Mesoscale regionalisation of the western Antarctic Peninsula

Statsraad Lehmkuhl / One Ocean Expedition

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Abstract

As part of the One Ocean Expedition onboard the Statsraad Lehmkuhl, scientists from Argentina, Chile, Uruguay and Norway met for 10 days to discuss the Southern Ocean Action Plan (SOAP) in the context of the southern Scotia Arc and western Antarctic Peninsula. This geographical region represents an area of strong research and commercial interests for all the participating nationalities, and key questions from the SOAP were applied through this regional lens. The physical, ecological and anthropological complexity of the region coupled with the rapid and ongoing changes driven primarily by climate change mean that a “one management strategy fits all” approach is unlikely to be appropriate. It was agreed that a more ecologically realistic regionalisation is a necessary first step in understanding the distribution of threats, their impacts and how they are likely to change over time. At the conclusion of the meeting, the group agreed that there was sufficient scientific literature and motivation to write a peer-reviewed article outlining a putative bioregionalisation of the southern Scotia Arc and western Antarctic Peninsula, and such an article could be used as a reference point for future scientific collaborations and research proposal development.

Introduction

The Southern Ocean Action Plan (SOAP) presents the key challenges in a research, logistic and uptake context for ensuring that the Sustainable Development Goals of the United Nations Ocean Decade are achieved in a polar context. The SOAP represents the synthesized outcome of international expert Working Groups focusing on each of the seven desired UN Ocean Decade Societal Outcomes.

As part of the One Ocean Expedition, the Norwegian Polar Institute in collaboration with Antarctic researchers from Argentina, Chile and Uruguay conducted a workshop onboard the Statsraad Lehmkuhl to discuss mutual areas of Antarctic research interest and foster closer scientific collaborations between the nations. The workshop used the SOAP Working Group outputs to provide guidance on what have been identified as critical issues for Southern Ocean governance and societal outcomes, applying a geographical filter to them given the regional focus of the participants on the southern Scotia Arc (western Antarctic Peninsula (WAP) and South Orkney Islands).

The WAP is currently experiencing rapid modification due to the impacts of global climate change, and at the same time represents the region most impacted directly by human presence primarily from commercial fishing and tourism. Given the multifaceted impacts on the WAP and the ecosystem services it provides, ensuring that appropriate monitoring of ecosystem functioning is critical. However, a necessary precursor to appropriately monitoring how a region is changing, is an understanding of the underlying structure of the region in question as well as the distribution and pathways by which threatening processes manifest.

In light of this, we identified several common threads from the SOAP that were directly relevant in a WAP context. Specifically 1) an understanding of the role that multiple stressors can have in altering the marine ecosystem and how these individual stressors may act either cumulatively, synergistically or antagonistically; 2) connectivity between ecosystem components, across geographical space and how these relate to the distribution and relative impact of stressors; 3) cryosphere-ocean interactions and their variability across geographic space; and 4) identification of appropriate monitoring indices to appropriately capture the degree of expected heterogeneity in human impacts on the marine ecosystem of the WAP

(Jiang et al. 2022). The group agreed that the marine environment of the WAP is not homogenous, and thus the interaction among and between stressors and the physico-chemical and biological environments they occupied would more likely be best described as a mosaic.

The remainder of the report is structured to reflect discussions of how a mesoscale regionalization of the WAP might look in terms of physico-chemical and biological characterization and the spatiotemporal presence of stressors. In considering the WAP and the capacity to conduct scientific research (in terms of logistics and station support), the group defined its area of scientific interest as ranging from the Southern Scotia Arc (encompassing the South Orkney Islands archipelago to the South Shetland Islands), the eastern edge of Marguerite Bay and the shelf break as its eastern, western and northern limits respectively (Fig 1). However, for sake of clarity in the report, the term WAP is used to describe the peninsula of the Antarctic continent only. The group also agreed that given the added complexities of considering deep sea marine ecosystems in this way, the evaluation of mesoscale structuring would be constrained to approximately 400m depth reflecting the epipelagic zone bounded by the top of the mesopelagic layer. On agreeing this putative regionalization, connectivity between each mesoregion was also considered, as well as potential data streams (both new and existing) that may clarify such connectivity. The group also discussed how each mesoscale region might respond to future change, how these changes might propagate through the WAP and what this might represent in terms of societal implications. A range of research topics were developed to reflect the discussions and provide a springboard for future collaborative efforts. Finally the group agreed that progressing a peer-reviewed manuscript on the mesoscale regionalization of the WAP that would include a broader group of scientists, would be useful and could support future funding applications.

Hydrographic structuring of the WAP and primary productivity

Within the region of interest, the group agreed that a key driver of potential mesoscale structuring are the different hydrographic sources of input and their interactions with bathymetry. At the northern end of the WAP, Weddell sea water flows into the Bransfield Strait (BS) and continues westwards along the coastline, as far west as Tower Island in the northern Gerlache Strait (Bartlett et al. 2018, Niller et al. 1991). In contrast, modified Circumpolar Deep Water (mCDW) from the Drake Passage and Bellingshausen Sea flows eastwards along the shelf and shelf break, intruding into the southern Gerlache Strait at the Palmer Deep and into either end of the Bransfield Strait (between Snow and Smith Islands in the west and King George/25 de Mayo and Elephant Islands in the east; Bartlett et al. 2018) and the frontal system that these two opposing water masses creates within the BS is often referred to as the Peninsula Front (Wang et al. 2022) . In stark contrast; however, even though the South Orkney Islands are only ~500km from Elephant Island the archipelago is entirely dominated by the Weddell Sea (Murphy et al. 1995).

