Bargagli, R., & Rota, E. (2025). Influence of regional variations in ocean characteristics and trophic relationships on cadmium accumulation in Antarctic pelagic and benthic organisms. *Ukrainian Antarctic Journal*, *23*(2), 53–68.
https://doi.org/10.33275/1727-7485.2.2025.750

Influence of regional variations in ocean characteristics and trophic relationships on cadmium accumulation in Antarctic pelagic and benthic organisms

Roberto Bargagli, Emilia Rota*

University of Siena, Siena, 53100, Italy

*** Corresponding author:** rota@unisi.it

Abstract. Cadmium (Cd) concentrations in Antarctic marine organisms are much higher than expected for such a remote, pristine environment. Bioaccumulation is principally due to water circulation and upwelling, as well as the nutrient-like behaviour of Cd in areas of high primary productivity. The low availability of zinc (Zn) and other trace elements favours Cd use by diatoms as a cofactor in carbon anhydrase, and the metal is also highly concentrated by small autotrophs and heterotrophs that develop a high surface-to-volume ratio. Thus, in pelagic food webs, grazing micro- and mesozooplankton, as well as the juvenile stages of Antarctic krill with a small oral apparatus, accumulate high concentrations of Cd and transfer the metal to amphipods and other secondary consumers. In coastal marine ecosystems with high primary productivity, such as those bordering the Ross Sea, a large amount of phytoplankton sinks in the summer, contributing to Cd accumulation in benthic invertebrates. Total body Cd concentrations are lower in benthic and pelagic fish, seabirds, and marine mammals than in many invertebrate species. Seabirds that feed on amphipods and other crustaceans smaller than Antarctic krill accumulate higher amounts of Cd. Comparisons of Cd content in representative benthic invertebrate species, fish, and penguins from coastal marine ecosystems at King George Island and Terra Nova Bay (Ross Sea) indicate much higher bioaccumulation in the latter area. This is likely due to enhanced upwelling of seawater, high concentrations of soluble Cd in surface waters, notable algal blooms in spring and summer, and the involvement of invertebrate taxa other than Antarctic krill in transferring energy and metals along pelagic food webs.

Keywords: benthic communities, bioaccumulation, biophysical environmental settings, Cd, pelagic food webs, Southern Ocean

1 Introduction

Cadmium (Cd) makes up just 0.000015% of the Earth's crust. Unlike other heavy metals such as lead (Pb) and mercury (Hg), which have a long history of use, cadmium was not officially discovered until 1817, and its large-scale production only began less than a century ago. However, it was soon recognized as one of the most dangerous metals for the environment and human health and has been a concern for the EU since the 1970s (Ulrich, 2019). Consequently, numerous biomonitoring surveys of terrestrial and aquatic ecosystems began around fifty years ago, and those conducted in Antarctica, the last great wilderness on Earth, almost untouched by human activity, yielded unexpected and surprising results (Bargagli, 2008). Very high Cd concentrations were detected in the kidneys of Weddell seals (*Leptonychotes weddellii* (Lesson, 1826)) (Yamamoto et al., 1987) and minke whales (*Balaenoptera acutorostrata* Lacépède, 1804) (Honda et al., 1987), in species of pelagic crustaceans (Rainbow, 1989; Petri & Zauke, 1993), and in the benthic mollusc *Adamussium colbecki* (E. A. Smith, 1902) (Mauri et al., 1990). A comprehensive survey of coastal ecosystems at Terra Nova Bay (Ross Sea) revealed much higher concentrations of Cd in seawater, top sediments, phytoplankton, zooplankton, benthic invertebrates, and the livers and kidneys of fish than those measured by the same laboratory in equivalent environmental matrices from Mediterranean coastal ecosystems, which are much more impacted by human activities (Bargagli et al., 1996). The study concluded that Cd bioaccumulation in the Southern Ocean is a natural process and that Antarctic marine organisms have evolved in an environment with high bioavailability of the metal. In fact, Cd behaves similarly to phosphate (PO_4^{3-}) in the oceans (Boyle et al., 1976). In Terra Nova Bay, there are no natural or anthropogenic sources of the metal, and Cd concentrations in surface waters were observed to decrease from 66 ± 12 in spring to 13 ± 1 ng L^{-1} after the summer algal bloom (Capodaglio et al., 1991). The hypothesis of natural Cd bioaccumulation was later supported by the finding that seal hairs and lake sediments from King George Island (sub-Antarctica) showed no temporal variation in Cd concentrations over the past 1 500 years (Yin et al., 2006). Moreover, Cd levels higher than those usually associated with kidney damage in mammals were found in ringed seals (*Pusa hispida* (Schreber, 1775)) from Greenland (Dietz et al., 1998); since no kidney damage was evident, it was concluded that Arctic marine mammals were also likely to be adapted to high Cd levels.

It is known (e.g. Price & Morel, 1990; Finkel et al., 2007) that marine diatoms can use Cd as a cofactor in carbon anhydrase in waters with limited zinc (Zn) availability. However, the biogeochemical cycle and potential physiological role of Cd in marine organisms are not fully understood (Jiang et al., 2025). Considering the natural occurrence of high concentrations of soluble Cd in surface waters in spring (Capodaglio et al., 1991), it cannot be excluded that algae other than diatoms and their consumers could absorb the metal independently of any biochemical function.

Several biomonitoring surveys have examined Cd accumulation in Antarctic marine organisms (e.g. Jerez et al., 2013; Fromant et al., 2016; Webb et al., 2020; Tian et al., 2023; Ge et al., 2024). However, most of the available data refer to a single species or location, and a general overview of the metal distribution and availability in pelagic and benthic communities of different Southern Ocean regions is lacking. Phytoplankton, especially diatoms, play a key role in transferring Cd from waters to grazing zooplankton. Thus, the spatial distribution and composition of autotrophic communities likely influence the metal uptake by primary consumers and its transfer to higher trophic levels. In aquatic environments, the ad/absorption of metals by algae primarily occurs via passive mechanisms (Lee & Fisher, 2016), resulting in the largest bioconcentration step, especially in communities of pico- and nano-phytoplankton, which develop very high surface-to-volume ratios. Marine invertebrates and terminal consumers in cold Antarctic seawaters could also accumulate larger quantities of Cd than related species from other seas, because they have slower growth rates, longer life cycles, later sexual maturity, and a potentially slower ability to detoxify and excrete Cd.

Climate change and the melting of glaciers are modifying seawater salinity, stratification and circulation, especially in West Antarctica (Schofield et al., 2024), with increasing inputs of essential trace elements such as Zn, iron (Fe), copper (Cu) and cobalt (Co), as well as legacy heavy metals such as Hg, Pb and Cd (Potapowicz et al., 2019). Changes in sea ice thickness and extent will increase light availability, likely altering the development and composition of phytoplankton communities and the biogeochemical cycle of trace elements (Krumhardt et al., 2022). In this context, an overview of the available data on Cd distribution in different Antarctic marine ecosystems is needed to better understand the main environmental and bio-ecological factors that affect Cd bioaccumulation in pelagic and benthic food webs, as well as the potential impact of climate and environmental changes on the Cd biogeochemical cycle.

2 Cycling and bioavailability of cadmium in the Southern Ocean

The phytoplankton communities of the Southern Ocean are dominated by diatoms, which play a very important role in global carbon storage. In fact, diatoms are larger than many other algal plankton, and their frustules (silica cell walls) promote the sinking and transfer of carbon to the deep ocean. This biological carbon pump influences the distribution of major and trace elements in Southern Ocean waters, as well as the global biogeochemistry of oceans through the northward flow of deep Antarctic waters. The ecological success of diatoms and their ability to form massive annual algal blooms are due to their distinctive structural and metabolic features. These algae actually have a complex evolutionary history, containing genes from archaea, bacteria, green and red algae, and animals in their genome (Xu et al., 2008). They possess a unique pigment composition, distinct from plants and other algae, and several metalloenzymes (carbonic anhydrases) that enable them to rapidly interconvert HCO_3^- and CO_2.

