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Scientific article

Polar ocean–cryosphere dynamics across past, present, and future climate states: AWI research highlights 2021–2025

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Abstract. The polar regions play a central role in the Earth system through their influence on ocean circulation, ice sheets, sea level, carbon cycling, and climate variability. Rapid anthropogenic warming is transforming these regions, highlighting the need to understand the processes, feedbacks, and thresholds that govern ocean–cryosphere interactions across a wide range of timescales. Here we synthesize major scientific advances achieved at the Alfred Wegener Institute during 2021–2025 within the Helmholtz research program Changing Earth – Sustaining Our Future. Combining paleoclimate archives, sustained observations, process studies, and Earth-system modeling, these studies provide new insights into the sensitivity of the climate system under past, present, and future climate conditions. Key findings include new constraints on Antarctic Ice Sheet evolution during past greenhouse climates, improved understanding of links between Southern Ocean circulation and climate–carbon feedbacks, advances in reconstructing Northern Hemisphere ice-sheet dynamics and deglaciation processes, and evidence that regional climate variability is stronger and more persistent than represented in many current climate models. Observations and simulations further reveal accelerating changes in Greenland outlet glaciers, important couplings between cryospheric change and the carbon cycle, and a growing role of mesoscale ocean dynamics in shaping future Arctic and global climate change. Together, these results demonstrate the value of integrating observations, paleoclimate evidence, and high-resolution modeling to constrain Earth-system sensitivity, identify critical feedbacks, and improve projections of future climate change in a warming world.

1 Introduction

The ocean and cryosphere regulate some of the largest uncertainties in future climate change through their control on heat uptake, carbon storage, ice-sheet stability, and sea-level rise. Understanding the sensitivity, variability, and thresholds of these components is therefore essential for assessing future climate risks. Recent advances in observations, paleoclimate reconstructions, and Earth-system modeling provide new opportunities to constrain these processes across timescales from decades to millions of years. This review synthesizes recent advances in understanding ocean–cryosphere interactions across past, present, and future climate states. Particular emphasis is placed on the role of polar processes in regulat-

ing climate variability, abrupt transitions, sea-level change, and carbon-cycle feedbacks. By integrating evidence from paleoclimate archives, sustained observations, process studies, and Earth-system modeling, we highlight emerging insights into the mechanisms governing Earth-system sensitivity and climate predictability.

The synthesis draws primarily on research conducted at the Alfred Wegener Institute within the Helmholtz research program Changing Earth – Sustaining Our Future during 2021–2025. Rather than providing a comprehensive review of individual disciplines, we focus on selected advances that illustrate how observations, reconstructions, and numerical models can be combined to address key challenges in ocean and cryosphere research.

Despite substantial progress, major uncertainties remain concerning the stability of ice sheets, the response of large-scale ocean circulation, the magnitude of natural climate variability, and the feedbacks linking the ocean, cryosphere, and carbon cycle (IPCC, 2023). These uncertainties arise from processes operating across a wide range of spatial and temporal scales, from kilometer-scale ocean eddies to millennial-scale climate transitions preserved in geological archives (Lohmann et al., 2020). Addressing them requires the integration of observations, paleoclimate evidence, and Earth-system modeling to constrain climate sensitivity, identify critical thresholds, and improve projections of future change.

Earth's climate has evolved through a succession of contrasting climate states driven by changes in external forcing and internal feedbacks (Fig. 1). Over the past 70 million years, atmospheric CO_2 concentrations declined from greenhouse-world levels to the comparatively low values characteristic of the late Quaternary, accompanied by a long-term global cooling trend. Yet future emission scenarios project CO_2 concentrations back toward levels experienced during past warm climates such as the Early Eocene and Mid-Pliocene.

Figure 1 places ongoing anthropogenic climate change into this long-term Earth-system context by linking geological reconstructions, ice-core records, instrumental observations, and future projections. It highlights that future climate trajectories may enter a range of atmospheric CO_2 concentrations and climate states for which the most relevant analogues are found in the geological past. Understanding the response of oceans, ice sheets, and the carbon cycle under these conditions therefore requires integrating evidence from paleoclimate archives, modern observations, and Earth-system models.

2 Scientific questions and approach

Three overarching challenges motivate current ocean and cryosphere research. First, the sensitivity of ice sheets, ocean circulation, and carbon reservoirs to external forcing remains incompletely understood across different climate states. Second, the feedbacks and thresholds that govern abrupt climate transitions and regional climate impacts remain difficult to quantify. Third, the integration of observations, paleoclimate archives, and Earth-system models is required to improve projections of future climate change.

Addressing these challenges requires evidence spanning timescales from decades to millions of years. Instrumental observations provide process understanding of ongoing change, paleoclimate archives document the response of the Earth system under different boundary conditions, and numerical models offer a framework for testing mechanisms and assessing future trajectories.

Within the Helmholtz research program Changing Earth – Sustaining Our Future, Topic 2 ("Ocean and Cryosphere in Climate") addresses this challenge by combining observations, process studies, paleoclimate reconstructions, and Earth-system modeling. A central objective is to link present-day observations with evidence from past climate states and numerical simulations in order to understand climate variability, abrupt transitions, and long-term environmental change. The following scientific questions define key frontiers in ocean and cryosphere research addressed by AWI within this program.

- How sensitive are the ocean, cryosphere, and carbon cycle to external forcing across different climate states?
- Which feedbacks and thresholds govern climate variability, abrupt climate transitions, and sea-level change?
- How can observations, paleoclimate archives, and Earth-system models be integrated to constrain mechanisms and improve future climate projections?

Collaborations with GEOMAR and GFZ strengthen the integration of oceanographic, cryospheric, geodetic, and paleoclimate expertise. Joint activities include paleoclimate reconstructions, model development, model intercomparison, and storyline-based climate assessments (Wu et al., 2021; Balting et al., 2021; Blanchet et al., 2024; Martin et al., 2022; Hathorne et al., 2023; Kreibich et al., 2022, 2023; Schachtschneider et al., 2024; Song et al., 2023; Nagavciuc et al., 2024).

The following sections present examples of how observations, paleoclimate evidence, and numerical models can be integrated to reconstruct past climate states, understand ongoing change, and assess possible future trajectories.

3 Scientific outcomes and highlights

The following sections highlight major scientific advances across past, present, and future climate states, illustrating how AWI research has advanced our understanding of ocean–cryosphere dynamics and their role in the Earth system.

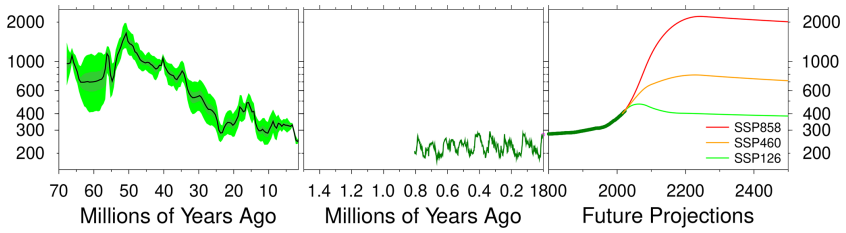


Figure 1. Atmospheric CO_2 concentrations (ppmv) across contrasting climate states and timescales. The left panel shows proxy-based reconstructions for 70 to 1.5 million years ago, illustrating the long-term decline from Cenozoic greenhouse climates toward the cooler conditions of the late Quaternary. The middle panel shows glacial–interglacial CO_2 variability over the last 800 000 years derived primarily from Antarctic ice-core records. The right panel combines instrumental observations with illustrative future emission scenarios extending to 2500. Together, the records place ongoing anthropogenic climate change in the context of Earth-system evolution and highlight that projected future CO_2 concentrations may approach levels characteristic of past warm climates. Data sources: CenCO$_2$PIP (The CenCO2PIP Consortium, 2023), Bereiter et al. (2015), Köhler et al. (2017), and Meinshausen et al. (2020).

3.1 Thresholds for ice sheets and the Antarctic Circumpolar Current

Antarctica plays a central role in the climate system through its influence on global sea level, ocean circulation, and climate feedbacks. The Antarctic Ice Sheet contains enough ice to raise global mean sea level by several tens of meters and interacts closely with the Southern Ocean through exchanges of heat, freshwater, and carbon. Recent observations indicate accelerating mass loss in parts of West Antarctica and increasing vulnerability of marine-based sectors of East Antarctica. Ocean warming associated with changes in Southern Ocean circulation and wind patterns enhances basal melting of ice shelves and may trigger sustained grounding-line retreat in susceptible regions. Understanding the sensitivity of the Antarctic Ice Sheet to climatic forcing therefore remains a key challenge for assessing long-term sea-level rise and its global consequences. Evidence from past greenhouse climates provides an important perspective on this question.

3.1.1 Antarctica: dive into Earth's past

Geological evidence from West Antarctica demonstrates that polar regions supported temperate rainforest ecosystems during Cretaceous greenhouse conditions, implying substantially reduced meridional temperature gradients and a fundamentally different climate state than today. Plausible projections of such future transitions into very different climate states require a profound understanding of the dynamics and changes in the Earth's past, e.g., the greenhouse climates of the Late Cretaceous (∼ 94–86 million years ago (Ma)) and Eocene (∼ 56–34 Ma), as well as transitions into or out of them. So far, reliable polar data from such periods have been particularly scarce, even though these regions react most sensitively to climatic changes. Previous work (DeConto and Pollard, 2003; Zachos et al., 2008) has shown that Antarctic Ice Sheet inception and retreat are strongly linked to atmospheric CO_2 thresholds, ocean gateways, and Southern Ocean circulation, but direct polar evidence from greenhouse climates remains sparse. Against this background, two AWI-led interdisciplinary studies based on paleo-samples from RV *Polarstern* expedition PS104 provided new constraints on Antarctic warm climates under high-CO_2 conditions (Klages et al., 2020, 2024).

First, the unexpected discovery of original remains of a former temperate rainforest only ∼ 900 km away from the South Pole (Klages et al., 2020) illustrates the severity of global climate conditions during greenhouse states – a fully vegetated South Pole region with annual mean temperatures of ∼ 12 °C presumes a drastically different global climate under high-CO_2 atmospheric concentrations (1120–1680 ppmv, i.e., 4× to 6× higher than pre-industrial levels) and associated oceanic and atmospheric circulation patterns. Second, a unique sedimentary drill core record from West Antarctica's Pacific margin combined with novel coupled climate–ice-sheet modeling puts the timing and location of permanent Antarctic Ice Sheet inception ∼ 34 million years ago in a new light (Klages et al., 2024). The study defined the size and location of the Antarctic Ice Sheet (AIS) during the last fundamental climate shift from the Eocene greenhouse to the current icehouse climate (Fig. 1) and demonstrates how regionally different the AIS reacted to external forcing during this last drastic climatic transition (Fig. 2).

While East Antarctica was already covered by a large and thick ice sheet, West Antarctica started to glaciate about 7 million years later, when atmospheric CO_2 levels dropped to values between 2× and 1× preindustrial CO_2 (560–280 ppmv). This result adds a regional perspective to the broader view that East and West Antarctica can respond differently to CO_2 forcing because of contrasting bed topography, ocean access, and ice-sheet dynamics. This emphasizes the fragility of the West Antarctic Ice Sheet and ramifications for global sea level and is essential knowledge to better understand climate dynamics during past and potential future climate reorganizations. Both studies therefore significantly help understanding polar responses to higher-than-present CO_2. With this research we constrain Earth-system

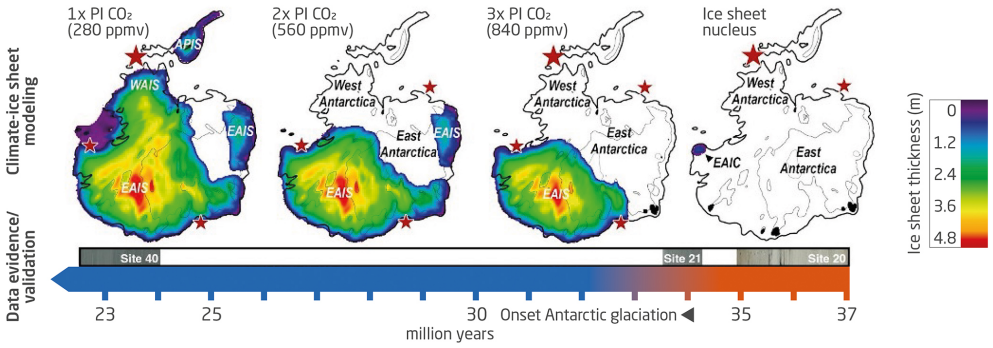


Figure 2. Results from coupled ice-sheet and Earth-system modeling compared to data reconstructions for the Eocene–Oligocene transition (~ 34 Ma; initiation of East Antarctic Ice Sheet build-up under atmospheric CO_2 concentrations of 840 ppmv) toward the latest Oligocene (onset of West Antarctic glaciation under < 500 ppmv). Sites indicating ice presence for the respective time intervals are highlighted by filled red stars (large: primary RV *Polarstern* PS104 MeBo sites; small: legacy data from other sources; see Klages et al., 2024). Colors refer to ice thickness above bedrock with black isolines indicating the minimum 34 Ma bed topography reconstruction (see Klages et al., 2024). EAIC: East Antarctic Ice Cap. APIS, WAIS, and EAIS denote the Antarctic Peninsula and the West and East Antarctic Ice Sheets, respectively.

models, which aim at simulating future ice-sheet and climate characteristics under CO_2-driven warmer-than-present conditions more reliably than currently possible.

