Deposition of organochlorine pesticides into the surface snow of East Antarctica

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ABSTRACT

Organochlorine pesticides (OCPs) were measured in surface snow collected on a ~1400-km inland traverse beginning from the coastal regions of East Antarctica during the Japanese Antarctic Research Expedition (JARE) of 2007/2008. Of the 22 OCPs, α-hexachlorocyclohexane (HCH), γ-HCH, and hexachlorobenzene (HCB) were frequently detected in the snow with concentration ranges of 17.5–83.2, 33–137, and ND–182 pg L^{-1}, respectively. The most abundant pesticide was γ-HCH, with a mean concentration of 69.9 pg L^{-1}, followed by α-HCH, with an average concentration of 44.5 pg L^{-1}. The spatial variability of α-HCH and γ-HCH was narrow, and the concentrations of α-HCH and γ-HCH increased slightly with increasing altitude along the traverse route. Dome Fuji, the highest altitude sampling point, had the highest γ-HCH concentrations in the snow. Backward air trajectory analysis showed that the air masses at the sampling sites came mainly from the Indian and Atlantic Oceans and over the Antarctic continent, indicating that the OCPs were subjected to long-range atmospheric transport and were deposited in the surface snow. Our data suggest that the snow of Antarctica contains low levels of OCPs.

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1. Introduction

Organochlorine pesticides (OCPs), like other persistent organic pollutants (POPs), are ubiquitous contaminants in the environment. OCPs are detected in air, water, and soil, even in remote regions of the Arctic and Antarctica, as well as in high-altitude mountains (Daly and Wania, 2004a; Wania and Mackay, 1993). The presence of OCPs in both high-latitude and high-altitude regions has been attributed to long-range atmospheric transport and a series of evaporation, deposition, and cold-condensation processes (Wania and Mackay, 1995).

Snow and ice are critically important environmental components of cold regions. Antarctica is the most pristine and remote region in the world, and snow and ice cover approximately 98% of the Antarctic continent. Falling snow contributes significantly to the deposition of airborne contaminants by washing out atmospheric aerosols and absorbing the gas phase vapors. Snow efficiently scavenges OCPs from the atmosphere, which influences not only the deposition of OCPs but also their fate in cold environments (Daly and Wania, 2004b; Stocker et al., 2007; Wania et al., 1998). Atmospheric OCPs appear in both the particulate phase and the gas phase. Although they are lipophilic, organic contaminants are stored in the snow and ice after deposition; thus, snow and ice serve as a reservoir for atmospheric OCPs. Such

OCPs preserved in frozen layers of snow and ice can then be released into the atmosphere when the snow and ice melt, resulting in adverse effects on different components of the environment (Bogdal et al., 2009; Geisz et al., 2008).

Peel (1975) and Peterle (1969) discovered the first presence of OCPs in Antarctic snow (Peel, 1975; Peterle, 1969). The snow collected from the Plateau station and inland of Halley Bay station contained measurable amounts of DDTs, which have been banned in most countries in agricultural applications since the 1970s. However, only two recent studies have determined the snow concentration of OCPs from Antarctica, focusing on coastal areas due to the difficulties in accessing the inland regions of the continent (Dickhut et al., 2005; Tanabe et al., 1983). Little is known about the distribution of OCPs in the inland regions of Antarctica. Because the spatial distribution patterns of OCPs in the surface snow from wide regions of Antarctica provide valuable information for identifying the extent of atmospheric dispersion of OCPs and for understanding the processes related to their deposition in Antarctica, monitoring OCPs in sufficiently extended regions of Antarctica helps us understand the effects of snow on the environmental behavior of semivolatile organic chemicals.

Because the data of the snow concentration of OCPs are much more limited than other environmental matrixes, the objective of this study is to report the concentrations of OCPs in surface snow along the interior East Antarctic continental traverse routes to understand the transport pathways of OCPs in East Antarctica.

