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SEA ICE IN THE ATMOSPHERE-ICE-OCEAN-BIOSPHERE SYSTEM: HOW, WHERE AND WHY IS IT CHANGING, AND WHAT ARE THE EFFECTS?

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ABSTRACTS SUBMITTED TO THE (CANCELLED) SCAR 2020 OSC IN HOBART

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Seasonal and interannual variability of landfast sea ice in Atka Bay, Weddell Sea, Antarctica

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Landfast sea ice attached to the Antarctic coast is a critical element of the local physical and ecological systems. Through its direct coupling with the atmosphere and ocean, fast ice and its snow cover are also a potential indicator of processes related to climate change. Since 2010, a monitoring program that is part of the Antarctic Fast Ice Network (AFIN) has been conducted on the seasonal fast ice of Atka Bay, located on the northern edge of Ekström Ice Shelf in the eastern Weddell Sea.
Here, we show results of regularly measured snow depth, freeboard, sea-ice- and sub-ice platelet layer thickness across the bay, combining them with observations from the meteorological observatory at Neumayer Station, as well as satellite images. On average, the annual fast-ice thickness at the end of the growth season is about 2 m, with a platelet layer thickness of 4 m beneath. Due to the substantial snow accumulation on the sea ice, a characteristic feature is frequent negative freeboard, and associated flooding of the snow/ice interface. Strong easterly winds in the area govern the year-round snow redistribution and also trigger the breakup events of the bay during summer months.
Since there is no obvious trend in any of the observed variables, neither in the present 9-year observation period, nor in comparison to studies from the 1980 and 90s, our monitoring efforts provide an important baseline for an Antarctic fast-ice system that will likely undergo drastic changes in the future, as already projected by climate modelling studies.

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Large Scale Biophysical Characterization of Antarctic Under-Ice Environments

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Sea ice is a highly heterogeneous habitat varying on scales from millimeters to kilometers. The spatial variability of physical properties dictates the variability of sea ice microbial communities and of sympagic fauna. Characterizing the biophysical environment at the sea ice-water interface at scales of meters to kilometers still faces logistical hurdles. In this study, we present under-ice data collected with a Surface and Under-Ice Trawl (SUIT) during three campaigns between 2013 and 2018 covering the seasons of winter and summer in the Weddell Sea. The SUIT is equipped with a sensors array from which we retrieve several environmental properties, including sea-ice thickness, spectral radiation and algal chlorophyll a concentration in the ice (in-ice chl a). With an average trawl distance of about 2 km, the SUIT covers scales that can rarely be sampled with classic methodologies. The present work, thus, represents the first multi-seasonal habitat characterization based on kilometer-scale profiles. The present data highlight regional and seasonal patterns in water properties. Antarctic sea ice thickness and snow depth remain quite uniform between seasons, and thickness distribution agrees well with data collected over larger scale with an EM-bird. Light transmission, however, is low in winter. Despite the thick snow depth, the overall under-ice light is considerable during Antarctic summer. In-ice chl a exceeds 7 mg chl a m^{-2} during Antarctic winter, when water chl a concentrations remains below 1.5 mg chl a m^{-2} , thus providing a potential food source for overwintering of sympagic and pelagic fauna.

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Hyperspectral imaging of sea-ice cores to map the microspatial variability of its biophysical properties

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Within the sea-ice biome, sea-ice algae constitute a large, yet poorly quantified fraction of biomass contributing to polar marine productivity and large-scale biogeochemical cycles. Albeit, the analyses of large-scale ecological patterns warrant for the integration of small-scale processes and the microspatial variability of ice algal biomass has remained mostly uncaptured and unquantified. To address this knowledge gap we present a field-deployable hyperspectral scanning set-up that can map both the vertical and horizontal chlorophyll-a proxies in sea-ice cores at sub-mm resolution. The set-up uses artificial light transmitted through horizontal sections of ice cores to enable the assessment of spectral indices against extracted chlorophyll-a. We developed new spectral indices which explain 85 % of variation in sampled chlorophyll-a for our study area. Indices were statistically validated and evaluated against traditional methods. Following a tailored image pre-processing workflow we present a regression model developed for both in situ and ice-core hyperspectral images. While validation remains a challenge under current sampling regimes, this preliminary result highlights the possibility to map chl-a in mg m2 at a mm-scale on a per-pixel basis. This methodology sheds light onto undocumented yet dominant features of the under-ice habitat.

