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Dynamic–thermal coupling drives increasing oceanic eddy-to-ice heat fluxes in the Arctic

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Abstract

Rapid Arctic sea-ice retreat is exposing the upper ocean to intensified mesoscale variability, yet whether the mechanism by which eddies deliver heat to the ice base evolves with this retreat remains unclear. Here we use an eddy-resolving coupled model to examine how basal heat-transfer mechanisms evolve over a century-long simulation of sea-ice retreat. As the marginal ice zone expands, eddy-driven ocean-to-ice heat flux intensifies and contributes an increasing share of the sea-ice heat budget. A decomposition of this eddy-driven flux into thermal, mechanical, and covariance components shows that the thermal and mechanical terms remain substantial across contrasting ice states, but neither exhibits a systematic increase across marginal ice regimes during sea-ice retreat. The overall strengthening is instead driven by the growth of the covariance term. As sea ice thins and retreats, intensified friction-velocity fluctuations become more tightly coupled to upper-ocean temperature anomalies, allowing mesoscale variability to transfer heat more efficiently to the ice base. These results reveal a state-dependent mesoscale pathway for Arctic sea-ice loss that is not captured by mean-gradient-based parameterizations in current climate models.

Introduction

Arctic sea ice is declining at an unprecedented rate, reshaping the high-latitude ocean–ice–atmosphere system (1–5). As the ice cover retreats and thins, the upper Arctic Ocean absorbs more solar radiation and receives enhanced lateral heat transport through the Atlantic and Pacific gateways, progressively increasing the oceanic heat available beneath the ice (6–10). On multi-decadal timescales, ocean-to-ice heat flux (OHF) is projected to exceed atmospheric forcing as the dominant driver of summer sea-ice loss (11). Yet it remains unclear whether this growing oceanic heat supply simply accelerates basal melt or also alters the dominant pathway by which heat is delivered to the ice base.

The marginal ice zone (MIZ), where fragmented and mobile sea ice interacts with the open ocean, has expanded substantially as Arctic sea ice has retreated and has become a key region of ocean-to-ice heat exchange (12). Within the MIZ, mesoscale eddies arising from ocean dynamical instabilities play an important role in redistributing heat and regulating its delivery to the ice base (13–19). Eddy activity is also projected to intensify as sea ice declines (20). By creating localized and intermittent pathways for oceanic heat to reach the underside of the ice, these eddies modulate basal melt (21–22) and influence sea-ice distribution within the MIZ (23–24). However, whether eddies

simply enhance ocean-to-ice heat transfer or whether the mechanisms of eddy-driven ocean-to-ice heat transfer themselves evolve as sea ice retreats remains unresolved.

Current climate models, limited by coarse horizontal resolution, parameterize rather than explicitly resolve mesoscale dynamics in the Arctic Ocean (25-26). Such parameterizations represent eddy effects through time-mean gradients and therefore do not explicitly capture covariance between friction-velocity fluctuations and thermal-driving anomalies at the ice-ocean interface. As sea ice thins and retreats, the mechanisms by which eddies transfer heat to the ice base may change in ways that mean-state parameterizations cannot represent.

Here we use the eddy-resolving global coupled model AWI-CM3, with 2-km ocean resolution in the Arctic, to diagnose how the mechanistic pathways of eddy-driven ocean-to-ice heat transfer evolve across contrasting sea-ice states in a century-long simulation. By decomposing eddy-driven OHF into thermal, mechanical and covariance components, we show that sea-ice retreat reorganizes the internal structure of eddy-driven heat transfer, with an emerging dynamic-thermal coupling at the ice base becoming the primary source of intensification. This covariance-driven pathway, which is not explicitly represented in current climate-model parameterizations, may become increasingly important for future basal heat transfer in the Arctic marginal ice zone.

Intensification of eddy-driven ocean-to-ice heat flux during sea ice retreat

Arctic sea-ice area declines throughout the twenty-first century in the AWI-CM3 simulation, with September showing the steepest reductions and approaching ice-free conditions by the end of the century (Fig. 1a). To examine how ocean-to-ice heat transfer evolves with this decline, we define three reference periods that represent contrasting ice states rather than predictions of specific future conditions: a Modern state (2004–2013), a Mid-term state (2050–2059), and a Long-term state (2090–2099). Simulated sea-ice variability agrees well with observations from the National Snow and Ice Data Center (NSIDC), with anomaly correlations of $R = 0.73$ for both annual-mean and September sea-ice area over 1989–2019 (Extended Data Fig. 1). Across all three reference periods, sea-ice loss is most pronounced in summer (June–August) (Extended Data Fig. 2a), when the marginal ice zone is most extensive and ocean-to-ice heat exchange is most active. We therefore focus on summer to examine how eddy-driven heat-transfer processes differ among contrasting ice states. Summer sea-ice area decreases from about 8.5 to 4 million km² across the three states, accompanied by a pronounced poleward retreat of the marginal ice zone (MIZ; sea ice concentration (SIC) < 80%) (Fig. 1b). Over the same period, sea surface temperature (SST) rises and sea-

surface eddy kinetic energy (EKE) more than doubles (Fig. 1c,d; Extended Data Fig. 2b,c), indicating a progressively more energetic upper ocean as ice cover declines.

As sea ice retreats, the marginal ice zone expands from the Atlantic inflow sector into the broader Arctic interior (Fig. 2a), accompanied by widespread thinning along the expanding ice edge (Extended Data Fig. 3). Ocean-to-ice heat flux (OHF) intensifies and extends poleward with the MIZ (Fig. 2b). In the Modern and Mid-term states, elevated OHF is largely confined to the Barents Sea and Fram Strait, where warm Atlantic inflow promotes basal melt. By the Long-term state, regions of high OHF extend across the Eurasian Basin and onto continental shelves, closely following the widened MIZ. Within this expanding zone, eddy-driven OHF increases in both magnitude and spatial extent, accompanied by intensified sea-surface EKE (Fig. 2c; Extended Data Fig. 4a,b). Areas where eddy contributions exceed 50% of total OHF are initially restricted to narrow bands along the ice edge in the Modern state, but expand across much of the MIZ by the Long-term state, particularly in the Barents Sea, Eurasian Basin, Chukchi Shelf and Baffin Bay. Within a fixed analysis domain encompassing the Modern MIZ (purple line in Fig. 2c), a sea-ice heat-budget analysis (Fig. 2d) is consistent with this transition: in the Modern and Mid-term states, atmosphere-to-ice heat flux exceeds OHF and eddy contributions are minor, whereas by the Long-term state OHF approaches the magnitude of atmospheric flux, with eddy-driven OHF becoming a substantial contributor (~26% of total OHF within the analysis domain).

The increase in eddy contribution is not spatially uniform across sea-ice concentration regimes (Fig. 3). The high-SIC region (>80%) retreats, whereas all MIZ regimes (<20%, 20–60%, and 60–80%) expand (Fig. 3a). Sea-ice thickness decreases in both the high-SIC and MIZ regions (Fig. 3b). In the high-SIC region, atmosphere-to-ice heat flux remains the dominant heat source across all three states and continues to exert a strong influence in regions with SIC above 60% (Fig. 3c). By contrast, in lower-SIC regions (<60%), OHF rivals or exceeds atmospheric flux as the primary driver of ice melt. The eddy fraction of total OHF increases across all SIC regimes, but most strongly in the <20% and 20–60% regimes (Fig. 3c). Across all three states, both the eddy-driven fraction of total OHF and sea-surface EKE increase as SIC decreases (Fig. 3c,d), with the largest eddy contributions and highest EKE consistently occurring in the least ice-covered regions. Because these lower-SIC regions also expand in area (Fig. 3a), they further amplify the Arctic-wide contribution of eddy-driven OHF. Within the MIZ, stable sea ice (lifetime ≥ 30 days) is concentrated mainly in the 20–60% and 60–80% SIC regimes, whereas the <20% regime is dominated by short-lived ice (Extended Data Fig. 5). We therefore focus the mechanistic analysis on partially ice-covered regimes (20–80% SIC), where persistent sea ice interacts most directly with eddy-driven ocean-to-ice heat transfer.