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2. Materials and methods

2.1. Sampling sites and methods

As part of the 2007–2008 International Trans Antarctic Scientific Expedition (ITASE) program, surface snow samples were obtained from the coastal areas to the interior regions of East Antarctica. During the scientific traverse on November to December 2007, a total of 35 surface snow samples were collected from Syowa Station (S27; 69°02′ 327″ S, 40°33′186″ E) near the coast via Dome Fuji (DK10; 77°14′940″ S, 39°14′160″ E) to the turning point (DK360; 76°01′140″ S, 26°17′ 610″ E) over a distance of ~1400 km in East Antarctica by the Japanese Antarctic Research Expedition (JARE) team (Fig. 1). The surface snow was collected by scrubbing the surface at a depth of less than 5 cm using a pre-cleaned 500 mL wide-mouth low density polyethylene (LDPE) bottle. Great precaution was taken during sample collection, handling, and storage to prevent the possibility of snow contamination (Hur et al., 2007). For example, the sampling was always conducted 100 m from snow vehicles and from the upwind side of the snow because of potential contamination resulting from human activity. The operators wore full clean room garments and polyethylene gloves in the field. The bottles were packed in double-sealed pre-cleaned LDPE bags and were kept frozen until analysis. Detailed information about the sampling dates, location, elevation, and snow type are described in Table S1. The surface snow samples were analyzed for OCPs and trace inorganic elements, such as total mercury (Hg_T), trace elements including lead (Pb), and the platinum group elements (Ir and Pt).

2.2. Chemical analysis and quality control

All sample handlings were performed under a class 10 clean bench in a class 1000 clean room at the Korea Polar Research Institute (KOPRI), and the analytical operations were performed at the Pohang University of Science and Technology (POSTECH). A full description of the analytical procedure is provided in Kang et al. (2009). Briefly, the snow samples were thawed at room temperature in a class 10 bench, and the melted samples (ca. 100 mL) were extracted using liquid–liquid extraction with dichloromethane. Without further cleanup, the extracted mixture was concentrated and then analyzed using a gas chromatograph (Agilent

6890N) coupled with a high-resolution mass spectrometer (Jeol JMS-800D) for the following 22 OCPs: α-HCH, β-HCH, γ-HCH, δ-HCH, HCB, Heptachlor, Heptachlor epoxide, Aldrin, Dieldrin, Endrin, Oxychlordane, trans-Chlordane, cis-Chlordane, trans-Nonachlor, cis-Nonachlor, o,p′-DDE, p,p′-DDE, o,p′-DDD, p,p′-DDD, o,p′-DDT, p,p′-DDT, and Mirex. The final volume was adjusted to less than 10 μL. The isotope dilution method was used for OCP determinations. Before the extraction, the ^{13}C-labeled OCP internal standards were spiked, and the ^{13}C-labeled recovery standards were spiked before the GC-HRMS analysis. The average recovery of internal standards was between 75 and 125% for each ^{13}C-labeled OCP. The detection limits were defined as three times the signal-to-noise ratio (S/N) and were calculated for each sample. The average detection limits of HCB, α-HCH, and γ-HCH were 3.0 pg L^{-1}, 10.0 pg L^{-1}, and 10.0 pg L^{-1}, respectively. The average detection limits of the other OCPs ranged from 10 to 105 pg L^{-1} (Kang et al., 2009).