3.1.2 The Antarctic Circumpolar Current dynamics

Later in Earth history (about 3 million years ago, in the Pliocene), we find that the Antarctic Circumpolar Current (ACC) accelerated as the Earth gradually cooled (Lamy et al., 2024; Wu et al., 2021). The ACC is a key regulator of Southern Ocean heat, carbon, and nutrient exchange and mediates the connection between wind forcing, ocean stratification, and global carbon storage (e.g., Rintoul et al., 2001; Marshall and Speer, 2012). Against this established background, recent proxy and modeling work has refined our understanding of how ACC strength varied across glacial–interglacial and Pliocene climate states. The acceleration is consistent with an enhanced meridional temperature gradient between low and high southern latitudes, which strengthened the Southern Hemisphere westerlies, a primary driver of the ACC. However, in the late Pliocene the ACC began to slow. The switch came at a time when the climate and the circulation in the atmosphere and the ocean experienced major changes linked to broad expanses of the Northern Hemisphere ice sheets and the expansion of the Antarctic Ice Sheet. This is attributed to changes in ocean currents, set off by tectonic processes, together with a long-term cooling of the ocean and decreasing atmospheric CO_2 levels. More ice-proximal drill records from the International Ocean Discovery Program (IODP) Expedition 379 and seismic analysis provide strong indication for an intensively dynamic West Antarctic Ice Sheet in the Amundsen Sea sector during a newly defined Pliocene Amundsen Sea Warm Period (4.2–3.2 Ma) with prolonged ice-sheet retreats (Gohl et al., 2021).

With regard to the last 800 000 years, in which the atmospheric CO_2 levels varied from 170 to 300 ppmv, we were able to identify a close connection between ACC strength and glacial cycles: during warm periods, in which the atmospheric CO_2 levels rose, the flow speed increased by up to 80 % compared to the present; during ice ages, it decreased by up to 50 %. At the same time, during transitions between interglacials and glacials, there was a shift in the ACC's position and therefore in the upwelling of nutrient-rich deep water in the Southern Ocean, as geochemical sediment analyses revealed. They show that the silicate shells of diatoms – the most important phytoplankton in the Southern Ocean – were deposited on the seafloor farther north in ice ages than in warm periods. A weaker ACC and lower atmospheric CO_2 levels during the ice ages of the Pleistocene indicate less pronounced upwelling and more stratification in the Southern Ocean, that is, more capacity for CO_2 storage (Lamy et al., 2024; Wu et al., 2021). Evaluation of these processes is essential for our understanding of climate–carbon feedback under warmer climates and highlights the necessity to equip climate models with additional components of the Earth system and to allow sufficient spatial resolution to capture processes that resolve the necessary dynamics. These findings provide important constraints on how Southern Ocean circulation, carbon storage, and Antarctic ice sheets may respond to future warming.

Together, these studies demonstrate that Antarctic Ice Sheet evolution and Southern Ocean circulation are strongly climate-state dependent. Geological evidence, proxy reconstructions, and coupled modeling indicate that the response of the Antarctic cryosphere cannot be described by a single CO_2 threshold. Instead, East and West Antarctica exhibit distinct sensitivities arising from differences in topography, ocean connectivity, and feedback processes. At the same time, changes in Southern Ocean circulation emerge as a key mechanism linking ice-sheet stability, carbon storage, and global climate evolution across both past and future warm climates.

3.2 Formation and disintegration of Northern Hemisphere ice sheets

During transitions between glacials and interglacials, the glaciers on Greenland and in North America and Europe wax and wane over timescales of tens of thousands of years. The more water stored in land ice, the less available in the oceans – and the lower the sea level. In the coupled ice–climate system, we are now investigating to what extent land ice would melt in the coming centuries due to anthropogenic climate change and how much sea level would rise as a result (e.g., Ackermann et al., 2020). To validate our models, we can look back into the past. If we understand ice growth and melt during past glacial–interglacial cycles, we will be able to examine the system sensitivity in warming situations, which is essential for future changes.

3.2.1 The missing ice problem

Reconstructing the distant past is a challenging task, as the thickness of glaciers and sea levels cannot be measured directly. As a result, climate researchers must rely on various forms of evidence for a complete picture of past climate changes. The challenge is that different types of evidence can lead to different interpretations of the past. Previous reconstructions of Last Glacial Maximum sea level and continental ice volume were difficult to reconcile, resulting in a long-standing discrepancy known as the "missing ice problem" (Clark et al., 2009; Lambeck et al., 2014). It describes the incongruity of two different scientific approaches that sought to reconcile sea level height and glacier thickness at the Last Glacial Maximum (LGM, ∼21 thousand years before present). The "missing ice problem" is based, on the one hand, on an analysis of sediments from core samples collected from the seafloor in the tropics. These contain traces of corals. Because corals only live in well-lit waters near the ocean's surface their remnants can tell us to what extent the sea level rose or fell over the millennia. The sediment cores in the tropics imply that the glacial sea level was roughly 130 m lower than today. On the other hand, previous models have suggested that the glacial masses were not large enough to explain such a low sea level. For the sea level to be that low, on a global scale an additional volume of water with twice the mass of the Greenland Ice Sheet (corresponding to ∼14 m of sea level change) would have to have been deposited on land; hence the "missing ice problem" (Gowan et al., 2021). In a project together with the excellence cluster "The Ocean Floor" at MARUM, we apply data assimilation to an ice sheet–solid-Earth model to provide an independent solution for ice volume changes based on oxygen isotopes in sediments. The approach integrates different key indicators such as the steepness of the ice surface, glacier flow directions and the resistance of rocks and sediments to basal ice flow. In addition, the ice sheet presses down on the Earth's crust in the respective areas, which is determined by the underlying pattern of mantle viscosity, resulting in LGM ice masses that can be reconciled with the sea level height reconstructions (Gowan et al., 2021). The resolution of the missing ice problem highlights the growing importance of data assimilation approaches that combine geological constraints with physically consistent ice-sheet and solid-Earth models.

3.2.2 Dynamics of the North American Ice Sheet: growth up to the LGM

Prior to the LGM, reconstructions of continental ice sheets are further complicated, since the glacial geomorphological record is mostly erased by the following ice-sheet expansion. Hence, considerable uncertainties exist in the initial ice-sheet configuration for the final glaciation phase (equivalent to a sea level drop of around 50 m) starting at ∼38 ka (upper panel of Fig. 3). Given such fundamental ice-sheet differences at 38 ka, the question remains as to how these differences impact the North American Ice Sheet evolution toward the LGM. In the framework of the BMBF-funded PalMod Project (https://www.palmod.de, last access: 30 December 2025), we have developed and used a coupled climate–ice model (the Earth-system model AWI-ESM, Ackermann et al., 2024) to study the dynamics of ice-sheet inception and evolution. The study simulates the build-up of the North American Ice Sheet before the LGM and shows which factors influenced its growth. With our new Earth-system model with interactive ice sheets, it is possible to adequately capture ice-sheet feedback mechanisms, which are not yet included in the current scenario simulations that produce projections of future climate. We find that distinct initial North American (Laurentide) ice-sheet configurations at 38 ka converge toward a configuration consistent with the LGM (lower panel of Fig. 3). The rapid expansion of the North American Ice Sheet can be explained by summer snowfall, which was caused by the transport of moisture from warmer lower latitudes of the Atlantic into the interior of the North American continent. This mechanism not only led to more ice but also to greater snow cover over North America, which reflected sunlight more effectively and thus additionally reduced melting (Niu et al., 2024). These feedbacks provide an effective mechanism for ice growth for a range of different initial ice-sheet states that converge to an LGM ice-sheet configuration and may also explain the rapid North American ice-volume increase during the last ice age and potentially driving growth during previous glacial periods.

3.2.3 Glacial ocean stratification matters for the subsequent termination

The transition from the cold LGM to warmer interglacial conditions is driven by gradual changes in Earth's orbit but also by abrupt shifts in global ocean circulation. These shifts amplify gradual external forcing by altering the exchange of heat and carbon between the ocean and atmosphere, facil-

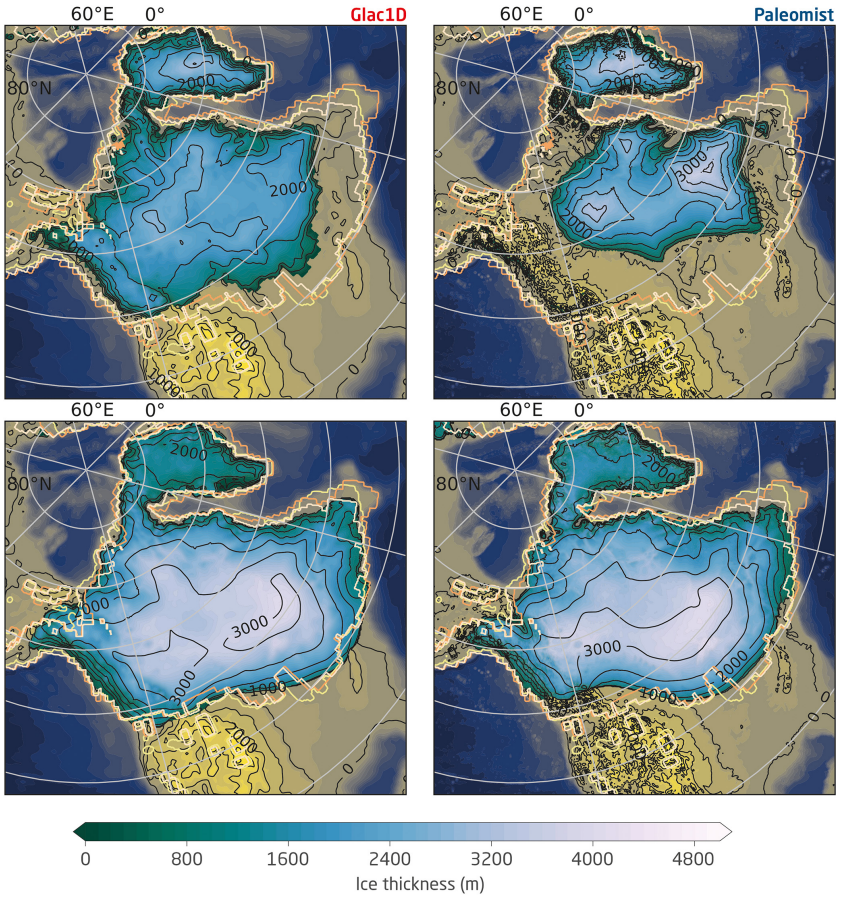


Figure 3. Evolution into LGM glacial ice (lower panels) from different initial configurations (upper panels), emphasizing internal climate–ice-sheet feedback. The initial ice thickness is at 38 ka, with quite different ice thickness distributions. Adapted from Niu et al. (2024).

itating deglaciation. However, it remains unclear why these interactions during other glacial periods did not lead to a successful termination and a new interglacial. To address this, we analyzed global hydrography changes using models and data (Knorr et al., 2021). Our findings show that during the LGM, ocean stratification was notably different, particularly in the deep South Atlantic, where increased salt stratification reduced the cooling effect of upwelled waters in response to an abrupt weakening of the Atlantic overturning circulation. This unique stratification led to a warmer high-latitude surface ocean, as the Southern Ocean tapped into deeper, less cold, and saltier waters than at other times in the glacial cycle. This mechanism amplified the Antarctic seesaw warming response, doubling the rate of warming across Antarctica on a multi-centennial scale compared to interglacial conditions. This helps explain the large magnitude and rapidity of glacial terminations in the late Quaternary.

3.2.4 The Arctic freshwater controversy

A key uncertainty in understanding sea level variations and paleoclimate is the freshwater balance and interpretation of oxygen isotope records. Evidence suggests a major ice shelf existed in the Central Arctic Ocean during glacial periods, a hypothesis supported by seafloor morphology (Jakobsson et al., 2016). Our study provides sedimentary geochemical evidence for this ice shelf and identifies traces of widespread freshwater at depths up to 2500 m, detected using advanced uranium-series isotope analysis at AWI (Geibert et al., 2021). The finding has stimulated extensive discussion because it implies a substantially different Arctic Ocean state during glacial periods. A more isolated and freshened Arctic Ocean would influence water-mass exchange with the North Atlantic, ocean circulation, carbonate chemistry, and the interpretation of oxygen-isotope records. The implications of such an "Arctic Mediterranean" are now being explored in both proxy studies and climate models.

