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POPs in Antarctic ecosystems: is climate change affecting their temporal trends?

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Climate change is affecting Antarctica and the Southern Ocean and effects have been already reported for the abiotic compartments of the ecosystems, *e.g.* ice loss and iceberg calving. Global warming can alter also the distribution of persistent organic pollutant (POPs) both at a global scale and in the Antarctic Region, due to their physical–chemical characteristics. Effects of climate changes have been already reported on feeding behaviour and reproductive process of organisms. Another consequence for organisms includes the POP bioaccumulation. Here we review the literature reporting the linkage between recorded effects of climate changes and POP bioaccumulation in resident marine Antarctic species (fish and penguins). Notwithstanding Antarctica is a final sink for persistent contaminants due to the extreme cold climate, a general decreasing POP trend has been observed for some POPs. Their concentrations in biota are reported to be linked to ice melting and large iceberg calving; the peculiar marine Antarctic ecosystems and the pelagic-benthic coupling may also contribute to alterations in the bioaccumulation processes. These effects are similar in polar regions, although the comparison with the Arctic biota is not possible due to the lack of data in the Antarctic Region. It remains an open question if the POP amount accumulated in the Antarctic ecosystems is decreasing or not.

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Environmental significance

The climate crisis is affecting the polar regions more than other areas and their ecosystems are particularly vulnerable due to their low resilience. Changes may affect the trophic web structure and functioning with consequences for persistent organic pollutant bioaccumulation. In the Arctic, these events have already been observed and bioaccumulation in organisms has been correlated to climate parameters. Very few data exist for the Antarctic Region; this highlights the urgent need of a pan-Antarctic collection of data to comprehend and predict how the climate crisis may affect these fragile marine ecosystems and their biota in a changing world. Future research and monitoring initiatives for Antarctica should take relevant findings on both polar regions into consideration.

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1. POPs in Antarctica and the Southern Ocean

1.1 Preface

The Arctic Monitoring and Assessment Programme (AMAP) prepared an Assessment (in 2019–2020) titled *AMAP Assessment 2020: POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change*, which was published in 2021.[1] The aim of this AMAP assessment was to review the recorded and predicted changes in levels and trends of Persistent Organic Pollutants (POPs) and Contaminants of Emergent Arctic Concern (CEAC) in the Arctic environment. The analyses focused on physical and ecological changes occurring under warming conditions in the Arctic and included some additional information from other cold regions. This review on the influence of climate change on POPs in the Antarctic ecosystems originates from this AMAP Assessment. The comparison between observations reported in the Arctic and Antarctic regions was included in the AMAP assessment because it can provide a global perspective on the effects of climate change on contaminant trends in polar regions, that have different remote sources and transport pathways of contaminants.

1.2 POPs in Antarctica and the Southern Ocean

The polar regions are sensitive areas exposed to changes resulting from global warming. The transport of persistent organic pollutant (POPs) to the Arctic and their cycling can be altered by the climate changes[2] and the same can be predicted in Antarctica. However, it must be considered that the human impacts on Antarctica and the Southern Ocean are still limited respect to the Arctic due to their remoteness and extreme climate, which make very difficult and challenging to live and work there.

The geography and oceanography of Antarctica and the Southern Ocean are responsible of the POP transport in the

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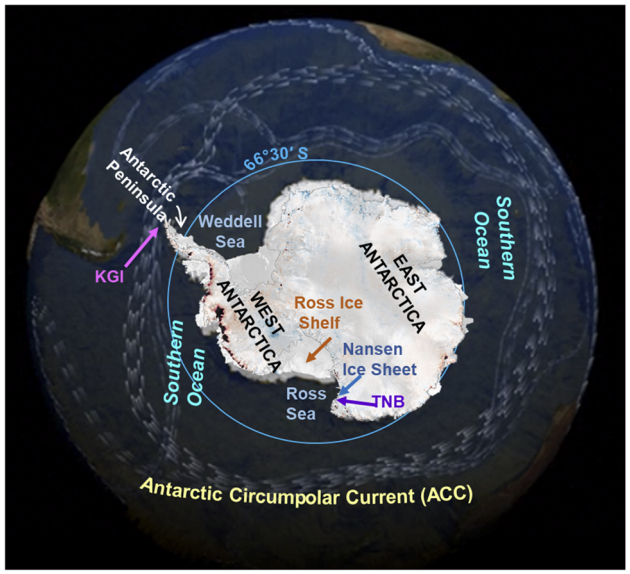