2.3. Meteorological parameters and conditions

Various meteorological data (e.g., wind speed, wind direction, air temperature, visibility, and atmospheric pressure) were measured during the JARE field traverse. Ground meteorological observations were recorded manually once daily by an observer at 15:00 GMT. The manually observed meteorological data during the JARE field traverse are presented in Table S2. Relatively mild and stable weather conditions were experienced during the field traverse expedition between November and December 2007, typified by low wind speeds and an average air temperature of −21.7 °C. The air temperatures displayed a wide range, from −6.0 °C to −32.8 °C, throughout the sampling period. The lowest air temperature was recorded at Dome Fuji on December 9th. The wind speed was generally low, averaging 5.2 m s^{-1} with maximum gusts of 14 m s^{-1}. The average wind speed at the sites from the coast to an elevation of 3000 m were 6.1 m s^{-1}, but those over 3000 m averaged 4.6 m s^{-1}. The wind direction was predominantly southeast, showing a magnetic wind direction of 130°. The prevailing wind direction at Dome Fuji was between 106° and 125°. The mean air pressure was 705 hPa, ranging from 601 hPa to 935 hPa. Meteorological data were also observed using an automatic weather station (AWS) from a snowmobile. To identify the origin of air
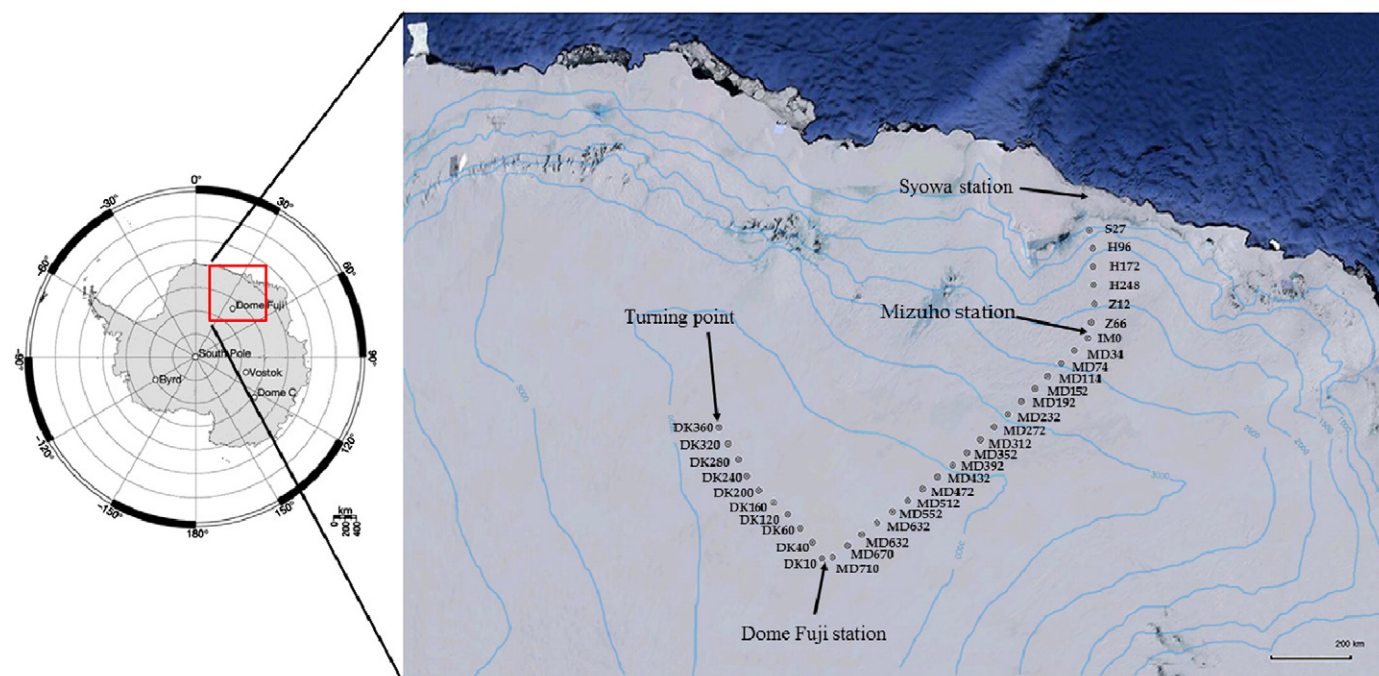

Fig. 1. Location of 35 sampling sites from Syowa Station to the turning point via Dome Fuji over the East Antarctica region.

masses arriving at the sampling sites, five-day backward air trajectories were calculated using the HYPLIT 4 model (http://www.arl.noaa.gov/ready/hysplit4.html).

3. Results and discussion

3.1. Concentrations of OCPs in the surface snow

The OCP concentrations at the 35 sampling sites of East Antarctica are presented in Table 1. Among the 22 OCPs investigated, α-HCH, γ-HCH, and HCB were detected in almost all the snow samples, while none of the other OCPs were detected in any of the samples. γ-HCH was the most abundant pesticide, ranging from 33.3 to 137 pg L^{-1}, followed by α-HCH, ranging between 17.5 and 83.2 pg L^{-1}. The snow concentrations of HCB ranged from ND (below the detection limit) to 182 pg L^{-1}. The mean concentrations of α-HCH, γ-HCH, and HCB were 44.5, 69.9, and 29.0 pg L^{-1}, respectively. The total OCP concentrations in the snow samples ranged between 65.4 and 326 pg L^{-1}. This study, to the best of our knowledge, revealed for the first time the snow OCP concentrations during a traverse from the coastal regions to the inland regions of East Antarctica. The abundance of HCHs and HCB in the surface snow compared with those of the DDTs confirmed that relatively volatile OCPs were subjected to long-range transport from the mid-latitude source regions to the high-latitude deposition regions by a series of evaporation and deposition steps known as the global distillation effect (Wania and Mackay, 1995).

