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Biogeosciences Discussions

Reviews and syntheses: A framework to observe, understand, and project ecosystem response to environmental change in the East Antarctic Southern Ocean

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Abstract. Systematic long-term studies on ecosystem dynamics are largely lacking for the East Antarctic Southern Ocean, although it is well recognized that such investigations are indispensable to identify the ecological impacts and risks of environmental change. Therefore, here we develop a framework for establishing a long-term cross-disciplinary study and argue why the eastern Weddell Sea and the easterly adjacent sea off Dronning Maud Land (WSoDML) is a well suited area for such an initiative. As in the Eastern Antarctic in general, climate and environmental change have so far been comparatively muted in this area. A systematic long-term study of its environmental and ecological state can thus provide a baseline of the current situation, an assessment of future changes, and sound data can act as a model to develop and calibrate projections. Establishing a long-term observation (LTO) and long-term ecological research (LTER) programme now would allow the study of climate-driven ecosystem changes and interactions with impacts arising from other anthropogenic activities, from their very onset. Through regular autonomous and ship-based LTO activities, changes in ocean dynamics, geochemistry, biodiversity and ecosystem functions and services can be systematically explored and mapped. This observational work should be accompanied by targeted LTER efforts, including experimental and modelling studies. This approach will provide a level of long-term data availability and ecosystem understanding that are imperative to determine, understand, and project the consequences of climate change and support a sound science-informed management of future conservation efforts in the Southern Ocean.

1 Introduction

Life in the Southern Ocean (SO) significantly contributes to global marine biodiversity and ecosystem services (Kennicutt et al., 2019; Steiner et al., 2021) and is, thus, of substantial importance for the global climate, biosphere and human wellbeing (Grant et al., 2013; Cavanagh et al., 2021). However, there is growing evidence that the Southern Ocean, as are polar regions in general, is particularly sensitive to the impacts and risks of environmental change, as highlighted, e.g., in the "6th Assessment Report of the Intergovernmental Panel on Climate Change" (IPCC) (IPCC, 2021; 2022) and, specifically, in the "IPCC Special Report on the Ocean and Cryosphere in a Changing Climate" (Meredith et al., 2019) as well as the "Antarctic Climate Change and the Environment" report (ACCE) of the "Scientific Committee on Antarctic Research" (SCAR) (Turner et al., 2014). In a joint report the IPCC and the "Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services" (IPBES) assessed the impact of climate change on global biodiversity in relation to land and ocean use and predicted that the proportion of climate change related biodiversity impacts will increase in the next decades (Pörtner et al., 2021; Smith et al., 2022). Due to the vast, remote, and harsh nature of the environment in the Antarctic region, any long-term observation system requires international collaboration to establish and provide access to infrastructure and data.

Despite increased scientific interest and efforts, the scientific community has recognized major knowledge gaps regarding the vulnerability of SO biotas to anthropogenic impacts and risks, especially those driven by climate change (Flores et al., 2012: Vernet et al., 2019; Rogers et al., 2020; Gutt et al., 2021). Such information is urgently needed to develop high-confidence projections of future ecosystem changes (Kennicutt et al., 2014; Chown et al., 2017; Meredith et al., 2019; Pörtner et al., 2021;

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IPCC, 2022) and to be able to support targeted action to mitigate or prevent such changes, as also recently requested in the Southern Ocean Action Plan in support of the UN Decade of Ocean Science for Sustainable Development (Janssen et al., 2022). SCAR also supports the "Southern Ocean Observation System" (SOOS) initiative, the "SCAR Antarctic Biodiversity Portal" (biodiversity.aq) and has launched a number of scientific research programmes, such as the former "Antarctic Thresholds - Ecosystem Resilience and Adaptation" (AnT-ERA; Gutt et al., 2013a) and "State of the Antarctic Ecosystem" (Ant-ECO) programs, and the ongoing "Integrated Science to Inform Antarctic and Southern Ocean Conservation" (Ant-ICON) program (SCAR, 2022). Together, these research efforts provide the best possible international scientific basis for climate-change detection and attribution (IPCC, 2022) as well as for decision-making with respect to nature conservation in the Antarctic.

Long-term observatories (LTO) have already been established in the Arctic and Antarctic, providing valuable information on mainly climate-driven shifts in and drivers of biodiversity and biological processes. Off the West Antarctic Peninsula and in the Atlantic sector of the SO, Antarctic krill stocks (*Euphausia superba*) experienced climate-induced reduction over decades; they partly shifted southward and have partly been replaced by salps (mainly *Salpa thompsoni*; Atkinson et al., 2004; 2019; Hill et al., 2019). In addition, the Palmer Long Term Ecological Research Network (Smith et al., 2013) identified changes in pelagic food webs west of the Antarctic Peninsula (Ducklow et al., 2006), where benthic inshore biodiversity has partly increased as a result of long-term glacier retreat at King George Island (Sahade et al., 2015; Zwerschke et al., 2022). However, the trends detected in primary production and higher trophic levels are inconsistent, largely due to the heterogeneity in sea-ice dynamics that in turn depend on meteorological conditions (e.g., Montes-Hugo et al., 2009; Lin et al., 2021), with consequences for oceanic CO_2 uptake (Brown et al., 2019).

The few existing long-term studies or surveys repeated after several years in the high-latitude East Antarctic SO are mostly mono-disciplinary and opportunistic in terms of geographic and environmental setting, organism groups, and methodology. For example, over years to decades sponges and ascidians showed an unexpectedly rapid recruitment and growth but also mass mortality in McMurdo Sound (Ross Sea) (Dayton et al., 2013; Kim et al., 2019) and in the Western Weddell Sea off the Larsen ice shelves (Gutt et al., 2011). These findings were related to changing phytoplankton blooms triggered by ice-shelf disintegration and calving icebergs in combination with sea-ice dynamics and iceberg scouring (Gutt and Piepenburg, 2003; Cape et al., 2014; Dayton et al., 2019). New blooms and benthic growth spurred by regional ice shelf losses can create new carbon sinks and feedback on climate (Peck et al., 2010; Barnes et al., 2018). SCAR's circumpolar "Retrospective Analysis of Antarctic Tracking Data" highlighted "Areas of Ecological Significance" based on tracking data from 17 Southern Ocean bird and mammal species over the past 30 years (Hindell et al., 2020; Ropert-Coudert et al., 2020) and predicted a net loss of 10.2% of Areas of Ecological Significance by 2100. While the essential large-scale hydrodynamic relationships are relatively well known for this region (Fig. 1), information on current distribution, abundance and sensitivity to climate change in the Weddell Sea is only partially available for a few species (Houstin et al., 2021).

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In the eastern Weddell Sea, long-term observations at the continental margin along the Prime Meridian have identified a warming trend in deep water properties (Smedsrud, 2005). The causes remain unclear (Fahrbach et al., 2006). More recently, studies of vertical (Cisewski and Strass, 2016) and horizontal structure (Kauko et al., 2021), together with the installation of a multidisciplinary moored ocean observatory along a shelf-slope transect at 6° E (de Steur et al., 2019), revealed large interannual variability of lower trophic abundance and characteristic phenology of different bloom regimes in the region.

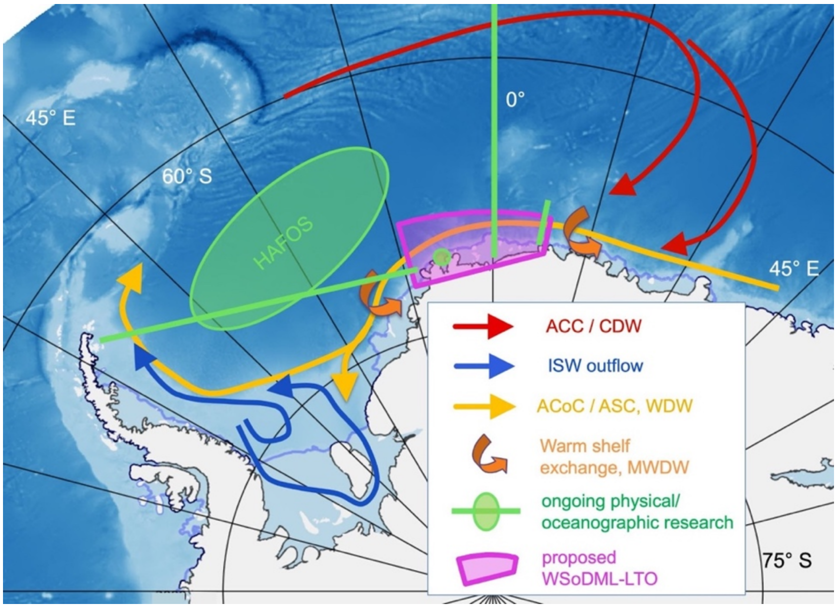

Figure 1: The location of the proposed WSoDML-LTO in the physical oceanographic environment of the Weddell Gyre and coastal current of the Southern Ocean. Arrows indicate large-scale advective pathways. ACC/CDW: Antarctic Circumpolar Current/Circumpolar Deep Water, ISW: Ice Shelf Water, ACoC/ASC: Antarctic Coastal Current/Antarctic Slope Current, MWDW: Modified Warm Deep Water. Design: Tore Hattermann. Only approximate location for the HAFOS area indicated.

