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Environmental contamination in Antarctic ecosystems

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ABSTRACT

Although the remote continent of Antarctica is perceived as the symbol of the last great wilderness, the human presence in the Southern Ocean and the continent began in the early 1900s for hunting, fishing and exploration, and many invasive plant and animal species have been deliberately introduced in several sub-Antarctic islands. Over the last 50 years, the development of research and tourism have locally affected terrestrial and marine coastal ecosystems through fuel combustion (for transportation and energy production), accidental oil spills, waste incineration and sewage. Although natural "barriers" such as oceanic and atmospheric circulation protect Antarctica from lower latitude water and air masses, available data on concentrations of metals, pesticides and other persistent pollutants in air, snow, mosses, lichens and marine organisms show that most persistent contaminants in the Antarctic environment are transported from other continents in the Southern Hemisphere. At present, levels of most contaminants in Antarctic organisms are lower than those in related species from other remote regions, except for the natural accumulation of Cd and Hg in several marine organisms and especially in albatrosses and petrels. The concentrations of organic pollutants in the eggs of an opportunistic top predator such as the south polar skua are close to those that may cause adverse health effects.
Population growth and industrial development in several countries of the Southern Hemisphere are changing the global pattern of persistent anthropogenic contaminants and new classes of chemicals have already been detected in the Antarctic environment. Although the Protocol on Environmental Protection to the Antarctic Treaty provides strict guidelines for the protection of the Antarctic environment and establishes obligations for all human activity in the continent and the Southern Ocean, global warming, population growth and industrial development in countries of the Southern Hemisphere will likely increase the impact of anthropogenic contaminants on Antarctic ecosystems.

1. Introduction

The Antarctic continent reached its current position about 45 million years ago (Ma) and it has been geographically isolated from the other continents since the separation of the Antarctic Peninsula from South America (about 30 Ma). The opening and deepening of the Drake Passage (Fig. 1) allowed the establishment of the Antarctic Circumpolar Current and the circumpolar cyclonic vortex, which enhanced the isolation of Antarctica and contributed to its extraordinary cooling. As about 98% of the continent is permanently covered by ice (average thickness of about 2 km, and maximum thickness of over 4 km), Antarctica is usually perceived as a remote and hostile place and as a symbol of the last great wilderness untouched by human disturbance. Unfortunately, the Antarctic environment is no longer pristine and like other remote regions on Earth, it is not escaping the impact of local and global anthropogenic activities (UNEP, 2002; Bargagli 2005;

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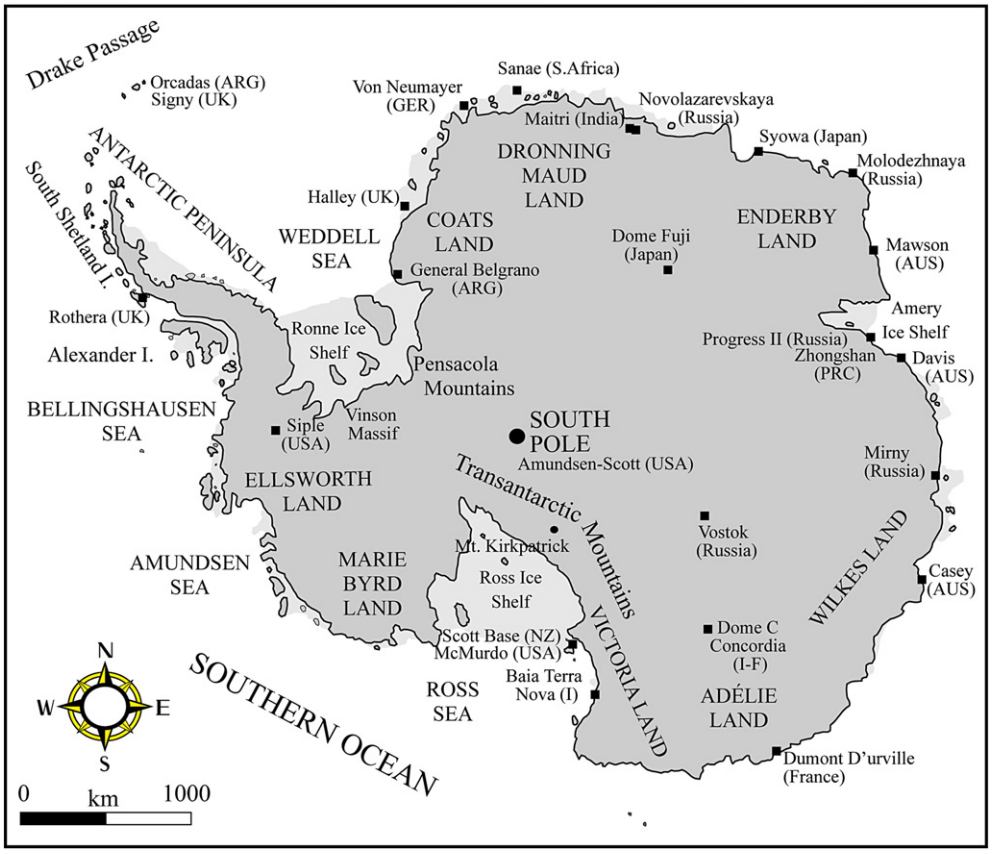

Fig. 1 – Map of Antarctica.

Bergstrom et al., 2006). For a long time its remoteness and physical geography discouraged exploration of the continent, but starting in the early 1900 s, an increasing number of persons were drawn to Antarctica and the Southern Ocean for sealing, whaling and exploration. Fishing and hunting drove some Antarctic marine species to the verge of extinction, and the deliberate transport and introduction of invasive plant and vertebrate species such as reindeer, cattle, sheep and cats has had a remarkable impact on the biodiversity and functioning of ecosystems in several subantarctic islands (Frenot et al., 2005). The development of Antarctic research (especially after the International Geophysical Year in 1958-1959, when 55 stations in the continent and subantarctic islands were occupied by more than 5,000 people), tourism and fishing activities in the last 50 years have resulted in a sharp increase in human presence. Since 1964 a series of legal instruments and recommendations for the management of natural resources and environmental protection have been introduced into the Antarctic Treaty System, for example the Convention on Conservation of Antarctic Marine Living Resources (CCAMLR) in 1980 and the Protocol on Environmental Protection to the Antarctic Treaty in 1991. This protocol designated Antarctica as "a natural reserve, devoted to peace and science", excluded territorial claims and the exploitation of natural resources and recognized the value of the continent and the Southern Ocean to science (e.g., as ideal archives of data for better understanding global processes, for studying organisms with unique ecophysiological characteristics due to their long evolutionary history in isolation, and for the unique opportunities to make astronomical and astrophysical observations or for investigating the Earth's magnetosphere and ionosphere).

Until 1980-1990, the waste at most Antarctic stations was simply dumped in conveniently located landfill sites close to the station, or alternatively, disposed into the sea or burnt in the open air. The Protocol provided strict guidelines for environmental management and protection, and established the obligation to clean-up abandoned work sites. Although some abandoned waste disposal sites were undocumented, several countries began to assess environmental pollution at scientific stations and developed strategies for clean-up and remediation (e.g., Kennicutt et al., 1995; Deprez et al., 1999; COMNAP-AEON, 2001; Webster et al., 2003; Stark et al., 2006). The Protocol establishes principles for the planning and conduct of all activities in Antarctica, but local impacts due to the increasing presence of humans are inevitable. The combustion of fuel (for transportation and energy production), waste incineration, sewage and accidental oil spills are among the main sources of contaminants in Antarctic air, snow, soil and biota. Rapid climate change in the Antarctic Peninsula and subantarctic islands may also enhance the success of colonization by pre-adapted alien species of bacteria, fungi, plants and animals inadvertently introduced by scientists or tourists in species-poor ecosystems (Hughes et al., 2006).

