Polar Ocean and Global Change

ABSTRACT

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Keynote Lecture

Multidecadal changes in the tropics drive predictability of Antarctic sea ice

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ENSO teleconnections are a key source of Antarctic sea-ice predictability, particularly in the Antarctic Dipole (ADP) region, but whether this predictability remains stable under the recent transition toward Central Pacific (CP) El Niño is unclear. Here, using a Markov model, we reveal an 83% decrease in sea ice concentration (SIC) predictability, measured by the anomaly correlation coefficient (ACC), during austral winter and spring since 2002. We show that this decline is linked to a weakened ENSO–Antarctic teleconnection, in which the CP El Niño-triggered Rossby wave train shifts northward away from the Antarctic sea-ice zone and toward the open ocean. This northward shift reduces the wave train's influence on Antarctic sea ice, dampens sea-ice persistence, lowers its signal-to-noise ratio, and consequently limits predictability. Our results suggest that ENSO–Antarctic teleconnections may provide a useful benchmark for evaluating and improving Antarctic sea-ice prediction models.

Session: Observation and Modelling of Marine Cryosphere

Long-term observations of sea ice thickness from SMOS and CryoSat-2 in the Arctic and Antarctic

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As a critical climate variable, sea ice has been monitored from space since several decades, providing information on both its extent and thickness. Sea ice thickness can be observed using both active and passive remote-sensing techniques. Radar and laser altimeters measure the freeboard of the snow and sea ice surface relative to the water level and subsequently derive sea ice thickness based on the assumption of hydrostatic equilibrium. In contrast, passive microwave radiometers measure the radiation from the Earth's surface, which contains information of sea ice thickness. Both methods have their advantage and limitations.

Since 2010, two ESA satellite missions have contributed significantly to our understanding of the spatial and temporal distribution of Arctic and Antarctic sea ice thickness. One is the Soil Moisture and Ocean Salinity mission (SMOS), which carries an L-band radiometer. Sea ice thickness of up to 1 m can be estimated from the brightness temperatures measured by SMOS. Owing to its broad swath width, SMOS provides daily coverage of the polar regions. In parallel, the Synthetic aperture Interferometric Radar Altimeter (SIRAL) on board of CryoSat-2 has measured the sea ice freeboards with a horizontal resolution of 300 m.

Sea ice thickness derived from SMOS has relatively low uncertainty for thin ice but rapidly loses sensitivity for ice thicker than 1m. In contrast, CryoSat-2 altimeter observations generally have higher uncertainties for thin ice but provide more reliable estimates for thicker sea ice. An optimal interpolation scheme has therefore been developed at the Alfred Wegener Institute, to merge the two satellite observations, achieving lower relative uncertainty.

Within the framework of the ESA projects "SMOS & CryoSat-2 Sea Ice Data Product Processing and Dissemination Service" and "SMOS Expert Support Laboratory", which were merged into SMOS DISC project since 2026, a daily Level-3 (L3) SMOS thin ice thickness product and a weekly Level 4 (L4) combined product based on SMOS and CryoSat-2 have been produced and disseminated for the polar regions. More recently, Sentinel-3A/B altimeter data have been integrated into the L4 merging scheme to improve the spatial resolution and increase data density.

The resulting long-term observation datasets provide an opportunity to quantify seasonal and interannual variability, as well as long-term trends in sea ice thickness in both hemispheres. Such observations are critical for improving our understanding of changes in the polar climate system.

Robust model selection for Arctic sea ice: Reducing uncertainty in CMIP6 projections

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Despite the widespread use of climate models for future projections, no consensus exists on which evaluation method for Arctic sea ice most robustly identifies skillful models from the CMIP6 ensemble. To address this gap, we applied a novel percentile-based method integrating eight statistical metrics – correlation, root-mean-square deviation, standard deviation difference, Climate Prediction Index, spatial trend mean and amplitude differences, and spatial bias mean and amplitude differences – assigning scores via percentile ranking (0–25% very good, 25–50% good, 50–75% satisfactory, 75–100% unsatisfactory). After summing scores, we ranked models and selected those from 0-25% interval. To test this method, we compared it with six other widely applied approaches, ranging from simple to complex, for Arctic air temperature across two periods (1951–1980 and 1981–2010). The percentile-based method demonstrated the highest consistency (72%) in model quality classification. Then, we applied the percentile-based method to Arctic sea ice area – evaluating 27 CMIP6 models against satellite observations (1979–2014) for annual mean and each warm-season month (June–November), selecting the top 25% (9 models) as a skillful sub-ensemble. A sensitivity analysis, using a "leave-one-out" approach, in which each metric is excluded one at a time, did not alter the final selection of the top nine models, confirming the robustness of the proposed model performance assessment and ranking approach. Our results demonstrate that the percentile-based method provides a robust, transferable framework for climate model selection across variables and regions, substantially reducing uncertainty. The study was funded by the Russian Science Foundation (RSF) grant No. 25-47-00104.

