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REVIEW ARTICLE

Persistent Organic Pollutants in Biotic and Abiotic Components of Antarctic Pristine Environment

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Abstract
Over the past decades, research in Antarctica has built a new understanding of Antarctica, its past, present and future. Human activities and long-range pollutants are increasing on the Antarctic continent. Research on persistent organic pollutants (POPs) has been carried out internationally by several countries having their permanent research stations to explain the impact of an ever increasing range of POPs in Antarctic ecosystem. POPs have been detected in Antarctica despite its geographical isolation and almost complete absence of human settlements. The presence of POPs in different abiotic (atmosphere, water bodies, sediments, soil, sea ice) and biotic components (mosses, lichens, krill, penguins, skua, etc.) in Antarctica has been studied and documented around for decades and has either been banned or strictly regulated but is still found in the environment. This review focuses on recent research pertaining to sources and occurrence of POPs in Antarctic lake water, soil, sediment, lichen, mosses and other Antarctic marine community. This review also proposes to summarize the current state of research on POPs in Antarctica environment and draw the earliest conclusions on possible significance of POPs in Antarctica based on presently available information from related Antarctic environment.

Keywords Persistent organic pollutants (POPs) · Biotic and abiotic compounds · Ecotoxicology and Antarctic pristine environment

1 Introduction

Antarctica is a continent of extremes: highest, driest, coldest, windiest, emptiest land largely covered by the Antarctic ice sheet. Approximately, 2% of the continent remains free from ice and snow which is available for colonization by plants, animals and microbes (Barrientos-Diaz et al. 2008; Chauhan et al. 2015a, b). It is one of the most pristine and untouched regions of the planet, geographically isolated from other continents, where low temperature, frequent freeze–thaw cycles, periods of prolonged dark in winter, different pH levels, low organic nutrient and water availability, strong winds and UV radiation are found (Cary et al. 2010). Antarctica delivers the cleanest atmospheric environment available for the study of chemicals stored in snow and collected on the polar ice sheets. According to Legrand and Mayewski (1997), atmosphere of the polar region is already affected by human activities. Environmental conditions are changing hastily due to increased human activities on the continents and the impact of climate change. With the comparison of total size of continent, the footprints of human on Antarctica are small; however, the impacts are not evenly spread. This review will provide a platform for a deeper and current understanding of POP concentration in Antarctic ecosystem. It begins with a short-term description of POPs in Antarctic pristine environment, source and distribution of POPs, grasshopper effect, transmission of POPs through the Antarctic food chains.

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1.1 Persistent Organic Pollutants (POPs) in Antarctic Pristine Environment

POPs are toxic in nature, semi-volatile organic compounds that resist photolytic, chemical, biological degradation and have fatal properties. POPs are considered by high lipid solubility and low water solubility. Kallenborn (2006) also described that due to lipophilicity these pollutants bioaccumulate in the food webs and reach the significant levels in the highest predators. Since 2004, it has been topic of discussion for the Stockholm Convention which is a legally binding treaty whose goal is to reduce and finally eliminate causes of these chemicals from the environment (UNEP 2002).

POPs belong to chemical class compounds that result from particular series/families of chemicals, currently used in disease control, agriculture, manufacturing or industrial processes, which contaminate all provinces of the world. Due to long life, POPs may persist for a tremendously long time in the environment and categorized as compounds which can have half-life period running into many years. Jacob (2013) stated that the inclusive quantity of POPs in the environment increases due to the huge disposal of PAH and BFR (brominated flame retardants are organ bromine compounds) materials which arise from chemical plants, combustion of fossil fuels and wide-spread use of pesticides. POPs including organochlorines are used for industrial purposes and pest control, are worldwide spread through the atmosphere and transferred to Polar Regions via cold condensation (Bidleman et al. 1993; Wania and Mackay 1996). According to Fuoco et al. 2009 and Barrie et al. 1992, these pollutants are transported globally through water, air and migratory species, after traveling long distances are deposited far from their original place. Soil, sediment and snow are the recorders of POP levels; they accumulate valuable information for previous environmental and climatic proceedings (Fuoco et al. 1996).

POPs are ubiquitous and have teratogenic effects (Ritter et al. 1995). These pollutants have harmful effects on humans through direct exposure and industrial accidents. POPs exposure for long term can cause allergy and hypersensitivity while short-term exposures of high concentration may result in illness and death. Long-lasting exposure of POPs may also be linked with an extensive range of adverse health and environmental effects. According to Stockholm Convention Secretariat (2011), some POPs are endocrine disrupters and can damage the endocrine system, reproductive system, immune system, central and peripheral nervous system. POPs may exist in different forms like natural and anthropogenic and have been used in large quantities. Ritter et al. (1995) summarized that pollutants like PCBs persist in the environment for long years and may bio-concentrate up to 70,000 fold.

POPs are generally halogenated and chlorinated compounds. The carbon–chlorine bond is stable to hydrolysis and the resistance to degradation of these compounds depends on the number of chlorine substitutions or functional groups (Kannan et al. 1998). Jacob (2013) describes POPs as quite durable and they degrade gradually because of their longer persistence in environment. The polar regions of earth are affected by changes in climate conditions. The anthropogenic levels of carbon dioxide are increasing in the atmosphere at the rate of approximately 1 million tons of carbon dioxide transfer to the world's ocean per hour.

1.2 Source and Distribution of POPs

Industrial sources are the key emitters of POPs in the environment. They can be incineration units, thermal power plants, refinery, etc. However, farm sprays, evaporation from water surfaces, soil or landfills are also contributors of POPs in the environment. These xenobiotics are transported to the Antarctic pristine environment by a complex mechanism involving successful volatilization and condensation from warmer areas towards colder areas, viz., both the poles and the Himalaya. However, in this context it is essential to define the level of POPs concentrations in the colder region, propagation and their modeling in future prospects. Wania et al. 1999 had explained that global cold trapping, fractionation and long-range atmospheric transport are the major sources of POPs to the cold polar regions (Larsson et al. 1992; Montone et al. 2003; Tanabe et al. 1983). Hale et al. 2008, Larsson et al. 1992 witnessed that research stations in Antarctica are also instrumental in adding POPs in colder regions as they act as local point sources. For some extent, natural processes like volcanic eruption are also responsible for releasing of dibenzofurans and dioxins in the atmosphere. The possible sources of PAHs in Antarctica are by-products of hydrocarbon fuel spillage nearby the research stations. Montone et al. (2003) very well studied that comparable level of contamination from sea water of north and south of the Antarctic convergence indicated that the atmosphere was the dominant medium for the long transport of PCBs compounds to the Antarctic, not the water. Impact of research bases and related activities are also local sources of transportation of PCBs in the environment (Risebrough et al. 1990).

1.3 Grasshopper Effect

POPs migrate across the earth by the process called "grasshopper effect". It is frequently a seasonal phenomenon in which POPs evaporate from a warmer region, enter into the atmosphere and are condensed in a comparative colder

region. This process is not just for once rather its cycle of successive evaporations and deposition as per the atmospheric currents. This process intensifies the amount of pollution that travels all the way to Antarctica. According to Hund (2014), this process affects the Arctic region more than the Antarctica. The grasshopper effect helps the pollutants arising from the southern hemisphere to settle at the Antarctic. Precipitation and air-to-sea gas exchange are process by which pollutants enter into the water bodies. A term "Global distillation" is used for the process of migration of pollutants from continent to the ocean. The term was coined by Goldberg (1975) while discussing the migration of DDT.

1.4 Transmission of POPs Through the Antarctic Food Chains

The ecosystems of Antarctic and Arctic have been mainly affected by POPs which have made their way into the food web. Plants, marine planktons and filtering organisms are the key moderators which absorb the nutrients in the water column. These are the food materials for fish. After consumption of these organisms as food, POPs present in them accumulate in their adipose tissue. The concentration of POPs in the adipose tissue goes higher up the food chain, where they can reach levels up to several tens of thousands of times higher than in the surrounding environment. POPs ascend in the food web from fish to birds and reach the large marine mammals including humans at the top of the food chain, at increasing concentrations. Migratory birds also spread POPs at several thousand kilometers from their original source (Figs. 1, 2).

1.5 Classification of POPs

Ritter et al. (1995) described that PAHs and halogenated hydrocarbons were the most important compounds of POP group and organochlorine compounds which have the characteristics resistant to degradation added later in this group and have had the broadest production, use and release. In all halogenated hydrocarbons, organochlorine compounds are also usually the most persistent in nature. Tanabe et al. (1983) have analyzed PCBs and OCPs in Antarctic atmosphere from Japanese Antarctic research stations. The POP levels were previously considered as tremendously low in the southern hemisphere due to the few possible industrial sources and remoteness of Antarctica. According to Kallenborn et al. (2013), more scientists took interest in Antarctica for the research on POPs. There are three common categories of POPs: pesticides, polychlorinated biphenyls (PCB) and polycyclic aromatic hydrocarbons (PAHs).