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The internal structure of East Antarctic pack ice in summer and its physical implications

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Antarctic sea-ice extent retreats to its annual minimum of about 3 million km² between late February and early March at which time most of the remaining ice is thick, free-drifting pack ice. These thick floes have already delivered nutrients for an early spring phytoplankton bloom via an extensive brine network that develops within the sea ice as the ice temperature increases. In late summer, snow loading becomes sufficient to depress the ice freeboard and refill the brine network with nutrient-replete seawater to sustain ice-algal growth. Few studies have focussed on what happens within pack ice between these two periods of algal growth. Here we show that between Wilkes and George V Lands (East Antarctica) around mid-summer 2016-17, pack ice was rotten and highly permeable, but that full-depth percolation was limited by impermeable superimposed ice layers and brine stratification. Despite insufficient snow loading to introduce surface flooding and/or upward brine flushing, permeable submerged layers allowed lateral intrusion of seawater and subsequent downward percolation. We conclude that these permeable subsurface layers were likely caused by historical ice floe rafting and glacial melt sourced ice crystal deposition, processes which are also likely responsible for growing the floes thick enough to persist through the summer. The mid-summer seawater incursions identified here present a mechanism for replenishing nutrients and allowing ice algal growth at an under-sampled time of year in an under-sampled region.

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Direct and indirect contributions of ice shelves to micronutrient supply to the surface waters around Antarctica

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Previous studies showed that satellite-derived estimates of chlorophyll in coastal polynyas over the Antarctic continental shelf are correlated with the basal melt rate of adjacent ice shelves. We use a 5 km resolution ocean/sea ice/ice shelf model of the Southern Ocean to examine mechanisms that supply the limiting micronutrient iron to Antarctic continental shelf surface waters. Four sources of dissolved iron are simulated with independent tracers, assumptions about the end member concentrations, and an idealized summer biological uptake. Direct injection of iron from melting ice shelves is important to the total dissolved iron supply to surface waters, providing about 6%. However, the contribution from deep sources of iron on the shelf is much larger at 71%. The relative contribution of dissolved iron supply from basal melt driven overturning circulation within ice shelf cavities is heterogeneous around Antarctica, but at some locations, such as the Amundsen Sea, it is the primary mechanism for transporting deep dissolved iron to the surface. Correlations between satellite chlorophyll in coastal polynyas around Antarctica and simulated dissolved iron suggest that productivity of the polynyas is linked to the basal melt of adjacent ice shelves. This correlation is the result of upward advection or mixing of iron-rich deep waters due to circulation changes driven by ice shelf melt, rather than a direct influence of iron released from melting ice shelves. The effect of possible changes in the winds on iron supply is expected to be heterogeneous around Antarctica and this is explored with the model.

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Understanding future changes in sea ice dynamics in the Southern Ocean on net community production of food: Results from a large data set synthesis

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Modeling suggests the response of Antarctic sea ice extent, seasonality, and thickness to future climate change will be complex, yet averaged over large areas sea ice is expected to be thinner, less extensive, form later, and melt earlier. These characteristics influence net productivity and phytoplankton community composition in the Southern Ocean. We assembled a large data set on sea ice and sea ice melt conditions, water column TCO2 deficits, [oxygen], particulate organic C standing stock and chlorophyll concentrations, surface water pCO2, and hydrographic data (temperature, salinity, mixed layer depth, water column stratification). We use data sets from 8 cruises spanning 22 years (NBP cruises 96-06, 97-09, 98-07, 01-01, 06-01, 06-08, 13-02, and 18-01) where the measurements were made by the same labs. Cruise tracks span the Bellingshausen Sea to the Ross Sea and on to the Edward VIII Gulf. We stratified estimates of net community productivity (NCP) according to the following regimes: >80% sea ice cover, <20% sea ice cover, sea ice edge melt water bloom, early/late season well-mixed water column, and mid-summer well-mixed water column. Significant differences exist in rates and extents of instantaneous and net seasonal primary production and estimated C export among these different regimes. Depth integrated NCP rates are highest in shallow mixed layers associated with melting sea ice as well as in open water Phaeocystis blooms in late Spring/early Summer. Our findings can be used with sea ice model projections to estimate future climate change impacts on Antarctic food webs.

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Wind-driven sea ice drift analysis in the Western Ross Sea, Antarctica, based on high-resolution satellite observation and modelled surface wind

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Sea ice drift is forced by winds and ocean currents and is an essential element in the dynamics of polar oceans. Sea ice extent, concentration, and thickness are heavily influenced by ice dynamics. For the accurate representation of sea ice in climate models, realistic parameterization of the sea ice motion and deformation rates are crucial. Here we present high-resolution sea ice deformation fields of the Western Ross Sea as a basis to explore ice-atmosphere interactions and influence of wind on sea ice drift over a short time scale. The study region includes the three main polynya areas (Ross Ice Shelf, McMurdo Sound, Terra Nova Bay) which experienced a significant increase in sea ice extent over the satellite observation period, and wind forcing is possibly the main driver of this change. Focusing on months with maximum sea ice extent (April – October) between 2002-2012, we used sequential high-resolution Advanced Synthetic Aperture Radar (ASAR) Envisat images in wide swath mode at 150m pixel resolution. Pattern-matching techniques were used to find the motion vectors, which are correlated to 3-hourly AMPS wind velocity data at a spatial resolution of 5 km. Here we present the long-term correlation results between sea ice drift velocity and wind velocity. Our study shows that the sea ice motion is strongly linked to the strong geostrophic winds, but due to the extremely variable wind patterns, a high temporal resolution (2-4 per day) of image acquisitions in key sea ice formation areas is essential.