Mechanistic evolution of eddy-driven ocean-to-ice heat flux

The intensification of eddy-driven OHF documented above indicates that basal heat transfer in the MIZ becomes increasingly sensitive to mesoscale variability as sea ice retreats. To identify the source of this intensification, we decompose eddy-driven OHF into three mechanistic components: a thermal term ($\overline{u_*'T_d'}$), representing transient thermal-driving anomalies acting on the mean friction velocity; a mechanical term ($u_*'\overline{T_d}$), reflecting friction-velocity fluctuations acting on the mean thermal driving; and a covariance term ($u_*'T_d'$), representing the temporal coupling between friction-velocity fluctuations and thermal-driving anomalies (Fig. 4a). In both Low-mid MIZ (20–60% SIC) and High MIZ (60–80% SIC), the thermal and mechanical terms dominate eddy-driven OHF in the Modern state, whereas the covariance term contributes a smaller fraction of eddy-driven OHF (Fig. 4a). As sea ice retreats, the thermal and mechanical terms remain substantial but show no systematic increase, whereas the covariance term increases substantially and becomes a major contributor—and is the only component that grows coherently across the three ice states (Fig. 4a).

The origin of this reorganization becomes clearer from the evolution of the underlying thermal and mechanical drivers. From the Modern to the Long-term state, friction-velocity anomalies, u_*' , increase markedly, whereas the mean friction velocity, $\overline{u_*}$, remains relatively stable and both the mean thermal driving, $\overline{T_d}$, and thermal-driving anomalies, T_d' , decrease (Fig. 4b, c). This weakening of local thermal contrast does not indicate a cooling upper Arctic Ocean, because basin-averaged SST increases from the Modern to the Long-term state (Fig. 1c). Instead, it reflects the poleward migration of the MIZ into colder background waters (Extended Data Fig. 6), while stronger friction-velocity variability compensates for the weaker thermal driving. As sea ice thins and becomes more mobile, mesoscale variability is transmitted more effectively into ice–ocean friction-velocity variability: for a given EKE, u_*' is systematically larger in the Long-term state (Fig. 4d). When these amplified friction-velocity fluctuations become temporally aligned with thermal-driving anomalies, the covariance term, $u_*'T_d'$, strengthens. This coherence becomes pronounced in the Long-term state across much of the Arctic (Extended Data Fig. 7). The thermal term weakens because it depends on T_d' , which decreases across ice states. The mechanical term shows a modest increase in the High MIZ, where amplified u_*' partly compensates for declining $\overline{T_d}$, but the increase is limited. Both contributions therefore remain important but are increasingly outpaced by the covariance term.

The covariance-driven intensification operates across the expanding MIZ, but the balance between the amplitude of u_*' and its coherence with T_d' differs between SIC regimes. Both controls strengthen as sea ice retreats, yet their relative importance varies with SIC. In the Low-mid MIZ, the temporal correlation between u_*' and T_d' is strong and spatially extensive (Extended Data Fig. 7), making coherence the main driver of covariance-term growth in this regime. In the High MIZ, the correlation is weaker, but u_*' is substantially larger for a given level of EKE, and this advantage increases from the Modern to the Long-term state (Fig. 4d). This contrast is consistent with differences

in ice conditions. In the Low-mid MIZ, sparse ice can drift more freely with the surface ocean, reducing ice–ocean relative velocity and thereby limiting friction-velocity fluctuations. In the High MIZ, ice is denser but remains mobile, providing sufficient mechanical resistance to sustain larger ice–ocean friction-velocity fluctuations while still responding to mesoscale forcing. Together, these complementary effects allow the covariance-driven pathway to intensify across the full width of the MIZ as sea ice retreats.

In addition to friction-velocity fluctuations, the covariance term also depends on the processes that sustain summer thermal-driving anomalies. Mixed-layer temperature variability in the MIZ is driven primarily by atmospheric heat flux, which remains the dominant source of upper-ocean warming across all three ice states (Extended Data Fig. 8). At the same time, horizontal and vertical eddy heat advection both intensify and expand with the widening MIZ (Extended Data Fig. 4c, d), providing an additional source of upper-ocean thermal variability along the ice edge and adjacent shelf seas. The covariance-driven pathway therefore links two processes: atmosphere-driven upper-ocean thermal anomalies and eddy-driven friction-velocity fluctuations at the ice base. Sea-ice retreat strengthens the latter while the former persists, allowing their temporal coupling to become an increasingly effective pathway for basal heat transfer. Ultimately, sea-ice retreat increases not simply the exposure of the ice base to oceanic heat, but the efficiency with which mesoscale variability transfers that heat across the ice–ocean interface.

Discussion

Our results show that Arctic sea-ice retreat does not simply increase eddy-driven ocean-to-ice heat transfer, but changes how mesoscale variability couples to the ice base. In the modern MIZ, eddy-driven OHF is mainly supported by thermal and mechanical terms, whereas covariance plays a minor role. As the MIZ expands and sea ice becomes thinner and more mobile, the covariance term becomes the fastest-growing component, linking atmosphere-sustained upper-ocean thermal anomalies with eddy-amplified friction-velocity fluctuations at the ice base. Thus, thermal and mechanical controls remain important, but basal heat transfer becomes increasingly sensitive to the temporal coupling between dynamic and thermal anomalies. This evolution suggests a potential positive feedback: as sea ice thins and retreats, the upper ocean becomes more dynamically active, intensifying covariance-driven ocean-to-ice heat transfer, which may promote further basal melt and MIZ expansion. At the same time, this feedback is likely self-limiting, operating only where sea ice remains sufficiently thick and dense to sustain ice–ocean friction-velocity fluctuations against mesoscale forcing.

The emergence of the covariance pathway has important implications for climate-

model development. Current coarse-resolution models can reproduce the broad trajectory of Arctic sea-ice decline (27–30), but many represent unresolved eddy effects primarily through parameterizations tied to mean-state gradients and therefore do not explicitly capture the covariance pathway identified here. Our results suggest that this limitation may be less consequential under modern conditions, when covariance contributions are small, but may become increasingly important as sea ice thins and the covariance term grows. The implication is not only one of model resolution. Even if a model reproduces the correct total OHF, it may do so through an incorrect combination of mechanisms and could therefore respond inaccurately as ice conditions move beyond the range over which present-day parameterizations were developed. Capturing the state-dependent coupling between interfacial friction-velocity variability and thermal-driving anomalies at the ice base may therefore be necessary to represent the changing efficiency of ocean-to-ice heat transfer under continued warming. Future projections of Arctic sea-ice loss may thus depend not only on simulated ocean heat near the ice margin, but also on how efficiently mesoscale variability transfers that heat to the ice base.

Several limitations should be acknowledged. Our analysis is based on a single eddy-resolving coupled simulation under the SSP5-8.5 scenario and therefore does not constrain the precise timing or spatial pattern of future sea-ice loss. The mechanism identified here should instead be interpreted as a state-dependent process emerging as the ice cover thins and the MIZ expands. In addition, the continuum sea-ice formulation in AWI-CM3 does not resolve floe-scale processes such as lateral melting, which may modify ice–ocean coupling (31–35). The decomposition framework also isolates pathways within the bulk OHF parameterization and does not explicitly represent smaller-scale processes such as under-ice turbulent mixing or meltwater-driven stratification. Testing this mechanism across other eddy-resolving models and with emerging under-ice observations will be necessary to assess the generality of the covariance-driven pathway across Arctic regions and ice states.

Despite these limitations, our results identify a state-dependent pathway by which sea-ice retreat can increase the efficiency of ocean-to-ice heat transfer. The emergence of this covariance-driven pathway highlights a mechanism that is not explicitly represented in many current climate-model parameterizations and that may become increasingly important for the future mass balance of the Arctic marginal ice zone.

Author Contributions

YL designed and performed the analyses and wrote the manuscript, building on an original idea proposed by RG. YL and RG jointly developed the study. GL and DS

provided climate model output and computational infrastructure. All authors contributed to the interpretation of the results and revision of the manuscript.

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Data Availability

The AWI-CM3 simulation output used in this study is available upon reasonable request due to the large data volume. Sea-ice concentration observations are from the NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (<https://nsidc.org/data/>).

Conflict of Interest

The authors declare no competing interests.