The interpretation critically depends on robust age models. Consequently, much of the subsequent work has focused on evaluating chronological uncertainties and testing independent dating approaches. Radiocarbon chronologies have been reassessed (Spielhagen et al., 2022; Geibert et al., 2022), while microscopic inspection of microfossils (Wollenburg et al., 2023), cosmogenic isotopes, and additional radiogenic

tracers (Nicolas et al., 2024) provide complementary constraints on sediment age and depositional history.

3.3 From millennial-scale variability to historical extremes

Paleoclimate observations suggest that many climate models underestimate variability on decadal-to-centennial timescales. Our systematic analysis of local and global temperature variability from (paleo-)observations of the last millennium and Holocene shows that regional temperature variations persisted for longer timescales than climate models are able to reproduce (Laepple et al., 2023). This not only influences the quality of regional projections but also has implications for attribution and impact studies. For example, an underestimation of the full temperature range can lead to underestimation of risks with respect to the probability of the occurrence of climate extremes. A decade of conditions on the lower end of the possible temperature range, for example, may bias our preparedness for decades of unexpectedly high temperatures as a society.

3.3.1 Global warming reached Greenland

One example of how natural variability can temporarily mask or amplify warming trends is the air temperature evolution on the Greenland Ice Sheet. Until now, the impact of global warming on the elevated parts of the ice sheet (up to 3000 m above sea level) has remained unclear due to the very strong natural climate variability and the lack of long-term observations. This uncertainty has fueled discussions of a "warming hiatus" – a delay or pause in the signature of global warming in Greenland, quite similar to the much discussed "pause" of global warming in the early 2000s (e.g., Box et al., 2009). By utilizing the unique infrastructure of the AWI (Polar-5 airplane) and benefiting from advancements in the ice core proxy understanding, we re-drilled and updated existing ice core records from central and northern Greenland. This allowed us to reconstruct air temperatures on the Greenland Ice Sheet over the past millennium with unprecedented quality (Hörhold et al., 2023), which complements the previously used Arctic-wide temperature reconstruction (Fig. 4). The analysis of these unique data shows that modern temperatures on Greenland are 1.5 °C warmer than those of the 20th century. It shows that anthropogenic-induced global warming has reached the high-elevation areas of central and northern Greenland. Our data also enabled us to generate an estimate of the meltwater runoff anomalies for Greenland over the past millennium to put the recent runoff anomalies into a long-term context. The findings suggest that current decadal meltwater runoff anomalies are unprecedented over the last thousand years and are likely to impact firn densification and meltwater storage capacity, with further implications for the ice sheet's mass balance.

3.3.2 Low-frequency regime of temperature variability

The reconstruction also revealed strong natural decadal temperature variability (Fig. 4) in Greenland (Hörhold et al., 2023). To understand the origins of climate variations, it is essential to examine the spatial patterns of temperature variability. By leveraging a comprehensive sedimentary pollen database developed at AWI along with instrumental data, we reconstruct the spatial pattern of terrestrial temperature variability across annual to millennial timescales (Hébert et al., 2022). We show that in coastal regions, strong ocean-driven climate variability overprints the local land climate on multi-decadal and longer timescales. Due to marine influence, regions characterized by stable oceanic climate at sub-decadal timescales experience stronger long-term variability, and continental regions with higher sub-decadal variability show weaker long-term variability. This fundamental relationship between timescales offers unique insights into the emergence of a low-frequency marine-driven regime that governs terrestrial climate variability. It also highlights that the muted slow climate variability observed in standard climate model simulations likely originates from the ocean.

One possible reason for the weak regional temperature variability on multidecadal and longer timescales in models could thus be related to limited spatial resolution. This leads to inadequacies in the representation of subgrid-scale processes, e.g., ocean eddies. We find that there is a tendency for higher-dimensional models to capture variability and extremal behavior better (Contzen et al., 2022). This underlines our goal of understanding and quantifying climate variability to improve modeling by bridging observations with model performance. Marine sediment archives provide an additional perspective on large-scale climate variability and ocean circulation changes. Using planktonic microfossil assemblages, Jonkers et al. (2023) reconstructed glacial sea-surface temperature patterns and biogeographic shifts across the North Atlantic. The study helps reconcile discrepancies between paleoclimate simulations and proxy reconstructions of the Last Glacial Maximum and illustrates how biological archives provide independent constraints on past ocean circulation and climate states. Understanding how eddies respond to climate warming and how their presence influences climate change is therefore critical for many aspects of Earth-system science, which will be covered in detail below.

3.4 Melting ice sheets

Northeast Greenland: a variable ice sheet

The Greenland Ice Sheet (GrIS) has steadily lost mass over the past decades, presently representing the second-largest single contributor to global sea level rise, next to the expansion of seawater by warming. Record melt years like 2012 and 2019, as detected by the GRACE/GRACE-FO satellites, are typically enabled by a stable high-pressure system over Greenland, causing the advection of warm air masses from

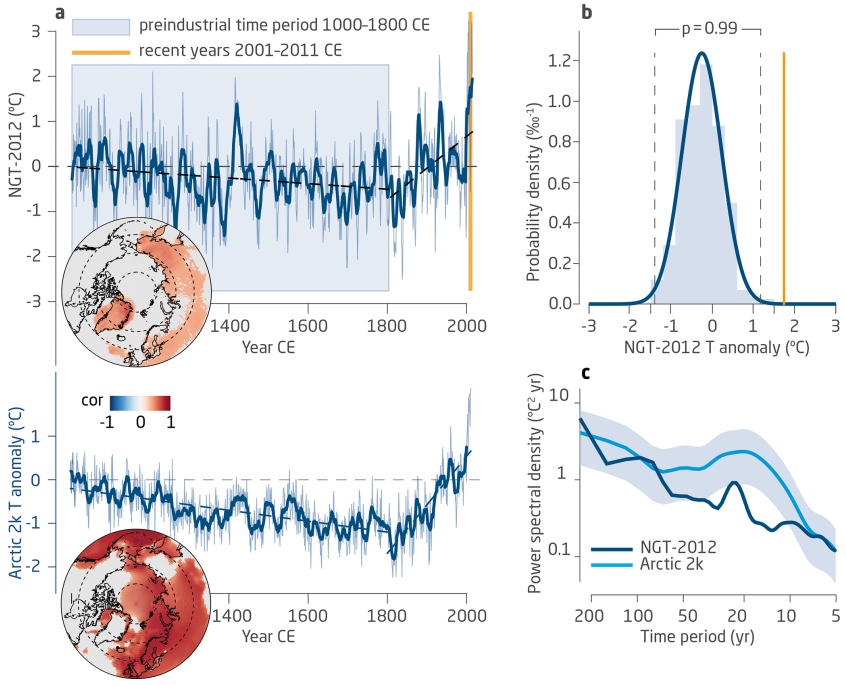


Figure 4. Unprecedented warming and natural variability in Greenland air temperature. **(a)** Reconstruction of air temperature from central to northern Greenland based on stacked ice core records (NGT-2012, upper panel) and the Arctic-wide temperature reconstruction (Arctic 2k, lower panel) presented as annual (thin lines) and 11-year means (thick solid lines). Point correlation maps (insets) between the NGT-2012 and Arctic 2k records with reanalysis fields of surface temperatures show the complementary spatial representativity of the two records. **(b)** A comparison of the distribution of preindustrial temperatures (blue) with those of the most recent decade (orange line) reveals unprecedented warming outside the bounds of natural variability. **(c)** Power spectra of preindustrial temperature variability reconstructed from the NGT-2012 ice core records (dark blue) and the Arctic 2k reconstruction (cyan) illustrate that Greenland's temperature exhibits pronounced decadal variability that masks the global warming signal. Figure adapted from Hörhold et al. (2023) with license: https://creativecommons.org/licenses/by/4.0/ (last access: 6 November 2026).

lower latitudes along the western coast of the ice sheet and northern Arctic Canada (Sasgen et al., 2020). Under these conditions, glaciers in Svalbard are influenced by cold air from the north, leading to opposite temperature and melt anomalies in both regions. The GRACE/GRACE-FO data show that in 15 out of 17 years since 2003, a large ice loss in Svalbard has been accompanied by a weaker loss in northern Arctic Canada and western Greenland, and vice versa. This phenomenon has been occurring more frequently since the 2000s (Sasgen et al., 2022).

We see that the outflow of ice from the GrIS is strongly localized, with only a few ice streams draining most of the entire ice sheet. These river-like zones, where ice flow is significantly faster than in their surroundings, are assumed to be triggered by either bedrock properties, enhanced sliding, and/or by deformation mechanisms leading to shear localization. Oceanic heat transport in the fjords leading up to marine-terminating outlet glaciers can trigger glacier retreat and acceleration of ice flow, which also affects the discharge of ice transported from the inner ice sheet to the coast. Thus, understanding ice stream behavior and its temporal variability is crucially important to project future rates of sea level change. The 500 km long Northeast Greenland Ice Stream (NEGIS) is by far the largest ice stream in Greenland (Joughin et al., 2001; Fahnestock et al., 2001). It feeds its three major outlets on the coast from the region of the central ice divide, and its catchment area covers 17.2 % of the ice-sheet area. While the gates in the coastal mountain range in the northeast of Greenland determine the location of the coastal outlets, its course in the interior of the ice sheet appears not to be constrained by bed topography. We investigate temporal changes in ice stream flow from decadal to millennial timescales to decipher the processes which control or initiate changes in NEGIS. All these data are essential pieces of a larger puzzle, with which we contribute to a better understanding of how ice streams work and how fast they can respond to changing boundary conditions. This will eventually lead to improved projections of sea level rise, and especially to more accurate timing.

Airborne radar surveys of ice stratigraphy in the NEGIS upstream area reveal how ice stream flow has shaped isochrone layering (Jansen et al., 2024). Data from the AWI Polar-6 aircraft and ultra-wideband radar system near the EastGRIP (https://eastgrip.org, last access: 30 December

2025) drilling camp show distinct shear margin signatures in the stratigraphy. A 3-D horizon, tracing an isochrone in the upper ice column, reveals how pre-existing folds are deformed within the shear margin, forming a "kink" that indicates a two-stage deformation process. First, large cylindrical folds formed under convergent flow; they then narrowed as sharp shear margins developed. Fold amplitude changes over time suggest the shear margins were fully established around 2000 years ago, challenging the idea that streaming is triggered and sustained by long-term heat flow anomalies, instead pointing to more abrupt ice-flow reconfigurations (Fig. 5).

The signature in the radar stratigraphy also remains as a record of deformation should the velocities change. It thus provides information on past ice flow regimes. Franke et al. (2022) find such evidence further north of the current NEGIS. The ancient ice-flow regime must have had NEGIS-type shear margins reaching far inland toward the ice divide and probably became deactivated when the main drainage system was reconfigured and relocated southwards. Thus, major ice streams in Greenland might start, shift, or abruptly disappear, and these processes are very likely linked to ice-sheet geometry and volume and to processes at the outlets which influence the mass discharge. Besides the shear margins, a high strain localization zone, the third interface enveloping and enabling the streaming of inland ice, is the subsurface of this "ice highway".

The project successfully drilled a 2668 m ice core from the Northeast Greenland Ice Stream (NEGIS), marking the first complete drill-through of an ice stream. We thus obtained unique access not only to the streaming material but to the bed properties. We find that the sediment under the ice is saturated with water, which is probably caused by basal melting of the ice sheet.

Changes in ice-stream dynamics ultimately influence the marine outlets through which ice is discharged into the ocean. Understanding the coupling between NEGIS and its outlet glaciers therefore requires both glaciological and oceanographic perspectives. More recently, the marine outlet of the NEGIS shows strong evidence of retreat. The most prominent example of this is the collapse of the floating ice tongue of Zachariæ Isstrøm (ZI). The loss of the ice tongue led to a speed-up of ice discharge into the ocean. The largest remaining floating ice tongue of Greenland is the neighboring Nioghalvfjerdsfjorden Glacier – also known as the 79° North Glacier (79NG) – which represents the second major outlet of NEGIS with considerable basal melting. Continuous thinning of the 79NG tongue by up to 30 % has occurred over the past 20 years. This process is caused by increased melting along the ice tongue base (Humbert et al., 2023; Zeising et al., 2024).