Ashraf et al. 2013 have stated that aldrin, DDT, endrin, dieldrin, chlordane, mirex, heptachlor, toxaphene, hexachlorobenzene and plychlorinated biphenyls (PCBs) are intentionally produced pollutants. However, polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCSFs) are the unintentionally produced pollutants. According to the Lerche et al. 2002, POPs include pesticides such as γ-hexachlorocyclohexane or 1,1,1-trichloro-2,2-diethane and polychlorinated biphenyls (PCBs), polycyclic

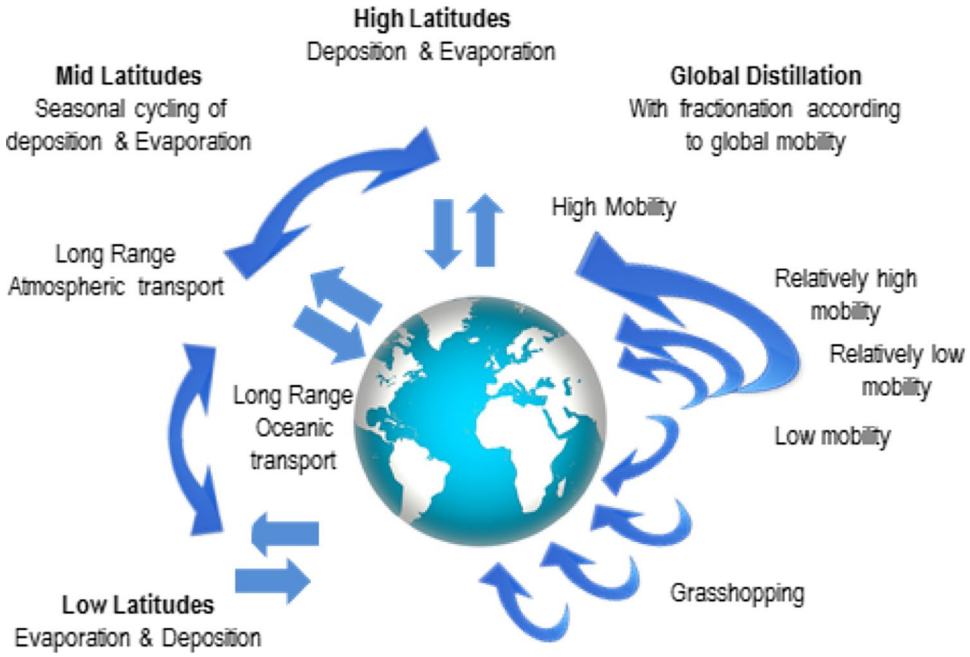

Fig. 1 Grasshopper effect explaining long-range transport of POPs in atmosphere and deposition at polar regions

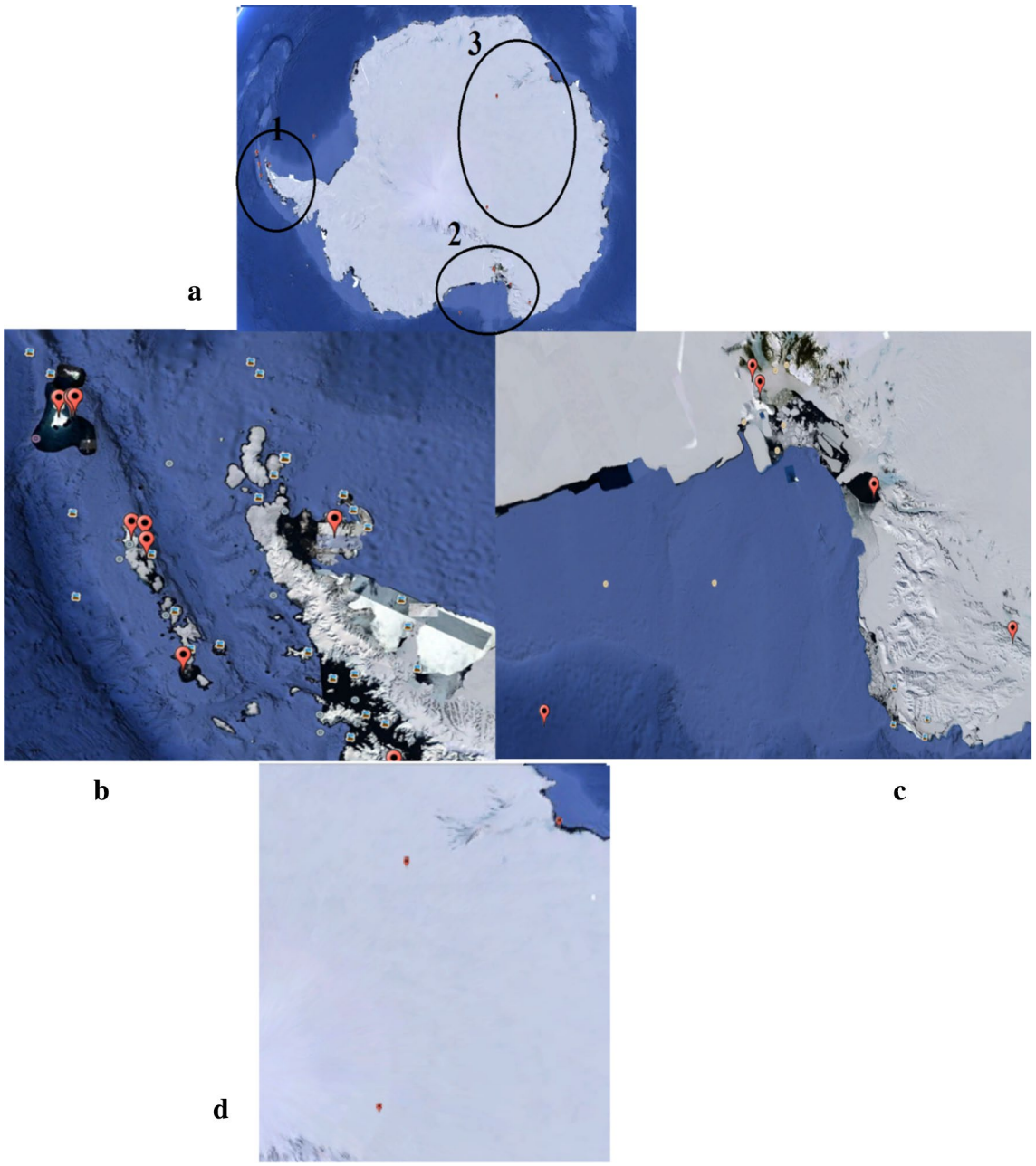

Fig. 2 Geographical presence of POPs (📍) in Antarctica (**a**), **b–d** represent regions in Antarctica where POPs have been reported

aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans, polychlorinated naphthalenes, brominated flame retardants (BFRs), hexabromocyclododecane, polybrominated diphenyl ethers as well as tetrabromobisphenol.

POPs group containing nine organochlorine pesticides, polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), flame retardants, surfactants and nine pesticides were added in the year of 2009; endosulfan was added (2011), hexabromocyclododecane was added (2013) and hexachlorobutadiene, pentachlorophenol and polychlorinated naphthalenes were added (2015) as per Stockholm Convention Secretariat.

1.6 Pesticides

Pesticides are divided in three groups: insecticides, herbicides, and fungicides. According to Iwata et al. 1993 and Simonich and Hites 1995, pesticides like HCH and DDT are released in the tropics and redistributed globally. Over spraying of pesticides directly adds in the atmosphere and

indirectly by the runoff from the farm after the rain. Rain water carries the most of the pesticide sprayed over the crop and takes them with it to the local water bodies and groundwater. Evaporation from the water bodies carry these pollutants to the atmosphere and then start the process of long-range transport. Weber and Goerke (1996) reported that HCB concentration in Antarctic organisms was found to be of the same level as that of organisms which were found in North Sea.

1.7 Dichlorodiphenyltrichloroethane (DDT)

It is a colorless, tasteless, crystalline, and odorless organochlorine compound. It is the most well-known insecticide and was used in World War II for protection of warriors from vector-borne diseases such as malaria and typhus. In many developing nations, it is still used to regulate malaria. The discovery of these insecticides (e.g.: DDT and analog) was supposed to be miracle and a long-lasting solution to pest control. In Antarctic fish, the levels of p,p′-DDE (metabolite of DDT) were studied by Weber and Goerke (1996) in the period of 1987–1991. This study indicated that these pesticides are used constantly in developing nations which exist close to the tropics. Bargagli (2006) has found the presence of DDT in Antarctic organisms, while it is banned globally according to Stockholm Convention on POPs. Chiuchiolo et al. 2004 studied the toxic effect of DDTs on Antarctic organisms like krill, penguins and skuas.