The Arctic and Antarctic snow concentrations of OCPs are summarized in Table 2. The snow OCP concentrations from East Antarctica in this study showed relatively narrow variations compared with those

from the Arctic snow. The mean concentrations of γ-HCH were 1500 pg L^{-1} in the snow at Tromsø on Storsteinen Mountain in the Arctic collected between February and March 2003 (Herbert et al., 2005). The surface snow samples collected from Ny-Ålesund of the Norwegian Arctic also showed higher γ-HCH concentrations, with a mean concentration of 1150 pg L^{-1} (Herbert et al., 2005). The concentrations of γ-HCH in this study were much lower than those measured in the snow from the Arctic. However, the mean HCB concentrations in the East Antarctic snow were consistent with the result from the Arctic snow. The snow OCP concentrations of this study were much lower than those of the previous study in East Antarctica. The Japanese scientific teams collected surface snow samples from Mizuho Station (IM0), Tottuki Point (about 13 km northeast from Syowa Station), and Lake Nurume (about 16 km southeast from Syowa station) in East Antarctica during May to September 1981 (Tanabe et al., 1983). The total HCH (sum of α-, β-, and γ-HCH) concentrations in the snow ranged from 2300 pg L^{-1} to 4900 pg L^{-1}, while the DDTs (sum of p,p′-DDE, p,p′-DDT, and o,p′-DDT) ranged from 15 pg L^{-1} to 17 pg L^{-1}. Over the past 26 years, the snow HCH concentration in East Antarctica has decreased from ~3300 pg L^{-1} to ~100 pg L^{-1}. However, fresh fallen snow concentrations of α-HCH and γ-HCH along the Western Antarctic Peninsula were lower than those found in the surface snow samples of our study (Dickhut et al., 2005). The mean concentrations of α-HCH and γ-HCH in snow collected upwind of a cruise ship during the winter of 2001 in the Western Antarctic Peninsula were 1.76 and 4.28 pg L^{-1}, respectively. These differences may be attributed to sampling time, sampling locations, and analytical methods. For the aspects of analytical methods, previous studies have used GC-LRMS (low resolution mass spectrometer) or GC-ECD (electron capture detector), while isotope dilution GC-HRMS method was used in this study to provide more reliable results.

The most abundant pesticide in the East Antarctic surface snow was γ-HCH, which is consistent with the result of the snow collected in the Western Antarctic Peninsula and East Antarctica (Dickhut et al., 2005). The ratio of α/γ-HCH ranged from 0.44 to 1.02, with an average of 0.66 ± 0.13, indicating the old usage of technical HCH and the dominance of γ-HCH through the more recent use of lindane in the Southern Hemisphere (Li et al., 1996; Tanabe et al., 1982; Wania et al., 1999). After the ban of technical HCH, the usage of lindane for agricultural purposes in the Southern Hemisphere resulted in a predominant influx of lindane versus technical HCH to the environment, which resulted in a lower α/γ-HCH ratio in the environment. Moreover, because γ-HCH is more water soluble than α-HCH due to a lower Henry's law constant, this compound can be anchored in the snowpack when the wind blows (Kang et al., 2009).

Higher levels of γ-HCH have been frequently detected in other environmental media, such as air, sea water, sea ice, and soil/sediment obtained from Antarctica (Table 3). Air samples collected from the Antarctic Peninsula during 2001–2002 showed that the mean concentration of α-HCH and γ-HCH was 0.31 and 0.78 pg m^{-3}, respectively (Dickhut et al., 2005). Antarctic air collected at northern Victoria Land, Terra Nova Bay, in the 2003–2004 field season contained α-HCH and γ-HCH with a mean concentration of 0.22 and 0.56 pg m^{-3}, respectively (Cincinelli et al., 2009). The concentrations of γ-HCH were ten times higher in the soil and sediment obtained on the eastern coast of Antarctica in 1998. The mean concentrations of α-HCH and γ-HCH in soils from the East Antarctic coast were 0.75 and 7.49 ng g^{-1} dry weight, and the mean ratio of α/γ-HCH was 0.13 (Negoita et al., 2003). The soil and sediment concentrations ranged between 0.14 and 1.34 ng g^{-1} for HCHs in James Ross Island in the Antarctic Peninsula, and the concentrations of γ-HCH were two times higher than those of α-HCH in soil and sediment samples (Klánová et al., 2008). The higher levels of γ-HCH detected in the surface sea water during the early part of summer may be due to an influx from melting sea ice and snow (Dickhut et al., 2005). However, soil and moss collected on Victoria Land in 1999 showed a high proportion of α-HCH (Borghini et al., 2005).

Table 1
Concentrations (pg L^{-1}) of OCPs detected in surface snow of East Antarctica, ratio of α/γ-HCH, and altitude (m) of sampling site.