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Production of iron-binding ligands in summer sea-ice

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East Antarctic land fast and pack ice cores were sampled during mid-summer (December 2016 – January 2017) for both physical and biogeochemical characterization. Temperature and salinity data indicated warm and highly permeable sea ice at this time of year. Chlorophyll-a maxima were found in bottom ice in fast ice stations (up to 127.5 µgL-1), and at intermediate depths in pack ice stations. Nevertheless, the overall low Chlorophyll-a and high particulate organic carbon concentrations found across all stations in summer sea ice, compared to earlier season ice surveys, suggest a highly heterotrophic biomass. This result is supported by nutrient stress, with NOx depletion (<0.2 µM) and a NH4+/NO3- ratio about 10 times higher than during springtime; by an average POC/PON ratio of 11.3 ± 4.2; and by concentrations of particulate exopolymeric substance (EPS) up to 16,290 µg xeq L-1.

Fast ice shows dissolved iron (DFe) concentrations (up to 20 nM) twice as high as those found in pack ice (0-10 nM). Regardless of the ice type, DFe was >99% organically complexed, with the organic ligands concentration always exceeding the DFe concentration. The conditional stability constant (logk'FeL = 12.4 ± 0.3) suggests that dissolved EPS represent the main type of Fe-binding ligands in summer sea ice. We are suggesting that bacteria in summer sea ice contribute to remineralization of organic matter and production of Fe-binding EPS, which help retain Fe in the system, therefore likely extending the fertilization potential of sea ice.

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Introduction of the Ice Algae Model Intercomparison Project phase 2 (IAMIP2)

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Ice algae play a fundamental role in shaping polar marine ecosystems and biogeochemistry. While this claim is supported by field observations, their influence at the regional and global scales remains unclear due to limited spatial and temporal coverage of observations. To address this knowledge gap, we introduce a new model intercomparison project (MIP), referred to here as the Ice Algae Model Intercomparison Project phase 2 (IAMIP2). IAMIP2 is built upon the experience from the previous MIP, and expands its scope into global covering both Arctic and Antarctic, and centennial spanning from the mid-twentieth century to the end of the twenty-first century. Participating models are three-dimensional regional and global coupled sea ice-ocean models that incorporate sea-ice ecosystem components. These models are driven by the same initial conditions and atmospheric forcing dataset by incorporating the protocols of the Ocean Model Intercomparison Project, an endorsed MIP of the Coupled Model Intercomparison Project phase 6 (CMIP6). Doing so provides more robust estimates of model bias and uncertainty, and consequently advance the science of polar marine ecosystems and biogeochemistry. A diagnostic protocol is designed to enhance the reusability of the model data products of IAMIP2. Lastly, the limitations and strengths of IAMIP2 are discussed considering prospective research outcome.

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Nutrient biogeochemistry in Antarctic land-fast sea ice and exchange with the surface ocean

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Sea ice is an important component of the Antarctic marine system due to its strong coupling with upper ocean processes, its exchanges with underlying seawater and the overlying atmosphere, and its ability to support life. The biogeochemical cycling of nutrients in sea ice and exchange of dissolved and particulate constituents with the surface ocean are particularly important in regulating primary production by ice algae, organic matter remineralisation within the ice matrix, and potentially seeding of phytoplankton blooms. We have produced an international compilation of nutrient concentration data from land-fast sea ice around the Antarctic continent. We will present and discuss these data with a view to describing the overall trends observed at the circum-Antarctic scale, and the differences in these trends between regions and over seasonal and interannual timescales. Our results highlight the importance of exchange with surface waters in supplying nutrients to the sea-ice matrix, and of ice thickness in regulating the availability of light to ice-algal communities concentrated close to the ice-ocean interface and therefore the degree of nutrient uptake. Our data further show strong seasonality in the nutrient content of the ice column, as well as a decoupling of the biogeochemical cycles of nitrogen, phosphorous and silicon. This international circum-Antarctic dataset will be useful in informing modelling efforts focusing on the role of sea ice in modulating Southern Ocean biogeochemistry and its importance in the Earth System.