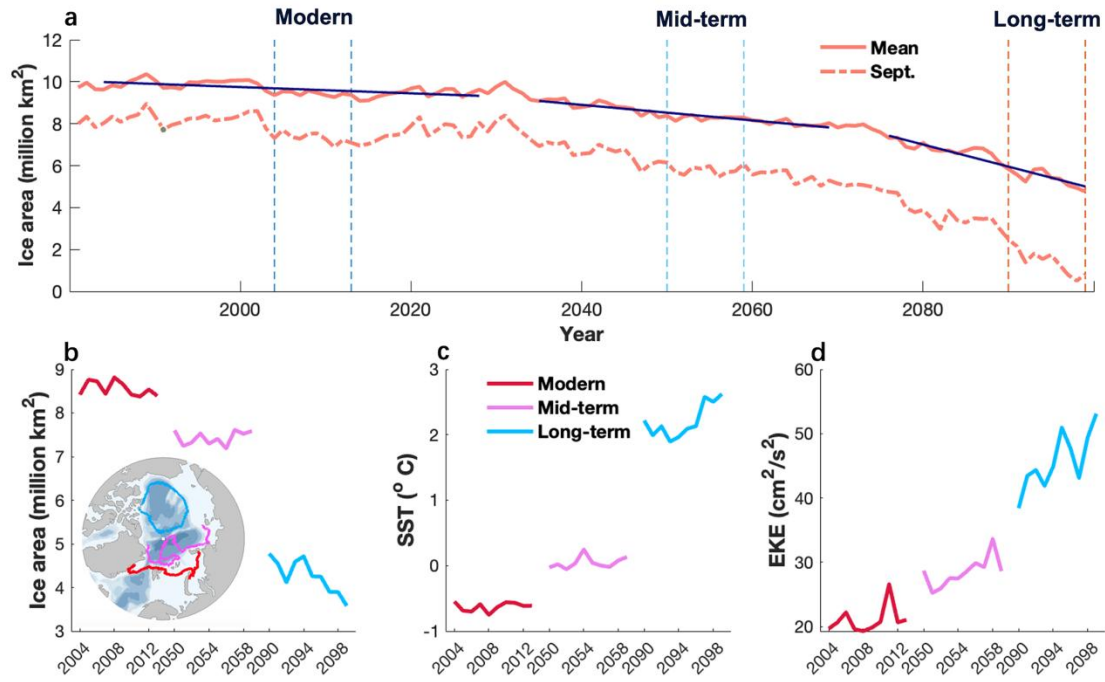


Fig. 1 | Long-term changes in Arctic sea-ice, sea surface temperature (SST), and eddy kinetic energy (EKE). **a**, Time series of Arctic sea-ice area from the high-resolution coupled simulation, showing annual means (red solid curve) and September minima (red dashed curve), with a linear fit to the annual-mean series (blue). Agreement with NSIDC observations is shown in Extended Data Fig. 1. Vertical dashed lines indicate the three reference periods analyzed here: the Modern (2004–2013), Mid-term (2050–2059), and Long-term (2090–2099) states. **b**, Summer (June–August) Arctic sea-ice area for the three reference periods. Inset, circumpolar ocean bathymetry and summer-mean marginal ice zone extent (MIZ; SIC < 80%) in 2010, 2055, and 2095, with boundaries color-coded by period. **c**, Arctic-mean summer SST in each period. **d**, Arctic-mean summer sea-surface EKE in each period. The decline in summer sea ice is accompanied by warmer surface waters and stronger eddy activity, consistent with a progressively more energetic upper ocean as sea ice retreats.

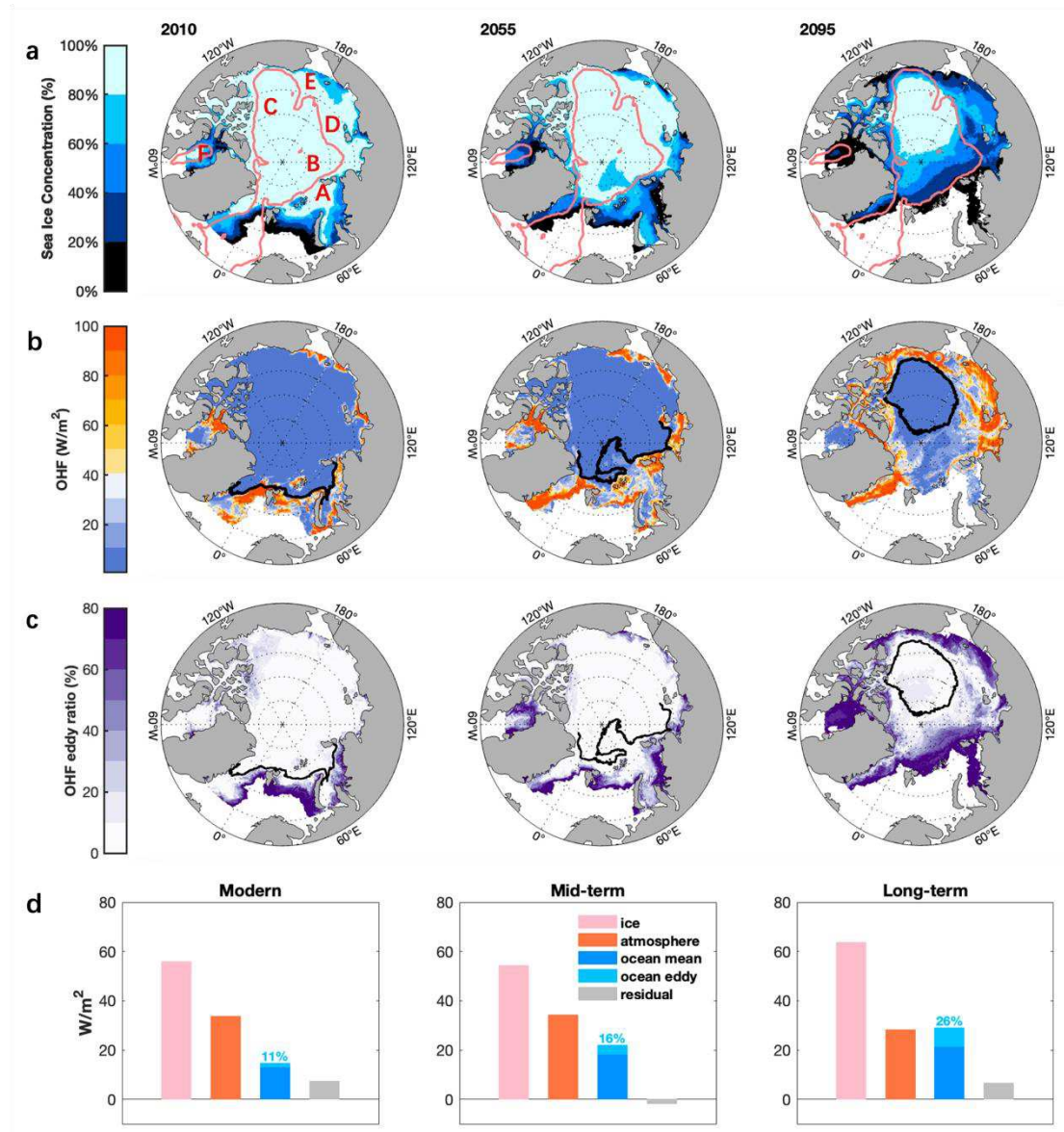


Fig. 2 | Long-term changes in Arctic summer sea-ice concentration, ocean-to-ice heat flux, eddy contribution to ocean-to-ice heat flux, and sea-ice heat budget. a, Summer (June–August) sea-ice concentration in 2010, 2055, and 2095 from the coupled simulation with 2-km ocean resolution in the Arctic. Regional domains are labeled as follows: A, Barents Sea; B, Eurasian Basin; C, Canadian Basin; D, Laptev Sea; E, Chukchi Shelf; and F, Baffin Bay. The light red contour marks the 1,000-m isobath. **b,** Spatial distribution of ocean-to-ice heat flux (OHF) for the three time slices. Black contours indicate the marginal ice zone (MIZ; SIC < 80%). **c,** Eddy contribution to OHF, expressed as the ratio of eddy-driven OHF to total OHF. The purple dashed line marks the northern boundary of the sea-ice heat-budget analysis shown in panel d. **d,** Components of the sea-ice heat budget for the Modern (2004–2013), Mid-term (2050–2059), and Long-term (2090–2099) states in the region south of the boundary shown in c. Numbers above the bars indicate the percentage contribution of eddy-driven

OHF to total OHF. As the MIZ expands, eddy-driven OHF becomes an increasingly important component of the Arctic summer sea-ice heat budget.