Marine soundscapes of biological and physical origin have been monitored continuously since 2008 by the HAFOS (Hybrid Antarctic Float Observing System) network and the Marine soundscape monitoring throughout the Weddell Sea area by the "Hybrid Antarctic Float Observing System" (HAFOS) and near the Neumayer Station III by the "Perennial Acoustic Observatory in the Antarctic Ocean" (PALAOA) and has revealed rich marine mammal communities that fluctuate in composition throughout the year and are sensitive to environmental anomalies that may increase in frequency under future climate conditions (e.g. Schall et al. 2021; Roca et al., in press). In addition, long-term monitoring of the Emperor penguin

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colony, the cryospheric environment (sea ice and ice shelf) and atmospheric and sub-ice shelf ocean conditions is carried out at adjacent Atka Bay. Off Coats Land and off western Dronning Maud Land southwest of Atka Bay, investigations on the benthos carried out over three decades indicate trends in taxonomic composition and traits (Pineda-Metz et al., 2020), which are superimposed by variations in sampling approaches and a pronounced small-scale heterogeneity (Gutt et al., 2013b).

To address the knowledge gaps and research needs mentioned above, we propose to establish a collaborative "Distributed Long-Term Observatory in the eastern Weddell Sea and adjacent western part of the sea off Dronning Maud Land" (WSoDML-LTO), approx. between 69°S, 16° and 6°E. It should provide a platform for "Long-Term Ecological Research" (LTER) to generate reliable fact-based evidence for changes in SO ecosystems over the decades to come, and the role of anthropogenic causes driving these changes. A rigorous cross-disciplinary "biodiversity exploratories" approach (combination of observations and first-principle process studies) is particularly suited to identify, describe, gauge, understand and project the impacts of climate change in representative regions and habitats (Fischer et al., 2010). In addition, a separation of intrinsic oscillations from extrinsic trends is necessary to attribute observed variability to climate change. The WSoDML-LTO shall consist of a sensitive "change-detection" array at number of sites distributed along ecologically important gradients (DBO approach; Moore and Grebmeier, 2018), at which standardized "ecosystem Essential Ocean Variables", eEOV sensu Constable et al. (2016) and "Essential Biodiversity Variables" (EBV; Pereira et al., 2013), will be observed and compared at regular time intervals, e.g. species abundance and composition, reproduction and growth, as well as fishery and pollution pressure. A detailed system understanding is to be enhanced through downscaling approaches, studying detailed species-specific ecological demands, processes and interactions. Upscaling of results from specific sites will improve model projections, which are important for the large-scale assessments of the IPCC, IPBES and the "World Ocean Assessment" of the UN, as well as scientific advisory bodies, such as SCAR and the "Committee for the Conservation of Antarctic Marine Living Resources" (CCAMLR) and the "Committee for Environmental Protection" (CEP), both being part of the Antarctic Treaty System. Fishing in the wider Weddell Sea region is currently limited to exploratory fishing of Antarctic toothfish (*Dissostichus mawsoni*) off Dronning Maud Land. Although the intention was expressed some years ago to also conduct exploratory fisheries for Antarctic krill in this region, no krill is currently fished there. The proposed WSoDML study area overlaps considerably with the proposed "Weddell Sea Marine Protected Area" (WSMPA) and would provide an important key hub for the required research and monitoring to be carried out in the WSMPA.

Despite all the existing valuable individual findings, a comprehensive quantitative assessment of possible climate-driven and other anthropogenic ecological impacts is not yet possible for the East Antarctic SO. As a consequence, the overarching objectives of this paper are to (1) develop a framework for the proposed WSoDML-LTO, addressing urgent research needs related to environmental-changes, (2) justify its placement in the eastern Weddell Sea and western part of the sea off Dronning Maud Land (Fig. 2), and (3) describe three scientific themes addressed by LTER to be performed at the WSoDML-LTO.

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2 Overarching concept

2.1 Knowledge gaps addressed

For a comprehensive assessment of climate-change impacts and evidence-based action recommendations, the current scientific knowledge is insufficient for a number of reasons. Firstly, the impacts of climate change and other anthropogenic activities are not uniform, in space, time and across organisms (Kennicutt et al., 2014; Rogers et al., 2020). Secondly, a whole-ecosystem response to external forcing and disturbances is generally difficult to assess (Walther et al., 2002) given that environmental stress cascading through the ecosystem is non-linear. Thirdly, some modern research strategies and their implementation that address the following knowledge gaps have not yet gained sufficient acceptance:

(1) Long-term and year-round data series that allow an assessment of climate-induced changes (vs natural variability) are lacking (IPCC, 2022).

(2) Although concepts for standardized protocols, operating procedures and data integration do exist (see e.g., Miller et al., 2015; Piazza et al., 2019; Van de Putte et al., 2021) these are often ignored. They have to be urgently applied to acquire large-scale and long-term comparable biogeographic data.

(3) An integration of multi-disciplinary data derived from experiments as well as digital and genomic analyses in coupled atmosphere-ocean-cryosphere-biosphere models is still in its infancy. Such models, however, can provide deeper insights in ecosystem functioning and carbon sequestration under specific climate change and protection scenarios (Gutt et al., 2018).

(4) The impacts of multiple stressors, e.g. how climate change amplifies fishing impacts or combined effects of sea-ice shrinking, ocean warming and ocean acidification, are so far only poorly studied (Kennicutt et al., 2014; Gutt et al., 2015). They are needed for a sound understanding of whole-ecosystem functioning and to recognize synergistic effects.

(5) The awareness of the contributions of SO biotas to global ecosystem services among some stakeholders and decision makers is still insufficient to assess their value in a global context.

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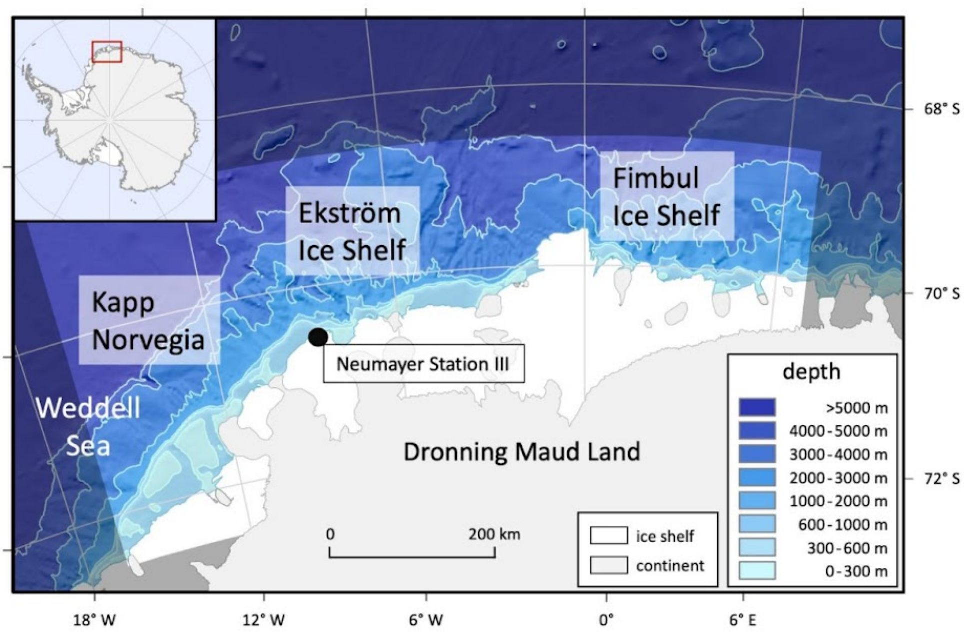

Figure 2: Location of the three areas of the proposed WSoDML-LTO, off the Fimbul and Ekström ice shelves, as well as off Kapp Norvegia. The exact positions of the survey sites (stations) within these areas have yet to be determined. Colour codes refer to the highlighted cutout; Bathymetry south of 60°S: Arndt et al. (2013); continent and ice shelf: https://www.npolar.no/quantarctica/ (last access 22 April 2022). Design: Rebecca Konijnenberg, Hendrik Pehlke, and Julian Gutt.

2.2 Geographical and environmental justification

For the following reasons, the WSoDML area is particularly suited for performing the proposed combination of LTO and LTER to detect and understand ecological changes and predict the future developments of the coupled atmosphere-cryosphere-ocean-biosphere system in the East Antarctic SO (Fig. 1):

(1) The region is characterized by high-latitude conditions of which most are typical for the East Antarctic, including a coast shaped by a glaciated land mass and ice shelves, bounded by ice rises, rumples, and small islands stabilizing the ice shelves (Matsuoka et al., 2015) but also leading to more complex circulation underneath them (e.g. Smith et al. 2020), frequent calving, transiting and grounding of icebergs, specific water masses, and high inter-annual as well as intra-annual variation in the seasonal sea-ice cover and primary production.

(2) Large-scale oceanographic features exposed to climate change are situated here (Fig. 1): being a conveyor of meridional exchange, the Weddell Gyre branches off from the westward flowing Antarctic Circumpolar Current (ACC; van Heuven et al., 2011) and converges between Gunnerus Ridge (30° East) and the Ekström Ice Shelf (8° West) with the eastward flowing

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Antarctic Coastal- and Slope Currents (ACoC/ASC) that facilitate zonal connectivity and shape the coastal environment. An overturning circulation (Jullion et al., 2014) with strong links to the carbon cycle (MacGilchrist et al., 2019) is associated with this circulation that is driven by winds and modulated buoyancy fluxes due to sea-ice melting, freezing and ice-shelf-ocean interactions.

(3) As in the East Antarctic SO (east of 20°W) in general, climate-driven changes are currently insignificant or less pronounced in the WSoDML area than further north and along the Antarctic Peninsula (Turner and Comiso, 2017). However, there is evidence for some initial changes in the East Antarctic SO (Eayrs et al., 2021). Profound and widespread climate change (IPCC, 2021), with severe ecological impacts (IPCC, 2022), is projected under all climate scenarios. Both warming (Kusahara and Hasumi, 2013) and freshening (de Lavergne et al., 2014) of coastal waters are projected in the WSoDML region, with interactions and feedbacks that may further enhance access of Warm Deep Water into the eastern (Hattermann, 2018) and southern WS (Hellmer et al., 2012; Daae et al., 2020) and melting of the Filchner-Ronne Ice Shelf (Timmermann et al., 2017) with unpredictable consequences for the marine ecosystem.