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The spatio-temporal patterns of landfast ice in Antarctica during 2006-2011 and 2016-2017 using high-resolution SAR imagery

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Landfast ice is an important component of the Antarctic sea ice regime. It affects the Antarctic climate and ecological system. In this study, the first high-resolution, long time series of the landfast ice edge from 2006 to 2011 and 2016 to 2017 is presented. The dataset was produced based on the improved net gradient difference algorithm using 2470 SAR scenes from ENVISAT and Sentinel-1A/B as well as manual analysis of MODIS imagery to fill in SAR data gaps. The study results show that the landfast ice area in November for all studied years was approximately 49.49±3.25 ×104 km2, accounting for about 3%~ 4% of the total Antarctic sea ice area. The maximum area was 55.70×104 km2 in November 2007, compared to the minimum area 44.01×104 km2 in 2011.The area in West Antarctica was about 40% of that in East Antarctica. The distribution of landfast ice in Antarctica has significant regional differences. The extent in the Indian Ocean sector is the maximum with a mean value of 16.49±1.1 ×104 km2; however, the ratio of the landfast ice area to the sea ice area in the Pacific Ocean sector is the highest. Twenty-four landfast ice zones with groups of small, grounded icebergs were identified, most of which were located in East Antarctica, particularly along the Wilkes Land and Oates Land. Two cases are presented to illustrate how giant, grounded icebergs affected landfast ice. Results from this study are well suited to underpin the Antarctic climate or ecological system studies.

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Unprecedented phytoplankton blooms in the Maud Rise polynya, Lazarev Sea

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Anomalously record lowest sea-ice extent and area observed since 2016 to 2019 with the maximum melting occurred in 2017, corresponding to the upper ocean warming of the Southern Ocean. A large polynya on the Maud Rise reappeared during austral winter-spring 2017 since its appearance in 1970s. Satellite derived chlorophyll-a concentration in the polynya showed unprecedented phytoplankton blooms with chlorophyll-a reached up to 4.67 mg m-3. Multi-satellite data indicated that the bloom appeared for the first time in the entire mission records started since 1978. Argo float located in the polynya provided evidence of bloom condition in austral spring 2017 (chlorophyll-a up to 5.47 mg m-3) compared to the preceding years of prevailed low chlorophyll-a. The net primary production from Aqua-MODIS chlorophyll-based algorithm showed that the Maud Rise polynya was as productive as the Antarctic coastal polynyas with the carbon fixation rates reached up to 415.08 mg C m-2 day-1. The performances of ocean-color based models were evaluated by comparing with the in-situ NPP estimated using 13C tracer during the Indian scientific expedition to the Southern Ocean.

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Airborne measurements of land-fast sea ice thickness in the SW Ross Sea

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The Victoria Land coast is fringed by land-fast sea ice that interacts with ice shelves and floating ice streams, resulting in the presence of a sub-ice platelet layer as an indicator of supercooled ice shelf meltwater at the ocean surface. Airborne electromagnetic induction (AEM) sounding characterises the thickness of sea ice and its sub-ice platelet layer. AEM surveys have been conducted over the spring fast ice of McMurdo Sound on five years between 2009 and 2017. The ice was mostly level and more than 2 m thick. It was underlain by a sub-ice platelet layer, with maximum thickness of more than 6 m near the ice shelf edge. The sub-ice platelet layer thickness distribution was in good agreement with in-situ measurements and was remarkably similar from year to year, suggesting weak interannual variability in the ocean circulation. In November 2017 the AEM survey extended along the coast of Victoria Land. Fast ice between Terra Nova Bay and the Adare Peninsula was more than 2 m thick and heavily deformed by onshore pack ice drift. A sub-ice platelet layer, up to 2.5 m thick, was observed in front of the Hell’s Gate Ice Shelf beneath 2 m of level sea ice. We use our knowledge of ice shelf outflow in McMurdo Sound to draw conclusions regarding fast ice adjacent to less accessible features of the Victoria Land coast. Our results have important implications for understanding ice shelf melt and the role of the fast ice/platelet ice in biological productivity.

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Was 2016 an atypical year for the carbonate system in the Gerlache Strait, Antarctica?

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Polar coastal regions are highly dynamic regions with large spatial changes mainly related to sea ice distribution and meteoric water. Moreover, ENSO conditions can considerably influence the input of water masses onto continental shelves along the Antarctic coast. The Antarctic Peninsula has been affected by climate change factors, e.g., ocean warming, freshening, and changes in sea ice extent, periodicity, and thickness. These changes also affect the polar biological community all through the food web. Therefore, it is important to well constrain the parameters of the carbonate system for a good determination of its variabilities and improvement of numerical models. This work investigates the local processes affecting the spatial distribution of carbonate system parameters in the Gerlache Strait waters during the austral summer of 2016. Data from NAUTILUS (2015-2018) were used to analyse the spatial distribution of carbonate system parameters. Results show a high dissolved oxygen (>300 µmol/kg) and low carbon (<2150 µmol/kg) pools in the strait, which is not observed in any other NAUTILUS year. This reflects into an aragonite saturation state >1.5. Results suggest a combined action of sea-ice meltwater arriving from the Bellingshausen region and local glacial meltwater discharge. The period of 2015-2016 was determined by El Niño conditions, which impacts the periodicity of sea ice over the Bellingshausen Sea continental shelf, thus, reflecting the low salinity observed in 2016. This combined event was probably responsible for the low oxygen pool observed in the strait, which is linked to a high biologically productive event in the same year.