The impact of climatology (primarily wind) also plays a large role in structuring the WAP at mesoscales. Hemispheric (El Niño Southern Oscillation; ENSO or the Southern Oscillation Index; SOI) and regional (Southern Annular Mode; SAM) weather phenomena interact with each other to drive a complex pattern of climate-induced marine structuring. The Amundsen Sea Low (ASL) in the Bellingshausen and Amundsen seas is a low pressure system whose intensity is modulated by the phase of SAM, with positive (negative) SAM driving a deepening (shallowing) of the ASL (Holland et al. 2018). Similarly, SOI impacts the ASL with La Niña (El Niño) strengthen (weaken) its intensity (Holland et al. 2018). However, ENSO-driven modulation of ASL is primarily stronger in autumn / spring whereas SAM influences are most strongly correlated with winter ASL characteristics. These complex broadscale climatic interactions drive opposing trends along the WAP; positive SAM brings more southeasterly (therefore colder) winds to the southern WAP while the same SAM phase leads to warmer northwesterlies across the northern WAP and Bransfield Strait (Holland et al. 2018, Hosking et al. 2016). Climate-ocean interactions through processes such as Ekman Transport lead to modification of the water column through upwelling / downwelling, phenomena which are dependent upon the prevailing direction of current flow, bathymetry and the orientation of the coastline. Ekman transport plays a central role in modulating the intrusion of mCDW onto the continental shelf and Weddell sea water into the Bransfield Strait and along the Peninsula coast. Given the geographic complexity of the WAP, it is unsurprising then that at local scales (i.e. at the scale of individual bays), wind-driven upwelling and downwelling can significantly impact the composition of the surface mixed layer and modify primary productivity at timescales of days (Wallace et al. 2008).

Cryospheric interactions with these different water masses and the subsequent variability in primary productivity throughout the WAP were also discussed by the group as were the relative importance of ice algal communities in ice covered areas. Along the nearshore aspect of the southern Gerlache Strait the upwelling of warm mCDW through climatological processes discussed above drives basal melting of glaciers which in turn increases the freshness of the surface layer and stabilizes the mixed layer to a (relatively) shallow depth. Outside the southern Gerlache Strait (i.e. shelf waters), sea ice is typically the dominant driver of water column stability (Stammerjohn et al. 2008). Through both mechanisms, the resulting shallow depth of the mixed layer drives increased primary productivity (Montes-Hugo et al. 2009); however, the contraction of seasonal sea ice extent and duration southwards and westwards is matched by a cline in primary productivity from nearshore to the shelf break. This is in stark contrast to the northern WAP (Wille et al. 2022), where glaciers have significantly retreated (Cook et al. 2016) and sea ice is mostly absent throughout the year. Positive SAM-driven northerly winds dominate in the northern WAP, giving it a more sub-antarctic climate with increased rain, cloud and humidity. This in turn leads to turbulent mixing of the Bransfield Strait upper water column, a deeper mixed layer and comparatively lower primary productivity (Fig 3 panel A, taken from Montes-Hugo et al. 2009).

The group considered the role that distinct water masses (warm, nutrient rich mCDW and cold, fresher Weddell sea water) and their interactions with bathymetry (e.g. canyons permitting intrusion onto the shelf) and wind-driven climatology (ENSO, SOI and Ekman Transport) play in mesoscale structuring of the WAP. The group agreed that a parsimonious mesoscale regionalisation of the WAP could consist of four geographic regions 1) South Shetland Islands and northern Bransfield Strait 2) southern Bransfield Strait and the Antarctic Peninsula 3) northern Gerlache Strait to Trinity Island and 4) southern Gerlache Strait, with the South Orkney Islands representing a distinct region given the dominance of the Weddell Sea (Fig 2). The group agreed that this characterisation could serve as a plausible “straw man” concept of mesoscale regionalisation for further discussion, and be the basis for developing testable hypotheses to support or reject such structuring.