Site ID	α-HCH (pg L^{-1})	γ-HCH (pg L^{-1})	HCB (pg L^{-1})	α/γ-HCH	Altitude (m)
S 27	30.9	38.0	19.2	0.813	948
H 96	29.2	33.3	123.0	0.875	1296
H 172	57.6	64.9	3.1	0.887	1535
H 248	50.0	93.6	182.0	0.534	1748
Z 12	56.0	91.4	21.1	0.613	1993
Z 66	49.1	48.1	32.9	1.022	2148
IM 0	28.6	33.7	7.7	0.847	2244
MD 34	40.8	62.5	ND	0.653	2351
MD 74	39.5	72.1	15.6	0.548	2439
MD 114	25.7	45.1	26.7	0.571	2577
MD 152	45.7	60.6	64.1	0.753	2714
MD 192	35.4	55.9	ND	0.633	2849
MD 232	73.8	108.0	ND	0.684	2966
MD 272	48.2	61.8	39.7	0.779	3101
MD 312	25.9	51.4	23.9	0.503	3224
MD 352	83.2	116.0	26.8	0.715	3308
MD 392	38.5	51.0	ND	0.756	3465
MD 432	55.7	74.7	ND	0.746	3517
MD 472	56.4	97.7	15.1	0.578	3586
MD 512	40.2	60.9	15.4	0.661	3632
MD 552	33.4	54.7	5.1	0.611	3666
MD 592	67.3	88.4	ND	0.761	3711
MD 632	20.8	41.9	12.8	0.496	3737
MD 670	29.2	51.9	39.0	0.563	3757
MD 710	48.0	94.4	36.6	0.509	3801
DK 10	67.1	137.0	ND	0.491	3801
DK 40	34.9	55.1	ND	0.634	3789
DK 120	53.7	75.5	68.4	0.712	3757
DK 80	39.6	65.8	24.6	0.603	3775
DK 160	31.7	63.0	113.0	0.503	3747
DK 240	44.6	74.3	99.2	0.600	3720
DK 200	17.5	41.3	6.66	0.423	3739
DK 280	40.0	50.1	47.2	0.798	3698
DK 320	70.9	106.0	46.3	0.671	3676
DK 360	72.1	109.0	40.0	0.662	3663
Detection Limits	10.0	10.0	3.0		

Table 2
Mean concentrations (range) of selected OCPs from Antarctic and Artic snow (pg L^{-1}).

Sampling sites	Sampling year	α-HCH	γ-HCH	HCB	Reference
East Antarctica	2007	44.5 (17.5–83.2)	69.9 (33.3–137)	29.0 (ND–182)	This study
Antarctic Peninsula	2001	1.76 (1.44–2.18)	4.28 (1.73–8.91)	NA	Dickhut et al. (2005)
East Antarctica	1981	NA	3333[a] (2300–4900)	NA	Tanabe et al. (1983)
Tromsø (Norway)	2003	130 (17.0–382)	1500 (265–4390)	22.8 (9.51–62.5)	Herbert et al. (2005)
Ny-Ålesund (Svalbard)	2001	742 (116–2000)	1150 (186–3090)	17.8 (3.10–35.3)	Herbert et al. (2005)

ND: not detected; NA: not available.
[a] Sum of α-HCH, β-HCH, and γ-HCH.

A correlation analysis showed that snow γ-HCH concentrations in East Antarctica were significantly and strongly correlated with snow α-HCH concentrations (r = 0.874, p < 0.001), but not with snow HCB concentrations (p > 0.48). These results indicated that the α-HCH and γ-HCH may have originated from similar sources, while the HCB was transported from different sources. However, air γ-HCH concentrations were not significantly correlated with air α-HCH concentrations (p > 0.50) in Antarctic air collected on coastal sites at both Terra Nova Bay and the Antarctic Peninsula (Cincinelli et al., 2009; Dickhut et al., 2005). Large amounts of lindane input to the Antarctic coastal sites during summer from Southern Hemisphere countries could explain the inconsistency in the air concentrations of α-HCH and γ-HCH.

3.2. Geographical distribution and altitudinal dependence

The spatial distribution of α-HCH, γ-HCH, and HCB along the East Antarctic traverse sites is shown in Fig. 2. The geographical variation of the three compounds did not fluctuate much along the traverse route, but the interior regions showed slightly higher concentrations of α-HCH and γ-HCH than the coastal regions. The distance of the traverse route for surface snow sampling was approximately 1400 km, from Syowa Station (S27) to the inland meeting point (DK360) via Dome Fuji Station (DK10), which covered a part of East Antarctica (Sugiyama et al., 2010). All sampling sites in this study were far from the expected source regions, such as continents in the Southern Hemisphere. It could be that the East Antarctic sampling sites were not directly affected by the air masses originating from the continents at a less than 60° S latitude. However, the HCB concentration showed a U-shaped distribution pattern, which may indicate that the coastal area near the station could be contaminated by the station's activity and by the combustion of diesel fuel during the traverse (Choi et al., 2008; Cooper, 2005). Moreover, the distribution pattern of HCB did not differ substantially from that of the HCHs, except for two cases where the HCB concentration was abnormally high in the coastal

regions (H96 and H248). Although the Antarctic regions have little human activity, from conducting and supporting scientific investigations, these activities may increase the emission of some POPs and could affect the environment (Hale et al., 2008).