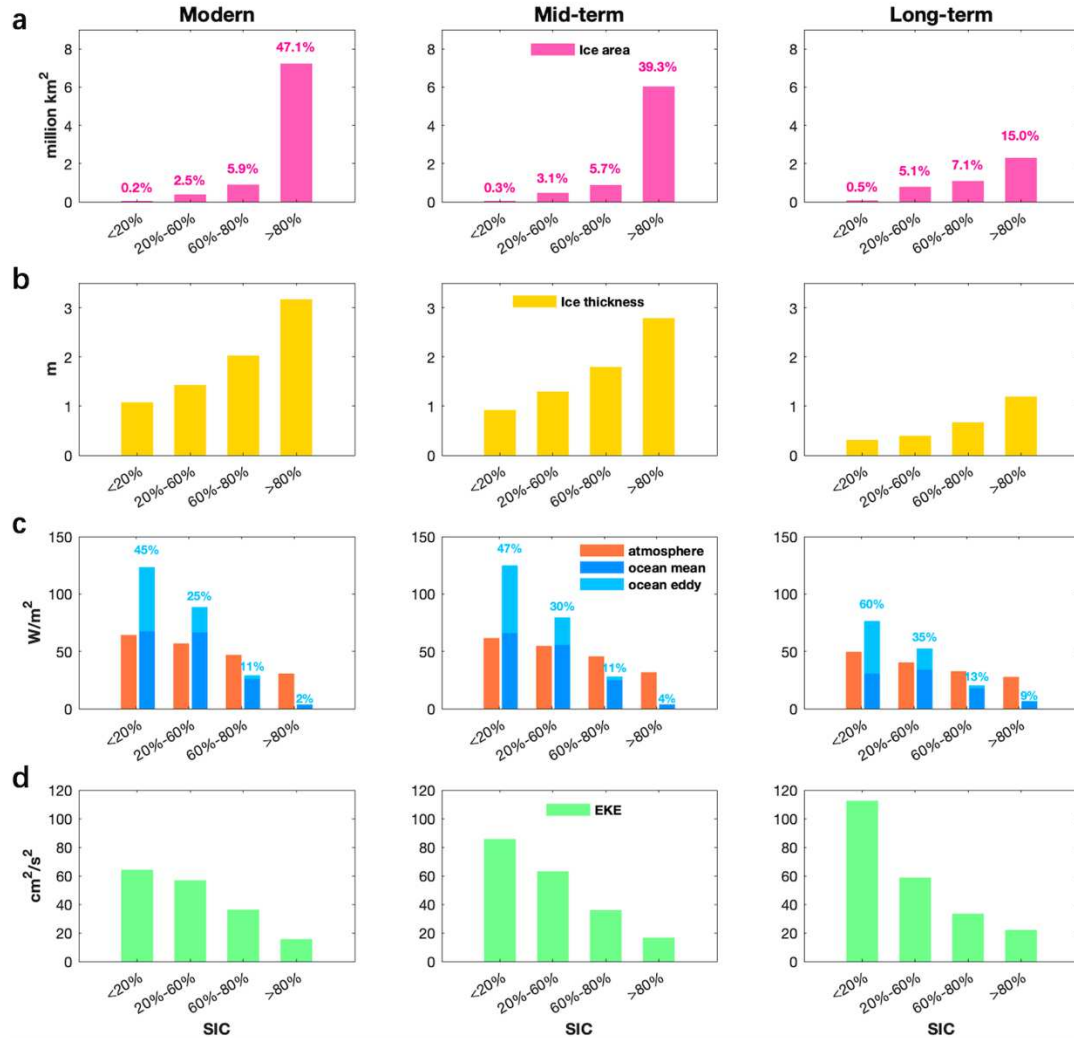


Fig. 3 | Simulated changes in Arctic sea-ice area, sea-ice thickness, sea-ice heat budget components, and eddy kinetic energy (EKE) across sea-ice concentration (SIC) regimes in summer. a, b, Sea-ice area and sea-ice thickness binned by SIC (<20%, 20–60%, 60–80%, and >80%) for the Modern (2004–2013), Mid-term (2050–2059), and Long-term (2090–2099) states. Percentages in panel a indicate the fractional area of each SIC bin relative to the total Arctic Ocean area within the analysis domain; the remainder corresponds to open water. c, Sea-ice heat-budget components averaged within each SIC bin. Percentages indicate the contribution of eddy-driven OHF to total OHF. d, Sea-surface EKE for each SIC bin. The increasing contribution of eddy-driven OHF is associated with the expansion of partially ice-covered regions, concurrent sea-ice thinning, and intensified eddy activity within the MIZ.

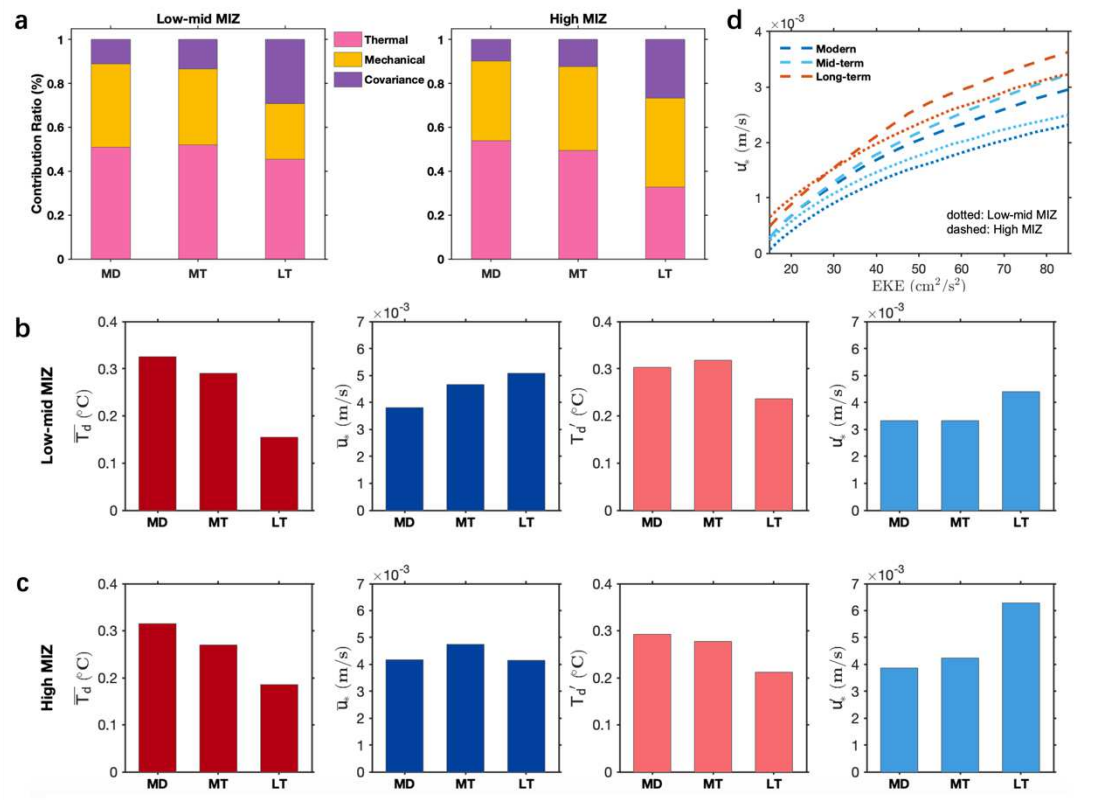


Fig. 4 | Mechanistic evolution of eddy-driven ocean-to-ice heat transfer across sea-ice states in summer. **a**, Decomposition of eddy-driven OHF into thermal ($\overline{u_* T_d'}$), mechanical ($\overline{u_*' T_d}$), and covariance ($\overline{u_*' T_d'}$) terms, shown as stacked contribution ratios in the Low-mid (20–60% SIC) and High (60–80% SIC) MIZ during the Modern (MD), Mid-term (MT), and Long-term (LT) states. **b**, **c**, Thermal component ($\overline{T_d}$ and T_d') and mechanical components ($\overline{u_*}$ and u_*') in the Low-mid (**b**) and High (**c**) MIZ. Panels **a**–**c** use daily data with eddy-driven OHF above 10 W/m^2 . **d**, EKE-bin-averaged u_* in the Low-mid (dotted) and High (dashed) MIZ regimes across the three states. The covariance term increases systematically across ice states, driven mainly by amplified friction-velocity fluctuations and stronger coupling between friction-velocity fluctuations and thermal-driving anomalies at the ice base.