Interannual variability of ocean heat content in the eastern Amundsen Sea controlled by wind

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Mass loss of the Antarctic ice sheet is largest in the Amundsen Sea Embayment, West Antarctica, due to basal melting by warm modified Circumpolar Deep Water (mCDW). In this study we find that subsurface temperature variability near the ice shelves in the Amundsen Sea Embayment from a global ocean-sea ice model is able to track observed temperature variability and satellite-derived basal melt rates. Simulated ocean temperature variability is controlled by a two-stage response to the regional winds. A weakening of the prevailing southeasterly winds initially redistributes heat by lifting the thermocline, bringing warm mCDW up from depth near the ice shelf front. This is followed by a lagged widespread warming across the continental shelf due to water mass property changes, driven by horizontal advection and vertical mixing. Our results suggest a limited role of internal ocean variability and meltwater feedbacks on the observed variability on interannual timescales.

Snow and ice thermodynamics in the changing climate: Modelling and observation

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Due to amplified climate warming in the Arctic, sea ice thickness and concentration have strongly declined, reducing the internal resistance of the ice field and resulting in faster sea ice drift. Consequently, the transpolar drift of sea ice has accelerated several-fold compared to the period of the Fram expedition 130 years ago. These changes over the past 40 years mark a transition toward a warmer mean state—heating at approximately four times the global average rate—superimposed by shifts in ice regimes and an increased frequency of extreme events. To evaluate the thermodynamic implications of these changes, we present a comprehensive suite of studies focusing on polar snow and ice interactions. First, we investigate the impact of sea ice drift speed on the thermodynamic mass balance of sea ice and snow. A thermodynamic snow and ice model is applied to simulate snow depth and ice thickness, utilizing meteorological conditions extracted from the ERA5 reanalysis along a predefined, idealized transpolar ice drift trajectory from point A (80°N, 155°E) across the North Pole to point B (80°N, 0°E). The ice drift speed is controlled by prescribing different transit durations for the ice to travel from A to B. Simulations are initiated at the beginning of each month from January 1979 through December 2021. For each experimental scenario (representing a unique drift speed), we isolate and calculate the thermodynamic components of both snow and sea ice. Second, we develop an optimized pan-Arctic snow depth product to improve sea-ice thickness estimations. Finally, extending our scope to the Southern Ocean, we focus on two scales: at the process level, we quantify the thermal conductivity of distinct sea-ice types; at a large scale, we perform a systematic intercomparison of snow depth across six ocean reanalyses, two satellite retrievals, and multi-source airborne and ship-based observations. Collectively, these efforts advance our understanding of polar sea ice responses to a rapidly changing climate

Impacts of Ocean–Ice shelf Interactions on Dense Shelf Water Formation in the Ross Sea

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Dense Shelf Water (DSW) formed on the Ross Sea continental shelf is an important precursor of Antarctic Bottom Water (AABW), and its formation is strongly influenced by freshwater input associated with ocean–ice shelf interactions. Here, we synthesize results from a series of observational and high-resolution modeling studies to investigate how ice-shelf meltwater regulates DSW formation and its downstream transformation in the Ross Sea. The Ross Sea and Amundsen Sea Ice–Sea Model (RAISE) reproduces the observed spatial and temporal variability of DSW but tends to overestimate its density, partly because of underestimated ice-shelf melting and missing freshwater sources associated with calving and subglacial discharge in the Amundsen Sea. A meltwater sensitivity experiment with enhanced freshwater input substantially reduces the simulated DSW density bias and improves agreement with observations, highlighting the importance of accurately representing ice-shelf freshwater forcing for DSW simulation. Further sensitivity experiments show that enhanced Amundsen Sea ice-shelf melting increases meltwater transport into the Ross Sea, freshens the continental shelf, strengthens stratification, and suppresses DSW formation and export. Under future climate forcing, this remote meltwater influence acts together with reduced local sea-ice production to drive a substantial contraction of DSW and weaken subsequent AABW formation. In the western Ross Sea, heat and salt budget analyses further demonstrate that exchange between the Ross Ice Shelf cavity and polynya, ice-shelf basal melting, and subglacial discharge jointly regulate shelf-water properties. Together, these results highlight the central role of ocean–ice shelf interactions and ice-sheet freshwater input in controlling the formation, variability, and future evolution of Ross Sea DSW and AABW.

Improving physical modelling of CryoSat-2 radar waveforms over sea ice using meter-scale topography

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Satellite radar altimetry provides basin-scale observations of sea ice freeboard and is therefore essential for estimating Arctic sea ice thickness and monitoring changes in the polar climate system. However, substantial uncertainty remains in the retrieved freeboard because the measured waveform is affected by complex interactions of the radar signal with the snow-cover sea ice, as well as small-scale surface and topographic features. Therefore, characterizing how these processes modulate radar waveforms is critical for our physical understanding of the measured satellite radar echoes and improving the freeboard retrievals.

In this study, we improve physical modeling of CryoSat-2 (CS2) delay-Doppler radar waveforms using collocated NASA Operation IceBridge (OIB) observations acquired on March 20, 2013. We combine IceBridge Airborne Topographic Mapper (ATM) measurements with Digital Mapping System (DMS) Level-3 topography from multiple OIB flight passes to construct meter-scale sea ice topography and ice-type maps that cover more than 5km across the CS2/OIB flight track. The high-resolution topography is incorporated into the Facet-Based Echo Model (FBEM) to simulate CS2 waveforms and waveform stacks. By varying the physical parameters of thin and thick ice, snow, and the spatial scale of sea ice topography, we investigate how heterogeneity, topographic characteristics (e.g., ridges and leads), and spatial scales modulate key radar waveform characteristics, such as Pulse Peakiness, leading-edge width, and stack characteristics. We additionally introduce randomized snow-depth distributions to assess the sensitivity of simulated waveforms to unresolved snow cover variability. These results enhance the physical interpretation of delay-Doppler radar waveforms and establish a foundation for reducing uncertainties in satellite-derived sea ice freeboard and thickness estimates.