Fig. 1 Map of Antarctica with sites cited in the text (modified from ©CPOM/Leeds/ESA, https://www.esa.int/ESA_Multimedia/Images/2014/05/Antarctica_s_ice_loss and NASA/Goddard Space Flight Center Scientific Visualization Studio at https://svs.gsfc.nasa.gov/vis/a000000/a003800/a003884/).

region. The presence of POPs in the Antarctic continent and Southern Ocean is mainly due to the long range atmospheric transport (LRAT[3,4]), as the Antarctic Circumpolar Current (ACC; 50°S–60°S, Fig. 1) acts as a natural northern boundary between the cold seawaters of the Southern Ocean and the warmer seawaters of the Pacific, Indian and Atlantic Oceans. At this boundary, the cold Antarctic seawaters sink beneath the warmer sub-Antarctic waters of the other oceans instead of mixing in the upper water column layers, as they show different physical–chemical characteristics (temperature, density). Therefore, seawaters from the other oceans take a long time before reaching and mixing to the Antarctic ones.

The remoteness of the Antarctic Region is supposed to cause a delay in the POP transport and bioaccumulation when compared to the Arctic: while POPs reach the Arctic in a few days or weeks by air and ocean transport,[5] they can take months or years before reaching the Antarctic region. Moreover, Antarctica is a remote, inhabited cold desert where only scientific stations are settled and no POP production have never occurred; local emissions are from scientific stations, *e.g.* flame retardants, building materials, combustion by-products,[6,7] electric and electronic parts, hydraulic fluids, textiles. The long distance of the region from any POP production areas and the limited human presence and activity (scientific stations, tourism, fishing) make the long range atmospheric transport (LRAT) the most important contamination source.

The Antarctic Treaty (AT, signed in Washington on 1 December 1959) protects and controls all human activities in the Antarctic continent and the Southern Ocean and aims to guarantee "the interest of all mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord" (https://www.ats.aq/). The Protocol on Environmental Protection to the Antarctic Treaty (signed in Madrid on 4 October 1991) designates Antarctica as a "natural reserve, devoted to peace and science", where all activities are subject to regulations and the exploitation of mineral or other resources is prohibited; only scientific research is permitted (https://www.ats.aq/). The consequence of these international efforts to protect the Antarctic Region have preserved it from POPs contamination, which is recognized to be among the lowest on Earth. However, the detection of a number of contaminants in the Antarctic ecosystems make the region no longer pristine; the human impacts are expected to increase in the near future due to intensifying scientific, touristic, and fishing activities. In the Antarctic Peninsula, the global and local human impacts have transgressed the barriers isolating the continent from the rest of the World and have caused an acceleration of previously observed changes.[8]

Increasing temperatures and changes in precipitation pattern are among the abiotic parameters that most influence the fate and transport of persistent contaminants: it was reported that the air surface temperature has increased 3–7 °C since the 1950s[9–11] in the Antarctic Region, mostly in West Antarctica. The satellite observations have confirmed the retreat,[12,13] thinning,[14,15] and disintegration[16] of ice shelves in Antarctica. The global warming does not affect the continental and marine ice at the same level everywhere and the ice losses in West and East Antarctica is different: it increases dramatically in the first, while it is less evident or show an opposite trend in the second one.[17] However, a dramatic and alarming event occurred in March 2022 in East Antarctica: the region was hit by an anomalous heatwave with temperatures reaching a record of −11.8 °C on March 18th at the scientific Concordia Station (average temperatures in March: −48 °C *ca.*).[18] In the same period, the Conger Ice Shelf calved in East Antarctica coast; the cause of this collapse is not clear yet, but global warming is likely a contributing factor.[18]

The scientific literature on the relationships between global change and contamination was reviewed for instance by Nadal *et al.*,[19] but no specific mention was reported for the Antarctic region; these authors predicted that global change would alter POP concentrations within a factor of 2–3. Other studies estimated the consequences of a temperature increase in Antarctica: for instance, a climate change-related increase of 1 °C in air temperature was estimated to increase the Antarctic atmospheric burden of PCBs by 21–45%. In addition, a concurrent increase of 0.5% of solid organic matter will counteract the influence of warming by reducing the POP fugacity in soil. A 1 °C increase in the Antarctic temperatures would induce a 25% increase of soil-vegetation organic carbon and associated POPs, making it a sink of POPs. Therefore, it is supposed that an amount of up to 70 times more POPs than the amount remobilized to the atmosphere will be trapped.[20] Casal *et al.*[21] demonstrated that sea spray aerosols can be an important source of perfluoroalkylated substances (PFASs) to Antarctic marine environments: PFAS scavenged during snow deposition and scavenging sea-salt aerosol were reported as important input of PFCAs to the Maritime Antarctica.