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Methods

Description of model simulations

The AWI Climate Model 3 (AWI-CM3) is a fully coupled climate model. Its ocean component, the Finite volume Sea ice–Ocean Model (FESOM2), developed at AWI, uses Arakawa B-grid finite-volume discretization on unstructured triangular meshes, allowing spatially variable resolution where needed (36). The computational mesh design follows the approach of ref. 37, which aims to distribute mesh nodes over the global ocean as efficiently as possible. Two criteria are used to determine the horizontal resolution. The first is eddy-resolving resolution based on the local baroclinic Rossby radius (Extended Data Fig. 9), for which half of the Rossby radius calculated from PHC climatology is adopted as the target scale. The second is enhanced resolution in regions of strong ocean variability. Relying only on the local Rossby radius would produce an excessively coarse mesh in the tropics, where the Rossby radius can exceed 200 km, and an excessively fine mesh at high latitudes. To avoid unrealistically high resolution, a minimum grid-spacing threshold is imposed. To better resolve the tropics and other eddy-active regions, the mesh is also adapted to observed sea surface height variance as a proxy for ocean variability. In this configuration, the ocean resolution ranges from about 2 km in the Arctic Ocean and shelf seas to 6–7 km in regions of strong variability, with a maximum grid spacing of 25 km. The model setup includes 13 million surface nodes and 60 vertical levels.

The atmospheric component of AWI-CM3 is OpenIFS, based on the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System (IFS). The atmospheric configuration uses a Tco639 computational grid, corresponding to a horizontal resolution of approximately 16 km.

The model spin-up was conducted in two stages. First, the ocean model was forced by atmospheric reanalysis for approximately 100 years. After this adjustment, the final ocean state was used to initialize the fully coupled AWI-CM3 simulation, which was integrated from 1920 to 2014 using historical CMIP6 forcing and then continued from 2015 to 2100 under the SSP5-8.5 forcing scenario.

Observation-based dataset

Sea-ice concentration observations are taken from the NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, which provides daily satellite-derived retrievals from SMMR, SSM/I and SSMIS on a 25 km × 25 km polar stereographic grid from 1978 to the present (<https://nsidc.org/data/>). The overlapping period 1989–2019 is used to evaluate the simulated interannual variability of Arctic sea-ice area against observations.

Eddy Kinetic Energy (EKE) Calculation

Eddy kinetic energy (EKE) is calculated from daily velocity anomalies relative to the seasonal mean for each year:

$$u' = u - \bar{u} \quad (1)$$

$$v' = v - \bar{v} \quad (2)$$

where u and v are the daily zonal and meridional velocity components, respectively, and $\bar{u}$ and $\bar{v}$ represent their corresponding seasonal means for the given year.

The daily EKE is then calculated as:

$$EKE = \frac{1}{2}(u'^2 + v'^2) \quad (3)$$

Finally, the seasonal mean $\overline{EKE}$ is obtained by averaging EKE over the given season.

Arctic sea-ice heat budget

The Arctic sea ice heat budget is evaluated using the equation (11):

$$\frac{d}{dt}HC = F_{ocn} + F_{atm} + F_{residual} \quad (4)$$

where HC represents the heat content of the snow and ice, F_{ocn} is the ocean-to-ice heat flux, F_{atm} is the atmosphere-to-ice heat flux, and $F_{residual}$ is the residual term accounting for the difference between $\frac{d}{dt}HC$ and the sum of the oceanic and atmospheric heat fluxes. The $F_{residual}$ term accounts for contributions from sea ice export across the boundaries of the heat budget calculation domain in the Arctic Ocean.

The sea ice heat content HC is calculated from the latent heat energy stored in sea ice within a given region.

$$HC = SIA \cdot m_{ice} \cdot \rho_{ice} \cdot L_f \quad (5)$$

where SIA indicates the sea ice area, m_{ice} indicates the sea ice thickness, $\rho_{ice} \sim 917 \text{ kg/m}^3$ indicates density of ice, and $L_f \sim 334000 \text{ J/Kg}$ indicates the latent heat of fusion of ice. This calculation assumes that changes in sea ice heat content are primarily governed by thermodynamic processes, such as melting and freezing, rather than dynamic processes like ice advection or deformation. This assumption is justified by the dominant role of thermodynamic processes in seasonal sea ice variability, particularly in the Arctic, where sea-surface energy fluxes and ocean heat uptake exert a significant influence on ice melt and growth (38-39). Furthermore, both observational analyses and numerical modeling studies have demonstrated that thermodynamic mechanisms are the primary drivers of long-term sea ice decline in response to climate warming (5,40).

To evaluate the ocean-to-ice heat flux (OHF) consistently across different reference periods, we employ a physically consistent bulk parameterization. The OHF represents the heat transferred from the uppermost ocean mixed layer to the sea ice base, formulated as (41-42):

$$OHF = \rho_{ocean} C_p u_* C_H T_d \quad (6)$$

where $\rho_{ocean} \sim 1023 \text{ kg/m}^3$ is the reference density of the mixed layer; $C_p \sim 3980 \text{ J/(kg}\cdot\text{K)}$ is the specific heat capacity of seawater; $u_* = \sqrt{|\tau_{ice-ocean}|/\rho_{ocean}}$ is the

friction velocity calculated from the ice–ocean stress $\tau_{ice-ocean} = \rho_{ocean} C_d |u_{ice} - u_{ocean}|(u_{ice} - u_{ocean})$, where $C_d \sim 0.0055$ is the ice-ocean drag coefficient, and u_{ice} and u_{ocean} are the sea-ice and surface-ocean velocity vectors, respectively; $C_H \sim 0.0057$ is the heat transfer coefficient; the thermal driving $T_d = T_{5m} - T_f$ denotes the instantaneous thermal driving, defined as the ocean temperature at 5-m depth (T_{5m}) relative to the freezing point (T_f). The choice of 5-m depth for temperature diagnosis accounts for the physical thickness of the sea-ice pack, ensuring that the temperature reflects the thermal state of the water immediately beneath the ice base rather than the immediate sea surface, which may be affected by intense localized brine rejection or skin layer effects.

To identify the origin of shifting ocean–ice interactions, the total OHF is decomposed into two components: the mean ocean-ice heat flux (OHF_{mean}) and the eddy ocean-ice heat flux (OHF_{eddy}), such that $OHF = OHF_{mean} + OHF_{eddy}$. The OHF_{mean} is obtained from the seasonal mean friction velocity ($\overline{u_*}$) and mean thermal driving ($\overline{T_d}$) for the given year. The residual of the total and mean heat flux represents OHF_{eddy} . This term captures sub-seasonal ocean-to-ice heat-transfer variability, which in the eddy-resolving MIZ simulated here primarily reflects mesoscale processes, consistent with previous operational definitions (16, 17, 20). To isolate the specific mechanistic drivers within this residual, we apply a Reynolds decomposition to the daily velocity and temperature fields, whereby OHF_{eddy} is explicitly partitioned as:

$$OHF_{eddy} = \rho_{ocean} C_p C_H (\overline{u_*} T_d' + u_*' \overline{T_d} + u_*' T_d') \quad (7)$$

In this formulation, the prime symbols denote daily deviations from the seasonal mean. This allows the total eddy-driven flux to be quantified through three distinct pathways: a thermal term ($\overline{u_*} T_d'$) driven by transient thermal anomalies, a mechanical term ($u_*' \overline{T_d}$) driven by high-frequency friction-velocity fluctuations, and a covariance term ($u_*' T_d'$) arising from the synchronous temporal coupling of dynamic and thermal fluctuations. We retain daily grid points with eddy-driven OHF above 10 W/m². Below this threshold, the flux signal is weak relative to the diagnosed heat-transfer events, and the fractional contributions of the three decomposition terms become numerically sensitive as the total flux approaches zero. The results presented are insensitive to the choice of threshold over the range 5–20 W/m² (not shown).