3.5 Cryospheric change impacts carbon cycling

The Arctic realm is currently warming at a pace that is up to 4 times faster than the global average (Rantanen et al., 2022). As a result, increased coastal erosion, owing to permafrost destabilization and glacier retreat, is increasing the quantity of old organic material that enters the ocean. It is typically understood that the organic material in old glacial deposits is unsuitable for microbial turnover – and that it is essentially inert. Sediments from the southernmost fjord of the island of Spitsbergen, Hornsund, which is characterized by extreme glacier retreat, were investigated to assess the bioavailability of old organic matter released by rapid glacier retreat. It was demonstrated that microbial communities in marine sediments are indeed capable of using old material as a carbon source if other more labile substrates are exhausted (Ruben et al., 2023). Based on compound-specific radiocarbon analyses of microbial membrane lipids, it was estimated that the microbial communities living in the sediments of Hornsund derive up to 50 % of their carbon turnover from these fossil organic materials that were previously assumed to be difficult to degrade. In light of climate change and the accelerating melting of glaciers, this process may pose a positive feedback on CO_2 emissions and could lead to even more fossil carbon being released into the atmosphere than current estimates would suggest.

It has been established, based on a comparison of simulated and reconstructed radiocarbon data, that the rise in atmospheric CO_2 (approximately 85 ppmv) during the last deglaciation is primarily attributed to physical changes in the ocean (Köhler et al., 2024), but this alone cannot explain the full amplitude of CO_2 fluctuations. The difference must originate from different components of the Earth system. Terrestrial and marine carbon sources, including ancient carbon from retreating ice sheets, can also be significant contributors. This includes the exposure of organic carbon-rich shales and the oxidation of petrogenic organic carbon (OCpetro), which can re-enter the carbon cycle. We provided evidence from sediment cores indicating substantial mobilization of OCpetro during the last deglaciation, particularly in glaciated regions like the Canadian Beaufort Sea (Wu et al., 2022). Based on geochemical records, it has been estimated that OCpetro contributed 50 %–80 % of total organic carbon accumulation in marine sediments during this period, significantly higher than in the late Holocene. Rapid sea level rise led to coastal erosion, which remobilized ancient permafrost carbon. This process is linked to significant pulses of carbon release, contributing to atmospheric CO_2 increases. The combined processes of oxidation of newly exposed petrogenic organic carbon and permafrost carbon release are estimated to have contributed an increase of approximately 8 ppmv in atmospheric CO_2 and to a decrease of 9 ‰ in atmospheric $\Delta^{14}C$ over the last 20 000 years. The findings suggest that ice sheets actively influence the global carbon cycle during deglaciation, challenging the notion of

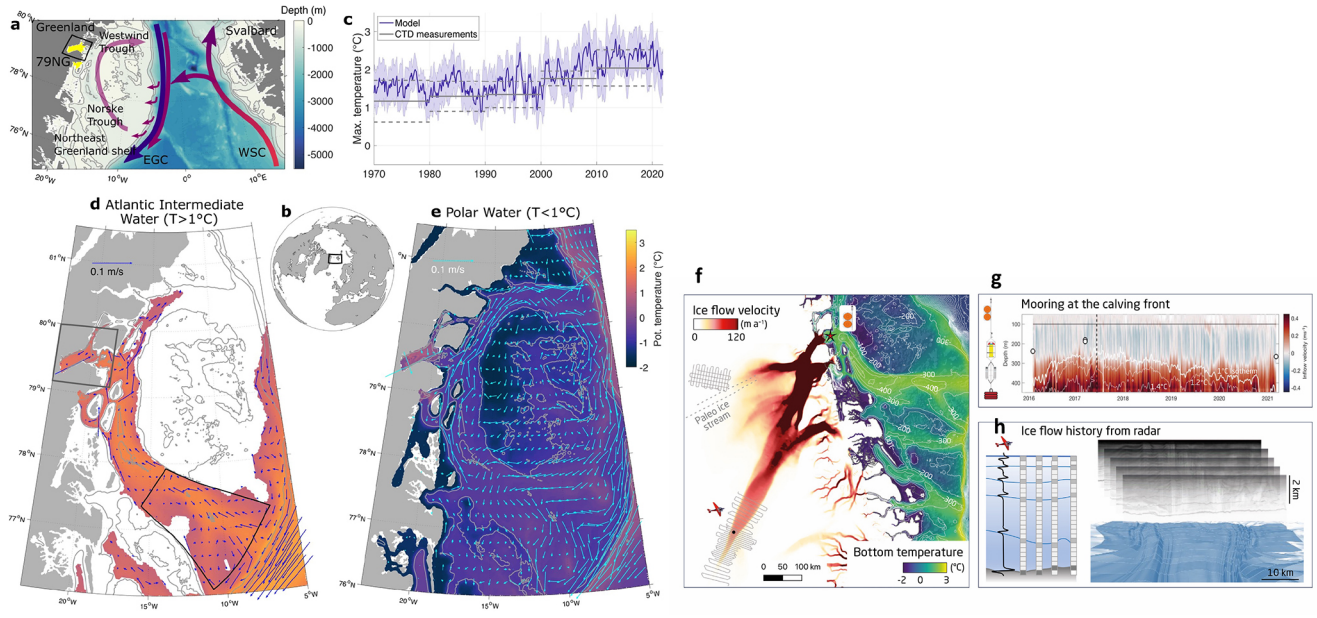


Figure 5. **(a)** Sketch of the ocean circulation in our study region. Purple arrows indicate the West Spitsbergen Current (WSC) transporting warm and salty Atlantic Water toward the Central Arctic Ocean. The blue arrow indicates the East Greenland Current (EGC) transporting fresh and cold Polar Water southwards. On the continental shelf, warm Atlantic Intermediate Water (AIW, light purple arrow) is transported through Norske Trough toward the 79 North Glacier (79NG). The extent of the floating ice tongues of the 79NG and Zachariæ Isstrøm are highlighted in yellow. **(b)** Study area on a global map. **(c)** Monthly mean (solid line) and associated standard deviation (shading) of simulated maximum temperature in the water column averaged over southern Norske Trough (black polygon shown in panel **d**). Solid and dashed gray lines indicate decadal averages and standard deviations, respectively, from historic hydrographic observations. **(d, e)** Mean velocity and potential temperature averaged over the AIW layer (defined by $T > 1\,°C$) and the Polar Water layer (defined by $T < 1\,°C$), averaged over 1970–2021. In white areas, the water masses are absent. Gray lines show isobaths at 200, 500, and 1000 m. The gray box at the 79NG in **(d)** indicates the region. **(f)** Map of northeast Greenland showing ice flow velocities (red shading) of the NEGIS and ocean bottom temperatures (blue–green–yellow shading) based on the FESOM ocean–sea-ice model. The black dot illustrates the EastGRIP deep drilling location. **(h)** The gray lines depict the Polar-6-based airborne radar surveys over the ice streams from which their shear margins (lower insets) were derived. The red cross at the calving front of the 79NG shows the location of an oceanographic mooring that has been serviced by *Polarstern*, from which the flow of warm Atlantic Intermediate Water into the cavity is derived **(g)**. Sources: modified from Jansen et al. (2024), Franke et al. (2022), Wekerle et al. (2024), and McPherson et al. (2024).

their passive role. The study highlights the need for further research into carbon dynamics related to ice-sheet retreat and its broader implications for climate change. Permafrost thawing and accelerated coastal erosion in the Arctic contributes additional ancient carbon to the Arctic Ocean system. The fate of this material and its potential to release greenhouse gases remains poorly understood. Incubation studies help reveal its potential impact. We have found that ancient carbon is readily released upon contact with seawater (Ruben et al., 2024), and about 2 % of organic matter is remineralized within a period equivalent to one summer season. Overall, this research underscores the complex interplay between glacial processes and carbon cycling, emphasizing the importance of understanding these dynamics and following an interdisciplinary approach as exemplified in our program, including the newly established cross-topic activity CTA Carbon, which links carbon-cycle observations, modeling, and synthesis across program components.

3.6 A link of the Greenland ice shelf to Atlantic Intermediate Water

At the mouth of the 79NG fjord, the connection to the continental shelf is constrained by a sill. Moreover, islands along the fjord mouth act as pinning points that stabilize the ice tongue. Covered by an ice tongue several hundreds of meters thick, the ocean circulation in the cavity of the 79NG has thus far been largely unknown. Warm Atlantic Intermediate Water enters the cavity beneath the floating tongue of Nioghalvfjerdsfjorden Glacier (79NG) and contributes to basal melting. Similar interactions between Atlantic-origin waters and Greenland outlet glaciers have been recognized as a key mechanism controlling marine-terminating glacier stability and mass loss around Greenland (Straneo and Heimbach, 2013). Building on this broader framework, our recent observations and high-resolution simulations provide new insights into the pathways and variability in ocean heat transport toward the 79NG system. Our oceanographic measure-

ments obtained by the RV *Polarstern* expeditions PS100 and PS109 at the calving front of the 79NG (Fig. 6) showed the important role that topographically steered subsurface currents play in transporting warm (> 1 °C) Atlantic Intermediate Water (AIW), which originates from the subtropical North Atlantic, across the continental shelf of northeast Greenland and into the cavity (Schaffer et al., 2020). Yet these continuous observations were only started in 2016 and do not yet allow one to investigate decadal changes in ocean heat supply.

Consequently, in order to answer questions about the details of the circulation of warm AIW in the cavity and about the means of basal meltwater export out from the cavity, we cannot rely fully on observations. Modeling can help to fill the observational gap and to improve the understanding of the dynamics at play. What are the reasons for the recent thinning of the ice tongue, and how do melt rates at the base of the ice tongue vary on decadal timescales? To answer these questions, we developed a high-resolution model setup based on the ocean sea-ice model FESOM developed at AWI, which resolves the cavity of the 79NG with a horizontal resolution of 700 m. With this novel setup we can seamlessly connect the global and regional ocean circulation to the circulation in the cavity (see also Fig. 5). Our simulation reveals a bottom-intensified current that transports the warm AIW into the cavity through a narrow trough, around 5 km wide (Wekerle et al., 2024). After crossing a sill, the jet accelerates and circulates cyclonically around the cavity. The inflow of AIW results in ocean temperatures above the freshwater freezing point in the cavity throughout the year, which leads to strong and persistent melting at the base of the ice tongue. The bulk of this submarine meltwater then exits the cavity at around 150 m depth.

In addition to the year-round inflow of the warm AIW, we found another factor that impacts the melting at the base of the ice tongue. Surface meltwater, resulting from ablation and rain upstream of the ice tongue, drains through the ice sheet. A part of the meltwater flows toward the grounding line of the ice tongue and enters the cavity as subglacial discharge. This source of buoyant freshwater speeds up the meltwater plume, thereby enhancing basal melting even more. Our simulation, however, revealed that interannual variability and the long-term trend of the basal melt below the 79NG are over the past 50 years mainly associated with changes in temperature of the AIW, with subglacial discharge playing a minor role (Wekerle et al., 2024). We could trace back the signature of the AIW across the continental shelf of northeast Greenland to the eastern Fram Strait with a lag of 3 years, implying a predictability of the basal melt of the 79NG (McPherson et al., 2023). Both the large-scale northward transport of Atlantic Water temperature anomalies from the subtropics toward the eastern Fram Strait and regional wind forcing within the Fram Strait regulate the quantity of AIW available for melting of the 79NG ice tongue from below.

Superimposed on the long-term warming of the AIW reaching the 79NG, our mooring-based direct ocean observations at the calving front revealed drastically decreasing AIW temperatures from 2018–2021 (right inset in Fig. 6), coinciding with reduced ocean heat transport into the cavity and a consequently reduced basal melt (McPherson et al., 2024). The reduced heat transport is a result of hydraulic control, meaning that the reduction in the layer thickness of AIW at a minor sill (= control point) close to the calving front caused the reduction in subsurface flow of warm AIW into the cavity.

Using a combination of long-term observations, obtained by AWI's FRAM observatory in the Fram Strait, and numerical ocean modeling, we could show that cooling of the AIW at the 79NG is linked to a slowdown of the large-scale ocean circulation supplying Atlantic Water across the Nordic Seas toward the Fram Strait and further onto the shelf of northeast Greenland. The slowdown and cooling appear to be driven by European atmospheric blocking patterns that strengthen cold air advection from the central Arctic through the Fram Strait. The anomalous southward flow of cold air both slowed down the Norwegian Atlantic Current and increased the loss of ocean heat to the atmosphere, resulting in a massive cooling of the AIW. Further, we could demonstrate that blocking has driven several major ocean cooling events in the Nordic Seas over the last 50 years and that this atmospheric mechanism will remain crucial in affecting northeast Greenland's glaciers.

The question remains as to how 79NG will evolve in the future. The fate of Greenland's largest floating ice tongue remains uncertain. As temperatures in the AIW layer on the northeast Greenland continental shelf are projected to increase until the end of this century, the ice tongue might eventually disappear, just as the one of the ZI did.

