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THE SOUTHERN OCEAN: OUR BEST OPPORTUNITY?

O Oceano Antártico: nossa melhor oportunidade?

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ABSTRACT

The Southern Ocean has a significant importance in global climate regulation because its great potential to sequester atmospheric carbon and its enormous contribution to the transport of heat and mass in the global ocean. Antarctic benthos presents unique characteristics developed after millions of years of evolution and greatly contribute to the maintenance of the global biodiversity and genetic pool. Ongoing anthropogenic pressure seriously threatens Southern Ocean's current characteristics and the ecosystems services they provide. In my opinion, individual actions toward environmental protection emerges as the fastest alternative to ameliorate the current situation.

Keywords: Antarctica, climate change, anthropogenic impacts, social behavior.

RESUMO

O Oceano Antártico tem importância significativa na regulação do clima global devido ao seu grande potencial para sequestrar carbono atmosférico e sua enorme contribuição para o transporte de calor e massa no oceano global. O bentos antártico apresenta características únicas, que foram desenvolvidas após milhões de anos de evolução, e contribui para a manutenção da biodiversidade global e do patrimônio genético. A pressão antropogênica contínua ameaça seriamente as características atuais do Oceano Antártico e os serviços ecossistêmicos que ele fornece. Na minha opinião, as ações individuais voltadas para a proteção do meio ambiente surgem como a alternativa mais rápida para amenizar a situação atual.

Palavras-chave: *Antártica, mudanças climáticas, impactos antropogênicos, comportamento social.*

INTRODUCTION

Antarctica and its polar climatic conditions started developing approximately 30 million years ago when the opening of the Tasmanian Gateway enabled the onset of the Antarctic Circumpolar Current, which modified the global ocean circulation (Scher *et al.*, 2015) and greatly contributed to the near thermal isolation of the current white continent. This geophysical characteristic gives to the Antarctic region a significant importance for the global climate regulation. Due to the massive sinking of cold, dense water, it has a major force in the ocean's thermo-haline circulation (also known as the global conveyor belt), which drives energy and matter around the globe, balancing heat among the equator and the poles (Gordon, 2001). Its enormous white colored surface (up to 40 million km^2 in winter and half of it during summer) has a high solar radiation reflective capacity or albedo, a very valuable aid to reduce global warming (Laine *et al.*, 2008). Further, the upper ocean mixing caused by strong westerly winds around the continent, makes the Southern Ocean (SO) very effective at absorbing the greenhouse gas carbon dioxide (CO_2) from the atmosphere, alleviating the ongoing increasing concentration trend of this gas. Most of CO_2 sequestration from the atmosphere takes place during summer. In this season, the SO hosts massive phytoplankton blooms, which transform gaseous carbon from the atmosphere (in the form of CO_2) into particulate organic material that sinks and feed abundant life forms thriving both in the water column and on the seabed, where eventually gets buried for thousands, even millions of years. The importance of the Antarctic region for life on Earth, as we know it nowadays, is fundamental; however, invisible.

The fauna dwelling on the Antarctic seabed has a long history too. The Antarctic continental shelf benthos has been evolving separated from its lower-latitude counterparts in rather constant conditions of low temperature, salinity and darkness since the late Cretaceous, millions of years ago (Arntz; Brey & Gallardo, 1994; Gili *et al.*, 2006). At shallower depths, benthos has been exposed to a drastic seasonality in light availability and sea ice cover, which strongly modulates life in the Antarctic. Unique environmental conditions of low temperature (mainly between -2ºC and 5ºC, depending on water depth), salinity (mainly between 34.6‰ and 34.9‰) and seasonality in sea ice extent and primary production, shaped the contemporary Antarctic benthic assemblages. These communities can reach biomasses representing > 3 kg of wet weight per m^2, both at shallow (< 100 water depth) and deep areas (> 300 m water depth) (Sáiz-Salinas *et al.*, 1997; Isla & Gerdes, 2019). Approximately 17 000 species of marine invertebrates constitute these communities, which show the highest endemism proportion of any continent and unique evolutionary characteristics (Arntz; Brey & Gallardo, 1994; Peck, 2018). Nevertheless, environmental conditions are dynamic and had changed since the Cretaceous. Along this time span, the Antarctic has undergone several glaciations and interglacial periods, with environmental conditions that modulated the geographic and bathymetric distribution of benthic fauna (Thatje; Hillenbrand & Lartes, 2005), with the last glacial maximum approximately 15000 to 18000 years ago. It has been proposed that since then, deep-sea benthic fauna recolonized the open space at the continental shelf, preserving the unique evolutionary characteristics observed at present (Thatje; Hillenbrand & Lartes, 2005; Thatje *et al.*, 2008). Currently, environmental changes derived from industrial activity are modifying the Antarctic marine environment at an unprecedented pace, which challenges the adaptation capacity of its biota, developed after millions of years of evolution (Arntz; Brey & Gallardo, 1994; Gutt *et* *al.*, 2018; Peck, 2018; Gutt *et al.*, 2021). Losing Antarctic marine biota will severely impact the maintenance of global biodiversity and genetic pool, which are some of the key ecosystem services that the Antarctic provides (Grant *et al.*, 2013; Pertierra *et al.*, 2021). Ecosystem services are the benefits that mankind obtains from natural ecosystems and, in the case of the Antarctic, in spite of being thousands of kilometers away from any human settlement not related to scientific activities. Other key Antarctic ecosystems services are the provision of fishery products, nutrient cycling, climate and air quality regulation and the cultural and marvelous aesthetic benefits, which we all can enjoy despite not being there.