(4) Sea ice has slightly increased in extent in the East Antarctic SO over the past decades, albeit with strong interannual variations. The unprecedented springtime retreat in 2016 (Turner et al., 2017) and generally lower summer extent between 2016 and 2021/2022 (compared to a 1981/2010 mean) may indicate the onset of a circum-Antarctic decline of sea-ice volume, at roughly stable sea-ice extent (Rackow et al., 2022). Increased upwelling, probably associated with the Southern Annular Mode, is the most reasonable explanation for changes in nutrient concentrations in the upper water column in the Weddell Gyre since the 1990's (Hoppema et al., 2015). This may explain an increase in sea surface phytoplankton biomass between 1997 and 2020 (Pinkerton et al., 2021). Expected and already observed changes in the Weddell Gyre include ocean acidification and a freshening of surface and deep waters (Jullion et al., 2013). So far, the East Antarctic SO is relatively pristine also with respect to noise, pollution, fisheries and tourism.

(5) Previous studies have shown that the WSoDML area houses a variety of habitats, which are representative of East Antarctic seas: neritic and oceanic pelagic, benthic and sympagic communities, overdeepened basins (innershelf depressions), flat shelf areas, a glaciated coast, a coastline formed by floating ice shelves with an almost unstudied underside and marine seabed and ice rises underneath, inlets in the ice shelves, iceberg grounding zones, fast-ice, pack-ice, and unusually shallow banks.

(6) For an East Antarctic region, the proposed area is comparatively well explored, as it has been subject to regular marine research expeditions for over 40 years, such as, e.g., the "European Polarstern Study" initiative (EPOS; Hempel 1993), the SCAR program "Ecology of the Antarctic Sea Ice Zone" (EASIZ; Arntz and Clarke, 2002; Clarke et al., 2006) and national programs such as HAFOS and "Continental Shelf Multidisciplinary Flux Study" (COSMUS) as well as the Norwegian expedition "Mind the gap: Bridging knowledge and decision-making across sectoral silos and levels of governance in ecosystem based management" (ECOgaps). Some of the ongoing studies are summarized by de Steur et al. (2019). The data gained during these investigations will provide a valuable knowledge base, which the proposed LTO and LTER programme

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can build upon. These studies have mostly been conducted during the austral summer, and there were only a few targeting multi-year dynamics, such as surveys in the Larsen A/B ice shelf areas between 2007 and 2011, the "Benthic Disturbance Experiment" (BENDEX) starting in 2003 or the "Lazarev Sea Krill Study" (LAKRIS) expedition (2004-2008). Data from the proposed WSoDML study area (Fig. 2) were compiled as a basis for the proposal of a "Weddell Sea Marine Protected Area" (WSMPA; Teschke et al., 2020a; 2020b). Basic circumpolar biogeographic and biodiversity knowledge were published in the biogeographic atlas of the "Census of Antarctic Marine Life" (De Broyer et al., 2014; Van de Putte et al., 2021).

2.3 Scientific goals

We propose the establishment of an overarching reference LTO system in the WSoDML area that will allow comprehensive and integrated marine climate-impact studies, with great potential for trans-disciplinary and international collaboration. The WSoDML-LTO will assess the future long-term (decennia-scale) impacts of expected climatic and other anthropogenic changes on environmental (physio-chemical) conditions and the biosphere. The latter comprises the regional biodiversity, key ecosystem functions (production, export, and biogeochemical cycles), and biological adaptations (species distribution and range shifts, behavioural and phenological adaptations, physiological acclimation and genetic mutations) on, in, and at the subsurface of the sea ice, in the water column, at the sea-floor and at the underside of floating ice shelves.

The four core aims of the WSoDML-LTO and the LTER work are:

(a) Collect long-term time-series of high quality data that allow the assessment of change and variability in intrinsic and extrinsic physical, geochemical and biological processes, and inform stakeholders.

(b) Understand the processes driving temporal ecological changes and spatial habitat-turnover.

(c) Project future ecosystem dynamics with coupled physical-biological models on time scales larger than the operational period of the WSoDML-LTO to support decision making with respect to environmental protection and sustainable use.

(d) Inform and educate future generations of polar researchers

We argue that the WSoDML-LTO is urgently needed because the recent relative environmental stability of East Antarctica provides a reliable baseline for climate-related ecosystem parameters that can be used to underpin and calibrate projected biological changes caused by climatic and non-climatic drivers.

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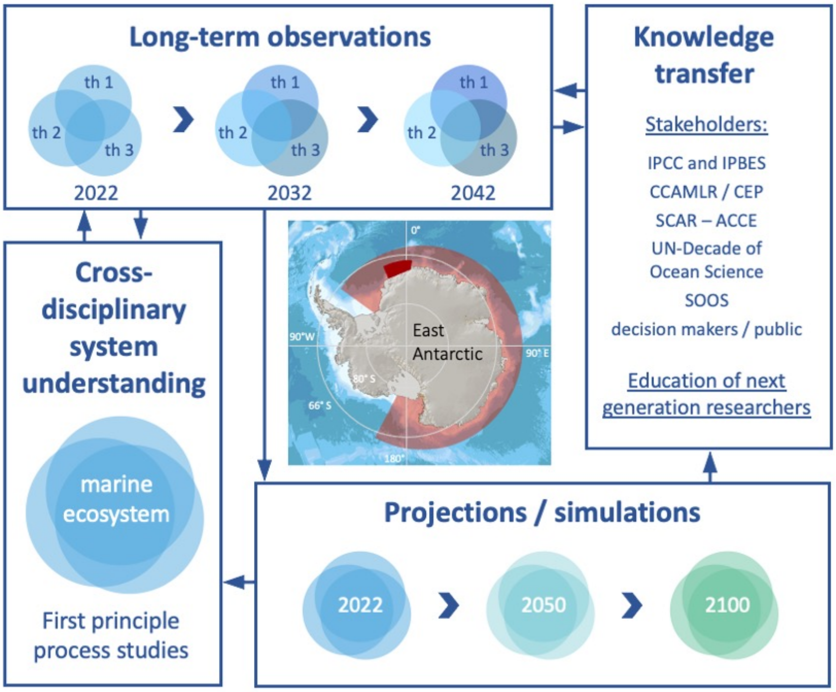

Figure 3: Relationships between approaches, objectives and potential stakeholders of the proposed WSoDML-LTO. The dark red rectangle in the map in the centre indicates where the WSoDML-LTO is proposed to be placed within the East Antarctic coastal Southern Ocean (light red, transparent). th = Ecological research theme.

2.4 Methodological approach: Observations, experiments, and models

To address the proposed objectives, a combination of observational work, experimental studies, data-integration and modelling, conducted at various spatial and temporal resolutions and scales, will be applied.

Observational work is at the core of the LTO concept, integrating data from various complementary approaches and sources (autonomous long-term in-situ monitoring, regular ship-based sampling, satellite-based remote sampling). Shipboard and autonomous data collections will take place within the three WSoDML-LTO sub-areas at water-depth transects along gradients reaching from the coastal shelf and slope, influenced by the ACoC, to the deep sea, influenced by the Weddell Gyre (Fig. 1). The actual position and size of the proposed subareas (Fig. 2) need to be defined after careful revision of environmental settings, spatial ecological heterogeneity, and detailed requirements of the proposed LTO and LTER programme. Thereby, environmental (physical and chemical) and biological information can be gained at a range of spatial and temporal resolutions, to assess changes at scales of years to decades through regular ship-based surveys but also resolve the timing of interlinked,

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strongly seasonal processes and episodic extreme events by complementing these ship-based snap-shot measurements with year-round high-frequency (hourly to weekly) observations through autonomous installations.

Along the WSoDML-LTO transects, shipboard work should be carried out at regular, if possible yearly, intervals, using standardized sampling protocols during cruises of ice-going research vessels, such as RV *Polarstern* or others. Focus of observational work should be on the systematic sampling of four types of "Essential Variables" (EVs) implemented by the scientific community: essential climate (ECV), ocean (EOV), biodiversity (EBV) and Ecosystem (EEV) variables (Van de Putte et al., 2021). This comprehensive approach would require the utilisation of a wide range of sampling methods, including casts of Conductivity Temperature Depth probes (CTD), pelagic and benthic catches and video observations (for more details see section 3 below), at fixed stations arranged in specific predefined patterns allowing for replicated sampling at different spatial scales, which is necessary to ensure temporal and spatial comparability as well as representativeness for a larger area. The shipboard work would complement the higher-resolution observations performed by autonomous systems at fewer core stations, allow for the technical maintenance of the autonomous platforms and contribute to the ground-truthing of remote-sensing and modelling studies. In addition, experimental work on specific objectives can be performed during the cruises, and top predators (seals and penguins) can be equipped with CTD-satellite trackers and biologging devices.

At few selected core stations in each of the WSoDML-LTO sub-areas, long-term in-situ observations and measurements at higher temporal resolution through autonomous moored platforms, as well as high-effort yearly shipboard sampling of EVs during the cruises, should be performed. The core stations can be placed at the centres of the LTO transects or at existing long-term observation transects (Weddell Sea/Kapp Norvegia, Prime Meridian). The platforms can include various systems, such as moorings, profilers, saildrones, sea-ice buoys, gliders, benthic landers, underwater fish observatories, and time-lapse cameras, with the potential to grow into a network of autonomous observation devices.