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The Antarctic marine ecosystems are fragile, meaning that even small alterations can cause extreme changes;[22] they also show low resilience. In this context, the climate crisis can have a devastating impact on the Antarctic ecosystems in a future changes-driven scenario. The overall effects on Antarctic biota are difficult to predict and assess, but consequences on the POP release trapped in the ice, their distribution and bioaccumulation are expected. Then it is important to monitor the POP contamination in relation to measurable changes of climatic parameters.

These observed or predicted changes may affect the POP distribution in the ecosystems and their bioaccumulation. The climate crisis may have an effect on the food web structure and an impact on the availability of food resources; these alterations may shift the trophic position of organisms and consequently the POP bioaccumulation pattern.[23] Changes of Antarctic seabird diet, distribution, and population dynamics were already observed in long-term studies[24] and these modifications may lead to a shift in foraging or breeding distributions, behaviour or other adaptations, decline or extirpation of populations.[24] For instance, it was reported that contaminants are significantly related to hormonal secretion in snow petrels and parental care is affected by hormone levels: the mercury (Hg) concentrations were higher in males that neglected their egg[25]. These authors suggested that in these Antarctic seabirds, the exposure to legacy POPs and Hg could make birds more susceptible to environmental stressors, despite they were not evaluated or correlated. The effects of changes in the POP distribution in trophic webs could be not easily and promptly detected due to the geographic isolation of the Southern Ocean, where contamination events are delayed respect to the Arctic.[23]

In other regions of the Earth, studies have shown the effect of some extreme events, such as floods and droughts, on the remobilization and bioaccumulation of POPs.[19] In Antarctic terrestrial ecosystems, warming-related increases in vegetation[26] and changes in soil chemistry (*i.e.* increased dissolved organic carbon)[20] may increase the capacity of soil to sequester POPs.[27] This in turn can result in greater inputs of contaminants into aquatic systems from the re-mobilization of contaminants in soils[28] through increased glacial melt projected under future climate scenarios.

The global climate change can also affect the accumulation and release of POPs in polar regions and those trapped in the ice may be released because of ice melting: in the marine environment, the input of POPs can increase with pack ice and glacier increasing melting:[29] Geisz *et al.*[29] (2008) speculated that 1–4 kg year^{-1} of $\sum$DDTs have been released into the Antarctic marine environment due to glacier ablation. Xavier *et al.*[24] overviewed the latest physical and biological modifications recorded in Antarctica under changing climate with a special focus on Antarctic seabirds. They reported that long-term datasets indicate rapid warming of some regions of Antarctica and Southern Ocean where the area of cold water is reducing its extension because of southward shifts of oceanic fronts; moreover, sea-ice extent and atmospheric conditions are increasing their variability.

Besides spatial differences, exposure scenarios for pelagic and benthic compartments of the marine environment may also vary. The pelagic-benthic coupling of the marine ecosystems includes fundamental processes that allow the exchange of energy and mass between the pelagic and benthic zones.[23] The pelagic domain can be affected by POP inputs through ice melting and water–air exchange and the benthic one, which receives nutrients from the upper water column, may depend on those events occurring at the sea surface. These exchanges between the pelagic and benthic ecosystems are also dependent on the seasonal sea-ice dynamics. The POP distribution in the marine pelagic and benthic trophic webs may be difficult to predict under different climatic conditions due to changes in the ecosystem functioning.[30]

The first detection of POPs in the Antarctic biota dates back to the 1960s when DDT was first documented in Adèlie penguins (*Pygoscelis adèliae*) and a crabeater sea (*Lobodon carcinophaga*),[31] and PCBs were detected in petrels.[32] Since then, an increasing number of articles have reported the presence of POPs in the ecosystems of the Antarctic continent and Ocean.[28,33] Unfortunately, only very few studies report also the climate parameters and correlations to contaminant concentrations. For instance, Bhardwaj *et al.* reviewed the scientific literature on the presence of POPs in the Antarctic environment, but no associations to climate parameters were highlighted.[34] Another article reports the annual cycle of POP concentration in an Antarctic planktonic communities, the potential implications for biomagnification, and the direct effects of increasing temperature on the redistribution of HCB under changing climate,[35] but no association to climate parameters were assessed.

1.3 Approach

This review was conducted as part of the AMAP Assessment "*POPs and Chemicals of Emerging Arctic Concern (CEACs): Influence of climate change*".[1] This article is based on peer-reviewed articles, which were known to the authors until April 2022. Many articles reports the concentration of POPs in Antarctic ecosystems, but only very few report time series of POP concentrations in associations with biological and/or physical parameters indicative of climate change. Thus, we selected and discussed those articles relevant to the aims of both the AMAP Assessment and the themed issue of *Environmental Science: Processes & Impacts* titled *POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change.*

The presence of POPs in the Antarctic ecosystems have been reported in an increasing number of articles since the 1960s, but their number is still low when compared to the literature on the Arctic contamination. According to Web of Science, since the beginning of polar research on contamination, only 500 articles were published on the contamination in the Antarctic Region, and 10 of them were review articles, while the literature on the Arctic includes more than 2000 articles, with more than 50 reviews among them.