In the last century the economic and industrial development of the Northern Hemisphere has had a dramatic impact on the global environment. Antarctica, the remotest continent in the Southern Hemisphere, has a negligible non-native population and is protected from the entry of lower latitude water and air masses by natural "barriers" such oceanic and atmospheric circulation; of all the regions on Earth, Antarctica was therefore least affected by global anthropogenic activities. However, over the last three decades, the recurring appearance of the Antarctic "ozone hole" and the rapid regional warming of the Antarctic Peninsula have indicated that Antarctica and the Southern Ocean are linked to global processes and are affected by the impact of anthropogenic chlorofluorocarbons (CFCs), CO_2 and other greenhouse gases. Pesticides have neither been produced nor applied in Antarctica, but Dichlorodiphenyltrichloroethane (DDT) and its congeners were detected in Antarctic marine biota in the 1960s (Sladen et al., 1963); since then, many other Persistent Organic Pollutants (POPs) such as Hexachlobenzene (HCB), Hexachlorocycloexanes (HCHs), aldrin, dieldrin, chlordane, endrin, heptachlor have been reported in biotic and abiotic matrices from Antarctica and the Southern Ocean (e.g., UNEP, 2002).

Although there is a limited input of anthropogenic contaminants from the Northern Hemisphere to Antarctica, the profiles of radioactive debris deposition in Antarctic snow and ice during the 1950s and 1960s revealed the presence of fission products released in the Northern Hemisphere (Koide et al., 1979). Under ambient temperatures POPs may volatilize from water, soils and vegetation into the atmosphere, where they are unaffected by breakdown reactions and may be transported over long distances before re-deposition. Volatilization/deposition cycles may be repeated many times and according to the theory of cold condensation and global fractionation (Wania and Mackay, 1993) the most volatile compounds such as HCHs, HCB and low-chlorinated Polychlorinated Biphenyls (PCBs) can redistribute globally. In polar regions POPs condense and settle out; the low temperatures reduce or block evaporation, thus producing relatively high environmental levels and biomagnification processes in food chains, potentially threatening (as endocrine disrupters) the health of wildlife.

Mercury emitted by anthropogenic and natural sources occurs in the atmosphere mostly in the gaseous elemental form (Hg^0), which has a long lifetime in tropical and temperate regions. Once deposited in terrestrial and aquatic ecosystems the metal is partly re-emitted into air, thus assuming the characteristics of global pollutants such as POPs. This metal is now acknowledged to be one of the most serious contaminants in polar ecosystems because of springtime Hg depletion events which have been reported in some costal areas of the high Arctic (Schroeder et al., 1998) and Antarctica (Ebinghaus et al., 2002).

Concern over the vulnerability of polar regions to organic and inorganic contaminants that originate from lower latitudes has increased in recent years. This journal (*The Science of the Total Environment*) has published several comprehensive reviews (e.g. Braune et al., 2005; Gamberg et al., 2005; Macdonald et al., 2000; Oostdam van et al., 1999; Braune et al., 1999) on the results of research on the occurrence and possible biological implications of persistent contaminants in Arctic, but not Antarctic ecosystems. It would be important to also complete a review of similar studies on Antarctic ecosystems, because the global pattern of persistent anthropogenic contaminants and green-house gases is rapidly changing due to the strong population growth and industrial development in countries of the Southern Hemisphere. At present, metal and POP concentrations in most Antarctic biota are usually below those documented to have biological effects on related species in temperate and Arctic regions. However, most organisms in the Southern Ocean are endemic species with unique ecophysiological characteristics resulting from a long evolutionary history in isolation and most species in terrestrial ecosystems reach the limits of their distribution under harsh Antarctic conditions. Organisms from Antarctica may thus be more stressed and more vulnerable to the adverse effects of persistent contaminants than those from other regions. This review summarizes current information on the distribution of persistent contaminants in abiotic and biotic compartments of Antarctic ecosystems, and discusses their possible biological effects and the likely trend of environmental contamination in relation to climate changes and increasing human activity in Antarctica and the Southern Hemisphere.

2. Terrestrial and marine ecosystems

During the austral summer only about 330,000 km^2 of the total area of Antarctica (about 13.6×10^6 km^2) is free of ice and snow. Ice-free areas are mainly located in the western Antarctic Peninsula; on the continent they only occur in scattered coastal areas, on the steep slopes of mountains or in nunataks. Most continental ice-free areas are cold desert environments with very sparse biotic communities of microorganisms, cryptogams and few species of microinvertebrates (springtails, mites, nematodes, tardigrades and rotifers). The bioavailability of liquid water, rather than biogeographical isolation or low temperatures, is the main factor limiting the development of biotic communities in Antarctic soils. Most organisms are desiccation-tolerant and have long lifecycles, slow growth rates and low reproductive outputs. In general, the most developed communities occur in coastal ice-free areas, where the sea mitigates temperatures, increases snow precipitation, and the presence of nesting seabirds enhances the availability of nutrients in soils. The Antarctic Peninsula and neighboring islands (Fig. 1) are milder and wetter, and the more developed soils support a greater abundance and variety of organisms, including two species of native flowering plants: *Colobanthus quitensis* and *Deschampsia antarctica*. Although continental Antarctica does not have stream-river drainage systems, there are many sub-glacial and sub-aerial lakes, and the summer melting of snow banks or glacier ice may originate small seeps and ephemeral streams in coastal areas. The main organisms in Antarctic inland waters are cyanobacteria (which may form thick films and mats), flagellates, diatoms, yeasts, protozoans, rotifers, nematodes and tardigrades. While in Victoria Land freshwater there are no crustaceans, in other parts of East Antarctica, such as the Vestfold Hills, the aquatic fauna also includes some species of copepods. The

diversity of freshwater planktonic and benthic organisms increases in the Antarctic Peninsula.

One of the most impressive aspects of Antarctic ecosystems is the startling contrast between the extreme impoverishment of terrestrial ecosystems and the richness and high biomass of marine organisms. The Southern Ocean is a deep marine system encircling Antarctica in a 2,500-km-wide, semi-closed belt. Dense, near-freezing (about -1.9 °C) water masses produced along the continental margin flow along the continental slopes and spread northwards into the lowermost oceanic basins, cooling and ventilating a large proportion of the global ocean. Unlike in the Arctic, the sea ice which encircles Antarctica in winter (forming a 400-2,000 km wide belt) melts during spring and summer. Marine areas at the retreating pack-ice edge are characterized by algal blooms which sustain large communities of pelagic tunicates, salps, copepods, gammarids, hyperiids, chaetognaths and, above all, krill (*Euphausia superba*). Shoals of krill provide the food base for cephalopods, myctophid fish, baleen whales, seals, penguins and other seabirds. The short food chain based on krill represents the most outcome of the long evolutionary processes in a cold and nutrient-rich sea with a seasonal ice cover and light availability. The shelf depth (about 400-500 m) near the continent is about three-fold higher than that of other continents. In the permanent pack ice or fast ice zone, phytoplankton production is usually restricted to a brief, intense summer period, and the zooplankton biomass is rather low. A large proportion of algae (inside or below fast ice), phytoplankton, and zooplankton organisms are therefore source of food for very rich benthic communities. These communities include many species of particle-feeding or scavenger invertebrates such as sponges, hydroids, tunicates, bryozoans, polychaetes, actinarians, echinoderms, nemertines, bivalves, nudibranchs, isopods, pycnogonids and fish (mostly endemic species of the suborder Notothenioidei). Although most Antarctic fish are benthic, some species such as *Pleuragramma antarcticum* (Antarctic herring) are pelagic or mesopelagic (e.g. *Dissostichus mawsoni*) or have specialized for life on the undersurface of sea ice (cryopelagic species such as *Trematomus borchgrevinki*). In general, Antarctic marine organisms are characterized by high levels of endemism, gigantism, longevity, slow growth rates, delayed maturation and absence of pelagic larval stages. While the trophic chain in the pelagic zone is based on krill, that in the continental shelf comprises benthic invertebrates involved in the transfer of persistent contaminants from phytoplankton and superficial sediments to fish, nesting seabirds and seals. The lengthening of the chain enhances the biomagnification of methylmercury (MeHg) and POPs (Bargagli et al., 1998a) and increases risks for marine organisms in coastal sites near Antarctic research stations.