Major threats

At present, climate change is perhaps the most important threat for Antarctic ecosystems (Gutt *et al.*, 2021). For example, ocean acidification will eventually impact the entire Antarctic region (Gutt *et al.*, 2015). Information on anthropogenic pollution is steadily increasing on both, its spatial extent and the presence of different types of pollutants, especially for plastics. However, regardless of the research line, understanding on the various biogeochemical and physical processes involved in the ongoing transformation of the Antarctic environment and the consequences for its biota, is still poor. To tackle this situation, International and cross-disciplinary scientific actions are urgent due to the rapid transformation pace of the SO and the impact on its inhabitants (Kennicutt II *et al.*, 2019; Gutt *et al.*, 2018, 2021). During the last decade there have been substantial advances in identifying knowledge gaps and organizing future scientific directions to better understand the Antarctic system and its influence on Earth's climate (Kennicutt II *et al.*, 2015, 2019; Gutt *et al.*, 2021). These advances aim to provide basis for accurate predictions to enlighten politicians, decision makers and the general public to take action towards a proper management and preservation of a continent, where it seems the anthropogenic footprint is still comparatively weak at a global scale.

The Antarctic already faces several anthropogenic threats and most likely the number will increase as human and industrial pressure and the measuring tools and their detection levels will do so. To describe all the ongoing and potential threats for the Antarctic will be sufficient to write a book but, given the limits of the present contribution, a good way to summarize, at least some them, is by their geographic extent (Gutt *et al.*, 2015), which in many cases can overlap, locally increasing their impact. For example, on the continental shelf and the coastal zone, where several of the most evident ongoing threats co-occur.

Ocean warming - shift of the polar front

Ocean warming affects the entire sea surface; however, temperature increases which may produce significant physiological responses in marine organisms have been identified in about 1 K (Peck, 2011; Peck *et al.*, 2014). This temperature increase affects already about 3% of the 50 m water column of the SO (~ 1 x 10^6 km^2), where the western Antarctic Peninsula (WAP) stands as the most affected (Gutt *et al.*, 2015). However, the deep ocean also carries a warm signal (Gille, 2002); the water masses flowing between 700 m and 1000 m water depth are about 0.2ºC warmer than in the 1950's and periodically intrude onto the continental shelf (~ 3 x 10^6 km^2, taken from Peck, 2018), which represents about 9% of the SO. This temperature increase has not reach 1 K yet; however, it is already contacting with the benthic fauna dwelling on the Antarctic continental shelf (Isla & Gerdes, 2019). Most of these continental shelf communities are constituted by sessile animals, which show low adaptation capacities and most likely won't be able to avoid temperature stress (Peck, 2018). Increasing temperatures may also produce an impact in the oxygen ventilation of the SO, nutrient fluxes and a possible collapse of ice-shelves, which could have an impact on entire marine communities (Gutt *et al.*, 2021). As temperature increase at the sea surface, the Antarctic Polar Front, dividing cold (5ºC to 2ºC) from freezing (< 2ºC) waters, migrates to the South together with its accompanying fauna, reducing the northern limit for Antarctic biota and enhancing the chances for non-indigenous fauna to colonize the Antarctic (Griffiths; Meijers & Bracegirdle, 2017). The southward migration of the Antarctic Polar Front represents an area of approximately 7% of the SO (~ 2 x 10^6 km^2).