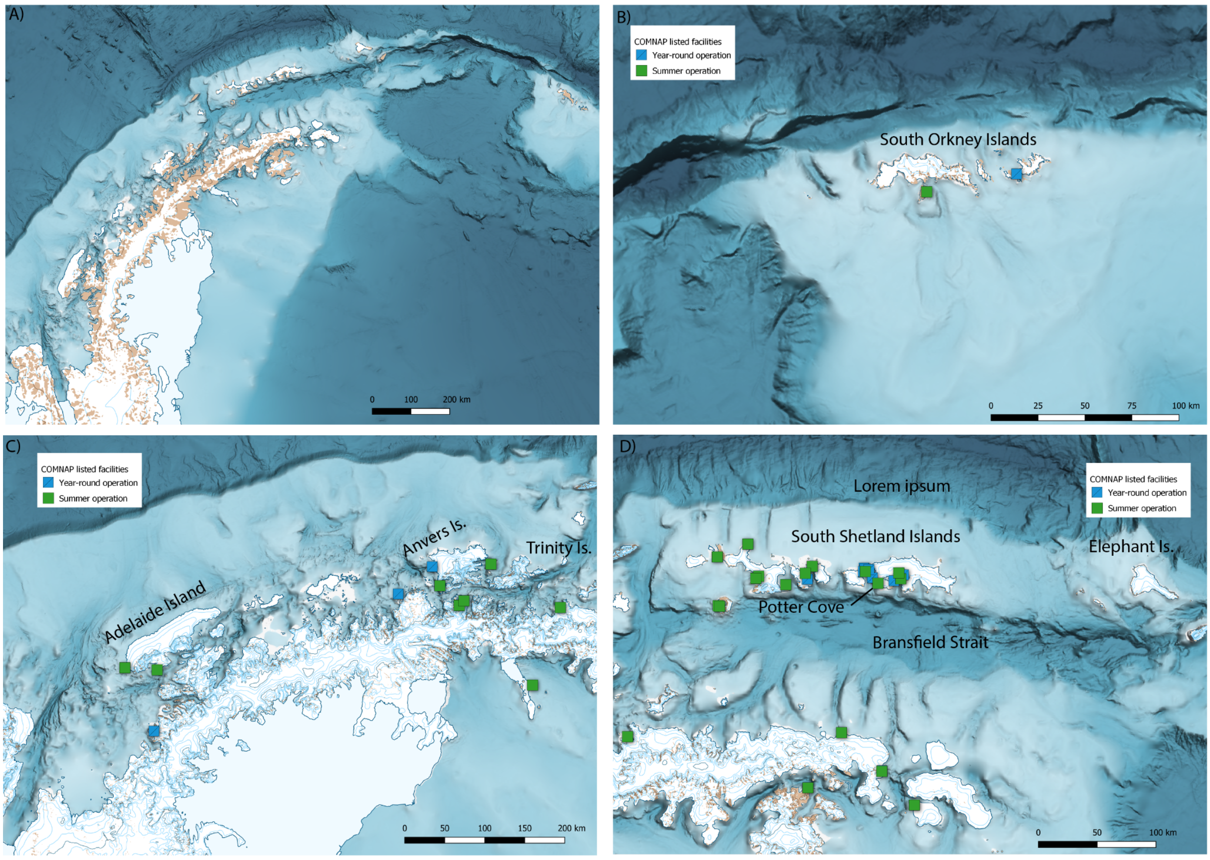
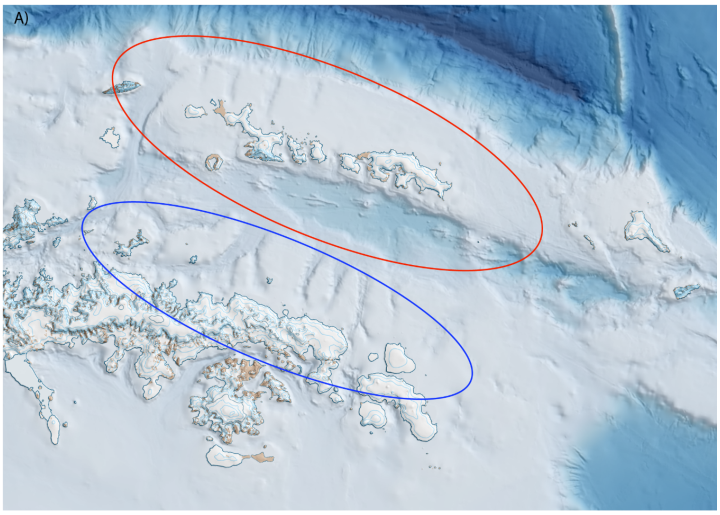


Fig 1. A) Given the national representation of the attendees, the broad area focussed upon by the working group was the western Antarctic Peninsula (WAP) and South Orkney Islands archipelago. B) The South Orkney Islands sits approximately 500km east of the tip of the WAP and has a very different climatic and oceanographic regime that reflects the dominance of the Weddell Sea. The areas of interest within the WAP are the C) Gerlache Strait and D) Bransfield Strait, reflecting the main geographic locations of logistics and research infrastructure (blue; year-round stations and green; summer-only stations. Data taken from the COMNAP Antarctic Facilities listing), and where key commercial activities recognised as potential ecosystem stressors occur.



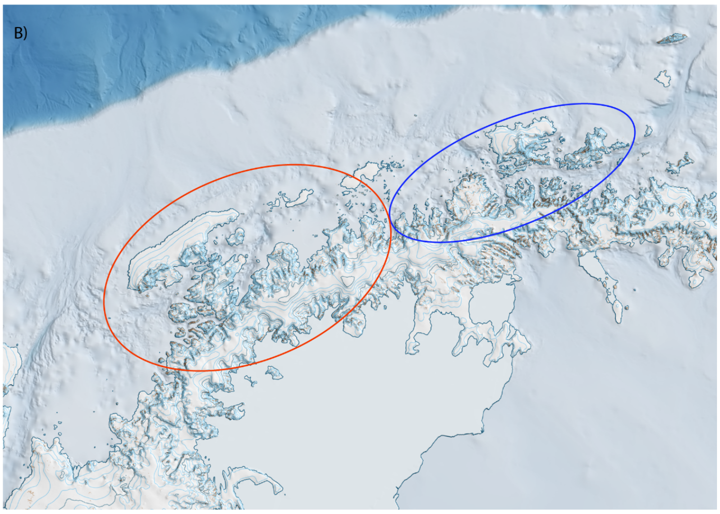


Fig 2. Due to the respective influence of Weddell Sea and modified Circumpolar Deep Water flowing into the Bransfield (BS) and Gerlache Straits, five mesoscale regions were ascribed A) in the BS, the South Shetland Islands and northern Bransfield Strait, and the southern side of the BS to the Antarctic Peninsula coastline and B) the northern and southern aspects of the Gerlache Strait. The working group considered the South Orkney Islands archipelago (not shown, see Fig 1) as its own mesoscale region distinct from the western Antarctic Peninsula given the strong influences of Weddell Sea climactic and hydrographic regimes. Colours represent the influence of colder, fresher Weddell Sea water (blue) and warmer, denser, more productive modified Circumpolar Deep Water (red).