The atmospheric-ice heat flux F_{atm} is derived from four primary components:

$$F_{atm} = F_{SW} + F_{sensible} + F_{latent} + F_{LW} \quad (8)$$

where F_{SW} represents the net absorbed shortwave radiation, $F_{sensible}$ denotes the sensible heat flux, F_{latent} corresponds to the latent heat flux, and F_{LW} represents the net longwave radiative flux.

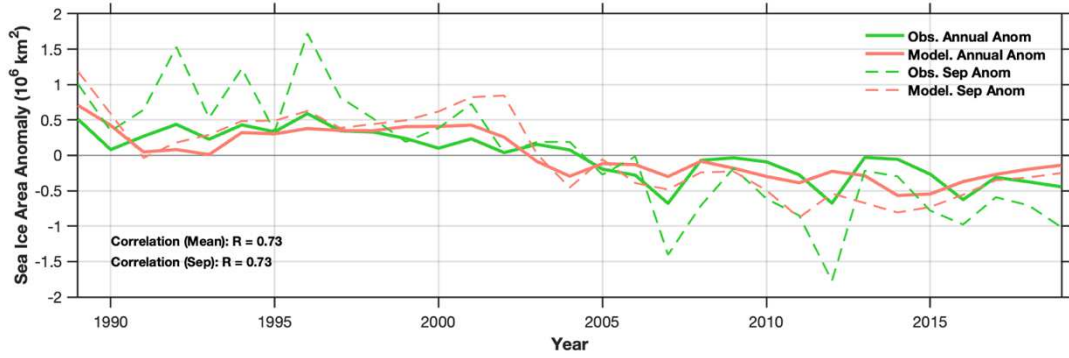
Eddy heat advection calculation

To quantify the specific contribution of eddies to temperature variations within the mixed layer, we calculate the eddy heat advection by considering both horizontal and vertical components. The horizontal velocity components (u , v) and ocean temperature

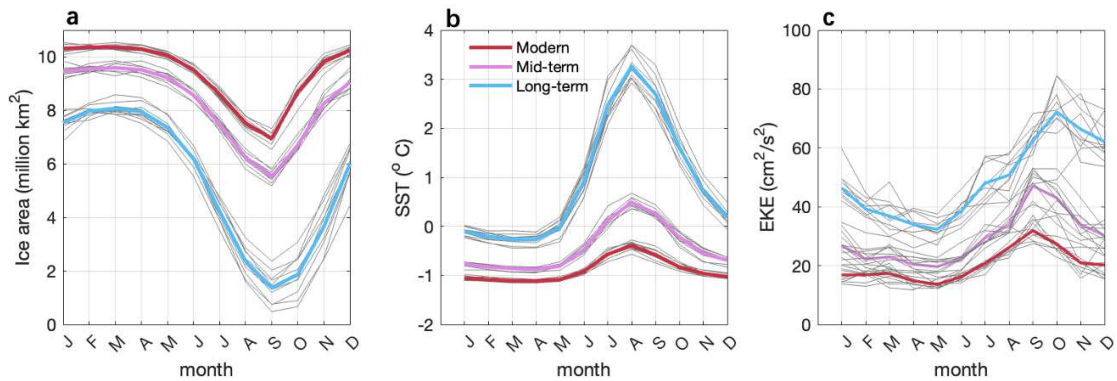
(T) are integrated and averaged over the mixed-layer depth (MLD), where the MLD is defined according to the Levitus criterion as the depth where the potential density increases by 0.125 kg/m^3 relative to the surface value. This MLD is determined by the specific yearly summer-average for each reference state. The horizontal eddy heat advection is thus defined as $\nabla \cdot (\mathbf{v}'T') = \frac{\partial(w'T')}{\partial x} + \frac{\partial(v'T')}{\partial y}$, where the variables represent these MLD-averaged anomalies. For the vertical component, $\frac{\partial(w'T')}{\partial z}$, the vertical velocity (w) and temperature are evaluated specifically at the base of the mixed layer to capture the cross-interfacial transport. Consistent with the *OHF* decomposition, this eddy heat advection is defined as the residual between the total instantaneous heat advection and the seasonal mean component, thereby isolating the heat transport driven by transient mesoscale fluctuations from the background mean advection. To maintain consistency with other heat-flux terms (W/m^2), the horizontal component is scaled by the mixed-layer depth ($\rho_{\text{ocean}}C_pH_{\text{MLD}}\nabla \cdot (\mathbf{v}'T')$), while the vertical component represents the eddy heat flux evaluated at the mixed-layer base ($\rho_{\text{ocean}}C_pw'T'|_{z=\text{MLD}}$).

References

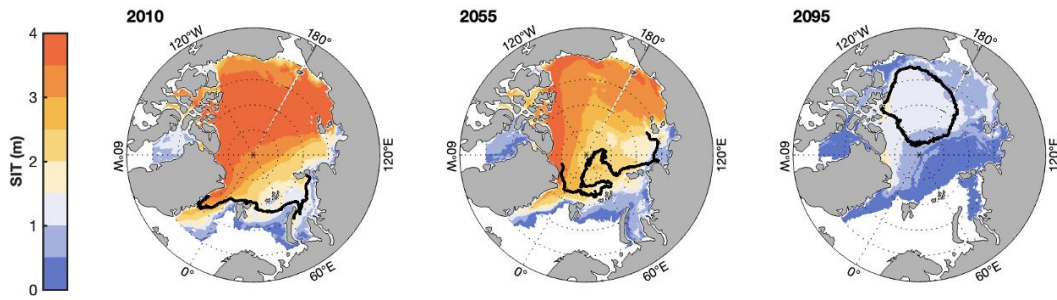
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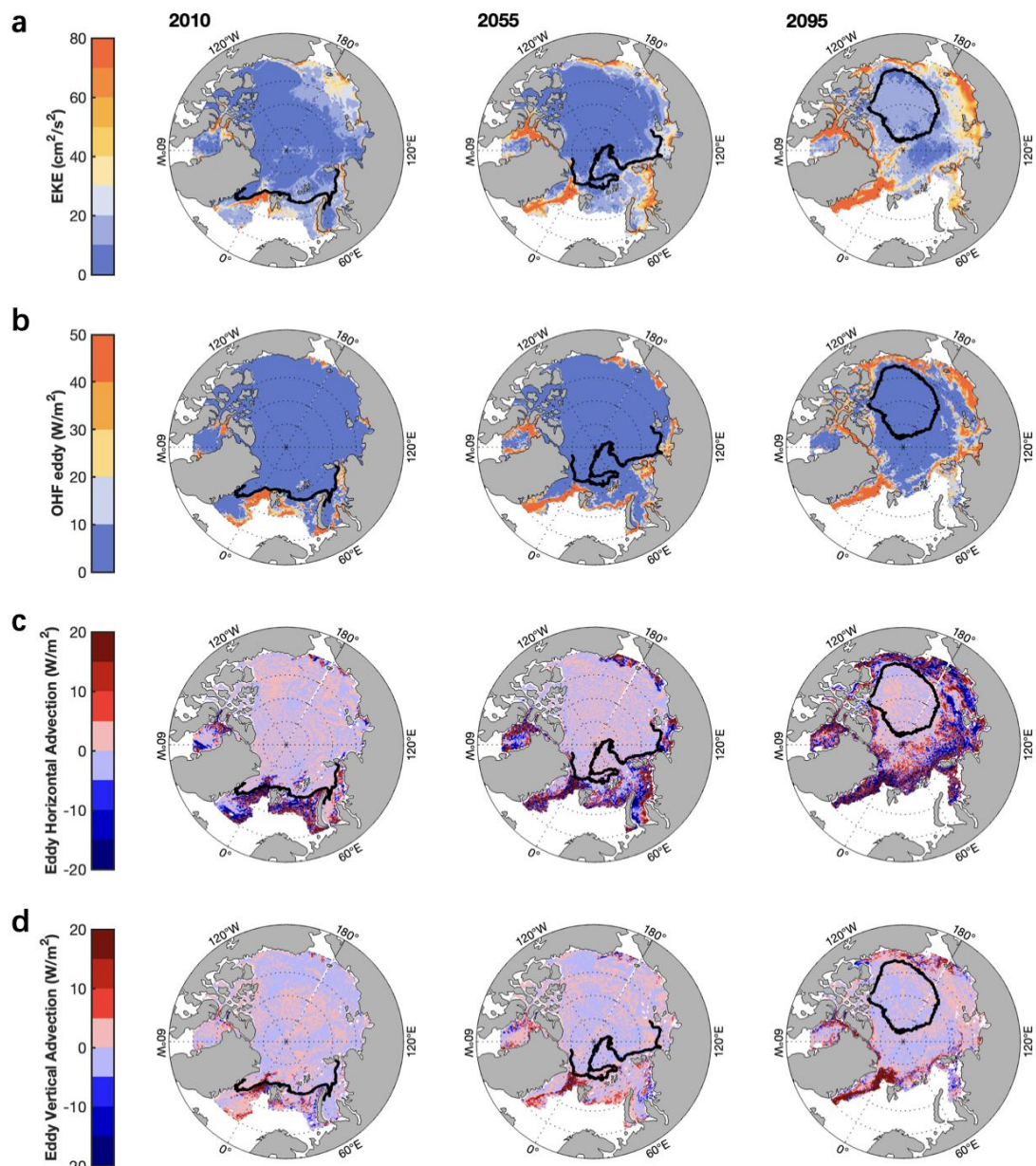
Extended Data Fig. 1 | Evaluation of simulated Arctic sea-ice area anomalies against observations. Annual-mean and September Arctic sea-ice area anomalies, calculated relative to the 1989–2019 mean for each dataset, from the coupled simulation (red) and NSIDC observations (green) over 1989–2019. Correlations of $R = 0.73$ for both annual-mean and September anomalies indicate that the simulation captures the observed large-scale variability and long-term decline of Arctic sea ice.