It is well known that Cd concentrations in the seawater column follow the distribution of macronutrients, and that diatoms are less sensitive to high concentrations of Cd ions than coccolithophores, dinoflagellates, and especially cyanobacteria (Brand et al., 1986). Price and Morel's (1990) discovery that Cd additions can enhance the growth of marine diatoms in Zn-limited waters, and that some diatom anhydrases use Cd or Co as cofactors rather than the canonical Zn, suggests that Cd can behave as an essential element, at least for diatoms (Jensen et al., 2019). Thus, the cycling and fate of Cd in the oceans are closely linked to the development of algae that deplete dissolved Cd in surface waters. Through sinking and re-mineralization, they increase its concentrations in the thermocline. Consequently, dissolved Cd concentrations exhibit a nutrient-type profile within the water column and are strongly correlated with phosphate (PO_4) and nitrate (NO_3) concentrations. However, due to the upwelling of nutrient-rich waters and the limited availability of Fe and other essential trace elements, the Southern Ocean is the largest high-nutrient low-chlorophyll (HNLC) region in the world. Under these conditions, phytoplankton cells with Cd-binding ligands (de Baar et al., 2017) can absorb large amounts of the metal relative to PO_4 and NO_3 (Vance et al., 2017). Diatoms have the highest Cd:P ratios compared to other phytoplankton taxa, and the tight coupling between their Cd and silicon (Si) concentrations confirms that they are important users of these elements (Sieber et al., 2019a). Thus, the cycling and bioavailability of Cd in different zones of the Southern Ocean depend on the interplay of seasonal mixing and upwelling of waters, the availability of Fe, Zn, and other essential trace elements, and the composition of phytoplankton assemblages.

Using a dataset of nearly 9 000 measurements of dissolved Cd, Jiang et al. (2025) estimated that the global ocean contains about 68–70 million metric tons of the metal, with a mean concentration of 0.51 nmol kg^{-1}. Due to water circulation and biological uptake, values are low in surface waters (the global average is 0.13 nmol kg^{-1}) and increase with depth, mirroring the concentrations of PO_4 and NO_3. The combined effects of low irradiance and low availability of Fe and other trace elements, together with strong vertical water mixing, contribute to higher concentrations of soluble Cd (>0.2 nmol kg^{-1} with values up to 1 nmol kg^{-1} at depths of 100–200 m) in surface waters south of the Polar Front than in waters from the sub-Antarctic Zone (often <0.01 nmol kg^{-1}) (Sieber et al., 2019b). In deeper waters, Cd concentrations remain relatively constant; however, values vary significantly in the euphotic zone across the different sectors of the Southern Ocean. The highest concentrations (>0.5 nmol kg^{-1}) occur in the open ocean waters of the Ross and Weddell gyres (Sieber et al., 2019b). Regarding the distribution of the different chemical forms of the metal, a study on the biogeochemistry of Cd and Zn in the Amundsen Sea (Tian et al., 2023) reported high concentrations of biogenic metal particulates in the surface waters, which decreased with depth as the biogenic particles were mineralized. Meanwhile, concentrations of Cd and Zn in lithogenic particulates within the water column were very low. The main sources of dissolved metals in the Amundsen Sea were found to be the Circumpolar Deep Waters, with small fluxes from shelf sediments. Atmospheric deposition and sea ice melt were deemed to be insignificant sources. Previous studies (e.g. Lannuzel et al., 2011) have also observed that, rather than atmospheric deposition, seawater is the main source of trace elements in Antarctic sea ice, and that seasonal sea ice melt does not significantly contribute to the concentrations of bioactive metals such as manganese (Mn), Cu, Zn, and Cd, except for Fe. The GEOTRACE database (https://www.geotraces.org/tag/southern-ocean/) shows that concentrations of these elements in Southern Ocean waters vary significantly throughout different regions. Antarctic phytoplankton, especially diatoms, play a crucial role, acting as a sink and regulating their concentrations and distribution in the water column (Bargagli & Rota, 2024a; de Souza & Morrison, 2024; Ge et al., 2024). Moreover, Cd and other metals accumulated by autotrophs contribute to the transfer to marine organisms at higher trophic levels through ingestion by grazing zooplankton.

3 Cadmium in Antarctic pelagic food webs

Collection and chemical analysis of different phytoplankton taxa are very difficult processes, and the limited data available from the Southern Ocean refers to mixed samples containing autotrophic and heterotrophic organisms and organic and inorganic particulates. Bargagli et al. (1996) measured Cd concentrations ranging from 0.8 to 4.8 mg kg^{-1} dry wt (mean = 2.1 ± 0.9 mg kg^{-1} dry wt) in 10 samples collected with conical nylon nets (50 μm mesh size) in the inner continental shelf of Terra Nova Bay (Ross Sea). Quite similar values were reported by Signa et al. (2019) for phytoplankton samples collected in the same marine area using a 20 μm plankton net. While these results are only indicative, they demonstrate that Cd concentrations in phytoplankton are 5–6 orders of magnitude higher than in Southern Ocean waters. As was found with the bioconcentration of Hg in pico- and nano-phytoplankton in the Mediterranean Sea (Tesán-Onrubia et al., 2023; Bargagli & Rota, 2024b), small algal cells in the Southern Ocean also likely accumulate higher Cd concentrations than larger ones, contributing to its transfer to grazing micro- and mesozooplankton with small oral apparatuses.

Much more data is available for Cd concentrations in Antarctic macrozooplankton, with values reported for Antarctic krill (*Euphausia superba* Dana, 1850) collected in different Southern Ocean regions usually being <1 mg kg^{-1} dry wt (Table 1). In general, no statistically significant differences were found in Cd concentrations between males and females of *E. superba*. However, Han and Zhu (2023) observed a trend of decreasing Cd concentrations with increasing size of *E. superba*, a pattern that is typically seen in Hg bioaccumulation (e.g. Palmer Locarnini & Presley, 1995).

Bargagli and Rota (2025) suggested that juvenile krill and micro-zooplankton accumulate more Hg in the Southern Ocean because they feed on very small autotrophic and heterotrophic plankton, which have a very high surface-to-volume ratio for the ad/absorption of metals, whereas adult krill are unable to graze on particles smaller than 10 μm in diameter (Haberman et al., 2003). Similarly, higher concentrations of Cd have been reported for Antarctic zooplankton species with much smaller oral apparatus and body dimensions than adult *E. superba* (Rainbow, 1989; Bargagli et al., 1996; Kahle & Zauke, 2003). For instance, total

Cd concentrations in the amphipods *Themisto gaudichaudii* Guérin, 1825 and *Hyperiella dilatata* Stebbing, 1888 and the chaetognath *Eukrohnia hamata* (Möbius, 1875) from deep Southern Ocean waters were 118, 231, and 17 mg kg^{-1} dry wt, respectively (Hennig et al.,1985). Even in *Euphausia triacantha* Holt and Tattersall, 1906, which is about half the length of *E. superba* and does not form swarms, the Cd content was as much as 50 mg kg^{-1} dry wt.

Cadmium primarily accumulates in organs involved in the detoxification and excretion of the metal, such as the kidneys and the digestive glands (or liver in vertebrates). The data summarized in Table 1 refer to the analysis of the whole organism, and *E. superba* has a higher growth rate and size than other pelagic crustaceans. Therefore, it cannot be ruled out that a lower proportion of digestive gland and kidney mass relative to muscle, fat, or gonad tissue could contribute to lower total body Cd content in this species compared to smaller crustaceans. The uptake and physiological responses of marine organisms to Cd accumulation are influenced by complex antagonistic or synergistic interactions with other elements such as Zn and calcium (Ca), and there is evidence that in clams, selenium (Se) can ameliorate or reverse many Cd-induced metabolic changes (Trombini et al., 2022).

The Southern Ocean is often considered a single ocean with regard to the short and energy-efficient diatom-krill-vertebrate food chain. However, the basin is characterised by significant spatial and temporal variations in water geochemistry and plankton assemblage composition. According to estimates by Yang et al. (2022), the biomass of mesozooplankton in the Southern Ocean is higher than that of phytoplankton and Antarctic krill. Moreover, while the latter concentrates in the mid-latitudes of the Atlantic and Pacific sectors, mesozooplankton hotspots occur especially near islands. At high latitudes in the Ross and Amundsen Seas, there is the highest primary production combined with a reduced presence of mesopelagic fishes and Antarctic krill. Thus, in regions where pelagic food webs are based almost exclusively on *E. superba*, terminal consumers ingest less Cd than in regions where the transfer of energy from autotrophs to terminal consumers involves small algae, micro-, meso- and macrozooplancton, and fish.