The altitudinal dependence of α-HCH and γ-HCH is plotted in Fig. 3. Correlation analysis showed that the concentrations of α-HCH and γ-HCH increased with increasing altitude, although the statistical significance was very weak (r = 0.111, p > 0.05 for α-HCH and r = 0.285, p < 0.05 for γ-HCH). The average elevation of the sampling sites was 3076 m. Between MD432 and DK360, the average elevation was over 3500 m. Dome Fuji, the highest sampling site in this study, is the second-highest summit in Antarctica, with an altitude of 3810 m. The increased concentrations of the contaminants in the Antarctic inland regions could be explained by the snow accumulation rate and the Antarctic atmospheric circulation. First, because the snow accumulation rate in the inland regions is much lower than that in the coastal regions, the surface snow obtained from the interior regions should be aged snow, which would contained chemicals used in the past (Goodwin, 1990; Hou et al., 2007). Second, the inland plateau regions have received air masses originating from the expected source regions by the Southern Hemisphere atmospheric circulation, resulting in convergence in the upper atmosphere and deposition into the surface snow (Russell and McGregor, 2010). The highest concentration of γ-HCH was observed at Dome Fuji (DK10), where there was no strong prevailing wind direction, and the wind speed and air pressure were low, with an annual mean wind speed of 5.9 m s^{-1} (Takahashi et al., 1998). These weather conditions may have contributed to the strong deposition of air masses with no ventilation of deposited contaminants by the wind, resulting in higher concentrations of γ-HCH. Moreover, the mean concentrations of α-HCH and γ-HCH at the sites >3500 m were higher than those at the sites <3500 m, although they were statistically nonsignificant (p > 0.01). At the low altitude sites in Antarctica, the wind speed was consistently >10 m s^{-1} as a result of katabatic flow, which is commonly found from the elevated ice sheets of Antarctica. At high wind speeds, the chemicals in the surface snow could be enhanced and

Table 3
Summary of selected OCPs concentration in abiotic matrix (air, sea water, ice, and soil/sediment) from Antarctica.

Sample	Sampling sites	Sampling year	α-HCH	γ-HCH	HCB	Reference
Marine atmosphere	Antarctica	1999–2000	0.3–0.21[a]	0.1–69[a]	NA	Lakaschus et al. (2002)
Marine atmosphere	Antarctic Peninsula	2001–2002	0.1–0.52[a]	0.06–2.98[a]	5.0–32.1[a]	Dickhut et al. (2005)
Land Atmosphere	Terra Nova Bay	2003–2004	0.1–0.35[a]	0.17–1.05[a]	8.5–20.4[a]	Cincinelli et al. (2009)
Sea water	Antarctic Peninsula	2001–2002	1.65–4.54[b]	0.9–10.5[b]	NA	Dickhut et al. (2005)
Sea water	Ross Sea	2003–2004	0.61–4.07[b]	0.83–8.79[b]	1.72–16.2[b]	Cincinelli et al. (2009)
Sea ice	Antarctic Peninsula	2001–2002	0.04–2.18[b]	3.6–5.7[b]	NA	Dickhut et al. (2005)
Soil	East Antarctic coast	1998	0.09–2.69[c]	0.71–40.1[c]	0.02–25.28[c]	Negoita et al. (2003)
Soil	Antarctic Peninsula	2005	0.49–1.34[c,d]	NA	2.41–7.75[c]	Klánová et al. (2008)
Soil	Victoria Land	1999	0.024–0.1[c]	NA	0.034–0.17[c]	Borghini et al. (2005)
Sediment	Antarctic Peninsula	2005	0.14–0.76[c,d]	NA	0.95–4.0[c]	Klánová et al. (2008)
Moss	Victoria Land	1999	0.43–4.0[c]	0.18–1.6[c]	0.82–1.95[c]	Borghini et al. (2005)

[a] pg m^{-3}.
[b] pg L^{-1}.
[c] ng g^{-1}.
[d] Sum of α-HCH, β-HCH, and γ-HCH.