The articles on the presence of POPs, time series and correlation to climate parameters are lacking for Antarctic

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environments. Thus, we considered for this review, only peer-reviewed articles that linked contaminant concentrations and climate parameters; due to their very limited number, the link to biological parameters was also taken into consideration. We selected articles on marine fish and Adèlie penguins because these species are native to Antarctic marine environment and thus suitable to study temporal changes of contaminant exposure in this region.

2. POP monitoring and time series

2.1 Introductory remarks

Organisms react to climate changes modifying their ecology (*e.g.* feeding habits and grounds, reproduction timeline and success[36–41]). For instance, the *Colobanthus quitensis* and *Deschampsia antarctica* (phanerogams which only grow in West Antarctica) have increased their seed maturation and germination, and seedling survival in response to a warming trend of air temperatures during Summer; this trend was evident in the region since the late 1940s.[42] Regarding the fauna, climate change may affect the structure of trophic webs and the availability of prey, thus they may feed on different items. A shift in the diet may cause different POP bioaccumulation and these variations can be related to climate changes when physical characteristics of the environment and weather conditions are recorded and correlated to POP concentrations. For instance, the POP temporal trend in zooplankton from the Nordic countries was reported to be affected by abiotic factors[43] such as an earlier ice breakup or the lack of ice cover.

After the calving of the Nansen Ice Shelf (Ross Sea) in 2016, the foraging ground of Adèlie penguins (Fig. 2) changed and penguins fed in this newly accessible sea area.[41] A linkage between food item, ice coverage, foraging range, and POP contamination in Adèlie penguins from a rookery in the Ross Sea (Fig. 1) was already reported in the 1990s.[44] Here, a sequence of events occurred in the 1995/96 summer season: the ice melted completely very early in the season and penguins during the rearing chick period foraged nearer to the shore to save energy instead of swimming offshore for feeding on krill. The penguin diet during the rearing period is based on krill, which are rich in lipids and thus highly energetic for chicks. During that season, the penguins fed mainly on fish and other food items; higher lipophilic POP concentrations were found in specimens whose stomach contents were richer in krill. This article highlighted how a changed environment affected the functioning of the trophic web and then the POP bioaccumulation;[44] unfortunately, concentrations were not directly correlated to the climate parameters.

The sea ice coverage in polar regions is a key issue for those species whose reproduction and feeding behaviour are strictly linked to it.[44] Altering oceanographic conditions, climate change affects penguin populations that preferentially use foraging areas where prey is abundant and predictable.[45] In particular, altered environmental conditions can affect the arrival, body weight and nutritive status before breeding or moulting, and the timing of egg laying, egg size, breeding success and ultimately the survival of individuals. Starvation due to a modified environment and food resources availability may be another cause of re-contamination from body lipid resources.[40] The climate-driven changes do not affect directly contamination in penguins, but the modification of the environment, foraging behaviour, and diet can affect the POP bioaccumulation processes.

Comparisons between observations reported in the Arctic and Antarctic can provide a global perspective on the characteristics of climate change effects on contaminant trends in polar regions, also because the two areas have different remote contaminant sources and transport pathways. Only a few studies have explored correlations between POP temporal trends and climate parameters in Antarctic abiotic compartments[27] and biota, such as fish[46] and penguins.[29] Climate change may affect the structure of Antarctic trophic webs and the availability of prey in the same way as described for the Arctic, and thus could have similar consequences on POP exposure and bioaccumulation in Antarctic ecosystems.

Fig. 2 An Adèlie penguin feeding its chick (©PNRA, photo S. Corsolini).

2.2 Terrestrial and freshwater ecosystems

In Antarctica, terrestrial ecosystems cover only 0.34%[47] of the continent currently without ice, seasonally or permanently. Limiting factors such as very low temperature, extreme dryness (very limited availability of liquid water), strong winds, and long winter darkness lead to a low level of biodiversity. Organisms (moss, lichens, algae, yeasts, bryophytes, invertebrates[48]) are extremely adapted to life in environments permanently or seasonally free from ice as soil, freshwater lakes, ponds, streams, and even rocks (cryptoendolithic communities[49]).