Optimizing the spring predictability barrier in Arctic sea-ice prediction using artificial intelligence

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Seasonal prediction of late-summer Arctic sea ice remains strongly constrained by the spring predictability barrier (SPB), yet the sources of predictive information that allow forecast skill to persist across spring are still not fully understood. Here, we develop an artificial-intelligence forecasting framework to investigate how different components of the Arctic climate system contribute to September sea-ice predictability. We use controlled experiments to separate the roles of the initialized sea-ice state, atmospheric thermal conditions, and upper-ocean heat storage. The AI model substantially improves spring-initialized September forecasts compared with dynamical and conventional statistical approaches. Further analyses show that sea-ice thickness provides important cryospheric memory, while atmospheric temperature and ocean heat content supply additional and complementary thermal information. Their contributions exhibit clear lead-time, spatial, and sea-ice-state dependence, with oceanic information retaining predictive value over longer temporal windows. These results suggest that overcoming the SPB depends not only on the initialized sea-ice state, but also on effectively extracting and integrating atmospheric and oceanic thermal memory. The study demonstrates the potential of artificial intelligence not only to improve Arctic sea-ice forecasts, but also to reveal the physical sources and limits of seasonal predictability.

Southern Ocean response to intensified Southern Hemisphere westerlies during the Last Interglacial

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The Southern Ocean is a key component of the climate system, through interactions among atmospheric circulation, ocean dynamics, biological productivity, and the carbon cycle. Yet how the Southern Ocean responds to changes in the Southern Hemisphere westerlies (SHW) under warm climate conditions remains poorly constrained. Here, we integrate sedimentary reconstructions of Antarctic Circumpolar Current (ACC) dynamics and export productivity to examine the response of the Southern Ocean to SHW during the Last Interglacial (LIG; 128-113 ka), a warm interval characterized by elevated global temperatures and atmospheric CO_2 concentrations relative to pre-industrial conditions. High-resolution sortable-silt records from the Scotia Sea show that the ACC underwent pronounced acceleration and poleward migration during the LIG, with bottom-current speeds reaching nearly three times Holocene values. In parallel, a synthesis of Antarctic and subarctic Pacific export-productivity records reveals a marked divergence during the late LIG: Antarctic export productivity remained elevated despite a >6 °C decline in Antarctic temperature, whereas subarctic productivity decreased. This divergence was most pronounced at ~115-113 ka, broadly coinciding with the strongest ACC reorganization. Together with independent evidence for enhanced nutrient supply, these coupled changes suggest that poleward- intensified SHW reorganized Southern Ocean circulation, strengthening ACC flow and Circumpolar Deep Water upwelling and thereby sustaining high Antarctic export productivity while promoting CO_2 outgassing. In contrast, the associated reorganization of Southern Ocean deep-water circulation likely reduced the supply of nutrient-rich deep waters to the subarctic Pacific, contributing to declining export productivity there. These results highlight a spatially heterogeneous biogeochemical response to wind-driven reorganization of Southern Ocean circulation during the LIG, linking changes in ocean dynamics to regional patterns of biological export and ocean-atmosphere carbon exchange.

Variability and changes in Antarctic snow depth from satellite microwave radiometer observations 2002–2025

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Snow on sea ice defines the atmosphere-sea ice boundary layer and is an important parameter in the Antarctic climate system. Due to its insulating properties snow has a direct impact on the sea ice growth and melt. Compared to open ocean, snow has a very high albedo and therefore modifies the ice-ocean to atmosphere heat fluxes. In addition, snow depth variability influences the under-ice biology, especially in spring. Knowledge about snow depth on sea ice is also important for sea ice thickness retrievals from satellite altimetry.

Microwave radiometer satellite observations like those from AMSR or the future CIMR sensors can be used to retrieve snow depth. They have the advantage of daily Antarctic-wide coverage and a long time series back to 2002 for AMSR. However, snow depth can only be retrieved indirectly: The scattering and emission of snow grains varies with frequency and the number of available scatterers along the propagation path, i.e., with snow depth. By combining different frequencies, the snow depth on sea ice can be estimated.

Snow depth can also be obtained by a combination of satellite laser and radar altimeter measurements. Here we use an ice drift-aware combination of ICESat-2 and CryoSat-2/Sentinel-3 available since 2018. To obtain a longer and consistent snow depth time series microwave radiometer and altimeter measurements can be combined.

We present here a spatio-temporal analysis of a new Antarctic snow depth product for the AMSR sensor series. We included a temporally varying snow density climatology to account for density changes throughout the season. The inclusion of the lower 6–11 GHz channels allow retrievals of thicker snow layers. The AMSR snow depth is referenced to, based on machine learning, and consistent with the altimeter snow depth product (from the freeboard difference between ICESat-2 and a merged CryoSat-2/Sentinel-3A/B dataset) developed as part of the ESA SO-SIMBA project, but extends further back in time and is available with daily coverage. A similar retrieval approach is proposed and currently developed for the future EU/ESA CIMR satellite mission.