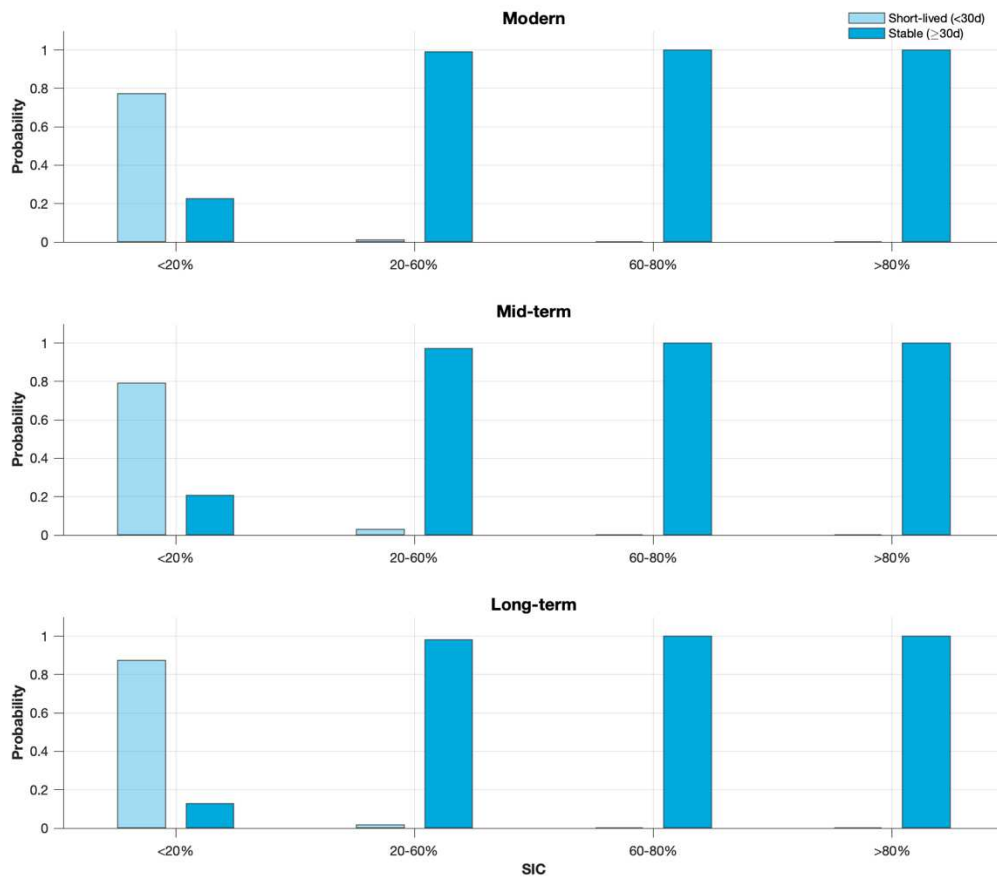
Extended Data Fig. 2 | Seasonal variations in Arctic sea-ice area, sea surface temperature (SST), and eddy kinetic energy (EKE). Monthly variations in **a**, sea-ice area, **b**, sea surface temperature, and **c**, sea surface EKE for the Modern (2004–2013), Mid-term (2050–2059), and Long-term (2090–2099) states from the coupled simulation with 2-km ocean resolution in the Arctic. The progressively deeper summer sea-ice minimum is accompanied by rising SST and stronger eddy activity, highlighting June–August as the key season for ocean–ice interactions in this study.



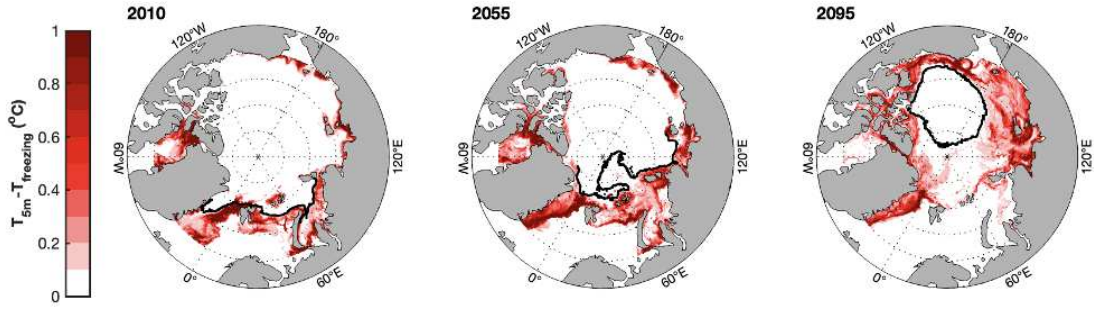
Extended Data Fig. 3 | Long-term changes in Arctic summer sea-ice thickness (SIT). Spatial distribution of summer (June–August) sea-ice thickness in 2010, 2055, and 2095. Black contours indicate the marginal ice zone (MIZ; SIC < 80%). **Thick sea ice retreats poleward and thins substantially as the MIZ expands, with basin-wide thinning most pronounced in the Long-term state.**



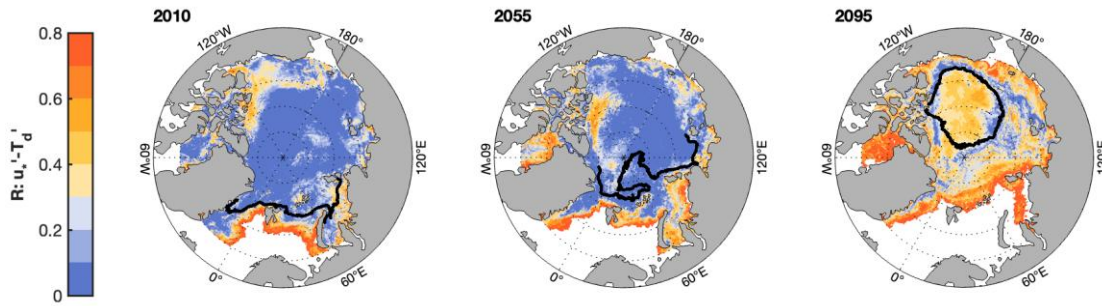
Extended Data Fig. 4 | Long-term changes in Arctic summer eddy kinetic energy (EKE), eddy-driven ocean-to-ice heat flux (OHF eddy), and eddy heat advection. Spatial distribution of **a**, sea-surface EKE, **b**, eddy-driven OHF, **c**, horizontal eddy heat advection within the mixed layer, and **d**, vertical eddy heat advection at the base of the mixed layer in 2010, 2055, and 2095. Black contours indicate the marginal ice zone (MIZ; SIC < 80%). The poleward expansion of elevated sea-surface EKE and eddy-driven OHF follows the migrating MIZ and is accompanied by intensified horizontal and vertical eddy heat advection along the ice edge and adjacent shelf seas.