Sea ice season length and extent

Sea ice extent is also changing in the Antarctic. Unlike the Arctic trend, sea ice in the Ross and the Weddell Seas presented sea ice extent increases in contrast to the evident retreats registered off the WAP (Gutt *et al.*, 2015). Observed sea ice extent increase maxima during 1979 to 2012 occupied approximately 3% of the SO in the Ross Sea and Weddell Sea sectors (~1 x 10^6 km^2), whereas decreases mainly off the WAP, were only 1.8% (0.6 x 10^6 km^2). Nevertheless, in the 2016/17 season an unprecedented rapid decrease and larger spatial retreat in sea ice extent was observed for the Weddell Sea (Turner *et al.*, 2017, 2020). Up to date, sea ice loss for the Antarctic seems to be balanced with sea ice increase; however, locally these variations produce impacts on the distribution of pelagic species such as salps and krill (Atkinson *et al.*, 2004; Montes-Hugo *et al.*, 2009). Krill populations are migrating toward the South, where colder and polar conditions persist at the time that salps occupy the northern areas, where warmer temperatures coexist with less sea ice. Krill is especially important in the Antarctic food web because its protein and energy content (higher than that in salps) maintains large biomasses of fish, mammals and birds (Savage & Foulds, 1987; Dubischar *et al.*, 2012; Harmelin-Vivien *et al.*, 2019). In addition to the cascading effects on the Antarctic trophic levels, especially for species primarily feeding on krill, the transfer of organic carbon to the sea floor may be also compromised. An 11-year time series off the WAP revealed that zooplankton community migration may have an impact on particle fluxes collected at 350 m depth (Ducklow *et al.*, 2007). Higher abundance of salps leaded to higher particle fluxes, whereas the dominance of krill was weakly related to smaller fluxes. In consequence, the supply of biogenic matter (e.g., organic carbon and biogenic silica) to sea floor may be also changing; hence, impacting benthos and the storage of carbon in sediment column (Sañé *et al.*, 2011, 2012; Isla & DeMaster, 2018).

Ice shelf disintegration and iceberg scouring

Warming of the ocean and the atmosphere is contributing to make ice shelf disintegration a regular event every austral summer. Ice shelf collapses reduce the albedo capacity of the Antarctic, negatively feeding back global warming. Since the 1960's this process affects 0.03 x 10^6 km^2 (Gutt *et al.*, 2015). In the absence of peer reviewed literature (at least to the author's knowledge) and based on public media information, during the last 6 years, this area has increased at least in 10 000 km^2, adding 4320 km^2 of iceberg A-76 and 6000 km^2 from the massive iceberg A-68, which calved from the Ronne (https://www.esa.int/esearch?q=a-76) and Larsen C Ice Shelves (https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Sentinel_satellite_captures_birth_of_ behemoth_iceberg), respectively; both events occurred in the Weddell Sea. Ice shelf collapses also open space for primary production at the sea surface (Bertolin & Schloss, 2009) and a subsequent flux of organic matter to the seabed that stimulates benthic colonization of the sea floor (Sañé *et al.*, 2011, 2012). It has been speculated that eventually, the sediment column beneath areas where ice shelves recently collapsed (e.g. years to decades ago), will accumulate carbon, alleviating ongoing global warming. However, it has been observed that carbon accumulation in these areas may take decades before becoming an effective carbon sink (Isla & DeMaster, 2018). Large icebergs generated after ice shelf collapses strongly erode the seabed, completely removing macrobenthic life but also stimulating recolonization processes, which are fundamental to maintain biodiversity (Gutt & Starmans, 2001). Projections for the end of the present century suggest that 65% of the entire Antarctic shelf will be affected by iceberg scouring (Gutt *et al.*, 2015). Given that the ice shelves at the western Weddell Sea are under high climate stress (Hellmer *et al.*, 2017), the northward circulation path of the Weddell Gyre and that iceberg scouring typically occurs over areas down-stream from the iceberg's starting drifting point, the eastern continental shelf of the Antarctic Peninsula emerges as an area especially favorable for iceberg scouring. Large icebergs can also release abundant and diverse microbial life and nutrients into the adjacent water column along their drifting paths, stimulating biological production and generating a positive effect for the marine biota (Smith Jr. *et al.*, 2007; Boetius *et al.*, 2015).