Unexpected return of late-summer sea ice in the Pacific Arctic

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During the 2024 Arctic summer, an unexpected sea ice patch (~100,000 km²) survived in the western Chukchi Sea, an event unseen in the past 20 years. This study combines satellite observations, PIOMAS, and ERA5 reanalysis to place this anomaly in the 2000–2024 context and examine its evolution and dynamic and thermodynamic drivers. July–August emerges as key months, with ice concentration and thickness determining September survival. Persistent northerly winds east of Wrangel Island drove dynamic thickening, while cooler-than-normal air temperatures supported stable ice presence during the melt season. This event is embedded in a broader late-summer Chukchi Sea ice recovery over 2020–2024, culminating in an abrupt retention that obstructed the Northeast Passage by September 2024 for the first time since 2001. This recovery coincides with a persistent poleward-shifted Pacific–Arctic cyclonic anomaly near the Bering Strait, producing a coupled dynamic–thermodynamic response. Arctic cold advection, enhanced cloud-induced cooling, reduced oceanic heat, and delayed seasonal thinning all together sustained late-summer ice retention. Furthermore, the Pacific–North American (PNA) mode is linked to summer Chukchi Sea ice variations through the regional position of this cyclonic anomaly, identifying the Chukchi Sea as a sensitive Pacific Arctic sector where natural circulation variability generates abrupt, localized reversals in summer sea-ice loss. These findings underscore that "New Arctic" conditions—thinning and increasingly mobile sea ice—raise the likelihood of unpredictable events, both sudden ice disappearance and unexpected survival, offering valuable insights for improving predictions, guiding safe navigation, and assessing marine ecosystem impacts.

Microwave sea surface temperature retrieval in the Arctic marginal ice zone based on a hybrid physical-deep learning model

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The Arctic Marginal Ice Zone (MIZ) is a highly dynamic region of ocean–ice–atmosphere interaction, where accurate sea surface temperature (SST) is essential for understanding Arctic climate change. Microwave remote sensing, with its all-day, all-weather capability, is an important means of observing SST in MIZ. In the MIZ, however, the coarse resolution of microwave radiometers produces mixed pixels containing both sea ice and open water, and sea ice emissivity involves complex dependencies beyond prior knowledge, leaving retrieval in a chicken-and-egg dilemma. To resolve it, we propose a Hybrid Physics–Deep Learning model (HPDL-SST) for AMSR3 observations, which jointly optimizes sea ice emissivity and SST. At the physical level, sea surface emissivity and atmospheric transmittance are precomputed for every pixel with the RTTOV fast radiative transfer model. At the empirical level, a neural network parameterizes sea ice emissivity, and antenna pattern weighting is embedded in the mixed-pixel radiative transfer calculation to represent the non-uniform distribution of ice and water. By minimizing the discrepancy between observed and simulated brightness temperatures, SST, the sea ice emissivity model and the empirical parameters are optimized jointly within the radiative transfer framework. Validated against ICOADS buoys, the retrieved SST has a standard deviation (STD) of 0.49 K, and against 1 km VIIRS L2 SST the STD is 0.38 K. This framework guarantees the accuracy of atmospheric radiative transfer while retaining the flexibility needed for complex sea ice emissivity, offering a new pathway for MIZ SST retrieval.

Session: Polar Marine Biogeochemical Cycles and Their Ecological and Environmental Effects

Into the Blue (i2B): Insights from past climates analogous to today's Arctic warming

- Preliminary results of the 2026 *R/V* Kronprins Haakon Arctic Expedition

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As part of the Into the Blue (i2B) project, the Norwegian research vessel R/V Kronprins Haakon carried out a 4-week expedition to the poorly explored and heavily ice-covered Central Arctic Ocean in 2026. The primary objective of this cruise was to reconstruct long-term Neogene-to-Quaternary paleoceanographic evolution and ice-sheet dynamics, leveraging past warm climate analogues to better understand ongoing Arctic warming. Targeting the southern Lomonosov Ridge, where Miocene and Pliocene strata are partially exposed at the seafloor, probably driven by glacial erosion and tectonic forcing, we successfully retrieved a series of long sediment cores serving as crucial climate archives. These pre-Quaternary records, particularly targeting the Pliocene (ca. 3 Ma) and Mid-Miocene Climatic Optimum (ca. 15 Ma), offer unprecedented insights into Arctic sea-ice extent, surface ocean conditions, and ecosystem responses under atmospheric CO_2 concentrations comparable to or higher than anthropogenic projections. While preliminary age assignments for the retrieved core-catcher sediment samples were established onboard based on microfossil assemblages (e.g., coccoliths and agglutinated foraminifera), more robust age models will be further constrained using an integrated, multi-proxy approach. Furthermore, several Quaternary sediment cores retrieved during the expedition likely extend across the Mid-Pleistocene Transition (MPT). These sequences feature distinct, recurrent dark-grey sediment units, likely archiving post-MPT glacial maxima (e.g., MIS 16, 12, and 6) characterized by prolonged, asymmetric, non-linear 100-kyr climate cycles. Our preliminary findings provide critical empirical constraints on Arctic climate sensitivity, offering vital perspectives for assessing the broader implications of current warming on the global Earth system.

