

How Important Is Research on Pollution Levels in Antarctica? Historical Approach, Difficulties and Current Trends

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Contents

1	Introduction	81
2	The Presence of Pollutants in Antarctica's Environment	82
2.1	Abiotic Environment	83
2.2	Biotic Environment	87
3	Types of Pollutants Present in Antarctica's Environment	90
4	Detailed Information Pertaining to Analytical Research in Antarctica	92
4.1	History of Research on the Chemical Composition of Samples from Antarctica ..	92
4.2	Pollution Concentration Levels Over Decades	92
4.3	Analytical Techniques in the Study of the Antarctic Environment	141
4.4	Impact of Research Station Activities on Pollution Levels	142
5	Summary and Conclusions	144
	References	145

List of Acronyms

AFS	Atomic fluorescence spectrometry
CCAMLR	The Commission for the Conservation of Antarctic Marine Living Resources
CD	Conductometry detector
CFCs	Chlorofluorocarbons
CHLs	Chlordanes
COMNAP	Council of Managers of National Antarctic Program
CZE	Capillary zone electrophoresis

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DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethane
DDT	Dichlorodiphenyltrichloroethane
DLCs	Dioxin-like compounds
ECD	Electron capture detector
GC-MS	Gas chromatography–mass spectrometry
GPC	Gel permeation chromatography
HBB	Hexabromobenzene
HCB	Hexachlorobenzene
HCFCs	Hydrochlorofluorocarbons
HCHs	Hexachlorocyclohexanes
HPLC	High-performance liquid chromatography
IC	Ion chromatography
ICP-AES	Inductively coupled plasma atomic emission spectrometry
ICP-MS	Inductively coupled plasma mass spectrometry
ICP-OES	Inductively coupled plasma optical emission spectrometry
IDMS	Isotope dilution mass spectrometry
LC-MS/MS	Liquid chromatography with tandem mass spectrometry detection
LOD	Limit of detection
LOQ	Limit of quantification
LRAT	Long-range atmospheric transport
NNA	Neuron activation analysis
OC	Organochlorine compound
OCP	Organochlorine pesticides
PAHs	Polycyclic aromatic hydrocarbons
PBDEs	Polybrominated diphenyl ethers
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PCNs	Polychlorinated naphthalenes
PFBS	Perfluorobutane sulfonate
PFHxA	Perfluorohexanoic acid
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
POPs	Persistent organic pollutants
QqQ	Triple quadrupole
SFC	Supercritical fluid chromatography
SML	Surface microlayer
TC	Thermal conductivity
TLC	Thin-layer chromatography
TOC	Total organic carbon
TOF	Time of flight analyzer
XRF	X-ray fluorescence

Highlights

- Scientific interest in the issue of presence of pollutants in Antarctica steadily increasing since 1960.
- In various samples from Antarctica a variety of harmful pollutants were identified.
- The analytic methods, which are dedicated to determine POPs and metals in different matrices, need to be developed.
- Antarctica is prone to storage of POPs, which may also undergo remobilization processes.

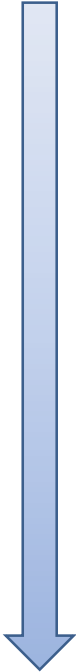
1 Introduction

The term “*Antarctica*” is used to define both the Antarctica continent itself as well as the Southern Ocean that surrounds the continent and the islands of this ocean. Antarctica is the most isolated continent; however, its specific location does not protect this area from negative impact of human activities (Aronson et al. 2011). A broad belt of the Southern Ocean’s waters constitutes a barrier, which makes it difficult to transport pollutants this way. Therefore, volatile and semi-volatile chemical compounds may reach Antarctica together with air masses moving in this direction (long-range atmospheric transport—LRAT) (Corsolini 2009). However, more and more attention has been recently paid to the determination of the size of the locally emitted contamination impact on Antarctic environment (Bengtson Nash et al. 2011).

The first information on the occurrence of anthropogenic pollutants comes from the 1960s and it pertains to the presence of dichlorodiphenyltrichloroethane (DDT) in sea organisms (Bargagli 2008). Further research pertained to chemical composition of samples of water, snow and ice and it included metal and ion determination. Since the 1960s, research on the presences of pollutants from the group of persistent organic pollutants (POPs), e.g. hexachlorobenzene (HCB), hexachlorocyclohexanes (HCHs), aldrin, endrin, heptachlor and other pollutants in samples of living and non-living matter collected in Antarctica has been undertaken (Bargagli 2008; Corsolini 2009).

However, due to difficult climatic conditions, research pertaining to pollution analysis in this area was conducted on irregular basis. In recent decades, there has been a growing interest in the problems of pollutants present in samples from various elements of Antarctica’s ecosystem. Figure 1 presents milestones of events influencing the development of research on Antarctica (including ones influenced development of chemical research).

Urbanised areas, especially those with intensive agriculture, as well as tropical and subtropical regions, where spraying is used for disease vector control, are the main sources of POPs and heavy metals in the Southern Hemisphere. The increase in the usage of many POPs has been observed in the 1990s in Asian countries and Southern Pacific islands (Bargagli 2008). Some large amounts of polychlorinated biphenyls (PCBs) used in older electrical devices were also deposited as landfill in some developing countries. The heaviest user of DDT, toxaphene and lindane, has



1773	The first expedition of Captain James Cook to Antarctica
1897/98	A Belgian expedition was the first to spend winter in Antarctica
1882/83	First International Polar Year
1904	The first all-year Orcadas polar station was established by Argentinian Scientists
1932/33	Second International Polar Year
1957/58	International Geophysical Year
1958	Establishment of the Scientific Committee on Antarctic Research (SCAR)
1959	Signature of the Antarctic Treaty by 12 member states (at present ratified by 43 states)
1960	First information about the occurrence of pollutants in marine organisms (DDT)
1964	Agreed Measures for the Conservation of Antarctic Fauna and Flora, Antarctica Specially Protected Areas (ASPAs)
1972	The Convention for the Conservation of Antarctic Seals (CCAS)
1980	The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR)
1988	Establishment of the Council of Managers of National Antarctic Programs (COMNAP)
1991	Protocol on environmental protection to the Antarctic Treaty (entered into force in 1998)
2007/08	Fourth International Polar Year

Fig. 1 Milestones of events connected with the development of Antarctic research (Köler 2013; SCAR Information; Dastidar and Ramachandran 2008; Dodds 2010)

historically been in South America. A comprehensive report by UNEP in 2002 gives more precise data on air levels of POPs in the Southern Ocean and Antarctica (Bargagli 2008).

A critical comparison and discussion of results of the research conducted over decades is not easy, as over a period of more than 50 years, methods and techniques used for research have undergone continuous changes. Moreover, while conducting research on such a complex ecosystem, it is necessary to frequently verify any possible changes by comparing the data acquired during different research projects and at different times. However, this task often cannot be practiced as the results may be achieved with the use of analytical techniques which present extremely different degrees of accuracy and sensitivity (Magi and Tanwar 2014).

The study presents information on the dynamics of the development of polar research (covering main groups of pollutants) both in terms of its methodology and the scope of research on Antarctica (diversity of tested samples and analytes) conducted over the past decades by members of teams working at polar research stations.

2 The Presence of Pollutants in Antarctica's Environment

Polar ecosystems consist of several key species. Mutual relationships between individual elements of the environment are closely connected; therefore, the presence of pollutants in one of elements of the ecosystem may have a significant

influence on the functioning of the other ones. To become familiar with the influence of pollutants on the functioning of Antarctica's ecosystem, research is conducted on both abiotic and biological samples.

2.1 *Abiotic Environment*

Abiotic environmental media (fresh water and seawater, precipitation, glaciers, soils, etc.), as well as all processes and phenomena connected with changes occurring in individual elements of the environment (meteorological, geological, geochemical processes, etc.), play a significant role in transporting pollutants in Antarctica (Cipro et al. 2012). Elements of abiotic environmental media, such as snow, glaciers and polar catchment areas are sources of water for all organisms living in Antarctica. Antarctica's ecosystem has a very simple structure, therefore, even a small amount of pollution present in abiotic elements of nature may constitute a significant hazard for any individual plant and animal species because of absence of advanced detoxification mechanisms (Bengtson Nash et al. 2011).

2.1.1 Air

The atmosphere plays an important role in transport of pollutants to polar areas. Over the past decade, a range of research has been conducted to determine mechanisms, which contribute to the presence of pollutants in Antarctica, as well as to distinguish between local sources of pollution and long-range atmospheric transport.

Information about Antarctica's air pollutants mostly comes from research conducted during cruises near Antarctica (Bengtson Nash et al. 2011) and is predominantly based on short-term (weeks–month) atmospheric monitoring (Kallenborn et al. 2013). Some of these data have been included in the assessment of global distribution of numerous POPs. However, due to the limited number of samples and non-continuous measurement periods, it is difficult to compare the results of air sample research conducted in Antarctica with the results of sample research from the Arctic region. A long-term atmospheric pollution monitoring in the polar regions is a significant scientific tool for assessing anthropogenic influences on the environment on a global scale. It enables the control or even changes of international legal regulations (Kallenborn et al. 2013).

The results of research on long-term monitoring of POPs were published in 2013 and focused on the concentrations of long-range transported contaminants (POPs) in the Antarctic environment. The research has revealed that the atmospheric long-range transport of polluted air masses is considered as the main source for the POPs monitored at Norwegian Troll station in Dronning Maud Land (Kallenborn et al. 2013). In the discussion about the presence of more volatile substances in Antarctica, as a source of it, long-range atmospheric transport is considered, while the presence of less volatile substances, which occur occasionally in Antarctic's air,

may rather indicate influence of local sources (Kallenborn et al. 2013). A particular impact of local sources is shown in the analysis of compounds from the polybrominated diphenyl ethers (PBDEs) group. Due to the fact that neither plastics nor PBDE manufacturing occur in Antarctica, the substantial indoor PBDE residues are likely to originate from losses of imported flame retarded plastic and electronic products. There are plenty of electronic devices in the research stations, but at the same time there is not much space for them. Moreover, the material transport to Antarctica is expensive (Hale et al. 2008). The first atmospheric measurement, which was constructed as a part of a new continuous monitoring effort, was presented in one of Australia's all-year research station—Casey Station (66°17' S 110°3' E). The results suggest a potential local source of the currently produced, involatile, decabrominated PBDE congener 209, which contributes to PBDE profiles in all the samples (Bengtson Nash et al. 2011).

These discussions prove that it is necessary to take additional precautions in order to stop further deterioration of the pristine air status in Antarctica caused by the human presence in this region.

2.1.2 Snow and Ice

In polar areas chemicals like POPs have been observed in seasonal snowpack and in older layers of firn and ice, providing accumulation time series (Herbert et al. 2006b).

During long-range atmospheric transport, pollutants may undergo decomposition and deposition processes, depending on the physicochemical properties of individual compounds.

The mechanisms of exchange of trace organic contaminants between the atmosphere and snow (both falling snow and standing snowpack) depend on the major processes like scavenging (vapour and particle) by falling snow, vapour sorption/desorption to the snow's surface, and diffusion of chemicals both into and out of the snowpack (Herbert et al. 2006b). These processes dictate the quantities of chemical compounds available to meltwater and in deeper areas (permanent snow and ice). Additionally, processes occurring after deposition, e.g. snow settling (fresh snow is gradually transformed into firn and then in a glacier layer, the volume of which becomes gradually reduced) are of importance. The snow-settling process is the first stage, during which compounds, e.g. from the polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) group, are adsorbed on snowflakes. These compounds due to their physicochemical properties are classified as semi-volatile compounds, may become released back to the gaseous phase during seasonal snowmelt or diffused into deeper snow layers (Wania 1997). This process *inter alia* depends on solubility (concentration of a given compound), the snow-air partitioning properties and the temperature gradient. The snow-air partitioning properties not only depend on the vapour pressure but also on the surface properties of the snow flakes/snow pack. These properties largely determine the sorption and diffusion processes (Herbert et al. 2006b).

Based on experimental diffusivities for a volatile tracer of sulfur hexafluoride in snowpack it was concluded that in the low-wind (up to 3 m/s) scenario the migration of sulfur hexafluoride in the snowpack can be largely attributed to diffusive transport, while at high wind speeds (up to 9 m/s) the chemical migration is largely due to advective transport (Albert and Shultz 2002). Snow and firn metamorphism processes depend on the temperature fluctuations. Grain growth may occur, which, in turn, increases the firn permeability. As a result of global migration of a broad range of compounds towards higher latitudes, they become accumulated in polar regions (Kozak et al. 2013). Systematic compound accumulation contributes to the formation of a pollutant reservoir. A large part of the pollutant load is stored in snow and ice. Chemical compounds, which may be trapped in polar areas, can constitute a long-term hazard due to the possibility of their subsequent release into the environment—the so-called reemission into the environment may occur (Herbert et al. 2006a). Quantities of pollutants released during the spring snowmelt could have significant influence on the quantities of pollutants present in both freshwater and marine system (Herbert et al. 2006b). This hypothesis is named “spring pulse” and currently researchers are working on the creation of snowmelt models concerning quantitative transport of pollutants from snow to other abiotic environmental media (Burniston et al. 2007; Herbert et al. 2006b; Wania et al. 1999).

2.1.3 Soil and Permafrost

For the study of air transported pollutants, soil samples are worthy of note materials because of their direct contact with the atmosphere. Antarctica’s soil may become polluted as a result of wet and dry deposition (LRAT) and accidental release of pollutants into the environment (oil spills) (Curtosi et al. 2007; Webster et al. 2003; Aisable et al. 2004).

The concentration limits of compounds in soil depend on the type of soil. Antarctica’s soil variability is mainly due to parent material, differences in land-surface age (range: from a few thousand to millions of years), topographic position and local climate (Aisable et al. 2004).

In general approach to the presence of pollutants in soil, permafrost and an active soil layer play an important role in migration of compounds in soil (Curtosi et al. 2007). An active soil layer and permafrost presence is a unique characteristic of polar areas. It is known that repeated freeze/thaw cycles occur in areas with an active layer of permafrost, as a result of which soil particles may undergo a slow process of screening. Small particles may migrate from the surface layer into deeper layers, while stones have a tendency to migrate from deeper layers to the surface. Pollutants are adsorbed mostly from the surface of particles with a smaller diameter. Research results show that the percentage (quantity) of small particles and their dynamics in the soil matrix are the key factors in determining the fate and degradation of pollutants, e.g. PAHs in Antarctic soil. In this way, thawing of the upper layer of the permafrost, which may be caused by global warming, will have widespread influence on the distribution of pollutants in this environment (Curtosi et al. 2007).

2.1.4 Catchment Areas

There are lakes and small streams, which thaw in the summer in small areas of Antarctica which are free from ice. Open water lakes in Antarctica are very rare due to low temperatures. However, the accumulation of pollutants also occurs in lakes and lake sediments. Much higher concentrations (as compared to concentrations of the same analytes in soil samples) of some compounds, e.g. HCH in lake sediments are probably determined by the nature of Antarctic lakes. Antarctic's lakes are formed from melting ice water, which is rich in atmospheric particles (trapped in it during formation) (Fuoco et al. 2009a; Vandal et al. 1998).

Another factor, which influences the level of pollutants in freshwater environment, is the transport of persistent chemicals by seabirds biovector. Higher concentration of POPs has been recorded in aquatic organisms from a seabird-affected lake. This is a proof that seabird-transported contaminants have been entering freshwater and thereby local food webs (Michelutti et al. 2010; Xie and Sun 2008). As long as detailed mechanism of pollution transfer by seabird's vectors are not widely described, further researches should be applied in this direction.

2.1.5 Ocean, Seas and Bottom Sediments

Oceans and seas plays a significant role in the circulation and removal of pollutants. Within Antarctica, the Antarctic Convergence Zone (also called the Antarctic Polar Front) is distinguished. It runs between 47°S and 62°S. It separates cold and less saline Antarctic waters from subantarctic waters. The zone may be the barrier for pollutants transported by sea (Bengtson Nash et al. 2011).

Relatively much attention was devoted to research targeted at estimating the degree of exchange of pollutants between the seawater surface (inter-phase) and the atmosphere and the role of seawater in the process of transporting chemical compounds to polar regions. The sea surface consists of layers, out of which the sea surface microlayer (SML) has been researched most broadly (0.1–0.001 mm). This is a place where pollutants, atmospheric particles and microorganisms accumulate. However, the majority of research projects focusing on measurements of pollutant content in SML samples were conducted using samples collected in coastal environments. There is very little data from open ocean samples (Fuoco et al. 2009a).

Another element of abiotic environmental media in the pollutant transportation process is bottom sediments. More hydrophobic organic compounds may undergo sorption on solid particles and microorganisms. Dead particles of organic matter and solid particles settle on the bottom and, thus, pollutants adsorbed on them accumulate in bottom sediments (Boutron et al. 1990). Pollutants present in bottom sediments may be re-emitted as a result of activity of bottom organisms and ocean currents. Thus, the bottom sediments can become secondary source of pollution.

2.2 *Biotic Environment*

Anthropogenic pollutants have an adverse effect on living organisms. Antarctic biota (e.g. seals and penguins) are particularly sensitive to contaminants. The natural stress on wildlife in extreme polar environments is often more severe than in temperate regions. Hence Antarctic species can be more vulnerable to the effects of pollutants in comparison with species which come from temperate regions (Schiaivone et al. 2009a). Moreover, due to very simple structures of polar ecosystems, relationships between individual organisms are important in terms of pollution transfer. Mutual connections between individual species determine the way, in which pollutants are transported (Cipro et al. 2012).

2.2.1 *Plants*

Mosses and lichens are the main components of the terrestrial flora of Antarctica's ecosystem. Bryophytes are predominantly useful for monitoring the atmospheric pollution (metals and organochlorine compounds) because they have no protective waxy cuticles and no root system (Borghini et al. 2005). The content of pollutants present in samples of these plants largely depends on precipitation. Thus, they can play a very important role of biomonitors, i.e. indicators of long-term pollutant deposition (Fuoco et al. 2009a).

As mentioned above, pollutants present in the air may undergo dry or wet deposition, thus getting into Antarctica's environment. Plants absorb pollutants from the atmosphere (through their above-ground parts, especially leaves) or/and from the soil (through the roots). For compounds with strong hydrophobic properties, transport through solids seems to have little significance. Literature data may be the basis for concluding that the main mechanism of collecting pollutants from the environment is absorption from the surrounding air into the leaf surface of pollutants in the gaseous phase or the solid phase (through particles settled on plant surfaces) (e.g. Borghini et al. 2005; Mão de Ferro et al. 2014; Poblet et al. 1997; Wu et al. 2014; Yogui and Sericano 2008; Yogui et al. 2011). Pollutants get into plants through stomata or leaf epidermis. Furthermore, the process of "assimilating pollutants" into plants is influenced by a range of physicochemical factors (e.g. partial pressure of water vapour, the numerical value of the octanol/water partition coefficient and the water/octanol partition coefficient), environmental factors (e.g. the temperature, precipitation, wind speed) and plant properties (e.g. the species, fat content, leaf morphology) (Yogui and Sericano 2008; Yogui et al. 2011).

2.2.2 *Crustaceans, Benthic Organisms and Fishes*

Antarctica's ecosystem has a very simple structure. Organisms at higher levels of the trophic chain depend on several key species, such as the Antarctic silverfish (*Pleuragramma antarcticum*) and the Antarctic krill (*Euphausia superba*). The

Antarctic silverfish and the Antarctic krill are the main sources of food for many maritime species of birds and mammals. As a result of the mutual relationship between the size of the krill and silverfish populations and the size of the populations of other species, a decrease in the krill and silverfish population size may have a negative impact on the entire environment of Antarctica's marine ecosystem (Corsolini et al. 2002b). As a result of close relationships between individual species, POPs are present in every level of the trophic chain (Corsolini et al. 2002b). The phenomenon of biomagnification plays a more important role than bioaccumulation itself in the case of Antarctic fish. Lower pollutant concentrations are observed in samples of fish, for which krill is the staple food. Values of harmful compound concentrations increase if invertebrates or other fish are the main source of food (Weber and Goerke 2003).

In pelagic fish a downward trend in concentrations of some persistent organic pollutants (e.g. HCB, dieldrin) is visible (Van den Brink et al. 2011). It contrasts distinctly with steady or increasing concentrations levels in benthic organisms. Transfer of contaminants between Antarctic pelagic and benthic food webs is associated with seasonal sea-ice dynamics and thus with different climatic conditions. This fact may hinder the predictability of future trends of emerging compounds in the Antarctic ecosystem (e.g. the brominated compounds). The discrepancy in trends between pelagic and benthic organisms still remains the question whether the total environmental burden of contaminants in the Antarctic ecosystem is declining or increasing (Van den Brink et al. 2011).

2.2.3 Seabirds

Marine birds are another link in the food chain, where penguins constitute the most numerous group. They belong to key-species in Antarctica's ecosystem. Penguins feed mainly on krill and also on fish (depending on krill's accessibility). Researchers have reported that predators may be a sink for chemicals (special for volatile and toxic ones) and this may pose an important environmental problem (Corsolini et al. 2007).

Penguins (Adèlie and Emperor) spend their whole life in the Southern Ocean, while marine bird species, such as migrating snow petrel, south polar skua, brown skua are species migrating all over Antarctica. In both cases, results of samples researched from these species could reflect the condition of their ecosystems (Corsolini et al. 2011). The aforementioned bird species rely on all krill species and the Adèlie penguin eats the most krill (Corsolini et al. 2011). The Emperor penguin also eats a lot of fish as well as crustaceans and cephalopods. The south polar skua feeds on penguins' eggs and chicks and it also eats Antarctic silverfish krill (over 80 %). In the nesting season, on the other hand, skuas depend on food found on land. The brown skua also relies on sea food (Corsolini et al. 2011). Moreover, the research results concerning detection of POPs in seabirds' eggs (including penguin and south polar skua eggs) proved the transfer of POPs from mothers to eggs (Corsolini et al. 2002a).

The most important link between Antarctic marine, freshwater and terrestrial ecosystems constitutes seabirds. In fact, they maintain the development of terrestrial flora due to the high amount of nutrients deposited by seabirds on the land (e.g. by guano). Seabirds usually transport loads of pollution. Unfortunately, endocrine mechanisms are still poorly investigated in free-living organisms, despite the fact, that contaminants have endocrine disrupting properties. In the scientific literature there is surprisingly only few data on the effect of age on contaminant levels, despite the fact that long-lived organisms are thought to be highly sensitive to pollution. Therefore, it is not clear if seabirds accumulate POPs with increasing age (Tartu et al. 2015).