During late austral winter and midsummer (2001–2002), several organochlorine pesticides and brominated diphenyl ethers (BDEs) have been reported in samples including sea ice algae, adult krill and water column plankton juvenile which were collected from the palmer Long Term Ecological Research (LTER) region west of the Antarctic peninsula. The concentration of BDEs has been reported 100–1000 times greater in ice algae and 2–10 times greater in phytoplankton (Chiuchiolo et al. 2004). Marine sediments and invertebrates close to waste water discharge at the American McMurdo base in Antarctica were found with high level of BFRs. Wang et al. (2012) studied the soil samples from Ardley Island and detected that BDE-47 was dominated congeners, whereas BDE-99 and 71 were more plentiful detected congeners. Hale et al. (2008) reported that BDE-209 had limited environmental mobility and was quantitatively detected in sludge, dust and marine sediments near to the Mc-Murdo station.

1.8 Polychlorinated Biphenyls

PCBs have been reported in abiotic and biotic components of the polar environment and the presence of these industrial contaminants influenced the researchers that long-range transport occurred due to their physio-chemical properties. PCBs are commonly used in transformers and capacitors as dielectric fluid which is released by partial combustion of certain pesticides. Effects of anthropogenic activity in the local area have been demonstrated by elevated levels of PCBs in the Antarctic ecosystem. Montone et al. (2003) reported that waste burning and dumping from Antarctic research stations are the causes of PCB emissions in the Antarctic atmosphere.

Choi et al. (2008) confirmed the evidence of local pollution of PCB in the Antarctic atmosphere from Antarctic research stations. Oil burning for producing electricity and domestic heating produce PCBs in the Antarctic research stations. PCB is also produced as a byproduct and released into the Antarctic environment. They have also observed a relatively high level of unusual source in the southern hemisphere known as PCB-11, in air samples, proposing an extensive atmospheric distribution of PCB-11 around the biosphere. PCB-11 was detected at significant stages and in most of the samples it was 20% of the total PCBs.

According to Gambaro et al. (2005), indigenous pollution of PCBs should be partial from the Antarctic research stations and the main influencing issue in Antarctic atmosphere is the long-range atmospheric transport on a worldwide scale. These chemicals are produced by human for beneficial purposes but they cause extensive damage to the environment, ecology and health. Breivik et al. (2007) studied that both PCBs and PBDEs were mainly produced for commercial and industrial purposes. It is recognized that less chlorinated PCBs accumulate less than the highly chlorinated PCBs. Metabolism and excretion are slow for highly chlorinated biphenyls and fast for less chlorinated PCBs. These toxic chemicals are released into the environment through agricultural and industrial processes, where they are readily incorporated into biological systems, especially those of Antarctic marine communities. It has been very well studied that soil has a significant role in the global fate and distribution of PCBs and has been identified as a basin for these toxic chemicals (xenobiotics) from where they can be released into water or air (Meijer et al. 2002).

1.9 Polycyclic Aromatic Hydrocarbon (PAHs)

PAHs are carbon-based compounds are typically colourless, white or pale yellow solids and they are ubiquitous in nature. Their common sources of origin are processing of coal and crude oil, combustion of natural gas, including for heating, combustion of refuse, vehicle traffic, cooking and tobacco smoking, fossil fuel and biomasses burning etc. These toxic chemicals are globally distributed on the earth (Cabrerizo et al. 2014). According to Mackenzie et al. 1982 and Ramdahl 1983, it has been reported that in many organisms,

PAHs are derived by the slow geochemical aromatization (millions of years) of sterols and triterpenes. PAHs persist in Antarctica due to emissions from anthropogenic activities including tourism, research, accidental spills of fuel and volatilization from soils and snow (Cabrerizo et al. 2012; Aislabie et al. 1999; Mazzera et al. 1999). MacDonald et al. (2000) identified natural and anthropogenic PAHs in the environmental samples and their accumulation was found to be more in Antarctic sediments and soils where oil spills have occurred earlier. Jacob (2013) suggested that agricultural fires and cooking also release PAH. PAH toxicity to marine ecosystem is affected by metabolism and photo-oxidation, in the presence of ultraviolet light PCBs that are usually more toxic (Abdel-Shafy and Mansour 2016).

1.10 Toxic Effects of POPs

Several illnesses, disorders and human disease have been caused by POPs. As carcinogens, they cause soft tissue sarcoma, adult onset of leukemia of breast, non-Hodgkin's lymphoma and pancreatic cancer. POPs also cause abnormal sperm, pre-term delivery, miscarriages, shortened lactation period, menstruation complications and low birth weight, behavioral problems, learning disabilities and impaired memory. Persons get exposed to POPs through contaminated foods. Drinking contaminated water and direct contact with chemicals are the routes of less common exposure. They also damage nervous system and disrupt the endocrine system's hormone regulation. Neurologic, behavioral, reproductive, developmental, endocrine, and immunologic adverse health effects have been linked to POPs. They are also linked to metabolic dysfunction, such as insulin resistance obesity and hypertension dyslipidemia (Lee et al. 2011; Penell et al. 2014; Lind et al. 2004).

1.11 Assessment of POPs in Biotic and Abiotic Components of Antarctica

Scientists from different organizations of the world having their permanent research stations in Antarctica have found and estimated varied concentration of POPs in different abiotic (atmosphere, water bodies, sediments, soil, sea ice) and biotic components (mosses, lichens, krill, penguins, skua, etc.). The concentration of reported POPs was found to be highly variable. This was due to the particular characteristics of the areas from where samples were taken. The lowest and the highest concentration of POPs reported in different abiotic and biotic components is summarized in Tables 1, 2, 3, 4, 5, 6, 7, 8, 9, 10. Investigations have also been carried out to study the vertical distribution of PCBs, pesticides and PAHs.

1.11.1 Abiotic Components

See Tables 1, 2, 3, 4 and 5.

1.11.2 Biotic Components

See Tables 6, 7, 8, 9 and 10

1.11.2.1 Effect of POPs on Climate Change The Intergovernmental Panel on Climate Change (IPCC) has agreed that greenhouse gases are the reason for substantial change in earth's climate. Studies have long-established that the mean temperature of the earth increased by 0.6 ± 0.2 °C during the twentieth century (IPCC, 2011). The global changes impact animal species and ecosystem processes (Moe et al. 2013), but they are changing the extent of human exposure to pollutants, changing the risks in the future (Balbus et al. 2013). The Mediterranean region is a susceptible zone with respect to climate change. Several climate-related events, such as higher sea levels, increased frequency of extreme climatic events including intense storms, heavy rainfall events and droughts (Kusangaya et al. 2014; McBean and Ajibade 2009), are probably going to occur. Moreover, the Mediterranean basin is believed as one of the most vulnerable regions of the world to climate change.

Distances of transport and air-surface exchange events are dependent on the surface characteristics as well as on the physical–chemical properties of the compound. Thus, persistent compounds, with a lower vapor pressure, will be preferably deposited in areas closer to the emission source, while those compounds which have higher vapor pressure are more prone of getting carried away farthest from its source of origin (Nadal et al. 2015). Environmental variables such as temperature, wind speed, precipitation, and solar radiations influence directly or indirectly in this process (Gusev et al. 2012). Among these parameters, temperature is one of the key meteorological parameters that impacts global distribution of POPs in the environment more severely (Dalla Valle et al. 2007).

Therefore, it is convincing to understand that global warming is influencing the environmental behavior of POPs by enhancing the volatilization from primary and secondary sources. It also influences their partitioning between soil, sediment, water and atmosphere, including air-surface exchange and wet/dry deposition (Noyes et al. 2009; Teran et al. 2012; Armitage et al. 2011).

Increase in the rainfall can cause a raise of POP deposition onto the soil. Regardless of the limited knowledge of the climate change impacts on the POP occurrence, it has been recommended that the rise in temperature would lead to faster degradation of these chemicals in the aquatic/marine ecosystem, resulting in a reduction of the dietary exposure