Molecular fingerprints of oceanic refractory organic carbon: Polarity, isomerism, and terrestrial sources

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Marine dissolved organic matter (DOM) is one of Earth's largest long-term carbon reservoirs, yet its molecular basis of persistence and sources remains incompletely resolved. Here, using liquid chromatography coupled with ultrahigh-resolution mass spectrometry (LC-HRMS) to distinguish polarity-defined fractions and structural isomer clusters, we combine mechanistic incubation experiments and global datasets to re-examine the ocean's refractory organic carbon at molecular resolution. First, we find that carboxyl-rich alicyclic molecules (CRAM), a widely used indicator of recalcitrant DOM (RDOM), are not uniformly biorecalcitrant. Lower-polarity CRAM are preferentially degraded during microbial incubation, whereas microbial reworking produces higher-polarity CRAM with increased oxidation state, nitrogen content, and aromaticity; some transformed CRAM occurs frequently across 1,485 seawater samples, suggesting potential persistence. Second, polarity-based LC-HRMS capable of discriminating RDOM isomer clusters shows that marine microbial consortia rapidly (≤90 days) convert diverse organic substrates into RDOM exhibiting extensive structural isomerism that closely mirrors natural seawater. A subset of these microbially derived compounds is near-ubiquitous (>99%) in a global dataset and progressively accumulates in the ocean interior, substantiating a direct microbial pathway to long-lived oceanic carbon. Third, we identify 269 molecular formulae transported from rivers to the ocean that resist biological and photochemical degradation. By relating their abundances to dissolved organic carbon concentrations and radiocarbon measurements, we estimate that 16.7–25.0% of oceanic DOM is terrestrially derived, 1.7–2.5 times higher than previously assumed. Together, these molecular fingerprints link intrinsic recalcitrance, rapid microbial production, and underestimated terrestrial inputs, providing a coherent framework to refine global carbon-cycle models.

Photophysiological and optical signatures of phytoplankton across Southern Ocean fronts

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This study investigates the relationship between phytoplankton photophysiology, light absorption properties, and pigment-derived community composition measured along a transect over 10 years in the Pacific sector of the Southern Ocean (40–70°S, 130–160°E). Normalizing fluorescence yields to phytoplankton absorption (aph) rather than chlorophyll alone using Fo/aph and Fm/aph in addition to the conventional Fo/Chl-a and Fm/Chl-a revealed that biomass-normalized photosynthetic parameters diverged from absorption-normalized ones in frontal transition zones, indicating that pigment packaging and cell-size effects modulate the apparent photosynthetic signal independently of biomass. The effective absorption cross-section of PSII normalized to aph (σPSII/aph) tracked shifts between size classes and taxonomic groups more closely than σPSII alone, while the turnover time of electron transport past PSII (1/τ) and its absorption-normalized form (τ/aph) indicated that communities in the PFZ and SAZ were more constrained by downstream electron transport capacity than by light absorption, consistent with iron limitation in these zones. These results demonstrate that combining FRRF-derived photophysiological parameters with in situ phytoplankton absorption and pigment-derived taxonomy provides a more mechanistic understanding of frontal-scale physiological variability than fluorescence or pigment data alone, with implications for interpreting satellite-derived primary productivity estimates in the Southern Ocean.

Freezing and melting stress on the photophysiology of ice algae: *ex situ* incubation of ice algae using an ice tank

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Sea ice algae contribute up to 25% of the primary productivity of polar seas and seed large-scale ice-edge blooms. Fluctuations in temperature, salinity, and light associated with the freeze/thaw cycle can significantly impact the photophysiology of ice-associated taxa. The effects of multiple co-stressors (i.e., freezing temperature and high brine salinity or sudden high light exposure) on the photophysiology of ice algae were investigated in a series of ice tank experiments with the polar diatom *Fragilariopsis cylindrus* under different light intensities. When algal cells were frozen into the ice, the maximum quantum yield of photosystem II photochemistry (PSII; F_v/F_m) decreased possibly due to the damage of PSII reaction centers and/or high brine salinity stress suppressing the reduction capacity downstream of PSII. Expression of the *rbcL* gene was highly up-regulated, suggesting that cells initiated strategies to enhance survival upon freezing in. Algae contained within the ice-matrix displayed similar levels of F_v/F_m regardless of the light treatments. Upon melting out, cells were exposed to high light (800 μmol photons m^{-2} s^{-1}), resulting in a rapid decline in F_v/F_m and significant upregulation of non-photochemical quenching (NPQ). These results suggest that ice algae employed safety valves (i.e., NPQ) to maintain their photosynthetic capability during the sudden environmental changes, our results infer that sea ice algae are highly adaptable when exposed to multiple co-stressors and that their success can, in part, be explained by the ability to rapidly modify their photosynthetic competence – a key factor contributing to algal bloom formation in the polar seas.

Light reshapes DNA virus-host interactions in Antarctic sea ice

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Light availability critically shapes microbial ecosystems within Antarctic sea ice, yet the responses of sea-ice viruses to varying irradiance remain poorly characterized. We conducted an *in-situ* incubation experiment simulating a natural light-transmittance gradient, integrating viromic, metagenomic, and metatranscriptomic analyses to assess viral diversity, activity, infection strategies, and functional potential. We identified 1,364 viral operational taxonomic units (vOTUs), of which more than 78% lacked close matches to existing Arctic and global ocean virome datasets, highlighting the novelty and habitat specificity of Antarctic sea-ice viruses. Viral transcriptional activity generally diverged more strongly than the relative abundance of viruses as light levels declined, indicating partial decoupling between the presence and activity of viruses. Moderate light reduction enhanced lytic viral activity, whereas more severe light limitation favoured temperate and chronic infection strategies. Concurrently, viral auxiliary genes shifted from those supporting host biosynthesis and cold adaptation under higher light levels to functions involved in nutrient recycling, metabolic maintenance, and host immune interactions at lower light. These findings demonstrate that light-driven changes modulate virus-host dynamics and viral functional roles, potentially influencing microbial carbon processing and ecosystem resilience in Antarctic sea ice under climate-induced alterations in snow cover and therefore irradiance.