A research station located on the adjacent land/shelfice can be used for technical supply of underwater equipment used during shipboard work, deployment and retrieval of long-range autonomous underwater vehicles and maintenance of autonomous observatories as well as coastal cryologic studies. The use of lab facilities of the research station for experiments and routine collection of local biotas has advantages over shipboard work. The Neumayer Station III would be well suited to serve as such a base, as well as for managing the WsoDML-LTO in the Ekström Ice Shelf subarea. From the base, field work including the sampling can be conducted by means of mobile sledge-based container systems, e.g., a diving hut, an aquarium container. The ice-shelf associated fauna can be monitored by sensors and cameras attached to moorings and frozen in ice shelf boreholes. Acquired data can be sent by cable to a recording station on the surface of the ice shelf where the data storage and energy supply is located.

Remote sensing data at large spatial and small temporal scales can be easily acquired from routine satellite observations of the WSoDML area for a number of ecologically relevant variables, such as ice concentrations, types, drifts and deformation, thickness, polynya activity, and primary productivity. The systematic collection of satellite imagery can also be used to monitor penguin and seal abundance to understand how environmental stochasticity influences the distributions and numerical abundance of sentinel species (e.g., LaRue et al., 2022; see also section 3.2.3).

There are challenges regarding the realisation of the proposed LTO and LTER programme. The research equipment to be used is mostly already available, indeed, but some devices need further technical development and targeted modification, e.g., regarding autonomous long-term recording of biological data with imaging methods or the application of genomic technologies (Brandt et al., 2016). Moreover, an adequate design of the proposed replicate sampling is of crucial importance for providing representative data that can be used for spatial upscaling and the intended spatial and temporal comparisons (Jurasinski and Beierkuhnlein, 2006). Existing approaches have to be customized for the specific conditions of the study area and the type of data acquired (e.g., seabed imaging along transects). Last but not least, the extreme high-latitude Antarctic conditions have to be taken into account, since there is quite a high likelihood of time-series data losses to occur because sampling stations may not be accessible at regular intervals due to changing sea-ice conditions and autonomous platforms (moorings or landers) are lost due to collisions with drifting icebergs.

2.4 Data management

For the proposed multidisciplinary approach, with various data to be integrated into an aggregated question-driven data product, the utilization of a data management system is essential. It should address the specific properties of the Southern Ocean, be compatible in a global context and make use of existing platforms and standards. Its data, algorithms, and tools should rigorously apply the principles of FAIR (Findable, Accessible, Interoperable, and Reusable; Wilkinson et al. 2016) and TRUST (Transparency, Responsibility, User Community, and Sustainability and Technology; Lin et al. 2020) (Van de Putte et al., 2021). It should be centred around Essential Variables (EOVs, EBVs, and eEOVs), be linked to the International Polar Year (IPY data vision) and, more recently, follow the principles put forward by the Polar Data policies. Biodiversity data should follow the Darwin Core standard developed by the Biodiversity Information Standards consortium, which is also used by the Ocean Biodiversity Information System and Global Biodiversity Information Facility (Beja et al., 2021). This biodiversity standard originally focussed on information on preserved specimens but is now capable of providing comprehensive metadata and links to other forms of data such as image repositories and molecular data.

3 Three long-term ecological research (LTER) themes

3.1 The physical-chemical environment: ecosystem drivers

3.1.1 Background

At the narrow continental shelf along the DML coast, the quasi-circumpolar westward flowing ACoC/ASC converge in the WSoDML area into a coherent boundary current system (Nunez-Riboni and Fahrbach, 2009; Le Paih et al., 2020). While the interior basin is a large contiguous region of upwelling, the wind-driven downwelling over the eastern continental shelf maintains a pronounced slope front (Sverdrup, 1953; Heywood et al., 1998) that protects the glaciated coast from Warm Deep

Water (WDW), a regional derivative of Circumpolar Deep Water (CDW) that is brought southward in the eastern branches of the Weddell Gyre. Coastal waters are part of the "fresh shelf" regime (Thompson et al., 2018), where interactions with the adjacent ice shelves are controlled by a seasonal interplay between wind-driven downwelling of solar-heated surface water (Zhou et al., 2014) and cross-front exchanges of modified WDW (mWDW) at depth (Nøst et al., 2011; Hattermann et al., 2014; Stewart and Thompson, 2015).

Direct observations and estimates of basal melt rates of the ice shelves derived from satellite remote sensing yield a spatially heterogeneous as well as temporarily variable distribution of basal melt (e.g. Lindbäck et al., 2019; Sun et al., 2019). These ice shelves interact directly with the ecosystem dynamics. In particular upwelling of sediment-laden plumes as part of the overturning inside the ice shelf cavities may be a major supplier of nutrients, trace metals (iron and other bio-essential elements), as well as inorganic and organic carbon. "Cold" ice shelf cavities are usually identified by outflows of ice shelf water plumes that are colder than the freezing temperature at surface pressure, which leads to platelet and potentially marine ice formation. Due to relatively fresh and hence buoyant continental shelf water masses, formation of dense High Salinity Shelf Water is absent along the DML coast, which is the driver of a vivid ice pump and marine ice formation in other regions of Antarctica (Nicholls et al., 2009: Herraiz-Borreguero et al., 2016). However, refreezing under the ice shelf (Hattermann et al., 2012), outflow of potentially supercooled ice shelf water (ISW) (Nøst et al., 2011), as well as accretion of significant amounts of platelet ice beneath coastal landfast ice (Arndt et al., 2020) have been observed, that could play a major role in the productivity of the whole Weddell Gyre (Kauko et al. 2021).

Over the recent decades, a slight increase in Antarctic sea ice extent has been observed, with considerable spatial and temporal variabilities (Parkinson, 2019). Even though the summer sea ice minimum has been below the long-term trend in the past seven years, particularly evident in the Weddell Sea (Jena et al., 2022), the low-extent period is not yet long enough to conclude on a change in long-term trends. Overall, the sea ice modulates surface momentum and buoyancy fluxes (Zhou et al., 2014) and affects the cycling of nutrient and gas exchanges between ocean and atmosphere (Vancoppenolle et al., 2013).

Due to anthropogenic emissions, the present-day CO_2 level of 413 ppm is going to increase at an unprecedented rate (Hoegh-Guldberg et al., 2010) and is projected to reach 936 ppm by the end of this century (RCP8.5 scenario, IPCC 2014). As iron chemical speciation strongly depends on CO_2 (Liu and Millero, 2002), iron seawater chemistry will be altered under high CO_2 concentrations (Ye et al., 2020), with unknown effects for SO phytoplankton productivity (Pausch et al., 2022). There is currently insufficient data for reliable projections of the responses of Antarctic organisms to ocean acidification together with other environmental factors, such as warming, light and nutrient availability (Seifert et al., 2020). Based on field observations, the increase in atmospheric CO_2 has already turned the Weddell Sea from a CO_2 source into a CO_2 sink due to elevated storage of CO_2 in the surface layer (Hoppema, 2004). However, the CO_2 exchange with the atmosphere is not well quantified for the entire high-latitude SO due to the paucity of data, especially from the winter season (Lenton et al., 2013). Warming induced strengthening of the subpolar westerlies (Thompson et al., 2011) causes stronger upwelling of carbon- and nutrient-rich deep water (Hoppema et al., 2015; Hauck et al., 2015).

Primary production in the upper water column and the sea ice is regulated by an interplay of mostly climate-sensitive environmental factors, including the seasonal sea-ice growth and melt, water-column stratification and associated light regimes (Arrigo et al., 2008; Arrigo et al. 1997), as well as the availability of nutrients and trace elements, especially iron (see e.g., McGillicuddy et al., 2015, Morley et al., 2020). In particular, trace metal measurements across the Weddell Sea are still sparse, with evidence of low concentrations of both iron and manganese (Balaguer et al. 2022). Meteorological features (e.g., storms) can produce sudden and massive particle pulses that may cover hundreds of square kilometres of the continental shelf with the sinking of tons of organic carbon in a few days (Isla et al., 2009) and causing strong temporal variations in sub-ice shelf melting, thus increasing freshwater fluxes. Although remineralization processes in the upper water column are particularly intense in the Weddell Gyre (Usbeck et al., 2002), the organic matter that reaches the seabed is sufficient to sustain diverse and abundant benthic communities, especially in shelf regions (Brasier et al., 2021).

3.1.2 Objectives

To address the current lack of understanding of observed and expected changes in the physico-chemical environment and their impacts on biogeochemical fluxes in the marine ecosystem, we shall address the following objectives (for closely related ecosystem services see sect. 3.3):

- monitoring the shelf-slope boundary current system and slope front structure as an indicator of climate change to (a) improve process understanding and develop links to ecosystem dynamics (b) to assess the along-flow evolution and spatial connectivity of in- and outflow gateways of the eastern Weddell Sea;
- understand basin-wide and climate-sensitive changes in ice-shelf/ocean interactions such as spatio-temporal variability of basal melt rates underneath the WSoDML ice shelves and production of platelet ice;
- understand the atmosphere-sea ice-ice shelf variability and interaction, in particular drivers for pack ice and fast ice dynamics and orographic changes of the cryosphere (e.g. ice shelf freeboard height), which can impact the ecosystem;
- quantify key variables that structure the main ecosystem compartments sea ice dynamics, water mass characteristics, as well as sea floor processes and allow to separate extrinsic (anthropogenic) from intrinsic (system-immanent) impact drivers;
- assess carbon, nutrient, and trace-element cycling within and among these ecosystem compartments under current and future climatic conditions, to contribute to a better understanding of SO ecosystem functioning and their changes over time.