Soil and pond sediment samples have been included in several studies on the POP contamination of the Antarctic regions (*e.g.*[6,50–52]), although an analysis of a temporal trend in association with climate change still lacks in the literature for these environments. Only an article reports the correlations between climate parameters and contamination in a terrestrial ecosystem of Livingston Island (West Antarctica).[27] The authors suggested that the remobilization of PCBs is driven by changes in temperature and soil content of organic matter; they suggested that the current and future POP remobilization and sinks

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in Antarctica, besides warming, are a function of the close coupling of climate change and carbon cycling.[27]

Sun *et al.*[53] studied the accumulation of chlorinated pesticides in lake cores collected from Niudu Lake in King George Island (West Antarctica): they analyzed lake sediment cores with and without glacier meltwater input, and found that the DDT accumulation flux showed an anomalous peak in the lake with glacier meltwater input. In the core sediments of the lake without glacier meltwater input, the DDT accumulation flux showed a gradually declining trend after the peak in the 1960s. These authors attributed this difference in DDT flux profiles between the two lake cores to regional climatic warming and the subsequent discharge of DDT stored in the Antarctic ice sheet into lakes.[54] The Authors ascribed this increase to the glacier meltwater derived from the regional warming from the early 1970s, which contributed to the release into the lakes of the pesticides trapped in the ice cap. Potapowicza *et al.*[55] reviewed the literature on the influence of permafrost degradation on the contaminant distribution and re-emission in Antarctica; the reviewed data allowed them to assume that the permafrost may constitute a sink for organic and inorganic contaminants. Permafrost in Antarctica is less extended than in the Arctic, but its degradation can contribute to remobilize trapped contaminants. Taking into account that penguins nest in deglaciated areas with permafrost, the release of contaminants may affect directly the terrestrial and marine ecosystems.

Corsolini *et al.*[6] reported correlations with some climate parameters in pond soil from the Victoria Land, although the temporal trend was not investigated. In this study, a trend respect to wind direction was observed, in agreement with data reported for PCBs in air samples from the same area,[56] where the highest levels were found in the theoretically less polluted site (Nansen Ice Shelf; Fig. 1), where air masses come mainly from the Antarctic continent.[51,56–58] These findings suggest a potential influence of climate on the distribution of POPs in the Antarctic environments.

In the Arctic, available data on temporal trends, or effects of climate change on POP trends, show a significant decrease over time for many POPs in Greenland freshwater fish.[59] A comparison to Antarctic freshwater fish is not possible as no fish are present in continental waters.

There is an urgent need to intensify studies on the temporal trend and climate change in these environments, which are then vulnerable to human impacts, as many scientific stations are located in free-ice areas with permafrost.

2.3 Marine environment

In order to compare with and complement observations in the Arctic, the following discussion focuses on POP temporal trends in marine fish and Adèlie penguins. These species are native to Antarctic marine environment and thus suitable to study temporal changes in contaminant exposure in this region. The Tables 1–4 report the concentrations of POPs in the most studied fish and penguin species. Among POPs, we selected PCBs, *p*,*p*′-DDT, *p*,*p*′-DDE, DDTs, and HCB since other chemicals, including emergent contaminants, were reported only in few articles.

Fig. 3 A specimens of *Trematomus bernacchi* (©PNRA, photo Stefano Schiaparelli).

A study on POP temporal trends in the muscle of emerald rockcod (*Trematomus bernacchii*) (Fig. 3) from the Ross Sea over a 30 year period from the early 1980s to 2011 observed two elevated concentration peaks within generally decreasing trends of POPs[46,60] (Table 1). These concentration peaks occurred in 2001 and 2005 for PCBs, and in 2005 for *p*,*p*′-DDE and PBDEs.[46,61,62] The iceberg B15 calved from the Ross Ice Shelf at the beginning of 2000. This iceberg broke into several pieces in 2000, 2002 and 2003 [63] and it was suggested as the possible source of POPs which were trapped in it and then released into seawater contributing to the higher POP concentrations detected in fish.[46] These observations provide an example of the potential effects of warming-induced polar ice melt and collapse on POP concentration trends in biota. In the Arctic, observations of relationships between climate and POP trends in fish are limited to freshwater species where associations have been found between POP concentrations and climate oscillation indices, temperature, precipitation and consequences of permafrost thaw. The direct effects of iceberg calving and melting on POP availability to marine fish have not been studied in the Arctic, although such effects are plausible. However, the POP concentrations in the entire trophic web over time were reported to change after the retreatment of tidewater glaciers.[64]