Marine glacier retreats

Antarctic marine glacier fronts have been retreating, particularly on the Antarctic Peninsula and the islands nearby, where 90% of glacier fronts showed clear retreats since the second half of the past century (Davies *et al.*, 2012; Cook *et al.*, 2016). It has been calculated that approximately 1% of Antarctic circumference has been affected by this process so far (Gutt *et al.*, 2015). Most likely the spatial extent of this process will increase in the future given the ongoing temperature increasing trend. Despite that fact that melting of glaciers may represent a comparatively small spatial extent, the local impact of this process could be of high importance because of its cascading effects on the biota. On a first step, melt water inputs may fertilize the marine water column stimulating algal blooms and sinking organic carbon fluxes (Gutt *et al.*, 2021); however, eventually, the sediment loads from glacier inputs may collapse entire zooplankton populations and the adjacent benthic communities interrupting the flux of organic carbon to higher trophic levels (Sahade *et al.*, 2015; Fuentes *et al.*, 2016). It has been observed that the bays and fjords shaping the Antarctic Peninsula coast line host high primary production rates, which enable the export of organic carbon to the open sea maintaining pelagic life there (Isla *et al.*, 2004; Höfer *et al.*, 2019). However, if production near the coast is compromised it may propagate its negative effects to the areas off shore. Further, releases of anthropogenic pollutants accumulated on top of the ice caps can reach the adjacent water column via glacier runoffs and eventually affect the Antarctic marine biota (please see the Anthropogenic Pollution Section).

Ocean acidification

So far, ocean acidification (OA) appears as the single factor able to affect the entire SO in the near future (Gutt *et al.*, 2015). The SO is especially sensitive to OA because of its great extent and consequent atmospheric CO_2 absorbing capacity, the enhanced solubility of CO_2 at lower temperatures, naturally low levels of calcium carbonate (added to higher solubility in projected more acidic water masses) in its waters, and a lower buffering capacity to attenuate acidic effects (Petrou *et al.*, 2019; Hancock *et al.*, 2020). Further, strong upwelling, bringing deep CO_2-rich waters to the surface, produces a synergistic effect (Land *et al.*, 2015; Hancock *et al.*, 2020). OA affects important species in the pelagic and benthic systems such as calcifying coccolithophorids and pteropods, echinoderms and corals (Doney *et al.*, 2009; Riebesell & Tortell, 2011; Bednaršek *et al.*, 2012; Wittmann & Pörtner, 2013), consequently, several trophic interrelationships could change. It is expected that the efficiency of phyotosynthesis and the biological carbon pump may be also compromised (Riebesell *et al.*, 2007; Tortell *et al.*, 2009; Hofmann *et al.*, 2011a,b). For example, reductions of 30% to 35% in foraminifera shell weight compared to preindustrial weights were found at the northern margin of the SO (Moy *et al.*, 2009). However, given the central position of krill in the Antarctic trophic relationships (e.g., feeding fish, mammals and birds), it is of great concern that the development and the carbonate structures of young Antarctic krill, echinoderms and molluscs may be disrupted (Bylenga; Cummings & Ryan, 2017). Further, the hatching success and suitable habitat of krill is projected to decrease (Kawaguchi *et al.*, 2013).

Anthropogenic pollution

Anthropogenic pollutants are widespread over the Antarctic, mainly due to long-range atmospheric transport (LRAT), which drives pollutants thousands of kilometres along a sequence of deposition and resuspension events (Grannas *et al.*, 2013). LRAT moves semi-volatile organic pollutants to high latitudes with an estimated transport time of a week or less from their sources at lower latitudes (Wania, 2003; Grannas *et al.*, 2013). Once at the SO, anthropogenic pollutants also accumulate on top of Antarctic ice caps and remain latent until snow and glacier melting occurs, driving these molecules into the adjacent water column and eventually in the food web (Corsolini, 2009). For example, DDT has been found in penguin fat despite been banned or severely restricted since the 1970s, most likely because DDT deposited onto glaciers surface, has been released into the adjacent water column, where it incorporated into the marine food web (Geisz *et al.*, 2008). Persistent organic pollutants or POPs (e.g., polycyclic aromatic hydrocarbons (PAHs), polychlorobiphenyls (PCB), organochlorine pesticides) have been observed along the Antarctic trophic food web from phytoplankton to birds (Risebrough *et al.*, 1976; Chiuchiolo *et al.*, 2004; Geisz *et al.*, 2008). Antarctic low temperatures and long periods of darkness, "cold-trap" anthropogenic pollutants, enhancing their persistence in this polar setting (Potapowicz *et al.*, 2019). Further, POPs have been detected in the high-latitude Antarctic 235 km away from the coastline; although, with lower levels than those observed in the Arctic (Kallenborn *et al.*, 2013). In addition to POPs, the presence of plastics, particularly microplastics, is becoming more evident every season, despite it seems to be more concentrated near touristic and research facilities. Apparently, the major source of microplastics to the marine environment is the laundry activity of these facilities (Alurralde *et al.*, 2022). Heavy metals also reach the Antarctic via LRAT (e.g., from mining and combustion); however, paint debris and inadequate waste management from vessels and research stations have been identified as a source of these pollutants too (Bargagli, 2008). Up to date, the predominant heavy metals found in the Antarctic are Al, Ca, Cd, Cr, Cu, Pb and Zn with the highest concentrations in the vicinity of polar stations (Potapowicz *et al.*, 2019).