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To integrate the above points into a holistic understanding of the physio-biogeochemical system, co-located and coordinated observations of multidisciplinary parameters are needed at a new set of distributed nodes that are able to resolve the spatial connectivity in along-flow and across-gradient dimension. Also, existing long-term hydrographic, nutrients, iron, CO_2 and oxygen (and transient tracers) records must be continued (Fahrbach et al., 2011; van Heuven et al., 2011), while parameters and measurement as well as analysis methods need to be reassessed and adapted to allow for the detection of drivers of change (e.g., the importance of buoyancy fluxes from air/sea-ice interactions and the role of ocean eddies for cross-shelf exchange). This approach will also likely enable the detection of abrupt and extreme events (e.g., storms) and periodic mechanisms (e.g., tides; Isla et al., 2006) that may be essential for the overall energy and matter flow but are often overlooked.

The time-series measurements at the LTO shall monitor inflow and outflow of the eastern WS boundary current to enable discrimination between meridional overturning, lateral advection processes, and water mass transformations that connect local processes with the large-scale circulation. On a basin-wide scale, these data shall complement the on-going ARGO float programme in the interior WS and serve as an upstream gauge for the recently established observatories at the southern WS continental slope/shelf, beneath the Filchner Ice Shelf, and at the Antarctic Peninsula. In particular, the Kapp Norvegia area is a key location for observing the evolution downstream of the open ocean (Kauko et al., 2021), fast ice and under ice shelf observatories at Fimbul Ice Shelf (Hattermann et al., 2012), and for monitoring changes that are expected to affect much of the southern WS. The LTO stations in the coastal Ekström area shall complement with on-going long-term observations of the fast ice-shelf ice-ocean interactions (including regular measurements of fast ice properties, the water column beneath and the basal/surface mass budget of the adjacent shelf ice) and PALAOA in Atka Bay and at Neumayer Station III, adding to the understanding of the impact of ice shelf-ocean interactions in the eastern WSoDML coast. Moreover, Neumayer Station III shall provide an in-reach laboratory for process studies, in particular when combined with long-term moorings beneath the ice shelf that are currently under development.

3.1.3 Methods

The major observing systems shall combine fixed moorings, drifting sea-ice observatories, benthic observatories, autonomous underwater vehicles (including gliders), regular ship-based observation work and satellite-based remote sensing. These will be complemented by atmospheric, biological, cryospheric and oceanographic LTO infrastructure at and in the vicinity of Neumayer Station III. Long-term moorings shall be equipped with sediment traps, and sensors for monitoring transport, bottom water characteristics, WDW interface depth, and the upper ocean buoyancy budget as well as biogeochemical parameters, e.g. dissolved O_2, turbidity, pCO_2, photosynthetically active radiation, and pH, fluorescence (as a proxy for chlorophyll and phytoplankton abundance) and other in-situ tracers. Optical sensors will be used to measure nitrate and Colored Dissolved Organic Matter. It is also envisaged to make use of the promising recent development of Lab on Chip sensors for assessing Dissolved Inorganic Carbon, pH, nitrate, phosphate, iron (Nightingale et al., 2015). Active acoustic techniques shall be used to determine depth profiles of currents, zooplankton and fish abundance. In addition, bio-optical platforms equipped with

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particle cameras and gel traps shall collect sinking particles to assess the flux of organic matter from the mixed layer to the seafloor.

For sea-ice monitoring, upward looking sonar and acoustic Doppler current profiler (thickness and ice drift velocity) at the backbone moorings shall be combined with fixed electromagnetic induction (EM) stations and monitoring of optical properties and relevant biogeochemical properties through fast ice. Drifting ice-moored autonomous observatories will provide data on biogeochemical properties of sea-ice and the water column, zooplankton and fish distribution during their drift through the Weddell Gyre. Repeated airborne EM and broadband radar grids shall provide coincident snow and ice thickness and roughness information and quantify sea ice accretions, to characterize ice regimes of first- and second year sea ice of different origin. Ice/ocean buoys shall provide year-round time series of meteorological parameters and air/sea-ice/ocean interactions in a larger geographical context, covering an extended set of "Essential Climate Variables" (Lavergne et al., 2022), as well as ocean-surface stress and ocean-surface heat flux to support the interdisciplinary concept of the WSoDML-LTO. Benthic geochemical observatories shall complement the moorings, equipped with a similar suite of sensors to monitor conservative and reactive compounds in the nepheloid layer as well as currents. Benthic oxygen fluxes shall be determined using eddy covariance technology and repeated sediment O_2-profiling.

Open ocean observations of cryospheric components will be complemented by stationary observations of the sea ice LTO in Atka Bay (monthly records of snow-cover, sea-ice and platelet-ice layer thickness), including sub-sea ice ocean properties from manual CTD casts. LTO of glaciological characteristics (snow accumulation, snow-water equivalent, sub-ice shelf melt) will be available from several sites on the Ekström Ice Shelf, in continuous to bi-weekly resolution. To improve continuous data coverage of near-coastal ocean properties, a mooring should be deployed underneath the Ekström Ice Shelf.

Satellite-based remote sensing shall be used to determine sea-ice variables (extent, concentration, thickness, snow cover, drift, age, surface temperature, surface albedo), sea surface temperatures, glaciological variables (surface elevation, ice-flow velocity, basal melting, total mass balance, calving), the spatio-temporal distribution of pelagic primary producers (chlorophyll), and to systematic monitoring of seal and penguin population abundances and distributions.

Shipborne air-chemistry and autonomous remote particle concentration measurements are also desirable. They can be tied to the data from the Neumayer air-chemistry LTO. Ship-board measurements will also allow the ground-truthing of the automated systems, ad-hoc experiments and field studies. The latter encompasses CTD transects and concurrent sampling for radiotracers, trace metals and nutrients.

At the seabed, observations and samplings shall be conducted at LTO station with grabs and corers to assess benthic-pelagic coupling processes (e.g., seasonal deposition and degradation of labile organic matter), sediment redox cycling, and early diagenetic processes using rate measurements, as well as biomarker and stable isotope analysis. Sediment traps shall enable the determination of the dynamics of sinking rates and the relative importance of different types of particles at various scales of time. Benthic geochemical observatories shall complement the moorings, equipped with a similar suite of sensors to monitor

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conservative and reactive compounds in the nepheloid layer as well as currents. Benthic oxygen fluxes shall be determined using eddy covariance technology and repeated sediment O_2-profiling. For additional methods to acquire biological data also in the context of the flux of energy and biomass see sect. 3.2.3.

3.2 Organisms and ecosystems – adaptations, biodiversity and ecosystem functioning

3.2.1 Background

The anticipated sea-ice decline and changes in the water column (Moline et al. 2004; Trimborn et al. 2017; Eayrs et al. 2021) are expected to affect primary production and zooplankton composition, whose shifts in biomass and species composition will have so far largely unknown implications for the entire SO food web including top predators and the benthic system (Atkinson et al. 2004, 2019; Flores et al. 2012, Hill et al. 2019, Böckmann et al. 2021). In general, all organisms being part of the different trophic guilds respond to environmental changes by migration, extinction or they cope with the changes through phenotypic plasticity and genotypic adaptation through natural selection. The underlying genetic architecture of organismic adaptation is responsible for shifts in the ecological niche width of a species under the new conditions. Comprehensive process studies, which relate transcriptomic/proteomic responses and threshold temperatures to long-term ecophysiological parameters including growth performance (Windisch et al. 2014), are lacking so far for key species in the high latitude SO. Such studies would facilitate long-term objectives of establishing the missing link between the genotype and phenotype (Oellermann et al. 2015) and of understanding the role of population structure and temporal variation for the adaptability to environmental change (Lancaster et al. 2016).

The adaptation of single species to their environment, and, therefore, changes in their physiological and behavioural performances, has consequences for species interactions, the biodiversity and functioning of communities (Gutt et al., 2018). This includes competition, predator-prey relationships and responses to disturbances including extreme events in sea-ice dynamics, by iceberg calving and scouring, spatio-temporal shifts in water masses or weather-driven mass occurrence of phytodetritus at the sediment surface (Sañé et al., 2012).

It is generally known that biodiversity drives ecosystem functioning (BEF), such as productivity, energy transfer and remineralization (Naem et al., 2012), including the effect of biodiversity on ecosystem stability. So far, the BEF relationship and its climate-sensitivity are virtually unknown for high-latitude SO pelagic and benthic systems, although such knowledge is essential to predict and understand developments in ecosystem structure and function in response to climate and other environmental change. Also, our knowledge of whole-community vulnerability or robustness is still very poor, especially for the slow-growing and immobile epibenthos (Gutt et al. 2018), which cannot respond to rapid environmental changes with immediate shifts in spatial distribution (Isla and Gerdes, 2019) but provides with its three-dimensional architecture specific micro-habitats for a rich associated fauna.

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Although population sizes have been estimated for emperor penguins (*Aptenodytes forsteri*) (Fretwell et al. 2012) and Weddell seals (*Leptonychotes weddellii*) (LaRue et al. 2021) based on satellite images, for most Weddell Sea meso- and top-predator species population sizes are still unknown (Gurarie et al. 2017, Richter et al. 2018), restricting our ability to determine population health and trends as well as predator responses to climate change. Filling this gap is especially important because the wider proposed area of investigation is a foraging ground for five Antarctic phocid seal species and penguins (McIntyre et al. 2012, Bester et al. 2020, Wege et al. 2021a).