3. Atmospheric transport of contaminants to Antarctica

Although migrating species of marine birds and mammals may contribute to the southward transfer of POPs, their transport to the Southern Ocean and Antarctica occurs through marine and especially atmospheric pathways. Antarctica is the highest continent (the huge mass of ice has an average elevation of about 2,300 m a.s.l.) and its atmosphere loses more heat by radiative cooling than it gains by surface energy exchange. In the interior of the continent (the Antarctic plateau) the strong cooling over the surface of ice sheets and the persistent surface-temperature inversion generate the outward and downward flow of cold, dense air masses (katabatic winds) towards the coast. The katabatic drainage flow is compensated by a poleward air flow from the mid-latitude high troposphere which transports water vapor, gases and aerosols to Antarctica. This long-range transport is affected both by circumpolar low-pressure systems (at an annual average latitude of about 66° S) and by the high-pressure system over the polar plateau. Particles and reactive gases in air masses are partly removed by cyclonic storms in the belt of "westerlies" and are then replaced by evaporation and the bursting of entrained air bubbles in the Southern Ocean (Shaw, 1988). The isotopic composition of snow in Antarctic coastal areas mostly reflects that of seawater at the northern edge of the pack-ice zone, and studies on atmospheric concentrations of POPs along north-south transects usually reveal much higher values in subtropical areas and in the belt of cyclonic storms than in Antarctic coastal sites (e.g., Bidleman et al., 1993; Kallenborn et al., 1998; Ockenden et al., 2001; UNEP, 2002). However, during the austral summer the circumpolar vortex disappears, and long-term records of mineral dust, black carbon and ^{210}Pb at the South Pole and at some coastal Antarctic stations indicate an enhanced poleward transport of air masses (Wolff and Cachier, 1998). As a result, although concentrations of long-range transported contaminants in the Antarctic environment and biota are lower than in the rest of the Southern Hemisphere, they show similar patterns (UNEP, 1996).

During the dry season intense biomass burning occurs in the tropics, and satellite imagery each year shows large smoke plumes downwind of fires in continents in the Southern Hemisphere. Biomass burning releases water vapor, smoke particles, CO_2, CH_4 and many other trace gases. Their convective transport affects O_3 concentrations in the middle and upper troposphere, and their effects have been detected in the atmosphere over the remote South Pacific (Talbot et al., 1999). In some zones of the South Atlantic Thompson et al. (1996) measured O_3 concentrations comparable to those occurring downwind of major urban/industrial areas in the Northern Hemisphere. Black carbon particles are reliable tropospheric tracers of the transport of contaminants from biomass-burning areas, and their concentration patterns in Antarctica seem to be controlled by the timing of burning in the tropics (Wolff and Cachier, 1998).

The seasonal variability in the amount and chemical composition of airborne particles in Antarctica, variations between coastal and inland sites, and the different sampling and analytical procedures make it difficult to compare the results of different studies. Given the large expanse of oceans with respect to landmasses in the Southern Hemisphere, Antarctic aerosol is usually dominated by sea-salt particles, marine biogenic and volcanic emissions, and small amounts of soil dust (e.g. Wagenbach et al., 1998; Arimoto et al., 2001; Six et al., 2005). Most trace elements in Antarctic aerosol have a natural origin (e.g. Arimoto et al., 2008) however, especially

in samples from the Antarctic Peninsula, high Cr, Cu, Ni, Pb, V and Zn enrichment factors with respect to both mean crustal and seawater compositions have usually been attributed to inputs from human activity in Antarctica and/or elsewhere in the Southern Hemisphere (e.g., Planchon et al., 2002; Mishra et al., 2004; Hur et al., 2007). The above elements are among those released by the combustion of coal, oil and gasoline and by non-ferrous metal production (Pacyna and Pacyna, 2001).

The main sources of POPs in the Southern Hemisphere are urbanised areas, those with intensive agriculture, and tropical and subtropical regions where spraying is used for disease vector control (Forget, 1991; Ngabe and Bidleman 1992). The demand and use of many POPs increased in the 1990s in Asian countries and Southern Pacific islands and large amounts of PCBs used in older electrical devices were deposited as landfill in some developing countries (Iwata et al., 1994). South America has historically been among the heaviest users of DDT, toxaphene and lindane. Literature data on air levels of POPs in the Southern Ocean and Antarctica were summarized in a comprehensive report by UNEP (2002). In general, concentrations of DDT, chlordane, heptachlor, HCB and HCHs decrease southward with the lowest values usually occurring in air samples from the continent (e.g. Tanabe et al., 1983; Bidleman et al., 1993). As in the case of trace elements, POP concentrations are higher in air samples from the Antarctic Peninsula and sub-Antarctic islands than in those from continental sites (Bargagli, 2005). Unlike pesticides, some industrial POPs such as PCBs have been used in Antarctica and PCB contamination was reported, for instance, by Risebrough et al. (1990) at McMurdo Station on Ross Island. When comparing literature data on mean annual air concentrations of PCB congeners at Alert (Canadian Arctic) in 1994 with those recorded at Halley Station in 1999, Ockenden et al. (2001) found that average concentrations of PCB-28, PCB-138 and PCB-153 were similar, while those of all other congeners were two-four times higher at Alert.

A rough comparison between available data indicates that concentrations of most POPs in the Antarctic atmosphere have decreased over the last twenty years. In austral summer 2003-2004 concentrations of gas-phase PCBs at a coastal site in Victoria Land ranged from below the detection limit to 0.25 pg m^{-3} (mean concentration Σ PCB = 1.06 pg m^{-3}; Gambaro et al., 2005). Relationships were not found between seasonal variations of ΣPCB concentrations and air temperature, and more than 78% of the total PCB content was due to congeners with 1-4 chlorine atoms. It was therefore concluded that most PCBs are transported over long distances to Antarctica.

4. Persistent contaminants in Antarctic snow

Snow and ice are by far the most important components of the Antarctic environment. Snowy precipitation is a very efficient mechanism for cleansing the air of airborne contaminants. After extensive Pb contamination was found in ice cores from Greenland (Murozumi et al., 1969), the analysis of polar snow and ice cores became one of the most suitable approaches for assessing (global or hemispheric) deposition of atmospheric contaminants and for reconstructing changes in atmospheric composition and climate history. The average annual precipitation on the Antarctic plateau is very low (usually 2-4 g cm^2 $year^{-1}$; Brownich and Parish, 1998), with the advantage that a 1-m ice core covers many years; however, this makes it difficult to assess short-term variations in atmospheric deposition.