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Spatial distribution of chlorophyll-a in the Bransfield Strait and its relationship with glacier coverage during the southern summer 2018

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Chlorophyll-a being the major component of photosynthetic organisms allows to determine the trophic state of marine ecosystems and is also an indicator of primary marine productivity. The goal of this research was to estimate the spatial distribution of the chlorophyll-a concentration during the southern summer in the Bransfield Strait (-60.16° and -63.04° South; 55.63° and -62.17° West) and its relationship with glacier coverage. We processed the four-band algorithm (OC4) of Landsat 8 OLI sensor satellite images to obtain the chlorophyll-a values satellite. These values were correlated with in situ data obtained from the collection of 45 samples of sea surface along the Strait. The results show that the surrounding glacier areas were related to chlorophyll-a concentrations. The analysis of in situ and satellite data has a correlation coefficient of 0.95 with an average chlorophyll-a variation of ~ 0.19 mg/m3. Also, a higher concentration of chlorophyll-a is observed in areas with less glacier coverage (King George Island and Elephant Island) with values of 1.11 mg/m3; while in areas influenced by cold currents from the Antarctic Peninsula the concentration is lower (0.06 mg/m3).

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Influence of the glacial contribution (sediments - fresh water) on marine nutrients of the Bransfield Strait during the austral summer 2018

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Antarctic glaciers are complex and dynamic systems that provide fresh water and sediments to the ocean, this constitutes an inorganic source of nitrogen and phosphorus for photosynthetic organisms. The goal of this research was to estimate the spatial distribution of marine nutrients during the southern summer in the Bransfield Strait (-60.2° and -63.0° South; 55.63° and -62.17° West). There were analyzed phosphates, silicates, nitrites and nitrates concentrations of 44 surface seawater samples along the Strait. The glacier coverage was obtained from the supervised classification of Landsat 8 images. To estimate the spatial distribution of nutrients and their relation to glacier coverage, the kriging method was applied.
The results show that the concentration of nutrients varies inversely to the proximity of the sediment feathers from glaciers. In the coasts a lower concentration is observed due to the reactivation of algae and microorganisms, released by the glacial contribution, that use the nutrients for their reproduction (greater chlorophyll-a, up to 1.03 µg/L).

The Antarctic Peninsula coasts that have more glacier coverage and low sediment feathers have a higher concentration of nutrients (1.44 phosphates; 60.69 silicates; 0.24 nitrites; 13.35 nitrates µM) compared to South Shetland Islands. The Elephant Island is located in the northwest in the open sea has a greater accumulation of nutrients in their surroundings (1.61 µM phosphates).

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Characterisation of under-ice habitats in the Weddell Sea pack-ice zone during summer

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Sea ice plays a key role in Southern Ocean physics and biogeochemical cycles, and is a major driver of Antarctic marine ecosystem processes. Importantly, sea ice provides a substrate for ice algae which serve as food source for pelagic herbivores, e.g., Antarctic krill (Euphausia superba). The under-ice environment also provides a spatially complex refuge from predators. Coincident measurements of sea-ice parameters and krill under the sea ice are critical to understand the habitat utilisation of this Antarctic key species.
During a summer voyage to the Weddell Sea we combined classical ice coring methods with the deployment of novel instrumented under-ice observing platforms to collect concomitant measurements of ice algal biomass and the abundance of Antarctic krill at sea ice - water interfaces, under different types sea ice. Particularly, we deployed horizontally profiling platforms (Remotely Operated Vehicle (ROV) and Surface and Under Ice Trawl (SUIT)) to measure ice algal biomass and krill abundance along 100-1000m long transects. Algal biomass was estimated from under-ice irradiance data, cross-calibrated with point measurement from ice cores. Krill abundance was determined from SUIT catches and from images of the ice-water interface taken with an up-ward looking camera mounted to the ROV. Our data show high small-scale spatial variability in both ice algal biomass and krill abundance. First analyses indicate that the Weddell Sea marginal ice zone, particularly areas with a high amount of brash ice, harbour high ice algal standing stocks with associated high abundances of krill dwelling directly at the sea-ice water interface during summer.