(a)

(b)

(c)
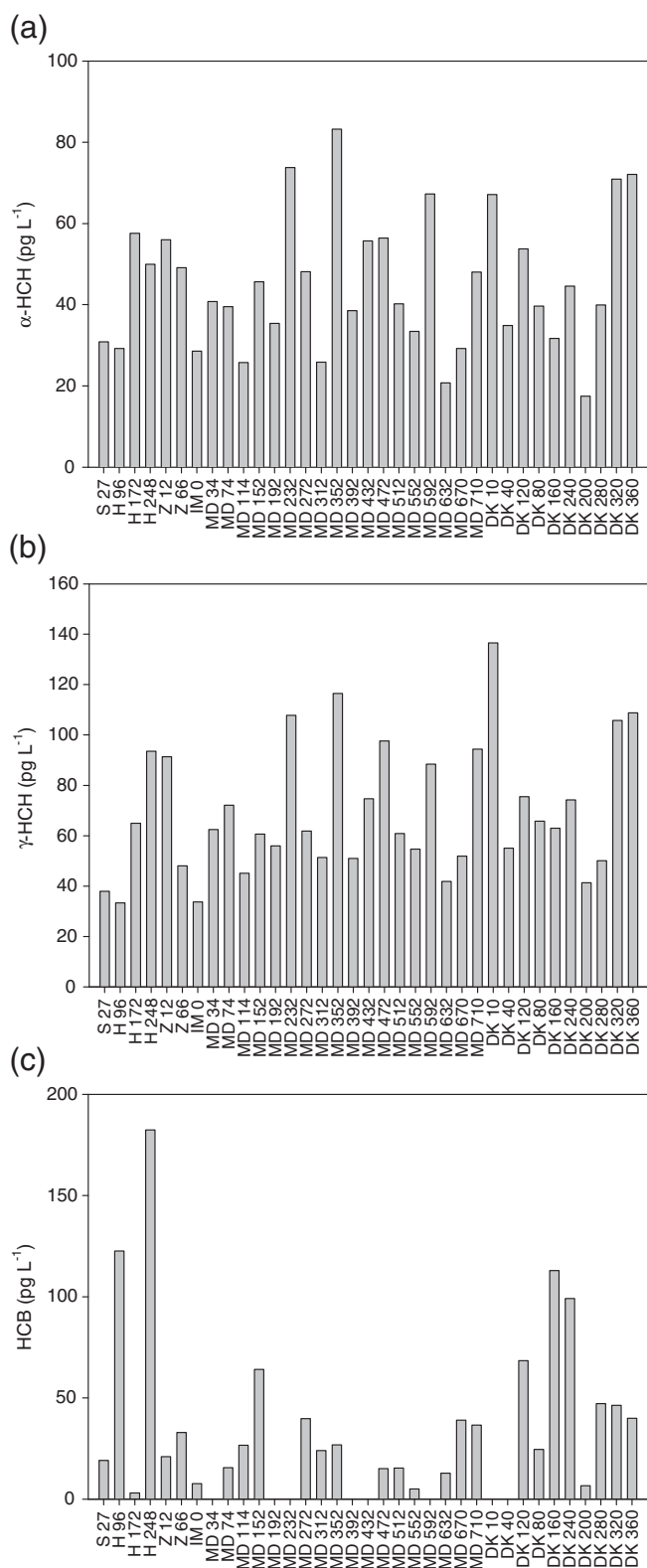
Fig. 2. Geographical distribution of the concentrations for (a) α-HCH, (b) γ-HCH, and (c) HCB.
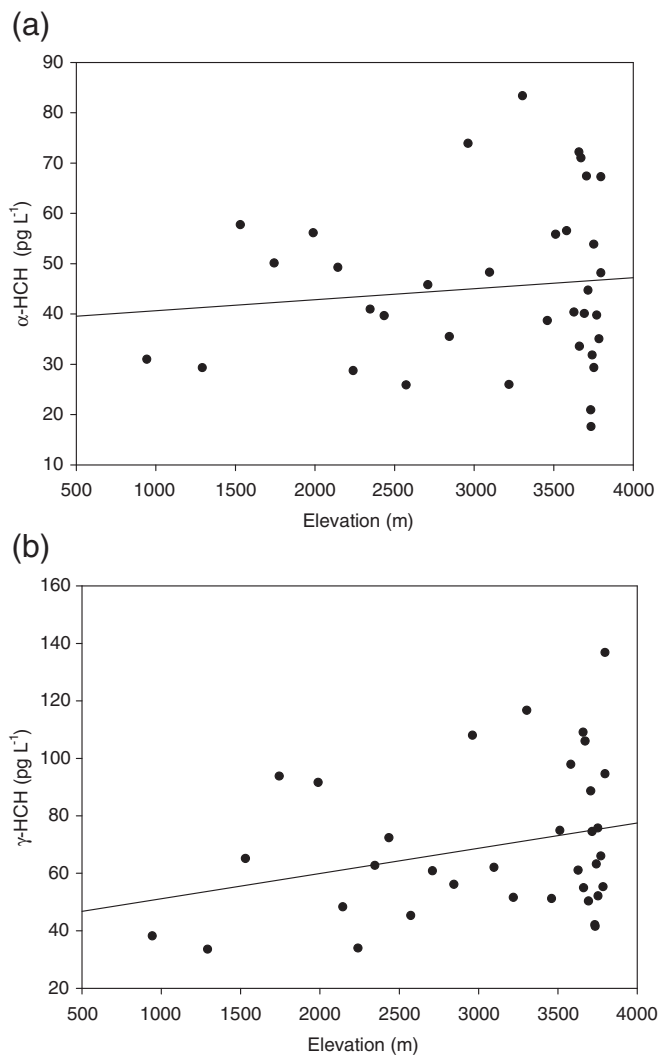
(a)