Lead pollution can be considered as a paradigm of hemispheric-scale anthropogenic impact on Antarctica (Bargagli, 2005). From variations in Pb/Ba concentration ratio and Pb isotopic composition in snow pit samples from Victoria Land (dating from 1872 to 1994 AD), Van de Velde et al. (2005) found enhanced Pb deposition from 1891 to 1908 and from 1948 to 1994. During the earlier Pb contamination event about 50% of the metal deposited in Victoria Land originated from anthropogenic emission sources in the Southern Hemisphere such as non-ferrous metal production and coal combustion. The more recent Pb contamination corresponds to the widespread use of gasoline alkyl Pb additives in automobiles in the Southern Hemisphere. This deposition pattern agrees with previous snow peat surveys which revealed a rapid increase in Pb concentrations from the 1950s, up to peak values in the mid-1970s in Coats Land (Atlantic sector; Wolff and Suttie, 1994) and in the mid-1980s in Victoria Land (Ross Sea, Pacific sector; Barbante et al., 1997). The earlier decrease of Pb concentrations in Coats Land snow was probably due to the adoption of alcohol fuels in Brazil about 10 years before the introduction of unleaded gasoline in Australia and other countries in Oceania (Barbante et al., 1997). Increasing human activity in Antarctica, especially during the International Geophysical Year and after the establishment of several scientific stations probably contributed to the increase in levels of Pb and other metals in Antarctic snow. However, the composition of snow samples collected at increasing distance from Antarctic stations (e.g. Boutron and Wolff, 1989; Suttie and Wolff, 1993) showed that emission from human activity in Antarctica account for only a limited percentage of metal fallout to the continent.

Recent literature data on the chemical composition of recent Antarctic snow show that concentrations of most elements are very low (Table 1) and that their sources are mainly natural (rock and soil dust, sea-salt spray and active volcanoes such as Mount Erebus or volcanoes in the sub-Antarctic islands). However, increasing time trends in Cr, Cu, Zn, Ag, As, Pb, Bi and U concentrations indicate that the transport of metals to Antarctica is not limited to Pb and Cu, as previously thought (e.g. Wolff et al., 1999), but probably also involves other elements mainly released during the mining and smelting of non-ferrous metals in Chile, Peru, Zaire, Zambia and Australia (Planchon et al., 2002; Hur et al., 2007). The chemical composition of different sections of the Vostok deep Antarctic ice core (Table 1) reveals the high variability of element concentrations with lower values during interglacial periods and much higher element inputs during glacial periods (Gabrielli et al., 2005). The enhanced element deposition in the Antarctic ice cap during the coldest periods is assumed to have been driven by large changes in wind strength and a decrease in humidity in dust source areas such as Patagonia (Rothlisberger et al., 2002).

The presence of DDT residues and PCBs has been detected in Antarctic snow since the 1970s (e.g. Risebrough et al., 1976), and available data (Fuoco and Ceccarini, 2001; Montone et al., 2003) corroborate the general decreasing trend in atmospheric

Table 1 – Mean trace element concentrations (pg g^{-1}) in recent snow and ice from continental Antarctica

Element	Lambert Glacier [a]	Coats Land [b]	Vostok (ice core) [c]	
	(1998–2002)	(1989–1990)	5750 yr BP	65,080 yr BP
Ag	–	0.14	–	–
Al	165	130	3700	120,000
As	10.0	–	4.0	16
Ba	2.4	1.2	12	429
Bi	0.028	0.052	0.08	0.80
Cd	0.21	0.14	–	–
Co	–	–	1.1	11
Cr	–	1.6	<4.1	30
Cu	5.3	2.4	–	–
Fe	45	–	–	–
Li	–	–	9.0	96
Mn	3.7	4.5	18	552
Pb	4.0	1.6	–	–
Rb	–	–	4.0	115
Sr	–	–	81	740
U	0.029	0.016	0.1	3.1
V	0.46	0.40	3.0	82
Zn	–	0.80	–	–

[a] Hur et al., 2007.
[b] Planchon et al., 2002.
[c] Gabrielli et al., 2005.

concentrations over Antarctica since the late 1980s and the 1990s. Zoccolillo et al. (2007) measured concentrations of some volatile chlorinated hydrocarbons (VCHCs) such as chloroform, 1,1,1-trichloroethane, tetrachloromethane, 1,1,2-trichloroethylene and tetrachloroethylene in superficial snow samples collected during two Italian ITASE (International Trans Antarctic Scientific Expedition) expeditions through Victoria, Adélie, George V and Oates Lands. The results showed an increasing trend of VCHC concentrations towards the continent interior and the absence of correlation between VCHC concentrations and annual snow accumulation rate. Zoccolillo et al. (2007) concluded that the falling snow is the main scavenger of atmospheric VCHC and it produces concentrations of these contaminants in Antarctic superficial snow which are comparable with those measured in snow from temperate zones.

5. Contaminants in terrestrial and freshwater ecosystems

Fuel oil spills are one of the most widespread sources of localized pollution near scientific stations, especially in zones for refuelling of aircraft and vehicles. High concentrations of PAHs have generally been reported in soils where oil spills have occurred (e.g., Kennicutt et al., 1992; Aislabie et al., 1999; Mazzera et al., 1999). There is evidence that hydrocarbon spillage in soils can result in an increase in hydrocarbon-degrading microbes and a concomitant decrease in the diversity of the soil microbial community (Aislabie et al., 2004). However, the "in situ" biodegradation rate is probably very low, because aliphatic and aromatic compounds can be detected in soils more than 30 years after a spill. Antarctic soils have low contents of moisture (often <1%), organic matter and microbiota, and soluble and insoluble persistent chemicals are therefore moved or transformed slowly. High metal concentrations have been detected in abandoned dump sites or in areas affected by scattered rubbish or emissions from incinerators, generators and vehicles (e.g. Kennicutt et al., 1995; Claridge et al., 1995; Webster et al., 2003). Research and logistic activities have determined anthropogenic input into lakes in the vicinity of Antarctic stations (e.g. Ellis-Evans 1996; Burgess and Kaup, 1997; Gasparon and Burgess 2000; Goldsworthy et al., 2003). However, with a few notable exceptions, the contribution of human activities to total concentrations of trace metals in soils and sediments is negligible. According to Gasparon and Matschullat (2006) this contribution can be identified and quantified only if natural baselines, their variability, and processes controlling the mobility of metals in terrestrial and aquatic ecosystems, have been fully characterized.

Under the Protocol on Environmental Protection, monitoring is required to evaluate the effectiveness of environmental remediation strategies and of existing conservation measures around Antarctic stations. Mosses and lichens are the main biotic component of Antarctic terrestrial ecosystems, and they can play an important role as (active or passive) biomonitors of atmospheric deposition of persistent contaminants (e.g. Bacci et al., 1986; Poblet et al., 1997; Bargagli, 1998; Bargagli et al., 1998b, Olech et al., 1998; Hong et al., 1999). Because these organisms can tolerate long periods of desiccation and extreme temperatures, are perennial and some species are widespread throughout the continent and sub-Antarctic islands, it is possible to establish large-scale biomonitoring networks. As a rule, concentrations of local and long-range transported persistent contaminants are much higher in cryptogamic organisms than in the atmosphere, snow or soil, thereby making analytical determinations easier and cheaper. Average concentrations of HCB, HCHs, DDTs and PCBs in Antarctic lichens and mosses (range 0.1-35 ng g^{-1} dry wt.; e.g. Bacci et al., 1986; Focardi et al., 1991; Borghini et al., 2005) are generally some orders of magnitude higher than those in Antarctic abiotic matrices. Baseline concentrations of most trace elements in Antarctic lichens and mosses are in the same range as those measured in samples from the Arctic (Table 2); the main difference is the higher Pb content in samples from remote areas of the northern Hemisphere.

