

TANGO - Estimating Tipping points in habitability of Antarctic benthic ecosystems under GLOBAL future climate change scenarios

The West Antarctic Peninsula (WAP) is characterised by rapid and dramatic environmental changes in marine ecosystems, of which many are ice-dependent. Increasing variation in the duration of the sea ice season, extended glacier retreats, ice shelf collapse, warming of surface waters, and shifts in local primary productivity are some of the observed effects of climate change in this area. In this BELSPO funded project on 'Estimating Tipping points in habitability of Antarctic benthic ecosystems under GLOBAL future climate change scenarios' (TANGO) we investigated the response of nearshore, shallow marine ecosystems to environmental shifts. Climate change impacts representing ongoing and future effects on coastal ecosystems were approached through a longitudinal gradient along the WAP, where a set of research sites spanning ~ 600 km represents a gradient of sea ice dependence. At these sites, an integrated ecological study was performed, combining biogeochemical carbon cycle measurements from the atmosphere, through the water column to the sediment with multiple food web approaches, and detailed habitat mapping. Our goals were to unravel the functioning of these nearshore shallow coastal habitats in relation to changing sea-ice conditions along this N-S gradient, with shorter winter sea-ice duration in the North, and especially in the southern stations where changes are most extreme. Since rapid physical changes interact with biological processes across spatial scales, this project aimed to develop mechanistic approaches to (1) detect early-warning signals of ecological thresholds, (2) quantify the impacts of climate-driven alterations in sea-ice and temperature on food webs and carbon cycling, and (3) assess the habitability and long-term stability of Antarctic coastal ecosystems under continued global change. We investigated climate change effects at different levels of organization, from individual level, over species interactions, processes and functions to whole ecosystems, with the results from one level feeding into the next.

Two sampling campaigns (TANGO 1 and 2) took place on board of the RV Australis, a small, agile, low impact vessel which allowed to reach uncharted areas, never studied before and being relevant for this project. In order to sample along a North South gradient representing different climate change impacts, the TANGO expeditions focused on five island systems: Dodman Island (66°00'S, 65°46'W) and Blaiklock Island (67°33'S, 67°12'W) during TANGO1, and Melchior Island (64°19'S, 62°56'W), Hovgaard Island (65°6'S, 64°4'W), and Føyn Harbor (64°32'S, 61°59'W) during TANGO2, in February-March 2023 and 2024, respectively. Sample and data collection was mainly based on ROV surveys with image analysis, seafloor sediments and benthos sampling by scientific divers and sea ice and water sampling from the vessel or a small zodiac. Also, sediment traps were deployed at several locations. Additional experimental work was done on various locations on board or at different Antarctic research stations in the area.

In a first work package we focussed on keystone species to understand the respective importance of environmental descriptors such as temperature and food resources on their physiological performance. A first step in our research was the complementation of reference databases, which is essential for molecular identifications of key species under investigation, but also for gut content analysis and for environmental and microbial DNA studies of the Antarctic biodiversity. Through novel approaches, we increased estimates of species richness by at least one order of magnitude as compared to morphological identifications. We generated 110 novel DNA barcodes identifying multiple key species at our sampling locations, mainly for the phyla Echinodermata, Mollusca, Polychaeta, and Crustacea. Our DNA barcoding approach identified at least 10 novel species and detected several instances of potential cryptic diversity.

A long-term experiment across generations on the physiological performance of the Antarctic keystone sea star species *Odontaster validus* (Lamare et al., 2024) confirmed that higher temperatures have dramatic effects. In this experiment, exposure of adults to higher temperatures did not preadapt the population to global warming; on the contrary, the offspring of these adults showed reduced survival, and growth, and arrested larval development. If such cross-generational effects of raised temperatures are common among many species, it suggests greater ecosystem disruption than previously anticipated.

Furthermore, it was observed that gut microbiota in keystone species vary spatially, adding a hidden layer of biodiversity critical for host resilience, shaping their physiological response. Therefore, microbes may help organisms cope with extreme conditions, but their role under rapid change is poorly understood.

In a second work package we investigated the food web properties and trophic flexibility of key taxa under conditions of environmental change. Gut content analysis of some abundant benthic taxa revealed a frequent occurrence of diatoms across multiple host species, aligning with the established ecological role of diatoms within Antarctic food webs. However, different echinoderm species exhibited evidence of trophic connectivity to macroalgal forests via the detrital pathway (i.e., the “brown food web”). Furthermore, the diversity of carbon sources utilized was found to be higher in rocky habitats compared to soft sediment environments, likely due to the incorporation of macroalgal-derived carbon in rocky areas. In sedimentary habitats, the food web appears to be coupled with the decomposition of organic matter and subsequent assimilation by microphytobenthos.