Table 1 Occurrence of POPs in atmosphere

S. no	POPs category	Nature of sample	Location	Concentration (pg/m^3)	References
1	PAHs	Atmosphere	Terra Nova Bay	0.001–0.2	Vincenti et al. (2001)
2	PCBs	Marine atmosphere	Admiralty Bay	12.1–42.9	Montone et al. (2001a, b)
3	HCH-α HCH-γ	Air 20 m above from sea level	Neumayer Station	0.36 0.15	Lakaschus et al. (2002)
4	PCBs	Marine atmosphere	Admiralty Bay	12.1–92.6	Montone et al. (2003)
5	HCH-α HCH-γ	Marine atmosphere	Western Antarctica Peninsula	< 0.05–0.49 < 0.02–2.98	Dickhut et al. (2005)
6	HCB	Marine atmosphere	Western Antarctica Peninsula	< 5–32.1	Dickhut et al. (2005)
7	Heptachlor, Heptachlor epoxide	Marine atmosphere	Western Antarctica Peninsula	< 1–19.1 < 0.3–20.7	Dickhut et al. (2005)
8	HCB	Marine atmosphere	61°16′S 55°07′ W 62°11′S 58°63′W 61°18′S 55°05′W	21.9–25.3	Montone et al. (2005)
9	HCH-α HCH-γ	Marine atmosphere	61°16′S 55°07′W 62°11′S 58°63′W 61°18′S 55°05′W	3.3–4.5 < 2.7–4.6	Montone et al. (2005)
10	DDE-p,p′ DDD-p,p′ DDT-p,p′	Marine atmosphere	61°16′S 55°07′W 62°11′S 58°63′W 61°18′S 55°05′W	< 2.5–5.2 < 2.7 < 2.7	Montone et al. (2005)
11	PCBs	Marine atmosphere	61°16′S 55°07′W 62°11′S 58°63′W 61°18′S 55°05′W	52.6–69.9	Montone et al. (2005)
12	PCBs	Atmosphere	Northern Victoria Land	0.63–1.78	Gambaro et al. (2005)
13	PCBs	Atmosphere	King Sejong Station on King George Island	2.10–8.07 0.18–0.91 45.21–117.80 60	Choi et al. (2008)
14	PCBs	Atmosphere	Korean Antarctic Research Station	0.85–3.12	Choi et al. (2008)
15	PCBs	Atmosphere	Antarctic Peninsula	20–43	Bengston Nash (2011)
16	PBDE	Atmosphere	King Sejong Station on King George Island	0.67–2.98	Li et al. (2012) a
17	PCBs	Atmosphere	Terra Nova Bay	0.16–2.07	Piazza et al. (2013)
18	PBDEs	Atmosphere	Terra Nova Bay	0.14–1.69	Piazza et al. (2013)
19	PCBs	Atmosphere	Norwegian Troll Station	0.78–3.68	Kallenborn et al. (2013)
20	PCBs	Atmosphere	Chilean station	1–4	Pozo et al. 2014
21	PCBs	Atmosphere	Chinese Great Wall Station, West Antarctica	0.91–35.9	Wang et al. (2017)
22	PBDEs	Atmosphere	Chinese Great Wall Station, West Antarctica	0.60–16.1	Wang et al. (2017)

PCBs polychlorinated biphenyls, *HCH-α* alpha-hexachlorocyclohexane, *HCH-γ* gamma-Hexachlorocyclohexane, *HCB* hexachlorobenzene, *DDE-p,p′* dichlorodiphenyldichloroethylene, *DDD-p,p′* dichlorodiphenyldichloroethane, *DDT-p,p′* dichlorodiphenyltrichloroethane, *PAHs* polycyclic aromatic hydrocarbons, *PBDEs* polybrominated diphenyl ethers

to POPs (McKone et al. 1996; Macdonald et al. 2005; Ma et al. 2004; Bard 1999).

Finizio et al. (1998) reported for the very first time the potential impact of climate change on POPs, and more specifically on some organochlorine pesticides (DDT, HCHs, chlordane, toxaphene, aldrin). The re-volatilization of α-HCH, DTT and cis-chlordane deposited in water and ice sinks was investigated by Ma et al. 2011. Temperature was found to be an important drive to the global cycling of POPs, through its influence on emissions from primary and secondary sources, gas-particle distributions, reaction rates, air-surface exchange, and global transport (Nadal et al. 2015).

Table 2 Occurrence of POPs in Antarctic water bodies

S. no	POPs category	Nature of sample	Location	Concentration	References
1	PCBs	Surface micro layer, sub surface water	Gerlache Inlet, Ross Sea	427 pg/l 48 pg/l	Fuoco et al. (2005)
2	PAHs	Surface micro layer, sub surface water	Gerlache Inlet, Ross Sea	2300 pg/l 325 pg/l	Fuoco et al. (2005)
3	HCH-α, HCH-γ	Surface water	Western Antarctica Peninsula	1.65–4.54 pg/l 0.9–10.5 pg/l	Dickhut et al. (2005)
4	PCBs	Surface sea water	Ross Sea and Terra Nova Bay	55–84 pg/l 23 pg/l 36–53 pg/l	Fuoco et al. (2009)
5	PAHs	Surface sea water	Ross Sea and Terra Nova Bay	122–330 pg/l 328–360 pg/l 96–281 pg/l	Fuoco et al. (2009)
6	PCBs	Lake water	Victoria Land	46–143 pg/l	Vecchiato et al. (2015a, b)
7	PBDEs	Lake water	Victoria Land	60–151 pg/l	Vecchiato et al. (2015a, b)
8	Dichlorvos, Propoxur, Dimethoate, Carbofuran, BHC, Atrazine, Diazinon, Lindane, Phosphamidon, Methyl-parathion, Fenitrothion, Aldrin, Malathion, Fenthion, Parathion, Endosulfan, Dieldrin, o,p DDT, Ethion, p,p DDT, Captafol, Phosalone, Permethrin, Cypermethrin, Fenvalerate, Deltamethrin, 2,4-D, Isoproturon, Monocrotophos	Water sample	Fisher Island of Larsemann Hills	BDL (detection limit-0.0002 mg/l)	Bharti and Niyogi, (2015)

PCBs polychlorinated biphenyls, *PAHs* polycyclic aromatic hydrocarbons, *HCH-α* alpha-hexachlorocyclohexane, *HCH-γ* gamma-hexachlorocyclohexane, *BHC* benzene hexachloride, *DDT-p,p′* dichlorodiphenyltrichloroethane, *2,4-D* dichlorophenylacetic acid, *PBDEs* polybrominated diphenyl ethers

2 Conclusion and Path Forward

The application of sophisticated instruments has greatly improved the understanding of POPs estimation in terrestrial and marine ecosystem in Antarctica. With the help of these instruments, scientist can detect POPs even at picogram level which are very much required. POPs are found to be highly varied between different regions of the continent and within region, varying primarily with climate change and biogeochemical control of the global cycling and fate of these xenobiotics. Occurrence of POPs in Antarctic environment and their accumulation into Antarctic biodiversity may cause problems such as mutagenicity, genotoxicity, reproductive disorders, disruption of the immune system and interference with the development of the young. To decrease the risk of POPs, we need more efficient monitoring system at base levels which checks and monitors the emission of these pollutants.

Developing countries can contribute in preventing the emission of POPs, especially pesticides by improving their regulations and policies, strengthening poorly monitored pesticide regulations, effective monitoring by apex agencies for banned pesticides, proper training for the use of pesticides, its dosages according to the pests and crops, use of integrated pest managements (IPM), etc. These steps could be preliminary towards monitoring the emission and thereby limiting the global distillation/propagation of these pollutants and migration in the polar regions.

Opting for clean energy would be also an appreciable step. Usage of coal in the power plants is one of the key emission sources. Power plants emit PCBs; they are very much persistent in the environment. Developing countries are coming forward to help the underdeveloped/developing nations to have clean energy options like nuclear power plants and solar power plants. These steps would help in controlling emission and transportation of these xenobiotics in atmosphere and thereby into the Antarctic ecosystem.

Research in Antarctic is also at the cost of its pristine ecosystem. Use of generators, vehicle, helicopters, flights, ships and other modes of transport which use fossil fuels