In contrast to other trace metals which are inherently associated with atmospheric aerosols, Hg in ambient air mainly exists as gaseous elemental Hg (Hg^0). In temperate and tropical regions Hg° has a long atmospheric residence time (from months to more than one year) and is removed by wet or dry deposition after transformation into ionic or particulate forms. Once deposited in terrestrial and aquatic ecosystems Hg is partly transformed by microorganisms into MeHg, a compound of particular concern because it accumulates in organisms and moves up food chains (biomagnification). However, a significant proportion of the metal is re-emitted into the air and the atmosphere ensures its global distribution. In the early 1990s, a survey of Hg distribution in terrestrial ecosystems of northern Victoria Land based on the analysis of lichen thalli (Bargagli et al., 1993) revealed an enhanced deposition of the metal in the Nansen Ice Sheet (a

Table 2 – Baseline 2 concentrations (mean ± SD; μg g^{-1} dry wt.) of trace elements in the lichen *Umbilicaria* 3 *decussata* and the moss *Bryum pseudotriquetrum* from northern Victoria Land (Antarctica) compared with 4 literature data for lichens and mosses from remote areas in the Northern Hemisphere

Region	Species	Al	Cd	Cr	Cu	Fe	Hg	Mn	Pb	Zn
Northern Victoria Land[a]	*Umbilicaria decussate*	727±515	0.18±0.10	1.6±0.8	5.3±3.8	812±536	0.39±0.27	19±7.0	0.65±0.41	20±6.0
NW Canada[b]	*Umbilicaria polyphylla*	–	0.19±0.05	3.0±0.9	5.2±3.1	–	–	–	10.4±5.6	2.2±3.4
Northern Victoria Land[c]	*Bryum pseudotriquetrum*	4600±3120	0.13±0.04	6.8±3.5	9.0±4.8	3542±1780	0.13±0.04	239±106	4.6±3.3	65±18
Alaska[d]	*Hylocomium splendens*	4300±2600	–	20±14	15±9	4900±3600	–	530±500	6.8±1.9	65±58

[a]Bargagli et al. (1998b); [b]Chiarenzelli et al. (1997); [c]Bargagli et al. (1995); [d]Wiersma et al. (1986).

coastal region between 74° and 76° S facing the Ross Sea). At the time it was impossible to explain why lichens from this regions accumulated Hg concentrations in the same range as those usually measured in urban and industrial areas. More recently, Sprovieri et al. (2002) found that summer concentrations of Hg° in the same region range from 0.9 to 1.3 ng m^{-3} however, the oxidation of Hg^0 may produce concentrations of divalent Hg compounds which are as high as those measured in some industrial areas (up to 334 pg.m^{-3}). Through highly time-resolved measurements (performed for 12 months at the German von Neumayer coastal Antarctic station; Fig. 1), Ebinghaus et al. (2002) found springtime Hg depletion events like those previously described in Arctic coastal sites (e.g., Schroeder et al., 1998; Lindberg et al., 2002). The results of a recent survey using mosses and lichens (Fig. 2) confirmed the enhanced Hg bioaccumulation in samples from the Nansen Ice Sheet (Bargagli et al., 2005). As this region faces the Terra Nova Bay coastal polynya, ice crystal (frost flowers") growing in the polynya are thought to be a source of sea salt aerosols and bromine compounds, which are involved in springtime Hg depletion events. Field evidence of increased Hg accumulation in cryptogamic organisms raises concern that Antarctica may become an important sink in the global Hg cycle, especially in view of possible changes in sea ice coverage and increasing anthropogenic emissions of Hg in countries of the Southern Hemisphere.

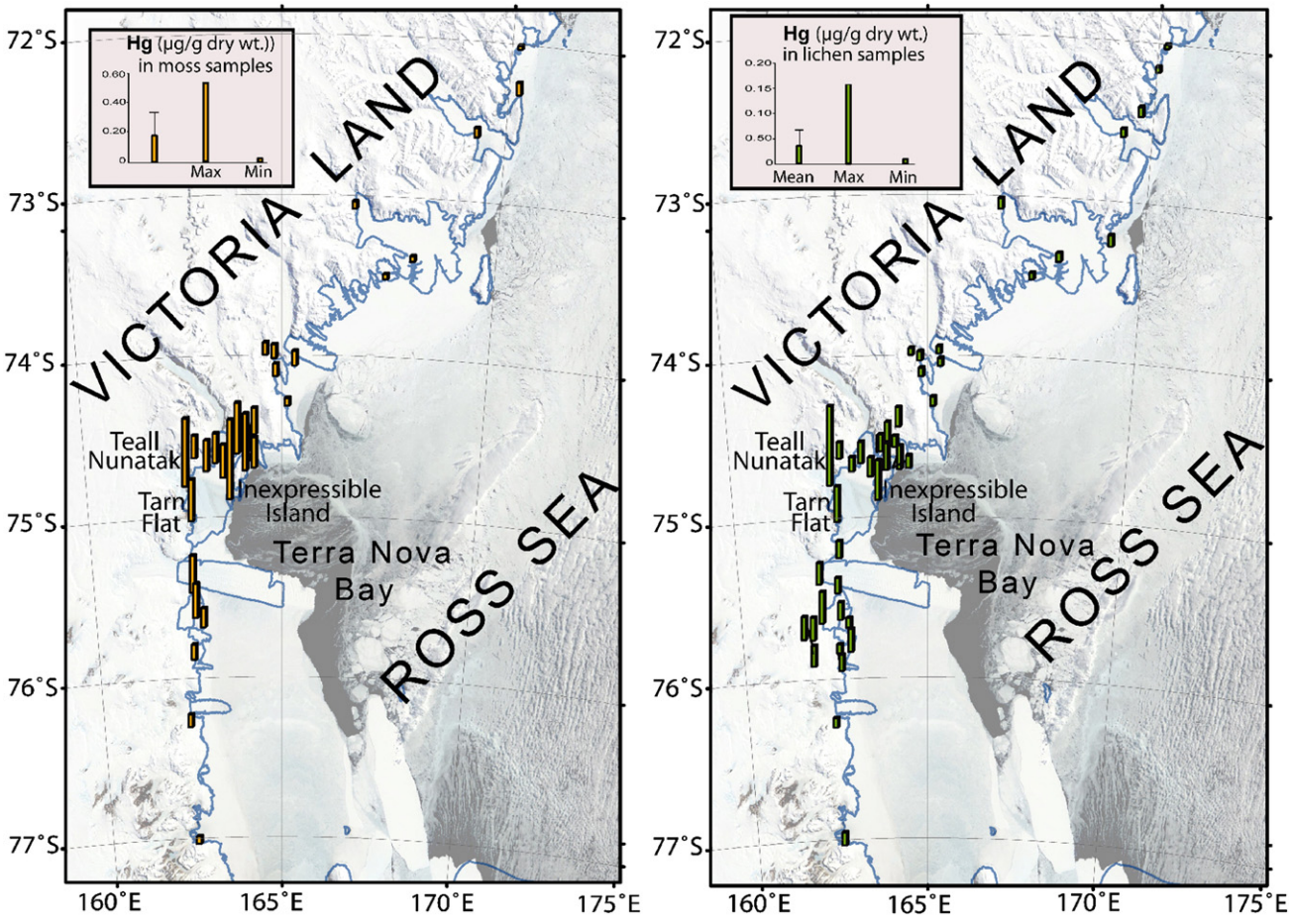

Fig. 2 – Distribution of total Hg concentrations in the moss *Bryum pseudotriquetrum* and the lichen *Umbilicaria decussata* from Victoria Land terrestrial ecosystems.