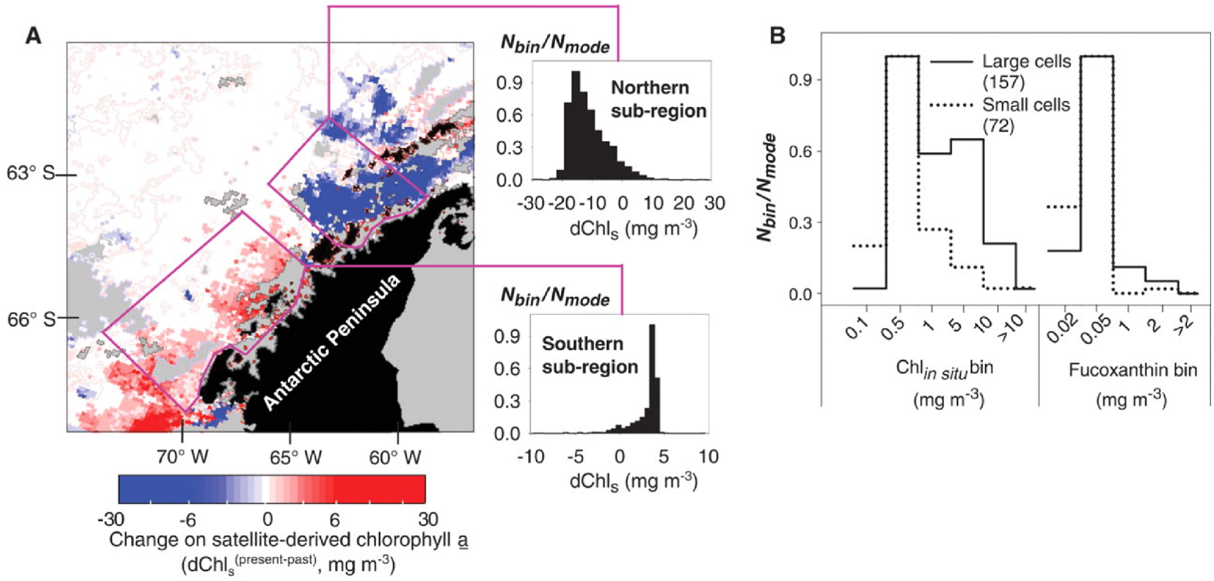


Fig 3. (taken from Montes-Hugo et al. 2009). Panel A) represents the mean by-pixel difference in concentration of Chlorophyll *a* between 1978-1986, demonstrating the clear polarisation in productivity between the Gerlache Strait and Bransfield Strait, primarily due to large-scale climatological shifts in wind patterns and temperatures, and the decrease in sea ice extent and duration.

Biological structuring

While conceptualizing a mesoscale regionalisation of the WAP was tractable using hydrographic and climatological information, the group agreed that performing a similar exercise using biological data beyond primary productivity would be challenging primarily due to the varying spatial and temporal scales at which different functional groups occupied (e.g. benthic infauna sensu Morley et al. 2022 and penguins), that most empirical data are often seasonally or geographically constrained and that life history stages of nekton exhibit differing capacities for active movement. Thus, the group considered that discussing how the biological and ecological structuring of the WAP and South Orkney Islands and the degree of data availability in the context of the straw man concept outlined above may be more appropriate. The group broadly agreed that upper trophic air breathing predators represented a functional grouping for which the available information may be sufficient to correlate usage to mesoscale structure, though noted that most data are limited to the austral summer period. Penguins represent some of the most studied upper trophic taxa throughout the WAP and South Orkney Islands, with geographically resolved demographic data collated and maintained through the “Mapping Antarctic Penguin Population Dynamics (MAPPD)” program, which have been used previously to highlight a complex spatial pattern in penguin population trajectories that is difficult to explain by a simple combination of stressors (Lynch et al. 2012; Fig 4). Similarly, time series data on penguin breeding phenology are collected by the Conservation of Antarctic Marine Living Resources (CCAMLR) through its Environmental Monitoring Program (CEMP). Baleen whales (humpbacks, fins, blues and minkes) have been the focus of studies relating to foraging movement (e.g. Friedlander et al. 2006, Friedlander et al. 2013), as have the key seal species that utilize the WAP for breeding or foraging (Weddell seal; Daneri et al. 2018, crabeater seal; Huckstadt et al. 2020, leopard seal; Cassaux et al. 2009, Antarctic fur seal; Lowther et al. 2020). The group felt that there were sufficient energetic models available for top predators to permit estimation of prey consumption, which may be a useful metric to look at through the lens of mesoscale structuring (Subramaniam et al. 2022, Warwick-Evans et al. 2022).