Table 3 Occurrence of POPs in Antarctic sediments

S. no	POPs category	Nature of sample	Location	Concentration	References
1	PCBs	Marine sediment	Admiralty Bay	0.47–2.47 ng/g dry wt	Montone et al. (2001a, b)
2	PCBs	Marine sediment	Winter Quarters Bay	250–4300 ng/g	Crockett and White (2003)
3	PAHs	Marine sediment	Winter Quarters Bay	360–13,000 ng/g	Crockett and White (2003)
4	PAHs	Marine surface sediment	Admiralty Bay around the Brazilian Station	9.45–270.5 ng/g	Martins et al. (2004)
5	PCBs	Marine sediment	Scott Base McMurdo Base Turtle Rock, Cape Evans	< 5–40 µg/g 220–373 ng/g < 5 ng/g	Negri et al. (2006)
6	PAHs	Marine sediment	Scott Base McMurdo Sewage Outfall Turtle Rock, Cape Evans	110–370 ng/g 1100–2100 ng/g 70–360 ng/g	Negri et al. (2006)
7	PAHs	Marine sediment	Scott Base McMurdo Sewage Outfall Turtle Rock, Cape Evans	15–30 ng/g 270–550 ng/g 10–30 ng/g	Negri et al. (2006)
8	PAHs	Marine benthic sediment	Mc-Murdo Station	1077–2053 ng/g 621–5024 ng/g	Kim et al. (2006)
9	PAHs	Marine sediment	Potter Cove (South Shetland Islands)	28–312 ng/g dry wt 36–1908 ng/g dry wt	Curtosi et al. (2007)
10	PAHs	Marine sediment	James Ross Island	20–50 ng/g	Klanova et al. (2008)
11	PCBs	Marine sediment	James Ross Island	0.4–0.5 ng/g	Klanova et al. (2008)
12	PBDEs	Sediment	Mc-Murdo Sound	< 677 ng/g (TOC basis)	Hale et al. (2008)
13	HCH-γ	Marine sediment	James Ross Island	0.2–0.3 ng/g	Klanova et al. (2008)
14	HCB	Marine sediment	James Ross Island	2–4 ng/g	Klanova et al. (2008)
15	DDTs	Marine sediment	James Ross Island	0.3–0.6 ng/g	Klanova et al. (2008)
16	PCBs	Sediment	James Ross Island	0.32–0.83 ng/g	Klanova et al. (2008)
17	HCH	Sediment	James Ross Island	0.14–0.76 ng/g	Klanova et al. (2008)
18	DDTs	Sediment	James Ross Island	0.19–1.15 ng/g	Klanova et al. (2008)
19	HCB	Sediment	James Ross Island	0.95–4.0 ng/g	Klanova et al. (2008)
20	PCB	Sediment	James Ross Island	0.21–1.08 ng/g	Klanova et al. (2008)
21	PAHs	Sediment	James Ross Island	1.4–205 ng/g	Klanova et al. (2008)
22	HCB	Sediment	West Antarctic Peninsula	2–130 pg/g dw	Zhang et al. (2013)
23	p,p′-DDE	Sediment	West Antarctic Peninsula	20.0 pg/g dw	Zhang et al. (2013)
24	PCBs	Lake sediment	Victoria Land	10–634 pg/g	Vecchiato et al. (2015a, b)
25	PBDEs	Lake sediment	Victoria Land	193–1682 pg/g	Vecchiato et al. (2015a, b)
26	HCBs	Sediment	King George Island	57.7 pg/g dw	Zhang et al. (2015)
27	HCHs	Sediment	King George Island	3.05 pg/g dw	Zhang et al. (2015)
28	DDTs	Sediment	King George Island	577 pg/g dw	Zhang et al. (2015)
29	α-HCH	Sediment	King George Island	3.05 pg/g dw	Zhang et al. (2015)
30	p,p′-DDE	Sediment	King George Island	38.1 pg/g dw	Zhang et al. (2015)
31	p,p′-DDT	Sediment	King George Island	313 pg/g dw	Zhang et al. (2015)

PCBs polychlorinated biphenyls, *PAHs* polycyclic aromatic hydrocarbons, *PBDEs* polybrominated diphenyl ethers, *HCH-α* alpha-hexachlorocyclohexane, *HCB* hexachlorobenzene, *DDT* dichlorodiphenyltrichloroethane, *HCH* hexachlorocyclohexane

are also partial contributor in the local Antarctic regions, especially nearby stations. Use of personal care products, physical contaminants, plastic, construction material, etc. if not monitored effectively would surely leave the chemical footprints. Food supplies of Antarctic researchers probably vegetables are very much prone to carry pesticide residues and could also be a contributor of POPs in the Antarctic environment.

A comprehensive collaborative research effort focusing on the above factors is urgently required to identify the gap

Table 4 Occurrence of POPs in Antarctic soil

S. no	POPs category	Nature of sample	Location	Concentration	References
1	PCBs	Soil	Russian Stations	0.2–157 ng/g dry wt	Negoita et al. (2003)
2	HCHs	Soil	Russian Stations	0.9–43.1 ng/g dry wt	Negoita et al. (2003)
3	HCB	Soil	Russian Stations	0.02–25.3 ng/g dry wt	Negoita et al. (2003)
4	p,p′-DDE, p,p′-DDT	Soil	Russian Stations	0.03–3.2 ng/g dry wt 0.04–14.9 ng/g dry wt	Negoita et al. (2003)
5	PCBs	Soil	Victoria Land	0.4–0.6 ng/g dry wt	Borghini et al. (2005)
6	p,p′-DDE, p,p′-DDT	Soil	Victoria Land	0.05–0.09 ng/g dry wt < 0.005–0.02 ng/g dry wt	Borghini et al. (2005)
7	HCB	Soil	Victoria Land	0.034–0.17 ng/g dry wt	Borghini et al. (2005)
8	HCH-α, HCH-γ	Soil	Victoria Land	0.03 ng/g dry wt < 0.01(LOD)	Borghini et al. (2005)
9	PAHs	Soil	Mc-Murdo Station	1724–46,479 ng/g 664–74,267 ng/g	Kim et al. (2006)
10	PAHs	Soil	Potter Cove (South Shetland Islands)	10–1182 ng/g dry wt 12–552 ng/g dry wt	Curtosi et al. (2007)
11	PCBs	Soil sediment from lake and river	James Ross Island	0.5–2 ng/g 0.4–0.8 ng/g	Klanova et al. (2008)
12	HCH-γ	Soil sediment from lake and river	James Ross Island	0.5–1.3 ng/g 0.1–0.7 ng/g	Klanova et al. (2008)
13	DDTs	Soil sediment from lake and river	James Ross Island	0.5–3.7 ng/g 0.1–1.3 ng/g	Klanova et al. (2008)
14	HCB	Soil sediment from lake and river	James Ross Island	4–8 ng/g 1–4 ng/g	Klanova et al. (2008)
15	PAHs	Soil sediment from lake and river	James Ross Island	35–170 ng/g 5–200 ng/g	Klanova et al. (2008)
16	PCBs	Soil sample	James Ross Island	0.51–1.82 ng/g	Klanova et al. (2008)
17	HCH	Soil sample	James Ross Island	0.49–1.34 ng/g	Klanova et al. (2008)
18	p,p-DDT, p,p-DDE and p,p-DDD	Soil sample	James Ross Island	0.51–3.68 ng/g	Klanova et al. (2008)
19	HCB	Soil sample	James Ross Island	2.41–7.75 ng/g	Klanova et al. (2008)
20	PCB	Soil sample	James Ross Island	0.59–2.24 ng/g	Klanova et al. (2008)
21	PAH	Soil sample	James Ross Island	34.9–171 ng/g	Klanova et al. (2008)
22	PCBs	Soil sample	West Antarctica	0.008–0.03 ng/g dw	Park et al. (2010)
23	PCBs	Soil SURFACE (1 cm)	West Antarctica	0.012–0.32 ng/g dw	Cabrerizo et al. (2012)
24	HCB	Soil surface (1 cm)	West Antarctica	0.07 ng/g dw	Cabrerizo et al. (2012)
25	p,p′-DDE	Soil surface (1 cm)	West Antarctica	0.20 ng/g dw	Cabrerizo et al. (2012)
26	PAH	Soil surface (1 cm)	West Antarctica	0.30–4.6 ng/g dw	Cabrerizo et al. (2012)
27	PCBs	Soil surface (0–5 cm)	West Antarctica	0.005–0.14 ng/g dw	Cabrerizo et al. (2012)
28	HCB	Soil surface (0–5 cm)	West Antarctica	0.004 ng/g dw	Cabrerizo et al. (2012)
29	p,p′-DDE	Soil surface (0–5 cm)	West Antarctica	0.002 ng/g dw	Cabrerizo et al. (2012)
30	PAHs	Soil surface (0–5 cm)	West Antarctica	0.16–3.51 ng/g dw	Cabrerizo et al. (2012)
31	PCBs	Soil	Victoria Land	112–561 pg/g	Vecchiato et al. (2015a, b)
32	PBDEs	Soil	Victoria Land	0.77–33 ng/g	Vecchiato et al. (2015a, b)
33	HCBs	Soil	King George and Adley Island	67.9–108 pg/g dw	Zhang et al. (2015)
34	HCHs	Soil	King George and Adley Island	6.25–31 pg/g dw	Zhang et al. (2015)
35	DDTs	Soil	King George and Adley Island	18.8–277 pg/g dw	Zhang et al. (2015)
36	α-HCH	Soil	King George and Adley Island	5.01–15.2 pg/g dw	Zhang et al. (2015)
37	γ-HCH	Soil	King George and Adley Island	11.9 pg/g dw	Zhang et al. (2015)

Table 4 (continued)

S. no	POPs category	Nature of sample	Location	Concentration	References
38	p,p′-DDE	Soil	King George and Adley Island	10.6–181 pg/g dw	Zhang et al. (2015)
39	p,p′-DDT	Soil	King George and Adley Island	4.19–44.8 pg/g dw	Zhang et al. (2015)
40	PCBs	Soil	Chinese Antarctic Zhongshan Station	A-8.20 ± 7.72 pg/g C-3.41 ± 1.97 pg/g	Mwangi et al. (2016)
41	PCDD/Fs	Soil	Chinese Antarctic Zhongshan Station	A-18.5 ± 49.5 pg/g C-3.73 ± 3.51 pg/g	Mwangi et al. (2016)
42	PBDD/Fs	Soil	Chinese Antarctic Zhongshan Station	A-2.62 ± 6.95 pg/g C-0.248 ± 0.357 pg/g	Mwangi et al. (2016)
43	PBDEs	Soil	Chinese Antarctic Zhongshan Station	A-154 ± 109 pg/g C-136 ± 67.8 pg/g	Mwangi et al. (2016)