Compared to temperate and tropical seas, the Southern Ocean has a smaller number of pelagic fish species and their predators. Furthermore, most studies on metal accumulation in Antarctic fish report Cd concentrations in muscle tissue rather than in organs (liver and kidneys) involved

Table 1. Total Cd concentrations (mg kg^{-1} dry weight, mean ± SD, range) in *Euphausia superba* from different regions of the Southern Ocean

Site	n	Size, mm	Cd	Reference
South Georgia Island	(44)	37.9 ± 2.6	0.85 ± 0.29	Han & Zhu, 2023
Northern Antarctic Peninsula				
South Shetland Islands	(32)	43.1 ± 2.3	0.15 ± 0.13	
Bransfield Strait (west basin)	(35)	38.1 ± 4.9	0.24 ± 0.15	Wang & Zhu, 2022
Bransfield Strait (central basin)	(31)	39.9 ± 4.4	0.23 ± 0.13	
NW Weddell Sea (Powell Basin)		9–63	0.387 (0.267–0.704)	Mirzoeva et al., 2022
Paradise Bay (Antarctic Peninsula)	(3)		0.26 ± 0.16	Espejo et al., 2018
Deception Island	(20)		0.5 ± 0.1	Deheyn et al., 2005
Western Antarctic Peninsula		36–56	0.29 (0.13–0.75)	Palmer Locarnini & Presley, 1995

in the detoxification and excretion of Cd. Goutte et al. (2015) measured 2.41 mg kg^{-1} dry wt in the liver of the cryopelagic fish *Pagothenia borchgrevinki* (Boulenger, 1902) and 4.45 mg kg^{-1} dry wt in the liver of the semi-pelagic fish *Trematomus hansoni* Boulenger, 1902 from Adélie Land. In Terra Nova Bay, the diet of *T. hansoni* mainly consists of fish juveniles and eggs (La Mesa et al., 1997), and the mean Cd content in the liver and kidney of 18 specimens was 9.84 ± 3.52 and 2.49 ± 0.87 mg kg^{-1} dry wt, respectively (Bargagli et al., 1996). Bustamante et al. (2003) reported higher Cd concentrations (28.5 ± 16.9 and 15.7 ± 8.10 mg kg^{-1} dry wt in the liver and kidney, respectively) in the pelagic fish *Gymnoscopelus piabilis* (Whitley, 1931) collected near the Kerguelen Islands, which feeds mainly on hyperiids and mysids. Thus, in the Ross Sea and other marine areas with high mesozooplankton density, such as the Kerguelen Islands, consumers seem to be exposed to higher Cd uptake. For instance, Fromant et al. (2016) found higher Cd concentrations in the liver of the Antarctic prion, *Pachyptila desolata* (Gmelin, 1789), than those usually reported in other Antarctic seabirds (Table 2) and suggested that Cd accumulation in this species was mainly due to consumption of hyperiid amphipods.

Most surveys on metal accumulation in Antarctic seabirds use non-destructive approaches, such as feather analysis. Few data are available on Cd concentrations in their livers and kidneys. Moreover, the available data is highly variable even among birds of the same species collected in geographically close areas. For example, on the coasts of the Weddell Sea, Schneider et al. (1985) reported lower Cd concentrations in emperor penguins (*Aptenodytes forsteri* G. R. Gray, 1844) from Gould Bay than from Atka Bay (Table 2). The Cd content in the kidney is always much higher than in the liver, suggesting chronic exposure to the metal in long-living Antarctic seabirds. Usually, juveniles have lower Cd concentrations than adults. In Adélie penguin chicks (*Pygoscelis adeliae* (Hombron & Jacquinot, 1841)) aged 7–20 days, Smichowski et al. (2006) measured 0.102 and 0.339 mg kg^{-1} dry wt of Cd in the liver and kidney, respectively. Jerez et al. (2013) found higher Cd levels in adult gentoo (*P. papua* (Forster, 1781)), chinstrap (*P. antarcticus* (Forster, 1781)), and Adélie penguins than in juveniles. They also

Table 2. Cadmium concentrations (mg kg^{-1} dry weight, mean ± SD)
in the liver and kidney of adult Antarctic seabirds from different Antarctic regions

Site	Species	Liver Cd	Kidney Cd	Reference
Kerguelen Archipelago	*Pachyptila desolata*	36 ± 8	105 ± 37	Fromant et al. (2016)
King George Island	*Pygoscelis papua*	1.05 ± 1.43	11.37 ± 14.10	
	P. antarcticus	0.16 ± 0.08	0.49 ± 0.32	
	P. adeliae	4.41	54.41	
Deception Island	*P. antarcticus*	27.54 ± 14.47	263.93 ± 139.77	Jerez et al. (2013)
Avian Island	*P. adeliae*	22.03 ± 10.47	351.84 ± 0.08	
Dronning Maud Land	*Thalassoica antarctica*	10.2	61.8	Nygård et al. (2001)
	Stercorarius maccormicki	10.0	68.3	
Atka Bay	*Aptenodytes forsteri*	27.7 ± 15.6	270.2 ± 126.8	Steinhagen-Schneider (1986)
	P. adeliae	7.5 ± 2.4	263.8 ± 216.6	
	S. maccormicki	27.0 ± 16.8	142.3 ± 43.4	
Gould Bay	*A. forsteri*	5.7 ± 7.7	23.8 ± 39.3	Schneider et al. (1985)
Atka Bay	*A. forsteri*	48.3 ± 21.0	382.2 ± 199.2	
	P. adeliae	15.2 ± 7.0	174.9 ± 88.1	

reported much higher Cd levels in adults from Deception Island and Avian Island than King George Island (Table 2). The stomach contents of all penguins consisted mainly of krill, and the researchers speculated that the higher Cd concentrations in samples from the southernmost islands were likely due to upwelling of Cd-rich waters, algal blooms, and possible Cd inputs from local volcanism. As Wang and Zhu (2022) also discussed, hydrographic and phytoplankton dynamics are probably among the main factors influencing spatio-temporal changes in Cd bioavailability.

The mean Cd concentrations in the livers and kidneys of crabeater seals (*Lobodon carcinophagus* (Hombron & Jacquinot, 1842)) and Weddell seals from Atka Bay were 34.7 ± 15.8 and 22.5 ± ± 10.2 mg kg^{-1} dry wt, and 139.4 ± 87.1 and 174.3 ± 67.3 mg kg^{-1} dry wt, respectively (Schneider et al., 1985). Kunito et al. (2002) reported a mean Cd concentration of 59.5 ± 29.0 mg kg^{-1} dry wt in the livers of 17 minke whales from the Southern Ocean, which was higher than in cetaceans from other regions. The researchers found that Cd concentrations in the liver were positively correlated with body length and Cd content in the skin of the cetaceans. Thus, they concluded that analysing trace metals in the skin could be a valuable approach to monitoring minke whale exposure to Cd.

4 Cadmium accumulation in coastal benthic communities

Despite ice scouring, well-developed and diverse communities of macroalgae can thrive at depths of up to 100 m along the coasts of Antarctica. These communities contribute significantly to global seaweed carbon fixation (Tait et al., 2024). Different species of macroalgae from King George Island exhibited average Cd concentrations ranging from less than 0.1 to 2.20 mg kg^{-1} dry wt, with an exception of 10.4 mg kg^{-1} dry wt in *Adenocystis utricularis* (Bory) Skottsberg, 1907 (Farías et al., 2002). Some algal species from Windmill Islands (Runcie & Riddle, 2004) and Terra Nova Bay (Bargagli et al., 1996; Dalla Riva et al., 2004) had mean Cd concentrations ranging from 3.1 to 9.1 mg kg^{-1} dry wt (Figure).

Benthic communities in coastal Antarctic ecosystems receive Cd through many sources, such as sinking sympagic algae, phytoplankton, macroalgae-derived materials, zooplankton detritus, fecal pellets, and Cd re-mobilized from surface sediments. Two benthic octopuses from the Kerguelen Islands (*Graneledone* sp. and *Muusoctopus thielei* G. R. Robson, 1932) were found to have Cd concentrations in their digestive gland one order of magnitude higher than those in European cephalopods, a finding suggesting that these molluscs might play a key role in transferring the metal to some species of penguins, albatrosses and marine mammals (Bustamante et al., 1998). Indeed, 104 mg kg^{-1} dry wt of Cd had been found by McClurg (1984) in the liver of Ross seals (*Ommatophoca rossii* (Gray, 1844)) feeding primarily on squid and to a lesser extent on fish and krill.