Disregarding the correlation to climate parameters, stable or slightly increasing POP levels have been reported in benthic feeding Antarctic fish, such as the humped rockcod (*Gobionotothen gibberifrons*) and blackfin icefish (*Chaenocephalus aceratus*),[33] whereas stable or decreasing concentrations occurred in the more pelagic Antarctic silverfish (*Pleuragramma antarctica*)[44] and mackerel icefish (*Champsocephalus gunnari*)[65,66] (Table 2). Data on PCBs and DDT in icefish (*C. aceratus* and *C. gunnari*) collected around the Antarctic Peninsula (Table 2 and Fig. 1) have shown an increasing trend since the 1990s, while other POPs (*e.g.* hexachlorobenzene, HCB), have shown a stable or slightly decreasing trend.[67] Benthic fish collected between 1988 and 1996 from Terra Nova Bay (TNB, Ross Sea) (Fig. 1) also

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Table 1 Concentration (ng g^{-1} wet wt; * = lipid wt, ** = dry wt) of PCBs, *p,p′*-DDE, DDTs, and HCB in *Trematomus bernacchi* from the literature. The articles with information on climate and temporal trend are in italic (YoS = year of sampling; KGI = King George Island; TNB = Terra Nova Bay or Mario Zucchelli Station)

Authors	YoS	Tissue	Site	PCBs	*p,p′*-DDE	DDTs	HCB
Subramanian *et al.*[79] 1983	1981	Whole body	Syowa Station	0.12–0.24		0.5–0.9	
Subramanian *et al.*[80] 1984	1981	Muscle	Syowa Station	0.25		0.63	
Focardi *et al.*[68] 1992	1989	Muscle	TNB	12.8		4	0.27
Focardi *et al.*[68] 1992	1989	Liver	TNB	186		67	3.4
Larsson *et al.*[81] 1992	1989	Liver	Ross Sea	0.07*	0.01*		
Focardi *et al.*[82]	1992	Liver	TNB	21			
Corsolini *et al.*[83] 2003	1999	Muscle	TNB	6.35	0.16		2.6
Corsolini *et al.*[61] 2006	2001	Muscle	TNB	6.35	2.53	8.6	1.44
Borghesi *et al.*[62] 2009	2005	Muscle	TNB	1.65			
Cincinelli et al.[46] *2016*	*2010*	*Muscle*	*TNB*	*0.08*		*0.43*	*0.12*
Wolschke *et al.*[84] 2015	2010	Muscle[a]	KGI	102			

[a] Not specified.

Table 2 Concentration (ng g^{-1} wet wt; * = lipid wt, ** = dry wt) of PCBs, *p,p′*-DDE, DDTs, and HCB in the other *Notothenioidei* including *Channichthyidae* fish species from the literature. The articles with information on climate and temporal trend are in italic (YoS = year of sampling; KGI = King George Island; TNB = Terra Nova Bay or Mario Zucchelli Station)

Species	Authors	YoS	Tissue	Site	PCBs	*p,p′*-DDE	DDTs	HCB
C. gunnari	*Weber et al.*[65] *2003*	*1987*	*Liver*	*Elephant Island*		*4**		*26*
	Weber et al.[65] *2003*	*1996*	*Liver*	*Elephant Island*		*5**		*20.4*
G. gibberifrons	*Weber et al.*[65] *2003*	*1987*	*Liver*	*Elephant Island*		*3.7**		*22.6*
	Weber et al.[65] *2003*	*1996*	*Liver*	*Elephant Island*		*7.5**		*18.6*
C. aceratus	*Weber et al.*[65] *2003*	*1987*	*Liver*	*Elephant Island*		*7.2**		*17*
	Weber et al.[65] *2003*	*1996*	*Liver*	*Elephant Island*		*14.5**		*15.5*
C. hamatus	Focardi *et al.*[68] 1992	1989	Liver	Ross Sea	202**		49**	8.4**
	Focardi *et al.*[68] 1992	1989	Muscle	Ross Sea	9.5**		3.3**	0.61**
	Focardi *et al.*[82] 1995	1992	Liver	Ross Sea	36			
	Kumar *et al.*[85] 2002	1995	Muscle	Ross Sea	0.35			
	Corsolini *et al.*[86] 2002	1995	Muscle	Ross Sea	8.4	0.2		1.25
	Borghesi *et al.*[62] 2009	2005	Muscle	TNB				
	Strobel *et al.*[67] 2018	2015–2016	Muscle	Weddell Sea	427	73	140	

showed increasing concentrations of polychlorobiphenyls (PCBs), *p,p′*-DDE and HCB.[44,68] However, it is not known if these recently increasing trends are related to climate change in any direct or indirect way. Lana *et al.*[69] analyzed POP data from seventeen fish species from four Antarctic regions: Antarctic Peninsula, Weddell Sea, Ross Sea, Adelie Land (Fig. 1). They suggested that PCB burdens in the Antarctic region had not yet reached a steady state, probably because the environmental reservoirs of POPs, that continue to exist after primary emissions, have declined, and may be remobilized by warmer conditions due to climate change.[27]