3.2.2 Objectives

The proposed time-series observations of biodiversity and ecosystem variables, to be conducted in parallel with physical-chemical parameters (see Theme 1 above), will address the following objectives:

- identify key species, assemblages and functional groups (ecologically important, all trophic levels, all major habitats, covering other important traits, such as population size, and reproduction, mortality and growth rates as well as competition) for monitoring as preparation for the LTER;
- assess the adaptive and acclimatory scope of ice-associated, pelagic and benthic key species: genetic diversity, ecophysiological plasticity, adaptive strategies and capacities, spanning the whole life-cycle over several generations;
- determine changes in spatial distribution of selectively neutral and adaptive alleles (e.g., stress response) in populations of vulnerable species (genomics, transcriptomics);
- determine changes in species spatial distribution and foraging habitats compared to known distributions and calculated Areas of Ecological Significance (Hindell et al., 2020);
- evaluate taxonomic and functional biodiversity of ice-associated, pelagic and benthic biota, encompassing a wide range of organisms from microbes to top predators and identify Areas of Ecological Significance based on species in addition to top predators;
- identify and understand relationships between biodiversity and ecosystem functioning including climate feedbacks, such as energy flow, production, and species interactions;
- assess robustness or vulnerability of WSoDML ecosystems and the impact of multiple drivers with respect to anthropogenic changes in biodiversity (including the establishment and spread of non-indigenous species).

Comprehensive knowledge on the structure and functioning of genes is the basis to assess the role of individuals in their population, community or ecosystem. In cases where not (yet) the entire species-specific ecophysiology can be studied by biomolecular "-omics" studies, whole organism in situ or in vitro experiments can provide valuable insights (Strobel et al., 2012). Therefore, the proposed LTER work will survey ecophysiological parameters, gene expression and life cycles of ecological key taxa, such as phytoplankton, crustaceans (e.g., copepods, amphipods, euphausiids), fishes (mostly

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notothenioids), echinoderms, molluscs and selected sessile suspension feeders. All such studies aim to determine the environmental plasticity of single organisms and species with their intra- and inter-specific variability and validate the results from experiments or single-species models (Somero, 2010). The results will allow understanding of the complex environmental conditions under which organisms can persist or become locally extinct.

The presence of reliable ice cover is crucial for the reproduction of ice-breeding pinnipeds and emperor penguins and as a potential winter retreat for some species, e.g. Antarctic minke whales (Filun et al., 2020). Polynyas also play a major role as foraging areas (e.g. Malpress et al., 2017; Labrousse et al., 2018; 2019). For other meso- and top-predator species, availability of ice-free surface for breeding and access to productive foraging grounds are the key long-term population drivers (Younger et al., 2016). The logistical challenges of systematic long-term in-situ data collection are limiting our understanding of habitat use by top predators and their prey for many parts of the SO, including the continental slope areas, home to adult Antarctic toothfish. The multi-disciplinary character of the proposed WSoDML LTO allows the combination of remote sensed population assessments (e.g. Richter et al., 2018; Gonçalves et al., 2020; Wege at al., 2020, 2021b; LaRue et al., 2021; 2022) and continued studies of distribution, foraging ranges and behaviour (*cf.* Hindell et al., 2020; Houstin et al., 2021) as well as passive acoustic monitoring studies of SO top predator species (Van Opzeeland et al., 2010; Thomisch et al., 2016; Schall et al., 2021) related to key environmental features (e.g. Oosthuizen et al., 2021; Wege et al., 2021a).

The fundamental BEF relationship shall be investigated in detail to assess ecosystem stability versus vulnerability for the given biodiversity. For instance, analyses shall be carried out on whether a possible decline in species richness affects primary production, energy transfer and nutrient recycling through changes in functional redundancy at a community level. An increase in ecosystem functions (e.g., primary and secondary production) with decreasing biodiversity might be expected if fast-growing species (e.g., "pioneers") become dominant. Regional biodiversity may also increase with a shift towards less polar conditions, if sub-Antarctic species (e.g. Patagonian toothfish) immigrate into the WS displacing native high-Antarctic benthic species (e.g. Antarctic toothfish) (Griffiths et al., 2017). However, high Antarctic species can show high eurybathy and thus may preserve their climate envelopes by migrating deeper (as may have been done in the past, see Barnes and Kuklinski, 2010) aided perhaps by boosted primary production mediated by sea-ice losses (Arrigo et al., 2008). Mobile pelagic species are foraging and travelling further southward from their sub-Antarctic island colonies to forage at the ice-edge of Southern Ocean waters, increasing competition potential with Antarctic species (Cristofari et al., 2018; Péron et al., 2012; Krüger et al., 2018; Reisinger et al., 2022). These objectives demand investigations of patterns and processes of biodiversity in all their facets, such as species richness, evenness, functional diversity, dispersal, reproduction (including brood care of icefish, see Purser et al., 2022), recruitment, growth and mortality, as well as abundance and biomass. Analyses of such species-specific key traits, shall be linked to "first principle" process studies to understand the relationship of the sympagic, pelagic and benthic communities, including apex predators, with ecosystem functions and services (see section 3.3). Moreover, the effect of different spatial scales shall be taken into account, since reduced local biodiversity can lead to a higher spatial species patchiness and higher temporal species turnover with yet unknown consequences for ecosystem stability, resilience and function.

3.2.3 Methods

Information on key taxa will be collected across the spatial scales of the LTO (Fig. 1) by means of various methodological approaches and in parallel to the flux studies (see section 3.1). Phytoplankton and pelagic primary consumers, such as krill, copepods and young fish larvae, as well as secondary consumers, such as the Antarctic silverfish *Pleuragramma antarctica*, shall be studied by CTD and rosette casts and pelagic net catches, to assess species composition, abundance, population parameters and feeding condition, and compared with data provided by acoustic systems. The proposed benthic surveys shall primarily be conducted by means of minimally invasive methods (e.g., traps, corers, autonomous seabed and under-shelf ice sampling and acoustic as well as optical imaging, and scientific long-line fishery), to minimize the anthropogenic impact of invasive sampling methods (e.g., bottom trawls).

Higher-order predator studies will be continued by the instrumentation of animals with CTD-satellite trackers and biologging devices (e.g. Nachtsheim et al., 2019; Houstin et al., in press) as well as physiological and nutritional studies. Population estimates and habitat distribution (e.g. Wege et al., 2021b; LaRue et al., 2021) of seal and penguin populations will be monitored using airborne as well as Very High Resolution satellite imaging including autonomous year-round observations (Richter et al., 2018; Fretwell and Trathan, 2021). Images will focus on locations representative for the core stations established at regular intervals. Both biologging data and VHR imagery data can be used to determine critical habitats. As more data become available, we can project distribution changes of these core habitats into the future using climate modelling (e.g. Reisinger et al., 2022). Oceanographic conditions at emperor penguin foraging hotspots will be studied using autonomous underwater vehicles that can be deployed from Atka Bay by actively following satellite tagged specimens. Passive acoustic monitoring data will be used for larger spatio-temporal scale soundscape studies (Menze et al., 2017) and to investigate how marine mammal occurrence relates to fluctuations in their ice-dominated habitats.

However, recurring sampling and archiving of organisms suitable for molecular analysis (e.g., every five years) shall also take place to ensure ground-truthing of non-invasive methods. A concept shall be developed, which allows a sound identification of ecological key species or functional groups and addresses the limitations of resources (time, taxonomic experts, sorting efforts). Using molecular (meta) barcoding, cryptic species shall be identified. Imaging surveys will allow for detecting shifts in benthic community composition, species traits, interactions, diversity, biomass and size structure of populations. Existing semi-automated analyses of such images by deep-learning networks (see e.g., Schöning et al., 2012) shall be adapted and improved for analysis of SO benthos. The analysis of eDNA allows especially whole-community changes in biodiversity and potential changes therein. Quantitative information on all benthos fractions is important to separate short-term remineralization from long-term burial of carbon and other nutrients.

The advent of high-throughput next-generation sequencing methods brought cost-effective analysis of multilocus molecular markers into reach that are complementary to approaches centred around presence and absence of species. By comparing the response of several thousand genes from the transcriptomes we want to detect an organismic response that may be too weak to be expressed in a single gene and detect shifts in populations forced by changing environmental factors even along the evolutionary short monitoring time.

Once observational and analytical baselines have been established, advanced experimental field studies (e.g., in situ respirometry, http://www.mbari.org/emerging-science-of-a-high-co2low-ph-ocean-deep-water-foce/, last access: 22 April 2022) and long-term video observations of local key species and assemblages within their natural habitats and a focus on interactions could follow. In combination with on-site laboratory experiments (e.g., at the Neumayer Station III), they will help to unravel life-history strategies, life stage-specific spatial and temporal distributions and their adaptive scope over generations. As technology continues to develop, internal and external data loggers suitable for smaller marine organisms such as fish, audio-visual loggers to study foraging behaviour of predators, long-term tracking of their preferred water temperature and depth, but also of physiological parameters, such as heart rate, blood flow and tissue oxygenation, shall come into reach. Semi-permanent moorings and lander systems (see theme 1, section 3.1) shall serve as a (power) base for those applications and allow for controlled deployment of traps and other gear. Otoliths of fishes can be used as an archive of temperature preference and utilized resources in fishes.

The pelagic community will be sampled with an ultra-clean CTD and under-way filtration systems for phytoplankton, Rectangular Midwater Trawls for plankton and nekton and multinets and imaging zooplankton profilers for the mesofauna. Net catches will be used to ground-truth biomass and community data derived from continuous sampling with multi-frequency broadband echosounders as well as from autonomous observatories equipped with echosounders. The community under the sea ice will be sampled using under-ice trawls (Flores et al., 2012), and the sympagic in-ice community composition will be investigated on ice stations by ice core sampling using both molecular and morphological techniques (Miller et al., 2015).