Benthic invertebrates have been widely used as biomonitors of persistent environmental contaminants in coastal ecosystems of Antarctica and sub-Antarctic islands, especially at King George Island and Terra Nova Bay. The Figure compares the mean Cd concentrations measured in representative autotrophic and consumer species at different trophic levels in these two coastal marine environments located at about 62°20′S and 74°50′S, respectively. Due to the significant differences in climate, lithology, geochemistry, sea ice conditions, water circulation, primary productivity, and food web composition between the two areas, as well as the substantial variability in Cd concentrations among samples of the same species collected within the same marine area, the values and comparisons in Figure are only indicative.

Nevertheless, starting with the macroalga *Iridaea cordata* (Turner) Bory, 1826, and the primarily herbivorous sea urchin *Sterechinus neu-*

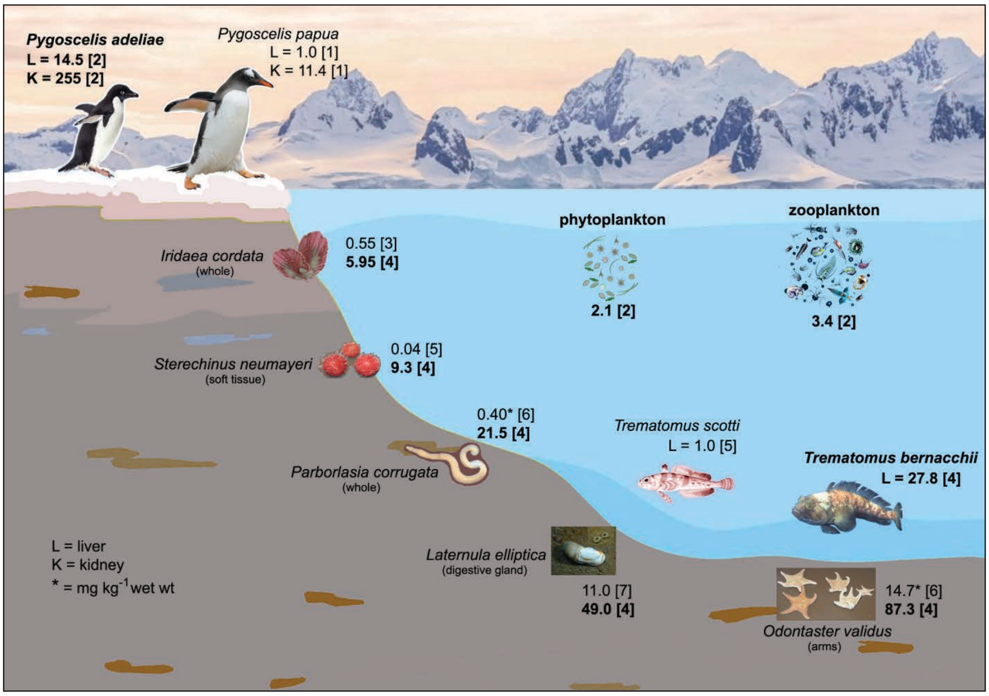

Figure. Mean Cd concentrations (mg kg^{-1} dry wt) in marine organisms from King George Island and Terra Nova Bay (values in bold). References: [1] Jerez et al., 2013; [2] Bargagli et al., 1996; [3] Farías et al., 2002; [4] Dalla Riva et al., 2004; [5] Deheyn et al., 2005; [6] de Moreno et al., 1997; [7] Vodopivez et al., 2015

mayeri (Meissner, 1900), benthic organisms from Terra Nova Bay exhibit much higher levels of Cd than those from King George Island. Around the Antarctic Peninsula and adjacent islands, the limpet *Nacella concinna* (Strebel, 1908) grazes on biofilms on rocky substrates, forming dense patches, and it has been widely used as a biomonitor of metal contamination. Its mean Cd concentrations in samples from King George Island (5.0 ± 1.6 mg kg^{-1} dry wt according to Ahn et al. (2002)) are lower than those in *S. neumayeri* from Terra Nova Bay (Figure). In the latter area, other benthic invertebrates such the nemertine worm *Parborlasia corrugata* (McIntosh, 1876) (a scavenger), the clam *Laternula elliptica* (P. P. King, 1832) (a suspensivorous filter-feeder), and the sea star *Odontaster validus* Koehler, 1906 (an opportunistic predator) have much higher Cd concentrations (Figure). The filter-feeding scallop *Adamussium colbecki* and the predatory snail *Neobuccinum eatoni* (E. A. Smith, 1875) have been widely used as biomonitors in Terra Nova Bay, with around 150–200 mg kg^{-1} dry wt of Cd usually reported in their digestive glands (e.g. Mauri et al., 1990; Nigro et al., 1997; Dalla Riva et al., 2004).

The fish fauna in Terra Nova Bay is dominated by notothenioids, which are predominantly benthic with a few pelagic and semipelagic species. *Trematomus bernacchii* Boulenger, 1902 is likely the most common benthic species, feeding primarily on polychaetes, molluscs, and other invertebrates. Dalla Riva et al. (2004) reported Cd concentrations of 27.8 ± 4.0 mg kg^{-1}dry wt in the liver of this species (Figure), while Bargagli et al. (1996) measured 9.89 ± 5.80 and 3.89 ± 2.52 mg kg^{-1} dry wt in the liver and kidney, respectively. Similar values were reported by Goutte et al. (2015) for the livers of *T. bernacchii* and other benthic or epibenthic notothenioid species from the Géologie Archipelago (Adélie Land, East Antarctica). On King

George Island, the diet of *Trematomus scotti* (Boulenger, 1907) is comparable to that of *T. bernacchii*, and Deheyn et al. (2005) measured a mean Cd concentration of 1.0 mg kg^{-1} dry wt in its liver and intestine. Unlike other notothenioids, ice fishes (Channichthyidae) feed almost exclusively on fish and euphausiids (La Mesa et al., 2004); samples of *Chionodraco hamatus* (Lönnberg, 1905) and *Cryodraco antarcticus* Dollo, 1900 from Terra Nova Bay typically have lower Cd concentrations in their organs than *Trematomus* fish collected in the same coastal area (Bargagli et al., 1996). Thus, at increasing trophic levels, there is a bio-dilution of Cd concentrations, which has usually been attributed to the greater detoxification and excretion capacity of fish compared to pelagic and benthic invertebrates (Espejo et al., 2018; Signa et al., 2019). In the wide continental shelf of the Ross Sea, Antarctic krill and mesopelagic fish are virtually absent, and *Euphausia crystallorophias* Holt & Tattersall, 1906 and the silverfish *Pleuragramma antarcticum* Boulenger, 1902 are the most important prey for Adélie penguins (La Mesa et al., 2004). Gentoo penguins are generally larger and heavier than Adélie penguins and are opportunistic feeders, consuming fish, krill, other crustaceans, and even cephalopods. However, Cd concentrations in the liver and kidneys of gentoo penguins from King George Island were much lower than in the same organs of Adélie penguins from Terra Nova Bay (Figure). The two species belong to the same genus (*Pygoscelis*), and their feeding ecologies do not appear to explain this striking difference in Cd bioaccumulation. Therefore, it is likely that Adélie penguins are more exposed to Cd uptake, given that the Ross Sea has a greater occurrence of sea ice, upwelling currents, and soluble Cd in its surface waters, as well as a massive seasonal build-up of diatoms and other phytoplankton species. Additionally, the transfer of energy from autotrophs to fish and their predators involves small crustaceans, such as copepods, rather than *E. superba*.

5 Climate change and the biogeochemical cycle of Cd in the Southern Ocean

In the Southern Ocean, global warming will likely alter the intensity and extent of algal blooms by affecting water and sea ice dynamics, as well as light and nutrient availability. While there is evidence that Circumpolar Deep Waters are the main source of dissolved Cd and other trace elements in Southern Ocean waters (e.g. Tian et al., 2023), climate change, with its enhanced glacier melting and weathering processes in coastal ice-free areas with different lithological features, will probably alter the local bioavailability and cycling of Cd, especially in coastal marine ecosystems. It is difficult to predict whether levels will increase or decrease, in part because the impact of climate change on the biogeochemical cycles of essential and potentially toxic elements will likely differ in different regions of the Southern Ocean. Unicellular phytoplankton are particularly sensitive to these changes due to their rapid reproduction rates, and possible variations in metal bioavailability and phytoplankton community composition will likely affect the transfer of potentially toxic elements along Antarctic marine food webs.