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The functional role of marginal sea ice in trace metal dynamics in the Southern Ocean

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Samples were collected during the austral winter and early spring of 2019 to better understand the partitioning and seasonal cycling of bioactive trace metals and their effect on ocean biogeochemistry in the Antarctic marginal sea ice zone (MIZ) (57ºS-59ºS:0ºE-25ºE). Trace metals (TM), nutrients, Chl a and pigments were analyzed in wet and dry aerosols, snow, sea ice, and underlying water column. The preliminary results show the TM concentration in the ice cores were higher than the underlying seawater column and the overlying snow layers. Within the ice cores, the metals showed a boomerang-shaped profile with a top and bottom maxima and intermediate minima. The profiles mimic the salinity profiles. Chl a, a proxy for phytoplankton growth, was consistently observed in the ice cores, especially in the early spring, with higher concentrations associated with high TM content in the ice. We believe that the formation of marginal ice during winter not only prevents the exchange of trace metals (TM) between the atmosphere and sea, it also partitions dissolved TM within the ice phase. During spring and summer melting; however, MIZ acts as a source of bio-limiting metals to the adjacent seawaters that are known to cause phytoplankton blooms. It is estimated that 15% of yearly net primary production in the Southern Ocean (Taylor et al., 2013) occurs in MIZ.

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Hot spot next to ice: an unusual haven for krill reproduction

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Conventional Antarctic biology dictates that adult krill offshore move in to the slope and shelf break in summer, where they spawn. Shallow waters near to the ice shelf and adjacent sea-ice are not the typically cited locations for krill reproduction. Here we report substantial occurrences of larval krill in waters next to ice shelf and iceberg-embedded sea ice in the Amundsen Sea from our sampling, mostly a mesh filtration of near-surface sea water supplied to on-board laboratories. Such larval concentrations were accompanied by unique acoustic signals and there was an obvious spatial variability that favors particular types of habitat. Surface water temperature tended to be low, being close to either ice shelf or sea ice. Reasonable supply of diatoms to fuel krill reproduction existed in the water column, even when there was a Phaeocystis bloom developed nearby, which often essentially displaces diatoms. The localities of high larval density were rather shallow, sometimes with distinct topography, less than 500 meters in depth, beyond the reach of Circumpolar Deep Water, known to facilitate the hatching of krill eggs. This is contrary to traditionally known krill spawning locations as deep as 1000 meters. Krill furcilia were found mostly where thick sea ice was present, and hardly ever in open waters close to glaciers. Where the parent population comes from, where these young krill a long way from Antarctic Circumpolar Current will end up and whether they will join the mainstream of circumpolar krill population remain as intriguing questions.

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Ice algal phenology in a changing cryosphere

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The Arctic decline in the past decades is being well reproduced by CMIP5 and CMIP6 models (Tedesco et al 2019; Tedesco et al In preparation). In contrast, CMIP6 models largely underestimate the Antarctic sea-ice extent trend for all months (Vichi et al In preparation). Also, while the decline of Artic sea ice is being undergoing largely on a pan-Arctic scale (Tedesco et al In preparation), we will show that regional and seasonal differences in the Southern Ocean are often represented by models in a opposite way (Vichi et al In preparation).

Recent studies (Tedesco et al 2019) combining sea-ice biogeochemical modelling with CMIP5 models presents future scenarios of largely altered Arctic ice algal primary production and phenology. The expected increase in production turns limited by the diminished seasonal areas, while blooms in areas with expanding first-year ice become limited by narrow growth windows. Disruption of the seasonality of the algal blooms have already created mismatches for the timing of zooplankton production, which in turn may lead to the possibility of phenological uncoupling with secondary and tertiary consumers.

The large disagreement between model simulations and satellite observations of Antarctic sea-ice extent trends raises the fundamental question whether CMIP6 models can be used for hindcasts and projections of ice algae dynamics as done for the Arctic. While an understanding of the discrepancies is a fundamental step forward, climate models remain the only available tools to quantitatively assess long-term changes in sea-ice biogeochemical dynamics also in the Southern Ocean.

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3D imaging of ocean surface in the Antarctic marginal ice zone: Surface waves dynamics and interaction with sea ice

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We report simultaneous underway measurements of pancake ice properties and ocean wave characteristics from a winter expedition to the Antarctic marginal ice zone aboard the S.A. Agulhas-II. Observations were gathered with a stereo camera system, which allows the reconstruction of the 3D ocean surface. Focus is given to properties of intense waves-in-ice propagating through a 100% sea-ice cover comprised of pancakes floes (60%) and interstitial frazil ice (40%) during an explosive polar cyclone crossing the Antarctic marginal ice zone. Results show propagation of ocean waves into the sea ice up to approximately 100 km from its edge, spectral changes and concurrent energy attenuation as well as properties of individual waves, including the highest waves (height of 8.5 m) ever recorded this far into the marginal ice zone. Measurements underscore low wave dissipation in pancake ice, and a spectral evolution towards longer periods due to the differential attenuation of the spectral wave components. The directional energy spreading narrows at the edge and subsequently broadens deeper into the marginal ice zone.