Comparing research results concerning pollution in birds' tissues from other areas of the world, shows that POPs concentrations in penguins are relatively low (Corsolini et al. 2007). In relation to species and sex, different chemical accumulation patterns are observed. Penguins are showing low detoxifying capacities and therefore studies on their xenobiotic metabolism should be carried out (Corsolini et al. 2007).

2.2.4 Marine Mammals

During the evaluation of contamination presence in the marine mammals' tissues scientists should bear in mind the migratory habits of these organisms. Some species of marine mammals (including cetaceans) exist in Antarctica' seawaters in summer time and then go northward during winter, while other species, e.g. some seals, spend their entire life cycles in the Southern Ocean and on the Antarctic coasts. In migrating organisms what may affect the amount of pollution in Antarctic organisms is the forage or breed during summer, as well as exposition to pollutants in more contaminated areas during winter. Species and individuals staying in anthropized areas during migration contribute to greater exposure to contamination compared with those that stay in Antarctica all year round. Furthermore, pollution (like POPs) accumulation in marine mammals depends on some other factors including metabolism (Corsolini 2009).

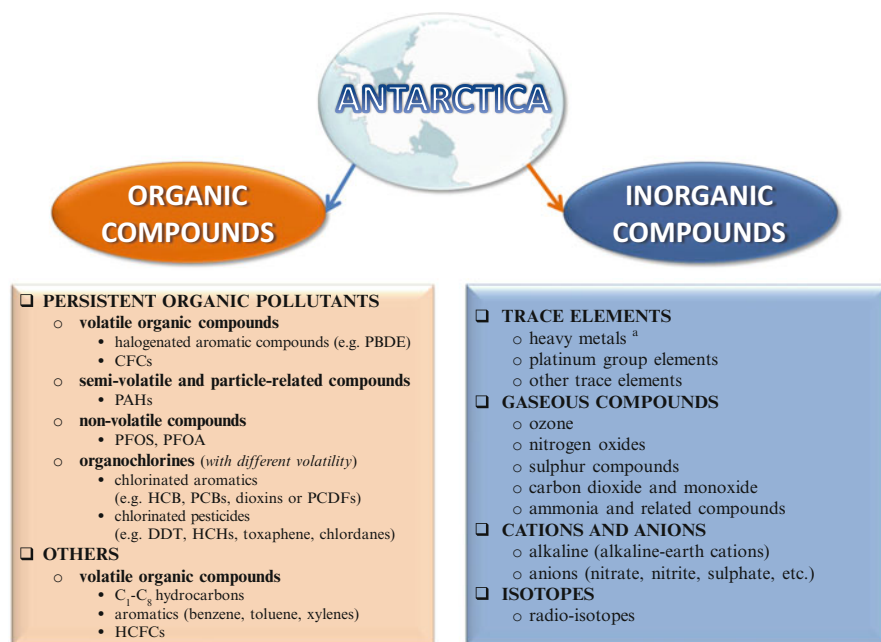
Marine mammals differ from the land ones with a high lactation transfer of all lipophilic substances (including pollutants) to young animals (Schiafone et al. 2009a; Trumble et al. 2012). This mostly results from an increased fat content in the mother's milk (Schiafone et al. 2009a). For cetacea and pinnipeds a vast majority (approx. 90 %), of the total amount of chloroorganic pollutants occurring in newborns are transferred in the mother's milk (Cipro et al. 2012). Due to the position of mammals in the trophic chain of the marine environment, a relatively long life and an increased demand for energy, the pinniped species can be treated as an indicator (reference) species for the examination of harmful effects of pollutant bioaccumulation in organisms (Cipro et al. 2012).

Marine mammals have been exposed also *inter alia* to heavy metals. Scientists are devoting particular attention to mercury because of its toxicity as well as the fact that it is widespread within the environment, and can be biomagnified in marine food chains. Very important is also the fact that Hg is available mainly because of human activities (e.g. Jerez et al. 2011). However, data of concentrations of Hg in seals and other vertebrates of Antarctica's are sparse (Szefer et al. 1993). Moreover, most of the attention in marine mammals' research is devoted to the identification of organic contaminants. Some reports lead even to observation of an increasing trend of PCBs and chlorinated pesticides: HCB, HCHs, chlordanes (CHLs), DDTs in minke whales (*Balaenoptera bonaerensis*) feeding on Antarctic krill between 1984/1985 and 1992/1993 (Aono et al. 1997). Concentration of DDTs, PCBs and HCB have been reported in various species of marine mammals during last decades. However, data on the presence of other POPs (including new emerging ones, like poly- and per fluorinated organic compounds (PFCs)), even if it was reported in oceanic and lake water samples (Cai et al. 2012), in marine mammals tissues are still scarce (Corsolini 2009).

Only a few of the hundreds of thousands of different industrial chemicals produced on a world scale have been studied and reported in the Antarctic environment. Antarctica's trophic chains are relatively simple and short and therefore understanding the detailed information on the levels of pollutants in different parts of the environment (including abiotic part) is very important. Animals at the top of the food webs depend on a few key species. Therefore affecting one of these key species could have a devastating impact on the whole ecosystem.

3 Types of Pollutants Present in Antarctica's Environment

Anthropogenic pollutants in Antarctica may come from global (LRAT) and local sources. Global sources include industrialised sites situated all over the Southern Hemisphere, from which pollutants are transported to Antarctica by various routes (Bargagli 2008). Local sources, on the other hand, include, amongst other things, scientific activities which are connected with the use of waste incineration plant, fuel consumption, sewage production, developing tourism and related intensification of ship transport (Cincinelli et al. 2009). The most polluted areas include areas around historic bases and polar stations where soil is often polluted by fuel remains, solid waste and household sewage (Negri et al. 2006; Webster et al. 2003). Anthropogenic pollutants are present in various elements of the environment in Antarctica. Because of their specific (also hazardous) properties POPs and heavy metals are described in this article in detail. However, authors do not include any chapter about general sources, properties and toxicity of pollutant groups determined in various types of samples collected from the Antarctic environment. This information has been given in other literature sources (e.g. Aisable et al. 2004; Borghesi et al. 2008; Cincinelli and Dickhut 2011; Corsolini 2009; Fuoco et al. 2012; Houde et al. 2011; Ma et al. 2014; Planchon et al. 2002; Vecchiato et al. 2015).



^aincluding mercury itself and its transformation products (e.g. methylmercury-organic compound)

Fig. 2 The group of chemical compounds identified in Antarctica

Despite the fact that environmental studies represent only a small part of scientific research in Antarctica (Magi and Tanwar 2014), polar explorers are increasingly also interested in chemical research. Figure 2 shows a group of chemical compounds that are of interest to researchers in Antarctica (after Walton et al. 2001).

In the discussion on the presence of organic compounds in the Antarctic environment, scope of interest is mainly focused on POPs like HCB, PCBs, DDTs, PBDE and PAHs. Over the past decades, sporadic research also pertained to identification and determination of compounds such as: CHL, dioxins, dioxin-like compounds (DLCs), PFCs, pesticides (dieldrin, mirex, heptachlor, endosulfan), aliphatic hydrocarbons, n-alkanes and cumulative parameters such as total organic carbon (TOC) in various environmental samples.

The presence of metals in remote Antarctica is not, as it was thought previously, limited only to lead and copper, but also other includes metallic elements, metalloids and radioactive elements, such as: V, Cr, Mn, Zn, Co, Ag, Cd, Ba, Bi, U, Pt, Ir, Rh, Mo, Tl, As, Sb (Hong et al. 2012; Soyol-Erdene et al. 2011).

4 Detailed Information Pertaining to Analytical Research in Antarctica

For a long time Antarctica was not available to scientists mainly because of the specificity of its location. Initial research was aimed at getting to know geological properties of the area. With time, also meteorological, magnetic and botanic research was undertaken and in recent years, chemical research was also conducted. The implementation of this research requires enormous involvement and determination on the part of scientists, mostly due to very difficult weather conditions (Köler 2013).

4.1 *History of Research on the Chemical Composition of Samples from Antarctica*

Research conducted in Antarctica has always been interdisciplinary. One area of research includes actions connected with determining the chemical composition of biotic and abiotic samples. Initially, it was research using classical analytical techniques; however, the scope of determined compounds has been expanded over time. Table 1 presents the historical calendar pertaining to the development of the scope of analytical research of the Antarctic environment conducted up to the end of 1989.¹

4.2 *Pollution Concentration Levels Over Decades*

The scope of analytical researches conducted over individual decades is differentiated both in respect of the place of research and types of samples and analytes which are determined in them. Monitoring of the environment allows for reliable observation changes and information contained in publications pertain to individual parts of the Antarctic ecosystem and various groups of pollutants. At present, scientists devote a lot of attention to research on pollutant levels in Antarctica's environment; however, there are still areas which have not been researched in this respect. Figure 3 shows the percentage of most commonly studied regarding the presence of contaminants in the environment of Antarctica up to end of 2014.

In this article, the authors pay particular attention to the research on determination of persistent organic compounds and heavy metals in different samples from

¹ Analytical research is applied in Antarctic since the early 1960s. (that gives 55 years period of research). Hence authors decided to designate first three decades as historic ones (up to the end of 1989). During this period only few data has been published, hence this period is three decades long.

Table 1 Historical calendar pertaining to the development of the scope of analytical research of the Antarctic environment conducted up to the end of 1989

Year	Sampling place	Analytes or subject of research	Type of sample	The analytical techniques	Literature
1960	n/a ^a	DDTs	Adelie penguins, crabeater seal	n/a	Bargagli (2008)
1963	Princess Elizabeth Land	Trace metals: Sr, Br,	Lake water	n/a	Burton (1981)
1964	South Victoria Land	Element: I	Lake water	n/a	Burton (1981)
1966	Mc Murdo Dry Valley	Chemical composition (Cl^- , Mg^{2+} , Ca^{2+} , C –biocarbonate ion concentration) temperature, density, solar radiation penetrating the ice, conductivity	Lake water	Classical analytical techniques (titration), selenium photo-electric cell, a bolometer, remote control conductivity probe	House et al. (1966)
1967	McMurdo Station, Hut Point Peninsula Saddle, Taylor Valley, Ross Ice Shelf, Mt. Discovery	NO_2 , SO_2 aldehydes	Air	Portable air sampling apparatus	Fischer et al. (1967)
	South Victoria Land	Trace metals: Mn, Fe, Mo, Pb, Zn, Bi, Rb, Cs	Lake water	n/a	Burton (1981)
1969	Pacific Ocean	PCBs	Sea birds	n/a	Risebrough et al. (1969)
	Interior of The Antarctic Continent	Pollutant lead aerosols, terrestrial dusts and sea salts	Snow strata	n/a	Murozumi et al. (1969)
	Plateau Station	DDT	Surface snow	n/a	Peterle (1969)
1972	Mimv, Vostok	Cl, Na, Mg, K, Ca, Mg, Fe	Surface firn	Atomic absorption, neutron activation	Boutron et al. (1972)
	Doumer Island, Antarctic Peninsula	PCBs	Penguin eggs	n/a	Risebrough and Carmignani (1972)
1975	Halley Bay	DDT	Snow	n/a	Peel (1975)
1976	n/a	DDTs, PCBs	Snow penguin eggs	n/a	Aono et al. (1997), Risebrough et al. (1976)

(continued)

Table 1 (continued)

Year	Sampling place	Analytes or subject of research	Type of sample	The analytic techniques	Literature
1978	East Antarctic, South Polar Station And Dome C	Sulfate SO_4^{2-}	Snow	Classical analytical techniques (titration)	Delmas and Boutron (1978)
1978/1979	Ross Island and the Wrightand Taylor Valleys	Fe, Hg	Sediments, clays and rock fines	Atomic absorption spectrophotometry	Siegel et al. (1981)
1980	Mc Mundo	Environmental assessment of Antarctic research	Rocks, ice cores, soil samales, meteorites, certain biota, fossils	n/a	Myers et al. (1980)
	King Edward Cove	Aliphatic hydrocarbons, PAHs	Plants, soil, fresh-water sediment, zooplankton	Gas chromatography-mass spectrometry (GC-MS)	Platt and Mackie (1980)
	James Ross Island	Acidity	Precipitation	pH determination or titration	Delmas and Gravenhorst (1983)
1981	Signy Island, King Edward Cove	Aliphatic and aromatic hydrocarbons	Marine benthic invertebrates	n/a	Clarke and Law (1981)
	Syowa Station	DDTs, PCBs	Fish (whole body)	Gas chromatography—electron capture detector (GC-ECD)	Subramanian et al. (1983)
1982	The Geographic South Pole	Na, Mg, K, Ca, Fe, Al, Mn, Pb, Cd, Cu, Zn and Ag	Snow layers	Atomic absorption techniques	Boutron (1982)
1983	n/a	DDTs, PCBs	Fish tissues	n/a	Aono et al. (1997)
	Ross Sea	DDTs, PCBs	Weddell seal blubber	n/a	Aono et al. (1997)
	East Antarctica	Pb	Snow cores	Isotope dilution mass spectrometry (IDMS)	Boutron and Patterson (1983)
1984	The Coast On Riiser-Larsenisen Ice Shelf	Ions (for example: SO_4^{2-} , Na^+)	Snow profiles	n/a	Gjessing (1984)
	n/a	DDTs, PCBs	Mink whale liver, Ross seal blubber	n/a	Aono et al. (1997)

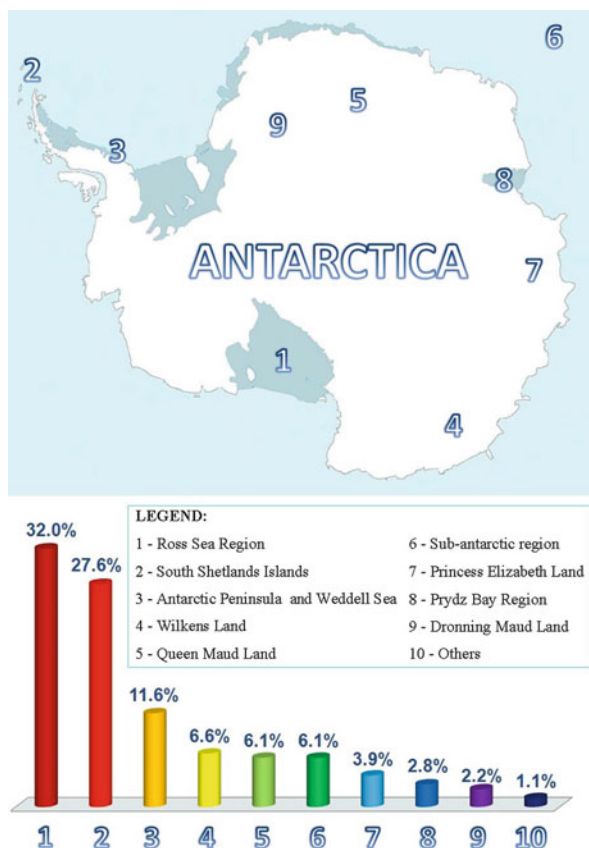
1979	Areas of the Antarctic ice cap	Heavy metals (Pb, Cd, Cu, Zn, Ag)	Snow	Atomic absorption techniques	Boutron (1979)
1984	n/a	Trace metals and chlorinated hydrocarbons	Ross seal tissues	Atomic absorption techniques, gas-liquid chromatograph fitted with ECD	McClurg (1984)
	East Antarctica	Cd, Cu, Zn, Au, Se, SO_4^{2-}	Prehistoric ice	n/a	Boutron et al. (1984)
	n/a	Na^+ , NH_4^+ , K^+ , Cl^- , NO_3^- , SO_4^{2-}	Snow and ice	Ion chromatography (IC)	Legrand et al. (1984)
1986	Antarctic Peninsula	Chlorinated hydrocarbon residues (HCB, HCH isomers, p,p' DDT, DDE, PCB congeners)	Lichen and moss samples	n/a	Bacci et al. (1986)
	Adelie Land	Na^+ , NH_4^+ , K^+ , Cl^- , NO_3^- , SO_4^{2-} , Mg^{2+}	Precipitation	IC	Legrand and Delmas (1986)
	n/a	DDTs, PCBs	Penguin tissues	n/a	Aono et al. (1997)
1987	Ross Sea, Wilkes Land	Normal alkanes (n-C-C ₃₆), isoprenoid hydrocarbons (i-C ₁₅ , i-C ₁₆ , i-C ₁₈ , i-C ₁₉ , and i-C ₂₀) triterpanes (C ₂₇ -C ₃₂), and (C ₂₇ -C ₂₉)	Quaternary sediment	n/a	Kvenvolden et al. (1987)
	Syowa Station, Antarctica	Heavy metals	Tissue of the Weddell seal	n/a	Yamamoto et al. (1987)
	n/a	NH_4^+ , F^- , COOH^- , CHOO^- , CH_3SO_3^- , F^- , NH_4^+ ions	Ice	IC	Saigne et al. (1987)
1988	The South Shetland Islands	Pb	Aerosols	IDMS	Völkering et al. (1988)
	The Ekström ice shelf, "Georg-von-Neumayer" station	Heavy metals	Surface snow	IDMS, differential pulse anodic stripping voltammetry (DPASV)	Völkering and Heumann (1988)
					(continued)

Table 1 (continued)

Year	Sampling place	Analytes or subject of research	Type of sample	The analytic techniques	Literature
1989	Weddell Sea, Antarctic Peninsula	HNO ₃	Surface snow	IDMS	Neubauer and Heumann (1988)
	Sections Of the Byrd Station	Liquid conductivity, acidity, sulfate, nitrate, aluminum, and sodium concentrations	Ice containing tephra (volcanic ash) layers	n/a	Palais (1988)
	Vostok Station	Na ⁺ , NH ₄ ⁺ , K ⁺ , Ca ²⁺ , Mg ²⁺ , H ⁺ , Cl ⁻ , NO ₃ ⁻ , SO ₄ ²⁻	Ice core	n/a	Legrand et al. (1988)
	Mc Muurdo Sound	Fatty acids, -alcohols, n-alkanes, PAH	Marine sediments	n/a	Venkatesan (1988)
	n/a	Organochlorine pesticides, PCBs and mercury	Seabird eggs and tissues	n/a	Luke et al. (1989)
	The coastal area of Antarctica	SO ₄ ²⁻ /Na ⁺ , SO ₄ ²⁻ /Cl ⁻ , SO ₄ ²⁻ /Mg ²⁺	Snow	n/a	Gjessing (1989)
	Wright Valley, Antarctica	Mn, Fe, Co, Ni, Cu, Cd	Fresh water	n/a	Green et al. (1989)

^ano data

Fig. 3 The percentage of areas most commonly studied regarding the presence of contaminants up to end of 2014 in the Antarctic environment



Antarctica because of the toxic properties and the threat which is associated with their presence in the polar environment. Table 2 presents general information on xenobiotics determined in samples collected from various parts of the Antarctic ecosystem.

In the discussion pertaining to the presence of pollutants in Antarctica, it is very important to become familiar with accurate levels of concentration present in individual elements of both, biotic and abiotic, environments. Table 3 (A, B, C) data referring to levels of detected contamination present in the whole Antarctic environment and Fig. 4 presents a summary of POPs and heavy metals concentration levels determined in various elements of Antarctica's environments during three time periods (up to end of 2014).

As is showed in Fig. 4 studies on the determination of the pollutants concentrations in biotic and abiotic samples over the decades are irregular. It makes presentation of concentrations trends very difficult. However, as a main source of air contamination the LRAT from Africa, South America or Australia (Negoita et al. 2003) is administered. Nevertheless, the year-round operation of stations

Table 2 Summary of literature data on results of analytical research on various types of (a) abiotic and (b) biotic samples collected in Antarctica in three time periods

Abiotic samples													
Type of sample	Time range within which the results were published	Analytes											
		OCP				PCBs	PBDEs	PAHs	PFCs	Metals	Other ^b	Literature	
		DDTs	HCHs	HCB	Other ^a								
Air	Up to 1989	x											Sen Gupta et al. (1996), Fischer et al. (1967)
	1990–1999	x	x	x	x			x			x		Larsson et al. (1992), Kallenborn et al. (1998), Caricchia et al. (1995), Bidleman et al. (1993), Rindlein and Heumann (1995)
	2000–2014	x	x	x	x						x		Cincinelli et al. (2009), Cabrerizo et al. (2013), Galbán-Malagón et al. (2013a, c), Gambaro et al. (2005), Li et al. (2012), Choi et al. (2008), Montone et al. (2003), Baek et al. (2011), Montone et al. (2005), Kallenborn et al. (2013), Dickhut et al. (2005), Ma et al. (2014), Fischer et al. (2002), Sprovieri et al. (2002)

Snow	Up to 1989	x	x							x							Kang et al. (2012), Sen Gupta et al. (1996), Delmas and Boutron (1978), Boutron and Patterson (1983), Wania et al. (1998), Boutron et al. (1972), Aono et al. (1997), Risebrough et al. (1976), Völkening and Heumann (1988)
	1990–1999									x							Suttie and Wolff (1992), Görlach and Boutron (1992), Wolff et al. (1999), Vandal et al. (1995), Capelli et al. (1998), Vandal et al. (1998)
	2000–2014		x							x		x					Kang et al. (2012), Vecchiato et al. (2015), Fuoco et al. (2012), Nemirovskaya (2006), Antony et al. (2011), Cai et al. (2012), Zoccolillo et al. (2007), Edwards et al. (2001), Planchon et al. (2002), Planchon et al. (2001), Thamman and Thakur (2013), Fortner et al. (2011), Witherow and Lyons (2008), Han et al. (2013), Velde et al. (2005), Burn-Nunes et al. (2011), Vallelonga et al. (2010)
Ice	Up to 1989																Boutron et al. (1984)
	1990–1999																Green et al. (1992), Hong et al. (1998), Vandal et al. (1995)
	2000–2014												x				Nemirovskaya (2006), Vallelonga et al. (2010), Jiratu et al. (2009)

(continued)

																				Yuguang and Junlin (1991), Giordano et al. (1999), Ciaralli et al. (1998), Crespi et al. (1993), Niemi and Perttinen (1995), Ahn et al. (1996), Alam and Sadiq (1993), Santos et al. (2005), Lenihan (1992)
	2000–2014	x	x	x	x				x											Zhang et al. (2013), Klánová et al. (2008), Montone et al. (2001), Curtosi et al. (2007), Dauner et al. (2014), Kim et al. (2006), Negri et al. (2006), Crockett and White (2003), Martins et al. (2010), Siegel et al. (1981), Santos et al. (2007), Ribeiro et al. (2011), Ribeiro et al. (2010), Waheed et al. (2001), Negri et al. (2006), Ianni et al. (2010), Huang et al. (2014), Townsend and Shape (2008), Sun et al. (2013), Vodopivec et al. (2015), Curtosi et al. (2010), Andrade et al. (2001)
Soil	Up to 1989								x											Platt and Mackie (1980)
	1990–1999		x	x	x				x											Aislabie et al. (1999), Mazzera et al. (1999), Kennicutt et al. (1995),