This combined glaciological and oceanographic investigation of the NEGIS-79NG system is a prime example of the role of AWI's infrastructure (*Polarstern*, Polar 6 aircraft) in enabling unique missions by methodology advancements: the sophistication of remote sensing data analysis on the one hand and of ground truthing by autonomous measurement stations on the other hand is combined with advanced engineering of sampling of ice material (e.g., drilling technologies). Furthermore, advances both in data science, e.g., of extensive airborne radar data, and seamless scale-resolving ocean modeling allows for important interdisciplinary findings in Earth-system science.

The ATWAICE Expedition (PS131, June–August 2022) significantly contributed to the research directed at these questions. Valuable insights into sea ice dynamics and interactions in the marginal ice zone north of Svalbard were obtained. Key achievements include the ongoing monitoring of Fram Strait exchange flows and impacts on Greenland's marine-terminating glaciers, as well as a lithospheric study at the Aurora vent field of the Gakkel Ridge.

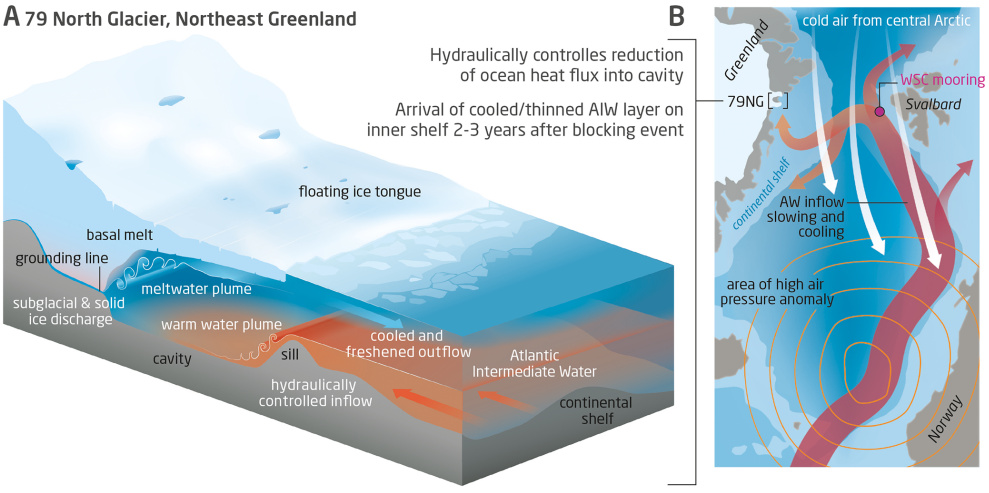


Figure 6. **(A)** Cavity circulation at the 79 North Glacier (79NG) and the ocean–glacier interactions. The inflow of Atlantic Intermediate Water (AIW) below the ice tongue is constrained by the sill through hydraulic control, determined by the AIW conditions upstream on the northeast Greenland continental shelf. Downstream of the sill, heat is transported into the cavity, which melts the glacier from below. The heat lost due to the melting results in a meltwater plume and outflow of cooler waters at the surface. The floating ice tongue is a prominent feature of the 79NG. **(B)** Summary of the proposed atmospheric and oceanic forcing that drives anomalous Atlantic Water (AW) cooling in the West Spitsbergen Current (WSC). European blocking sets up atmospheric conditions that slow down the northwards flow of the AW toward the Arctic and enhance surface heat fluxes upstream of the WSC, which lowers AW temperatures. The AW temperature anomalies in the Fram Strait are then recirculated westwards to the northeast Greenland continental shelf and 79NG, where a resultant cooler and thinner inflow of AIW would cross the sill below the ice tongue between 2 to 3 years after the blocking event. Source: McPherson et al. (2024). Reprinted with permission from AAAS.

3.7 Modeling mesoscale ocean dynamics

Many of the largest uncertainties in future ocean circulation arise from processes operating at scales that remain unresolved in most Earth-system models. Mesoscale ocean eddies influence the transport of heat, carbon, nutrients, and momentum, thereby linking small-scale turbulence to large-scale climate dynamics. These eddies are essential for ocean circulation, the uptake of heat and carbon at depth, gas exchange with the atmosphere, and the transport of nutrients. Understanding how they respond to climate warming is therefore critical for many aspects of Earth-system science. Exploiting the latest developments in climate modeling along with cutting-edge high-performance computing (HPC) systems, we examined for the first time how ocean eddy activity will evolve in the 21st century as the world continues to warm. Depending on the spatial resolution employed in climate simulations, we find substantial differences in the large-scale gyres, in the eddying Arctic and Southern Ocean, and in Atlantic Meridional Overturning Circulation shifts.

3.7.1 Western boundary currents and evolution of ocean eddies

Western boundary currents (WBCs) are fast-moving ocean flows that are warming at rates 2–3 times faster than the rest of the ocean due to climate change. These currents are vital for regulating regional climates and ecosystems, with warming hotspots affecting sea level rise, marine heatwaves, and fisheries. Ocean eddies are emerging as key drivers of rapid warming in WBCs, such as the Gulf Stream and the Kuroshio Current, with recent advances highlighting their critical role in shaping ocean dynamics under climate change. Our studies using satellite data (Yang et al., 2020, 2023) and high-resolution models (Beech et al., 2022) reveal that intensifying poleward-moving eddies are the primary contributors to this rapid warming.

In our recent research using the AWI climate model (AWI-CM), part of AWI's contributions to the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Semmler et al., 2020), discussed in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6 IPCC), we uncovered a significant role of mesoscale eddies in shaping ocean circulation in a warming climate (Beech et al., 2022; Yang, 2022). Leveraging the model's unstructured mesh capability to resolve eddy-rich regions, the study provides unprecedented insights into how eddy activity evolves under anthropogenic climate change. Mesoscale eddies influence western boundary current extensions such as the Gulf Stream and Kuroshio by redistributing heat, salt, and momentum. Changes in eddy kinetic energy (EKE) are therefore regionally important, but they do not necessarily imply a uniform response of all western boundary currents. In the North Atlantic, changes in Gulf Stream variability must be interpreted together with basin-scale density gradients and

AMOC changes; in the North Pacific, Kuroshio variability reflects a different dynamical setting.

A key novelty of this approach lies in its ability to simulate long-term changes in eddy activity using high-resolution modeling. Unlike previous studies limited by satellite altimetry records or coarse-resolution models, AWI-CM captures the fine-scale processes driving shifts in eddy dynamics. For example, poleward shifts in EKE align with the expected movement of major ocean currents under warming, while the decline in Gulf Stream eddy activity reflects the cascading impacts of AMOC weakening. The model also shows that intensifying westerly winds over the Southern Ocean amplify ACC eddy activity without significantly altering its overall transport capacity, reinforcing the concept of eddy saturation.

We clarify that the relevant mechanism is not a simple increase in deep-water formation causing AMOC decline. Rather, regional changes in density transformation, freshwater forcing, and pathway shifts can modify where and how deep waters are formed, while the basin-scale overturning weakens. These results show that resolving mesoscale processes is not merely a technical refinement. It can change the simulated response of large-scale circulation and regional climate extremes.

3.7.2 Arctic eddy activity to surge in a warming world

Especially in the Arctic Ocean, eddy activity is set to intensify significantly in a warming world, with far-reaching consequences for the region's climate and ecosystems. Using the high-resolution global sea ice-ocean model FESOM, our study provides a novel projection of how EKE in the upper Arctic Ocean will evolve under a +4 °C warming scenario (Fig. 7).

The findings reveal a 3-fold increase in EKE, driven primarily by enhanced baroclinic instability, which fuels eddy generation. This unprecedented resolution allows us to capture mesoscale eddies, overcoming the limitations of most existing climate models, which cannot resolve these critical small-scale processes. This work represents the first quantitative assessments of Arctic eddy activity under extreme warming, offering new insights into the dynamics of the rapidly changing Arctic Ocean.

A key novelty lies in the interplay between sea ice decline and eddy damping. Despite the significant loss of sea ice, the damping of eddies through interactions with sea ice and winds – commonly referred to as "eddy killing" – is projected to maintain its annual mean effect. This challenges conventional assumptions that reduced sea ice would weaken eddy damping and further accelerate eddy activity. Instead, our findings reveal a complex balance where the processes of eddy generation and dissipation adjust dynamically, with baroclinic instability emerging as the dominant driver of increased EKE.

The implications of this study extend beyond the Arctic. The projected surge in eddy activity will enhance the transport of heat, salt, carbon, and nutrients, fundamentally altering air–sea interactions, ocean circulation, and regional ecosystems. These changes highlight the critical importance of incorporating high-resolution eddy dynamics into climate models to improve predictions of Arctic and global climate responses. By resolving these mesoscale processes, we can better understand and anticipate the cascading impacts of Arctic warming on the Earth system. One of these potential cascading effects is linked to the Atlantic Meridional Overturning Circulation.

3.7.3 Future Arctic marine heatwaves and their potential impacts on the ecosystem

Marine heatwaves (MHWs) have intensified in recent decades, and high-resolution climate models show that Arctic MHW variability will significantly strengthen in the 21st century, driven by sea ice retreat. With little ice cover, strong interannual variability could emerge, surpassing previous intensification levels. This increase in MHWs correlates with rapid temperature changes and enhanced stratification, which may disrupt Arctic ecosystems. Close collaboration between climate scientists and biologists (Gou et al., 2025) highlights the potential for MHWs to impact Arctic food webs, both directly through temperature effects and indirectly through nutrient shifts and species changes.

3.7.4 Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) plays a central role in the global climate system in that it transports enormous quantities of heat across latitudes. Global warming is expected to weaken the AMOC, which could lead to serious climatic changes in Europe. Our current program work focuses on key factors driving the AMOC behavior. Analyses combining observations and model simulations suggest that the AMOC has undergone changes in its structure and stability (Dima et al., 2025). Climate models predict a significant slowdown of the circulation system in the future as carbon dioxide concentrations continue to increase and as melting of the Greenland Ice Sheet accelerates.

We show that under the influence of global warming the AMOC shows regional and disproportionately abrupt shifts, contrary to previous results that suggest a long-term and smooth decline (Gou et al., 2024). The high-resolution model study uncovers a startling twist: the AMOC may strengthen in the subarctic Atlantic due to warming, defying the widespread belief that this vital current system is uniformly weakening. Advanced climate models now reveal that, under extreme greenhouse gas emissions (RCP8.5), the AMOC could experience sharp declines in some areas, while paradoxically increasing in the Arctic. This unexpected regional strengthening occurs despite an overall weakening trend in AMOC activity (Gou et al., 2024). This leap in modeling precision exposes critical regional variations, ocean ed-

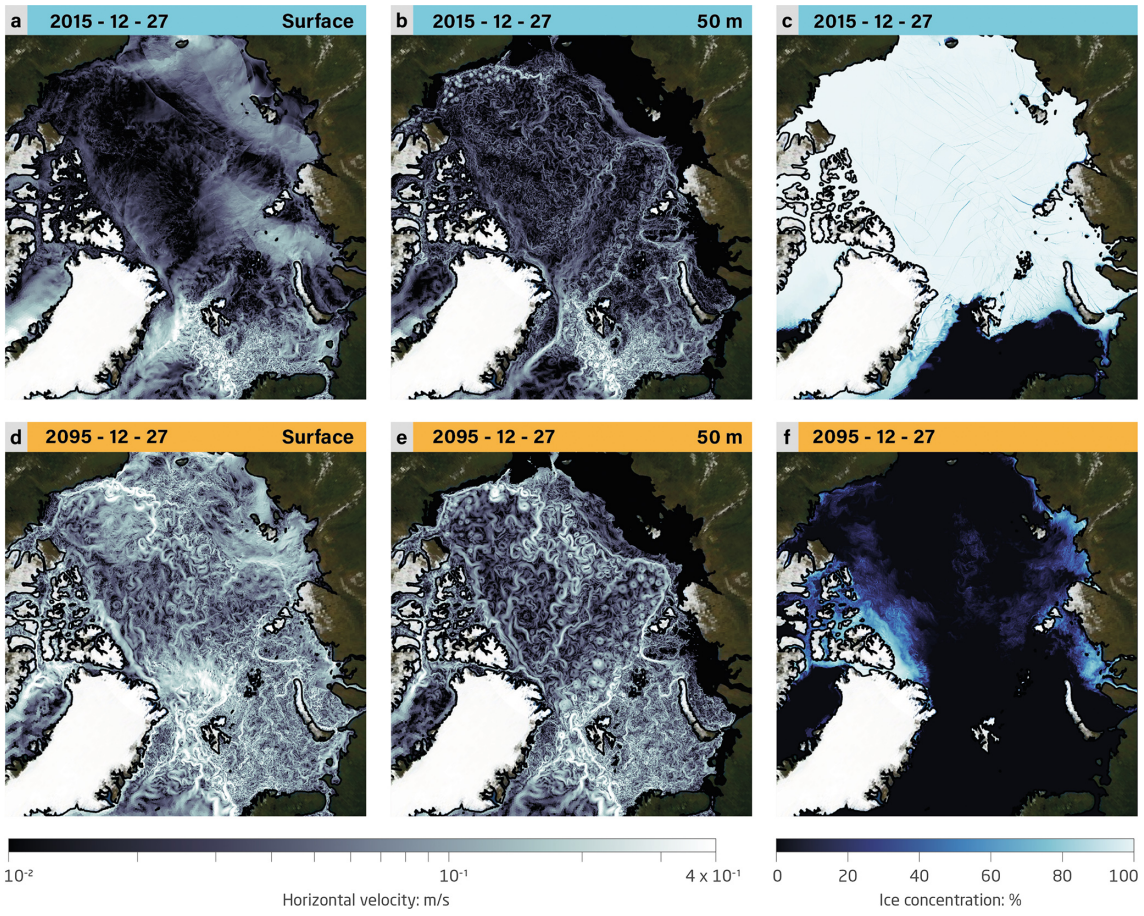


Figure 7. Snapshots of ocean currents and eddy activity at the surface **(a, d)** and at 50 m deep **(b, e)** from a global sea ice-ocean simulation with a resolution of 1 km in the Arctic. The right column shows the corresponding Arctic sea ice concentration **(c, f)**. The upper row is for 27 December 2015 (present-day climate), and the bottom row is for 27 December 2095 (approximately +4 K warmer world). Modified from Li et al. (2024).

dies, and tipping points that were previously hidden due to limitations to model dynamics of coarser models. The findings highlight the urgent need to incorporate regional dynamics, as these localized shifts could have profound impacts on climate and on marine ecosystems.