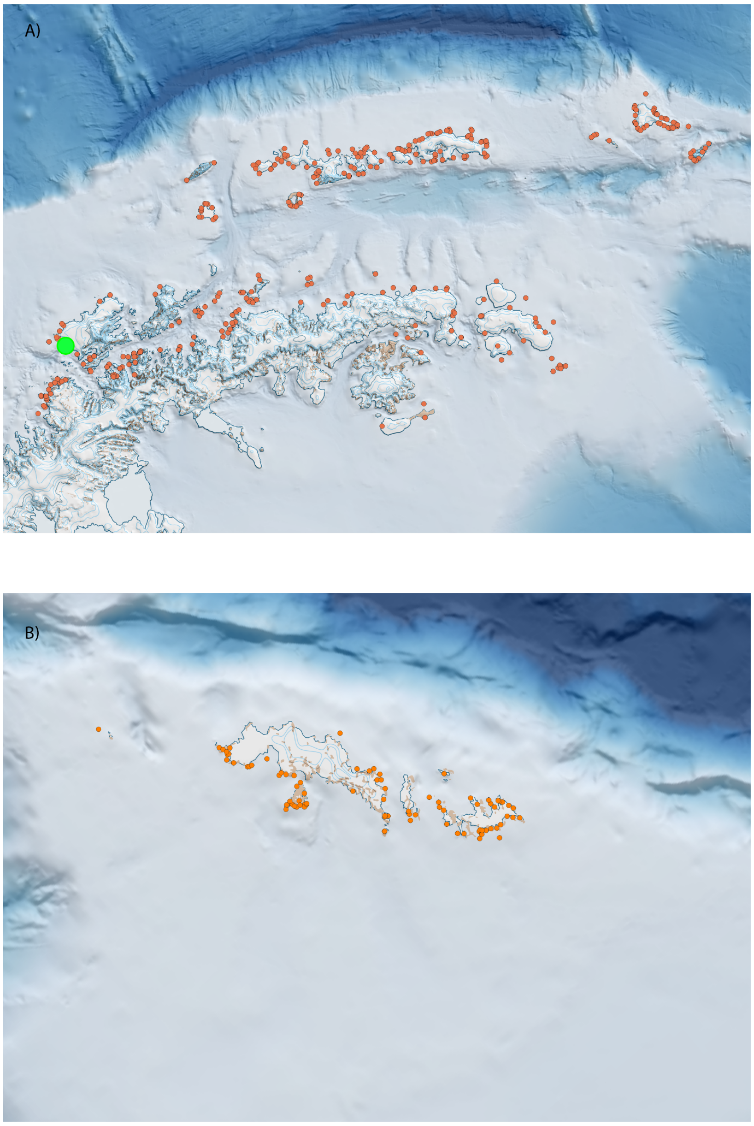


Fig 4. Locations of Mapping Penguin Population Dynamics (MAPPD) sites, where population demographic data are held for three species of breeding pygoscelid penguins (Adelie, Chinstrap and gentoo penguins). Many sites have sporadic data; however, there is a relatively consistent distribution between the putative mesoscale regions in A) the WAP and B) South Orkney Islands proposed by the group in Fig 2. B) Palmer Station (green circle), from which the Palmer Long Term Ecological Research program is conducted.

Fishes were identified as a functional group that may be strongly influenced by the physical and climatological characteristics of the WAP. There was general agreement that there is little data regarding their seasonal movement (but see La Mesa et al. 2022 and Trokhymets etl al. 2022 on recent work regarding notothenioid spatial distribution), habitat preferences or spawning grounds though that collecting such data should be a priority, given that some species were historically overexploited and information on their recovery is still sparse. Given the relatively detailed studies conducted by the IAA (Argentine Antarctic Institution) on notothenioids spawning habitat (primarily at Potter Cove; Novillo et al. 2018, 2019, 2021), the group discussed the utility of using these data to extrapolate out potential spawning habitat using species distribution models, as such exercises are useful to identify potential areas for research when funding and support are limited and recommended prioritising this as a research topic (see Section "Research topics" below). Given the study area boundaries agreed at the onset of the meeting, the group also acknowledged the lack of ecological data on pelagic fishes (pleuragramma and myctophidae; Dornan et al. 2022, Corso et al. 2022 and Saunders et al. 2019). Cephalopods are often considered key species within Southern Ocean food webs (Collins and Rodhouse 2006), however the group did not possess sufficient expertise to discuss them in the context of how mesoscale physical structuring may influence their biology. There was general agreement that drawing in expertise on this functional group would be important in the development of the manuscript, and suggested that Dr. Jose Xavier may be an appropriate person to contact in this regard.

Macrozoplankton, particularly species of commercial value such as Antarctic krill (Cutter et al. 2022), also represent a functional group for which considerable scientific attention has been given. Besides its economic relevance, as an abundant pelagic suspension feeder, this species has been recognized to play a major role in benthic-pelagic coupling, since their faecal pellets are known as relevant components of the OM flux to the benthos through sinking along the water column (Belcher et al. 2017; Alurralde et al. 2019). Detailed studies of Antarctic krill have been conducted as part of the Palmer Long Term Ecological Research time series (Palmer LTER) in the southern WAP (Fig 4), while several Member States of CCAMLR have undertaken synoptic acoustic surveys and process-based studies at varying spatial scales though most are limited to summer. Gelatinous macrozooplankton were also briefly discussed, particularly in terms of an alternate lower-quality food source for upper trophic predators (sensu the junk food hypothesis and Smith et al. 2012) and how their relative abundance in space and time may vary as a function of mesoscale structuring. However, similar to cephalopods, the group agreed that a lack of macroplankton expertise hampered its ability to determine how this functional group may respond to mesoscale structure but acknowledged that this expertise existed (e.g. the SCAR Krill Action Group, SKAG) and could be exploited in the context of developing the manuscript.

Plankton and primary productivity was also revisited briefly by the group, primarily to capture that time series of empirical data exist for mesoscale level productivity (e.g. the Rothera Time Series RaTS and Palmer LTER), and that reasonably sophisticated and well parameterised models have been developed to hypothesise the drivers of change in productivity (for example, the overwinter drivers of summer productivity) which in turn could be deployed, as hypothesis generators, within the putative mesoscale regions suggested here.

Stressors as an asymmetrical pressure

The group considered the concept of anthropogenic stress as being heterogenous in both space and time, starting with global pressures and their local manifestation at local scales. Examples included in the discussion were the amplification of marine acidification by increased presence of freshwater in the absence of productivity such as regions where Weddell sea water intrudes into the Bransfield Strait as opposed to increased nutrient input from upwelled mCDW into the southern Gerlache Strait which might stabilize acidification in the short term. Similarly, increased sedimentation rates due to runoff into the marine environment from land-terminating glaciers or due to increased levels of rainfall, both linked to increasing air temperatures and shifting climatology patterns (e.g. Meredith et al. 2018; Vignon et al. 2021). Also considered was the introduction of biota (micro and macro) (Dulière et al. 2022) and the process by which global climate change may influence their establishment, as well as the potential for increased prevalence of zoonotically transferred diseases; currently, the physiological thresholds of invasives may not allow them to reproduce, however as environments are modified this may cease to be the case (e.g. Smith et al. 2012). In all these cases, mesoscale climate anomalies such as heatwaves will elicit different responses that reflect the conditions present i.e. marine or land terminating glaciers. The calving of icebergs from marine-terminating glaciers is also likely to be a mesoscale phenomena, impacting the composition of benthic communities through periodic scouring and glacier melt-water runoff (e.g. Gutt 2001; Moon et al. 2015, Ingels et al. 2020). In addition, the group noted that benthic secondary production and particularly the suspension feeders trophic group play an important role due to their high carbon sink potential through biodeposition (i.e. blue carbon storage; Coppari et al. 2019), but a potential increase in sedimentation rates in coastal shallow waters due to melting of marine-terminating glaciers may negatively affect benthic suspension feeders biodeposition and consequently, their energy balance (Alurralde et al. 2019). The group also revisited climatological phenomena discussed during the initial formulation of the putative mesoscale regions, but at smaller scales. The complex coastline of the WAP, with both northward and southward-facing coastlines and prevailing currents in opposing directions could create a highly complex mosaic of wind-driven upwelling and downwelling which will impact *inter alia* local productivity and glacial melting. Increased runoff may also induce a potential shift from diatoms to cryptophytes (not accurate food source for krill). This also could increase salp proliferation (not preferred by top predators such as penguins) and krill migration (Moline et al. 2004).The group agreed that, with the provision of appropriate climatological data (wind speed and direction, humidity, dew point etc) maps of predicted Ekman transport for given climatic conditions could be generated that would be useful in understanding mesoscale ecosystem dynamics.