6. Localized pollution in coastal marine ecosystems

Several local hydrocarbon pollution incidents caused by shipwrecks, collisions or accidents during bunker fuel transfer have occurred in Antarctica (e.g. Croxall, 1987; Cripps and Shears, 1997). The worst incident with the release of about 550 m^3 of diesel fuel was the sinking of the Argentine supply ship *Bahia Paraiso* on 28 January 1989 at Arthur Harbor, near Anvers Island and the US Palmer research station. The US National Science Foundation undertook efforts to contain environmental pollution and sponsored a Quick Response Team for environmental monitoring of the area (e.g. Kennicutt et al., 1991, 1995). Within four days of the accident, 100 km^2 of the sea surface was covered by an oil slick, and intertidal *Nacella concinna* populations within a few kilometers of the wreck were reduced by 50%. In these areas high concentrations of total PAHs accumulated in sediments and limpets and in the stomach content (amphipods and limpets), liver and muscle of the fish *Notothenia coriiceps neglecta* (McDonald et al., 1992). The spill occurred at the middle to end of the seabird breeding season, and in the following weeks several Adélie penguins, blue-eyed shags and south polar skua died and/or suffered reproductive failure. However, after two years, in most intertidal zones affected by the spill, PAH concentrations in *N. concinna* tissues decreased to values at or near the detection limit of the analytical method (Kennicutt et al., 1992).

Although concern about local environmental pollution around scientific stations has been expressed since the 1970s (e.g. Cameron, 1972), the value of the Antarctic environment to science was only definitively acknowledged in the late 1980s. Throughout the 1970s, wastes from McMurdo station were routinely discharged along the eastern shoreline of Winter Quarter Bay, which also provided docking facilities for ships. In 1988 the US National Science Foundation began a dumpsite cleanup and abatement program and the bay became one of the most studied marine environments in Antarctica. As a rule, trace metals, PAHs and other by-products of combustion and incineration processes, including Polychlorinated Dibenzo-p-Dioxins (PCDDs), Polychlorinated Dibenzofurans (PCDFs) and PCBs are among the most widespread pollutants found in coastal marine ecosystems within a few hundred meters of scientific stations (UNEP, 2002; Bargagli, 2005; Santos et al., 2005; Negri et al., 2006). Chemicals are introduced in the coastal marine environment through wastewater, leachates from dump sites, and deposition of particulates from station activity and ship operations. Some detailed chemical studies have attempted to fingerprint the source of contaminants or to use chemical signatures to evaluate the time and rate of environmental contamination. Townsend and Snape (2008) for instance, used stable Pb isotopes to asses contamination by Pb from Australian deposits, in sediments from Brown Bay (adjacent to the current and former Australian Station at Casey) and to differentiate Australian- and American-derived Pb sources in marine sediments adjacent to the abandoned Wilkes Station (manned by the US from 1957 to 1959 and by Australia between 1961 and 1969).

Significant disturbance of benthic communities has generally been reported in the proximity of the most polluted coastal sites (e.g., Lenihan and Oliver, 1995; Conlan et al., 2000; Stark et al., 2003; Thompson et al., 2007). Organism responses to the combined effects of toxic pollutants and organic enrichment from sewage disposal usually involve a decrease in the abundance and diversity of benthic fauna and an increase in resistant and opportunistic species. Such changes in community structure can result from both direct toxicity and indirect effects of contaminants; in general, marine sediments contaminated with hydrocarbons and trace metals display greater abundances of polychaetes and gastropods than uncontaminated sediments (Stark et al., 2003). Research on polluted sediments near Casey Station (Cunningham et al., 2005) has revealed that benthic diatom communities are good indicators of anthropogenic metal contamination and may be useful in monitoring the success of environmental remediation strategies in polluted Antarctic sites.

7. Persistent contaminants in pelagic and coastal food chains

Southern Ocean waters have some distinctive physico-chemical features deriving from their circulation pattern (around a continent covered by ice and lacking river drainage systems), the seasonal distribution of sea ice, and primary productivity. Although shallow shelf areas, marginal sea ice zones and upwelling regions along the Antarctic Polar Front are regions of intense algal blooms (>3 g C m^{-2} day^{-1}; El-Sayed and Fryxell, 1994), the offshore waters constitute a major oceanic region with high concentrations of nutrients and low productivity rates. “In situ” fertilization experiments (e.g. Boyd et al., 2000) indicate that the low productivity is mainly due to the lack of Fe and Mn and/or to co-limitation by Si. The impact of trace metals from remote anthropogenic sources can be hardly detected in Southern Ocean waters or sediments, and Pb concentrations in Weddell Sea waters are about half those usually measured in other ocean environments (e.g. Sañudo-Wilhelmy et al., 2002). However, the anthropogenic component of the metal reflects the Pb isotopic composition of aerosols from other continents in the Southern Hemisphere (Alleman et al., 2001) and there is evidence that many species of seabirds and marine mammals may accumulate high concentrations of potentially toxic elements such as Cd and Hg (Table 3). Concentrations of Cd (about 0.7 nmol l^{-1}) and phosphate (about 2.0 μmol l^{-1}) in Southern Ocean surface waters are much higher than in other ocean surface waters, and several species of Antarctic crustaceans may accumulate high concentrations of Cd (e.g., Bargagli et al., 1996; Kahle and Zauke, 2003; Keil et al., 2008). The krill (*Euphausia superba*) which can form dense aggregations (up to several square kilometers) and is by far the dominant herbivore in the Southern Ocean and the main feeding resource for cephalopods, fish, seabirds, seals and baleen whales, accumulate lower Cd concentrations than other species of Antarctic zooplankton (Table 3). Comparisons among Cd concentrations measured in whole organisms and expressed in relation to their weight are unreliable because the metal mainly accumulates in the digestive gland and kidney, and *E. superba* has a much higher growth rate and size than other crustaceans (i.e. a lower proportion of digestive gland and kidney mass with

Table 3 – Mean concentrations (μg g^{-1} dry wt.) of Cd and Hg in some representative organisms of the Southern Ocean pelagic food webs