Warming of the North Atlantic region in climate history was often associated with massive melting of the Greenland Ice Sheet. To identify the meltwater's impacts and isolate these from internal variability and other global warming factors, we run single-forcing simulations including small ensembles using three complex climate models differing only in their ocean components (Martin et al., 2022). The ocean translates the step-change perturbation into a multidecadal-to-centennial signature in the deep overturning circulation. In all simulations, internal variability creates notable uncertainty in estimating trends, time of emergence, and duration of the response.

New high-resolution modeling reveals that the AMOC is particularly vulnerable to shifts in salinity in the Irminger Sea off Greenland from increasing Arctic meltwater (Ma et al., 2024). As such, this region plays a critical role in powering AMOC, a conclusion supported by recent observations. Due to a more northward part of the AMOC branch, boundary currents carry warm Atlantic Water along the Norwegian coast toward the Fram Strait and Barents Sea Opening. The heat transport keeps large parts of Barents Sea ice-free in wintertime and represents the most important heat source of the Arctic Ocean. It has long been shown that the strength of Atlantic water inflow into the Barents Sea is enhanced during positive states of the North Atlantic Oscillation (Heukamp et al., 2023). The inflow was largely absent during the period from 1995 to 2005 due to pronounced atmospheric blocking in the North Atlantic sector. This implies that an adequate representation of blocking is necessary in climate models to reliably simulate changes in poleward ocean heat transport and thus Arctic climate.

As for the role of climate change interacting with natural variability in governing the Arctic climate, we have also made considerable progress in deciphering recent drastic changes in Antarctica.

3.7.5 The Antarctic sea ice paradox and its implication for modeling

Despite global warming, the extent of Antarctic sea ice has been enormously dynamic but on average has remained surprisingly stable since satellite observations began in 1979. This stood in sharp contrast to existing climate model simulations, which typically predict a significant decline in Antarctic sea ice over the same period – a discrepancy known as the "Antarctic sea-ice paradox". This paradox has drawn attention to the quality of 21st-century sea ice projections, a concern also emphasized in previous IPCC reports. However, since 2017 Antarctic sea ice extent has dropped sharply and the region may have entered a new stage due to upwelling of warmer waters (e.g., Purich and Doddridge, 2023; Silvano et al., 2025) challenging both previous and present understanding and future predictions of the controls on Antarctic sea ice coverage.

We demonstrated that AWI-CM with the FESOM in a high-resolution, i.e., locally eddy-permitting, ocean configuration simulates a much slower decline in Antarctic sea ice compared to its standard-resolution counterpart (Rackow et al., 2022). This suggests that coarser-resolution CMIP-type models overestimate Southern Ocean sea ice loss. Mesoscale ocean eddies, a critical feature often underrepresented in previous models, play a key role in these differences. Our high-resolution simulations reveal that Antarctic sea ice, particularly in September, could remain stable until the mid-21st century. The more accurate representation of mesoscale processes in high-resolution models enhances heat transport toward the Equator in response to global warming. This mechanism moderates the impacts of anthropogenic warming near Antarctica, effectively delaying the decline in sea ice.

Despite these results, there remains uncertainty about the competing roles of the ocean and atmosphere for the recent Antarctic sea ice changes that may have ended the Antarctic sea ice paradox. We have carried out several *Polarstern* cruises and remote sensing studies to verify what actual changes the ice has experienced. Results show that snow properties and the formation of superimposed ice, which provide evidence of changes in the surface energy balance in the absence of strong surface melt, have changed little (Arndt et al., 2021; Xu et al., 2024). This provides further evidence for the strong role of oceanic processes in governing Antarctic sea ice variability and change.

The Antarctic sea ice paradox underscores the importance of mesoscale processes in regulating polar climate systems. Eddies could influence the stability of the Antarctic system by mediating ocean–atmosphere exchanges and delaying feedback that could destabilize sea ice and ice sheets. These findings open new pathways for integrating mesoscale dynamics into Earth-system models and for refining predictions of polar climate impacts. Validation of the newly available models needs high-quality data and suitable analytical tools.

3.8 Feedback mechanisms in a warming world

3.8.1 Rapid surge in global warming in 2023: reduced planetary albedo

In 2023, global temperatures reached nearly 1.5 °C above pre-industrial levels, setting an alarming record (Bevacqua et al., 2025). While best-guess effects from greenhouse gas emissions, aerosol reduction, El Niño, and natural events explain much of the warming, a 0.2 °C gap remains. In our recent study, we propose a significant contributing factor: a sharp decline in planetary albedo, primarily caused by a reduction in low-altitude cloud cover (Fig. 8).

Analyzing satellite and reanalysis data, we found that planetary albedo – the fraction of solar radiation reflected back into space – reached its lowest level in 2023 since at least 1940. While the loss of Arctic and Antarctic ice contributed, it accounts for only 15 %. The key driver appears to be a substantial decrease in low-altitude clouds, including over the North Atlantic which experienced record-high sea surface temperatures. Low clouds play a vital role in cooling the planet by reflecting sunlight, and their decline attenuates this important cooling effect. Without the albedo reduction starting in 2020, global mean temperatures in 2023 would have been approximately 0.23 °C cooler.

The reasons for this cloud decline are multifaceted. Stricter regulations on marine fuel might have played a role in reducing aerosol concentrations, which serve as condensation nuclei for cloud formation. Natural variability may have also contributed. However, global warming itself may also be suppressing low-cloud formation, creating a feedback loop that amplifies warming, which is an important theme in our future studies.

If this feedback continues, future warming could exceed current average projections, pushing global temperatures past the 1.5 °C threshold sooner than anticipated. These findings suggest a relatively high climate sensitivity, highlighting an urgent need to improve the representation of low-cloud feedback mechanisms in climate models. These findings highlight the importance of improving the representation of cloud feedbacks and ocean–cloud–aerosol interactions in climate models, both for constraining climate sensitivity and for assessing future climate risks.

3.8.2 Extreme events – making climate change impacts tangible

AWI has been at the forefront of developing and applying storylines of extreme events with global climate models, transforming the way we understand and communicate the impacts of climate change. By illustrating how recent extreme events – such as European heatwaves, marine heatwaves (see above), and extreme rainfall – would have unfolded in pre-industrial climates (attribution) and how they might evolve in future warming scenarios (+2, +3, or +4 °C projections), this methodology bridges cutting-edge climate

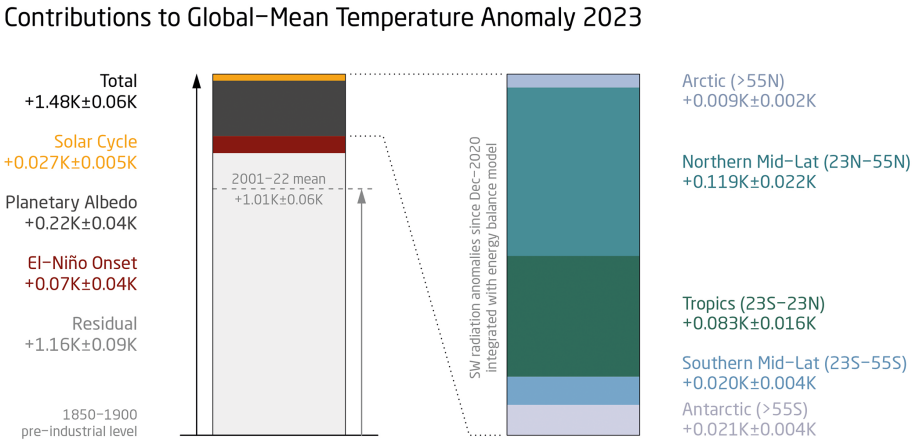


Figure 8. Contributions to the global-mean surface temperature anomaly 2023, with 90 % confidence intervals. Left: from the El Niño onset (red), from absorbed solar radiation (ASR) anomalies since December 2020 due to incident solar radiation anomalies (orange), and planetary albedo anomalies (dark gray). Right: the ASR-related contributions further decomposed into contributions from five zonal bands. Figure adapted from Goessling et al. (2025).

science and actionable insights for society. Storyline analyses have quantified how anthropogenic warming has amplified the severity and frequency of heatwaves, informing risk assessments and heat adaptation measures (Fig. 9). Furthermore, investigations into marine extremes reveal their potential future impacts on ecosystems and economies, highlighting the critical role of ocean variability under a changing climate (Athanase et al., 2024a). Moreover, projections of unprecedented rainfall intensities for hydrological extremes in autumn 2024 under warming scenarios emphasize the urgent need for robust flood mitigation and planning (Athanase et al., 2024b). To this end, this approach can look into the fingerprints of extreme solar and volcanic activities in the climate system and its possible impact on population (Rimbu et al., 2024; Wirtz et al., 2024) which is a subject for future activities in the newly funded InnoPool project SOLVE.

AWI has expanded the reach of these storylines through innovative communication tools. A recently launched online platform (https://climate-storylines.awi.de/, last access: 30 December 2025) enables users worldwide to explore storylines of weather and climate events, fostering greater public understanding of complex climate risks. This prototype was successfully showcased in July 2023 in collaboration with Zeit Online, Germany's leading weekly online newspaper, demonstrating its potential to connect cutting-edge science with diverse audiences.

The storyline methodology is now a key component of the Climate Digital Twin (Bauer et al., 2021) within the EU's Destination Earth initiative, offering global and regional climate services with enhanced granularity and utility. Its inclusion in the new Innovation Pool project ACTUATE (2025–2027) underscores the importance of this approach in the program and its transformative potential for supporting adaptation strategies and increasing resilience to future climate extremes. By making climate impacts tangible, AWI's storylines empower decision-makers and stakeholders with actionable insights, bridging the gap between scientific understanding and societal resilience. This approach not only enhances climate literacy including the concept of climate change attribution but also provides a foundation for more effective and proactive climate adaptation and mitigation strategies globally.

These projections and their implications for extreme events are enabled by advanced methodologies that underpin the research, showcasing innovation and scalability. We highlight here the interdisciplinary and international year-round expedition in the Arctic. Integrating our advanced methodologies with climate insights across timescales underscores the transformative impact of our research.

3.9 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC)

The MOSAiC initiative started with the interdisciplinary and international expedition in the Arctic led by AWI under the umbrella of the *International Arctic Science Committee* (IASC) and is continued as a major integrative activity of the current program. Around 90 polar research institutes from 20 nations participated in the expedition, which aimed to take a holistic approach to studying critical processes involved in the coupling of different climate system compartments in the "new Arctic". The primary focus was on deciphering ill-described processes in the coupled atmosphere–ocean–sea-ice system, with an emphasis on physical, ecosystem, and biogeochemical interactions across an entire annual cycle. This work is crucial for improving our understanding of the Arctic system and eradicating long-standing biases in climate models in support of advanced climate change projections – in the Arctic and beyond.