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Crucial role of Antarctic virioplankton in organic primary aerosol production

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During the winter season, sea-ice is a refuge of Antarctic microbial communities including phytoplankton, heterotrophic protists, bacteria and viruses. Then, along summer, due to sea ice melting, those microorganisms are released to the water and their metabolism and trophic interactions play a key role in the biogeochemical cycles in the ocean. Viral infections on microorganisms produce large quantities of dissolved and particulate organic matter (OM) including cell debris and other colloidal material. This OM may be incorporated in bubble-mediated spray production forming cooling marine aerosols and cloud layers potentially affecting climate. We therefore, tested experimentally the effect of viral lysis on bacteria, heterotrophic protists and phytoplankton, and their contribution to the production of aerosol precursors compounds during a field study carried out near the Antarctic peninsula in February 2019 using fixed and mobile platforms. We performed four experiments on melted sea ice incubated for 48-72 h in 60 L mesocosm (using two treatments: unamended natural viruses and viral addition) and subjected to still and bubbled periods. The generated aerosols were monitored by on-line and off-line aerosol techniques.
Our results - systematically for all four experiments - showed that after viral addition the microbial mortality (rate of lysed cells/mL/ d) increased. Concurrently, the released organic C, N, P augmented and significantly correlate with the concentration of dissolved organic carbon measured in the sea ice samples. We discuss that our data support the crucial role of virus mediated lysis of microbes on sea-ice-ocean-atmosphere interactions, including aerosol particle production.

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Phytoplankton phenology is driven by sea ice seasonality in climate simulations of the Southern Ocean

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Earth system models from the Climate Model Intercomparison Project are strongly biased in Southern Ocean phytoplankton phenology, especially along the ice edge where production is larger. In this study we describe the mechanisms driving CMIP models to misrepresent seasonal primary production in the Atlantic marginal ice zone during late winter. We link subsurface light availability during this period to simulated early growth, arguing that a combination of ice cover and deeper winter mixing prevent biomass accumulation in the real ocean, while in models this combination of factors is not present. Furthermore, we find a statistically significant correlation across the CMIP5 model ensemble between vertical stratification and the location of the ice edge; whereby the more equatorward the ice edge is, the closer to the surface stratification occurs. This relationship is also evident in CMIP6 models. We argue that models may be grouped according to how strongly they express two major controls on their phenology, namely, the location of the ice edge and the degree of stratification present in the water column in late winter. We find that models with small biases in just one of these controls (but large biases in the other) are able to simulate bloom initiation close to observations, while models with significant biases in both controls initiate growth 2–4 months early.

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In-situ measurements of sea ice drift and response to ocean waves

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Sea ice dynamics are intrinsically coupled to the forces of wind, currents and waves. Prediction of sea ice drift, break-up and, consequently, sea ice extent requires a comprehensive understanding of the response of sea ice to the environment. Such understanding is, however, strongly restricted by the limited observations available in this harsh climate. In December 2019, we deployed four instruments on landfast Antarctic sea ice (69°S 76°E) a few kilometers apart to measure sea ice vertical motion, as a response to ocean waves, and sea ice drift. The instruments include two Sofar Spotter wave buoys and two low-cost open-source ice motion loggers. Nearly one month after deployment the instruments started moving after a large ice floe of approximately 15 by 20 km broke off, possibly triggered by an energetic swell event from the Southern Ocean. The instruments separated after disintegration of the large ice floe. At the end of the deployment, a Southern Ocean storm produced swell in excess of 4 m near the continent, leading to wave heights of up to 60 cm in the sea ice cover. This event was closely followed by a different low pressure system passing over the site with winds of up to 15 m/s, with instruments measuring waves of up to 2 m height. The rapid changes of the sea ice cover and energetic response to ocean waves originating from the Southern Ocean emphasises the need of continuous observations of waves and sea ice dynamics along the Antarctic continent.

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Using under-ice hyperspectral transmittance to determine land-fast sea ice algal biomass in Saroma-ko Lagoon, Hokkaido, Japan

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Sea ice, which forms in polar and non-polar areas, transmits light to sea ice algal communities. To non-invasively study the distribution of sea-ice algae, algorithms to estimate its biomass using under-ice transmitted hyperspectra have been developed in the Arctic and Antarctica but are lacking for non-polar regions. This study, for the first time, examined the relationships between normalized difference indices (NDI) calculated from the hyperspectra, and sympagic algal biomass in the non-polar Saroma-ko Lagoon. We analyzed physico-biogeochemical properties of snow and ice supporting 27 paired bio-optical measurements along three transects covering over 250 m × 250 m in February 2019. Snow depth (0.084 ± 0.011m) and ice-bottom brine volume fraction (0.21± 0.02) have low (0.06) and high (0.58) correlations with chlorophyll a, respectively. Our NDI (636 nm,607 nm) explains 69% of algal biomass variability, similar predictability was achieved using ice-bottom salinity (68%) from literature. Our estimates overlap the observed range while others are over (561%) and underestimated (91%), suggesting the necessity of the bio-optical algorithm for non-polar areas. A hybrid estimation was introduced to increase the resolution of observations and unveil algal biomass structures. This algorithm can be applied to estimate sympagic algal biomass of Saroma-ko Lagoon using moorings and unmanned underwater vehicles.