Organism	Species	Organ	Cd	Hg	References
Krill	*Euphausia superba*	Whole	0.85	<0.10	(Stoeppler and Brandt, 1979;
			0.29	0.025	Palmer Locarnini and Presley, 1995)
		Liver	28±17	–	
Myctophid fish	*Gymnoscopelus piabilis*	Kidney	16±8	–	Bustamante et al. (2003)
		Muscle	<0.1	0.31±0.13	
Cephalopods	*Graneledone* sp.	Digestive gland	369	–	
	Diomedea	Liver	14.4±5.3	295±173	
	exulans	Kidney	39.4±17.0	–	
	Thalassoica	Liver	14.9±2.5	9.2±4.2	
	antarctica	Kidney	44.2±16.4	–	Lock et al. (1992)
Seabirds	*Fulmarus*	Liver	18.7±6.9	19.9±7.9	
	glacialoides	Kidney	43.1±18.8	–	
	Pygoscelis adeliae	Liver	13.0	0.20	Honda et al. (1986)
Seals	*Lobodon carcinophagus*	Liver	13±12	7.6±5.6	Szefer et al. (1993, 1994)
	Hydrurga leptonyx	Liver	5.9±1.9	18.1±0.9	
	Ommatophoca rossii	Liver	110±88	4.6±4.3	McClurg (1984)
Whales	*Balaenoptera acutorostrata*	Liver	45±26	0.21±0.1	Honda et al. (1987)

respect to that of muscle, fat or gonads). The liver of vertebrates and the digestive gland of invertebrates are two partly analogous organs, and data summarized in Table 3 show that the liver and kidney of pelagic seabirds in the Southern Ocean accumulate some of the highest Cd and Hg concentrations reported for any vertebrate. Hindell et al. (1999), for instance, measured maximum Cd concentrations (>260 μg^{-1} dry wt.) in the kidney of wandering and royal albatrosses, which have oceanic patterns and are largely confined to the Southern Ocean. *Fulmarus glacialoides* is slightly larger and has higher Cd concentrations in the liver and the kidney than its counterpart (*F. glacialis*) in the Northern Hemisphere. Cadmium concentrations in seabirds do not usually increase with age, and values measured in the tissues of juveniles are often in the same range or even higher than those in adults; it is therefore likely that Antarctic seabirds, during their evolution in an ocean environment characterized by enhanced natural bioavailability of Cd, adopted metabolic patterns to regulate the metal content to some extent.

Unlike Cd, the biological half-life of MeHg is months or years and it progressively accumulates in muscle or other tissues, reaching peak concentrations in long-lived animals at higher levels of the food web (Tables 3 and 4). Seabirds are more exposed to MeHg accumulation than birds in terrestrial ecosystems, because the former feed on crustaceans, fish or squid which "preconcentrate" MeHg by eating phyto- and zooplankton organisms. Hindell et al. (1999) measured

Table 4 – Mean concentrations (μg g^{-1} dry wt.) of Cd and Hg in representative organisms of Antarctic coastal food webs

Region	Organism	Species	Organ	Cd	Hg	References
Windmill Is.	Macroalgae	*Himantothallus grandifolius*	Thallus	7.5±8.6		Runcie and Riddle (2004)
	Macroalgae	*Iridaea cordata*	Thallus	3.1±0.4	0.09±0.04	
	Phytoplankton	Pooled across species	Whole	2.1±0.9	0.04±0.01	
	Zooplankton	Pooled across species	Whole	3.4±2.3	0.07±0.03	
	Porifera	Pooled across species	Whole	26.4±14.8	0.08±0.05	
	Holothuroidea	Pooled across species	Whole	7.7±3.8	0.23±0.09	
	Asteroidea	*Odontaster validus*	Arms	13.6±1.8	0.11±0.06	
	Echinoidea	*Sterechinus neumayeri*	Soft tissues	13.0±4.8	0.10±0.06	
	Polychaeta	*Harmothoe spinosa*	Whole	6.8±0.6	0.07±0.02	
	Amphipoda	*Paramoera walkeri*	Whole	7.2±2.7	0.07±0.03	
Terra Nova Bay	Bivalvia	*Adamussium colbecki*	Digestive gland	55.7±27	0.35±0.08	Bargagli (2001)
		Neobuccinum eatoni	Digestive gland	227±65	0.24±0.10	
	Fish	*Trematomus bernacchii*	Liver	9.9±5.8	0.46±0.25	
			Muscle	0.04±0.02	0.83±0.65	
		Chionodraco hamatus	Liver	2.9±0.8	0.19±0.12	
			Muscle	0.03±0.02	0.44±0.31	
	Birds	*Pagodroma nivea*	Feathers		0.54±0.18	
		Pygoscelis adeliae	Feathers		0.82±0.13	
		Catharacta maccormicki	Feathers		2.91±1.93	
			Liver	3.1±2.1	35±16	
South Shetland Is.	Seals	*Leptonychotes weddellii*	Muscle	0.03±0.02	1.9±0.7	Szefer et al. (1993, 1994)
			Kidney	25±18	13±8	

1,800 μg g^{-1} dry wt. of Hg in the liver of a wandering albatross (i.e. a level much higher than those found to be toxic for many other bird species). Available data on Hg concentrations in water, sediments, phytoplankton, macroalgae, krill and several species of benthic invertebrates (Tables 3 and 4) indicate that unlike Cd, there is no enhanced bioavailability of Hg in the Southern Ocean. As discussed by Hindell et al. (1999) and Bargagli (2001), Hg bioaccumulation in Antarctic seabirds is probably a natural process mainly determined by species-specific life histories and metabolic pathways. Moulting and egg laying are important route for MeHg excretion in birds, but wondering albatrosses, for instance, have a low reproductive rate (one egg every two years) and replace feathers over a period of years rather than annually. However, part of the MeHg ingested by seabirds with food is demethylated in the liver (where it is stored as inorganic molecules; Thompson and Furness, 1989). Albatrosses and petrels accumulate Se in the liver and the kidney (Kim et al., 1996), where it can act as an antidote to the toxic effects of Hg (e.g. Koeman et al., 1973). By analyzing museum feathers of seabirds from the Northern Hemisphere, Thompson et al. (1992) found that anthropogenic emissions caused a three-fold increase in Hg over a 100-year period; on the contrary, feathers from Procellariformes collected in the Southern Hemisphere before and after the 1950s revealed no significant increases in Hg concentrations. Like the accumulation of Cd that of Hg in Southern Ocean seabirds is probably mainly due to natural processes. The decrease of wandering albatross populations in many sub-Antarctic islands is therefore probably not due to Cd and Hg bioaccumulation, but to the unintended capture of these birds on hooks set by vessels which tow huge, heavily bated long-lines for Patagonian toothfish.

In the past, several species of Antarctic marine mammals were mainly threatened by commercial hunting whereas at present they are affected by other types of human activity, such as fishing and unintentional catching of cetaceans, noise pollution from active sonar systems, the possible effects of climate change (i.e., changes in primary productivity and krill availability), and environmental pollution. Like seabirds, Antarctic marine mammals accumulate rather high concentrations of Cd in the liver and especially in the kidney. Cadmium concentrations in the kidney of Ross seals may be much higher than the critical value (200 μg g^{-1} wet wt.) associated with kidney damage in mammals, including humans (WHO, 1992). Antarctic and Artic seabirds and marine mammals are probably adapted to naturally high levels of Cd, and Dietz et al. (1998) found no morphological differences between the kidneys of seals with low or high (up to 581 μg g^{-1} wet wt.) Cd concentrations. Predatory species of marine mammals generally have higher Hg concentrations, and values are positively related to the body length (Wagemann et al., 1998). However, minke whales in the Southern Ocean mainly feed on *E. superba*, which has low Hg concentrations (Table 3), and despite their long lifespan (about 50 years), Southern Ocean whales accumulate much less Hg in the liver than do West Greenland minke whales, which feed mostly on sand eels (Hansen et al., 1990). The different feeding behavior and the low environmental contamination probably contribute to the much lower POP concentrations in whales from the Southern Ocean than in those from the northern Pacific (O'Shea and Brownell, 1994). However, data by Aono et al. (1997) showed that in the 1984-1994 period, DDT and HCB concentrations in the blubber of northern minke whales were decreasing, whereas those in southern whale samples were increasing. Furthermore, the composition of HCH isomers indicated that lindane was being used to a greater extent in countries of the Southern Hemisphere than in those of the Northern Hemisphere. Table 5 summarizes recent literature data on POP concentrations in different organs and tissues of key species of Antarctic marine organisms from different regions of the Southern Ocean. In general, although POP concentrations increase in fish-eating seabirds and seals, average values are lower than those reported for zooplankton, fish, seabirds and seals at lower latitudes. Goerke et al. (2004) found an increase (in the decade 1987-1996) in POP concentrations in two benthic fish species feeding on benthic invertebrates and assumed that it was due to the sorption of contaminants to sinking particles and the progressive accumulation of contaminants in surface sediments.