(continued)

Table 2 (continued)

																			Fuoco et al. (1996), Carrasco and Predez (1991), Bargagli et al. (1995), Bargagli et al. (1999)
	2000–2014	x	x	x															Borghini et al. (2005), Klánová et al. (2008), Cabrerizo et al. (2012), Negoita et al. (2003), Curtosi et al. (2007), Kang et al. (2012), Webster et al. (2003), Lu et al. (2012)
Biotic samples																			
Type of sample	Time range within which the results were published	Analytes				PCBs	PBDEs	PAHs	PFCs	Metals	Other ^d	Literature							
		OCP	DDTs	HCHs	HCB								Other ^c						
Krill	Up to 1989																		Platt and Mackie (1980), Bargagli (2008), Moreno et al. (1997)
	1990–1999	x	x	x	x														Sen Gupta et al. (1996), Aono et al. (1997), Bargagli (2008), Petri and Zauke (1993)
	2000–2014	x	x	x	x														

Zooplankton and phytoplankton	Up to 1989					x				x								x			Platt and Mackie (1980)	
	1990–1999																				–	
	2000–2014	x		x					x									x			Bargagli (2008), Galbán-Malagón et al. (2013b)	
Benthic organisms	Up to 1989					x												x			Platt and Mackie (1980), Clarke and Law (1981)	
	1990–1999																	x			Ahn et al. (1996), Moreno et al. (1997)	
	2000–2014	x	x	x					x									x			Zhang et al. (2013), Hale et al. (2008), Poigner et al. (2013), Vodopivec et al. (2015), Negri et al. (2006), Bargagli (2001), Majer et al. (2014), Bargagli (2008)	
Fishes	Up to 1989	x							x									x			Subramanian et al. (1983), Platt and Mackie (1980), Aono et al. (1997)	
	1990–1999																	x			Moreno et al. (1997)	
	2000–2014	x	x	x					x									x			Corsolini et al. (2002a, b), Corsolini et al. (2006), Corsolini (2009), Hale et al. (2008), Borghesi et al. (2009), Borghesi et al. (2008), Weber and Goerke (2003), Lana et al. (2014), Bargagli (2001), Santos et al. (2006)	

(continued)

Table 2 (continued)

Seabirds	Up to 1989	x					x				x		Sen Gupta et al. (1996), Risebrough et al. (1969), Aono et al. (1997), Luke et al. (1989), Bargagli (2008)
	1990–1999	x	x					x					Sen Gupta et al. (1996), Court et al. (1997), Aono et al. (1997), Inomata et al. (1996)
	2000–2014	x	x	x	x	x	x	x	x	x	x		Corsolini et al. (2006), Corsolini et al. (2011), Schiavone et al. (2009a), Geisz et al. (2008), Cipro et al. (2010), Yogui and Sericano (2009), Taniguchi et al. (2009), Van den Brink et al. (2011), Corsolini et al. (2007), Busnes et al. (2006), Llorca et al. (2012), Van den Brink et al. (2011), Senthil et al. (2002), Tao et al. (2006), Taniguchi et al. (2009), Brasso and Polito (2013), Santos et al. (2006), Smichowski et al. (2006), Jerez et al. (2013a), Jerez et al. (2011), Bargagli (2001)

Marine mammals	Up to 1989	x					x				x		Schiavone et al. (2009a), Aono et al. (1997), Bargagli (2008), Risebrough and Carmignani (1972), McClurg (1984), Yamamoto et al. (1987)
	1990–1999					x	x				x		Aono et al. (1997), Schiavone et al. (2009a), Malcolm et al. (1994), Moreno et al. (1997), Aono et al. (1997), Szefer et al. (1993)
	2000–2014	x	x	x		x	x	x		x	x		Cipro et al. (2012), Schiavone et al. (2009c), Schiavone et al. (2009a), Corsolini et al. (2002a), Trumble et al. (2012), Krahn et al. (2007), Bengtson Nash et al. (2010), Senthil et al. (2002), Tao et al. (2006), Santos et al. (2006)
Algae	Up to 1989												–
	1990–1999										x		Moreno et al. (1997)
	2000–2014	x	x	x				x		x	x		Caberizo et al. (2012), Runcie and Riddle (2004), Santos et al. (2006)
Antarctic lichens	Up to 1989												–
	1990–1999										x		Poblet et al. (1997), Olech et al. (1998), Upreti and Pandey (1994), Bargagli et al. (1999)
	2000–2014	x	x	x					x		x		Cipro et al. (2011), Caberizo et al. (2012), Yogui and Sericano (2008),

(continued)

Table 3 Detailed literature data on results of analytical research on (a) main POPs; (b) remaining organic compounds; (c) heavy metals in various types of biotic and abiotic samples collected in Antarctica in three time periods

Main POPs detected in biotic samples										
Type of sample	Sample	Localization	Range or average concentrations (±standard deviation, if available)				PAHs	Unit	Literature	
			DDTs ^a	PCBs ^b	HCHs ^c	HCB	PBDEs ^d			
Data reported in 80th years and earlier										
Fish	Antarctic fishes; whole body (<i>Pygothenia borchgrevinki</i> , <i>Trematomus bernacchii</i> , <i>T. hansonii</i> , <i>T. Newnesi</i> , <i>T. Borchgrevinki</i>)	near Syowa Station	0.03–1.9	0.08–0.77	–	–	–	–	µg/g wet wt	Subramanian et al. (1983)
		King Edward Cove	–	–	–	–	–	0.01–0.5	ng/g wet wt	Platt and Mackie (1980)
	Antarctic cod; flesh (<i>Notathenia rossii</i>)	–	–	–	–	–	–	0.01–0.11	ng/g wet wt	
	Antarctic cod; liver (<i>Notathenia rossii</i>)	–	–	–	–	–	–	–	ng/g wet wt	
Seabirds	Chinstrap penguin (<i>Pygoscelis antarcticus</i>)	–	0.63–4.27	–	–	–	–	–	µg/g	Sen Gupta et al. (1996)
	Macaroni penguin (<i>Eudyptes chrysophilus</i>)	–	500	–	–	–	–	–	µg/g	
	Migrating snow petrel (<i>Pagodroma nivea</i>)	–	600	–	–	–	–	–	µg/g	
Marine mammals	Crabeater seals (<i>Lobodon carcinophagus</i>)	–	7–17	–	–	–	–	–	ng/g	Corsolini (2009)
Data reported from 1990 up to 1999										
Crustaceans	Krill (<i>Euphausia superba</i>)	Dakshin Gangotri, Queen Maud Land	31.1–44.4	146.9–166.2	141.3–164.3	–	–	–	µg/g dry wt	Sen Gupta et al. (1996)
		–	0.56	<1.0	0.028	0.30	–	–	–	ng/g wet wt
Seabirds	Penguin; feathers	Dakshin Gangotri, Queen Maud Land	30.8–35.7	105.8–113.6	103.6–112.8	–	–	–	µg/g dry wt	Sen Gupta et al. (1996)
		Cape Bird, Ross Island	12.1–97.4	18.7–110.6	–	12.5–57.2	–	–	ng/g dry wt	Court et al. (1997)
	Adelie penguin; eggs (<i>Pygoscelis adeliae</i>)	24.3 ± 12.8	618.0 ± 506.0	–	15.9 ± 3.9	–	–	–	ng/g	
	Adelie penguin; liver (<i>Pygoscelis adeliae</i>)	263.4 ± 209.2	2546.0 ± 1675.0	–	49.6 ± 26.0	–	–	–	ng/g	
	South polar skuas; liver (<i>Catharacta macconnicki</i>)	30.8–972.3	43.2–1583.6	<LOD ^e –39.3	42.3–1159.7	–	–	–	ng/g	Inomata et al. (1996)

Table 3 (continued)

Marine mammals	Mink whale, blubber (<i>Balaenoptera acutorostrata</i>)	–	27–380	13–210	0.67–5.7	39–290	–	ng/g wet wt	Aono et al. (1997)
Flora	Antarctic mosses	Key Island, Ross Sea and Antarctic Peninsula	0.2–0.5	<5–16	0.2–1.7	0.3–0.8	–	ng/g dry wt	Focardi et al. (1991)
Data reported from 2000 up to 2014									
Crustaceans	Krill (<i>Euphausia superba</i>)	Ross Sea	0.22–2.30	85.27–282.29	–	0.2–0.6	–	ng/g wet wt	Consolini et al. (2002b)
			0.07–0.10	–	0.28 ± 0.04	0.23 ± 0.01	0.17–0.23	ng/g wet wt	Consolini et al. (2006)
			–	–	0.001–0.32	0.006–0.06	–	ng/g wet wt	Cincinelli et al. (2009)
			–	1.9	–	–	–	ng/g wet wt	Consolini et al. (2002a)
			0.05–0.79	4.66–13.6	–	<LOD–0.06	–	ng/g wet wt	Cipro et al. (2010)
Phytoplankton	–	Southern Ocean areas (Weddell, South Scotia, and Bellingshausen Seas)	–	2.67 ± 0.86–14.07 ± 12.72	0.16 ± 0.17–1.81 ± 2.11	1.64 ± 2.4–4.34 ± 4.34	–	ng/g dry wt	Galbán-Malagón et al. (2013b)
			–	–	0.45 ± 0.38–1.24 ± 1.65	2.9 ± 1.76	–	ng/g lipid wt	Chiuchio et al. (2004)
Benthic organisms	Antarctic invertebrates (<i>Protelipidia murrayi</i> , <i>Penagone vignoni</i> , <i>Bathyploes natans</i> , <i>Molpadia muscidus</i>)	Western Antarctic Peninsula	0.26 ± 0.15	0.84–10.3	0.14–0.35	0.87 ± 0.34	–	ng/g lipid wt	Zhang et al. (2013)
			–	–	–	–	356 ± 196	ng/g lipid wt	Hale et al. (2008)
	Antarctic invertebrates clams (<i>Laternula elliptica</i>), sea stars (<i>Odonaster validus</i>), sea urchins (<i>Sterechinus neumayeri</i>), sponges (<i>Halictona</i> sp. and <i>Homaxinella balfourensis</i>), proboscis worms (<i>Parborlasia corrugatus</i>)	Mc Murdo Sound	–	–	–	–	–	–	–

Fish	Silverfish; larva (<i>Pleurogramma antarcticum</i>)	Ross Sea	1.51–2.03	497.81–509.88	–	0.88–4.04	–	ng/g wet wt	Corsolemi et al. (2002b)
	Silverfish; adults (<i>Pleurogramma antarcticum</i>)		0.04–5.70	16.2–1050.58	–	0.07–14.93	–		
	Silverfish (<i>Pleurogramma antarcticum</i>)		–	138	–	–	–	ng/g wet wt	Corsolemi et al. (2002a)
	Rockcod; whole body (<i>Trematomus bernacchii</i>)		0.02–2.53	–	0.03–0.17	1.35 ± 1.24	0.15–0.16	ng/g wet wt	Corsolemi et al. (2006)
	Rockcod; muscle (<i>Trematomus bernacchii</i>)		0.11–1.1	–	0.03–1.23	1.44 ± 0.45	0.02–0.06	–	
	Rockcod; (<i>Trematomus bernacchii</i>)		–	–	–	–	1520–1840	ng/g lipid wt	Hale et al. (2008)
	Antarctic fish (<i>Chionodraco hamatus</i> , <i>Chaemopsoccephalus gunnari</i> , <i>Gymnoscapellus nicholsi</i> , <i>Trematomus eulipoides</i>)		–	–	–	–	0.001–0.13	ng/g wet wt	Borghesi et al. (2009)
	Crocodile icefish; muscle (<i>Chionodraco hamatus</i>)		–	0.07–0.95	–	–	(0.085–0.300)	ng/g wet wt	Borghesi et al. (2008)
	Crocodile icefish; liver (<i>Chionodraco hamatus</i>)		–	0.75–3.30	–	–	(0.001–0.320)	–	
	Emerald rockcod; muscle (<i>Trematomus bernacchii</i>)		–	(0.35–4.20)	–	–	(0.220–0.530)	–	
	Emerald rockcod; liver (<i>Trematomus bernacchii</i>)		–	(5.20–28)	–	–	(0.500–1.100)	–	
	Antarctic fish; liver (<i>Gobionotothen gibberifrons</i> , <i>Chaemopsoccephalus gunnari</i> , <i>Chaenocephalus acerans</i>)	Elephant Island, South Shetland Islands	5–13	0.4–2	–	15–20	–	ng/g lipid wt	Weber and Goerke (2003)
	Sharp-spined notothen (<i>Trematomus pennellii</i>)	Ross Sea	–	111–175	–	–	–	ng/g wet wt	Corsolemi et al. (2002a)
	Notothenioids fish; muscle (<i>Trematomus newnesi</i> , <i>Notothenia coriiceps</i> , <i>Notothenia rossii</i>)	Potter Cove, King George Island	<LOD–7.31	<LOQ–8.33	<LOQ–3.44	–	<LOQ–8.53	ng/g lipid wt	Lana et al. (2014)
	Notothenioids fish; liver (<i>Trematomus newnesi</i> , <i>Notothenia coriiceps</i> , <i>Notothenia rossii</i>)		<LOD–10.5	<LOQ–7.00	<LOQ–0.99	–	<LOQ–73.6	ng/g lipid wt	Lana et al. (2014)
	Notothenioids fish; gonads (<i>Trematomus newnesi</i> , <i>Notothenia coriiceps</i> , <i>Notothenia rossii</i>)		<LOQ–98.8	<LOQ–46.9	2.41–24.2	–	<LOQ–4.86	ng/g lipid wt	Lana et al. (2014)
	Notothenioids fish; gills (<i>Trematomus newnesi</i> , <i>Notothenia coriiceps</i> , <i>Notothenia rossii</i>)		<LOQ–43.0	<LOQ–14.8	1.57–9.95	–	<LOQ–39.8	ng/g lipid wt	Lana et al. (2014)

(continued)

Table 3 (continued)

Seabirds	Penguin adèle; eggs (<i>Pygoscelis adeliae</i>)	Ross Sea	0.31–20.7	–	0.05–0.54	18.7 ± 8.0	0.03–0.65	–	ng/g wet wt	Consolini et al. (2006)
									ng/g wet wt	Consolini et al. (2011)
									ng/g wet wt	Consolini et al. (2011)
									ng/g wet wt	Consolini et al. (2011)
									ng/g wet wt	Schiavone et al. (2009a)
									ng/g lipid wt	Geisz et al. (2008)
									ng/g wet wt	Consolini et al. (2011)
									ng/g wet wt	Cipro et al. (2010)
									ng/g lipid wt	Yogui and Sericano (2009)
									ng/g wet wt	Schiavone et al. (2009a)
									ng/g lipid wt	Yogui and Sericano (2009)
									ng/g wet wt	Schiavone et al. (2009a)
									ng/g lipid wt	Taniguchi et al. (2009)
									ng/g lipid wt	Geisz et al. (2008)
									ng/g lipid wt	Van den Brink et al. (2011)

Penguin adèle, preen oil (<i>Pygoscelis adeliae</i>)	Hop Island	–	1–37	–	–	2–567	–	–	ng/g lipid wt	Van den Brink et al. (2011)
Southern fulmar, preen oil (<i>Fulmarus glacialis</i>)	Hop Island	–	1–40	–	–	1–314	–	–	ng/g lipid wt	Van den Brink et al. (2011)
Penguin blood (pooled together) Penguins adèle (<i>Pygoscelis adeliae</i>) Gentoo penguin (<i>Pygoscelis papua</i>) Chinstrap penguin (<i>Pygoscelis antarcticus</i>)	Admiralty Bay, King George Island	2.7–16	1.5–17	–	–	0.4–20	0.0017–1726	–	ng/g wet wt	Corsolini et al. (2007)
Migrating snow petrel, eggs (<i>Pagodroma nivea</i>)	Ross Sea	3.64–10.83	15.23–22.66	0.03–0.37	–	10.43–15.40	–	–	ng/g wet wt	Corsolini et al. (2011)
South polar skua, eggs (<i>Catharacta maccormicki</i>)	Ross Sea	<LOD–64.75	1.69–64.23	<LOD–0.080	–	9.23–43.39	–	–	ng/g wet wt	Corsolini et al. (2011)
	Antarctic Peninsula	–	–	–	–	–	19.0–558	–	ng/g lipid wt	Yogui and Sericano (2009)
South polar skua, blood (<i>Catharacta maccormicki</i>)	Dronning Maud Land	0.4–40.9	1.0–50.5	<0.1–6.5	–	0.6–21.2	–	–	ng/g lipid wt	Bustnes et al. (2006)
Migrating brown skua, eggs (<i>Catharacta antarctica</i>)	Bransfield Strait	0.09–27.87	31.28–68.62	<LOD–0.04	–	1.80–27.49	–	–	ng/g wet wt	Corsolini et al. (2011)
Migrating brown skua, fat tissue (<i>Catharacta antarctica</i>)	King George Island, South Shetland	6118 ± 3813	19,720 ± 9620	1.22–3.11	–	573 ± 278	–	3375 ± 1588	ng/g lipid wt	Taniguchi et al. (2009)
Antarctic tern, fat tissue (<i>Sterna vittata</i>)	King George Island, South Shetland	524 ± 205	613 ± 187	<0.12–2.60	–	601 ± 256	–	5744 ± 2546	ng/g lipid wt	Taniguchi et al. (2009)
Blue-eyed shag, fat tissue (<i>Phalacrocorax atriceps</i>)	King George Island, South Shetland	374	282	1.33	–	161	–	3961	ng/g lipid wt	Taniguchi et al. (2009)
Snowy sheathbill, fat tissue (<i>Chionis alba</i>)	King George Island, South Shetland	468	297	<0.12	–	282	–	4090	ng/g lipid wt	Taniguchi et al. (2009)

(continued)

Table 3 (continued)

Marine mammals	Southern elephant seal; liver (<i>Mirounga leonina</i>)	King George Island, South Shetland	460	150	–	2	–	–	ng/g lipid wt	Cipro et al. (2012)
	Antarctic fur seal; liver (<i>Arctocephalus gazella</i>)	Livingston Island, Antarctic Peninsula	<2–2254 ± 3969	3 ± 0.8–429 ± 145	12 ± 20	<2	<0.04–10 ± 18	–	ng/g lipid wt	Schiavone et al. (2009c)
	Antarctic fur seal pup; liver (<i>Arctocephalus gazella</i>)	Livingston Island, South Shetland	191 ± 106	59 ± 43	–	2.2 ± 0.88	–	–	ng/g wet wt	Schiavone et al. (2009a)
	Antarctic fur seal pup; muscle (<i>Arctocephalus gazella</i>)		103 ± 55	33 ± 22	–	1.37 ± 0.69	–	–		
	Antarctic fur seal; fat tissue (<i>Arctocephalus gazella</i>)	King George Island, South Shetland	168	523	3.21	4.72	–	–	ng/g lipid wt	Cipro et al. (2012)
	Weddel seal; fat tissue (<i>Leptonychotes weddelli</i>)		131	300	2.59	5.77	2.04	–		
	Crabeater seal; fat tissue (<i>Lobodon carcinophagus</i>)		14.4	154	0.223	7.23	–	–		
	Weddel seal; blubber (<i>Leptonychotes weddelli</i>)	Terra Nova Bay	1.5–660	395	–	–	–	–	ng/g wet wt	Corsolini et al. (2002a)
		McMurdo Sound	–	0.52–18	–	–	1.2–1.8	–		Trumble et al. (2012)
	Killer whales (<i>Orcinus orca</i>)	Ross Sea	–	1.6 ± 1.1	–	–	–	–	µg/g lipid wt	Krahn et al. (2007)

Flora	Antarctic lichen (<i>Usnea</i> spp.)	King George Island	0.353 ± 0.04	7.76 ± 2.3	0.205 ± 0.08	0.141 ± 0.10	0.236 ± 0.05	—	ng/g dry wt	Cipro et al. (2011)
	Antarctic lichens (<i>Usnea Antarctica</i>)	Southern Shetlands	0.003–0.01	0.043–0.61		0.002–0.31	—	15–40	ng/g dry wt	Cabrerizo et al. (2012)
	Antarctic lichens (<i>Usnea aurantiaco-atra</i>)	Admiralty Bay, King George Island,	—	—	—	—	139 ± 33.6	—	pg/g dry weight	Yogui and Sericano (2008)
	Antarctic lichens (<i>Usnea aurantiaco-atra</i>)		—	—	—	—	262 ± 48.7	—		Yogui et al. (2011)
	Antarctic lichens (<i>Usnea Antarctica</i>)		—	—	—	—	192 ± 93.9	—		Yogui and Sericano (2008)
	Antarctic lichens (<i>Usnea aurantiaco-atra</i>)		—	—	—	—	262 ± 48.7	—		Yogui et al. (2011)
	Antarctic mosses (<i>Santonia uncinata</i>)		—	—	—	—	818 ± 270	—		Yogui and Sericano (2008)
	Antarctic mosses (<i>Santonia uncinata</i>)		—	—	—	—	1022 ± 348	—		Yogui et al. (2011)
	Antarctic mosses (<i>Santonia uncinata</i>)		—	—	—	—	718	—		
	Antarctic mosses (<i>Syntrichia princeps</i>)		—	—	—	—	276	—		
	Antarctic mosses (<i>Brachythecium</i> sp.)		—	—	—	—	328	—		
	phanerogam (<i>Colobanthus quitensis</i>)		—	—	—	—	—	—		
	Antarctic mosses (<i>Bryum argenteum</i> , <i>Pottia heinii</i> , <i>Ceratodon purpureus</i>)	Victoria Land	0.54–7.9	23–34	0.18–4.0	0.82–1.95	—	—	ng/g dry wt	Borghini et al. (2005)
	Antarctic mosses (<i>Brachitecium</i> sp. <i>Syntrichia princeps</i> <i>Santonia uncinata</i>)	King George Island	<LOQ–1.73	7.76–18.6	<LOQ–1.20	0.141–1.06	0.276–0.893	—	ng/g dry wt	Cipro et al. (2011)
	Antarctic mosses (<i>Santonia uncinata</i>)	Southern Shetlands	0.005–0.04	0.04–0.76	—	0.21–0.12	—	4.4–34	ng/g dry wt	Cabrerizo et al. (2012)
	Hair grass (<i>Oeschampsia antarctica</i>)	Southern Shetlands	0.061–0.09	0.39–2.40	—	0.080–0.20	—	6–10	ng/g dry wt	Cabrerizo et al. (2012)
	Pearl-wort (<i>Colobanthus quitensis</i>)	Shetlands	0.04	0.31	—	0.04	—	9.5	ng/g dry wt	
	Green algae (<i>Prasiola crispa</i>)		0.08	0.86	—	0.033	—	7		
	Red snow algae		0.28	3.07	—	0.67	—	141		