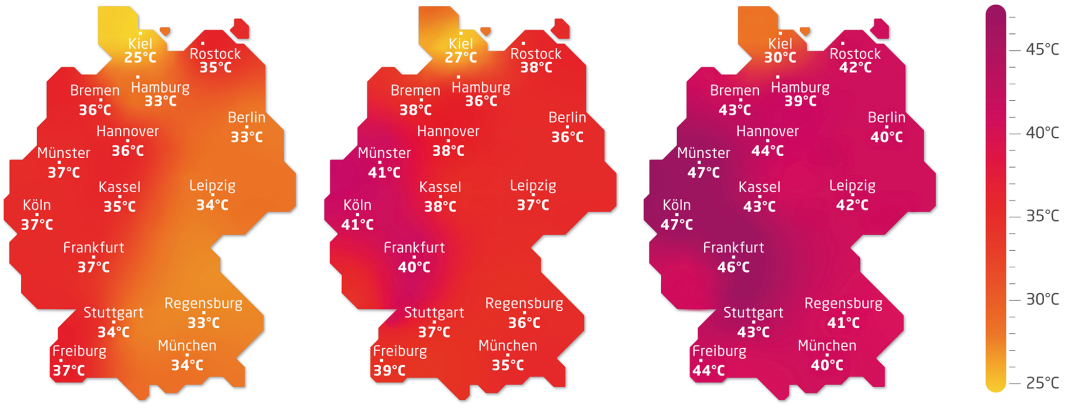


Figure 9. Simulated heatwave in Germany on 25 July 2019 across three climates: pre-industrial conditions (left), present-day climate (middle), and a +4 °C warmer future world (right). The comparison highlights the intensification of heatwave severity and extent under anthropogenic warming. Adapted from Sánchez-Benítez et al. (2022).

Our research icebreaker *Polarstern* (Knust, 2017) drifted through the central Arctic from October 2019 to October 2020, starting from the Siberian sector of the Arctic and heading to the Fram Strait, including additional routes. MOSAiC comprised a central observatory (CO) on an ice floe, a large number of instruments on *Polarstern*, and a distributed network of instruments up to 40 km away from the CO. To foster collaboration, AWI organized four international science symposia, covering the full scope of MOSAiC research, with another planned for 2027. The consortium managed to make all MOSAiC data publicly available in January 2023.

During the initial analysis phase, AWI researchers prioritized publishing comprehensive overview contributions across various scientific domains to ensure the integrated nature of the observations was preserved and to provide a framework for process-related studies.

The core aim of MOSAiC has been to apply the process knowledge from local in situ observations to upscaling to the larger scale. This includes merging MOSAiC data with remote sensing products and applying models. In the following, we present some examples of recent progress: von Albedyll et al. (2022) analyzed sea ice thickness from airborne observations together with ice mass balance and position buoy observations (see Rabe et al., 2024). One unexpected result was the large dynamic thickening that occurred during spring due to the mobile sea ice pack and periodic sub-daily motion. Negative feedbacks of thermodynamic sea ice growth reduce the loss of sea ice volume in large parts of the Arctic (Ricker et al., 2021). New SAR-derived lead fraction products offered further insights into sea ice lead formation that are crucial for understanding ocean–atmosphere interactions (von Albedyll et al., 2024). A comprehensive analysis of the MOSAiC ice floe and of its local environment provides a profound physical characterization and several legacy datasets of sea ice thickness and surface elevations, melt pond bathymetry, and sea ice optical properties and their seasonal evolution (Hutter et al., 2023; Neckel et al., 2023; Fuchs et al., 2024; Tao et al., 2024).

Based on airborne survey data gathered by AWI over the past 3 decades and during MOSAiC (Krumpen et al., 2025), we observe a shift in Arctic sea ice toward a smoother surface with fewer pressure ridges and lower surface drag, which is related to the loss of old ice. An increase in seasonal ice cover amplifies the overall deformation and acts as a negative feedback mechanism that slows the decline in ridges. While thinner and less-frequent ice ridges benefit industries such as shipping, these changes could significantly affect the energy and mass balance as well as the ecosystem of the Arctic Ocean.

During MOSAiC, the vertical migration of zooplankton under very low light late autumn conditions is studied with autonomous devices. Connecting the field observations with climate model studies, we show (Flores et al., 2023) how future sea ice changes will impact the under-ice light climate and how this impacts ecological key species, functions, and biodiversity.

We have successfully used MOSAiC data to evaluate global coupled climate models at the process level by employing spectral nudging of winds to ERA5 data (Pithan et al., 2023), demonstrating a novel approach to compare global climate model output with field campaign data. This evaluation led to improved sea ice atmosphere coupling in AWI-CM3 (Streffing et al., 2022). This improvement supports AWI's contributions to the upcoming CMIP7 effort in support of IPCC. Additionally, the evaluation of climate models against MOSAiC data was also integrated into AWI's modeling efforts for the European Destination Earth Initiative (John et al., 2026), where the AWI climate model is being used as part of the Climate Adaptation Digital Twin.

As the focus of the MOSAiC analysis shifts from disciplinary to interdisciplinary questions, our work has equipped us with a rich dataset and the necessary tools to address

these challenges. Since mid-2022, approximately six peer-reviewed publications have been published per month, based on open-access datasets mainly provided by the Earth-system data infrastructure PANGAEA (https://pangaea.de/, last access: 30 December 2025).

The studies reviewed here reveal several recurring themes, including the state dependence of climate sensitivity, the central role of ocean circulation, and the importance of natural variability across timescales. The methodological and infrastructural developments enabling these advances are summarized in Appendix A.

4 Conclusions and Outlook

Understanding future climate change requires an Earth-system perspective that links ocean, cryosphere, and carbon-cycle dynamics across a wide range of temporal and spatial scales. Evidence from paleoclimate archives, contemporary observations, and numerical simulations shows that climate sensitivity, feedback strength, and the response of major Earth-system components depend strongly on the underlying climate state. The geological past therefore provides an essential framework for constraining the mechanisms, sensitivities, and thresholds relevant to future change.

Results from Antarctic Ice Sheet evolution, Southern Ocean circulation, glacial–interglacial transitions, and contemporary cryosphere change demonstrate that the response to external forcing depends strongly on the underlying boundary conditions and climate state. East and West Antarctica, for example, exhibit distinct sensitivities to atmospheric CO_2 forcing because of differences in topography, ocean connectivity, and ice-sheet dynamics. The cryosphere is not merely a passive responder to climate forcing: changes in sea ice, glaciers, and ice sheets can themselves modify ocean circulation, freshwater budgets, surface energy fluxes, and sea level. Climate sensitivity is thus not a fixed property of the Earth system but emerges from interactions among the atmosphere, ocean, cryosphere, and carbon cycle.

Ocean circulation emerges as a key regulator of Earth-system change. Across timescales ranging from decades to millions of years, changes in Southern Ocean circulation, ocean stratification, Arctic freshwater balance, and Greenland ice–ocean interactions influence the storage and redistribution of heat, carbon, and freshwater. At the same time, paleoclimate records reveal stronger and more persistent variability on decadal-to-centennial timescales than represented in many current climate models, pointing to unresolved processes and feedbacks. Resolving these dynamics is essential for reducing uncertainties in projections of future climate change, sea-level rise, and carbon-cycle feedbacks.

Important uncertainties remain concerning ice-sheet stability, future changes in large-scale ocean circulation, carbon-cycle feedbacks, and the role of natural variability in shaping regional climate change. Addressing these questions requires more than incremental advances within individual disciplines. It requires sustained observations, long-term perspectives, and a continued effort to bridge process understanding across scales, from local interactions to the dynamics of the Earth system as a whole. New ice-core and marine sediment records, sustained observing systems, advances in data assimilation (e.g., Masoum et al., 2024), and kilometer-scale Earth-system models provide new opportunities to investigate climate processes across climate states and timescales.

The central lesson emerging from these studies is that Earth-system responses cannot be understood independently of the climate state in which they occur. Processes operating from days to millions of years interact across scales, while local ocean and cryosphere processes can shape large-scale climate evolution. The past is therefore not simply an analogue for the future but a natural laboratory for identifying how sensitivities, feedbacks, and thresholds change across climate states. Linking the geological past, the observational present, and possible future climates provides a powerful basis for distinguishing transient variability from enduring change, identifying emerging risks and critical thresholds, assessing the reversibility of transitions, and placing future trajectories within the longer context of Earth-system evolution.

Appendix A: Research infrastructure, scientific capabilities, and international partnerships

The preceding sections reviewed scientific findings from the 2021–2025 program phase. The following section changes perspective and describes the observational, computational, and communication tools that enabled these findings and will shape future research. We distinguish between tools for knowledge creation, such as platforms, observatories, models, and data infrastructure, and tools for knowledge use, such as data portals, decision-support products, and stakeholder-oriented communication.

A1 Autonomous technologies

The ocean observing system FRAM (FRontiers in Arctic Marine Monitoring, https://www.awi.de/forschung/biowissenschaften/tiefsee-oekologie-und-technologie/observatorien/fram-ocean-observing-system.html, last access: 30 December 2025) was established to address the need for comprehensive three-dimensional observations in space and time with dense data coverage. This initiative focuses on implementing the first distributed observatory spanning from sea ice to the deep-sea floor in the Fram Strait (2014–2021, extended until 2023). Autonomous sea ice technologies include plane-operated equipment, such as the EM Bird for sea ice thickness measurements, to ship-deployed autonomous buoys and profilers equipped with various sensors drifting with the ice. Deep-sea technologies

include complex autonomous modules for water and particle sampling, imaging, sensing, passive acoustic recording, and seismic technologies (OBS), which can be deployed year-round under sea ice in the Arctic and Antarctic. A current infrastructure investment is MUSE (Marine Environmental Robotics and Sensor Technologies for Sustainable Research and Management of Coastal, Ocean, and Polar Regions), a large competitive Helmholtz research infrastructure project undertaken with GEOMAR. Within our research program, MUSE strengthens modular observing systems ranging from ice-borne units to deep-sea camera observatories. Ocean variables essential to assessing the environmental status from local to global scales are made available for sustainable ocean research in the coming years. This includes advances in robotic technologies (von Appen et al., 2021) by further developing cross-center robotic sensor modules, sustainable energy and data solutions, and high-tech system integration to transform existing robotic systems into an integrated and coordinated fleet of measurement platforms to tackle urgent challenges of ocean observations.

Novel and elaborate measurement techniques opened new possibilities for future success stories, such as a ground-based Global Navigation Satellite System (GNSS) application to measure specific surface mass balance (Steiner et al., 2023) of ice sheets and glaciers, being one of the major uncertainties in ice-sheet mass balance estimates for sea level reconstructions. The system, developed in collaboration with GFZ, has now become part of the Neumayer meteorological observatory, and further development of an autonomously and remotely operating system is currently in the implementation phase as part of AWI/HGF's Innovation Fonds project. This tool also supports knowledge transfer through industrial cooperation with ANavS in Munich, Germany. We expect that this will lead to a transfer of knowledge into the economy and availability of cheap systems for widespread polar applications.

Over the last years we collected valuable in situ data, highlighting the extreme spatial as well as considerable temporal variability in subglacial melting and enabling improved process understanding. This was achieved by the routine deployment of autonomous phase-sensitive radar systems toward performing longer-term measurements at several locations of the Greenland and Antarctic ice tongues and shelves and supported by development of improved analysis methods. The observations will be used to provide ground truthing and constraints for extrapolating the ice–ocean interaction in our models.

A2 Earth-system modeling

The examples of our research presented above illustrate not only that the research within our program is at the forefront of observational methodologies but also that it pushes the boundaries of current modeling capabilities. To remain at the cutting edge of science, we have made significant progress in implementing our modeling strategy, centered around two major developments: first, the push toward kilometer-scale climate simulations; these simulations enable the representation of small-scale processes with unprecedented detail, enhancing our understanding of coupled climate dynamics and enabling provision of climate change information with local granularity, globally. Major EU projects such as nextGEMS, the AWI-coordinated EERIE project, and the Destination Earth Initiative – where AWI is one of the leading partners – play a central role in advancing these efforts toward kilometer-scale Earth-system simulations. The second is the development of Earth-system configurations with advanced capabilities. These include interactive representations of ice sheets, icebergs, and cavities for both hemispheres (Nissen et al., 2022; Niu et al., 2024; Ackermann et al., 2024), as well as coupled ocean biogeochemistry REcoM (Wekerle et al., 2024; Butzin et al., 2024; Ye et al., 2025). These configurations are critical for investigating feedback mechanisms across cryosphere–ocean ecosystem systems. Coupled ice-sheet–climate models will set a new standard for sea level projections under warming conditions (both for Northern and Southern hemispheres). Ongoing model developments of further relevant aspects, such as ice-sheet base properties and physical ice dynamics models, will again move to more realistic descriptions on long timescales.

At the core of this strategy is the first mature global sea ice-ocean model FESOM, developed at AWI (Scholz et al., 2022). FESOM leverages unstructured meshes, offering unparalleled flexibility in mesh design, which allows for resolution enhancements in dynamically active regions. Its scalability characteristics further ensure efficient performance on state-of-the-art supercomputers (Koldunov et al., 2019), making it a key asset for high-resolution modeling efforts.