(b)

Fig. 3. Correlation plots for the concentrations of (a) α-HCH and (b) γ-HCH vs. elevation.

3.3. Air trajectory for finding the source

The potential source of OCPs in the sampling regions of East Antarctica was evaluated by examining five-day backward air trajectories. The plots of the trajectories at the sampling sites are presented in Fig. 4. The backward air trajectory analysis showed that the air masses arriving at the East Antarctic sampling sites were coming mainly from the Indian and Atlantic oceans and passing over the Antarctic continent during the sampling periods. As the air masses of the sites traveled over the continent and through the Oceans, the contaminants from the source would be diluted in the atmosphere, resulting in low contamination levels in the surface snow. Air masses collected from Terra Nova Bay transported across the Antarctic continent contained low levels of OCPs (Cincinelli et al., 2009). The Western Antarctic Peninsula could be directly influenced by emissions from Argentina and Chile during the summer season (Dickhut et al., 2005). At the same time, even with the low contamination level in the Antarctic snow, the volatilization of the contaminants from the surface snow due to wind ventilation could be a potential source of contaminants to the remote Antarctic atmosphere. It is clear that the surface snow of the sampling sites in East Antarctica received pollutants by the deposition of long-range transported air masses through the continent and the oceans.

In conclusion, our results suggest that the surface snow in East Antarctica contained low levels of persistent organic pollutants such
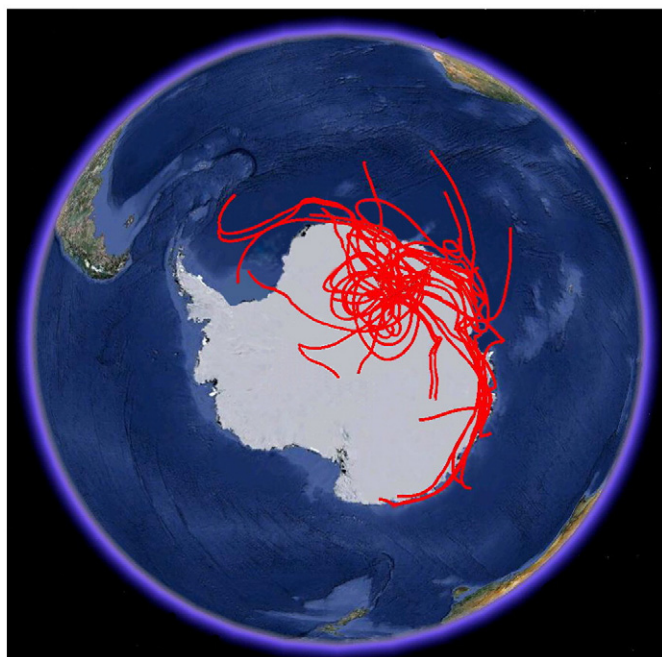
released into the atmosphere (Halsall, 2004). Katabatic wind may be a factor in the exchange of chemicals between the air and the surface snow. In addition, the t-test showed that the α-/γ-HCH ratio was significantly different between the sites >3500 m and those <3500 m ($p < 0.01$).

Fig. 4. Five-day backward air trajectories at the sampling sites during the sampling periods.

as HCHs and HCB and that Antarctic surface snow could be a potential source of POPs, which could affect Antarctic ecosystems.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2012.06.037.

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