Main POPs detected in abiotic samples

Type of sample	Localization	Range or average concentrations (±standard deviation, if available)							UNIT	LIT
		DDTs	PCBs	HCHs	HCB	PBDEs	PAHs			
Data reported in 80th years and earlier	Air	–	150	–	–	–	–	–	pg/m ³	Sen Gupta et al. (1996)
	Snow	–	–	2300–4900	–	–	–	–	pg/L	Kang et al. (2012)
	–	0.63–4.27	–	–	–	–	–	–	–	Sen Gupta et al. (1996)

(continued)

Table 3 (continued)

Fresh water	–	1.3–30.7	–	1665	–	–	–	pg/L	Sen Gupta et al. (1996)
Sediments	King Edward Cove	–	–	–	–	–	2–220	ng/g dry wt	Platt and Mackie (1980)
Data reported from 1990 up to 1999									
Air	Ross Island	1.0–2.0	12.2	25.8	–	–	–	pg/m ³	Larsson et al. (1992)
Air (ambient air)	Signy Island	0.07–0.40	0.02–17	22	–	–	–	pg/m ³	Kallenborn et al. (1998)
Air (atmospheric particulates)	Terra Nova Bay	–	–	–	–	–	<1.5–689	pg/m ³	Caricchia et al. (1995)
Soil	McMurdo Sound—Dry Valley Region (fuel-oil contaminated area)	–	–	–	–	–	46–3398	ng/g dry weight	Aislabie et al. (1999)
Sediments	McMurdo Station	–	–	–	–	–	28–27,000	ppb	Mazzera et al. (1999)
	Victoria Land	–	–	–	–	–	6267–6339	ppm	Kennicutt et al. (1995)
		–	60	–	–	–	–	pg/g dry wt	Fuoco et al. (1996)
	Ross Sea	–	80	–	–	–	–	pg/g dry wt	Fuoco et al. (1996)
	Winter Quarters Bay	–	100–1400	–	–	–	–	ng/g	Risebrough et al. (1990)
Seawater	Victoria Land	–	120	–	–	–	–	pg/g dry wt	Fuoco et al. (1996)
	–	605.03–844.9	–	92.9–123.2	–	–	–	pg/g	Sen Gupta et al. (1996)
	Admiralty Bay, King George Island	–	–	–	–	–	0.003–0.011	µg/L	Bicego et al. (1996)
Polynya water	Dakshin Gangotri	24.8–26.5	96.8–103.8	85.6–90.7	–	–	–	pg/L	Sen Gupta et al. (1996)

Data reported from 2000 up to 2014

Air (gase phase)	Western Ross Sea	–	–	–	0.1–1.05	7.23–20.39	–	–	pg/m ³	Cincinelli et al. (2009)
	Western Antarctic Peninsula	–	–	–	0.06–2.98	11.9–32.1	–	–		Dickhut et al. (2005)
	Livingston Island (Antarctica)	–	–	4–29	–	–	–	–		Cabrerizo et al. (2013)
	South Scotia Sea	–	–	–	1.63 ± 1.52–1.70 ± 2.16	49.71 ± 8.19	–	–		Galbán-Malagón et al. (2013a)
	Weddell	–	–	–	0.16 ± 0.14–0.87 ± 0.88	11.93 ± 15.77	–	–		
	Livingston Island	–	–	–	0.79 ± 0.77–2.27 ± 0.68	10.30 ± 4.81–11.97 ± 2.67	–	–		
	Southern Ocean, Antarctic Peninsula	–	–	1–70	–	–	–	–		Galbán-Malagón et al. (2013c)
	Terra Nova Bay	–	–	<LOD–0.25	–	–	–	–		Gambaro et al. (2005)
	Southern Ocean	–	–	–	–	–	–	0.03–4.58	ng/m ³	Cabrerizo et al. (2014)
	Southern Ocean, Antarctic Peninsula	–	–	0.04–0.4	–	–	–	–	pg/m ³	Galbán-Malagón et al. (2013c)
Air	King George Island	–	–	1.66–6.5	–	–	0.67–2.98	–	pg/m ³	Li et al. (2012)
		–	–	<LOD–117.8	–	–	–	–		Choi et al. (2008)
		–	–	<LOD–33.2	–	–	–	–		Montone et al. (2003)
		–	–	–	2.5–3.65	–	–	–		Back et al. (2011)
	Antarctic Ocean	<2.7–5.2	<2.3–22.8	<2.7–4.6	3.3–25.3	–	–	–		Montone et al. (2005)
	Dronning Maud Land	0.02–0.20	–	0.02–0.46	22	–	–	–		Kallenborn et al. (2013)
Snow	Dome Fuji, East Antarctica	–	–	–	17.5–137.0	<LOD–182	–	–	pg/L	Kang et al. (2012)
	Victoria Land	–	–	110–580	–	–	130–340	0.65–140	pg/L	Vecchiato et al. (2015)
Snow/finn core	Talos Dome	–	–	0.03–0.24	–	–	–	0.35–4.6	ng/L	Fuoco et al. (2012)

(continued)

Table 3 (continued)

Soil	Victoria Land	0.053–0.086	0.36–0.59	–	0.034–0.17	–	–	ng/g dry wt	Borghini et al. (2005)
	James Ross Island	0.51–3.68	0.51–1.82	0.49–1.34	2.41–7.75	–	34.9–171	ng/g	Klánová et al. (2008)
	Southern Shetlands	LOQ–0.20	0.005–0.15	–	<LOQ–0.07	–	0.16–3718	ng/g dry wt	Cabreriño et al. (2012)
	East Antarctic coast	0.11–1.22	0.20–0.41	0.86–4.69	–	–	12 ± 1– 1182 ± 113	ng/g dry wt	Negoita et al. (2003)
	Potter Cove, Jubany Station	–	–	0.09–40.1	0.02–25.28	–	–	ng/g	Kang et al. (2012)
		–	–	–	–	–	19–42	ng/g dry wt	Curtosi et al. (2007)

^aDDTs: p,p'-DDE; o,p'-DDT; p,p'-DDD; p,p'-DDT

^bpCBs: congeners (penta-CB: 99, 101, 105, 118; hexa-CB: 128, 138, 146, 149, 151, 153, 156; hepta-CB: 170, 171, 174, 177, 180, 183, 187; octa-CB: 194, 195, 199; nona-CB: 206; deca-CB: 209)

^cHCHs: α-HCH; β-HCH; γ-HCH

^dpBDEs: BDE-47; BDE-99; BDE-100 and others congeners (nos: 28, 153, 154, 183)

^eLOD—limit of detection

^fLOQ—limit of quantification

Table 3b Detailed literature data on results of analytical research on (a) main POPs; (b) remaining organic compounds; (c) heavy metals in various types of biotic and abiotic samples collected in Antarctica in three time periods

Various chemical compounds identified in biotic samples					
Type of sample	Compound groups/ determined compounds	Range or average concentrations (±standard deviation, if available)	Unit	Literature	
Data reported in 80th years and earlier					
Crustaceans	Krill (<i>Euphausia superba</i>)	n-alkanes	0.5	µg/g wet wt	Platt and Mackie (1980)
	Bivalve (<i>Yoldia eightsii</i>)	n-alkanes	0.4		
Fish	Antarctic code; flesh (<i>Notothenia rossii</i>)	n-alkanes	0.05		
	Antarctic code; liver (<i>Notothenia rossii</i>)	n-alkanes	1.9		
Marine mammals	Crabeater seal, tissues (<i>Lobodon carcinophagus</i>)	PCDFs	3.7–6.1	pg/g lw	Schiavone et al. (2009c)
	Minke whale; blubber (<i>Balaenoptera Acutorostrata</i>)	CHLs ^g	9.6–59	ng/g wet wt	Aono et al. (1997)
Flora	terrestrial plants (<i>Tortula robusta</i> , <i>Rostkovia magellanica</i> , <i>Festuca contracta</i> <i>Poa flabellata</i> , <i>Acaena magellanica</i>)	n-alkanes	15.7–420.5	µg/g wet wt	Platt and Mackie (1980)
Data reported from 1990 up to 1999					
Crustaceans	Krill (<i>Euphausia superba</i>)	CHLs	68	pg/g wt wt	Aono et al. (1997)
Marine mammals	Minke whale; blubber (<i>Balaenoptera Acutorostrata</i>)	CHLs	18–75	ng/g wet wt	Aono et al. (1997)
	Antarctic fur seal; tissues (<i>Arctocephalus gazella</i>)	Dioxins	15.7	pg/g wet wt	Schiavone et al. (2009c)
		PCDFs	7		
Data reported from 2000 up to 2014					
Crustaceans	Krill (<i>Euphausia superba</i>)	OCP	Chlordanes ^h	ng/g wet wt	(Cipro et al. (2010)
			Drins ⁱ	<LOD–0.54	
		Dioxin	total PCDD/DFs	27	Senthil et al. (2002)

Fish	Antarctic fishes; muscle (<i>Chionodraco Hamatus</i> , <i>Trematomus Bernacchii</i>)	Dioxins	PCDDs	2.69–5.8	pg/g wet wt	Borghesi et al. (2008)
		DLCs	PCDFs	1.53–1.68		
		Dioxins	PCDDs	4.6–4.94		
		DLCs	PCDFs	1.25–2.3		
	Antarctic fishes; liver (<i>Chionodraco Hamatus</i> , <i>Trematomus Bernacchii</i>)					
	Antarctic fishes; (Trematomus pennelli, Chionodraco hamatus)	Dioxin	Total PCDD/DFs	11–17	pg/g	Senthil et al. (2002)
	Emerald rockcod: (Trematomus bernacchii)	OCP	CHLs	2.61 ± 2.07	ng/g wet wt	Corsolini (2009)
	Antarctic fishes; liver (<i>Champscephalus gunnari</i> , <i>Gobionotothen gibberifrons</i> , <i>Chanocephelus aceratus</i>)	OCP	Mirex	1–7	ng/g lipid wt	Weber and Goerke (2003)
	Penguin; dung (Pygoscelis papua)	Surfactants	PFCs ^j	0.63–603	ng/g	Llorca et al. (2012)
	Penguin; muscle tissues (Pygoscelis papua)	Surfactants	PFCs	<LOQ ⁱ –2.28	ng/g	Llorca et al. (2012)
Seabirds	Penguin; preen oil (Pygoscelis adeliae)	OCP	Dieldrin	2–24	ng/g lipid wt	Van den Brink et al. (2011)
	Penguins; fat tissue (Pygoscelis adeliae, Pygoscelis papua, Pygoscelis antarctica)	OCP	Dieldrin	47.1 ± 12.4	ng/g lipid wt	Cipro et al. (2012);
			Mirex	26.4 ± 20.2		Cipro et al. (2010);
			Dieldrin	26.4 ± 19.1		Corsolini
			Mirex	90.6 ± 70.6		et al. (2007); Senthil et al. (2002),
	Penguin; blood (Pygoscelis adeliae)	Surfactants	PFOS	<0.1	ng/ml	Tao et al. (2006); Taniguchi
	Penguin; blood (Pygoscelis adeliae, Pygoscelis papua Pygoscelis antarctica)	Dioxins	PCDDs	0.7–103	pg/g wet wt	et al. (2009)
		DLCs	PCDFs	0.8–194		
						(continued)

Table 3b (continued)

Penguin: eggs (<i>Pygoscelis adeliae</i>, <i>Pygoscelis papua</i> <i>Pygoscelis antarctica</i>)	Surfactants	PFOS	<0.1–8.8	ng/g
	OCP	Chlordanes	0.32–7.57	ng/g wet wt
		Mirex	0.67–6.37	
		Drins	0.06–35.8	
	Dioxins	eoni PCDD/DFs	23	pg/g
	Surfactants	PFOS	<0.24–1.36	ng/ml
	Surfactants	PFOS	2.08–3.12	ng/g
	OCP	Chlordanes	977 ± 445	ng/g lipid wt
		Oxychlordane	408 ± 169	
		Dieldrin	254 ± 158	
		Mirex	2210 ± 1590	
	OC	Chlordanes	80.6 ± 47.1	
		Oxychlordane	44.2 ± 21.0	
		Dieldrin	<0.48–23.0	
		Mirex	260 ± 58	
	OCP	Chlordanes	3.05	
Blue-eyed shag: fat tissue <i>(Phalacrocorax Ariceps)</i>		Oxychlordane	<0.24	
		Dieldrin	<0.48	
		Mirex	89.2	
	OCP	Chlordanes	468	
		Oxychlordane	63.3	
		Dieldrin	22.4	
		Mirex	149	
	OCP	Chlordanes	468	
Snowy sheathbill: fat tissue <i>(Chionis alba)</i>		Oxychlordane	63.3	
		Dieldrin	22.4	
		Mirex	149	
	OCP	Chlordanes	468	

Marine mammals	Whitechinned petrel; pectoral muscle (<i>Procellaria aequiactialis</i>)	surfactants	PFOS	1.2–2.0	ng/g	Llorca et al. (2012)
	Southern fulmar; preen oil (<i>Fulmarus glacialisoides</i>)	OCP	Dieldrin	1–38	ng/g lipid wt	Van den Brink et al. (2011)
	Seals; tissues (muscle, blubber, fur)	OCP	Drins	18.4–82.4	ng/g lipid wt	Cipro et al. (2012); Bengtson Nash et al. (2010); Schiavone et al. (2009a, c); Corsolini et al. (2002b)
	Antarctic fur seal (<i>Arctocephalus gazella</i>)		Endosulfan (I/II)	2.09–21.15		
	Other seal species (<i>Leptonychotes weddelli</i> , <i>Lobodon carcinophagus</i>)		Mirex	5.53–17.0		
			Chlordanes	9.5–78.2		
			PCNs	0.01–3.08		
			PCDDs	3.5–53.6	ng/g wet wt	
		Dioxins	PCDFs	8.5–96.4		
		DLCs	PFCs	<0.4–2.0	ng/g	
	Seals; liver	Surfactants			ng/g lipid wt	
	Southern elephant seal (<i>Mirounga leonine</i>)	Pesticides	Drins	6.88		
		OCP	Endosulfan (I/II)	2.72		
	Antarctic fur seal (<i>Arctocephalus gazella</i>)		Mirex	16.2		
			Chlordanes	37.7		
		Dioxins	PCDDs	10.6	ng/g wet wt	
		DLCs	PCDFs	153.7		
	Weddell seal; liver (<i>Leptonychotes weddelli</i>)	Surfactants	PFCs	<0.4–12.6	ng/g	Senthil et al. (2002)
		Dioxin	total PCDD/DFs	8.9	pg/g	
	Southern elephant seal; blood (<i>Mirounga leonine</i>)	PFCs	PFOS	<0.08–3.52	ng/ml	Tao et al. (2006)

(continued)

Table 3b (continued)

Various chemical compounds identified in abiotic samples					
Type of sample	Compound groups/determined compounds	Range or average concentrations (± standard deviation, if available)	Unit	Literature	
Data reported in 80th years and earlier					
Snow	–	Sulphate	50–100	ng/g	Delmas and Boutron (1978)
Soil	Hydrocarbons	n-alkanes	0.6	µg/g	Platt and Mackie (1980)
Freshwater sediments	Hydrocarbons	n-alkanes	0.9–1.7		
Seawater	Hydrocarbons	n-alkanes	5.8		
Data reported from 1990 up to 1999					
Air	OCP	Heptachlor epoxide	0.52	pg/m ³	Bidleman et al. (1993); Kallenborn et al. (1998)
		Chlordanes + nanochloris	1.8		
		Chlordanes	0.04–0.9		
Seawater	Hydrocarbons	n-alkanes	2.6–7.6	µg/L	Guerra et al. (2013)
		n-alkanes	353–968	ng/L	Stortini et al. (2009)
		n-alkanes	2.6–7.6	µg/L	Cripps (1992)
Seawater (particulate matter)	Hydrocarbons	Aliphatic hydrocarbons	0.07–0.17	µg/L	Green et al. (1992)
Marine sediment	OC	Chlorinated terphenyls	30–1200	ng/g	Risebrough et al. (1990)
	Hydrocarbons	Aliphatic hydrocarbons	45–48	µg/g	Green et al. (1992)
	Organic carbon	TOC	0.34	g %	Vandal et al. (1998)
Sea ice	Hydrocarbons	Aliphatic hydrocarbons	1.9–12.5	mg/m ²	Green et al. (1992)

Data reported from 2000 up to 2014					
Air (gas phase)	Pesticides	Heptachlor	<1–19.1	pg/m ³	Dickhut et al. (2005)
		Heptachlor epoxide	<0.3–20.7		
Air	–	Chlorinated paraffin	3.7–20.8	pg/m ³	Ma et al. (2014)
	Pesticides	Aldrin and dieldrin	12.2–88.5	pg/m ³	Baek et al. (2011)
	Hydrocarbons	Akryl nitrates	<LOD–1.11	ppt(v)	Fischer et al. (2002)
Snow	Organic carbon	TOC	88–928	µg/L	Antony et al. (2011)
	Surfactants	PFCs	1129.2–2491.3	pg/L	Cai et al. (2012)
	Hydrocarbons	Chlorinated hydrocarbons	<LOD–380	µg/g	Zoccolillo et al. (2007)
	Surfactants	PFCs	2121.8–5767.9	pg/L	Cai et al. (2012)
	Surfactants	PFCs	<3.0–51	pg/L	Ahrens et al. (2010)
Fresh water	Surfactants	PFCs	531.9–15,284	pg/L	Cai et al. (2012)
Surface water	Hydrocarbons	n-alkanes	0.03–0.41	µg/g	Dauner et al. (2014)
Seawater	Hydrocarbons	n-alkanes	1.1–2.1	µg/g	Negri et al. (2006)
Sediments	Hydrocarbons	Total hydrocarbons	81–144		

^aCHLs: oxychlordane + cis-chlordane + trans-nonachlor + cis – nonachlor
^bChlordanes: heptachlor + epoxides + oxychlordane + α- and β-chlordane
^cLOD—limit of detection
^dDrins: aldrin + endrin + dieldrin + isodrin
^ePFCs: PFHxA, PFOA, PFNA, PFBS, PFOS
^fLOQ—limit of quantification

Fish	Notothenia; muscle (<i>Notothenia coriiceps</i>)	Antarctic Peninsula	–	<0.05	–	–	–	0.04–0.5	0.01–0.10	–	–	1.00–6.70	µg/g wet wt	Moreno et al. (1997)
Marine mammals	Antarctic fur seal; liver (<i>Arctocephalus gazella</i>)	Bird Island, South Georgia; Sub-Antarctic	0.1	350	–	1	–	263	215	–	–	384	ng/g dry wt	Malcolm et al. (1994)
		Antarctic Peninsula	–	1.90–3.50	–	–	–	11.90–16.20	4.10–7.60	–	–	25.30–38.40	µg/g wet wt	Moreno et al. (1997)
	Antarctic fur seal; muscle (<i>Arctocephalus gazella</i>)	Antarctic Peninsula	–	<0.05	–	1.10–1.50	–	–	<0.05	–	–	12.70–25.70	µg/g wet wt	Moreno et al. (1997)
	Antarctic fur seal; kidney (<i>Arctocephalus gazella</i>)	Antarctic Peninsula	–	3.70–5.90	8.40–22.30	–	–	–	0.20–0.30	–	–	23.80–38.90	µg/g wet wt	Moreno et al. (1997)
	Antarctic fur seal; fat (<i>Arctocephalus gazella</i>)	Antarctic Peninsula	–	<0.05	0.20–0.60	–	–	–	<0.05	–	–	3.20–8.40	µg/g wet wt	Moreno et al. (1997)
	Crabeater seal; muscle (<i>Lobodon carcinophagus</i>)	Antarctic Peninsula	–	–	–	–	–	–	0.27–6.2	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Crabeater seal; liver (<i>Lobodon carcinophagus</i>)	Antarctic Peninsula	–	–	–	–	–	–	1.7–16.3	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Crabeater seal; kidney (<i>Lobodon carcinophagus</i>)	Antarctic Peninsula	–	–	–	–	–	–	1.7–2.5	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Crabeater seal; kidney (<i>Lobodon carcinophagus</i>)	Antarctic Peninsula	–	–	–	–	–	–	1.06–3.22	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Leopard seal; muscle (<i>Hydrurga leptonyx</i>)	Antarctic Peninsula	–	–	–	–	–	–	8.78–18.1	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Leopard seal; liver (<i>Hydrurga leptonyx</i>)	Antarctic Peninsula	–	–	–	–	–	–	4.64–6.05	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Leopard seal; kidney (<i>Hydrurga leptonyx</i>)	Antarctic Peninsula	–	–	–	–	–	–	1.18–3.61	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Weddell seal; muscle (<i>Leptonychotes weddellii</i>)	Antarctic Peninsula	–	–	–	–	–	–	21.1–48.8	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Weddell seal; liver (<i>Leptonychotes weddellii</i>)	Antarctic Peninsula	–	–	–	–	–	–	9.67–15.9	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Weddell seal; kidney (<i>Leptonychotes weddellii</i>)	Antarctic Peninsula	–	–	–	–	–	–	0.17–0.19	–	–	–	µg/g dry weight	Szefer et al. (1993)
	Southern elephant seal; muscle (<i>Mirounga leonine</i>)	Antarctic Peninsula	–	0.05–0.12	–	–	–	0.57–0.68	0.09–0.14	–	–	24.37–28.58	µg/g wet wt	Moreno et al. (1997)
	Southern elephant seal; skin (<i>Mirounga leonine</i>)	Antarctic Peninsula	–	<0.05	–	–	–	0.49–0.52	<0.05	–	–	25.07–30.72	µg/g wet wt	Moreno et al. (1997)
	Southern elephant seal; fat (<i>Mirounga leonine</i>)	Antarctic Peninsula	–	<0.05	–	–	–	0.54–1.46	<0.05	–	–	0.30–0.84	µg/g wet wt	Moreno et al. (1997)
	Minke whale; blubber (<i>Balaenoptera acutorostrata</i>)	Antarctic Peninsula	262.88–2050	0.03–0.28	–	1.4–8.9	–	1.63–93	0.08–0.43	6.77–443	0.7–9.5	0.6–19.8	ng/g wet wt	Aono et al. (1997)