Session: Polar Ocean Dynamic Processes and Their Climate Effects

Arctic sea ice meltwater as a forcing and feedback on the Atlantic Meridional Overturning Circulation

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Recent work has shown that the weakening of the Atlantic meridional overturning circulation (AMOC) under anthropogenic climate change is sensitive not only to the amount of atmospheric CO_2 increase but also to the rate of CO_2 increase. In this work, we explicitly test whether a previously proposed AMOC–sea ice feedback controls the AMOC's sensitivity to the rate of CO_2 increase using mechanism-denial experiments in a global climate model. We find that when the AMOC–sea ice feedback is suppressed, the AMOC is nearly insensitive to the rate of CO_2 increase, supporting the hypothesis that this feedback is the primary reason for the AMOC's sensitivity to the rate of CO_2 increase. Additionally, we show that the reduction of sea ice meltwater in the North Atlantic that is caused by the retreat of Arctic sea ice in a warming climate constitutes a large strengthening forcing on the AMOC, reducing the total amount of AMOC weakening by nearly half. The strong influence of sea ice meltwater on the AMOC---both in its role as a forcing and feedback---occurs through the ability of the meltwater to modulate how much surface water mass transformation occurs via ocean heat loss to the atmosphere over the deep convection zones in the North Atlantic. This work demonstrates that Arctic sea ice–AMOC interactions are a first-order control on future AMOC weakening and highlights the importance of constraining present-day sea ice meltwater fluxes to assess their potential counteracting influence on the weakening of Earth's AMOC.

Future responses of mesoscale eddy activity in subantarctic mode water formation regions

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Subantarctic Mode Water (SAMW) plays a vital role in the uptake of heat and carbon, thereby regulating global climate. Mesoscale eddies affect mode-water subduction and transport in the Southern Ocean. However, it remains unclear how SAMW-related eddy activity will evolve under anthropogenic warming, because most state-of-the-art climate models do not explicitly resolve mesoscale eddies. Using an eddy-resolving climate model we explore the evolution of mesoscale eddy activity in SAMW formation regions under global warming, finding that eddy activity exhibits opposite trends, with modest weakening in the Indian Ocean but a marked strengthening in the Pacific. These contrasting responses are linked to projected changes in local wind stress and baroclinic instability. The resulting regional differences drive opposite trends in eddy-induced vertical transport in SAMW formation regions. Our results demonstrate that regional differences in eddy variability may influence future ocean heat and carbon storage in SAMW.

Mesoscale and submesoscale eddies in the marginal ice zone of Arctic seas

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The Marginal Ice Zone (MIZ) is often associated with enhanced number of mesoscale and submesoscale eddies, which, in turn, strongly affect position of the MIZ and thus modify local ocean-atmosphere heat and moisture exchange.

Coherent eddies in MIZ areas of the marginal Arctic Seas were derived from Envisat ASAR, ALOS 2 PALSAR 2, Sentinel 1 A/B satellites for summer and autumn of 2007 and 2014-2022. The results show an enhanced eddy activity in the MIZ along the northern East-Greenland Current and in the north-western part of the Barens Sea. Relatively large number of MIZ eddies were detected in the Chukchi Sea and the Beaufort Gyre. These areas also were characterized by large eddy radii.

The results of a high-resolution FESOM model (1 × 1 km) along the East-Greenland Current showed that eddy exchange forms local horizontal heat fluxes towards the MIZ that reach 1 TW. The heat flux by mesoscale eddies towards the ice edge largely balances the sea ice convergence via sea ice advection by the mean flow. Large anticyclones provide the dominant contribution. As a result, sea ice can retreat at a velocity up to several kilometers per day. Analysis showed that the maximum sea-surface temperature at the warm side of the MIZ governs the intensity of eddy heat advection towards the ice edge. The dynamic instability of the East-Greenland Current at sharp bends of the continental margin is suggested to be the principal mechanism for eddy generation. The dynamic instability increases with an increase of the along-coast current velocity induced by wind or long coastally trapped waves. The study was funded by the Russian Science Foundation (RSF) grant No. 25-17-00309.

Dynamical downscaling simulations and future projections of the Arctic Ocean

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The Arctic is one of Earth's regions highly susceptible to climate change. However, in-situ long-term observations used for climate research are relatively sparse in the Arctic Ocean, and current climate models exhibit notable biases in Arctic Ocean simulations. Here we present an Arctic Ocean dynamical downscaling dataset, obtained from the global ocean-sea ice model FESOM2 with regionally refined horizontal resolution of 4.5 km in the Arctic region, which is driven by bias-corrected surface forcings derived from a climate model. The dataset includes 115 years (1900–2014) of historical simulations and two 86-year future projection simulations (2015–2100) for the scenarios SSP126, SSP245 and SSP585. The historical simulations demonstrate substantially reduced biases in temperature, salinity and sea ice thickness compared to CMIP6 (the Coupled Model Intercomparison Project phase 6) climate models. Common biases in the representation of the Atlantic Water layer found in climate model simulations are also markedly reduced in the dataset. Using this dataset, we investigate Arctic Ocean changes in a warming climate, including rapid warming of the Atlantic Water layer, intensification of the Beaufort Gyre, and modified freshwater export toward the North Atlantic under ongoing climate warming. Serving as a crucial long-term data source for climate change assessments and scientific research for the Arctic Ocean, this dataset provides valuable information for the scientific community.