The decreasing concentrations of POPs observed in Antarctic pelagic fish over time generally corresponds with declining trends observed in pelagic-feeding Antarctic seabirds, such as Adèlie penguins[30] (Fig. 2). This is evident for the development of PCB concentrations since the 1990s, but not equally clear for DDTs, increasing again in the 2000s[70] (Tables 3 and 4). These contrasting trends can be ascribed to the exchange of organic contaminants between the pelagic and benthic environments that is especially efficient in the Antarctic region because of its close relation to sea ice dynamics. The transport of organic matter from the water–ice interface and pack ice may be affected by climate change: more ice will melt, contributing to the release of entrapped organic matter to the water column, more lipophilic contaminants will be released to the underlying waters from where they can fall down to the benthic environment and community. Moreover, benthic organisms have limited capability to metabolize these contaminants.[68,71]

Geisz *et al.*[29] explored the potential effects of climate change on DDT levels in Adèlie penguins from the Antarctic Peninsula (Table 4 and Fig. 1). They found that $\sum$DDT concentrations in Adèlie penguin eggs from the Palmer Archipelago did not decrease from the 1970s to the 2000s, which is in contrast to the observations reported for thick-billed murres, northern fulmars, and black-legged kittiwakes in the Arctic during the same time period.[29,72] The detection of *p,p′*-DDT in the penguins, despite the bans and restrictions on its use in the 1970s, suggests there may be a current source of this chemical to the Antarctic marine environment. A previous study indicated that there had been very little recent DDT deposition in

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Table 3 Concentration (ng g^{-1} wet wt) of PCBs, *p,p′*-DDT, *p,p′*-DDE, DDTs, and HCB in Adèlie penguin from the literature. The articles with information on climate and temporal trend are in italic (YoS = year of sampling; KGI = King George Island; TNB = Terra Nova Bay or Mario Zucchelli Station)

Authors	YoS	Tissue	Site	PCBs	*p,p′*-DDT	*p,p′*-DDE	DDTs	HCB
Sladen *et al.*[31] 1966	1964	Fat	Ross Sea		23	52	77	
George *et al.*[87] 1966	1964	Fat	Ross Sea		0.17			
Luke *et al.*[88] 1989	1981	Egg	Davis Station			5		20
Subramanian *et al.*[79] 1986	1981	Fat	Syowa Station	39.5		228		
Court *et al.*[89] 1997	1989	Egg	Cape Bird	8.8		6.3	7.1	5.6
Lara *et al.*[90] 1990	1989	Blood	KGI	14			1.2	0.45
Focardi *et al.*[82] 1995	1992	Liver	Ross Sea	101				
Wanwimolruk *et al.*[91] 1999	1993	Egg	KGI	0.25	0.25	4	4.5	13.5
Corsolini *et al.*[86] 2002	1995	Egg	Ross Sea	2.8		0.1		0.1
Corsolini *et al.*[61] 2006	1995	Egg	TNB	24.9		20.7	23	18.7
Kumar *et al.*[85] 2002	1995	Egg	Ross Sea	3.3				
Corsolini et al.[70] *2011*	*1995–2001*	*Egg*	*Ross Sea*	*21.99*				*4.74*
Corsolini et al.[70] *2011*	*1995–2001*	*Egg*	*KGI*	*12.03*	*0.49*	*18.95*		*7.64*
Corsolini *et al.*[92] 2017	2001	Blood	Ross Sea	2.59			0.757	0.371
Schiavone *et al.* 2009[93]	2004	Egg	KGI	12			23	7.6
Cipro *et al.*[94] 2010	2005	Egg	KGI	32.5			6.29	22.1
Rudolph *et al.*[95] 2016	2009	Feces	Kopaitic Is	12.93				
Jara-Carrasco *et al.*[96] 2017	2011	Feces	Base O'Higgins; KGI	1.61			1.61	0.53

Table 4 Concentration (ng g^{-1} lipid wt) of PCBs, *p,p′*-DDT, *p,p′*-DDE, DDTs, and HCB in Adèlie penguin from the literature. The articles with information on climate and temporal trend are in italic (YoS = year of sampling; KGI = King George Island; TNB = Terra Nova Bay or Mario Zucchelli Station)