(continued)

Table 3c (continued)

Flora	Algae (<i>Desmarestia</i> sp., <i>Durvillea</i> Antarctica, <i>Adenocystis</i> sp., <i>Ascoseyria</i> sp., <i>Cytosphaera</i> sp., <i>Iridaea</i> sp., <i>Leptosomia simplex</i> st.)	Antarctic Peninsula	–	–	–	–	0.10–4.32	–	–	–	–	–	–	–	–	2.12–27.31	µg/g dry wt	Moreno et al. (1997)
	Antarctic mosses (<i>B. argentatum</i> , <i>B. pseudotriquetrum</i> , <i>Ceratodon purpureus</i> <i>Potlia heimii</i>)	Edmonson Point	–	–	–	–	–	–	–	–	–	–	–	–	–	–	µg/g dry wt	Bargagli et al. (1995)
	Antarctic lichens (<i>Usnea aurantiacoatra</i>)	King George Island	262.88–1364.8	<LOD ^a –0.015	–	–	–	1.63–5.79	–	–	–	–	–	–	–	3.64–17.92	µg/g dry wt	Poblet et al. (1997)
	Antarctic lichens (<i>Usnea antarctica</i>)	King George Island	283.37–1115.1	<LOD–0.03	–	–	–	2.17–9.49	–	–	–	–	–	–	–	5.52–21.43	µg/g dry wt	Poblet et al. (1997)
	Antarctic lichens (<i>Usnea decussata</i>)	Trishvil Hill base, East Antarctica	4966–12,760	–	–	–	4.2–3.36	45–93	–	–	–	–	–	–	–	–	ppm	Olech et al. (1998)
		Victoria Land	802 ± 402	0.21 ± 0.11	–	–	1.3 ± 0.6	5.3 ± 5.1	–	–	–	–	–	–	–	18.6 ± 4.1	µg/g dry wt	Bargagli et al. (1999)
	Data reported from 2000 up to 2014																	
Zooplankton	Whole body amphipoda (<i>Parameira orrug</i>)	Windmill Island	–	7.2 ± 2.7	–	–	–	–	–	–	–	–	–	–	–	–	µg/g dry wt	Bargagli (2008)
	Whole pooled across species	Windmill Island	–	3.4 ± 2.3	–	–	–	–	–	–	–	–	–	–	–	–		
	Krill (<i>Euphausia superba</i>)	Admiralty Bay	72	–	–	–	–	–	–	–	–	–	–	–	–	50.2	µg/g; *ng/g	Santos et al. (2006)
	Pooled across species (<i>Bonellia gigantea</i> , <i>Chiririmedon femoratus</i> , <i>Gondogeneia antarctica</i>)		388–1108	–	–	–	–	–	–	–	–	–	–	–	–	62.1–84.1		

Table 3c (continued)

Penguin Adèle; liver (<i>Pygoscelis adeliae</i>)	Potter Cove, King George Island	–	–	18 ± 1	269 ± 10*	10.0 ± 0.2	–	202 ± 9*	–	µg/g; *ng/g dry wt	Smichowski et al. (2006)
	South Shetland Islands	1364.01 ± 351.09	0.12 ± 0.06	92.06 ± 74.53	–	12.01 ± 5.80	0.01 ± 0.01	0.04 ± 0.07	133.88 ± 71.42	µg/g dry wt	Jerez et al. (2013a)
	Potter Cove, King George Island	–	<0.07*	677 ± 32*	–	1.5 ± 0.1	–	121 ± 7*	–	µg/g; *ng/g dry wt	Smichowski et al. (2006)
	South Shetland Islands	154.97 ± 66.71	0.01 ± 0.02	–	–	1.13 ± 0.40	0.04 ± 0.03	0.04 ± 0.10	104.34 ± 49.70	µg/g dry wt	Jerez et al. (2013a)
Penguin Adèle; bone (<i>Pygoscelis adeliae</i>)	South Shetland Islands	277.18 ± 135.74	0.01 ± 0.004	57.81 ± 35.82	–	10.57 ± 8.76	0.41 ± 0.41	0.04 ± 0.10	227.01 ± 121.11	µg/g dry wt	Jerez et al. (2013a)
	Antarctic Peninsula	59.74 ± 45.26	0.04 ± 0.02	–	–	1.3 ± 1.16	0.55 ± 0.55	0.64 ± 1.09	82.45 ± 13.10	µg/g dry wt	Jerez et al. (2011)
	Terra Nova Bay	–	–	–	–	0.82 ± 0.13	–	–	–	–	Bargagli (2001)
	Admiralty Bay	87	–	–	–	1401.4*	–	–	61.5	µg/g; *ng/g	Santos et al. (2006)
Chinstrap penguin; kidney (<i>Pygoscelis antarctica</i>)	South Shetland Islands	79.80 ± 62.22	0.13 ± 0.08	–	–	2.01 ± 0.52	0.05 ± 0.03	0.24 ± 0.38	61.11 ± 20.30	µg/g dry wt	Jerez et al. (2013a)
	South Shetland Islands	397.49 ± 82.35	0.54 ± 0.29	–	–	10.19 ± 2.63	0.08 ± 0.06	0.14 ± 0.02	92.83 ± 32.19	µg/g dry wt	Jerez et al. (2013a)
	South Shetland Islands	2075.44 ± 1745.28	0.11 ± 0.08	–	–	11.42 ± 3.24	0.07 ± 0.07	0.18 ± 0.02	132.20 ± 64.40	µg/g dry wt	Jerez et al. (2013a)
	South Shetland Islands	328.59 ± 102.73	0.01 ± 0.01	–	–	2.55 ± 1.53	1.83 ± 2.67	0.20 ± 0.06	105.08 ± 55.41	µg/g dry wt	Jerez et al. (2013a)
Chinstrap penguin; bone (<i>Pygoscelis antarctica</i>)	South Shetland Islands	117.49 ± 40.10	0.004 ± 0.001	–	–	12.50 ± 2.13	3.82 ± 2.52	0.14 ± 0.02	235.01 ± 40.62	µg/g dry wt	Jerez et al. (2013a)
	South Shetland Islands	173.86 ± 173.09	0.02 ± 0.03	–	–	2.25 ± 3.17	0.13 ± 0.10	0.06 ± 0.04	94.99 ± 5.29	µg/g dry wt	Jerez et al. (2013a)
	Antarctic Peninsula	164.26 ± 149.75	0.1 ± 0.05	–	–	3.26 ± 2.68	1.18 ± 1.1	1.76 ± 1.74	97.27 ± 21.35	µg/g dry wt	Jerez et al. (2011)
	South Shetland Islands	302.35 ± 103.68	0.20 ± 0.05	–	–	7.54 ± 3.47	0.06 ± 0.05	0.0008	125.43 ± 12.60	µg/g dry wt	Jerez et al. (2013a)
Gentoo penguin; kidney (<i>Pygoscelis papua</i>)	South Shetland Islands	854.55 ± 136.61	0.08 ± 0.04	–	–	10.51 ± 3.74	0.01 ± 0.01	0.0008	152.91 ± 45.53	µg/g dry wt	Jerez et al. (2013a)
	South Shetland Islands	–	–	–	–	63.85	–	–	–	–	–

(continued)

Table 3c (continued)

Table 3c (continued)

Sediment	Chinese Great Wall station	–	–	–	16–23	–	–	–	–	–	41–73	µg/g	Yuguang and Junlin (1991)
	Terra Nova Bay	37 300 ± 14 400	1.96 ± 3.89	–	48.1 ± 9.2	–	–	–	16.1 ± 2.7	23.5 ± 20.1	100 ± 24.5	µg/g	Giordano et al. (1999)
	Terra Nova Bay	1.64	–	–	20.3	–	–	–	6.3	20.7	42	µg/g	Ciaralli et al. (1998)
	Italian station, Terra Nova Bay	–	–	–	21–328	–	–	–	–	–	–	µg/g	Crespi et al. (1993)
	Weddel Sea	–	0.04–0.72	–	91–146	31–44	0.014–0.044	–	53–63	7–9	78–89	ng/g	Niemistö and Perttälä (1995)
	King George Island	2.42	–	–	7.6	77	–	–	15.4	8.7	69	µg/g	Ahn et al. (1996)
		2.37	–	–	2.6	52	–	–	11.5	121.0	74	µg/g	Alam and Sadiq (1993)
		6.28	–	–	–	68	–	–	41.3	14.9	60	µg/g	Santos et al. (2005)
	McMurdo Station	–	–	–	–	11	–	–	68.0	7.0	32	µg/g	Lenihan (1992)
	King George Island	2.79	–	–	–	111	–	–	12.5	7.7	66	µg/g	Santos et al. (2005)
Data reported from 2000 up to 2014													
Air	Terra Nova Bay	–	–	–	–	–	0.29–2.3	–	–	–	–	ng/m ³	Sprovieri et al. (2002)
	Deception Island	–	0.019	–	–	0.078	–	–	–	0.049	–	µg/L	Mão de Ferro et al. (2013)
Snow	Princess Elizabeth Land	–	–	–	–	–	–	–	–	503–1158	–	pg/g	Edwards et al. (2001)
	Ross Sea	–	–	–	–	–	–	–	–	749–982	–		
	Dumont d'Urville Sea	–	–	–	–	–	–	–	–	42–85	–		
	Prydz Bay	–	–	–	–	–	–	–	–	376–727	–		
	Coats Land	–	0.03–0.8	0.1–1.2	0.09–7.3	0.7–11.9	–	–	–	0.1–10.3	0.2–10.8	pg/g	Planchon et al. (2002)
		–	–	–	0.1–5.2	0.7–12	–	–	–	0.1–10	–	pg/g	Planchon et al. (2001)

(continued)

Table 3c (continued)

Surface snow	Ingrid Christensen Coast, East Antarctica	0.23–2.88	–	0.01–0.18	0.04–0.55	0.14–4.6	–	0.04–1.66	–	–	1.31–14.45	µg/L	Thamban and Thakur (2013)
Snow pit	Antarctic Taylor Valley glaciers (Commonwealth, Canada, Howard)	–	<0.057–0.53	–	–	<0.56–190	–	–	–	0.029–13	–	nM	Fortner et al. (2011)
	Glacier, Taylor Valley, Victoria Land	–	–	–	–	–	0.3–40	–	–	–	–	pg/g	Witherow and Lyons (2008)
	Dome Fuji	–	–	–	–	–	<0.32–2.93	–	–	–	–	pg/g	Han et al. (2013)
Firn core	Victoria Land	–	–	–	–	–	–	–	–	1.5–21.2	–	pg/g	Velde et al. (2005)
	Victoria Land	–	–	–	–	–	–	–	–	1.1–10.3	–	pg/g	Velde et al. (2005)
	Law Dome; Wilkes Land	–	–	–	–	–	–	–	–	0.08–5.2	–	pg/g	Burn-Nunes et al. (2011)
Ice core	–	–	–	–	–	–	–	–	–	0.5–124	–	nM	Edwards et al. (2006)
	–	–	–	–	–	–	–	–	–	0.21–7.00	–	pg/g	Vallelonga et al. (2002)
	Dome C	–	–	–	–	–	<1–65	–	–	–	–	pg/g	Jiratu et al. (2009)
Sediments	–	–	–	–	–	–	–	–	–	0.36–13.4	–	pg/g	Vallelonga et al. (2010)
	Ferraz station, The King George Island	6.15	–	–	40	44	–	442	5.1	11.5	52	µg/g	Santos et al. (2005)
	–	–	–	–	25–52	–	–	–	–	–	87–134	µg/g	Santos et al. (2007)
	Admiralty Bay	–	0.4–0.9	–	7–12	47–84	–	–	3–10	3–11	44–89	µg/g	Ribeiro et al. (2011)
	–	–	–	–	–	80–91	–	–	–	–	50–57	µg/g	Ribeiro et al. (2010)

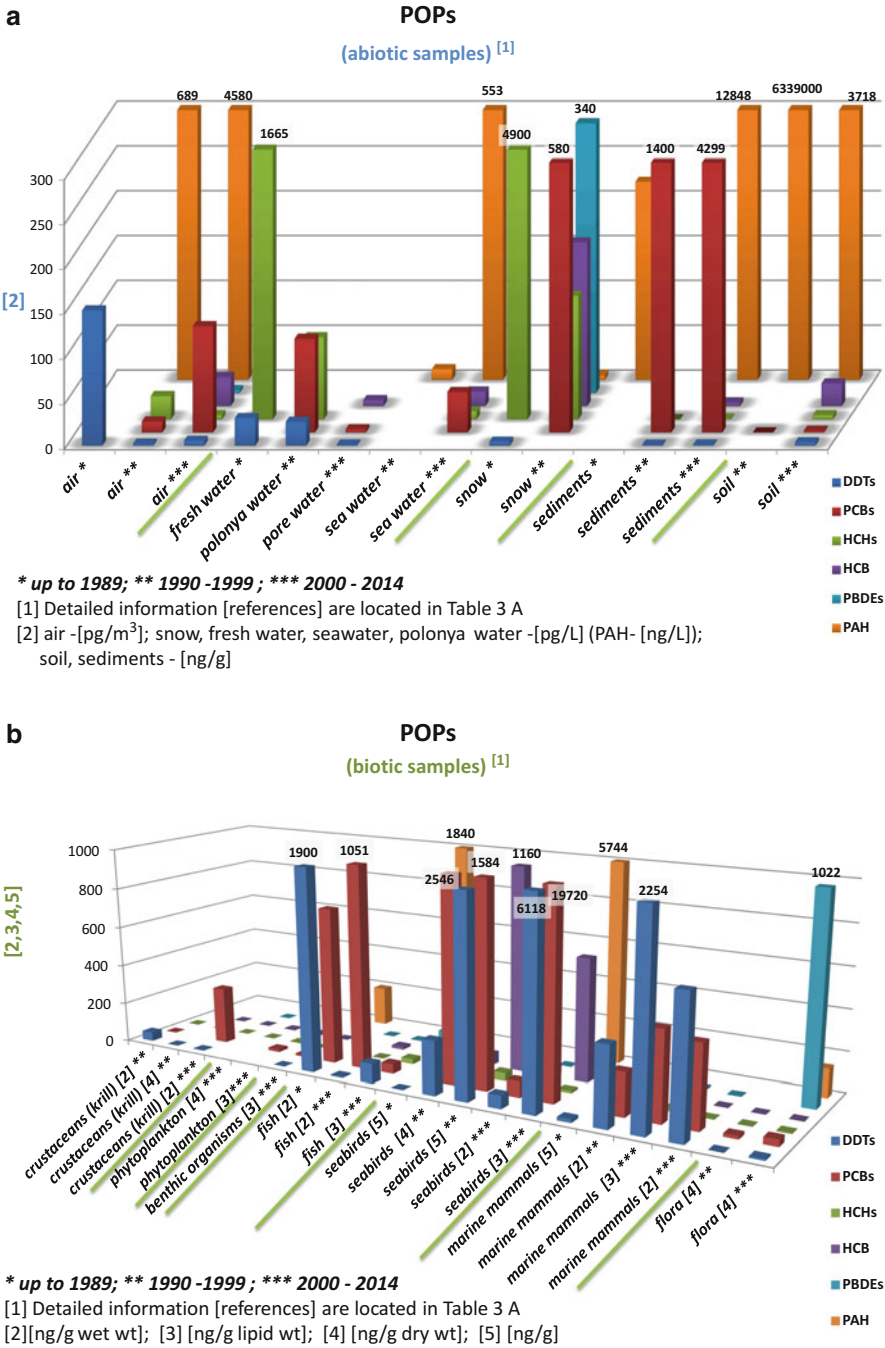


Fig. 4 Contamination concentration levels during three time periods: (a) POPs in abiotic samples, (b) POPs in biotic samples, (c) heavy metals in abiotic samples, (d) heavy metals in biotic samples

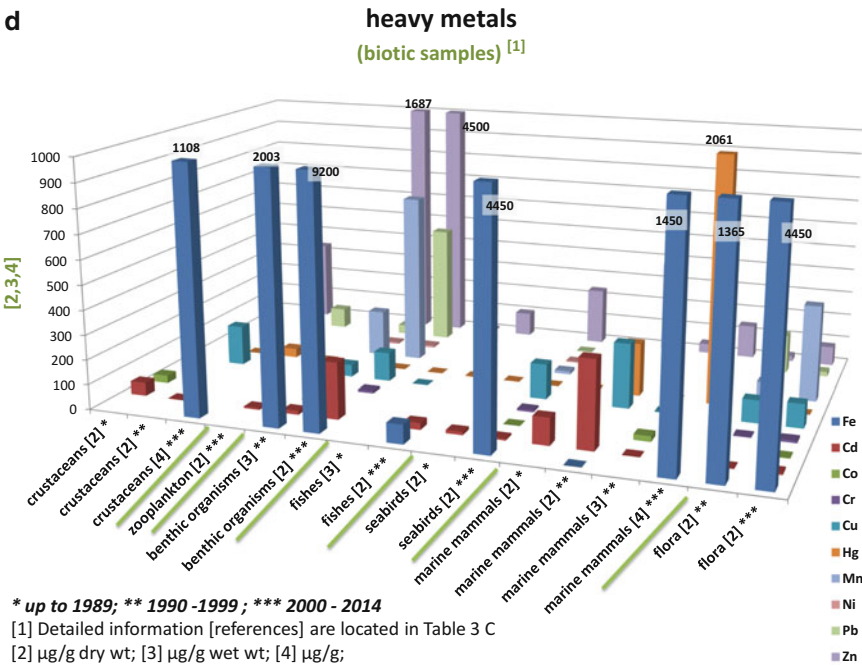
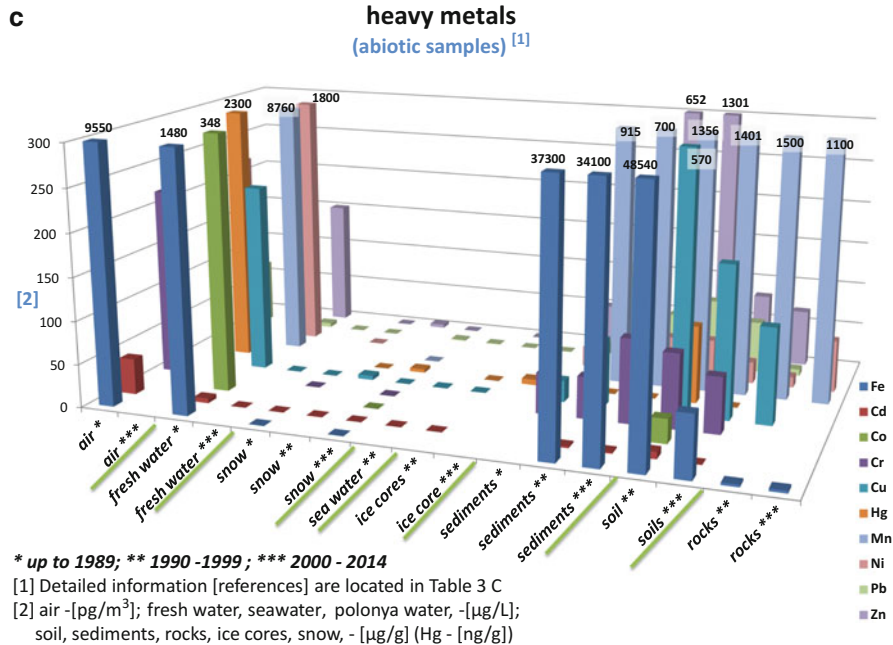


Fig. 4 (continued)

and activities of tourists and scientists can result in the detectable contaminants (PBDE, PFAS) in most stations' areas in Antarctica (Cai et al. 2012). Every part of the abiotic environment (as well as Antarctica's atmosphere and reservoirs: soil and snow) are currently closely coupled. These parts, affecting each other, have a tendency for re-volatilization of POPs to the atmosphere. These are so called secondary sources of pollution. However it is not known to what extent this remobilization is a part of a seasonal cycle with volatilization during summer and deposition during winter (Cabrerizo et al. 2013). Glacial melt may carry pollutants to nearby lakes and the adjacent coastal marine areas, thereby spreading the contamination and increasing its impacts (Majer et al. 2014). Glacier meltwater can be a current source of pollution to Antarctica's marine food web as a result of an unexpected consequence of climate change (Geisz et al. 2008). Therefore the monitoring and remediation of this scenario is essential. The active layer/permafrost transition zone was revealed to be a low-permeability barrier to downward migration of chemical compounds (Curtosi et al. 2007). Near Antarctica's stations exhibiting PAHs contamination in soils, this behaviour highlights the risk for coastal marine environments (Curtosi et al. 2007). An analysis of stations' emissions and transect sampling of abiotic matrices are carried out. The research provides indication as to the significance of research stations as local sources of POPs contamination (Bengtson Nash et al. 2010). Only few studies have determined PCB and organochlorine pesticides (OCP) concentrations in sediments in Antarctica (Zhang et al. 2013). Pollution in marine sediments are the end result of a long term accumulation and this is not directly correlating with activities on land. Unfortunately, pollutants in sediments will persist for many years to come (Kim et al. 2006), hence it is necessary to control the levels of pollution in every part of abiotic environment including sediments.

Referring to abiotic research the monitoring programs need to be extended to facility points far from major bases, assessing the extent of contamination in order to prevent local pollution episodes. This kind of studies should verify the hypothesis of a decline of PCBs in the last decade in Antarctica (Vecchiato et al. 2015).

In the discussion of biological research, what is important is using organisms for monitoring. Atmospheric monitoring of POPs using conventional instrumental methods is expensive and difficult. Scientists can overcome this limitation using biomonitoring methods and thereby provide reliable information assessing the impact of pollutants on the biota and various ecosystems. Most popular in Antarctica is using mosses to define the relationship between the concentrations of POPs in Antarctic environment and in the atmosphere (Wu et al. 2014). It should be noted, based on PBDEs studies, that mosses can accumulate more POPs than lichens (Yogui et al. 2011).

Equally important is the transport of pollution between organisms. Collected data can be useful to notice that the high concentrations of POPs encountered in the brown skua is certainly correlated to its migratory habits as well as its high trophic level position (Taniguchi et al. 2009). A useful tool to trace migration behaviour of seabirds and marine mammals can be the research of POPs levels in tissues (Kallenborn et al. 2013). Moreover, the transfer of contaminants between

Antarctica's pelagic and benthic organisms is associated with seasonal sea-ice dynamics (Van den Brink et al. 2011). The concentrations of organochlorines in penguin eggs may be toxicologically insignificant, but more studies are needed to assess the real health risks associated with these levels of pollutants because Antarctica's seals and penguins are more sensitive to contaminants than those living in temperate regions (Schiavone et al. 2009b).