PCBs polychlorinated biphenyls, *DDE-p,p′* dichlorodiphenyldichloroethylene, *DDT-p,p′* dichlorodiphenyltrichloroethane, *HCB* hexachlorobenzene, *HCH-α* alpha-hexachlorocyclohexane, *HCH-γ* gamma-hexachlorocyclohexane, *PAHs* polycyclic aromatic hydrocarbons, *HCH-α* alpha-hexachlorocyclohexane, *PCDD/Fs* polychlorinated dibenzo-p-dioxins and dibenzofurans, *PBDD/Fs* polybrominated dibenzo-p-dioxins and dibenzofurans, *PBDEs* polybrominated diphenyl ethers

Table 5 Occurrence of POPs in Antarctic sea ice/snow

S. no	POPs category	Nature of sample	Location	Concentration (pg/l)	References
1	HCH-α, HCH-γ	Sea ice	Western Antarctica Peninsula	< 0.04–2.18 3.6–5.7	Dickhut et al. (2005)
2	Heptachlor, Heptachlor epoxide	Sea ice	Western Antarctica Peninsula	< 2.5–5.8 < 0.6–2.2	Dickhut et al. (2005)
3	PCBs	Snow	Victoria Land	110–580	Vecchiato et al. (2015a, b)
4	PBDEs	Snow	Victoria Land	130–340	Vecchiato et al. (2015a, b)

HCH-α alpha-hexachlorocyclohexane, *HCH-γ* gamma-hexachlorocyclohexane, *PBDEs* polybrominated diphenyl ethers

Table 6 Occurrence of POPs in Antarctic Mosses

S. no	POPs category	Nature of sample	Location	Concentration	References
1	PCBs	Mosses	Victoria Land	23–34 ng/g dry wt	Borghini et al. (2005)
2	p,p′-DDE, p,p′-DDT	Mosses	Victoria Land	1.1–7.9 ng/g dry wt 0.6–0.9 ng/g dry wt	Borghini et al. (2005)
3	HCB	Mosses	Victoria Land	0.9–1.9 ng/g dry wt	Borghini et al. (2005)
4	HCH-α, HCH-γ	Mosses	Victoria Land	0.4–4 ng/g dry wt 0.2–1.6 ng/g dry wt	Borghini et al. (2005)
5	HCB	Mosses	King George Island	811 ± 180 pg/g dw	Cipro et al. (2011)
6	HCH	Mosses	King George Island	1200 ± 810 pg/g dw	Cipro et al. (2011)
7	DDT	Mosses	King George Island	1620 ± 580 pg/g dw	Cipro et al. (2011)
8	PCBs	Mosses	West Antarctica	0.04–0.76 ng/g dry wt	Cabrerizo et al. (2012)
9	HCB	Mosses	West Antarctica	0.021–0.12 ng/g dry wt	Cabrerizo et al. (2012)
10	p,p′-DDE	Mosses	West Antarctica	0.005–0.04 ng/g dry wt	Cabrerizo et al. (2012)
11	PAH	Mosses	West Antarctica	4.4–34 ng/g dry wt	Cabrerizo et al. (2012)
12	HCB	Mosses	King George Island	139–663 pg/g dw	Zhang et al. (2015)
13	HCH	Mosses	King George Island	21.1–162 pg/g dw	Zhang et al. (2015)
14	DDTs	Mosses	King George Island	20.1–324 pg/g dw	Zhang et al. (2015)
15	HCH-α	Mosses	King George Island	9.48–83.6 pg/g dw	Zhang et al. (2015)
16	HCH-γ	Mosses	King George Island	78.7 pg/g dw	Zhang et al. (2015)
17	p,p′-DDE	Mosses	King George Island	19.9–228 pg/g dw	Zhang et al. (2015)
18	p,p′-DDT	Mosses	King George Island	50.8 pg/g dw	Zhang et al. (2015)

PCBs polychlorinated biphenyls, *DDE-p,p′* dichlorodiphenyldichloroethylene, *DDT-p,p′* dichlorodiphenyltrichloroethane, *HCB* hexachlorobenzene, *HCH-α* alpha-hexachlorocyclohexane, *HCH-γ* gamma-hexachlorocyclohexane

Table 7 Occurrence of POPs in Antarctic Lichen

S. no	POPs category	Nature of sample	Location	Concentration	References
1	PCBs	Lichen	Russian Stations	3.3 ng/g dry wt	Negoita et al. (2003)
2	HCHs	Lichen	Russian Stations	59.7 ng/g dry wt	Negoita et al. (2003)
3	HCB	Lichen	Russian Stations	0.3 ng/g dry wt	Negoita et al. (2003)
4	p,p′-DDE, p,p′-DDT	Lichen	Russian Stations	0.40 ng/g dry wt 0.71 ng/g dry wt	Negoita et al. (2003)
5	PCBs	Lichen	West Antarctica	0.005–0.004 ng/g dry wt	Park et al. (2010)
6	HCB	Lichen	King George Island	141 ± 100 pg/g dw	Cipro et al. (2011)
7	HCH	Lichen	King George Island	205 ± 80 pg/g dw	Cipro et al. (2011)
8	DDT	Lichen	King George Island	353 ± 40 pg/g dw	Cipro et al. (2011)
9	PCBs	Lichen	West Antarctica	0.043–0.61 ng/g dry wt	Cabrerizo et al. (2012)
10	HCB	Lichen	West Antarctica	0.002–0.31 ng/g dry wt	Cabrerizo et al. (2012)
11	p,p′-DDE	Lichen	West Antarctica	0.003–0.01 ng/g dry wt	Cabrerizo et al. (2012)
12	PAH	Lichen	West Antarctica	15–40 ng/g dry wt	Cabrerizo et al. (2012)
13	HCB	Lichen	King George Island	207–632 pg/g dw	Zhang et al. (2015)
14	HCH	Lichen	King George Island	58.4–293 pg/g dw	Zhang et al. (2015)
15	DDTs	Lichen	King George Island	25.5–125 pg/g dw	Zhang et al. (2015)
16	HCH-α	Lichen	King George Island	26.1–96.9 pg/g dw	Zhang et al. (2015)
17	HCH-γ	Lichen	King George Island	19.6–52.1 pg/g dw	Zhang et al. (2015)
18	p,p′-DDE	Lichen	King George Island	25.5–66.1 pg/g dw	Zhang et al. (2015)
19	p,p′-DDT	Lichen	King George Island	31.6 pg/g dw	Zhang et al. (2015)
20	PCBs	Lichen	Chinese Antarctic Zhongshan Station	A-16.4 pg/g B-7.93 pg/g E-26.2 pg/g	Mwangi et al. (2016)
21	PCDD/Fs	Lichen	Chinese Antarctic Zhongshan Station	A-1.87 pg/g B-1.77 pg/g E-2.00 pg/g	Mwangi et al. (2016)
22	PBDD/Fs	Lichen	Chinese Antarctic Zhongshan Station	A-13.3 pg/g B-16.2 pg/g E-5.70 pg/g	Mwangi et al. (2016)
23	PBDEs	Lichen	Chinese Antarctic Zhongshan Station	A-18,300 pg/g B-25,700 pg/g E-7240 pg/g	Mwangi et al. (2016)

PCBs polychlorinated biphenyls, *HCH* hexachlorocyclohexane, *HCB* hexachlorobenzene, *DDE-p,p′* dichlorodiphenyldichloroethylene, *DDT-p,p′* dichlorodiphenyltrichloroethane, *PCDD/Fs* polychlorinated dibenzo-p-dioxins and dibenzofurans, *PBDD/Fs* polybrominated dibenzo-p-dioxins and dibenzofurans, *PBDEs* polybrominated diphenyl ethers