Recent estimates of the spatial distribution of phytoplankton and zooplankton biomass suggest that changes will manifest at different intensities and in different forms in various regions of the Southern Ocean. The west of the Antarctic Peninsula experienced significant warming between 1959 and 2000, with increases in air and seawater temperatures of about 3 °C and 1 °C, respectively. Changes in weather patterns, including increased cloud cover and precipitation, decreased ice cover, and variations in water chemistry and circulation, have triggered significant changes in phytoplankton communities (Montes-Hugo et al., 2009). Specifically, there has been a shift over the shelf from larger diatoms (>20 μm) to smaller phytoplankton cells, driven by ice shelf and glacier recession and increased light availability. This shift may have enhanced Cd accumulation in zooplankton and benthic communities. Moreover, since diatoms are the primary food source for Antarctic krill, there have been negative cascading effects on the reproductive rates of penguin, seal, and whale populations (Schofield et al., 2024).

In many marine ecosystems, especially fjordic coastal environments, the melting of land-based ice will increase the freshening and stratification of seawater, and the increased input of sediments and trace elements will modify the biogeochemical cycles of essential and potentially toxic elements. In the Ross Sea, the expected decrease in summer sea ice and the expansion of coastal polynyas will likely increase primary productivity, with possible shifts in the composition of phytoplankton assemblage and primary consumer communities (Rogers et al., 2020). However, while increased biomass of autotrophs could enhance the bioavailability of Cd to herbivores, the increased concentrations of hydrogen ions (H^+) under ocean acidification could compete with Cd^{2+} for binding sites on the surfaces of algae, thereby reducing Cd accumulation in diatoms (Zhang et al., 2024). Some laboratory studies (e.g. Shi et al., 2016) indicate that increased water acidity could enhance Cd accumulation in bivalves due to higher Cd^{2+} concentrations and a higher Cd^{2+}/Ca^{2+} ratio, which would increase Cd influx through Ca channels.

Compared to related species from lower latitudes, many Antarctic organisms have a limited ability to withstand the challenges posed by rising temperatures. Being specialised to living in cold waters with high oxygen (O_2) concentrations, a decrease in oxygen availability due to rising temperatures could negatively affect their metabolic activities. Seawater acidification is another climate-related stressor that influences the resilience of Antarctic marine organisms and, consequently, the structure and functioning of marine ecosystems. Long-term measurements taken with floating robotic instruments equipped with biogeochemical sensors (BGC-Argo) show that pH values are decreasing by about 0.02 units per decade in large regions of the Southern Ocean (Mazloff et al., 2023). Negrete-García et al. (2019) estimated that this ocean could experience aragonite undersaturation by 2050, which would affect calcifying organisms. Although Ca concentration in local seawater may vary in different regions and depths due to biological processes, it generally has the typical values of open-ocean waters: about 10.2 µmol kg^{-1} (Sun & Ellwood, 2025). Some species, such as Antarctic krill, appear resilient to projected near-future acidification (Ericson et al., 2018), but other groups, such as pteropods (free-swimming pelagic gastropods), appear particularly vulnerable (Mekkes et al., 2021).

6 Conclusions

Despite the limited impact by local natural and anthropogenic sources and long-range atmospheric transport, Cd concentrations in Southern Ocean waters and organisms are higher than those usually reported in other marine areas. In the oceans, Cd has a nutrient-like behaviour, and in spring and summer, the circulation of Antarctic waters facilitates the movement of soluble forms to surface waters, where they are readily taken up by the abundant phytoplankton biomass. While there is no data on the accumulation of Cd in different species of Antarctic algae, it is known that diatoms use Cd metalloenzymes to interconvert HCO_3^- and CO_2 in waters with limited availability of Zn, Fe, and other essential elements, such as in the Southern Ocean. Moreover, soluble metals are ad/absorbed by algae through passive mechanisms, and smaller autotrophic and heterotrophic organisms with a high surface-to-volume ratio can concentrate the metal at levels 5–6 orders of magnitude higher than in seawater. Thus, micro- and mesozooplankton grazers with small oral apparatuses accumulate high Cd concentrations, as do juvenile Antarctic krill, which accumulate higher concentrations than adults. Estimates of phytoplankton and zooplankton biomass in the Southern Ocean, as well as their distribution, indicate that, contrary to commonly held notions, the short diatom-krill-vertebrate pelagic food chain in certain Antarctic regions is supplanted by alternative food webs. These alternative food webs involving different taxa of zooplankton and fish are less efficient at transferring energy, but contribute to enhanced Cd accumulation in the digestive glands and kidneys of terminal consumers. Amphipods, for instance, are an important food source for marine vertebrates and accumulate much more Cd than adult Antarctic krill. Marine invertebrates and fish absorb chemical elements through their gills as well as through food. In the Southern Ocean, they grow very slowly compared to related species in temperate or tropical seas. Thus, longer exposure to Cd ions in seawater may contribute to an increase in Cd concentrations in their organs.

The coastal benthic ecosystems of Antarctica contain some of the richest marine habitats, and the main source of energy for primary consumers is closely linked to the seasonal dynamics of sea ice. The shrinking of the sea ice in spring and its breakup in summer promote the development of sympagic algae, phytoplankton, and benthic macroalgae. These organisms contribute to the transfer of Cd into surface sediments and benthic food webs. In the Ross Sea, the presence of coastal polynyas promotes a very high primary production, and the limited grazing favours the sinking of organic materials containing Cd. Thus, benthic invertebrates in the inner shelf of the Ross Sea accumulate much higher concentrations of Cd than related species from King George Island (Figure).

In general, the trophic ecology of pelagic and benthic marine invertebrates seems to play a very important role in Cd accumulation in their digestive glands and kidneys. However, unlike methylmercury, Cd does not biomagnify along marine food webs, and total body concentrations decrease from pelagic and benthic invertebrates to fish and higher vertebrates. While the latter can accumulate high concentrations of Cd in the liver and kidneys, they are likely adapted to detoxify and excrete the metal ingested through food.

The possible future impact of climate and environmental changes on marine biotic communities and Cd bioaccumulation is difficult to foresee. Some responses of Antarctic organisms to the warming can be deduced from past events on the Antarctic Peninsula. However, as previously discussed, the Southern Ocean is not a single ocean, so climate and environmental changes will affect regions with different oceanographic and bio-ecological characteristics differently.

Data availability statement. Not applicable.

Author contributions. Conceptualisation, R. B.; investigation and structure, R. B. and E. R.; data curation, R. B. and E. R.; writing — original draft preparation, R. B.; writing — review and editing, E. R and R. B.; visualisation, R. B. and E. R; supervision, R. B. All authors have read and agreed to the published version of the manuscript.

Funding. This research received no external funding.

Conflict of Interest. The authors declare no conflict of interest.

References

Ahn, I.-Y., Kim, K-W., & Choi, H. J. (2002). A baseline study on metal concentrations in the Antarctic limpet *Nacella concinna* (Gastropoda: Patellidae) on King George Island: variations with sex and body parts. *Marine Pollution Bulletin*, *44*(5), 424—431. https://doi.org/10.1016/S0025-326X(01)00297-1

Bargagli, R. (2008). Environmental contamination in Antarctic ecosystems. *Science of the Total Environment*, *400*(1—3), 212—226. https://doi.org/10.1016/j.scitotenv.2008.06.062

Bargagli, R., & Rota, E. (2024a). Environmental contamination and climate change in Antarctic ecosystems: an updated overview. *Environmental Science: Advances*, *3*(4), 543—560. https://doi.org/10.1039/d3va00113J

Bargagli, R., & Rota, E. (2024b). Mercury biogeochemistry and biomagnification in the Mediterranean Sea: Current knowledge and future prospects in the context of climate change. *Coasts, 4*(1), 89—107. https://doi.org/10.3390/coasts4010006

Bargagli, R., & Rota, E. (2025). Drivers of mercury accumulation in juvenile Antarctic krill, epipelagic fish and Adélie penguins in different regions of the Southern Ocean. *Environments, 12*(6), 180. https://doi.org/10.3390/environments12060180

Bargagli, R., Nelli, L., Ancora, S., & Focardi, S. (1996). Elevated cadmium accumulation in marine organisms from Terra Nova Bay (Antarctica). *Polar Biology*, *16*, 513–520. https://doi.org/10.1007/BF02329071

Boyle, E. A., Sclater, F., & Edmond, J. M. (1976). On the marine geochemistry of cadmium. *Nature,* 263, 42–44. https://doi.org/10.1038/263042a0

Brand, L. E., Sunda, W. G., & Guillard, R. R. L. (1986). Reduction of marine phytoplankton reproduction rates by copper and cadmium. *Journal of Experimental Marine Biology and Ecology*, *96*(3), 225–250. https://doi.org/10.1016/0022-0981(86)90205-4

Bustamante, P., Bocher, P., Chérel, Y., Miramand, P., & Caurant, F. (2003). Distribution of trace elements in the tissues of benthic and pelagic fish from the Kerguelen Islands. *Science of the Total Environment*, *313*(1–3), 25–39. https://doi.org/10.1016/S0048-9697(03)00265-1

Bustamante, P., Cherel, Y., Caurant, F., & Miramand, P. (1998). Cadmium, copper and zinc in octopuses from Kerguelen Islands, Southern Indian Ocean. *Polar Biology*, *19*(4), 264–271. https://doi.org/10.1007/s003000050244

Capodaglio, G., Scarponi, G., Toscano, G., & Cescon, P. (1991). Cadmium complexation in surface seawater of Terra Nova Bay (Antarctica). *Annali di Chimica*, 81, 279–296.