High-latitude Southern Ocean warming hotspot induced by ocean mesoscale eddies

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The high-latitude (poleward of ~50° S) Southern Ocean is recognized as a region of delayed surface warming during periods of transient CO_2 increase; however, the uniformity of this pattern remains unclear. Here, based on observational and reanalysis datasets, we identify locally (50° S–61° S, 80° E–130° E) accelerated surface warming of 1.5 °C per century for 1982–2023 in the high-latitude Indian Ocean sector. This warming rate is three times the average over the high-latitude Southern Ocean (0.5 °C per century) and close to the global mean of 1.6 °C per century. Analysis of a state-of-the-art high-resolution climate simulation suggests that the hotspot warming is primarily attributed to increased upward heat transport by mesoscale eddies in response to an enhanced Antarctic Circumpolar Current under anthropogenic climate change. Our findings underscore the important role of mesoscale eddies in regulating Southern Ocean warming and the need for their faithful representation in models to ensure reliable projections of future climate change.

Upper ocean salinity variability and impact in the Southeast Indian Subantarctic Mode Water formation region during the Argo era

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Salinity is a state variable that determines the fundamental physical properties of the ocean, and understanding its changes and effects has important implications for the regional and global climate system. Based on Argo observations, changes in upper ocean salinity and their impacts in the Southeast Indian Subantarctic Mode Water (SEISAMW) formation region are investigated from 2004 to 2022. The upper ocean salinity in this region shows significant interannual variability, being relatively salty during 2010–2016 and fresh during 2005–2008 and 2019–2022, respectively. A diagnostic analysis indicates that the interannual variability of winter mixed layer depth and stratification are mainly affected by upper ocean salinity rather than temperature. In the SEISAMW formation region, higher upper ocean salinity acts to weaken the stratification and deepen the mixed layer. Conversely, lower upper ocean salinity acts to strengthen the stratification and shallow the mixed layer. A mixed layer salinity (MLS) budget analysis reveals that horizontal advection, predominantly influenced by meridional Ekman advection, governs the interannual variability of MLS. Furthermore, the interannual variability of meridional Ekman advection is mainly affected by the meridional Ekman velocity associated with zonal wind stress.

Session: Polar-Tropical Interactions

Multiyear tropical warm pool warming drives slowdown in Antarctic mass loss

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Antarctic mass loss has been a major contributor to global sea-level rise for most of the last few decades, mainly driven by West Antarctica. During 2021–2023, however, a sharp increase in surface mass balance over Queen Mary Land and Wilkes Land in East Antarctica offset West Antarctic loss and slowed the rate of total ice mass loss. Although this slowdown is consistent with the expected long-term precipitation response to global warming through poleward-shifted storm tracks and Antarctic moistening, our results point to a different mechanism. Here we show that the recent ice mass gain was linked to a recurrent atmospheric teleconnection driven by sea surface temperature anomalies in the tropical warm pool, which experienced unusually persistent warming from 2021 to 2023 relative to the previous two decades. On the basis of observations and model experiments, we find that tropical warm pool warming excites a poleward-propagating Rossby-wave train that induces a high-pressure anomaly over East Antarctica, enhancing Queen Mary Land and Wilkes Land precipitation and driving the observed mass gain, with moisture primarily sourced from the mid-latitude Indian Ocean. Similar multiyear warming in the tropical warm pool recurs about once per decade in observations and historical simulations, and its influence on precipitation is distinct from the effects of global warming. Therefore, the recent Antarctic Ice Sheet mass gain is probably temporary and does not yet reflect a sustained, global-warming-driven moistening of Antarctica.

Climate forcing and Antarctic cryospheric response: From shifting drivers to future glacier instability

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Antarctic cryospheric variability is strongly influenced by large-scale climate modes such as the Southern Annular Mode (SAM), El Niño–Southern Oscillation (ENSO), and Indian Ocean variability. Recent studies show that these forcings affect Antarctic sea ice, atmospheric circulation, and precipitation through pronounced seasonal and time-lagged responses. In particular, SAM exerts a delayed influence on circum-Antarctic fast ice, while the Amundsen Sea Low responds to ENSO through seasonally evolving teleconnection pathways. Over East Antarctica, Indian Ocean Dipole-like warming also contributes to reduced precipitation, highlighting the importance of remote oceanic forcing in shaping regional Antarctic climate.

Under future warming, however, these climate–cryosphere linkages are expected to change substantially. Changes in the atmospheric background state can reorganize teleconnection pathways and weaken present-day relationships between tropical climate variability and Antarctic mass balance. In West Antarctica, for example, the El Niño-related increase in snowfall and ice-mass accumulation may largely disappear in a warmer climate. These shifts suggest that Antarctic glacier and ice-sheet stability will depend not only on the magnitude of warming, but also on how large-scale climate drivers and their teleconnections evolve in the future.