Table 8 Occurrence of POPs in Antarctic Krill

S. no	POPs category	Nature of sample	Location	Concentration	References
1	HCB	Krill	Ross Sea	0.37 ± 0.17 ng/g wet wt	Corsolini et al. (2002)
2	PCBs	Krill	Ross Sea	167.40 ± 84.69 ng/g wet wt	Corsolini et al. (2002)
3	DDE-p,p′	Krill	Ross Sea	0.86 ± 0.98 ng/g wet wt	Corsolini et al. (2002)
4	PCBs	Krill	Ross Sea	0.03 ng/g wet wt 0.88 ng/g lipid wt	Kumar et al. (2002)
5	PCDD/DF	Krill	Ross Sea	0.85×10^{-3} ng/g wet wt, 0.027 ng/g lipid Wt	Kumar et al. (2002)
6	HCB	Krill	Elephant island, Weddel sea and Shetland Islands	1.0 ng/g	Goerke et al. (2004)
7	DDE-p,p′	Krill	Elephant island, Weddel sea and Shetland Islands	0.7 ng/g	Goerke et al. (2004)
8	PCB-153 PCB-138 PCB-180	Krill	Elephant island, Weddel sea and Shetland islands	0.1 ng/g 0.08 ng/g 0.04 ng/g	Goerke et al. (2004)
9	Mirex	Krill	Elephant island, Weddel sea and Shetland Islands	0.18 ng/g	Goerke et al. (2004)
10	PCBs	Krill	Ross Sea in Terra Nova Bay	1.67 ng/g wet wt (whole body)	Corsolini et al. (2006)
11	HCHs	Krill	Ross Sea in Terra Nova Bay	0.28 ng/g wet wt	Corsolini et al. (2006)
12	HCB	Krill	Ross Sea in Terra Nova Bay	0.23 ng/g wet wt	Corsolini et al. (2006)
13	DDTs	Krill	Ross Sea in Terra Nova Bay	0.18 ng/g wet wt	Corsolini et al. (2006)
14	PBDEs	Krill	Ross Sea in Terra Nova Bay	0.20 ng/g wet wt (whole body), 5.60 ng/g lipid wt	Corsolini et al. (2006)
15	DDE-p,p′, DDTs	Krill	12 sampling stations (NE sector)	0.13 ng/g wet wt, 2.6 ng/g lipid wt 0.18 ng/g wet wt, 3.5 ng/g lipid wt	Bengtson Nash et al. (2008)
16	HCB	Krill	12 sampling stations (NE sector)	0.2 ng/g wet wt, 4.37 ng/g lipid wt	Bengtson Nash et al. (2008)
17	HCH-α, HCH-β, HCH-γ	Krill	12 sampling stations (NE sector)	0.01 ng/g wet wt, 0.28 ng/g lipid wt, 0.01 ng/g wet wt, 0.16 ng/g lipid wt, 0.01 ng/g wet wt, 0.13 ng/g lipid wt	Bengtson Nash et al. (2008)
18	PBDE-99 PBDE-47	Krill	12 sampling stations (NE sector)	0.03 ng/g wet wt, 0.67 ng/g lipid wt, 0.007 ng/g wet wt, 0.35 ng/g lipid wt	Bengtson Nash et al. (2008)
19	PCBs	Krill	12 sampling stations (NE sector)	0.05 ng/g wet wt 1.2 ng/g lipid wt	Bengtson Nash et al. (2008)

DDE-p,p′ dichlorodiphenyldichloroethylene, *DDT-p,p′* dichlorodiphenyltrichloroethane, *HCB* hexachlorobenzene, *HCH* hexachlorocyclohexane, *HCH-α* alpha-hexachlorocyclohexane, *HCH-β* β-hexachlorocyclohexane, *HCH-γ* gamma-hexachlorocyclohexane, *PBDEs* polybrominated diphenyl ethers, *PCBs* polychlorinated biphenyls, *PCDD/Fs* polychlorinated dibenzo-p-dioxins and dibenzofurans)

Table 9 Occurrence of POPs in Antarctic Adelie Penguin

S. no	POPs category	Sample type	Location	Concentration	References
1	PCBs	Adelie penguin eggs (unhatched, $n = 5$)	Edmonson Point (74°20′56.7″S and 165°08′10.03″E)	3.3 ng/g wet wt, 30 ng/g lipid wt	Kumar et al. (2002)
2	PCDD/DF	Adelie penguin eggs (unhatched, $n = 5$)	Edmonson Point (74°20′56.7″S and 165°08′10.03″E)	2.6×10^{-3} ng/g wet wt, 0.02 ng/g lipid wt	Kumar et al. (2002)
3	DDE p,p′	*P. Adeliae*	Waters around Elephant Island	3.5 ng/g	Goerke et al. (2004)
4	HCB	P. Adeliae	Waters around Elephant Island	25 ng/g	Goerke et al. (2004)
5	PCB-153	P. Adeliae	Waters around Elephant Island	2 ng/g	Goerke et al. (2004)
6	Mirex	*P. Adeliae*	Waters around Elephant Island	0.6 ng/g	Goerke et al. (2004)
7	PBDEs	Penguin(eggs)	Ross Sea in Terra Nova	0.29 ± 031 ng/g wet wt	Corsolini et al. (2006)
8	PCBs	Penguin eggs	Ross Sea in Terra Nova Bay	24.9 ± 21.6 ng/g wet wt	Corsolini et al. (2006)
9	DDE p,p′	Adélie penguin blood, Gentoo penguin blood, Chinstrap penguin blood	King George Island, Lenie Field Station, Admiralty Bay	8.2 ± 3.3 ng/g wet wt 6.8 ± 4.2 ng/g wet wt 4 ± 3.1 ng/g wet wt	Corsolini et al. (2007)
10	HCB	Adélie penguin blood, Gentoo penguin blood, Chinstrap penguin blood	King George Island, Lenie Field Station, Admiralty Bay	6.7 ± 6.1 ng/g wet wt 3.6 ± 1.9 ng/g wet wt 2.7 ± 1.4 ng/g wet wt	Corsolini et al. (2007)
11	PBDEs	Adélie penguin blood, Gentoo penguin blood, Chinstrap penguin blood	King George Island, Lenie Field Station, Admiralty Bay	291 ± 477 ng/g wet wt 108 ± 105 ng/g wet wt 117 ± 108 ng/g wet wt	Corsolini et al. (2007)
12	PCBs	Adélie penguin blood, Gentoo penguin blood, Chinstrap penguin blood	King George Island, Lenie Field Station, Admiralty Bay	227 ± 363 ng/g wet wt 201 ± 153 ng/g wet wt 719 ± 1264 ng/g wet wt	Corsolini et al. (2007)
13	PCBs	Adélie penguin blood, Gentoo penguin blood, Chinstrap penguin blood	King George Island, Lenie Field Station, Admiralty Bay	9.8 ± 3.8 ng/g wet wt 4.5 ± 2.4 ng/g wet wt 3.4 ± 1.6 ng/g wet wt	Corsolini et al. (2007)
14	DDE p,p′	Adelie penguin eggs	Palmer Archipelago Cape Crozier, Ross Island	58.5–755 ng/g lipid wt 73.0–176 ng/g lipid wt	Geisz et al. (2008)
15	HCB	P. adeliae	Hop Island (68°09′S, 58°27′W)	153 ng/g	Van den Brink et al. (2011)
16	PCBs	P. adeliae	Hop Island (68°09′S, 58°27′W)	62 ng/g	Van den Brink et al. (2011)
17	HCB	Penguin (Pygoscelis adeliae)	Ross Sea (East Antarctica)	4.74 ± 4.11 ng/g	Corsolini et al. (2011)
18	p,p′-DDE	Penguin (Pygoscelis adeliae)	Ross Sea (East Antarctica)	4.27 ± 9.96 ng/g	Corsolini et al. (2011)
19	PCBs	Penguin (Pygoscelis adeliae)	Ross Sea (East Antarctica)	21.99 ± 25.58 ng/g	Corsolini et al. (2011)
20	HCB	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	7.64 ± 1.80 ng/g	Corsolini et al. (2011)
21	p,p′-DDE	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	18.95 ± 9.73 ng/g	Corsolini et al. (2011)
22	o,p′-DDE	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	1.00 ± 1.07 ng/g	Corsolini et al. (2011)
23	p,p′-DDD	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.68 ± 0.63 ng/g	Corsolini et al. (2011)
24	o,p′-DDD	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	1.05 ± 2.47 ng/g	Corsolini et al. (2011)
25	o,p′-DDT	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.74 ± 1.25 ng/g	Corsolini et al. (2011)
26	p,p′-DDT	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.49 ± 0.51 ng/g	Corsolini et al. (2011)

Table 9 (continued)

S. no	POPs category	Sample type	Location	Concentration	References
27	α-HCH	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.11 ± 0.05 ng/g	Corsolini et al. (2011)
28	β-HCH	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.59 ± 0.79 ng/g	Corsolini et al. (2011)
29	γ-HCH	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.37 ± 0.29 ng/g	Corsolini et al. (2011)
30	λ-HCH	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	0.74 ± 0.41 ng/g	Corsolini et al. (2011)
31	HCH	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	1.81 ± 1.23 ng/g	Corsolini et al. (2011)
32	PCBs	Penguin (Pygoscelis adeliae)	Brainsfield Strait (West Antarctica)	12.03 ± 3.91 ng/g	Corsolini et al. (2011)
33	DL-PCBs	Penguin	King George Island	154 pg/g dw	Wolschke et al. (2015)
34	PBDEs	Penguin	King George Island	6.2 pg/g dw	Wolschke et al. (2015)
35	HCB	Penguin (*Pygoscelis* Sp.)	(62°10′S, 58°26′W)	0.30–132.2 ng/g	Montone et al. (2016)
36	PCBs	Penguin (*Pygoscelis* Sp.)	(62°10′S, 58°26′W)	221–1115 ng/g	Montone et al. (2016)
37	PAHs	Penguin (*Pygoscelis* Sp.)	(62°10′S, 58°26′W)	60.1–238.7 ng/g	Montone et al. (2016)
38	HCB	Penguin (*Pygoscelis* Sp.)	(62°11′S, 58°17′W)	24.0–49.1 ng/g	Montone et al. (2016)
39	PCBs	Penguin (*Pygoscelis* Sp.)	(62°11′S, 58°17′W)	114–325 ng/g	Montone et al. (2016)
40	PAHs	Penguin (*Pygoscelis* Sp.)	(62°11′S, 58°17′W)	76.7–202.3 ng/g	Montone et al. (2016)
41	PCBs	Adelie Penguin	Chinese Antarctic Zhongshan Station	144,000 pg/g	Mwangi et al. (2016)
42	PCDD/Fs	Adelie Penguin	Chinese Antarctic Zhongshan Station	434 pg/g	Mwangi et al. (2016)
43	PBDEs	Adelie Penguin	Chinese Antarctic Zhongshan Station	2190 pg/g	Mwangi et al. (2016)