In a comprehensive approach to the issue of the presence of pollutants in Antarctica, it is also very important to become familiar with accurate levels of heavy metals in this environment. In a discussion of heavy metals in abiotic environment, the geochemical characteristics of the area should be further investigated, in particular, the transport of metals as particulate or soluble fraction from the terrestrial to the marine environment (Vodopivec et al. 2015). Based on lead isotopic data, Southern South America is an important source of dust deposited in Antarctica's ice (Vallelonga et al. 2010). Moreover, based on results of research on ice cores, anthropogenic activities have become the most important source of heavy metals in Antarctica (Yin et al. 2006). Antarctica is a kind of a sink for heavy metals (e.g. Hg). Considering long atmospheric lifetime and the ability to deposit and be re-emit from soil and oceans, the ability of heavy metals to bioaccumulate suggests that their deposition would indeed have a serious effect for environment (Sprovieri et al. 2002).

Referring to heavy metals present in biological samples, particular attention should be paid to the biomagnification process which depends upon the food web (high trophic level animals have a higher content than lower trophic level ones) (Moreno et al. 1997). The presence of potentially toxic elements (such as Cd and Hg) in penguins suggest, that the accumulation of elements depends on the geochemical characteristics of the area, age of individuals and also on their diet (mainly krill) (Smichowski et al. 2006). Moreover, the results of research indicated, that a slight increase in Mn and Cr levels in Antarctica could be related mainly to human presence (usage of combustibles and oil contamination). Other studies indicate common sources of pollution (such as Cr, Ni, Pb, Mn, Cd or As), which are correlated with anthropogenic activities (plane and ship trips related to the tourism industry) (Jerez et al. 2013a). Feathers can be an important identifiers of the absorbed heavy metals (e.g. Pb) in penguins (Jerez et al. 2013b). For a better understanding of spatio-temporal trends feathers of Antarctic penguins, put together with other penguin tissues, are useful tools for long-term monitoring of trace elements in Antarctic marine environment (Jerez et al. 2011).

Furthermore mercury and its transformation products (e.g. methylmercury), because of their high bioaccumulation properties, should be investigated more precisely. A quantitative understanding of pathways and mechanisms that affect the transport of mercury from sources to ecosystems as well as the conversion of mercury to methylmercury, and their bioaccumulation in food webs are fundamental to evaluating and managing human and wildlife health risks in a local and global scale (Driscoll et al. 2013). The observations that have been made in polar marine ecosystems showed progressive increase in mercury concentrations in the food web (Bargagli et al. 1998). The role of Antarctic coastal ecosystems as sink in the global

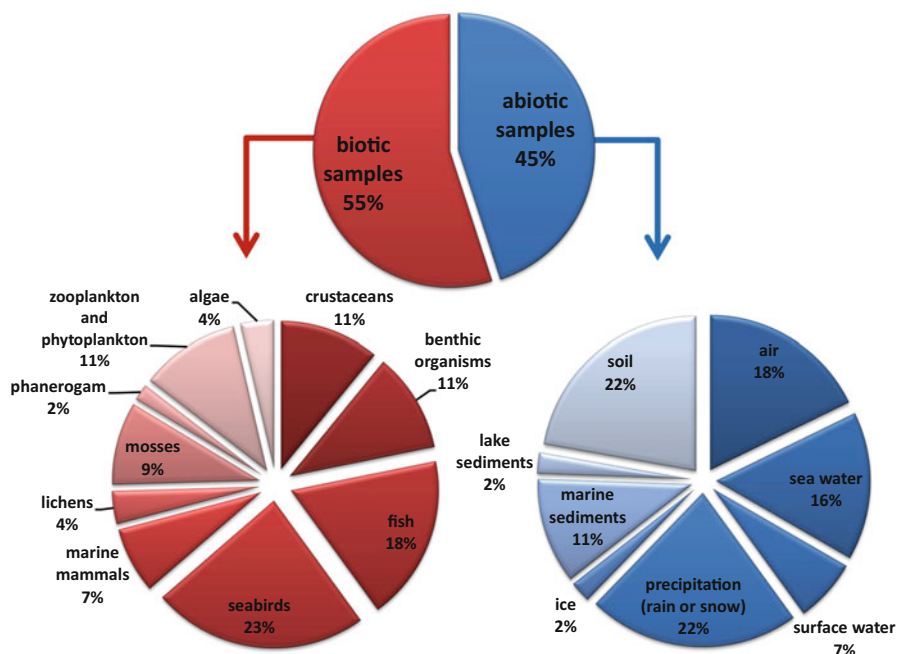


Fig. 5 Classification of analytical research according to types of environmental samples collected in the years 2000–2014

mercury cycle can be enhanced by the global warming and the possible change in the ice coverage together with increasing anthropogenic emissions of gaseous mercury in countries of the Southern Hemisphere (Bargagli et al. 2007). It clearly demonstrates the need for understanding how climatic variability and anthropogenic disturbances (e.g., increases of population, perturbations to food chains, changes in other air pollutants) affect mercury and methylmercury concentrations in Antarctic ecosystems (Driscoll et al. 2013; Bargagli 2008). Research data on pollutant levels has been enhanced during last two decades. Figure 5 presents information on the proportion of various types of analytical research in a general number of studies aimed at getting to know the degree of pollution of the Antarctica's environment during the last two decades.

The most popular research locations were the areas of the Antarctic Peninsula (including South Shetland Islands) and Ross Sea. A little more attention (55 % of contemporary research) is paid to tests of biological samples, mostly due to the interest in the actual influence of pollutants on Antarctica's ecosystem and becoming familiar with new directions of pollutant movement in the food web. Research on the chemical composition of inorganic samples (45 % of contemporary research), is equally important, as elements of abiotic environmental media are the first link in the pollutant movement process in Antarctica.

4.3 Analytical Techniques in the Study of the Antarctic Environment

Together with the development of science and instruments, various analytical procedures and techniques were used in analytical practice to test environmental samples (abiotic and biotic) collected in Antarctica.

Nowadays, Antarctica's researchers have gained access to many different analytical techniques of scope detection, power and robustness, which they couldn't even dream of some decades ago (Caroli 2001). For the chemical elements they can use: atomic absorption spectrometry (AAS) with flame or electrothermal (another name—graphite furnace (GF)) atomisation, inductively coupled plasma—atomic emission spectrometry (ICP-AES), inductively coupled plasma—optical emission spectrometry (ICP-OES), atomic fluorescence spectrometry (AFS), mass spectrometry (MS) with different ionization sources (e. g. ICP), X-ray fluorescence spectrometry (XRF), neutron activation analysis (NAA), ion-selective electrodes and isotope dilution mass spectrometry (IDMS). For organic substances, depending on properties of organic substances, analysts can choose one of the following techniques: gas chromatography (GC), high performance liquid chromatography (HPLC), thin layer chromatography (TLC), supercritical fluid chromatography (SFC) and gel permeation chromatography (GPC) with several detection systems (electron capture (EC), flame ionization (FI)), thermal conductivity (TC), flame photometry (FP), infrared spectroscopy (IR), UV absorption spectrophotometry, fluorescence (F), capillary zone electrophoresis (CZE) and MS (Caroli 2001). To determine ionic compound concentration the analysts use ion chromatography (IC) with various types of detection (e.g. conductometry detector (CD), ICP).

Applications with impressively high-resolution and full scan performances were made possible by modern instrumental configuration, that is hybrid mass spectrometers. Quantification of highly polar organic pollutants without derivatization, lower than the ppt level (nanogram per liter or per kilogram of matrix) in environmental samples, is possible by the use of tandem mass spectrometry combined with liquid chromatography. The measurement of emerging contaminants in environmental analysis are performed using the achievements of liquid chromatography—mass spectrometry (LC-MS) like the more recent advancements in triple quadrupole (QqQ), linear ion trap, time of flight analyzer (TOF) and Orbitrap mass spectrometers (Magi and Tanwar 2014).

Generally, the analysts are warned of pushing the instrumental method beyond its intrinsic limits, in terms of limits of detection, optimal working range and applicability to specific groups of substances. Otherwise, the rapid increase in the overall uncertainty associated with the experimental data will be observed soon (Caroli 2001).

Polar regions are an excellent place to study some natural phenomena as well as historical trends mostly due to the large distance between them and anthropogenic emissions sources. The concentration of micro-constituents or micro-pollutants in

polar regions is rather low and therefore it is necessary to develop some analytical methods of high sensitivity.

The chemical specification of such a variety of samples requires scientific experience and skills from different areas of science. The wide choice of analytical techniques, from the classical to the most innovative ones, which are available nowadays, offers the scientists an opportunity to face challenging qualitative and quantitative determinations. What is more, some more precise chemical information can be achieved by developing hyphenated methodologies, which means the combination of different instrumental techniques (Magi and Tanwar 2014).

Nowadays the most useful analytical tool seems to be the mass spectrometry, which was designed for determining a wide range of compounds present in environmental samples. In combination with such techniques as gas or liquid chromatography, it creates the possibility of specifying the organic (GC-MS, LC-MS) as well as inorganic compounds (ICP-MS) with a large degree of sensitivity and selectivity. Another advantage of such an analytical solution is the fact that MS provides more chemical information using a minimum amount of sample than any other analytical method (Gasparics and Maria 2000; Magi and Tanwar 2014; Planchon et al. 2001).

Determination of organic contaminants in various matrices is usually performed using chromatographic techniques (Plotka et al. 2013). Actual trend in chromatography is development of multidimensional approaches (e.g. Ouyang et al. 2015; Seeley and Seeley 2013). Multidimensional chromatography is a technique for isolating and identifying volatile (GC) and semi-volatile (GC and LC) organic compounds present in complex mixtures during one analytical cycle. Hence this techniques coupled with mass spectrometry can provide an important tool in a future monitoring of organic chemicals in Antarctica. Therefore, because of a low concentration of chemical compounds in complex matrices (feathers, leathers and internal organs of organisms) (Magi and Tanwar 2014), Antarctica poses a real challenge of developing innovative analytical approaches as well as improving MS instrument performances.

4.4 Impact of Research Station Activities on Pollution Levels

Research stations are and will be an inseparable element of the Antarctic environment. Individual polar stations have a different nature. A detailed description of the operations of polar stations is presented in Table 4. The influence that each station can have on Antarctic environment is related with length of time it has been operated or/and number of people present at station etc. This information is given regularly each year by Council of Managers of National Antarctic Program (COMNAP) on its webpage (e.g. [COMNAP Information](#)). It is also important that the development of research (the use of the station and the construction of new facilities) should not additionally contribute to environmental pollution. There are numerous ways of operating stations without polluting the environment. The

Table 4 Characteristics of polar stations operating in Antarctica (SCAR Information)

Division according to the infrastructure	
Type of infrastructure	Description
Station	– consists of durable buildings and mechanical services, – buildings are equipped with power supply and water and sewage systems
Camp	– more basic and less durable sleeping facilities are situated at the camp (tents, shelters), – these places are often used only for a few seasons,
Refuge	– has a permanent nature, – usually small and easy to install single huts
Airfield	– infrastructure (camp or shelter) is situated near the airport, it is usually connected with it, – not distinguished according to the size
Depot	– for storing food, fuel and other things
Division according to the specificity of operations	
Specificity of operations	Description
Year-round	– operate both in summer and in winter
Seasonal	– operate in summer
Closed	– the facility does not exist any more
Temporarily closed	– the facility has been closed on a temporary basis, ready to be re-opened, if necessary
Closed stations	– stations closed for an indefinite period of time – the facility can be renovated and/or re-used at any time

Princess Elisabeth Antarctica Station is an example of a station that virtually has no impact on the environment. At this station, electricity is produced using photovoltaic panels, solar collectors and wind turbines. The use of renewable sources of energy in Antarctica in the twenty-first century should not be a sign of modernity in this area, but a necessity. Reduction of potential anthropogenic pollution sources to a minimum allows to obtain reliable research results, in particular in research on long-range atmospheric transport of pollutants ([Polar Foundation Information](#)). The results of work on the design process of a photovoltaic (PV)-wind power system were recently published. This system could be installed in very challenging ambient conditions. This work has been done in the French-Italian Antarctic Base (Concordia Base). Work in this scope should be continued in other polar bases. Pollution can affect important research activities in this area (e.g. astronomical observations, studies of physics of atmosphere and Earth science). The ambient conditions significantly affect the quality of the research results. Usage of renewable energy leads to reduce usage of diesel generator and thereby leads to preserve an ecosystem, which is mandatory for heritage of the humanity (Boccaletti et al. [2014](#)).

5 Summary and Conclusions

The environment of polar regions is characterised by the lowest pollution levels in the world. However, the growing number of studies on the presence of a broad range of chemical compounds in various elements of the Antarctic environment may indirectly indicate the scale of the problem of growing symptoms of global human influence in this area.

Over the past decade, the scope of tested samples has been extended; however, the type of pollutants identified in individual samples (in the years 2000–2014) differs from the previous decades, *inter alia* is enhanced to new emerging pollutants. Most of the information about the presence of pollutants in biotic samples pertains to samples of Antarctic mosses krill, molluscs and invertebrates, various fish species and maritime birds—mostly penguins. Research of biotic samples have a special value as more and more attention is devoted to the phenomenon of bioaccumulation and its consequences within one plant or animal species as well as to biomagnification in the food chain. Research data about pollutants detected in abiotic samples are also important mainly due to direct and continuous contact with Antarctic biota.

A significant part of research is targeted at the occurrence of POPs compounds in the environment (Fuoco et al. 2009a, b). A possibly exhaustive list of information pertaining to POPs present in Antarctica's environment is possible only for several groups of compounds (HCB, PCB, DDTs, PBDE and PAHs). Their presence may largely result from the activity of research stations and the development of tourism. Over the past decades, sporadic research also pertained to identification and determination of compounds, such as: CHL, dioxins, DLC, PFCs, pesticides (dieldrin, mirex, heptachlor, endosulfan), aliphatic hydrocarbons, n-alkanes and cumulative parameters such as TOC in various environmental samples. In the future emerging pollutants exhibiting characteristics of persistence comparable to POPs should also be considered in long term monitoring.

Heavy metals are global pollutants and can reach almost any location on Earth. They come from natural, volcanic or geological sources, or as a result of anthropogenic activities. Accordingly with increasing human presence in Antarctic region the presence of metals in this area is becoming an issue that needs to be more investigated. Especially issues like: understanding of pathways and mechanisms that affect the transport of mercury from sources to ecosystems, the conversion of mercury to methylmercury, and its bioaccumulation state in food webs should be continuously studied.

Regrettably, data on pollutants in Antarctica's environment are dispersed in many magazines. It is worth mentioning that over the years different methods of POPs quantification have been used. Often information is scarce or lacking on the biology of the sampled species (age, sex, nutritional status, reproductive status, etc.). This makes data difficult to compare (Trumble et al. 2012). The fact that research results are presented in various units (g/g wet wt, g/g dry wt., etc.) is a further inconvenience, as it also makes it difficult to compare results of studies

conducted in various areas of Antarctica. To overcome this problem, some of scientists have presented their results expressed in multiple units (Court et al. 1997; Yogui et al. 2011); unfortunately very few researchers have done so.

Research on the influence of research stations on the pollution levels in the surrounding environment is also important. Detailed research in this areas leads to differentiate sources of pollutants between influence of local sources and global sources (LRAT). Additionally polar stations should implement usage of renewable energy in whole possible areas. This kind of solution of energy production leads to reduced usage of diesel generators and thereby lead preservation of the polar ecosystem.

The analysis of available information allows for concluding that human activity on a local and global scale leads to affecting and/or degradation of Antarctic ecosystems. The basic direction for contemporary Antarctic research pertaining to pollutants should be:

- carrying out the long term atmospheric monitoring for main POPs and new emerging pollutants coupled with meteorological data,
- carrying out the long-term monitoring of man-made chemicals (as well as new emerging pollutants monitoring) in Antarctic abiotic environment and endemic species in order to follow the future trends of global contamination,
- the detailed description of remobilization processes and “second sources” (e.g. melting glaciers) of pollutant in polar areas,
- the enlargement of research using non-invasive samples (like feathers and preen oil) as a useful tool to POPs and heavy metals monitoring,
- the determination of reaction and tolerance individual pollution levels for Antarctica’s fauna and flora towards individual anthropogenic chemicals (examination of the toxicological sensitivity of Antarctic key species),
- the detailed description of environmental fate (including biotic and abiotic environment) and negative effects on Antarctic ecosystem of anthropogenic compounds,
- the development of innovative analytical approaches improving the limits of detection of chemical compounds in various abiotic and biological matrices.

References

- Ahn I-Y, Lee SH, Kimt KT, Shim JH, Kim D-Y (1996) Baseline heavy metal concentrations in the Antarctic clam, *Laternula elliptica* in Maxwell Bay, King George Island, Antarctica. *Mar Pollut Bull* 32:59–598
- Ahrens L, Xie Z, Ebinghaus R (2010) Distribution of perfluoroalkyl compounds in seawater from Northern Europe, Atlantic Ocean, and Southern Ocean. *Chemosphere* 78:1011–1016
- Aisable J, Balks M, Foght J, Waterhouse A (2004) Hydrocarbon spills on Antarctic soils: effects and management. *Environ Sci Technol* 38:1265–1274
- Aislabie J, Balks M, Astori N, Stevenson G, Symons R (1999) Polycyclic aromatic hydrocarbons in fuel-oil contaminated soils, Antarctica. *Chemosphere* 39:2201–2207

- Alam IA, Sadiq M (1993) Metal concentrations in antarctic sediment samples collected during the Trans-Antarctica 1990 expedition. *Mar Pollut Bull* 26:523–527
- Albert MR, Shultz EF (2002) Snow and firn properties and air–snow transport processes at Summit, Greenland. *Atmos Environ* 36:2789–2797
- Andrade S, Poblet A, Scagliola M, Vodopivec C, Curtosi A, Pucci A, Marcovecchio J (2001) Distribution of heavy metals in surface sediments from an Antarctic marine ecosystem. *Environ Monit Assess* 66:147–158
- Antony R, Mahalinganathan K, Thamban M, Nair S (2011) Organic carbon in Antarctic snow: spatial trends and possible sources. *Environ Sci Technol* 45:9944–9950
- Aono S, Tanabe S, Fujise Y, Kat H, Tatsukawa R (1997) Persistent organochlorines in minke whale (*Balaenoptera acutorostrata*) and their prey species from the Antarctic and the North Pacific. *Environ Pollut* 98:81–89
- Aronson RB, Thatje S, Mc Clintock JB, Hughes K (2011) Anthropogenic impacts on marine ecosystems in Antarctica. *Ann N Y Acad Sci* 1223:82–107
- Bacci E, Calamari D, Gaggi C, Fanelli R, Focardi S, Morosini M (1986) Chlorinated hydrocarbons in lichen and moss samples from the Antarctic Peninsula. *Chemosphere* 15:747–754
- Baek S-Y, Choi S-D, Chang Y-S (2011) Three-year atmospheric monitoring of organochlorine pesticides and polychlorinated biphenyls in Polar Regions and the South Pacific. *Environ Sci Technol* 45:4475–4482
- Bargagli R, Brown DH, Nelli L (1995) Metal biomonitoring with mosses: procedures for correcting for soil contamination. *Environ Pollut* 89:169–175
- Bargagli R (2008) Environmental contamination in Antarctic ecosystems. *Sci Total Environ* 400:212–226
- Bargagli R, Monaci F, Bucci C (2007) Environmental biogeochemistry of mercury in Antarctic ecosystems. *Soil Biol Biochem* 39(1):352–360
- Bargagli R, Sanchez-Hernandez JC, Martella L, Monaci F (1998) Mercury, cadmium and lead accumulation in Antarctic mosses growing along nutrient and moisture gradients. *Polar Biol* 19:316–322
- Bargagli R, Sanchez-Hernandez JC, Monaci F (1999) Baseline concentrations of elements in the Antarctic macrolichen *Umbilicaria decussata*. *Chemosphere* 38:475–487
- Bargagli R (2001) Trace metals in Antarctic organisms and the development of circumpolar biomonitoring networks. *Rev Environ Contam Toxicol* 171:53–110
- Bengtson Nash M, Xiao H, Schlabach M, King C, Stark JS, Hung H (2011) Contaminant profiles of air and soil around Casey station, Antarctica; Discerning local and distant contaminant sources, Society for Environmental Toxicology and Chemistry (SETAC) Europe Proceedings, 21. <http://milano.setac.eu/?contentid=291>. Accessed 28 Oct 2015
- Bengtson Nash S, Rintoul SR, Kawaguchi S, Staniland I, Hoff J, Tierney M, Bossi R (2010) Perfluorinated compounds in the Antarctic region: ocean circulation provides prolonged protection from distant sources. *Environ Pollut* 158:2985–2991
- Bicego MC, Weber RR, Goncalves Ito RR (1996) Aromatic hydrocarbons on surface waters of Admiralty Bay, King George Island, Antarctica. *Mar Pollut Bull* 32:549–553
- Bidleman TF, Walla MD, Roura R, Carr E, Schmidt S (1993) Organochlorine pesticides in the atmosphere of the Southern Ocean and Antarctica. *Mar Pollut Bull* 26:258–262
- Boccaletti C, Felice P, Santini E (2014) Integration of renewable power systems in an Antarctic Research Station. *Renew Energ* 62:582–591
- Borghesi N, Corsolini S, Focardi S (2008) Levels of polybrominated diphenyl ethers (PBDEs) and organochlorine pollutants in two species of Antarctic fish (*Chionodraco hamatus* and *Trematomus bernacchii*). *Chemosphere* 73:155–160
- Borghesi N, Corsolini S, Leonards P, Brandsma S, Boer J, Focardi S (2009) Polybrominated diphenyl ether contamination levels in fish from the Antarctic and the Mediterranean Sea. *Chemosphere* 77:693–698
- Borghini F, Grimalt JO, Sanchez-Hernandez JC, Bargagli R (2005) Organochlorine pollutants in soils and mosses from Victoria Land (Antarctica). *Chemosphere* 58:271–278
- Boutron CF, Patterson CC (1983) The occurrence of lead in Antarctic recent snow, firn deposited over the last two centuries and prehistoric ice. *Geochim Cosmochim Acta* 47:1355–1368