Dalla Riva, S., Abelmoschi, M. L., Magi, E., & Soggia, F. (2004). The utilization of the Antarctic environmental specimen bank (BCAA) in monitoring Cd and Hg in an Antarctic coastal area in Terra Nova Bay (Ross Sea—Northern Victoria Land). *Chemosphere*, *56*(1), 59–69. https://doi.org/10.1016/j.chemosphere.2003.12.026

de Baar, H. J. W., van Heuven, S. M. A. C., Abouchami, W., Xue, Z., Galer, S. J. G., Rehkämper, M., Middag, R., & van Ooijen, J. (2017). Interactions of dissolved CO_2 with cadmium isotopes in the Southern Ocean. *Marine Chemistry, 195*, 105–121. https://doi.org/10.1016/j.marchem.2017.06.010.

Deheyn, D. D., Gendreau, P., Baldwin, R. J., & Latz, M. I. (2005). Evidence for enhanced bioavailability of trace elements in the marine ecosystem of Deception Island, a volcano in Antarctica. *Marine Environmental Research, 60*(1), 1–33. https://doi.org/10.1016/j.marenvres.2004.08.001

de Moreno, J. E. A., Gerpe, M. S., Moreno, V. J., & Vodopivez, C. (1997). Heavy metals in Antarctic organisms. *Polar Biology*, *17*, 131–140. https://doi.org/10.1007/s003000050115

de Souza, G. F., & Morrison, A. K. (2024). The Southern Ocean hub for nutrients, micronutrients, and their isotopes in the global ocean. *Oceanography, 37*(2), 46–59. https://doi.org/10.5670/oceanog.2024.414

Dietz, R., Nørgaard, J., & Hansen, J. C. (1998). Have Arctic marine mammals adapted to high cadmium levels? *Marine Pollution Bulletin*, *36*(6), 490–492. https://doi.org/10.1016/S0025-326X(98)00045-9

Ericson, J. A., Hellessey, N., Kawaguchi, S., Nicol, S., Nichols, P. D., Hoem, N., & Virtue, P. (2018). Adult Antarctic krill proves resilient in a simulated high CO_2 ocean. *Communications Biology*, 1, 190. https://doi.org/10.1038/s42003-018-0195-3

Espejo, W., Padilha J. A., Kidd, K. A., Dorneles, P. R., Barra, R., Malm, O., Chiang, G., & Celis, J. E. (2018). Trophic transfer of cadmium in marine food webs from Western Chilean Patagonia and Antarctica. *Marine Pollution Bulletin*, *137*, 246–251. https://doi.org/10.1016/j.marpolbul.2018.10.022

Farías, S., Arisnabarreta, S. P., Vodopivez, C., & Smichowski, P. (2002). Levels of essential and potentially toxic trace metals in Antarctic macro algae. *Spectrochimica Acta Part B: Atomic Spectroscopy, 57*(12), 2133–2140. https://doi.org/10.1016/S0584-8547(02)00183-0

Finkel, Z. V., Quigg, A. S., Chiampi, R. K., Schofield, O. E., & Falkowski, P. G. (2007). Phylogenetic diversity in cadmium: phosphorus ratio regulation by marine phytoplankton. *Limnology and Oceanography*, *52*(3), 1131–1138. https://doi.org/10.4319/lo.2007.52.3.1131

Fromant, A., Carravieri, A., Bustamante, P., Labadie, P., Budzinski, H., Peluhet, L., Churlaud, C., Chastel, O., & Cherel, Y. (2016). Wide range of metallic and organic contaminants in various tissues of the Antarctic prion, a planktonophagous seabird from the Sothern Ocean. *Science of the Total Environment*, *544*, 754–764. https://doi.org/10.1016/j.scitotenv.2015.11.114

Ge, Y., Zhang, R., Zhu, Z., Zhao, J., Zhu, Z., Li, Z., Li, B., Zhang, Z., Zhang, Y., Zhou, M., John, S., & Smith Jr., W. O. (2024). Distribution of nutrients, trace metals, phytoplankton composition, and elemental consumption in the Ross and Amundsen Seas. *Marine Chemistry*, 265–266, 104436. https://doi.org/10.1016/j.marchem.2024.104436

Goutte, A., Cherel, Y., Churlaud, C., Ponthus, J.-P., Massè, G., & Bustamante, P. (2015). Trace elements in Antarctic fish species and the influence of foraging habitats and dietary habits on mercury levels. *Science of the Total Environment*, *538*, 743–749. https://doi.org/10.1016/j.scitotenv.2015.08.103

Haberman, K. L., Ross, R. M., & Quetin, L. B. (2003). Diet of the Antarctic krill (*Euphausia superba* Dana): II. Selective grazing in mixed phytoplankton assemblages. *Journal of Experimental Marine Biology and Ecology, 283*(1–2), 97–113. https://doi.org/10.1016/S0022-0981(02)00467-7

Han, S., & Zhu, G. (2023). Niche separation, dynamics, and transport pattern of trace elements along Antarctic krill (*Euphausia superba*) to its exclusive predator, mackerel icefish (*Champsocephalus gunnari*). *Marine Pol-*

lution Bulletin, 191, 114956. https://doi.org/10.1016/j.marpolbul.2023.114956

Hennig, H. F.-K. O., Eagle, G. A., McQuaid, C. D., & Rickett, L. H. (1985). Metal concentrations in Antarctic zooplankton species. In W. R. Siegfried, P. R. Condy, & R. M. Laws (Eds.), *Antarctic nutrient cycles and food webs* (pp. 656–661). Springer-Verlag, Berlin. https://doi.org/10.1007/978-3-642-82275-9_91

Honda, K., Yamamoto, Y., Kato, H., & Tatsukawa, R. (1987). Heavy metal accumulations and their recent changes in southern minke whales *Balaenoptera acutorostrata*. *Archives of Environmental Contamination and Toxicology*, *16*, 209–216. https://doi.org/10.1007/BF01055801

Jensen, E. L., Clement, R., Kosta, A., Maberly, S. C., & Gontero, B. (2019). A new widespread subclass of carbonic anhydrase in marine phytoplankton. *The ISME Journal*, *13*(8), 2094–2106. https://doi.org/10.1038/s41396-019-0426-8

Jerez, S., Motas, M., Benzal, J., Diaz, J., Vidal, V., D'Amico, V., & Barbosa, A. (2013). Distribution of metals and trace elements in adult and juvenile penguins from the Antarctic Peninsula area. *Environmental Science and Pollution Research*, *20*, 3300–3311. https://doi.org/10.1007/s11356-012-1235-z

Jiang, Z., Liao, E., Li, Z., & Zhang, R. (2025). Modeling the global ocean distribution of dissolved cadmium based on machine learning–SHAP algorithm. *Science of the Total Environment, 958*(1), 177951. https://doi.org/10.1016/j.scitotenv.2024.177951

Kahle, J., & Zauke, G.-P. (2003). Trace metals in Antarctic copepods from the Weddell Sea (Antarctica). *Chemosphere*, *51*(5), 409–417. https://doi.org/10.1016/S0045-6535(02)00855-X