Challenges

Preserving our planet's environment is currently our major challenge because life as we know it nowadays, depends on this. Within this frame, Southern Ocean's environment, is fundamental because of the important role as global climatic regulator and biodiversity reservoir. Geophysical boundaries are no longer effective; anthropogenic pressure already demonstrated its strength in breaking barriers and its effects on the Antarctic are already visible. In the scientific community, there is consensus on the need for urgent international plans to improve our knowledge on the physical and biogeochemical processes governing the transformation of the Antarctic, which appears as a challenge due to the organization level that these plans may require and the rapid pace of ongoing climate change (Kennicutt *et al.*, 2019). For example, implementing a coordinated network of systematic, cross-disciplinary circumpolar oceanographic expeditions to produce simultaneous physical-biogeochemical data sets and a Pan-Antarctic picture of the current environmental variation. Coordinating satellite data acquisition with field observations to better understand ocean-atmosphere coupling processes. Establishing a network of long-term (decadal) observing stations to generate comparable data sets along the Antarctic and accurately distinguish natural and anthropogenic variations to develop environmental predictions with higher confidence. However, in my opinion, two other important challenges emerge; on the one hand the scientific community should provide clear, convincing messages to stake-holders, who may trigger effective actions directed to reduce the deterioration of the environment and preserve the Antarctic. On the other hand, another set of messages, if different to those for stake-holders, directed to the general public aiming to change the way we live on daily basis. From my point of view, the solution to change the direction we are moving on, is based on individual behavior/actions. We, as individuals, families, neighborhoods and ultimately countries, should act thinking on how our behavior will impact the environment. Not only on the Antarctic, also on our parks, cities, urban water and garbage systems, etc. Any action counts.

We now know that despite some of our "business as usual" actions are not visible nearby, they produce an effect in remote places. The Antarctic is perhaps the least impacted region of the planet and its ecosystem services benefit all of us, so taking care of our nearby, and consequently, our remote environment, it is perhaps, our best opportunity to demonstrate ourselves that we really can change for our own good.

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REFERENCES

Alurralde, G.; Isla, E.; Fuentes, V.; Olariaga, A.; Maggioni, T.; Rimondino, G. & Tatián M. Anthropogenic microfiber flux in an Antarctic coastal ecosystem: the tip of an iceberg? *Mar. Poll. Bull.*, v. 175, 113388, 2022. DOI: 10.1016/j.marpolbul.2022.113388.

2022. DOI: 10.1016/j.marpolbul.2022.113388..

Arntz, W.E.; Brey, T. & Gallardo, V.A. Antarctic zoobenthos. *Oceanogr. Mar. Biol. Ann. Rev.*, v. 32, p. 241-304, 1994.

Atkinson, A.; Siegel, V.; Pakhomov, E. & Rothery, P. Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, v. 432, p. 100-103, 2004.

Bargagli, R. Environmental contamination in Antarctic ecosystems. *Sci. Total Environ.*, v. 400, p. 212-226, 2008.

Bednaršek, N.; Tarling, G.A.; Bakker, D.C.; Fielding, S.; Cohen, A.; Kuzirian, A. & Montagna, R. Description and quantification of pteropod shell dissolution: a sensitive bioindicator of ocean acidification. *Global Change Biol.*, v. 18, p. 2378-2388, 2012.

Bertolin, M.L. & Schloss, I.R. Phytoplankton production after the collapse of the Larsen A Ice Shelf, Antarctica. *Polar Biol.*, v. 32, p. 1435-1446, 2009.

Boetius, A.; Anesio, A.M.; Deming, J.W.; Mikucki, J.A. & Rapp, J.Z. Microbial ecology of the cryosphere: sea ice and glacial habitats. *Nature Rev. Microbiol.*, v. 13, p. 677-690, 2015. DOI: 10.1038/nrmicro3522.

Bylenga, C.H.; Cummings, V.J. & Ryan, K.G. High resolution microscopy reveals significant impacts of ocean acidification and warming on larval shell development in Laternula elliptica. *PLoS One*, v. 12, e0175706, 2017.