Despite regional differences along the WAP, the overall vertical trophic structure remains broadly conserved. Both sea-ice and benthic algal production contribute to the carbon sources used by benthic consumers across habitats. Thus, food source diversity is also linked to changes in sea ice cover. Warming will therefore result in profound effects on food web properties, especially on the quantity, diversity and origin of primary carbon sources. Since an increase in biomass and diversity of macroalgal cover and non-linear changes in planktonic/sympagic production is predicted, food webs in soft-bottom habitats may shift from water-column dependence (planktonic/sympagic production) to stronger benthic dependence (microalgal/macroalgal primary production). We further observed that some benthic invertebrate species are likely plastic enough in their diet to adapt to these changes, while many are not. Therefore, drastic changes in benthic diversity and food web properties are likely to occur in the near future.

A food web model in an area of glacier retreat from sea to land has shown that glacial melt does not merely reduce overall primary produced carbon availability. The system becomes less reliant on autotrophic benthic production and internal recycling, and more dependent on detrital inputs and opportunistic taxa, signalling a functional reorganization of the benthic food web under intensified melt. As glacial retreat along the Antarctic Peninsula accelerates, such shifts are likely to intensify, reshaping benthic community structure, reducing carbon transfer efficiency, and altering energy pathways in shallow Antarctic fjords.

A third work package investigated the primary production, pelagic export, benthic storage and carbon flow along the climate gradient. The sea ice, only present in the southern stations, was found to contain significant concentrations of chlorophyll a in gap layers; porous seawater filled layers within deteriorating sea ice found mostly at the end of summer. In accordance, water column chlorophyll concentrations are two to three times higher in the south (i.e., Dodman and Blaiklock Island) than in

the north (i.e., Melchior and Hovgaard Island and Føyn Harbor). The presence of sea ice also appeared to lead to a greater vertical flux of organic matter to the seafloor, distinguishing between northern and southern stations. These differences in deposition rates however did not relate to differences in benthic mineralization rates or sediment properties. Total seafloor mineralization rates were mostly a function of proximity to glacial deposition sources since biogeochemical patterns indeed differed between close and far glacier influence sites.

Microphytobenthos appears to play a profound role in benthic nutrient cycling in these shallow sedimentary habitats, generally increasing retention of nutrients in the seafloor during periods of photosynthetic activity. Finest sediments situated closest to glacier outputs, featured the highest porewater solute buildup rates and a signature of a strong reducing environment. In almost all stations, methane fluxes from the sediment are above the average sediment-water fluxes measured around Antarctica. Observations of surface waters, expected to represent an integrated picture of biogeochemical processes below, indicated that the demand of dissolved inorganic carbon (DIC) by water column and benthic primary producers makes the WAP act as a sink during Antarctic summers. The fine-grained nature of the visited sites where anoxic mineralization is expected to dominate organic matter mineralization, and the presence of Greenhouse gasses (GHG) in subglacial run off makes the WAP also a seasonal source of GHG such as methane and N₂O.

A fourth work package dealt with ecosystem complexity and functioning at different spatial scales along the climate gradient. Macroalgae play scale-dependent roles in structuring shallow Antarctic benthic communities: as broad indicators of sea-ice conditions, habitat productivity and complexity at large scales, and as direct biotic drivers and ecosystem engineers at finer scales. Furthermore, our results highlight the importance of ice dynamics as drivers of benthic community composition at multiple spatial scales in the study area. From our Bayesian network analysis based on ROV surveys, it is not directly clear how future declines in sea-ice cover will affect benthic communities, but we can use the statistical dependencies between macroalgae and other taxa to infer possible indirect changes in faunal composition due to changes in macroalgae abundance. Furthermore, Antarctic shallow benthos is not solely shaped by environmental drivers, but also by a dynamic web of species interactions that vary in strength across densities and contexts.

Based on our findings we formulated some specific recommendations of which the most important is to follow up on effects of glacial runoff and sediment GHG emissions to refine Antarctic carbon budgets. We also recommend to adopt integrated management plans that consider scale-sensitive features such as species interactions and habitat complexity, and that account for broad climate drivers.

By aligning with the Antarctic Treaty System and IPCC, our findings can be integrated into global climate models and mitigation strategies.