More obvious, direct anthropogenic stressors such as tourism and commercial fishing were also considered. Both marine industries represent highly seasonal and spatially heterogenous stressor that, during the period in which they are present, appear to be spatially consistent (Fig 5). The primary tourist season coincides with the breeding season of centrally foraging penguins and seals, as well as a large influx of cetaceans (Johannessen et al. 2021). Tourist operations are mainly concentrated on the WAP region with only a handful of tourist vessels visiting the South Orkney Islands. In contrast, the krill fishery operates predominantly off the western coastline of the South Orkney Islands during the austral summer, moving into the WAP and northern Gerlache Strait during late summer until early winter. The concentrated presence of shipping traffic is known to alter the marine soundscape and impact wildlife (Rolland et al. 2012, Celi et al. 2016, Pine et al. 2021) however even basic information on the degree to which these vessels impact the marine soundscape is lacking in the Antarctic. In the case of tourist vessels, which often remain in fixed locations overnight, potential impacts of consistent acoustic and light pollution could adversely impact the biological community at very small scales. Tourist vessels also remain in locations for long periods during the day while passengers visit land sites; prop wash from multiple vessels visiting the same sites on a daily basis has the potential to resuspend large amounts of particulate matter which is likely to impact both benthic and pelagic communities. For both marine industries, incidences of bird and cetacean interactions with vessels are issues with the regulating bodies (primarily flag state) requiring record-keeping of all incidents; however, "near misses" and the mechanisms by which these interactions are driven are often poorly understood. Specific to the fishing industry, the dispersal of prey (krill) by trawling and the potential for creating top predator dependency on the fishery (for example, seabirds targeting trawlers) were also identified as potential stressors. Of growing concern are the presence, spread and cumulative effects of emergent pollutants in the marine environment (e.g. the first appearance of microplastics in Antarctic snow reported by Aves et al. 2022). The impacts of such pollutants are (intuitively) unknown, however recording their distribution and tracking their progress through foodwebs are likely to be important in the context of predicting future impacts on ecosystem dynamics.

The group briefly considered the idea of inter- and intraspecific competitive interactions between breeding and nonbreeding predators as a spatially and temporally heterogenous stressor. Examples of nonbreeding male Antarctic fur seals, Adelie penguins and humpback whales were used to highlight the non-uniform way in which these life history stages occupied marine habitat in comparison to their breeding conspecifics (Lowther et al. 2020, Johannessen et al. 2021, Oosthuizen et al. 2022), and the group agreed that expanding on this with other species might help in more appropriately assigning cause to demographic trends of penguins.