- Boutron C (1979) Alkali and alkaline earth enrichments in aerosols deposited in Antarctic snow. *Atmos Environ* (1967) 13:919–924
- Boutron C, Echevin M, Lorius C (1972) Chemistry of polar snows. Estimation of rates of deposition in Antarctica. *Geochim Cosmochim Acta* 36:1029–1041
- Boutron C, Leclerc M, Risler N (1984) Atmospheric trace elements in antarctic prehistoric ice collected at a coastal ablation area. CACGP Symposium on Tropospheric Chemistry with Emphasis on Sulphur and Nitrogen Cycles and the Chemistry of Clouds and Precipitation. *Atmos Environ* (1967) 18:1947–1953
- Boutron C (1982) Atmospheric trace metals in the snow layers deposited at the South Pole from 1928 to 1977. *Atmos Environ* (1967) 16:2451–2459
- Boutron CF, Bolshov MA, Koloshnikov VG, Patterson CC, Barkov NI (1990) Direct determination of lead in Vostok antarctic ancient ice by laser excited atomic fluorescence spectrometry. *Atmos Environ* 24:1797–1800
- Brasso RL, Polito MJ (2013) Trophic calculations reveal the mechanism of population-level variation in mercury concentrations between marine ecosystems: case studies of two polar seabirds. *Mar Pollut Bull* 75:244–249
- Burniston DA, Strachan WJM, Hoff JT, Wania F (2007) Changes in surface area and concentrations of semivolatile organic contaminants in aging snow. *Environ Sci Technol* 41:4932–4937
- Burn-Nunes LJ, Vallelonga P, Loss RD, Burton GR, Moy A, Curran M, Rosman KJR (2011) Seasonal variability in the input of lead, barium and indium to Law Dome, Antarctica. *Geochim Cosmochim Acta* 75:1–20
- Burton HR (1981) Chemistry, physics and evolution of Antarctic saline lakes. *Hydrobiologia* 82:339–362
- Bustnes JO, Tveraa T, Henden JA, Janssen K, Skaare JU (2006) Organochlorines in Antarctic and Arctic Avian top predators: a comparison between the South Polar Skua and two species of Northern Hemisphere Gulls. *Environ Sci Technol* 40:2826–2831
- Cabrerizo A, Dachs J, Barceló D, Jones KC (2012) Influence of organic matter content and human activities on the occurrence of organic pollutants in Antarctic soils, lichens, grass, and mosses. *Environ Sci Technol* 46:1396–1405
- Cabrerizo A, Dachs J, Barceló D, Jones KC (2013) Climatic and biogeochemical controls on the remobilization and reservoirs of persistent organic pollutants in Antarctica. *Environ Sci Technol* 47:4299–4306
- Cabrerizo A, Galbán-Malagón C, Del Vento S, Dachs J (2014) Sources and fate of polycyclic aromatic hydrocarbons in the Antarctic and Southern Ocean atmosphere. *Global Biogeochem Cycles* 28:1424–1436
- Cai M, Yang H, Xie Z, Zhao Z, Wang F, Lu Z, Sturm R, Ebinghaus R (2012) Per- and polyfluoroalkyl substances in snow, lake, surface runoff water and coastal seawater in Fildes Peninsula, King George Island, Antarctica. *J Hazard Mater* 209–210:335–342
- Capelli R, Minganti V, Chiarini C, Pellegrini R (1998) Mercury in snow layers from the Antarctica. *Int J Environ Anal Chem* 71:289–296
- Caricchia AM, Chiavarini S, Cremisini C, Morabito R, Perini A, Pezza M (1995) Determination of PAH in atmospheric particulates in the area of the Italian base in Antarctica: report on monitoring activities during the last three scientific expeditions. *Environ Pollut* 87:345–356
- Caroli S (2001) Environmental chemistry in Antarctica: the quest for accuracy. In: Caroli S, Cescon P, Walton DWH (eds) *Environmental contamination in Antarctica. The challenge to analytical chemistry*. Elsevier, Amsterdam, pp 1–32
- Carrasco MA, Prendez M (1991) Element distribution of soils of continental Chile and the Antarctic Peninsula. Projection to atmospheric pollution. *Water Air Soil Pollut* 57–58:713–722
- Chiuchiolo AL, Dickhut RM, Cochran MA, Ducklow HW (2004) Persistent organic pollutants at the base of the Antarctic marine food web. *Environ Sci Technol* 38(13):3551–3557
- Choi S-D, Baek S-Y, Chang Y-S, Wania F, Ikonomou MG, Yoon Y-J, Hong S (2008) Passive air sampling of polychlorinated biphenyls and organochlorine pesticides at the Korean Arctic and

- Antarctic research stations: implications for long-range transport and local pollution. *Environ Sci Technol* 42:7125–7131
- Ciaralli L, Giordano R, Lombardi G, Beccaloni E, Sepe A, Costantini S (1998) Antarctic marine sediments: distribution of element and textural characters. *Microchem J* 59:77–88
- Cincinelli A, Dickhut RM (2011) Levels and trends of organochlorine pesticides (OCPS) in Antarctica. *Environ Res J* 5(4):523–545
- Cincinelli A, Martellini T, Bittoni L, Russo A, Gambaro A, Lepri L (2008) Natural and anthropogenic hydrocarbons in the water column of the Ross Sea (Antarctica). *J Mar Syst* 73:208–220
- Cincinelli A, Martellini T, Del Bubba M, Lepri L, Corsolini S, Borghesi N, King MD, Dickhut RM (2009) Organochlorine pesticide air–water exchange and bioconcentration in krill in the Ross Sea. *Environ Pollut* 157:2153–2158
- Cipro CVZ, Bustamante P, Taniguchi S, Montone RC (2012) Persistent organic pollutants and stable isotopes in pinnipeds from King George Island, Antarctica. *Mar Pollut Bull* 64:2650–2655
- Cipro CVZ, Taniguchi S, Montone RC (2010) Occurrence of organochlorine compounds in *Euphausia superba* and unhatched eggs of *Pygoscelis* genus penguins from Admiralty Bay (King George Island, Antarctica) and estimation of biomagnification factors. *Chemosphere* 78:767–771
- Cipro CVZ, Yogui GT, Bustamante P, Taniguchi S, Sericano JL, Montone RC (2011) Organic pollutants and their correlation with stable isotopes in vegetation from King George Island, Antarctica. *Chemosphere* 85:393–398
- Clarke A, Law R (1981) Aliphatic and aromatic hydrocarbons in benthic invertebrates from two sites in Antarctica. *Mar Pollut Bull* 12:10–14
- COMNAP Information (2015). <https://www.comnap.aq/Information/SitePages/Home.aspx>. Accessed 18 Sep 2015
- Corsolini S, Borghesi N, Ademollo N, Focardi S (2011) Chlorinated biphenyls and pesticides in migrating and resident seabirds from East and West Antarctica. *Environ Int* 37:1329–1335
- Corsolini S, Borghesi N, Schiamone A, Focardi S (2007) Polybrominated diphenyl ethers, polychlorinated dibenzo-dioxins, -furans, and -biphenyls in three species of Antarctic Penguins. *Environ Sci Pollut Res* 14:421–429
- Corsolini S, Covaci A, Ademollo N, Focardi S, Schepens P (2006) Occurrence of organochlorine pesticides (OCPS) and their enantiomeric signatures, and concentrations of polybrominated diphenyl ethers (PBDEs) in the Adelie penguin food web, Antarctica. *Environ Pollut* 140:371–382
- Corsolini S, Kannan K, Imagawa T, Focardi S, Giesy J (2002a) Polychloronaphtalenes and other dioxin-like compounds in Arctic and Antarctic marine food webs. *Environ Sci Technol* 36:3490–3496
- Corsolini S, Romeo T, Ademollo N, Greco S, Focardi S (2002b) POPs in key species of marine Antarctic ecosystem. *Microchem J* 73:187–193
- Corsolini S (2009) Industrial contaminants in Antarctic biota. *J Chromatogr A* 1216:598–612
- Court GS, Davis LS, Focardi S, Bargagli R, Fossi C, Leonzio C, Marili L (1997) Chlorinated hydrocarbons in the tissues of South Polar Skuas (*Catharacta maccormicki*) and Adélie Penguins (*Pygoscelis adeliae*) from Ross Sea, Antarctica. *Environ Pollut* 97:295–301
- Crespi VC, Genova N, Tositti L, Tubertini O, Bettoli G, Oddone M, Meloni S, Berzero A (1993) Trace elements distribution in Antarctic sediments by neutron activation analysis. *J Rad Nucl Chem* 168:107–114
- Cripps GC (1992) The extent of hydrocarbon contamination in the marine environment from a research station in the Antarctic. *Mar Pollut Bull* 25:288–292
- Crockett AB, White GJ (2003) Mapping sediment contamination and toxicity in winter quarters bay, McMurdo station, Antarctica port station for the United States Antarctic Program (USAP), and is located Ad-Jacent to Winter Quarters Bay (WQB), a small embayment on Ross Island. *Environ Monit Assess* 85:257–275

- Curtosi A, Pelletier E, Vodopivec CL, Mac Cormack WP (2007) Polycyclic aromatic hydrocarbons in soil and surface marine sediment near Jubany Station (Antarctica). Role of permafrost as a low-permeability barrier. *Sci Total Environ* 383:193–204
- Curtosi A, Pelletier E, Vodopivec C, Louis R, Mac Cormack WP (2010) Presence and distribution of some persistent toxic substances in sediments and marine organisms of Potter Cove, Antarctica. *Arch Environ Contam Toxicol* 59:582–592
- Dastidar PG, Ramachandran S (2008) Intellectual structure of Antarctic science: a 25-years analysis. *Scientometrics* 77:389–414
- Dauner ALL, Hernández E, MacCormack WP, Martins CC (2014) Molecular characterization of anthropogenic sources of sedimentary organic matter from Potter Cove, King George Island, Antarctica. *Sci Total Environ* 502:408–416
- Delmas RJ, Gravenhorst G (1983) Background precipitation acidity. In: *Acid deposition. Commission of the Communities, Brussels*, pp 82–107
- Delmas R, Boutron C (1978) Sulfate in Antarctic snow: spatio-temporal distribution, Sulfur in the Atmosphere Proceedings of the International Symposium Held in Dubrovnik. Yugoslavia, 7–14 Sep 1977, pp 723–728
- Dickhut RM, Cincinelli A, Cochran M, Ducklow HW (2005) Atmospheric concentrations and air-water flux of organochlorine pesticides along the Western Antarctic Peninsula. *Environ Sci Technol* 39:465–470
- Dodds K (2010) Governing Antarctica: contemporary challenges and the enduring legacy of the 1959 Antarctic Treaty. *Global Policy* 1:108–115
- Driscoll CT, Mason RP, Chan HM, Jacob DJ, Pirrone N (2013) Mercury as a global pollutant: sources, pathways, and effects. *Environ Sci Technol* 47:4967–4983
- Edwards R, Sedwick P, Land E (2001) Iron in East Antarctic snow: implications for atmospheric iron deposition and algal production in Antarctic waters. *Geophys Res Lett* 28:3907–3910
- Edwards R, Sedwick P, Morgan V, Boutron C (2006) Iron in ice cores from Law Dome: a record of atmospheric iron deposition for maritime East Antarctica during the Holocene and Last Glacial Maximum. *Geochem Geophys Geosy* 7:1–15
- Fischer WH, Lodge JP, Wartburg AF, Pate JB (1967) Estimation of some atmospheric trace gases in Antarctica. *Environ Sci Technol* 78:1967–1969
- Fischer R, Weller R, Jacobi H-W, Ballschmiter K (2002) Levels and pattern of volatile organic nitrates and halocarbons in the air at Beumayer Station (70°S), Antarctic. *Chemosphere* 48:981–992
- Focardi S, Gaggi C, Chemello G, Bacci E (1991) Organochlorine residues in moss and lichen samples from two Antarctic areas. *Polar Record* 27:241–244
- Fortner SK, Lyons BW, Olesik JW (2011) Eolian deposition of trace elements onto Taylor Valley Antarctic glaciers. *Appl Geochem* 26:1897–1904
- Fuoco R, Capodaglio R, Muscatello B, Radaelli M (2009a) Persistent organic pollutants (POPs) in the Antarctic environment. A review of findings. The SCAR Action Group on Environmental Contamination in Antarctica. http://www.iau.gub.uy/medioambiente/docs-mamb/Otros-docs/POPs_in_Antarctica.pdf. Accessed 28 Oct 2015
- Fuoco R, Colombini MP, Ceccarini A, Abete C (1996) Polychlorobiphenyls in Antarctica. *Microchem J* 54:384–390
- Fuoco R, Giannarelli S, Onor M, Ghimenti S, Abete C, Termine M, Francesconi S (2012) A snow/firn four-century record of polycyclic aromatic hydrocarbons (PAHs) and polychlorobiphenyls (PCBs) at Talos Dome (Antarctica). *Microchem J* 105:133–141
- Fuoco R, Giannarelli S, Wei Y, Ceccarini A, Abete C, Francesconi S, Termine M (2009b) Persistent organic pollutants (POPs) at Ross Sea (Antarctica). *Microchem J* 92:44–48
- Galbán-Malagón C, Cabrerizo A, Caballero G, Dachs J (2013a) Atmospheric occurrence and deposition of hexachlorobenzene and hexachlorocyclohexanes in the Southern Ocean and Antarctic Peninsula. *Atmos Environ* 80:41–49
- Galbán-Malagón CJ, Del Vento S, Berrojalbiz N, Ojeda M-J, Dachs J (2013b) Polychlorinated biphenyls, hexachlorocyclohexanes and hexachlorobenzene in seawater and phytoplankton from the Southern Ocean (Weddell, South Scotia, and Bellingshausen Seas). *Environ Sci Technol* 47:5578–5587

- Galbán-Malagón CJ, Del Vento S, Cabrerizo A, Dachs J (2013c) Factors affecting the atmospheric occurrence and deposition of polychlorinated biphenyls in the Southern Ocean. *Atmos Chem Phys* 13:12029–12041
- Gambaro A, Manodori L, Zangrando R, Cincinelli A, Capodaglio G, Cescon P (2005) Atmospheric PCB concentrations at Terra Nova Bay. *Environ Sci Technol* 39:9406–9411
- Gasparics T, Maria R (2000) Determination of trace elements in Antarctic krill samples by inductively coupled atomic emission and graphite furnace atomic absorption spectrometry. *Microchem J* 67:279–284
- Geisz HN, Dickhut RM, Cochran MA, Fraser WR, Ducklow HW (2008) Melting glaciers: a probable source of DDT to the Antarctic Marine Ecosystem. *Environ Sci Technol* 42:3958–3962
- Giordano R, Lombardi G, Ciaralli L, Beccaloni E, Sepe A, Ciprotti M, Costantini S (1999) Major and trace elements in sediments from Terra Nova. *Sci Total Environ* 227:29–40
- Gjessing Y (1989) Excess and deficit of sulfate in polar snow. *Atmos Environ* 23:155–160
- Gjessing Y (1984) Marine and non-marine contribution to the chemical composition of snow at the Riiser-Larsenisen Ice Shelf in Antarctica. *Atmos Environ* (1967) 18:825–830
- Görlach U, Boutron CF (1992) Variations in heavy metals concentrations in Antarctic snows from 1940 to 1980. *J Atmos Chem* 14:205–222
- Green G, Skerratt JH, Leeming R, Nichols PD (1992) Hydrocarbon and coprostanol levels in seawater, sea-ice algae and sediments near Davis station in eastern Antarctica: a regional survey and preliminary results for a field fuel spill experiment. *Mar Pollut Bull* 25:293–302
- Green WJ, Ferdelman GF, Canfield DE (1989) Metal dynamics in Lake Vanda (Wright Valley, Antarctica). *Chem Geol* 76:85–94
- Guerra MBB, Neto EL, Prianti MTA, Pereira-Filho ER, Schaefer CEGR (2013) Post-fire study of the Brazilian Scientific Antarctic Station: toxic element contamination and potential mobility on the surrounding environment. *Microchem J* 110:21–27
- Hale RC, Kim SL, Harvey E, Guardia MJ, Mainor TM, Bush EO, Jacobs EM (2008) Antarctic research bases: local sources of polybrominated diphenyl ether (PBDE) flame retardants. *Environ Sci Technol* 42:1452–1457
- Han Y, Huh Y, Hong S, Hur S, Motoyama H (2013) Evidence of air-snow mercury exchange recorded in the snowpack at Dome Fuji. *Antarctica. Geosci J* 18:105–113
- Herbert BMJ, Halsall CJ, Jones KC, Kallenborn R (2006a) Field investigation into the diffusion of semi-volatile organic compounds into fresh and aged snow. *Atmos Environ* 40:1385–1393
- Herbert BMJ, Villa S, Halsall CJ (2006b) Chemical interactions with snow: understanding the behavior and fate of semi-volatile organic compounds in snow. *Ecotox Environ Safe* 63:3–16
- Hong S, Boutron CF, Edwards R, Morgan V (1998) Heavy metals in Antarctic Ice from Law Dome: initial results. *Environ Res A* 78:94–103
- Hong S, Soyol-Erdene T-O, Hwang HJ, Hong SB, Hur SD, Motoyama H (2012) Evidence of global-scale As, Mo, Sb, and Tl atmospheric pollution in the Antarctic Snow. *Environ Sci Technol* 46:11550–11557
- Houde M, De Silva AO, Muir DC, Letcher RJ (2011) Monitoring of perfluorinated compounds in aquatic biota: an updated review. *Environ Sci Technol* 19:7962–7973
- House DA, Hoare RA, Popplewell KB, Henderson RA, Prebble WM, Wilson AT (1966) Chemistry in the Antarctic. *J Chem Educ* 43:502–505
- Huang T, Sun L, Wang Y, Chu Z, Qin X, Yang L (2014) Transport of nutrients and contaminants from ocean to island by emperor penguins from Amanda Bay, East Antarctic. *Sci Total Environ* 468–469:578–583
- Ianni C, Magi E, Soggia F, Rivaro P, Frache R (2010) Trace metal speciation in coastal and off-shore sediments from Ross Sea (Antarctica). *Microchem J* 96:203–212
- Inomata ONK, Montone RC, Lara WH, Weber RR, Toledo HHB (1996) Tissue distribution of organochlorine residues – PCBs and pesticides – in Antarctic penguins. *Antarct Sci* 8:253–255
- Jerez S, Molas M, Benzal J, Diaz J, Barbosa A (2013a) Monitoring trace elements in Antarctic penguin chicks from South Shetland. *Mar Pollut Bull* 69:67–75

- Jerez S, Motas M, Benzal J, Diaz J, Vidal V, D'Amico V, Barbosa A (2013b) Distribution of metals and trace elements in adult and juvenile penguins from the Antarctic Peninsula area. *Environ Sci Pollut Res Int* 20:3300–3311
- Jerez S, Motas M, Palacios MJ, Valera F, Cuervo JJ, Barbosa A (2011) Concentration of trace elements in feathers of three Antarctic penguins: geographical and interspecific differences. *Environ Pollut* 159:2412–2419
- Jiratu P, Gabrielli P, Marteel A, Plane JMC, Planchon FAM, Gauchard PA, Ferrari CP, Boudron CF, Adams FC, Hong S, Cescon P, Barbante C (2009) Atmospheric depletion of mercury over Antarctica during glacial periods. *Nat Geosci* 2:505–508
- Kallenborn R, Breivik K, Eckhardt S, Lunder CR, Manø S, Schlabach M, Stohl A (2013) Long-term monitoring of persistent organic pollutants (POPs) at the Norwegian Troll station in Dronning Maud Land, Antarctica. *Atmos Chem Phys Discuss* 13:6219–6246
- Kallenborn R, Oehme M, Wynn-Williams DD, Schlabach M, Harris J (1998) Ambient air levels and atmospheric long-range transport of persistent organochlorines to Signy Island, Antarctica. *Sci Total Environ* 220:167–180
- Kang J-H, Son M-H, Hur SD, Hong S, Motoyama H, Fukui K, Chang Y-S (2012) Deposition of organochlorine pesticides into the surface snow of East Antarctica. *Sci Total Environ* 433:290–295
- Kennicutt M II, McDonald S, Sericano J (1995) Human contamination of the marine environment - Arthur Harbor and McMurdo Sound, Antarctica. *Environ Sci Technol* 29:1279–1287
- Kim M, Kennicutt MC, Qian Y (2006) Molecular and stable carbon isotopic characterization of PAH contaminants at McMurdo Station, Antarctica. *Mar Pollut Bull* 52:1585–1590
- Klánová J, Matykiewiczová N, Máčka Z, Prošek P, Lásková K, Klán P (2008) Persistent organic pollutants in soils and sediments from James Ross Island, Antarctica. *Environ Pollut* 152:416–423
- Köler P (2013) Stulecie zdobycia południowego bieguna ziemi. *Kwart Hist Nauki Tech* 58:57–75, <http://cejsh.icm.edu.pl/cejsh/element/bwmeta1.element.cejsh-11f2d66e-c096-4c87-9b37-327c9f94f8d7>. Accessed 29 Oct 2015
- Kozak K, Polkowska Ż, Ruman M, Kozioł K, Namieśnik J (2013) Analytical studies on the environmental state of the Svalbard archipelago - critical source of information about anthropogenic global impact. *Trends Anal Chem* 50:107–126
- Krahn MM, Hanson MB, Baird RW, Boyer RH, Burrows DG, Emmons CK, Ford JKB, Jones LL, Noren DP, Ross PS, Schorr GS, Collier TK (2007) Persistent organic pollutants and stable isotopes in biopsy samples (2004/2006) from southern resident killer whales. *Mar Pollut Bull* 54:1903–1911
- Kvenvolden KA, Rapp JB, Golan-Bac M, Hostettler FD (1987) Multiple sources of alkanes in Quaternary oceanic sediment of Antarctica. *Org Geochem* 11:291–302
- Lana NB, Berton P, Covaci A, Ciocco NF, Barrera-Oro E, Atencio A, Altamirano JC (2014) Fingerprint of persistent organic pollutants in tissues of Antarctic notothenioid fish. *Sci Tot Environ* 499:89–98
- Larsson P, Järnmark C, Södergren A (1992) PCBs and chlorinated pesticides in the atmosphere and aquatic organisms of Ross Island, Antarctica. *Mar Pollut Bull* 25:281–287
- Legrand BMR, Delmas RJ (1986) Relative contributions of tropospheric and stratospheric sources to nitrate in Antarctic snow. *Tellus* 38B:236–249
- Legrand M, Angelis M, Delmas RJ (1984) Ion chromatographic determination of common ions at ultratrace levels in Antarctic snow and ice. *Anal Chim Acta* 156:181–192
- Legrand MR, Lorius C, Barkov NI, Petrov VN (1988) Vostok (Antarctica) ice core: atmospheric chemistry changes over the last climatic cycle (160,000 years). *Atmos Environ* (1967) 22:317–331
- Lenihan HS (1992) Benthic marine pollution around McMurdo Station, Antarctica: a summary of findings. *Mar Pollut Bull* 25:318–323
- Li Y, Geng D, Liu F, Wang T, Zhang Q, Jiang H (2012) Study of PCBs and PBDEs in King George Island, Antarctica, using PUF passive air sampling. *Atmos Environ* 51:140–145