Trophic relationships including match-mismatch phenomena are to be studied by a variety of methods such as, analyses of gut content, of tissues for storage lipids and isotope ratios, gonads for maturity, and entire specimens for condition factor, indicating their general health.

3.3 Ecosystem services and human impacts

3.3.1 Background

The ecosystem services framework (ES; denoting the benefits that people obtain from ecosystem functions, also called *Nature's Contributions to People* to compensate for negative effects, Díaz et al., 2018) have received increased attention from stakeholders during recent years. This framework aligns economic considerations with nature conservation and thereby addresses diverse and powerful questions (Simpson, 2011). However, the quantification of ES is one of the greatest challenges of current ecosystem science (Burkhard et al., 2012), especially due to the spatial and temporal variability of ecosystems,

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particularly in the marine domain (Barbier, 2007). This challenge is aggravated by the fact that many seascapes are under-represented in global assessments (e.g., TEEB, 2012), and not yet the subject of any detailed SO regional ES assessment (Grant et al., 2013). The fact that most ES provided by the oceans, particularly by remote marine areas, seldom have on-site beneficiaries adds to the complexity of the topic. For instance, markets for Antarctic fisheries products, such as toothfish, are mainly in Japan and North America (Catarci, 2004); also the introduction of a payment for ecosystem services (PES) has been discussed for Antarctic tourism (Verbitsky, 2018).

Regulating ES provided by the SO including the WS are also beneficial to human populations on a global scale, e.g., regarding climate regulation, sea-level rise, carbon sequestration, oxygen production, and natural genetic heritage and biodiversity (Deininger et al., 2016; Pertierra et al., 2021; Steiner et al., 2021). The proposed LTO and LTER programme shall primarily contribute to a better understanding of core ecosystem functions and services with regard to two aspects: refined carbon sequestration budgets and consequently, contrast direct human impacts (fishing) with conservation efforts.

A meta-analysis revealed that ocean acidification could negatively affect autotrophic organisms, mainly phytoplankton, at CO_2 levels above 1,000 µatm and invertebrates above 1,500 µatm (Hancock et al., 2020). Hence, Antarctic organisms are likely to be susceptible to ocean acidification and thereby likely to change their contribution to ecosystem services in the future.

The SO, especially the coastal parts, has the potential to be a strong sink for anthropogenic carbon (Arrigo et al., 2008), but it is a highly dynamic and heterogeneous region (Gutt et al., 2013b; Tagliabue and Arrigo 2016, Jones et al. 2017) that is poorly sampled along large areas (Arrigo et al., 2015). The supply of iron is considered to control how much CO_2 is biologically fixed by phytoplankton. There is, however, a lack in knowledge on the magnitude and the importance of different iron sources on phytoplankton productivity, including melting of sea ice and icebergs, dust deposition and Fe recycled by different grazers, with changes to be expected in the future (Trimborn et al., 2017; Böckmann et al., 2021). Furthermore, models of the present-day export production and CO_2 uptake disagree on the processes that lead to the export of organic carbon today, let alone in the future (Laufkötter et al., 2016). These deficiencies in our understanding of biological processes induce large uncertainties in projections of primary production (Frölicher et al., 2016) and the future of the oceanic carbon sink, thus hindering the quantification of an important ES from the SO. Research on carbon sequestration is closely linked to research on ecosystem functioning; as a result, this research theme overlaps partially with sect. *3.1 The physical-chemical environment: ecosystem drivers*.

The WS is the last SO area where, to date, no or only limited fishing has taken place. Commercial krill fisheries are concentrated around the Antarctic Peninsula and the Scotia Sea, where krill abundances are much higher than in the southern and eastern WS (Atkinson et al., 2019). Adult Antarctic toothfish are demersal top predators, which can grow to over 2 metres in length and reach over 50 years in age. Over almost the last 20 years, longline exploratory fishing for Antarctic toothfish has been carried out on the continental slope in the CCAMLR Statistical Area 48.6, i.e., off the ice shelf where Neumayer Station III is located and further eastwards (Teschke et al., 2016). The climate-sensitivity of these fish populations (Cheung et al.,

2008) and of the marine ecosystems and food webs they are part of is a main reason for the plan to establish an MPA in this region (Fig. 4). In terms of conservation of biodiversity, special attention has to be paid to rare habitats, since they are especially vulnerable, e.g., a poorly researched polar marine domain: the underside of ice shelves and floating glacier tongues or the unusually shallow and especially diverse Norsel Bank in the Kapp Norvegia area.

A hierarchical classification of benthic biodiversity has been carried out in the context of assessing protected areas in the Southern Ocean (Douglass et al., 2014), but in general, an understanding of the mechanisms driving observed or projected changes, including the role of the relatively high benthic biodiversity for the stability of the entire system, remains largely unknown.

3.2.3 Objectives

The objectives to quantify carbon sequestration as a major ecosystem service and protect the conservation of the ecosystem functioning and services of the WS and DML coast are as follows:

- Quantify the carbon sink, its change, and drivers and temporal change in the WSoDML LTO region by analysing the biologically- and physically-mediated transport of carbon from the surface to sediments and oxygen production through primary production.
- Develop a robust understanding of biogeochemical processes from interdisciplinary high-resolution time-series data, which may also be used for model evaluation and development.
- Identify key taxa responsible for the carbon and nutrient transfer, especially for carbon export, storage and remineralization to improve projections developing future scenarios.
- Develop strategies to protect species assemblages based on the knowledge of key species and rare, unique, highly diverse or endemic habitats including essential habitats for top predators.
- Provide the scientific basis to protect environmental features and species (including their populations and life history stages) on various geographical scales, which are key to the functional integrity and viability of regional ecosystems processes.
- Establish scientific reference areas to monitor the effects of climate change, fishing and other human activities.
- Protect potential refugia for, inter alia, top predators, fish, other ice-dependent and highly cold-adapted and sympagic species, to support their resilience and ability to adapt to the effects of climate change.

The proposed LTER efforts shall provide the opportunity to study the year-round carbon flux into and out of the mixed layer and by sediment traps in relation to meteorological (e.g., wind) and biological drivers (primary production and composition, abundance, growth, metabolism, as well as mortality of key grazers).

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The proposed LTO system and LTER work would aid in providing an estimate of the biological carbon sink structure and, thus, of the sequestration of CO_2 from the atmosphere for hundreds to thousands of years. This would include baseline and variability in carbon capture, storage and sequestration components by the sinking of faeces and phytodetritus, include potential changes in the eastern WS region (such as climate change feedback strength), and contribute to a circumpolar assessment. The LTER shall separate the physical from biological processes that lead to a transfer of carbon to the ocean interior and seabed. The carbon flux to the sea floor further determines the redox state of sediments and is positively correlated with the efflux of nutrients and iron (Graham et al., 2015). This positive feedback is pronounced in shallow shelf seas where vertical pathways are short and where pelagic-benthic coupling triggered by sedimentation events is enhanced. At least some benthic suspension feeders have significantly increased benthic carbon and silicate storage on the seafloor of the proposed area of investigation over the last two decades (Gutt et al., 2013c; Barnes, 2015) and contribute to the remineralization of organic matter to be further quantified. Resulting data shall provide the basis for the development and validation of regional biogeochemical budgets and models (e.g., carbon). They will also allow changes in the efficiency of carbon export to deeper waters, benthic carbon supply, as well as the fate of other nutrients and the role of the planned study sites being representative for the mostly ice-covered high latitude SO as a potential carbon sink to be assessed (see also sect. 3.3).

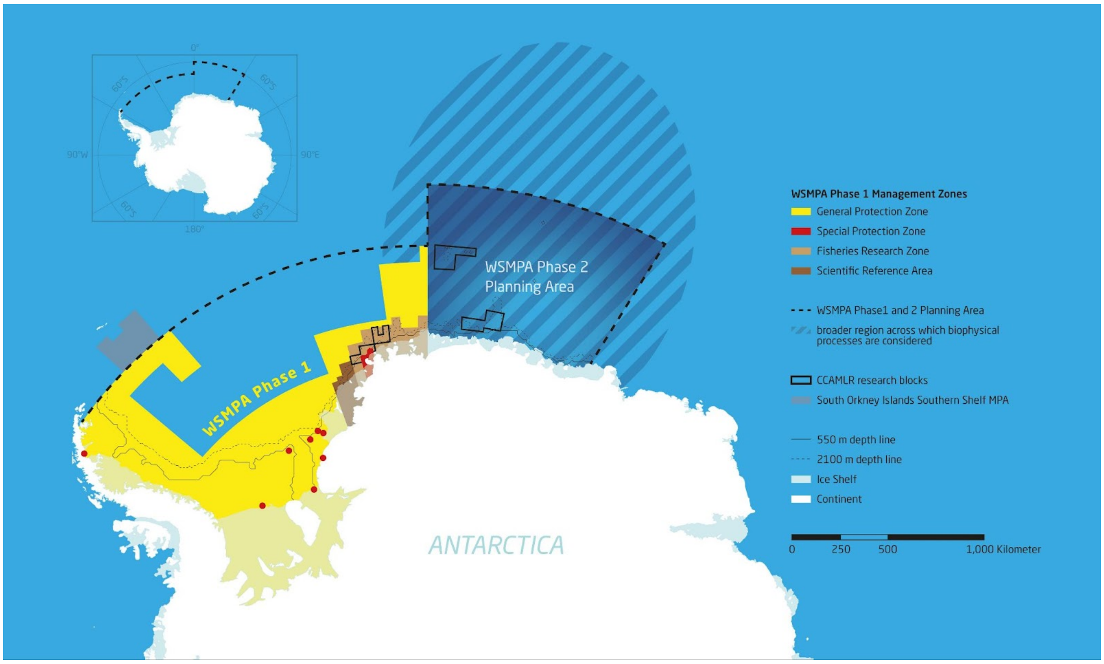

Figure 4: Proposed area for Weddell Sea Marine Protected Area Phase 1 and Phase 2. From: AWI Factsheet Weddell Sea: 8 Reasons for a Marine Protected Area (https://www.awi.de/fileadmin/user_upload/AWI/Ueber_uns/Service/Presse/2016/4_Quartal/KM_Weddellmeer_MPA/WEB_DE_Factsheet_Weddellmeer.pdf, last access 22 April 2022). Map design by Yves Nowak, AWI.

