enhances computational efficiency. To further accelerate the solving of the Helmholtz equation, a Stiefel iteration solver based on Chebyshev polynomials is employed in the model, which estimates the maximum and minimum eigenvalues only once during model initialization. Additionally, a high-capacity input/output (I/O) interface has been implemented to handle large datasets, enabling high-frequency diagnostics suitable for mesoscale and submesoscale research. Using over 16,000 cores, the model achieved a simulation rate of approximately 7.5 simulated days per day from February 2019 to October 2020, covering the MOSAiC expedition (Multidisciplinary drifting Observatory for the Study of Arctic Climate). The total output reached 5.7 PB, with data saved in parallel at frequencies as high as hourly.

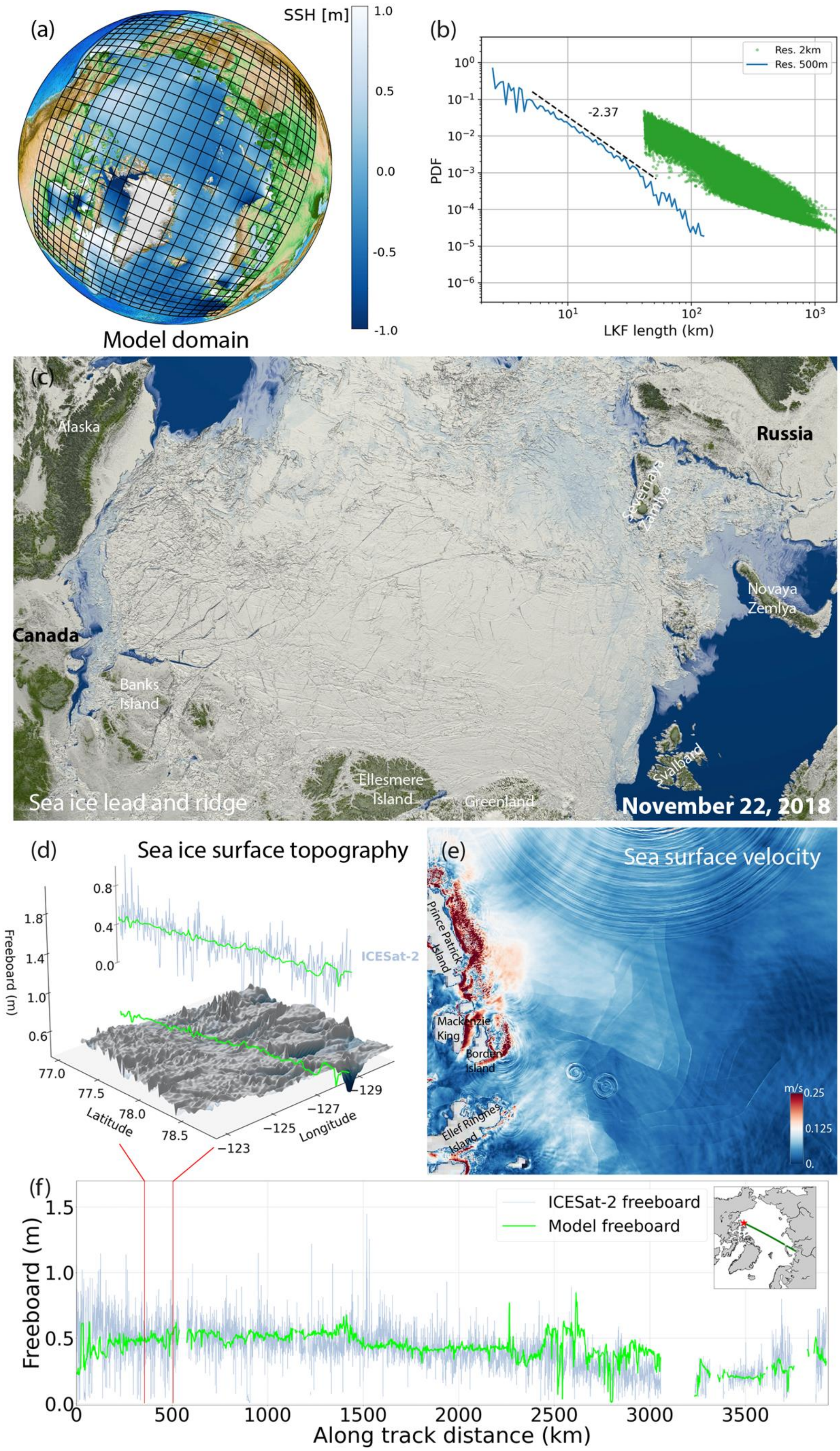
(a)
SSH [m]
1.0
0.5
0.0
-0.5
-1.0
Model domain
(b)
Res. 2km
Res. 500m
-2.37
PDF
LKF length (km)
(c)
Alaska
Russia
Severnaya Zemlya
Novaya Zemlya
Canada
Banks Island
Ellesmere Island
Greenland
Svalbard
Sea ice lead and ridge
November 22, 2018
(d)
Sea ice surface topography
ICESat-2
Freeboard (m)
Latitude
Longitude
(e)
Sea surface velocity
Prince Patrick Island
Mackenzie King
Borden Island
Ellef Ringnes Island
m/s
(f)
ICESat-2 freeboard
Model freeboard
Freeboard (m)
Along track distance (km)