Authors	YoS	Tissue	Site	PCBs	*p,p′*-DDT	*p,p′*-DDE	DDTs	HCB
Risebrough *et al.*[32] 1968	1967	Egg	Ross Sea	6			0.128	
Risebrough *et al.*[97] 1976	1975	Egg	Doumer Is	0.07		0.126		
Schneider *et al.*[98] 1985	1981	Fat	Weddell Sea	346	38	361		232
Court *et al.*[89] 1997	1989	Egg	Cape Bird	37.3		26.9	29.9	22.5
Focardi *et al.*[99] 1993	1991–92	Muscle	TNB	2281			810	349
van den Brink *et al.*[100] 1998	1993	Blood	Davis Station	286		123		372
Inomata *et al.*[101] 1996	1991–1993	Preen oil	AP	895		401		1137
van den Brink *et al.*[102] 1997	1994	Preen oil	Hop Is	469				620
van den Brink et al.[30] *2011*	*1993/1994*	*Preen oil*	*Hop Island*	*PCB153 = 69*		*93*		*232*
van den Brink et al.[30] *2011*	*2003/2004*	*Preen oil*	*Hop Island*	*PCB153 = 2*				*136*
Geisz et al.[29] *2008*	*2004*	*Egg*	*Palmer Station*			*170*		
Geisz et al. 2008	*2004*	*Egg*	*Cape Royds*			*158*		
Geisz et al.[29] *2008*[29]	*2005*	*Egg*	*Palmer Station*			*177*		
Kim *et al.*[103] 2015	2008–2009	Muscle	KGI	3.2	1.24	127	134	
Mwangi *et al.*[104] 2016	2009	Various tissues	Zhongshan Station	144				

Antarctica,[73] although levels in Antarctic glacial meltwater were measurable.[74] Thus, glacial meltwater was proposed as a possible source of DDT to the Antarctic marine food web. This hypothesis is supported by measurement-based estimates of the amount of DDT released annually from Antarctic glacial ablation (1–4 kg $\sum$DDT y^{-1}).[29]

3. Conclusions and recommendations

Contrary to the Arctic, where the availability of long-term monitoring data allows the study of correlations between climate parameters and POPs in biota over time,[75] data on POP concentrations in the Antarctic have been collected less systematically and climate parameters have not been recorded, except very few studies. In some Antarctic fish, POP concentrations have declined over the last two decades; however, these temporal trends appear to be weak and variable. Additionally, concentration peaks of PCBs, DDTs, and PBDEs observed in Antarctic fish were potentially related to the release of POPs after iceberg B15 calved from the Ross Ice Shelf. Comparisons between Arctic and Antarctic data can provide insight into the influence of global change on the distribution of POPs globally, and specifically in polar environments.

The lack of data on the POP contamination and the link to climate parameters in the Antarctic make not possible both a comparison to the Arctic and general considerations on a global scale. This situation is due to the logistic difficulty to study in this Region, to the fragmentation of the research due to the lack of a pan-Antarctic research design. Despite the efforts on environment protection and on the study and monitoring of

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the climate change effects in the region,[76] no internationally coordinated programs have been established to monitor the POP contamination in the Antarctic region. This anomaly respect to the Arctic might be due to the absence of resident human populations in the region that might keep low the interest in funding the long-term monitoring of POP contamination and effects in organisms. The need for standardized methods was already highlighted in the 1990s[77] because comparable methods and regular monitoring are priority for the assessment of temporal trends. The Action Group on "Input pathways of persistent organic pollutants to Antarctica" (ImPACT, https://www.scar.org/science/impact/home/) of the Scientific Committee on Antarctic Research (SCAR, https://www.scar.org) was established (in 2018) with the aim of facilitating coordinated investigation and chemical monitoring; the United Nations Ocean Decade Action has also endorsed an Antarctic Monitoring & Assessment Program (AnMAP; https://www.oceandecade.org/actions/the-antarctic-monitoring-and-assessment-programme-anmap/). These initiatives aim to facilitate and promote coordinated research across Antarctica and the Southern Ocean, like in the Arctic, in order to collect data following standardized methods, which can allow comparisons and time trend assessment.

In general, data compiled from the Antarctic Region illustrates the potential effect of melting ice and glaciers on POP concentrations in biota; the available data need to be confirmed by further studies that should also include the record of and correlation to climate parameters. Antarctica is still a final sink for POPs due to the extreme cold climate and organisms, as reported previously, are still final receptors.[30] The peculiar marine Antarctic ecosystems and the pelagic-benthic coupling leave still open the question whether the POP amount accumulated in the Antarctic ecosystems is decreasing or not, as concentration peaks can still be observed in biota.[33,78] Future research and monitoring initiatives for the Arctic and Antarctica should take relevant findings to both polar regions into consideration.

Conflicts of interest

There are no conflicts to declare.

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