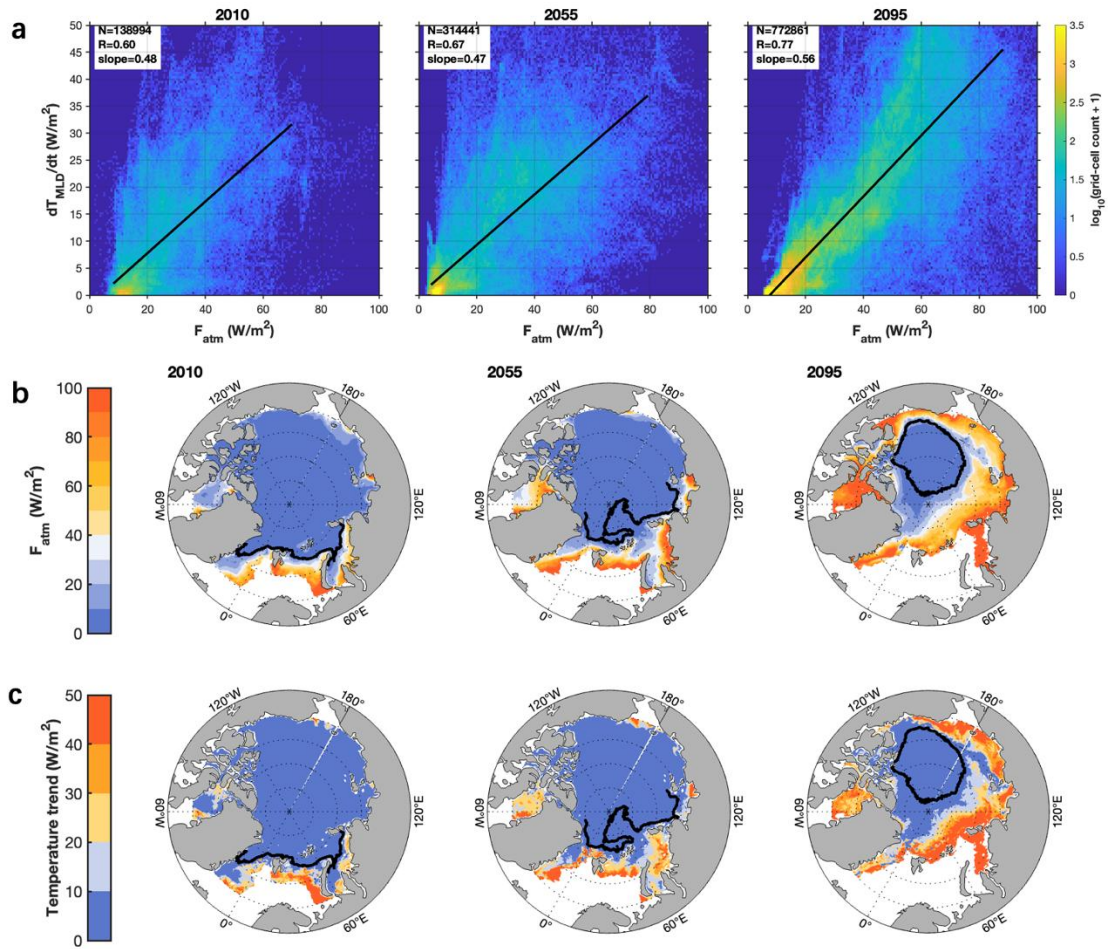
Extended Data Fig. 5 | Probability distribution of short-lived (<30 days) and stable (≥ 30 days) sea ice across sea-ice concentration (SIC) regimes. Short-lived ice dominates the <20% SIC regime across all three states, whereas stable ice is more prevalent in the 20–60% and 60–80% SIC regimes. These distributions support our focus on the 20–60% and 60–80% SIC regimes as the primary domain of persistent MIZ dynamics.



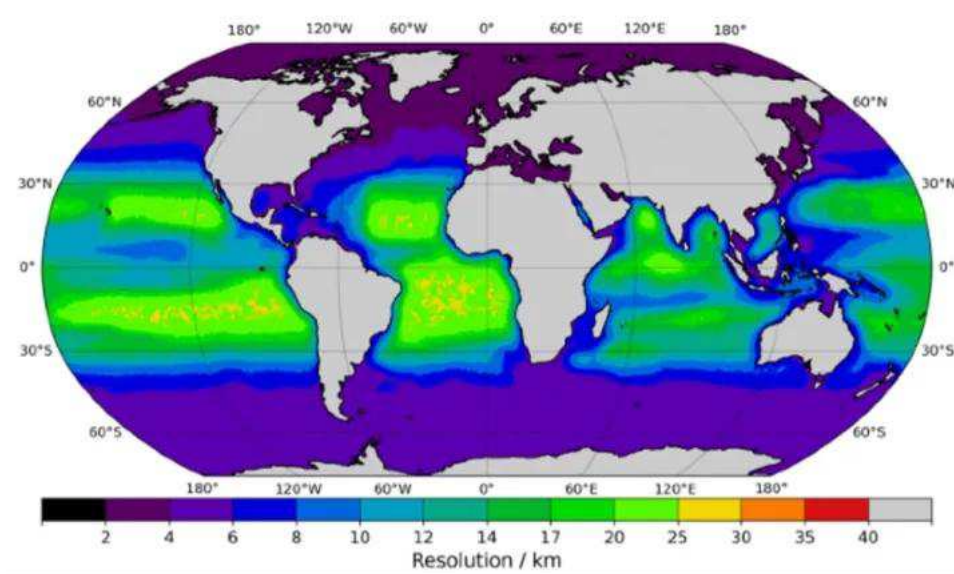
Extended Data Fig. 6 | Spatial evolution of summer mean thermal driving. Maps show summer mean $\overline{T_d} = T_{5m} - T_{freezing}$ in 2010, 2055 and 2095. Black contours mark the marginal ice zone (MIZ; SIC < 80%). The weakening of $\overline{T_d}$ within the MIZ reflects the poleward migration of the ice margin into colder background waters, despite the increase in basin-averaged SST (Fig. 2c).



Extended Data Fig. 7 | Temporal correlation between friction-velocity fluctuations and thermal-driving anomalies at the ice-ocean interface. Spatial distribution of the temporal correlation coefficient (R) between daily u_*' and T_d' during summer (June–August) in 2010, 2055, and 2095. Black contours indicate the marginal ice zone (MIZ; SIC < 80%). The poleward expansion of stronger correlation in the Long-term state indicates increasingly coherent friction-velocity fluctuations and thermal-driving anomalies at the ice base as sea ice retreats.



Extended Data Fig. 8 | Atmospheric heat flux and mixed-layer temperature tendency in the marginal ice zone (MIZ). a, Density scatter plots of summer atmospheric heat flux (F_{atm}) versus mixed-layer temperature tendency (dT_{MLD}/dt) within the 20–80% SIC regime for 2010, 2055, and 2095. The tendency dT_{MLD}/dt is calculated as the net heat storage rate over the ~90-day summer period (June–August), expressed in W/m^2 as $\rho_{ocean}C_pH_{MLD}\Delta T/\Delta t$. Numbers indicate sample size, Pearson correlation coefficient, and regression slope. b, Spatial distribution of atmospheric heat flux for the three years. c, Spatial distribution of mixed-layer temperature tendency. Black contours indicate the marginal ice zone (MIZ; SIC < 80%). The strong correlation ($R = 0.60\text{--}0.77$) indicates that atmospheric heat flux remains closely linked to upper-ocean warming across all three ice states, even as the MIZ expands.



Extended Data Fig. 9 | Spatial resolution of the global climate model AWI-CM3. Horizontal grid spacing in AWI-CM3 ranges from approximately 25 km in the tropics to about 2 km in the Arctic Ocean, enabling explicit simulation of mesoscale processes in polar regions.