Many other organic contaminants such as polybrominated diphenyl ethers (PBDEs), used worldwide as flame retardants, have recently been detected in Antarctic marine organisms (Corsolini et al., 2006; Hale et al., 2008). Prolonged exposure to these toxic compounds can affect thyroid and liver functions and can cause neurodevelopmental and estrogen disorders (Birnbaum and Staskal, 2004). Kumar et al. (2002) documented the presence of 2378-substituted polychlorinated dibenzo-*p*-dioxins(PCDDs), dibenzofurans and dioxin-like PCBs in

Table 5 – Average concentrations (ng g^{-1} wet wt.; normalised to the lipid content) of some POPs in key species of Antarctic marine organisms

Region	Species	Organ/tissue	HCB	*p,p'*-DDE	Σ PCBs	References
Ross Sea	*Euphausia superba*	Whole body	0.23±0.01	0.10±0.01	1.67±0.85	Corsolini et al. (2003, 2006)
		Muscle	1.44±0.45	2.53±4.67	6.35±4.80	
	Trematomus bernacchii	Whole body	1.35±1.24	1.10±1.04	9.25±8.04	
	Pleurogramma antarcticum	Whole body	4.85±5.49	0.15±0.06	3.51±3.03	
	Pygoscelis adeliae	Eggs	18.7±8.0	20.7±11.0	24.9±21.6	
Weddell Sea	*Euphausia superba*	Whole body	1.0	0.60	–	Goerke et al. (2004)
	Trematomus eulepidotus	Liver	5.0	3.2	–	
	Pygoscelis adeliae	Preen gland oil	25.0	18.0	–	
	Leptonychotes weddellii	Blubber	10.0	110	–	Corsolini et al. (2007)
King George Is.	*Pygoscelis adeliae*	Blood	6.7±6.1	8.2±3.3	9.8±3.8	Bustnes et al. (2007)
Dronning Maud Land	Catharacta maccromicki	Blood	6.46	5.40	7.57	

Weddell seal liver, fish (*Trematomus pennelli* and *Chionodraco hamatus*), krill, penguin (*Pygoscelis adeliae*) eggs and south polar skua (*Catharacta maccormicki*) eggs. The latter bird is an opportunistic top predator which during the breeding season in Antarctica preys or scavenges all available marine or terrestrial food resources such penguins, snow petrels or other seabirds. South polar skuas have one of the longest migration flights of any bird, and during the Antarctic winter they may cross the equator to reach the North Atlantic and Greenland. Early biomonitoring surveys (e.g., Risebrough and Carmignani, 1972) found that skuas accumulate higher concentrations of persistent contaminants than all other Antarctic vertebrates. Kumar et al. (2002), for instance, have found that concentrations of 2378-tetracholorodibenzo-*p*-dioxin equivalent (TEQs) in eggs of south polar skuas are close to those that may cause adverse health effects. Blood samples collected from the same bird species at Dronning Maud Land also had the highest concentrations of mirex (a formicide and fire retardant) ever reported in the blood and plasma of birds (Bustnes et al., 2007).

8. Concluding remarks and concern about the future

The development of scientific research, tourism and fishing is determining an increase in human presence in Antarctica and the Southern Ocean. Although the number of tourists visiting Antarctica is usually three-four times greater than that of the logistic and scientific personnel, the latter reside for a longer period in permanent or semi-permanent stations. Most stations are located in coastal areas, and the combustion of fuel for transportation and energy production, waste incineration, oil spillage and sewage will inevitably produce localized environmental impacts. A recent study by Hale et al. (2008) indicates for instance, that sewage management practices at McMurdo and Scott Stations are insufficient to prevent the dispersal and environmental contamination by PBDE (mostly derived from materials on stations treated with flame retardant). Furthermore, most research stations and tourism are concentrated in the sub-Antarctic islands and the Antarctic Peninsula. As these regions have less extreme climatic and environmental conditions and are affected by enhanced warming, they seem particularly at risk for environmental contamination as well as for the introduction of alien, pre-adapted organisms, including wildlife pathogens.

While the use of Hg and many POPs has declined or ceased in North America and Europe since the 1990s and earlier, the growing demand for energy, the burning of coal and biomass, the extraction of gold and other non-ferrous metals, intensive agriculture and the spraying of pesticides for disease vector control in Asia, Africa and South America is increasing the atmospheric burden of most persistent contaminants in the Southern Hemisphere. Furthermore, in most countries industrial growth is not accompanied by adequate measures for the abatement of atmospheric pollutants. This changing global pattern of persistent anthropogenic pollutants is also characterized by emerging new classes of chemicals. For instance, perfluorinated compounds (PFCs), which have a wide range of industrial applications and are toxic to several species of aquatic organisms, have been shown to occur in biota from various seas and oceans, including the Arctic and the Southern Ocean (Yamashita et al., 2005). Catalytic converters in motor vehicles are increasing global emissions of Pt and other companion elements such as Pd, Rh, Ru, Os and In. Increased concentrations of Rh, Pd and Pt with respect to ancient Greenland ice samples have been measured in surface snow from the Alps, Greenland and Antarctica (Barbante et al., 1999).

Climate change and global warming could enhance the transport and deposition of persistent contaminants in Antarctica. Although the oceanic transport of persistent contaminants is often considered to be much less important than atmospheric transport, models which combine the transport of semi-volatile chemicals in air and water, and consider continuous exchange between the two compartments, indicate that the overall transport of POPs to remote regions is accelerated with respect to models treating air and water separately (Beyer and Matthies, 2001). The rapid regional climatic warming of the Antarctic Peninsula has also been detected in oceanic waters to the west (e.g., Meredith and King, 2005). The warming of surface water can affect POP volatilization and transport. In contrast to organisms in temperate and tropical seas, those in the Southern Ocean are well adapted to narrow ranges of water temperature close to the freezing point. Slight increases in temperature may have a disproportionate influence on the properties of cell membranes and biological processes involved in the uptake and detoxification of environmental pollutants.

Although for continental Antarctica there is yet no significant trend in meteorological temperature, a loss of ice sheets such as that in the Antarctic Peninsula (seven ice sheets have disappeared in the last 50 years) could have dramatic effects on atmospheric precipitation (i.e., the deposition of contaminants), environmental biogeochemistry, and on the distribution and composition of biotic communities in terrestrial and freshwater ecosystems. Warming could enhance the role of Antarctica as a Hg “cold trap” through changes in the sea-ice cover and increased inputs of reactive halogens in the continental atmosphere.

The Protocol on Environmental Protection to the Antarctic Treaty provides strict guidelines for the protection of the Antarctic environment and its value to scientific research. Although the rigorous application of the Protocol will help minimize the local impact of tourists and scientists, it seems inadequate to reduce or prevent large-scale environmental contamination by metals and POPs from other continents. In order to protect Antarctic ecosystems it would thus be important to:

- develop continental-scale monitoring programs in order to assess the long-term effects of persistent contaminants in Antarctic organisms and food chains and to predict possible responses of terrestrial and marine ecosystems to climate changes and anthropogenic activity (local and remote).
- promote international agreements and the transfer of financial aid and technologies from rich countries to developing countries in the Southern Hemisphere in order to address global environmental threats.

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