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Sub-ice platelet layer in a one-dimensional thermodynamic sea ice model

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Land-fast sea ice grows due to conductive heat losses to the atmosphere. Near continental ice shelves, where Ice Shelf Water (ISW) exists at the ocean surface, fast ice also thickens because of interaction with the supercooled water column. This ISW creates specific sea ice forms: the porous, friable sub-ice platelet layer and incorporated platelet ice. However, their large-scale distribution and seasonality are not well documented, where model representations may help to progress the understanding of their role in the functioning of the Southern Ocean. This work introduces a representation of platelet ice processes in the one-dimensional Louvain-la-Neuve Sea Ice Model (LIM1D) based on mushy-layer physics. We evaluate the approach temporally by forcing LIM1D with meteorological observations and prescribed oceanic heat flux from an over-winter study in 2009 on the fast ice of McMurdo Sound, Antarctica. We evaluate simulation spatially along a ~20-km transect sampled in November 2009, applying reported oceanic heat fluxes and showing that measured and simulated sea ice and sub-ice platelet layer thicknesses agree within uncertainty range. Sub-ice platelet layers several meters thick are observed and simulated, and simulations highlight their low thermal conductivity and high heat capacity thermodynamically decouple the ocean from sea ice. Sensitivity experiments stress the roles of the oceanic heat flux, and insulating effect of deep snow that thickens the sub-ice platelet layer. Ultimately, the model not only help to understand the halo-thermodynamics within the layer and how this controls the sympagic biogeochemistry, but allows upscaling of these processes to the Southern Ocean scale.

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Low iron availability on ice algal photosynthesis: ex situ incubation of ice algae in artificial ice using a low-Fe ice tank

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Sea-ice algae are major contributors to the primary production of polar seas and also seed extensive ice-edge blooms. In the dynamic sea ice environment, they need to continuously acclimate their photosynthetic physiology to multiple co-stressors associated with ice formation and melt (i.e., freeze up: low temperatures and high brine salinity; ice melts: sudden high light exposure under chronic Fe starvation at the bottom of pack ice). The photophysiology of ice algae was investigated in a series of ice tank experiments with the sea ice diatom Fragilariopsis cylindrus under different Fe and light regimes. When algal cells were frozen into the ice, the maximum photochemical quantum yield (Fv/Fm) of photosystem II (PSII) sharply dropped, possibly because the high brine salinity suppressed the activity of downstream components of PSII. The algae within the ice showed almost identical levels of Fv/Fm regardless of iron and light availability, indicating that the diatom was capable of optimizing their photosynthesis during the frozen period. When the ice melted and the cells were exposed to high light, Fv/Fm sharply decreased, while non-photochemical quenching (NPQ) was less upregulated in low Fe treatments. Interestingly, the psbA gene encoding PSII reaction centres upregulated under high Fe conditions and vice versa. These results suggested that Fe availability significantly affected repair rates of the damaged PSII. Our results indicate that Fe-starved cells were not able to regulate their photosynthetic plasticity to the environmental changes. Ice algae would less contribute to ice-edge blooms if prolonged Fe deficiency occurs in their cells.

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The influence of snow on landfast sea ice in Prydz Bay, East Antarctica

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The observed snow depth and ice thickness on landfast sea ice in Prydz Bay, East Antarctica, were used to determine the role of snow in (a) the annual cycle of sea ice thickness at a fixed location (SIP) where snow usually blows away after snowfall and (b) early summer sea ice thickness within the transportation route surveys (TRS) domain farther from coast, where annual snow accumulation is substantial. The annual mean snow depth and maximum ice thickness had a negative relationship ($r = -0.58$, $p < 0.05$) at SIP, indicating a primary insulation effect of snow on ice thickness. However, in the TRS domain, this effect was negligible because snow contributes to ice thickness. A one-dimensional thermodynamic sea ice model, forced by local weather observations, reproduced the annual cycle of ice thickness at SIP well. During the freeze season, the modeled maximum difference of ice thickness using different snowfall scenarios ranged from 0.53–0.61 m. Snow cover delayed ice surface and ice bottom melting by 45 and 24 days, respectively. The modeled snow ice and superimposed ice accounted for 4–23% and 5–8% of the total maximum ice thickness on an annual basis in the case of initial ice thickness ranging from 0.05–2 m, respectively.

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