Chiuchiolo, A.L.; Dickhut, R.; Cochran, M.A. & Ducklow, H.W. Persistent organic pollutants at the base of the Antarctic marine food web. *Environ. Sci. Tech.*, v. 38, p. 3551-3557, 2004.

Cook, A.J.; Holland, P.R.; Meredith, M.P.; Murray, T.; Luckman, A. & Vaughan, D.G. Ocean forcing of glacier retreat in the western Antarctic Peninsula. *Science*, v. 353, p. 283-286, 2016. DOI: 10.1126/science.aae0017.

Corsolini, S. Industrial contaminants in Antarctic biota. *J. Chromatogr. A*, v. 1216, p. 598-612, 2009.

Davies, B.J.; Carrivick, J.L.; Glasser, N.F.; Hambrey, M.J. & Smellie, J.L. Variable glacier response to atmospheric warming, northern Antarctic Peninsula, 1988-2009. *Cryosphere*, v. 6, p. 1031-1048, 2012. https://doi.org/10.5194/tc-6-1031-2012.

Doney, S.C.; Fabry, V.J.; Feely, R.A. & Kleypas, J.A. Ocean acidification: the other CO2 problem. *Ann. Rev. Mar. Sci.*, v. 1, p. 169-192, 2009.

Dubischar, C.D.; Pakhomov, E.A.; von Harbou, L.; Hunt, B.P.V. & Bathmann, U.V. Salps in the Lazarev Sea, Southern Ocean: II. Biochemical composition and potential prey value. *Mar. Biol.*, v. 159, p. 15-24, 2012. DOI: 10.1007/s00227-011-1785-5.

Ducklow, H.W.; Baker, K.; Martinson, D.G.; Quetin, L.B.; Ross, R.M.; Smith, R.C.; Stammerjohn, S.E.; Vernet, M. & Fraser, W. Marine pelagic ecosystems: the west Antarctic Peninsula. *Philos. Trans. R. Soc. B: Biol. Sci.*, v. 362, p. 67-94, 2007.

Fuentes, V.; Alurralde, G.; Meyer, B. & Schloss, I.R.; Aguirre, G.E.; Canepa, A.; Wölfi, A.-C.; Hass, H.C. & Williams, G.N. Glacier melting: an overlooked threat to Antarctic krill. *Sci. Rep.*, 2016. DOI: 10.1038/srep27234, 2016.

Geisz, H.N.; Dickhut, R.; Cochran, M.A.; Fraser, W.R. & Ducklow, H.W. Melting glaciers: a probable source of DDT to the Antarctic marine ecosystem. *Environ. Sci. Tech.*, v. 42, p. 3958-3962, 2008.

Gili, J-M.; Arntz, W.; Palanques, A.; Orejas, C.; Clarke, A.; Dayton, P.K.; Isla, E.; Teixidó, N.; Rossi, S. & López-González P.J. A unique assemblage of epibenthic sessile suspension feeders with archaic features in the high-Antarctic. *Deep-Sea Res. II*, v. 53, p. 1029-1052, 2006.

Gille, S.T. Warming of the Southern Ocean since the 1950s. *Science*, v. 295, p. 1275–1277, 2002.

Gordon, A.L. Bottom water formation, p. 334-340, *in* Steele, J.H. (ed.). *Encyclopedia of ocean sciences*, Academic Press, 2001. ISBN 9780122274305. DOI: 10.1006/rwos.2001.0006.

Grannas, A.M. *et al.* The role of the global cryosphere in the fate of organic contaminants. *Atmos. Chem. Phys.*, v. 13, P. 3271-3305, 2013.

Grant, S.M.; Hill, S.L.; Trathan, P.N. & Murphy, E.J. Ecosystem services of the Southern Ocean: trade-offs in decision-making. *Ant. Sci.*, v. 25, p. 603-617, 2013.

Griffiths, H.; Meijers, A.J.S. & Bracegirdle, T.J. More losers than winners in a century of future Southern Ocean seafloor warming. *Nature Clim. Change*, v. 7, p. 749-754, 2017.

Gutt, J. & Starmans, A. Quantification of iceberg impact and benthic recolonization pattems in the Weddell Sea (Antarctica). *Polar Biol.*, v. 24, p. 615-619, 2001. https:// doi.org/10.1007/ s003000100263.

Gutt, J. *et al.* The Southern Ocean ecosystem under multiple climate change stresses - an integrated circumpolar assessment. *Global Change Biology*, v. 21, p. 1434-1453, 2015.