Krumhardt, K. M., Long, M. C., Sylvester, Z. T., & Petrik, C. M. (2022). Climate drivers of Southern Ocean phytoplankton community composition and potential impacts on higher trophic levels. *Frontiers in Marine Science, 9*, 916140. https://doi.org/10.3389/fmars.2022.916140

Kunito, T., Watanabe, I., Yasunaga, G., Fujise, Y., & Tanabe, S. (2002). Using trace elements in skin to discriminate the populations of minke whales in southern Hemisphere. *Marine Environmental Research*, *53*(2), 175–197. https://doi.org/10.1016/s0141-1136(01)00119-2

La Mesa, M., Eastman, J. T., & Vacchi, M. (2004). The role of notothenioid fish in the food web of the Ross Sea shelf waters: a review. *Polar Biology, 27*, 321–338. https://doi.org/10.1007/s00300-004-0599-z

La Mesa, M., Vacchi, M., Castelli, A., & Diviacco, G. (1997). Feeding ecology of two nototheniid fishes, *Trematomus hansoni* and *Trematomus loennbergii*, from Terra Nova Bay, Ross Sea. *Polar Biology*, *17*, 62–68. https://doi.org/10.1007/s003000050105

Lannuzel, D., Bowie, A. R., van der Merwe, P. C., Townsend, A. T., & Schoemann, V. (2011). Distribution of dissolved and particulate metals in Antarctic sea ice. *Marine Chemistry, 124*(1–4), 134–146. https://doi.org/10.1016/j.marchem.2011.01.004

Lee, C.-S., & Fisher, N. S. (2016). Methylmercury uptake by diverse marine phytoplankton. *Limnology and Oceanography, 61*(5), 1626–1639. https://doi.org/10.1002/lno.10318

Mauri, M., Orlando, E., Nigro, M., & Regoli, F. (1990). Heavy metals in the Antarctic scallop *Adamussium colbecki*. *Marine Ecology Progress Series*, *67*(1), 27–33.

Mazloff, M. R., Verdy, A., Gille, S. T., Johnson, K. S., Cornuelle, B. D., & Sarmiento, J. (2023). Southern Ocean acidification revealed by biogeochemical-Argo floats. *Journal of Geophysical Research: Oceans, 128*(5), e2022JC019530. https://doi.org/10.1029/2022JC019530

McClurg, T. P. (1984). Trace metals and chlorinated hydrocarbons in Ross seals from Antarctica. *Marine Pollution Bulletin*, *15*(10), 384–389. https://doi.org/10.1016/0025-326X(84)90173-5

Mekkes, L., Sepúlveda-Rodríguez, G., Bielkinaité, G., Wall-Palmer, D., Brummer, G.-J. A., Dämmer, L. K., Huisman, J., van Loon, E., Renema, W., & Peijnenburg, K. T. C. A. (2021). Effects of ocean acidification on calcification of the sub-Antarctic pteropod *Limacina retroversa*. *Frontiers in Marine Science*, *8*, 581432. https://doi.org/10.3389/fmars.2021.581432

Mirzoeva, N., Tereschchenko, N., Paraskiv, A., Proskurnin, V., Stetsiuk, A., & Korotkov, A. (2022). Metals and metalloids in Antarctic krill and water in deep Weddell Sea areas. *Marine Pollution Bulletin*, *178*, 113624. https://doi.org/10.1016/j.marpolbul.2022.113624

Montes-Hugo, M., Doney, S. C., Ducklow, H. W., Fraser, W., Martinson, D., Stammerjohn, S. E., & Schofield, O. (2009). Recent changes in phytoplankton communities associated with rapid regional climate change along the Western Antarctic Peninsula. *Science*, *323*(5920), 1470–1473. https://doi.org/10.1126/science.1164533

Negrete-García, G., Lovenduski, N. S., Hauri, C., Krumhardt, K. M., & Lauvset, S. K. (2019). Sudden emergence of a shallow aragonite saturation horizon in the Southern Ocean. *Nature Climate Change, 9*, 313–317. https://doi.org/10.1038/s41558-019-0418-8

Nigro, M., Regoli, F., Rocchi, R., & Orlando, E. (1997). Heavy metals in Antarctic molluscs. In B. Battaglia, J. Valencia, & D. W. H. Walton (Eds.), *Antarctic communities: species, structure and survival* (pp. 409–412). Cambridge University Press, Cambridge, UK.

Nygård, T., Lie, E., Røv, N., & Steinnes, E. (2001). Metal dynamics in an Antarctic food chain. *Marine Pollution Bulletin, 42*(7), 598–602. https://doi.org/10.1016/S0025-326X(00)00206-X

Palmer Locarnini, S. J., & Presley, B. J. (1995). Trace element concentrations in Antarctic krill, *Euphausia su-*

perba. Polar Biology, 15, 283—288. https://doi.org/10.1007/BF00239849

Petri, G., & Zauke, G.-P. (1993). Trace metals in crustaceans in the Antarctic Ocean. *Ambio,* 22, 529—536.

Potapowicz, J., Szumińska, D., Szopińska, M., & Polkowska, Ż. (2019). The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost: Part I. Case study of Antarctica. *Science of the Total Environment, 651*, 1, 1534—1548. https://doi.org/10.1016/j.scitotenv.2018.09.168

Price, N. M., & Morel, F. M. M. (1990). Cadmium and cobalt substitution for zinc in a marine diatom. *Nature*, 344, 658—660. https://doi.org/10.1038/344658a0

Rainbow, P. S. (1989). Copper, cadmium, and zinc concentrations in oceanic amphipod and euphausiid crustaceans, as a source of heavy metals to pelagic seabirds. *Marine Biology*, *103*, 513—518. https://doi.org/10.1007/BF00399583

Rogers, A. D., Frinault, B. A. V., Barnes, D. K. A., Bindoff, N. L., Downie, R., Ducklow, H. W., Friedlaender, A. S., Hart, T., Hill, S. L., Hofmann, E. E., Linse, K., McMahon, C. R., Murphy, E. J., Pakhomov, E. A., Reygondeau, G., Staniland, I. J., Wolf-Gladrow, D. A., & Wright, R. M. (2020). Antarctic futures: An assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. *Annual Review of Marine Science, 12*, 87—120. https://doi.org/10.1146/annurev-marine-010419-011028

Runcie, J. W., & Riddle, M. J. (2004). Metal concentrations in macroalgae from East Antarctica. *Marine Pollution Bulletin*, *49*(11—12), 1114—1119. https://doi.org/10.1016/j.marpolbul.2004.09.001

Schneider, R., Steinhagen-Schneider, G., & Drescher, H. E. (1985). Organochlorines and heavy metals in seals and birds from the Weddell Sea. In W. R. Siegfried, P. R. Condy, & R. M. Laws (Eds.), *Antarctic nutrient cycles and food webs* (pp. 652—655). Springer-Verlag, Berlin. https://doi.org/10.1007/978-3-642-82275-9_90

Schofield, O., Cimino, M., Doney, S., Friedlaender, A., Meredith, M., Moffat, C., Stammerjohn, S., Van Mooy, B., & Steinberg, D. (2024). Antarctic pelagic ecosystems on a warming planet. *Trends in Ecology & Evolution*, *39*(12), 1141—1153. https://doi.org/10.1016/j.tree.2024.08.007

Shi, W., Zhao, X., Han, Y., Che, Z., Chai, X., & Liu, G. (2016). Ocean acidification increases cadmium accumulation in marine bivalves: a potential threat to seafood safety. *Scientific Reports*, *6*, 20197. https://doi.org/10.1038/srep20197

Sieber, M., Conway, T. M., de Souza, G. F., Obata, H., Takano, S., Sohrin, Y., & Vance, D. (2019a). Physical and biogeochemical controls on the distribution of dissolved cadmium and its isotopes in the Southwest Pacific Ocean. *Chemical Geology, 511*, 494—509. https://doi.org/10.1016/j.chemgeo.2018.07.021

Sieber, M., Conway, T. M., de Souza, G. F., Hassler, C. S., Ellwood, M. J., & Vance, D. (2019b). High-resolution Cd isotope systematics in multiple zones of the Southern Ocean from the Antarctic Circumnavigation Expedition. *Earth and Planetary Science Letters, 527*, 115799. https://doi.org/10.1016/j.epsl.2019.115799