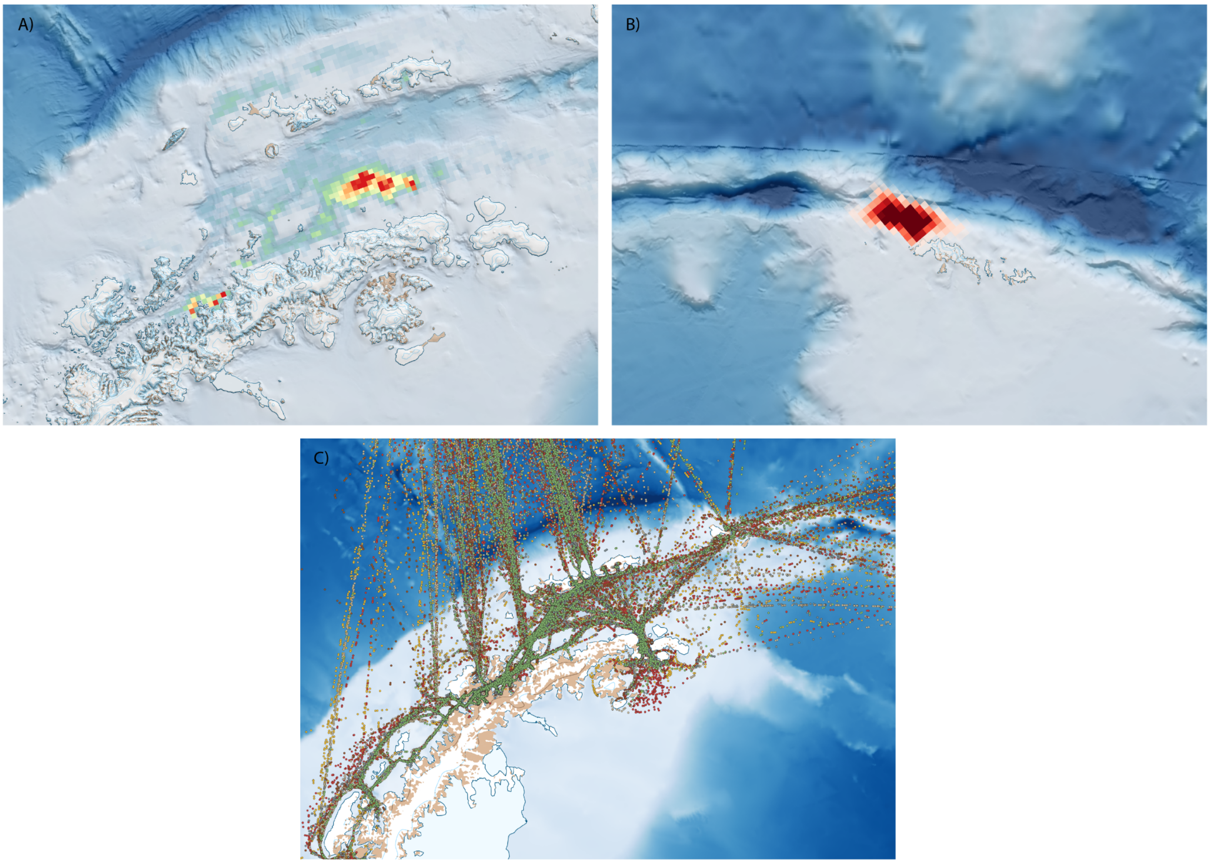


Fig 5. Examples of the heterogenous distribution of potential stressors resulting from activities of the marine industry in the WAP / South Orkney Islands. Fishing for Antarctic krill is highly seasonal, with discrete fishing areas in both A) winter and B) summer (rasters of tonnage caught per 5km grid cell, derived from C1 catch and effort data provided by the CCAMLR Secretariat). While the distribution of fishing catch does vary year-to-year, the concentrated aspect of catch means direct ecosystem stress is localised, though the group recognised that indirect / lagged effects may be more diffuse. C) Antarctic tourist fleet movement between 2015-2020 (different colours denote individual years of movement; AIS data provided by the Norwegian Coastal Administration). The Antarctic tourist fleet typically operates November-March each year, conducting repeated site visits leading to discrete areas of high usage that appear to be highly consistent between years.

Connectivity between mesoscale regions

The degree of connectivity between mesoscale regions was discussed by the group, however the group agreed to consider connectivity with other areas of Antarctica in a unidirectional context i.e. only ecosystem connection that propagated *into* the WAP / South Orkney Islands, not downstream connective input into *other* areas. Physical connectivity was considered to be a relatively straightforward way in which hydrographic models such as ROMS or NEMO could be used to track passive tracer movement in three dimensions over time. Such models are already parameterised and updated with empirical data frequently, and can be integrated with planktonic / biogeochemical models such as in the Nutrient Plankton Zooplankton Model (NPZM) or Biogeochemical Elemental Cycling model for ROMS (e.g. Nissen et al. 2021, Duarte et al. 2022).

The group agreed it would be useful to look at the genetic connectivity of taxa with limited movement capacity; incorporating passive transport of pelagic larval stages of sponges into hydrographic models could be achieved by using the typical lifespan of these life history stages to define the lifespan of passive tracers, in order to predict patterns of potential distribution across mesoscale region boundaries. Empirical testing of these model outputs could be achieved using advanced molecular sequencing techniques such as the detection of single nucleotide polymorphisms that can be used to determine population structure of sessile adult stages across these boundaries as an indicator of biological connectivity through passive movement (Busch et al. 2021). Foodweb connectivity was also discussed, in the context of community niche width within each region and across regional boundaries; techniques such as bulk and compound-specific biogeochemical analyses of communities would be one tractable method for establishing whether hydrographic boundaries translated into foodweb discontinuity (McCormack et al. 2019).

Beyond plankton, the degree of connectivity between regions from the perspective of free-ranging taxa varies considerably, as does the current level of scientific information. For example, the group identified that knowledge on fish movement was generally poor, but agreed that understanding the degree and significance of stock structure (and therefore connectivity) with respect to mesoscale structuring of the marine habitat would have implications for predicting future population trends with respect to climate change and the management of any future fishery.

As a direct result of the movement studies conducted on penguins, whales and seals there also exists information on the level of connectivity between the mesoscale regions identified. Consequently, the group agreed that current information on top predators may be amenable to identification of mesoscale areas of ecological importance for multispecies guilds (*sensu* Hindell et al. 2020) as well as determining to what degree they might respond to modifications of these mesoscale regions and concomitant changes in connectivity between them.

Future predictions

The group agreed that constructing predictive hypotheses about how each putative bioregion might respond to the cumulative impacts of asymmetrical stressors would be useful in a monitoring context. The direction of modification of bioregions (i.e. either homogenisation between regions or the removal of connectivity pathways) will also be of great interest in order to predict downstream effects of modifications. However the group noted that the availability of data to validate models (and indeed the existence of suitable modelling frameworks at all) may hinder how quantitative such future predictions might be.

One potential way in which quantitative predictions of bioregional modification could be to use Global Climate Model (GCM) outputs (i.e. CMIP6) to force local advection / circulation models (i.e. ROMS) for each bioregion into the future. Such a quantitative modelling process is tractable given the availability of GCM products and current, high resolution (<500m horizontal) circulation models in the region are already used to inform upper trophic species distribution modelling (e.g. Huckstadt et al. 2020). Species Distribution Modelling approaches can be applied, for example using the thermotolerance of fishes as thresholds to determine what conditions represent suitable fish habitat within and between bioregions, under the changing conditions predicted by local circulation models. This approach can also be used with key species for which their trophic vulnerability and spatiotemporal distribution is known (e.g. prey-switching or predators with highly specialised diets) and then model out potential habitat shifts over time (sensu Huckstadt et al. 2020). These approaches can also be linked, for example how top predators will react into the future in the context of salp introgression (Plum et al. 2020). More qualitative predictions can be made for future changes in primary productivity (both shallow benthic and pelagic), similarly for how the distribution and intensity of stressors could change. Qualitative modelling approaches can be spatially and temporally explicit (Fig 6., Melbourne-Thomas et al. 2013) and are more flexible to offering future predictions in the absence of data than quantitative models. The group considered that, for the development of a scientific article, refining and developing such a model to include more sophisticated representation of hydrographic barriers and the asymmetrical distribution in time and space of stressors was agreed to be a useful exercise to enable the prioritisation of research efforts. The group also agreed that it would be useful to construct alternate scenarios using such qualitative network models that reflected how "extreme" events such as El Niño/La Niña are likely to propagate through each putative bioregion, particularly in the context of the predicted increase in frequency of such events as the climate continues to change.