Gutt, J. *et al.* Cross-disciplinarity in the advance of Antarctic ecosystem research. *Mar. Genom.*, v. 37, p. 1-17, 2018.

Gutt, J. *et al.* Antarctic ecosystems in transition – life between stresses and opportunities. *Biological Rev.*, 2021. https://doi.org/10.1111/brv.12679.

Harmelin-Vivien, M.; Bănaru, D.; Dromard, C.R.; Ourgaud, M. & Carlotti, F. Biochemical composition and energy content of size-fractionated zooplankton east of the Kerguelen Islands. *Polar Biol.*, v. 42, p. 603-617, 2019. DOI: 10.1007/s00300-019-02458-8.

Hellmer, H.; Kauker, F.; Timmermann, R. & Hattermann, H. The fate of the Southern Weddell Sea continental shelf in a warming climate. *J. Clim.*, v. 30, p. 4337-4350, 2017.

Hofmann, G.E. *et al.* High-frequency dynamics of ocean pH: a multi-ecosystem comparison. *PLoS One*, v. 6, e28983, 2011a.

Hofmann, M. *et al.* Declining ocean chlorophyll under unabated anthropogenic CO_2 emissions. *Environ. Res. Lett.*, v. 6, 034035, 2011b.

Höfer, J.; Giesecke, R.; Hopwood, M.J.; Carrera, V.; Alarcón, E. & González, H.E. The role of water column stability and wind mixing in the production/export dynamics of two bays in the Western Antarctic Peninsula. *Progr. Oceanogr.*, v. 174, p. 105-116, 2019.

Isla, E.; Masqué, P.; Palanques, A.; Guillén, J.; Puig, P. & Sanchez-Cabeza, J.A. Sedimentation of biogenic constituents during the last century in western Bransfield and Gerlache straits, Antarctica: a relation to currents, primary production, and sea floor relief. *Mar. Geol*., v. 209, p. 265-277, 2004.

Isla, E. & DeMaster, D.J. Labile organic carbon dynamics in continental shelf sediments after the recent collapse of the Larsen ice shelves off the eastern Antarctic Peninsula: A radiochemical approach. *Geochim. Cosmochim. Acta*, v. 242, p. 34-50, 2018. DOI: 10.1016/j.gca.2018.08.011.

Isla, E. & Gerdes, D. Ongoing ocean warming threatens the rich and diverse microbenthic communities of the Antarctic continental shelf. *Progr. Oceanogr*., v. 178, 102180, 2019. DOI: 10.1016/j.pocean.2019.102180.

Kallenborn, R.; Breivik, K.; Eckhardt, S.; Lunder, C.R.; Manø, S.; Schlabach, M. & Stohl, A. Long-term monitoring of persistent organic pollutants (POPs) at the Norwegian Troll station in Dronning Maud Land, Antarctica. *Atmos. Chem. Phys*., v. 13, p. 6983-6992, 2013.

Kawaguchi, S. *et al.* Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Clim. Change*, v. 3, p. 843-847, 2013. DOI: 10.1038/nclimate1937.

Kennicutt, M.C. II *et al.* A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. *Antarct. Sci*., v. 27, p. 3-18, 2014.

Kennicutt, M.C. II *et al.* Sustained Antarctic research: a 21th century imperative. *One Earth*, v. 1, p. 95-113, 2019.

Laine, V. Antarctic ice sheet and sea ice regional albedo and temperature change, 1981-2000, from AVHRR Polar Pathfinder data. *Remote Sensing Environ*., v. 112, p. 646-667, 2008. https://doi.org/10.1016/j.rse.2007.06.005.

Land, P.E. *et al.* Salinity from Space Unlocks Satellite-Based Assessment of Ocean Acidification. *Environ. Sci. Techn*., v. 49, p. 1987-1994, 2015. DOI: 10.1021/es504849s.

Montes-Hugo, M.; Doney, S.C.; Ducklow, H.W.; Fraser, W.; Martinson, D.; Stammerjohn, S.E. & Schofield, O. Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic Peninsula. *Science*, v. 323, p. 1470-1473, 2009.

Moy, A.D.; Howard, W.R.; Bray, S.G. & Trull, T.W. Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geosci*., v. 2, p. 276-280, 2009.

Peck, L.S. Organisms and responses to environmental change. *Mar. Genom*., v. 4, p. 237-243, 2011.

Peck, L.S. Antarctic marine biodiversity: adaptations, environments and responses to change. *Oceanogr. Mar. Biol. Ann. Rev*., v. 56, p. 105-236, 2018.