Signa, G., Calizza, E., Costantini, M. L., Tramati, C., Sporta Caputi, S., Mazzola A., Rossi L., & Vizzini, S. (2019). Horizontal and vertical food web structure drives trace element trophic transfer in Terra Nova Bay, Antarctica. *Environmental Pollution, 246*, 772—781. https://doi.org/10.1016/j.envpol.2018.12.071

Smichowski, P., Vodopivez, C., Mucoz-Olivas, R., & Gutierrez, A.M. (2006). Monitoring trace elements in selected organs of Antarctic penguin (*Pygoscelis adeliae*) by plasma-based techniques. *Microchemical Journal*, *82*(1), 1—7. https://doi.org/10.1016/j.microc.2005.04.001

Steinhagen-Schneider, G. (1986). Cadmium and copper levels in seals, penguins and skuas from the Weddell Sea in 1982/1983. *Polar Biology*, *5*, 139—143. https://doi.org/10.1007/BF00441693

Sun, Y., & Ellwood, M. J. (2025). Calcium carbonate cycling in the Southern Ocean: insights from dissolved calcium and potential alkalinity tracers. *Limnology and Oceanography Letters*, *10*(2), 254—263. https://doi.org/10.1002/lol2.10457

Tait, L. W., Chin, C., Nelson, W., George, S., Marriott, P., O'Driscoll, R. L., Lamare, M., Mills, V. S., & Cummings, V. J. (2024). Deep-living and diverse Antarctic seaweeds as potentially important contributors to global carbon fixation. *Communications Earth & Environment*, 5, 205. https://doi.org/10.1038/s43247-024-01362-2

Tesán-Onrubia, J. A., Heimbürger-Boavida, L.-E., Dufour, A., Harmelin-Vivien, M., García-Arévalo, I., Knoery, J., Thomas, B., Carlotti, F., Tedetti, M., & Bănaru, D. (2023). Bioconcentration, bioaccumulation and biomagnification of mercury in plankton of the Mediterranean Sea. *Marine Pollution Bulletin, 194*, B, 115439. https://doi.org/10.1016/j.marpolbul.2023.115439

Tian, H.-A., van Manen, M., Wille, F., Jung, J., Lee, S.-H., Kim, T.-W., Aoki, S., Eich, C., Brussaard, C. P. D., Reichart, G.-J., Conway, T. M., & Middag, R. (2023). The biogeochemistry of zinc and cadmium in the Amundsen Sea, coastal Antarctica. *Marine Chemistry, 249*, 104223. https://doi.org/10.1016/j.marchem.2023.104223

Trombini, C., Rodríguez-Moro, G., Ramírez Acosta, S., Gómez Ariza, J. L., Blasco, J., & García-Barrera, T. (2022). Single and joint effects of cadmium and selenium on bioaccumulation, oxidative stress and metabolomic responses in the clam *Scrobicularia plana*. *Chemosphere*, *308*(3), 136474. https://doi.org/10.1016/j.chemosphere.2022.136474

Ulrich, A. E. (2019). Cadmium governance in Europe's phosphate fertilizers: Not so fast? *Science of the Total En-*

vironment, *650*, 1, 541—545. https://doi.org/10.1016/j.scitotenv.2018.09.014

Vance, D., Little, S. H., de Souza, G. F., Khatiwala, S., Lohan, M. C., & Middag, R. (2017). Silicon and zinc biogeochemical cycles coupled through the Southern Ocean. *Nature Geoscience*, *10*, 202—206. https://doi.org/10.1038/ngeo2890

Vodopivez, C., Curtosi, A., Villaamil, E., Smichowski, P., Pelletier, E., & Mac Cormack, W. P. (2015). Heavy metals in sediments and soft tissues of the Antarctic clam *Laternula elliptica*: More evidence as a? possible biomonitor of coastal marine pollution at high latitudes? *Science of the Total Environment, 502*, 375—384. https://doi.org/10.1016/j.scitotenv.2014.09.031

Wang, D., & Zhu, G. (2022). Antarctic krill (*Euphausia superba*) as a bioindicator of trace elements reflects regional heterogeneity in marine environments in the northern Antarctic Peninsula, Antarctic. *Ecological Indicators*, *136*, 108596. https://doi.org/10.1016/j.ecolind.2022.108596

Webb, A. L., Hughes, K. A., Grand, M. M., Lohan, M. C., & Peck, L. S. (2020). Sources of elevated heavy metal concentrations in sediments and benthic marine invertebrates of the western Antarctic Peninsula. *Science of the Total Environment, 698*, 134268. https://doi.org/10.1016/j.scitotenv.2019.134268

Xu, Y., Feng, L., Jeffrey, P. D., Shi, Y., & Morel, F. M. M. (2008). Structure and metal exchange in the cadmium carbonic anhydrase of marine diatoms. *Nature, 452*, 56—61. https://doi.org/10.1038/nature06636

Yamamoto, Y., Honda, K., Hidaka, H., & Tatsukawa, R. (1987). Tissue distribution of heavy metals in Weddell seals (*Leptonychotes weddellii*). *Marine Pollution Bulletin*, *18*(4), 164—169. https://doi.org/10.1016/0025-326X(87)90240-2

Yang, G., Atkinson, A., Pakhomov, E. A., Hill, S. L., & Racault, M.-F. (2022). Massive circumpolar biomass of Southern Ocean zooplankton: Implications for food web structure, carbon export, and marine spatial planning. *Limnology and Oceanography, 67*(11), 2516—2530. https://doi.org/10.1002/lno.12219

Yin, X., Liu, X., Sun, L., Zhu, R., Xie, Z., & Wang, Y. (2006). A 1500-year record of lead, copper, arsenic, cadmium, zinc level in Antarctic seal hairs and sediments. *Science of the Total Environment*, *371*(1—3), 252—257. https://doi.org/10.1016/j.scitotenv.2006.07.022

Zhang, Z., Ma, J., Chen, F., Chen, Y., Pan, K., & Liu, H. (2024). Mechanisms underlying the alleviated cadmium toxicity in marine diatoms adapted to ocean acidification. *Journal of Hazardous Materials*, *463*, 132804. https://doi.org/10.1016/j.jhazmat.2023.132804

Received: 28 May 2025
Accepted: 10 October 2025

Вплив регіональних варіацій характеристик океану та трофічних зв'язків на накопичення кадмію в антарктичних пелагічних та бентосних організмах

Роберто Баргаглі, Емілія Рота*

Сієнський університет, м. Сієна, 53100, Італія

*** Автор для кореспонденції:** rota@unisi.it

Реферат. Вміст кадмію (Cd) в морських антарктичних організмах значно вищий, аніж очікувалося для такого віддаленого, незабрудненого середовища. Біоакумуляція відбувається в основному через циркуляцію води та апвелінг, а також, в областях високої первинної продуктивності, через хімічну подібність кадмію до необхідних для життя елементів. Низька доступність цинку та інших мікроелементів створює сприятливі умови для використання Cd діатомовими водоростями як кофактору в карбоангідразі. Окрім того, його накопичують малі автотрофи та гетеротрофи з високим співвідношенням площі поверхні до об'єму. Так, у пелагічних трофічних мережах Cd концентрують мікро- та мезозоопланктонні організми, що виїдають фітопланктон, та ювенільні стадії антарктичного крилю із маленькими ротовими апаратами. Від них він переходить до амфіподів та інших вторинних консументів. У прибережних морських екосистемах з великою первинною продуктивністю (такі як екосистеми навколо моря Росса) велика частина фітопланктону влітку осідає, і це теж сприяє акумуляції кадмію в безхребетних тваринах бентосу. Загальна концентрація Cd нижча у бентосних та пелагічних рибах, морських птахах та ссавцях, аніж у багатьох видах безхребетних. Морські птахи, які харчуються амфіподами та іншими ракоподібними меншими за антарктичний криль, накопичують більше кадмію. Порівняння вмісту Cd в типових бентосних безхребетних, рибах та пінгвінах з прибережних екосистем біля о. Кінг-Джордж та в затоці Терра Нова (море Росса) вказує на те, що в затоці біоакумуляція набагато інтенсивніша. Це ймовірно пов'язано з підсиленим апвелінгом, високими концентраціями розчинного кадмію в поверхневих водах, значними «цвітіннями» водоростей навесні та влітку і залученням в перенос енергії та металів по пелагічних трофічних мережах не лише криля, а й інших безхребетних.

Ключові слова: Cd, бентосні угруповання, біоакумуляція, біофізичні параметри середовища, пелагічні трофічні мережі, Південний океан