Figure 1. Simulation results from the pan-Arctic ultra-high resolution sea ice-ocean coupled model.
(a) The model domain with sea surface anomaly covered by a coarse mesh every 500th grid point.
(b) The probability distribution function (PDF) of LKFs simulated by models with 2km (green dot) and 500 m resolution (blue line). Slope of the blue curve is denoted by the black dash line.
(c) A sea ice thickness snapshot showing simulated ice leads and ridges on November 22, 2018 over the entire Arctic.
(d) The simulated sea ice surface topography in the Beaufort Sea with ICESat-2 fly over. The model total freeboard is shown in green along the superimposed ICESat-2 trajectory. The comparison in a lifted axes shows the total freeboard simulated by the model and observed from the ICESat-2.
(e) Sea surface speed north of the Queen Elizabeth Islands, parts of the Canada Arctic Archipelago.
(f) The total freeboard from the model and ICESat-2 along a track crossing the Eurasian Basin and the Amerasian Basin. The red star in the trajectory in the figure inset marks the starting point.

Blurring the simulation-reality divide: high-fidelity sea ice leads and pressure ridges

Resolution is the primary factor governing the LKF generation within a Eulerian framework with a viscous-plastic rheology. Simulated sea ice leads populate the entire Arctic, closely resembling natural conditions (Figure 1c). Interactions with topography cause sea ice to fracture, resulting in open water, for example, when ice is driven away north of Banks Island. Notably, sea ice ridges emerge at this resolution—a feature not observed in other models—particularly north of Alaska in the Beaufort Sea and north of Russia in the East Siberian Sea. These ridges are generated by the convergence of sea ice motion driven by atmospheric forcing. The ridge generation is further illustrated by the sea ice surface topography shown in Figure 1d. The rugged ice surface exhibits large-scale ridges and inherent anisotropic characteristics, although local variability remains smaller than that captured by ICESat-2 on-track monitoring data. As illustrated by one of the 18,000 ICESat-2 trajectories over the simulated coverage (Figure 1f), the simulated total freeboard aligns well with observations across the Arctic at the basin scale. The ultra-high-resolution model reproduces LKFs with a length distribution slope of -2.37. In contrast to a 2 km resolution simulation, where LKFs show a higher probability of extending beyond 100 km and can reach lengths up to 1000 km, the ultra-high-resolution model restricts most LKF lengths to under 100 km (Figure 1b).

Multi-scale sea ice-ocean coupling processes

Coupling processes between sea ice and the ocean occur across multiple scales. The ultra-high-resolution model simulates physical processes that are theoretically expected but have been difficult to observe directly. As shown in Figure 1e north of Ellef Ringnes Island, sea ice fracture perturbs the ocean surface, generating gravity waves that manifest as concentric circles in the velocity fields. Sea ice leads form open water, which is accelerated by wind, creating local velocity maxima that appear as linear features in the velocity field. Interactions between waves and topography around these islands exhibit wave reflection and interference, contributing to the generation of polynyas and open water along the coast. In contrast, large-scale level ice damps and absorbs surface undulations, resulting in uniform velocity fields; these appear as triangular features north of Borden Island and Mackenzie King Island in Figure 1e. Vigorous ocean processes, akin to those in other high-resolution models[7], are also simulated. These include tidally generated internal waves north of Svalbard, a rich field of ocean eddies along the Atlantic Water pathway, submesoscale filaments, and strong frontogenesis in the Greenland Sea.

Summary and prospect

This study presents a pioneering pan-Arctic sea ice–ocean coupled model at an unprecedented ~500 m resolution, achieving highly realistic simulations of sea ice leads, pressure ridges, and multi-scale ice-ocean interactions that narrow the gap between modeling and reality. By explicitly resolving previously unobserved processes, the model provides new physical insights into Arctic dynamics and offers valuable guidance for designing future observational campaigns. Looking ahead, this high-resolution framework paves the way for next-generation Earth system models, supports AI-driven model optimization through its vast output dataset, and serves as a critical step toward developing a digital twin of the Arctic for enhanced climate prediction and strategic decision-making.

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Declaration of interests

The authors declare no competing interests.

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