Peck, L.S.; Morley, S.A.; Richard, J. & Clark, M.S. Acclimation and thermal tolerance in Antarctic marine ectotherms. *J. Exp. Biol*., v. 217, p. 16-22, 2014.

Pertierra, L.R. *et al.* Ecosystem services in Antarctica: Global assessment of the current state, future challenges and managing opportunities. *Ecosys. Serv*., v. 49, 101299, 2021. DOI: 10.1016/j.ecoser.2021.1012.

Potapowicz, J.; Szumińska, D.; Szopińska, M. & Polkowska, Z. The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost Part I. Case study of Antarctica. *Sci.Total Environ*., v. 651, p. 1534-1548, 2019.

Riebesell, U. *et al.* E. Enhanced biological carbon consumption in high CO_2 ocean. *Nature*, v. 450, p. 545-548, 2007.

iebesell, U. & Tortell, P.D. Effects of ocean acidification on pelagic organisms and ecosystems, p. 99-116, *in* Gattuso, J.P. & Hansson, L. (ed.). *Ocean acidification*. Oxford: Oxford University Press, 2011.

Risebrough, R.W.; Walker II, W.; Schmidt, T.T.; de Lappe, W. & Connors, C.W. Transfer of chlorinated biphenyls to Antarctica. *Nature*, v. 264, p. 738-739, 1976.

Sahade, R. *et al.* Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem. *Sci. Adv.*, v. 1, e1500050-e1500050, 2015. DOI: 10.1126/sciadv.1500050.

Sáiz-Salinas, J.I.; Ramos, A.; García, F.J.; Troncoso, J.S.; San Martin, G.; Sanz, C. & Palacin, C. Quantitative analysis of macrobenthic soft-bottom assemblages in South Shetland waters (Antarctica). *Polar Biol.*, v. 17, p. 393-400, 1997.

Sañé, E.; Isla, E.; Grémare, A.; Gutt, J.; Vetion, G. & DeMaster, D.J. Pigments in sediments beneath a recently collapsed ice shelves: the case of Larsen A and B shelves, Antarctic Peninsula. *J. Sea Res.*, v. 65, p. 94-102, 2011.

Sañé, E.; Isla, E.; Gerdes, D.; Montiel, A. & Gili, J-M. Benthic macrofauna assemblages and biochemical properties of sediments in two Antarctic regions differently affected by climate change. *Cont. Shelf Res.*, v. 35, p. 53-63, 2012.

Savage, G.P. & Foulds, M.J. Chemical composition and nutritive value of antarctic krill (*Euphausia superba*) and southern blue whiting (*Micromesistius australis*). *New Zeal. J. Mar. Freshwater Res.*, v. 21, p. 599-604, 1987. DOI: 10.1080/00288330.1987.9516264.

Scher, H.D.; Whittaker, J.M.; Williams, S.E.; Latimer, J.C.; Kordesch, W.E.C. & Delaney, M.L. Onset of Antarctic Circumpolar Current 30 million years ago as Tasmanian Gateway aligned with westerlies. *Nature*, v. 523, p. 580-583, 2015.

Smith Jr. *et al.* Free-drifting icebergs: hot spots of chemical and biological enrichment in the Weddell Sea. *Science*, v. 317, p. 478-482, 2007. DOI: 10.1126/science.1142834.

Thatje, S.; Hillenbrand, C.D. & Larter, R. On the origin of Antarctic marine benthic community structure. *Trends Ecol. Evol.*, v. 20, p. 534–540, 2005.

Thatje, S.; Hillenbrand, C.D.; Mackensen, A. & Larter, R. Life hung by a thread: endurance of Antarctic fauna in glacial periods. *Ecology*, v. 89, p. 682–692, 2008.

Tortell, P.D.; Trimborn, S.; Li, Y.; Rost, B. & Payne, C.D. Inorganic carbon utilization by Ross Sea phytoplankton across natural and experimental CO2 gradients. *J. Phycol.*, v. 46, p. 433-443, 2009.

Turner, J.; Phillips, T.; Marshall, G.J.; Hosking, J.S.; Pope, J.O.; Bracegirdle, T.J. & Deb, P. Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophys. Res. Lett.*, v. 44, p. 6868-6875, 2017. DOI: 10.1002/2017GL073656.

Turner, J. *et al.* Recent decrease of summer sea ice in the Weddell Sea, Antarctica. *Geophys. Res. Lett.*, v. 47, e2020GL087127, 2020. https://doi.org/ 10.1029/2020GL087127.