A unified modeling infrastructure – the ESM-Tools framework – has been developed to support these advancements (extensively used by AWI, GEOMAR and international partners). The ESM-Tools (Barbi et al., 2021) provide a standardized platform for Earth-system modeling. These publicly accessible tools foster collaboration and accelerate progress by enabling seamless integration of model components across disciplines.

A3 Data science

A cornerstone of our research methodology is the rapidly evolving field of data science, which enables transformative approaches through big data analysis, machine learning (ML), AI, and visual analytics. To fully exploit these opportunities, we educate a new generation of AI- and ML-proficient scientists through MarDATA, which trained about 40 PhDs in its first two cohorts (2019–2024) and is now successfully stabilized. MarDATA (https://www.mardata.de/, last access: 30 December 2025) fosters interdisciplinary ties between computer, marine, and cryospheric sciences, enabling the exploration of new possibilities and limitations

of data science and the development of advanced data processing methods. This has contributed significantly to our research by strengthening our ability to tackle Earth-system challenges through innovative data-driven approaches.

AI is driving innovation in modeling, as exemplified by the HClimRep project (https://hclimrep-project.de/, last access: 30 December 2025), funded by the Helmholtz Foundation Model Initiative. This initiative is developing a foundational model for long-term ocean and climate simulations and downstream applications (e.g., interpolation and counterfactuals) that incorporate atmospheric dynamics, tracer transport, and ocean coupling. The resulting model will enhance existing AI-based systems and provide valuable insights for climate adaptation and policy-making. We are also advancing emulators for sea ice models through the DataHub AI project (https://helmholtz.software/projects/datahub, last access: 30 December 2025) and EU-funded TerraDT (https://terradt.eu, last access: 30 December 2025), aiming to support forecasting, downscaling, and bias correction, opening new avenues for practical applications. AI-driven breakthroughs are also emerging in numerical weather prediction (NWP), where models now outperform traditional physics-based approaches on short timescales. We are exploring these AI-based models for climate simulations, particularly for high-resolution data interpolation and downscaling.

Large language models (LLMs) are revolutionizing research, data analysis, and climate information delivery. AWI, collaborating with leading experts, is at the forefront of applying LLMs to climate services. Notably, AWI developed *ClimSight* (Koldunov and Jung, 2024), the first prototype to integrate LLMs with climate data. This innovative software provides localized, actionable insights for sectors like agriculture and infrastructure and has the potential to transform climate services by enabling anyone, anywhere, to receive answers to climate change-related questions. Supported by the DestinE program, *ClimSight* represents a step toward global climate adaptation. In parallel, AWI is leveraging LLMs to enhance data analysis. With backing from DataHub AI-call funding, efforts are underway for routine data analysis and basic interpretation of climate model output. A prominent example is the recently developed PANGAEA GPT for efficient exploration of PANGAEA datasets, enabling search, analysis, and visualization via advanced AI models. It employs a multi-agent architecture, including specialized agents for dataset retrieval, data-frame analysis, and visualization – both general-purpose and domain-specific agents. A supervisor agent coordinates these components to effectively address user queries, tackling challenges in navigating complex environmental data.

A4 Remote sensing

Including AI methods for data processing, a joint cluster initiative with GEOMAR and GFZ, and a link to DLR Earth Observation (https://www.dlr.de/en/eoc, last access: 30 December 2025) will provide us with novel data toward a better understanding of the world's ocean, terrestrial surface waters, and ice sheet surfaces. To get ready to use these data, we work on joint method development and on joint ground truthing to validate the satellite data. We are developing retrackers with AI methods to improve the elevation estimation from satellite altimetry. These will also be employed at GEOMAR and GFZ, and we are combining the forces of all three centers in preparation for data processing chains. We will employ a new simulation tool for waveforms, a test case being provided by GFZ. For ground truthing, AWI extends its polar aircraft flights to specific altimeter tracks of SWOT over the ocean and around the Neumayer III station. For the same purpose, we also deploy joint autonomous stations with GFZ on the ice sheet and shelves in Greenland (NEGIS region), where we could confirm a model-predicted calving front disintegration at 79N Glacier (outlet of NEGIS, Humbert et al., 2023). This provides an example of an excellent combination of remote sensing and ground observations with ice-sheet modeling. Simulation studies were conducted assessing new resolving capabilities of ice-sheet processes with the future NASA/ESA gravity mission constellation MAGIC (Haagmans and Tsaoussi, 2020).

A5 Proxy analysis and tracers

Ongoing rapid climate change emphasizes the need to explore past climates toward gaining improved understanding of the Earth system, to test our models for their performance outside the short range of the instrumental record, and to examine possible surprises with regard to future abrupt climate change as far as practically possible. A very important pillar in this endeavor is proxy-data research. We used new paleo-tools, gained advanced proxy calibrations, improved chronologies, and synchronized different archives with each other. Novel micro-analytical techniques allow, for example, retrieving seasonally resolved climate proxy data from varved marine sediments (Hathorne et al., 2023) and high-resolution data from oldest ice core drillings (Beyond EPICA–Oldest Ice, https://www.beyondepica.eu/en/, last access: 30 December 2025).

Ground-breaking research has been made possible by the MICADAS accelerator mass spectrometer (MIniature CArbon DAting System, https://www.awi.de/en/science/geosciences/marine-geochemistry/micadas.html, last access: 30 December 2025). We benefit from the capability of reliably analyzing samples containing as little as around 50 µgC for their radiocarbon content. We have been able to apply the method of compound-specific radiocarbon analysis to generate insights into carbon metabolism of Arctic sedimentary microbes (Ruben et al., 2023) and to document release of ancient carbon from thawing permafrost and retreating glaciers (Wu et al., 2022). The enhanced methodologies also benefit research in small-scale radiocarbon analyses to allow assess-

ing carbon metabolism of deep-sea sponges (Morganti et al., 2022).

An important field of application of radiocarbon analyses is the determination of ages from geological and glaciological samples, for example for the development of age models for marine sediments. The new analytical capabilities allowed careful assessment of the effect of diagenetic alteration of calcareous microfossils used for this purpose (Wollenburg et al., 2023). In concert with novel approaches relying on other cosmogenic (^{10}Be, ^{26}Al) and radiogenic (^{230}Th) isotopes, great progress has been made in verifying age models of marine sediments used for deciphering the paleoclimatic evolution of the polar regions (Nicolas et al., 2024).

A6 GEOTRACES

AWI and GEOMAR are contributing jointly to the large international GEOTRACES program (https://www.geotraces.org/, last access: 30 December 2025), establishing baselines and process understanding for global trace elements and their isotopes in the ocean. This is a fundamental step forward in our understanding of elemental fluxes and their biogeochemical impact in the ocean, including changes due to human activities. The methods require clean highly specialized trace-metal analytical laboratory and sampling facilities, which is a rapidly evolving technique that is required for understanding biological and chemical oceanic processes. Here, a trace-metal clean sampling system infrastructure developed at AWI is operated jointly with an experienced trace metal sampling team from GEOMAR and international experts for various tracers. This expedition is the first approved full GEOTRACES repeat section (section GN06), acknowledging the fact that the Arctic Ocean is changing so rapidly. After the International GEOTRACES summer school "Introducing polar parameters" hosted at AWI in 2022, AWI also hosted the GEOTRACES Synthesis Preparation Workshop in July 2025 to prepare future synthesis activities.

A7 Additional transfer activities

A key goal is to transfer scientific knowledge to society, politics, and the economy while demonstrating the societal and economic benefits of climate science through innovative research and active stakeholder engagement. These efforts are supported by AWI's established technology and knowledge transfer offices, such as the Climate Office (https://www.awi.de/en/transfer/knowledge-transfer/climate-office.html, last access: 30 December 2025) and the German Arctic Office (https://www.awi.de/en/transfer/knowledge-transfer/arctic-office.html, last access: 30 December 2025) and a strong foundation of community outreach and policy contributions. Overarching Helmholtz initiatives, including REKLIM (Regional Climate Change and Humans, https://www.reklim.de, last access: 30 December 2025) and cross-Topic SynCom activities highlight the interdisciplinary and collaborative activities within the research program.

On an international scale, scientists have provided leadership in forums such as the IPCC, the Arctic Council working groups (https://arctic-council.org/about/working-groups/, last access: 30 December 2025), SCAR (https://scar.org/, last access: 30 December 2025), and the World Meteorological Organization (https://wmo.int, last access: 30 December 2025). Notably, the Year of Polar Prediction (YOPP, https://www.polarprediction.net/, last access: 30 December 2025), coordinated by AWI from 2013 to 2022, exemplified the institute's ability to bridge scientific research and operational applications. YOPP delivered advancements like the AROME-Arctic system, which significantly improved weather predictions over sea ice, and the enhancement of snow models at ECMWF (https://www.ecmwf.int/, last access: 30 December 2025).

The Digital Twin Climate Adaptation project (https://destine.ecmwf.int/news/climate-change-adaptation-digital-twin-a-window-to-the-future-of-our-planet/, last access: 30 December 2025), launched in 2022, introduces global kilometer-scale modeling to bridge the gap between global projections and local impacts (Bauer et al., 2021). The first operational Digital Twin was scheduled to provide, by 2025, the first operational Digital Twin will provide high-resolution climate data and actionable tools, enabling effective adaptation strategies and resilience planning. Collaboration with leading institutions such as ECMWF and the Barcelona Supercomputing Center (https://www.bsc.es, last access: 30 December 2025) ensures the successful implementation of this ambitious initiative.

AWI engages with communities to promote public awareness and action on climate change. The klimafit program (https://www.awi.de/transfer/transfer-storys/klimafit.html last access: 6 November 2026; https://www.klimafit-kurs.de, last access: 30 December 2025), part of the cross-cutting activity REKLIM initiative and developed with World Wide Fund For Nature (WWF) Germany, empowers citizens to become climate multipliers in their local communities. With over 5500 participants across 440 locations, klimafit has fostered grassroots climate action and was recognized with the UNESCO ESD Prize in 2023. Similarly, the annual REKLIM regional conferences connect stakeholders, policymakers, and federal agencies, creating sustainable bridges between science and society while driving forward cooperative networks and actionable outcomes. Bridging between research results and communication plays a central part in the collective answer of the research community to the outstanding climate changes (Lohmann, 2026).

In 2022, AWI scientists also contributed to the discovery of the legendary ship *Endurance*, famously lost during Ernest Shackleton's 1915 Antarctic expedition (https://www.bbc.com/news/science-environment-60662541, last access: 30 December 2025). Using ice drift hindcasts derived from historical data of Shackleton's journey, the team success-

fully located the shipwreck. This achievement, supported by expertise from the AWI spin-off Drift & Noise Polar Services GmbH, highlights the innovative applications of AWI's scientific capabilities and attracted widespread attention, including a feature on National Geographic TV.

The above-mentioned sea ice portal is another example of AWI's commitment to accessibility and impact (Grosfeld et al., 2016). By providing real-time open-access data on Arctic and Antarctic sea ice conditions, the portal supports a wide range of stakeholders, from policymakers to researchers and the public. A 2022 relaunch, supported by the Helmholtz DataHub, introduced an enhanced interface and expanded datasets, with further updates planned for 2025 to improve usability and functionality.

In addition to community-focused initiatives, AWI leads efforts to address global challenges such as carbon dioxide removal. Under the SynCom framework, AWI has advanced strategies for scaling carbon capture and storage (CCS, https://earthenvironment.helmholtz.de/changing-earth/syncom/projects/carbon-dioxide-removal/, last access: 30 December 2025) and bio-energy with CCS. The project focuses on advancing CDR technologies to achieve gigaton-scale CO_2 removal. It aims to evaluate the feasibility and potential of large-scale CDR demonstrators in Germany, leveraging Helmholtz's expertise in CDR methods (e.g., CCS, ocean fertilization, rock weathering). The efforts were showcased during a parliamentary breakfast in Berlin, where AWI experts engaged with members of the Bundestag on the latest developments in these climate mitigation approaches. Similarly, AWI's expertise in sea level rise has fostered collaboration between science and policy, including discussions on its impacts on parliamentary events.

AWI's contributions also extend to infrastructure resilience, exemplified by the BMBF-funded aKtiv project. By assessing water supply vulnerabilities during crises such as droughts and pandemics, aKtiv supports policy and research aimed at enhancing water predictability and security in Germany. Other examples include the *PolarPanorama* project (https://polarres.eu/polar-panorama-a-citizen-science-project/, last access: 30 December 2025), which explores societal perceptions of changes in the Arctic and Antarctic through an interactive citizen science initiative, and *Gateway to the Arctic* (https://www.reklim.de/wissenstransfer/capacitiy-building/gateway-to-the-arctic/, last access: 30 December 2025), which fosters interdisciplinary collaboration in polar research. From advancing international climate initiatives to fostering local climate action, AWI's multifaceted efforts demonstrate its integral role in shaping a sustainable and resilient future through science-driven solutions.

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