Interaction between Southern Ocean and lower latitudes

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The Southern Ocean is a central component of the global climate system, but its variability cannot be understood in isolation from the lower latitudes. Their interaction is intrinsically two-way and operates through both atmospheric and oceanic pathways across a wide range of timescales. Climate variability originating in the tropics and subtropics, including changes in the Pacific, Indian, and Atlantic Oceans, can reach the Southern Ocean through stationary Rossby wave trains, shifts in the Southern Hemisphere circulation, and changes in surface wind and buoyancy forcing. These processes modulate Southern Ocean circulation, ocean heat uptake, Antarctic sea ice, and the exchange of heat and carbon between the ocean and atmosphere. In the opposite direction, Southern Ocean temperature and sea-ice anomalies alter meridional temperature gradients and air-sea fluxes, thereby influencing the Hadley and Ferrel circulations, the subtropical and eddy-driven jets, and regional climate at lower latitudes. Oceanic adjustments associated with overturning circulation and interbasin transport provide an additional pathway for transmitting Southern Ocean signals toward the tropics. This presentation synthesizes recent observational evidence and model-based understanding of these coupled processes, with particular attention to the mechanisms that connect tropical forcing, Southern Ocean responses, and subsequent climate feedbacks. Clarifying this bidirectional interaction is essential for interpreting recent Antarctic and Southern Ocean changes and for improving predictions of their regional and global climate impacts.

Strengthened causal influence of Antarctic sea ice on East Asian summer precipitation following the mid-2010s sea-ice regime shift

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Antarctic sea ice expanded modestly for more than three decades and has contracted abruptly since the mid-2010s; however, whether this regime shift has altered the influence of Antarctic sea ice on remote climate remains unclear. In this study, the causal influence of Antarctic sea-ice concentration (SIC) on climate was investigated using the Liang–Kleeman information flow with the El Niño–Southern Oscillation (ENSO) signal excluded, based on ERA5 for 1979–2025. During 1979–2014, statistically significant information flow from Antarctic SIC during austral-winter (JJA) to 2-m temperature and precipitation was largely confined to the Southern Ocean and adjacent latitudes. In contrast, during 2015–2025, significant information flow expanded markedly into the tropics and the Northern Hemisphere, including the East Asian summer monsoon region. It should be noted that the causal signal in precipitation persisted when SIC led by one to three months, indicating a potential predictive information for East Asian summer precipitation. Furthermore, vertical circulation anomalies along 100°E–150°E regressed onto the leading SIC mode revealed a reorganized meridional overturning structure bridging the Southern Ocean and East Asia in the recent epoch. These results suggest that Antarctic sea ice provides a potential source of predictive information for East Asian summer precipitation under the new low-ice state.

Geographic origins of asymmetric polar amplification

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Polar regions warm more than the global average, yet the Arctic warms more strongly than the Antarctic—a longstanding feature of climate model simulations since the earliest numerical experiments. Although climate feedbacks that enhance polar warming are well established, the physical origin of this Arctic–Antarctic asymmetry remains a subject of active debate. Here we show that Earth's geographic features, such as bathymetry, land–sea distribution, and surface elevation, systematically control the polar climatology, which in turn governs the strength of climate feedbacks and ultimately determines the asymmetry in polar amplification (PA). Using a hierarchy of idealized abrupt-4×CO_2 Earth system model experiments, we find that in the absence of land–sea distribution, realistic bathymetry produces the largest Arctic–Antarctic PA asymmetry by enabling extensive sea-ice formation over former Northern Hemisphere land areas and a strong ice-albedo feedback. The asymmetry weakens as realistic continents and topography are progressively introduced, suppressing this sea-ice-mediated feedback. These results reveal a geographic origin of asymmetric polar warming and provide a framework for understanding future polar amplification. The magnitude of the asymmetry is controlled primarily by the ice-albedo feedback, with atmospheric dynamics also playing an important contributing role that cannot be interpreted as a passive response to albedo changes.

Revisiting the role of ocean circulation changes in polar ocean heat transport anomalies under global warming

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In response to greenhouse gas forcing, climate models predict that poleward ocean heat transport (OHT) weakens in the Southern Ocean but increases in the Arctic. The role of ocean circulation changes in this OHT response has been evaluated by decomposing OHT anomalies into a dynamic component (holding ocean temperature fixed while circulation evolves) and a thermodynamic component (holding ocean circulation fixed while temperature evolves). However, ocean temperature changes are themselves shaped by circulation changes through redistribution of the existing heat reservoir and subsequent effects on air–sea heat fluxes. The thermodynamic component can therefore be influenced by circulation changes, making the standard thermodynamic–dynamic decomposition incomplete for isolating the role of circulation changes in OHT anomalies. To address this issue, we use a passive–active decomposition to assess the relative contributions of ocean circulation and passive ocean temperature changes to polar OHT anomalies in a fully coupled climate model. Passive temperature changes are defined as those thermally forced by the atmosphere in the absence of circulation changes. In this passive–active decomposition, an advective term involving both circulation and passive temperature changes remains ambiguous—classifying it as active implies circulation changes dominate Southern Ocean OHT anomalies, whereas classifying it as passive implies temperature changes dominate. However, both interpretations imply that ocean circulation changes have a much weaker effect on polar OHT anomalies than inferred from the standard decomposition. These results help reconcile conclusions from studies using the standard decomposition with those using passive tracer methods to assess the role of circulation changes in polar OHT anomalies.