- Llorca M, Farré M, Tavano MS, Alonso B, Koremblit G, Barceló D (2012) Fate of a broad spectrum of perfluorinated compounds in soils and biota from Tierra del Fuego and Antarctica. *Environ Pollut* 163:158–166
- Lu Z, Cai M, Wang J, Yang H, He J (2012) Baseline values for metals in soils on Fildes Peninsula, King George Island, Antarctica: the extent of anthropogenic pollution. *Environ Monit Assess* 184:7013–7021
- Luke BG, Johnstone GW, Woehler EJ (1989) Organochlorine pesticides, PCBs and mercury in antarctic and subantarctic seabirds. *Chemosphere* 19:2007–2021
- Ma X, Zhang H, Zhou H, Na G, Wang Z, Chen C, Chen J (2014) Occurrence and gas/particle partitioning of short- and medium-chain chlorinated paraffins in the atmosphere of Fildes Peninsula of Antarctica. *Atmos Environ* 90:10–15
- Machado A, Lima EF, Chemale F Jr, Liz JD, Avila JN (2001) Química mineral de rochas vulcânicas da Península Fildes (Ilha Rei George), Antártica. *Revista Brasileira de Geociências* 31:299–306 (in Portuguese)
- Magi E, Tanwar S (2014) “Extreme Mass Spectrometry”: the role of mass spectrometry in the study of the Antarctic Environment. *J Mass Spectrom* 49:1071–1085
- Majer AP, Petti MAV, Corbisier TN, Ribeiro AP, Theophilo CYS, Ferreira PADL, Figueira RCL (2014) Bioaccumulation of potentially toxic trace elements in benthic organisms of Admiralty Bay (King George Island, Antarctica). *Mar Pollut Bull* 79:321–325
- Malcolm HM, Boyd IL, Osborn D, French MC, Freestone P (1994) Trace metals in Antarctic fur seal (*Arctocephalus gazella*) livers from Bird Island, South Georgia. *Mar Pollut Bull* 28:375–380
- Mão de Ferro A, Mota AM, Canário J (2014) Pathways and speciation of mercury in the environmental compartments of Deception Island, Antarctica. *Chemosphere* 95:227–233
- Mão de Ferro A, Mota AM, Canário J (2013) Sources and transport of As, Cu, Cd and Pb in the environmental compartments of Deception Island, Antarctica. *Mar Pollut Bull* 77:341–348
- Martins CC, Bicego MC, Rose NL, Taniguchi S, Lourenço R, Figueira RCL, Montone RC (2010) Historical record of polycyclic aromatic hydrocarbons (PAHs) and spheroidal carbonaceous particles (SCPs) in marine sediment cores from Admiralty Bay, King George Island, Antarctica. *Environ Pollut* 158:192–200
- Mazzera D, Hayes T, Lowenthal D, Zielinska B (1999) Quantification of polycyclic aromatic hydrocarbons in soil at McMurdo Station, Antarctica. *Sci Total Environ* 229:65–71
- McClurg TP (1984) Trace metals and chlorinated hydrocarbons in Ross seals from Antarctica. *Mar Pollut Bull* 15:384–389
- Merlin OH, Salvador GL, Vitturi LM, Pistolato M, Rampazzo G (1989) Preliminary results on trace element geochemistry of sediments from the Ross Sea, Antarctica. *Boll Oceanol Teor Applic* 7:97–108
- Michelutti N, Blais JM, Mallory ML, Brash J, Thienpont J, Kimpe LE, Douglas MSV, Smol JP (2010) Trophic position influences the efficacy of seabirds as metal biovectors. *Proc Natl Acad Sci U S A* 107:10543–10548
- Montone RC, Taniguchi S, Weber RR (2003) PCBs in the atmosphere of King George Island, Antarctica. *Sci Tot Environ* 308:167–173
- Montone RC, Taniguchi S, Weber RR (2001) Polychlorinated biphenyls in marine sediments of Admiralty Bay, King George Island. *Mar Pollut Bull* 42:611–614
- Montone RC, Weber RR, Taniguchi S (2005) PCBs and chlorinated pesticides (DDTs, HCHs and HCB) in the atmosphere of the southwest Atlantic and Antarctic oceans. *Mar Pollut Bull* 50:778–782
- Moreno JEA, Gerpe MS, Moreno VJ, Vodopivec C (1997) Heavy metals in Antarctic organisms. *Polar Biol* 17:131–140
- Murozumi M, Chow TJ, Patterson C (1969) Chemical concentrations of pollutant lead aerosols, terrestrial dusts and sea salts in Greenland and Antarctic snow strata. *Geochim Cosmochim Acta* 33:1247–1294

- Myers CE, Hatcher RF, Tucker RC, Waugh NS (1980) Environmental assessment of Antarctic research. *Environ Sci Technol* 14(6):668–672
- Negoita TG, Covaci A, Gheorghe A, Schepens P (2003) Distribution of polychlorinated biphenyls (PCBs) and organochlorine pesticides in soils from the East Antarctic coast. *J Environ Monit* 5:281–286
- Negri A, Burns K, Boyle S, Brinkman S, Webster N (2006) Contamination in sediments, bivalves and sponges of McMurdo Sound, Antarctica. *Environ Pollut* 143:456–476
- Nemirovskaya I (2006) Organic compounds in the snow-ice cover of eastern Antarctica. *Geochem Int* 44:825–834
- Neubauer J, Heumann KG (1988) Nitrate trace determinations in snow and firn core samples of ice shelves at the Weddell Sea, Antarctica. *Atmos Environ* (1967) 22:537–545
- Niemistö L, Perttilä M (1995) Trace elements in the Weddell Sea water and sediments in the continental shelf area. *Chemosphere* 31:3643–3650
- Olech M, Kwiatek WM, Dutkiewicz EM (1998) Lead pollution in the Antarctic Region. *X-Ray Spectrom* 27:232–235
- Osycka P, Dutkiewicz EM, Olech M (2007) Trace elements concentrations in selected moss and lichen species collected within Antarctic research stations. *Pol J Ecol* 55:39–48
- Ouyang X, Leonards P, Legler J, van der Oost R, de Boer J, Lamoree M (2015) Comprehensive two-dimensional liquid chromatography coupled to high resolution time of flight mass spectrometry for chemical characterization of sewage treatment plant effluents. *J Chrom A* 1380:139–145
- Palais JM (1988) Chemical composition of ice containing tephra layers in the Byrd Station ice core, Antarctica. *Quatern Res* 30:315–330
- Peel DA (1975) Organochlorine residues in Antarctic snow. *Nature* 254:324–325
- Peterle TJ (1969) DDT in Antarctic snow. *Nature* 224:620
- Petri G, Zauke CP (1993) Trace metals in crustaceans, in the Antarctic Ocean. *Ambio* 22:529–536
- Planchon FAM, Boutron CF, Barbante C, Wolff EW, Cozzi G, Gaspari V, Cescon P (2001) Ultrasensitive determination of heavy metals at the sub-picogram per gram level in ultraclean Antarctic snow samples by inductively coupled plasma sector field mass spectrometry. *Anal Chim Acta* 450:193–205
- Planchon FAM, Boutron CF, Barbante C, Cozzi G, Gaspari V, Wolff EW, Ferrari CP, Cescon P (2002) Short-term variations in the occurrence of heavy metals in Antarctic snow from Coats Land since the 1920s. *Sci Tot Environ* 300:129–142
- Platt HM, Mackie PR (1980) Distribution and fate of aliphatic and aromatic hydrocarbons in Antarctic fauna and environment. *Helgoländer Meeresunters* 33:236–245
- Plotka J, Tobiszewski M, Sulej AM, Kupka M, Górecki T, Namieśnik J (2013) Green chromatography. *J Chrom A* 1307:1–20
- Poblet A, Andrade S, Scagliola M, Vodopivec C, Curtosi A, Pucci A, Marcovecchio J (1997) The use of epilithic Antarctic lichens (*Usnea aurantiacoatra* and *U. antarctica*) to determine deposition patterns of heavy metals in the Shetland Islands, Antarctica. *Sci Total Environ* 207:187–194
- Poigner H, Monien P, Monien D, Kriews M, Brumsack HJ, Wilhelms-Dick D, Abele D (2013) Influence of the porewater geochemistry on Fe and Mn assimilation in *Laternula elliptica* at King George Island (Antarctica). *Estuar Coast Shelf Sci* 135:285–295
- Polar Foundation Information (2014) <http://www.polarfoundation.org>. Accessed 12 Jan 2014
- Ribeiro AP, Figueira RCL, Martins CC, Silva CRA, França EJ, Bicego MC, Mahiques MM, Montone RC (2010) Arsenic, copper and zinc in marine sediments from the proximity of the Brazilian Antarctic base, Admiralty Bay, King George Island, Antarctica. *Annual Activity Report* 137–140
- Ribeiro AP, Figueira RCL, Martins CC, Silva CRA, França EJ, Montone RC (2011) Arsenic and trace metal contents in sediment profiles from the Admiralty Bay. *Mar Pollut Bull* 62:192–196
- Riiddlein N, Heumann KG (1995) Size fractionated impactor sampling of aerosol particles over the Atlantic Ocean from Europe to Antarctica as a methodology for source identification of Cd, Pb, Ti, Ni, Cr, and Fe. *J Anal Chem* 352:748–755

- Risebrough RW, Reiche P, Olcott HS (1969) Current progress in the determination of the polychlorinated biphenyls. *Bull Environ Contam Toxicol* 4:192–201
- Risebrough RW, Carmignani GM (1972) Chlorinated hydrocarbons in Antarctic birds. In: Parker BC (ed) *Proceedings of the colloquium. Conservation problems in Antarctica*. Allen Press, Lawrence, KS, pp 63–78
- Risebrough RW, Walker W, Schmidt TT, Lappe BW, Connors CW (1976) Transfer of chlorinated biphenyls to Antarctica. *Nature* 264:738–739
- Risebrough RW, Lappe BW, Youngmans-Haug C (1990) PCB and PCT contamination in Winter Quarters Bay, Antarctica. *Mar Pollut Bull* 21:523–529
- Santos IR, Silva Filho EV, Schaefer C, Maria S, Silva CA, Gomes V, Passos MJ, Van Ngan P (2006) Baseline mercury and zinc concentrations in terrestrial and coastal organisms of Admiralty Bay, Antarctica. *Environ Pollut* 140:304–311
- Runcie JW, Riddle MJ (2004) Metal concentrations in macroalgae from East Antarctica. *Mar Pollut Bull* 49:1109–1126
- Saigne C, Kirchner S, Legrand M (1987) Ion-chromatographic measurements of ammonium, fluoride, acetate, formate and methanesulphonate ions at very low levels in antarctic ice. *Anal Chim Acta* 203:11–21
- Santos IR, Fávoro DIT, Schaefer CERG, Silva-Filho EV (2007) Sediment geochemistry in coastal maritime Antarctica (Admiralty Bay, King George Island): evidence from rare earths and other elements. *Mar Chem* 107:464–474
- Santos IR, Silva-Filho EV, Schaefer CERG, Albuquerque-Filho MR, Campos LS (2005) Heavy metal contamination in coastal sediments and soils near the Brazilian Antarctic Station, King George Island. *Mar Pollut Bull* 50:185–194
- SCAR Information (2014) <http://www.scar.org/information/>. Accessed 13 Feb 2014
- Schiavone A, Corsolini S, Borghesi N, Focardi S (2009a) Contamination profiles of selected PCB congeners, chlorinated pesticides, PCDD/Fs in Antarctic fur seal pups and penguin eggs. *Chemosphere* 76:264–269
- Schiavone A, Corsolini S, Kannan K, Tao L, Trivelpiece W, Torrens D Jr, Focardi S (2009b) Perfluorinated contaminants in fur seal pups and penguin eggs from South Shetland, Antarctica. *Sci Tot Environ* 407:3899–3904
- Schiavone A, Kannan K, Horii Y, Focardi S, Corsolini S (2009c) Occurrence of brominated flame retardants, polycyclic musks, and chlorinated naphthalenes in seal blubber from Antarctica: comparison to organochlorines. *Mar Pollut Bull* 58:1415–1419
- Seeley JV, Seeley SK (2013) Multidimensional gas chromatography: fundamental advances and new applications. *Anal Chem* 85:557–578
- Sen Gupta R, Sarkar A, Kureishey W (1996) PCBs and organochlorine pesticides in krill and water from Antarctica. *Deep-Sea Res II* 43:119–126
- Senthil K, Kannan K, Corsolini S (2002) Polychlorinated dibenzo-p-dioxins, dibenzofurans and polychlorinated biphenyls in polar bear, penguin and south polar skua. *Environ Pollut* 119:151–161
- Siegel SM, Siegel BZ, McMurtry G (1981) Antarctic iron-mercury abundance ratios: evidence for mercury depletion in an active volcanic zone. *Water Air Soil Pollut* 15:465–469
- Smichowski P, Vodopivec C, Muñoz-Olivas R, Gutierrez MA (2006) Monitoring trace elements in selected organs of Antarctic penguin (*Pygoscelis adeliae*) by plasma-based techniques. *Microchem J* 82:1–7
- Soyol-Erdene T-O, Huh Y, Hong S, Hur SD (2011) A 50-year record of platinum, iridium, and rhodium in Antarctic Snow: volcanic and anthropogenic sources. *Environ Sci Technol* 45:5929–5935
- Sprovieri F, Pirrone N, Hedgecock IM, Stevens RK (2002) Intensive atmospheric mercury measurements at Terra Nova Bay in Antarctica during November and December 2000. *J Geophys Res* 107:1–9
- Stortini AM, Martellini T, Del Bubba M, Lepri L, Capodaglio G, Cincinelli A (2009) N-Alkanes, PAHs and surfactants in the sea surface microlayer and sea water samples of the Gerlache Inlet sea (Antarctica). *Microchem J* 92:37–43

- Subramanian BR, Tanabe S, Hidaka H, Tatsukawa R (1983) DDTs and PCB isomers and congeners in Antarctic Fish. *Arch Environ Contam Toxicol* 12:621–626
- Sun W, Hu C, Weng H, Han Z, Shen C, Pan J (2013) Sources and geographic heterogeneity of trace metals in the sediments of Prydz Bay, East Antarctica. *Polar Res* 32:1–9
- Suttie ED, Wolff EW (1992) Seasonal input of heavy metals to Antarctic snow. *Tellus* 44B:351–357
- Szefer P, Czarnowski W, Pempkowiak J, Holm E (1993) Mercury and major essential elements in seals, penguins, and other representative fauna of the Antarctic. *Arch Environ Contam Toxicol* 25:422–427
- Taniguchi S, Montone RC, Bicego MC, Colabuono FI, Weber RR, Sericano JL (2009) Chlorinated pesticides, polychlorinated biphenyls and polycyclic aromatic hydrocarbons in the fat tissue of seabirds from King George Island, Antarctica. *Mar Pollut Bull* 58:129–133
- Tao L, Kannan K, Kajiwaru N, Costa MM, Fillmann G, Takahashi S, Tanabe S (2006) Perfluorooctanesulfonate and related fluoro-chemicals in albatrosses, elephant seals, penguins, and polar skuas from the Southern Ocean. *Environ Sci Technol* 40:7642–7648
- Tartu S, Angelier F, Wingfield JC, Bustamante P, Labadie P, Budzinski H, Chastel O (2015) Corticosterone, prolactin and egg neglect behavior in relation to mercury and legacy POPs in a long-lived Antarctic bird. *Sci Tot Environ* 505:180–188
- Thamban M, Thakur RC (2013) Trace metal concentrations of surface snow from Ingrid Christensen Coast, East Antarctica—spatial variability and possible anthropogenic contributions. *Environ Monit Assess* 185:2961–2975
- Townsend T, Snape I (2008) Multiple Pb sources in marine sediments near the Australian Antarctic Station, Casey. *Sci Tot Environ* 389:466–474
- Trumble SJ, Robinson EM, Noren SR, Usenko S, Davis J, Kanatous SB (2012) Assessment of legacy and emerging persistent organic pollutants in Weddell seal tissue (*Leptonychotes weddellii*) near McMurdo Sound, Antarctica. *Sci Tot Environ* 439:275–283
- Upreti DK, Pandey V (1994) Heavy metals of Antarctic lichens. 1. Umbilicaria. *Feddes Rep* 105:197–199
- Vallelonga P, Gabrielli P, Balliana E, Wegner A, Delmonte B, Turetta C, Burton G, Vanhaecke F, Rosman KJR, Hough S, Boutron CF, Cescon P, Barbante C (2010) Lead isotopic compositions in the EPICA Dome C ice core and Southern Hemisphere Potential Source Areas. *Quaternary Sci Rev* 29:247–255
- Vallelonga P, Velde K, Candelone J, Morgan VI, Boutron CF, Rosman KJR (2002) The lead pollution history of Law Dome, Antarctica, from isotopic measurements on ice cores: 1500 AD to 1989 AD. *Earth Planet Sci Lett* 204:291–306
- Van den Brink NW, Riddle MJ, Heuvel-Greve M, Franeker JA (2011) Contrasting time trends of organic contaminants in Antarctic pelagic and benthic food webs. *Mar Pollut Bull* 62:128–132
- Vandal GM, Mason RP, McKnight D, Fitzgerald W (1998) Mercury speciation and distribution in a polar desert lake (Lake Hoare, Antarctica) and two glacial meltwater streams. *Sci Total Environ* 213:229–237
- Vandal GM, Fitzgerald WF, Boutron CF, Candelone JP (1995) Mercury in ancient ice and recent snow from the Antarctic. In: *Ice core studies of global biogeochemical cycle*, vol 130. Springer, New York, NY, pp 401–415
- Vecchiato M, Argiriadis E, Zambon S, Barbante C, Toscano G, Gambaro A, Piazza R (2015) Persistent Organic Pollutants (POPs) in Antarctica: occurrence in continental and coastal surface snow. *Microchem J* 119:75–82
- Velde K, Vallelonga P, Gaspari V, Cozzi G, Barbante C, Udisti R, Cescon P, Boutron CF (2005) Pb isotope record over one century in snow from Victoria Land, Antarctica. *Earth Planet Sci Lett* 232:95–108
- Venkatesan MI (1988) Organic geochemistry of marine sediments in Antarctic region: marine lipids in McMurdo Sound. *Org Geochem* 12:13–27
- Vodopivec C, Curtosi A, Villamil E, Smichowski P, Pelletier E, Mac WP (2015) 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. *Sci Tot Environ* 502:375–384

- Völkening J, Baumann H, Heumann KG (1988) Atmospheric distribution of particulate lead over the Atlantic Ocean from Europe to Antarctica. *Atmos Environ* (1967) 22:1169–1174
- Völkening J, Heumann KG (1988) Determination of heavy metals at the pg/g level in Antarctic snow with DPASV and IDMS. *Fresenius' Z Anal Chem* 331:174–181
- Waheed S, Ahmad S, Rahman A, Qureshi IH (2001) Antarctic marine sediments as fingerprints of pollution migration. *J Rad Nucl Chem* 250:97–107
- Walton DWH, Scarponi G, Cescon P (2001) A scientific framework for environmental monitoring in Antarctica. In: Caroli S, Cescon P, Walton DWH (eds) *Environmental contamination in Antarctica. The challenge to analytical chemistry*. Elsevier, Amsterdam, pp 33–53
- Wania F (1997) Modelling the fate of non-polar organic chemicals in an ageing snow pack. *Chemosphere* 35:2345–2363
- Wania F, Hoff JT, Jia CQ, Mackay D (1998) The effects of snow and ice on the environmental behavior of hydrophobic organic chemicals. *Environ Pollut* 102:25–41
- Wania F, Semkin R, Hoff JT, Mackay D (1999) Modelling the fate of non-polar organic chemicals during the melting of an Arctic snowpack. *Hydrol Process* 13:2245–2256
- Weber K, Goerke H (2003) Persistent organic pollutants (POPs) in antarctic fish: levels, patterns, changes. *Chemosphere* 53:667–678
- Webster J, Webster K, Nelson P, Waterhouse E (2003) The behaviour of residual contaminants at a former station site, Antarctica. *Environ Pollut* 123:163–179
- Witherow RA, Lyons WB (2008) Mercury deposition in a polar desert ecosystem. *Environ Sci Technol* 42:4710–4716
- Wolff EW, Suttie ED, Prrl DA (1999) Antarctic snow record of cadmium, copper, and zinc content during the twentieth century. *Atmos Environ* 33:1535–1541
- Wu Q, Wang X, Zhou Q (2014) Biomonitoring persistent organic pollutants in the atmosphere with mosses: performance and application. *Environ Int* 66:28–37
- Xie Z, Sun L (2008) A 1,800-year record of arsenic concentration in the penguin dropping sediment, Antarctic. *Environ Geol* 55:1055–1059
- Yamamoto Y, Honda K, Hidaka H, Tatsukawa R (1987) Tissue distribution of heavy metals in Weddell seals (*Leptonychotes weddellii*). *Mar Pollut Bull* 18:164–169
- 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. *Sci Total Environ* 371:252–257
- Yogui GT, Sericano JL, Montone RC (2011) Accumulation of semivolatile organic compounds in Antarctic vegetation: a case study of polybrominated diphenyl ethers. *Sci Total Environ* 409:3902–3908
- Yogui GT, Sericano JL (2009) Levels and pattern of polybrominated diphenyl ethers in eggs of Antarctic seabirds: endemic versus migratory species. *Environ Pollut* 157:975–980
- Yogui GT, Sericano JL (2008) Polybrominated diphenyl ether flame retardants in lichens and mosses from King George Island, maritime Antarctica. *Chemosphere* 73:1589–1593
- Yuguang W, Junlin Z (1991) Determination of rare earths and other trace elements in samples of Antarctica by neutron activation analysis. *J Rad Nucl Chem* 151:345–355
- Zhang L, Dickhut R, DeMaster D, Pohl K, Lohmann R (2013) Organochlorine pollutants in Western Antarctic Peninsula sediments and benthic deposit feeders. *Environ Sci Technol* 47:5643–5651
- Zoccolillo L, Amendola L, Cafaro C, Insogna S (2007) Volatile chlorinated hydrocarbons in Antarctic superficial snow sampled during Italian ITASE expeditions. *Chemosphere* 67:1897–1903

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