DDE-p,p′ dichlorodiphenyldichloroethylene, *HCB* hexachlorobenzene, *PBDEs* polybrominated diphenyl ethers, *PCBs* polychlorinated biphenyls, *PCDD/Fs* polychlorinated dibenzo-p-dioxins and dibenzofurans)

Table 10 Occurrence of POPs in Antarctic Skuas

S. no	POPs category	Nature of sample	Location	Concentration	References
1	PCBs	South polar skua eggs ($n = 5$)	Terra Nova Bay	139 ng/g wet wt, 1440 ng/g lipid wt	Kumar et al. (2002)
2	PCDD/DF	South polar skua eggs ($n = 5$)	Terra Nova Bay	0.02 ng/g wet wt, 0.18 ng/g lipid wt	Kumar et al. (2002)
3	HCHβ-	South polar skuas blood	Svarthamaren in Dronning Maud Land	149.22 ng/g wet wt, < 100 ng/g wet wt	Bustnes et al. (2006)
4	HCB	South polar skuas blood	Svarthamaren in Dronning Maud Land	7.2 ng/g wet wt, 2300 ng/g lipid wt	Bustnes et al. (2006)
5	DDE-p,p′	South polar skuas blood	Svarthamaren in Dronning Maud Land	6.8 ng/g wet wt 2000 ng/g lipid wt	Bustnes et al. (2006)
6	PCBs	South polar skuas blood	Svarthamaren in Dronning Maud Land	9.0 ng/g wet wt, 2700 ng/g lipid wt	Bustnes et al. (2006)
7	Mirex	South polar skuas blood	Svarthamaren in Dronning Maud Land	20.7 ng/g wet wt, 6500 ng/g lipid wt	Bustnes et al. (2006)
8	DDTs	Brown skua fat tissue, Penguins fat tissue, Antarctic tern fat tissue, Blue-eyed shag fat tissue, Snowy sheathbill fat tissue	Brazilian and Polish Antarctic Station on King George Island	6118 ± 3813 ng/g lipid wt, 193 ± 16 ng/g lipid wt, 524 ± 205 ng/g lipid wt, 374 ng/g lipid wt 468 ng/g lipid wt	Taniguchi et al. (2008)
9	HCB	Brown skua fat tissue, Penguins fat tissue, Antarctic tern fat tissue, Blue-eyed shag fat tissue, Snowy sheathbill fat tissue	Brazilian and Polish Antarctic Station on King George Island	573 ± 278 ng/g lipid wt, 373 ± 177 ng/g lipid wt, 601 ± 256 ng/g lipid wt, 161 ng/g lipid wt 282 ng/g lipid wt	Taniguchi et al. (2008)
10	HCH	Brown skua fat tissue, Penguins fat tissue, Antarctic tern fat tissue, Blue-eyed shag fat tissue, Snowy sheathbill fat tissue	Brazilian and Polish Antarctic Station on King George Island	1.22–3.11 ng/g lipid wt, 12.3 ± 9.1 ng/g lipid wt, < 0.12–2.60 ng/g lipid wt,1.33 ng/g lipid wt, < 0.12 ng/g lipid wt	Taniguchi et al. (2008)
11	PCBs	Brown skua fat tissue, Penguins fat tissue, Antarctic tern fat tissue, Blue-eyed shag fat tissue. Snowy sheathbill fat tissue	Brazilian and Polish Antarctic Station on King George Island	19,720 + 9620 ng/g lipid wt, 256 + 125 ng/g lipid wt, 613 + 187 ng/g lipid wt, 282 ng/g lipid wt, 297 ng/g lipid wt	Taniguchi et al. (2008)
12	PAHs	Brown skua fat tissue, Penguins fat tissue, Antarctic tern fat tissue, Blue-eyed shag fat tissue, Snowy sheathbill fat tissue	Brazilian and Polish Antarctic Station on King George Island	3375 ± 1588 ng/g lipid wt, 1588 ± 654 ng/g lipid wt, 5744 ± 2546 ng/g lipid wt, 3961 ng/g lipid wt, 4090 ng/g lipid wt	Taniguchi et al. (2008)
13	Mirex	Brown skua fat tissue, Penguins fat tissue, Antarctic tern fat tissue, Blue-eyed shag fat tissue, Snowy sheathbill fat tissue	Brazilian and Polish Antarctic Station on King George Island	2210 ± 1590 ng/g lipid wt, 90.6 ± 70.6 ng/g lipid wt, 260 ± 58 ng/g lipid wt, 89.2 ng/g lipid wt, 149 ng/g lipid wt	Taniguchi et al. (2008)
14	HCB	South polar Skua	Ross Sea (East Antarctica)	19.38 ± 12.99 ng/g	Corsolini et al. (2011)
15	p,p′-DDE	South polar Skua	Ross Sea (East Antarctica)	26.95 ± 13.72 ng/g	Corsolini et al. (2011)
16	o,p′-DDE	South polar Skua	Ross Sea (East Antarctica)	0.06 ± 0.13 ng/g	Corsolini et al. (2011)
17	p,p′-DDD	South polar Skua	Ross Sea (East Antarctica)	< LOD 2.20 ± 1.29 ng/g	Corsolini et al. (2011)

Table 10 (continued)

S. no	POPs category	Nature of sample	Location	Concentration	References
18	o,p′-DDD	South polar Skua	Ross Sea (East Antarctica)	0.06 ± 0.13 ng/g	Corsolini et al. (2011)
19	p,p′-DDT	South polar Skua	Ross Sea (East Antarctica)	0.01 ± 0.03 ng/g	Corsolini et al. (2011)
20	λ-HCH	South polar Skua	Ross Sea (East Antarctica)	0.031 ± 0.03 ng/g	Corsolini et al. (2011)
21	HCH	South polar Skua	Ross Sea (East Antarctica)	0.03 ± 0.03 ng/g	Corsolini et al. (2011)
22	PCBs	South polar Skua	Ross Sea (East Antarctica)	32.42 ± 21.36 ng/g	Corsolini et al. (2011)
23	HCB	Brown Skua	Brainsfield Strait (West Antarctica)	13.10 ± 13.12 ng/g	Corsolini et al. (2011)
24	p,p′-DDE	Brown Skua	Brainsfield Strait (West Antarctica)	22.58 ± 5.19 ng/g	Corsolini et al. (2011)
25	o,p′-DDE	Brown Skua	Brainsfield Strait (West Antarctica)	0.09 ± 0.09 ng/g	Corsolini et al. (2011)
26	p,p′-DDD	Brown Skua	Brainsfield Strait (West Antarctica)	1.67 ± 0.56 ng/g	Corsolini et al. (2011)
27	p,p′-DDT	Brown Skua	Brainsfield Strait (West Antarctica)	0.01 ± 0.01 ng/g	Corsolini et al. (2011)
28	λ-HCH	Brown Skua	Brainsfield Strait (West Antarctica)	0.04 ± 0.01 ng/g	Corsolini et al. (2011)
29	HCH	Brown Skua	Brainsfield Strait (West Antarctica)	0.04 ± 0.01 ng/g	Corsolini et al. (2011)
30	PCBs	Brown Skua	Brainsfield Strait (West Antarctica)	53.41 ± 19.61 ng/g	Corsolini et al. (2011)
31	DL-PCBs	Skua	King George Island	54–100 pg/g dw	Wolschke et al. (2015)
32	PBDEs	Skua	King George Island	2390 pg/g dw	Wolschke et al. (2015)

DDE-p,p′ dichlorodiphenyldichloroethylene, *DDT-p,p′* dichlorodiphenyltrichloroethane, *HCB* hexachlorobenzene, *HCH* hexachlorocyclohexane, *HCH-β* β-hexachlorocyclohexane, *PCBs* polychlorinated biphenyls, *PAHs* polycyclic aromatic hydrocarbons, *PCDD/Fs* polychlorinated dibenzo-p-dioxins and dibenzofurans, *PBDEs* polybrominated diphenyl ethers)

areas emphasizing the recent developments in the POPs research. Distribution patterns, bio-magnification processes in Antarctic wildlife and modeling of the pollutant transport are the thrust areas to elucidate the eco-toxicological risk of POPs contaminants associated with Antarctic ecosystems.

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