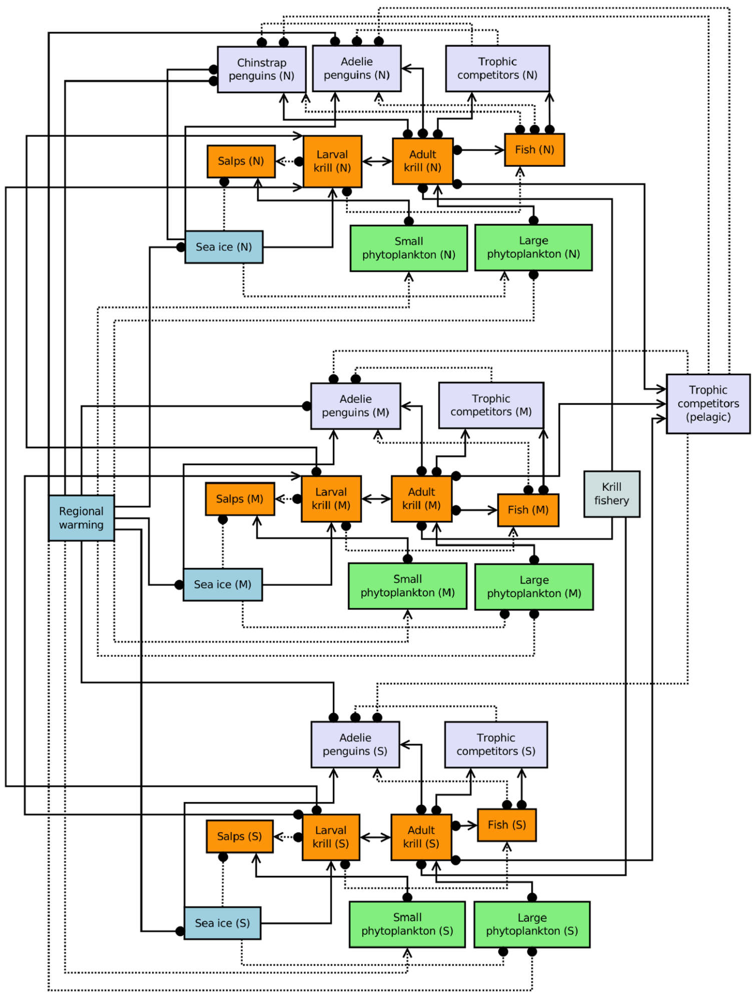


Fig 6. Accepting that the Antarctic Peninsula and southern Scotia Arc will likely continue to create formidable challenges in developing quantitative, numerical models of ecosystem structure and function, one tractable solution for being able to provide a degree of advice and prediction of future change may be qualitative network modelling. The above figure displays the network model from Melbourne-Thomas et al. (2013) describing the qualitative interactions between ecosystem components and two stressors (commercial krill fishing and climate change) that considers geographic variation similar in nature to that discussed by the group.

Societal Implications

The group agreed that mesoscale regionalisation of the southern Scotia arc was necessary in order to understand how the marine ecosystem was responding to change and thus to provide appropriate and timely advice to environmental managers so they may take action. Translating the work proposed into relatable product beyond scientific publications requires the integration of societal needs and concerns, and the group recognised it was lacking expertise in this regard. The group agreed that identifying and integrating expertise in the social sciences that are relevant to the Southern Ocean is important, and agreed to reach out to relevant individuals.

Research topics identified related to mesoscale regionalisation

1. *Physico-chemical:*

Q: local climatological impacts on hydrographic conditions at fine scales (embayment)

Q: Late winter / spring preconditioning for summer productivity across mesoregions

Q: Numerical modelling of local climatologies; drivers of fine scale variability in turbidity, up/downwelling, resuspension, etc etc

Q : Seeding species for spring blooms / summer startup (from sea ice, or from benthos).

2. Biological:

Q: Species Distribution Models (SDM) for inshore icefish (amongst others) spawning areas, using physiological tolerance and known habitat covariates.

Q: SDM for gelatinous zooplankton

Q: Benthic microalgae, macroalgae and ice-associated microalgae as a food source in the nearshore environment across different mesoregions.

Q: Fish connectivity

Q: Variation in ice affiliated versus migratory upper trophic predator species abundance and composition across the Gerlache Strait(mCDW v WS mesoregions) and into/out of Gerlache (i.e. from Bransfield Strait) – particularly at the temporal margins (autumn & spring)

3. Stressors:

Q: Junkfood Hypothesis as an asymmetrical stressor (sensu salps v krill)

Q : Sedimentary runoff increases near to bases

Q: Regional (sub WAP spatial scale) heatwaves and local impacts

Q: Benthic scouring by sea ice / ice bergs

Q: IAATO overnight stops and impacts on local communities (fish, benthic zoofauna

Q: IAATO prolonged and multi-vessel visitations, and the restructuring of benthic communities.

Q: IAATO marine mammal and bird strikes / near misses, and efficacy of speed limitations

4. Connectivity between microregions:

Q: (relative larval movement through WS advection and mCDW advection).

Q: acoustic tagging (vrap like) of notothenids for dispersion.

Q: Biogeochemical (compound specific) isotopic niche width across mesoregion boundaries

Q: Top predator guild composition within and across mesoregions