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With reference to the proposed WSMPA, the LTO shall provide the focal point for the necessary research and monitoring activities required and is important for the regular review of the effectiveness of the WSMPA. After the adoption of the WSMPA by CCAMLR, the proposed LTER work shall provide research-based long-term data on the natural development of the protected environments and biota in the eastern WSoDML coast. It shall also provide insight into the biology and life cycle of Antarctic toothfish, which, together with information obtained by longline fishing vessels, will improve the understanding of the role of this species in the food web. In addition, the LTO will be the ideal base to study effects of Antarctic toothfish fisheries on benthic habitats and food webs by comparing fished with unfished areas.

3.3.3 Methods

In the course of the proposed LTO/LTER work, sea-surface pCO_2 in a coastal Antarctic region shall be monitored with hourly resolution. Based on these data, the carbon sink in the region can be estimated. The estimates of physical and biogeochemical carbon transport shall be based on the interdisciplinary approach described above. The continuous time series at high-temporal resolution (hourly for sensors, biweekly for sediment traps) shall be used for the evaluation of global and regional biogeochemical models. The gained process understanding shall be used to improve parameterizations of biogeochemical processes in models, e.g., the mechanisms that lead to the formation/disaggregation of sinking particles. Recovering sediment cores will allow monitoring benthic remineralization rates and nutrient efflux in relation with benthic fauna composition enabling the estimation of changes in the upward mixing of essential nutrients.

Once the Weddell Sea MPA has been approved, the development and implementation of a detailed research and monitoring plan is a task for the CCAMLR members. The research and monitoring activities would be carried out in the WSoDML LTO area, used or supported by the LTO infrastructure (see sects 3.1 and 3.2), e.g. by monitoring the temporal variability of benthic fauna with time lapse cameras. In addition, scientific long-line fishing should be carried out in areas designated for this purpose. Advanced ecological spatially explicit and dynamic modelling including biotic and abiotic interactions will allow an assessment of disturbances and environmental changes including ES. A major challenge in such ecological modelling is that on the one hand a spatial resolution must first be found that takes into account the limitations of physical projections in downscaling approaches and on the other the small-scale nature of biological patterns.

4 Added value

4.1 International integration

The ecological complexity to be tackled by the proposed LTER demands and provides the potential for extensive international collaboration, since the complete portfolio of research cannot be studied otherwise. The planned WSoDML-LTO will also complement the work of similar observatories in the maritime Antarctic (e.g., Palmer LTER off the western Antarctic Peninsula) and in other regions in the high-latitude SO. Inter-comparability of methods and data among various LTER efforts

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would be a priority in the implementation of the planned activities in the WSoDML-LTO. In addition, this LTO can serve as a exemplar project within the initiative Southern Ocean Observing System (SOOS; Rintoul et al., 2012; Newman et al., 2019). Both the need of long-term observations, measurements and analyses as well as studies for a better system understanding have been identified during the community driven "1st Antarctic and Southern Ocean Horizon Scan of the Scientific Committee on Antarctic Research" (SCAR) as priority for future research directions (Kennicutt et al., 2014). The WSoDML LTER can significantly build upon the recently ended SCAR biology programs AnT-ERA and Ant-ECO as well as the ongoing program Ant-ICON and benefit from their networks of communication between experts. Moreover, a WSoDML LTER initiative would underpin the efforts within CCAMLR to establish a Weddell Sea MPA (Teschke et al., 2020). It would provide key reference sites to establish the required research and monitoring plan of the proposed MPA and enrich national research programs. All data acquired during the WSoDML LTO and LTER work will be stored in international data centres, with an either general scope or maintaining specific information for standard analyses. For example, surface pCO_2 data will be submitted to the annual updates of the Surface Ocean CO_2 Atlas (SOCAT) (Bakker et al., 2016), which is widely used for studies on regional and global scale. SOCAT informs the Global Carbon Project for its annual update of the Global Carbon Budget. Biogeographic and biological trait data are usually made available by "The SCAR Antarctic Biodiversity Portal", whilst a broad variety of other ecological data is to be uploaded to "Data Publisher for Earth and Environmental Science" (https://www.pangaea.de, last access 22 April 2022). Genetic and biodiversity data can further be stored in the "Barcode of Life Data System" database.

The Southern Ocean and Antarctic continent are managed within the framework of the *Antarctic Treaty System*, which is based upon scientific understanding and environmental protection. Some of the societal needs and challenges may overlap with a global context while others are and will remain unique (Van de Putte et al., 2021).

In general, all information, including data and their interpretation will contribute to the output of international scientific assessment programs such as IPCC and IPBES and other advisory bodies (Fig. 2).

4.2 Synergies

The LTER at the WSoDML-LTO will provide a unique opportunity to collect a comprehensive set of physical, geochemical and biological key data, eEOVs and EBVs, from all three main marine ecosystem compartments: sea ice, water column, and sea floor on a regular basis. It will employ a highly cross-disciplinary approach, integrating various research fields to gather physico-chemical information about marine environments, their exchange with other Earth system compartments, and investigate biological and ecological processes over a wide range of scales from biomolecules to organisms to ecosystems, weeks to decades. Importantly, the integration of the research needed for the proposed WSMPA and the WSoDML LTER would bring fisheries scientists and marine ecologists together, with experts from all the CCAMLR member states to explore the benefits of cross-science approaches and international collaboration.

The scientific work in the WSoDML-LTER being representative of the Antarctic Coastal Current (ACoC) in combination with the Weddell Gyre will benefit from the fact that this area has already been sampled for decades. For example, Fimbul is the

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southernmost part of the long-term hydrographic repeat section along the Prime Meridian between South Africa and Antarctica, and the eastern part of a hydrographic transect through the entire WS that starts off the Kapp Norvegia (Fig. 1). An added value of the proposed LTER would be the coordinated and integrated ecological program in the eastern SO applying standardized protocols for the sampling of material, analyses and observations to make the results directly comparable with comparative studies over space and time. On a wider geographic scale, LTER in the eastern WS and DML coast can be integrated into research performed in the Filchner-Ronne region in the southernmost WS and the above-mentioned three hydrographic transects in their entire lengths far to the North and West, respectively. Moreover, comparisons will be possible between the WSoDML-LTO areas and the ecosystems east and west of the Antarctic Peninsula, which are already being drastically impacted by climate-induced warming, sea-ice decline and glacier retreats, and still more stable sites in East Antarctica.

The proposed program would also be well suited to raise the awareness of the public, including school classes, for a healthy marine biosphere. It would provide perfect opportunities for education and training of the future generation of polar researchers generating opportunities for data analyses and thematically targeted fieldwork, which provides results being highly relevant to society.

5 Conclusions

A major conclusion from global and regional assessments is that the detection of the impacts of climate change on ecosystems demand long-term ecological observations and an improved understanding of ecosystem functioning (Rogers et al., 2020), including its drivers. Such studies can also provide insights into ecological processes in an applied context, e.g., climate-driven modifications of ecosystem services such as oxygen production and biological CO_2 uptake or potential changes resulting from other anthropogenic impacts. Filling knowledge gaps in this context would provide a sound and independent basis for the discussion especially on a global reduction of greenhouse gases since transformation strategies, proposed for intensively used ecosystems and nature-based solutions are hardly options for the Antarctic. Such studies can also provide valuable information on the effectiveness of the proposed WSMPA. The pressure from stakeholders to address such unanswered applied ecological questions should foster coordinated cross-disciplinary and international research, in which major advances are to be expected in more than single disciplines. The proposed long-term studies will also increase our knowledge in terms of basic research, e.g., on energy flow in food webs and on biodiversity patterns including their dynamics. Thus, the collected data are to be made publicly available for policy makers and appropriate action, and recommendations and should be suitable for publication in textbooks and in public media.

A specific stand-alone feature of the proposed LTO and LTER programme lies in the coordination of long-term physical, geochemical and biological research, which allows for gaining unique ecological insights. These will provide evidence for temporal variabilities of the environment and of biodiversity, which can be attributed with high confidence to ongoing climate change or variability. The data will also feed into ecological projections as a result of any anthropogenic climate change including fishing pressure. Both kind of results are urgently demanded by forthcoming IPCC and IPBES reports and address some of the aims of the UN Sustainable Development Goals, especially #13 "Take urgent action to combat climate change and its impacts" and #14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development". These initiatives and other assessments have the final aim to contribute through a healthy environment to the wellbeing of humans also in remote large areas such as the SO.

Author contribution

JG, DP and FM developed the general concept, wrote the general text incl. conclusions and contributed to themes 1-3, HG and AVdP contributed to the general concept and text, H-OP to the international implementation, SA, OE, CH, MH, TH, EI, MJ, SM, and ST mainly to theme 1, DKAB, HB, HF, CLB, HL, FM, FS, IvO, MW, and DZ to theme 2, TB, SH, SM, KT, and ST to theme 3. All authors contributed to the finalization of the entire text document.

Competing interests

The authors declare that they have no conflict of interest. Some authors are guest editors of the special SOOS-volume. The peer-review process was guided by an independent editor, and the authors have also no other competing interests to declare.

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