Organochlorine pesticides and PCBs in fish from lakes of the Tibetan Plateau and the implications

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High mountains may play significant roles in the global transport of persistent organic pollutants (POPs). This work aims to investigate the levels, patterns and distribution of semi-volatile organochlorine pollutants and to improve the understanding of the long-range atmospheric transport and fate of contaminants on the Tibetan Plateau. A total of 60 fish samples were collected from eight lakes located between 2813 and 4718 m above sea level across the Plateau. Concentrations of polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs) including dichlorodiphenyltrichloroethane and its metabolites (DDTs), hexachlorocyclohexanes (HCHs) and hexachlorobenzene (HCB) were measured in fish muscle. The results showed that concentrations of DDT, HCH and HCB were comparable to or lower than those found in remote mountains of Europe, Canada and US, while PCB concentrations in fish were, on average, about 4\textsuperscript{e}150 times lower on Tibet than at other mountain areas. The transport and fate of contaminants in the Plateau are significantly influenced by the unique climatological and meteorological conditions, particularly by the summer Indian monsoon and winter westerly jet stream.

1. Introduction

Persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) are of high concern, not only because of their detrimental health effects but also because they are persistent and semi-volatile, thus able to travel long distances and distribute globally. Long-range atmospheric transport (LRAT) is a primary global transport pathway for POPs (Wania and Mackay, 1994). In warm regions, POPs tend to evaporate into the atmosphere, and the transport is often directed towards the colder polar regions where they are efficiently scavenged from the atmosphere. Similarly, low temperatures in alpine regions could allow high mountains to act as cold condensers and thus influence the global transport of POPs (Daly and Wania, 2005).

In Europe and North America, recent research has shown evidence of cold trapping in alpine regions for various airborne pollutants (Daly and Wania, 2005; Blais et al., 1998).

The Tibetan Plateau (the Plateau) lies between the Himalayan range to the south and the Taklamakan Desert to the north. With an area of 2.5 million square kilometers and an average altitude over 4000 m above sea level (a.s.l.), the Plateau is the largest and highest plateau in the world. It is characterized by harsh climate featuring dramatic elevational temperature gradient and monsoon affected air movement and precipitation patterns. With sparse human population and minimal industrial activity, atmospheric transport is essentially the only source of POPs to most areas of the Plateau. Recent work showed an increase in some contaminants in conifer needles with increasing altitude along the northern slope of the central Himalayas and the southeast Tibetan mountains (Wang et al., 2006; Yang et al., 2008). These results are in accordance with the observation for the Canadian Rocky Mountains by Blais et al. (1998) and several other studies summarized by Daly and Wania (2005). Such an altitudinal trend can be confounded by other influencing factors such as proximity to sources, directions of diurnal and seasonal airflow, and the topographic feature of the sampling locations.

Alpine lakes are unique depositories of long-range transported contaminants. The lakes on the Plateau are generally characterized...
by low temperature, low dissolved organic carbon (DOC) and low nutrient level (Xiang and Zheng, 1989). In these lakes, the food chain is generally short and simple compared with the lowland aquatic ecosystems. The fish inhabiting the lakes often have higher lipid storage, longer lives and slower growth rate than those in lowland lakes (Wu and Wu, 1992). Such fish might be sensitive to long-term accumulation of persistent pollutants and can be used as an important environmental compartment for transport studies in remote areas (Demers et al., 2007).

In this study, fish samples were collected from eight alpine lakes across the entire Plateau. Concentrations of PCBs and OCPs including dichlorodiphenyltrichloroethane and its metabolites (DDTs), hexachlorocyclohexanes (HCHs) and hexachlorobenzene (HCB) were quantified in the muscle of 60 fish samples. The contaminant levels, congener profiles and dominant factors influencing on the spatial distribution of POPs in the fish were examined.

2. Experimental section

2.1. Sample collection

The sampling locations are shown in Fig. 1, and the related geographic information is summarized in Table 1. The eight alpine lakes are located on the Plateau between latitudes 28.9°N and 37.3°N, and longitudes 79.9°E and 100.3°E, with elevations ranging from 2813 to 4718 m above sea level (a.s.l.). All studied lakes were of natural origin and situated far from known pollution sources. Fish samples were collected using fishing nets in August 2007 (except Co Na Lake and Keluke Lake, which were sampled in August 2006). Each fish was individually wrapped in nitrile gloves were used when handling samples. Most fish species collected belonged to the same family Cyprinidae and subfamily Schizothoracinae, which are unique in the Plateau (Wu and Wu, 1992). All the fish taken from a single lake were of the same species. Samples were stored in an ice-cooled box during transportation.

2.2. Fish characterization

Each fish was treated as an individual sample except for fish from Co Na Lake and Keluke Lake. These two lakes were sampled during the early stage of this work, and three fish from each of these two lakes were pooled to form a composite sample for the lake. For each sample, muscle tissue was homogenized and freeze-dried, and the subsamples were kept at −20 °C until chemical analysis. The actual age of each fish was determined by counting the growth ring of the vertebrae of the fish. The lipid content was determined gravimetrically. The conditioning factor, which is the ratio of weight (cg: g·kg⁻¹) to cubic length (cm³), was measured to compare the relative health status of individual fish from each lake.

2.3. Chemical analysis

The analytical procedure for OCPs was similar to our previously established method with some modifications (Yang et al., 2007). One gram of freeze-dried sample was mixed with sodium sulfate and extracted on a Dionex 300 accelerated solvent extractor (ASE) in 1:1 (v/v) dichloromethane:hexane. Suitable amounts of two surrogate standards, 2,4,5,6-tetrachloro-m-xylene (TMX, 1 ng) and PCB209 (5 ng) were added. Lipid content was determined gravimetrically using 20% of the extract. The other extract was subsequently concentrated on a rotary evaporator and subjected to clean up on a glass column (12 mm i.d.) packed with 8 g of activated Florisil. The elution was conducted by 70 mL 4:1 (v/v) dichloromethane and finally concentrated to about 0.5 mL by a gentle stream of nitrogen gas. Thirteen kinds of OCPs, including α-, β-, γ-, δ-HCH, HCB, p,p’-DDE, o,p’-DDE, p,p’-DDD, o,p’-DDD, p,p’-DDT and p,p’-DDE were analyzed by an Agilent 6890N gas chromatography (GC) equipped with a 63Ni electron capture detector (micro-ECD) (USA). A DB-5 fused silica capillary column (30 m length × 0.25 mm i.d.) coated with 5% dimethylsiloxane (film thickness 0.25 µm) was used for separation. The oven temperature was held at 80 °C for 1 min, ramped at 10 °C/min to 180 °C, held for 5 min, then at 2 °C/min to 215 °C, held for 4 min, and finally at 25 °C/min to 280 °C and held for 15 min. The temperatures of injector and detector were 230 °C and

![Fig. 1. The study area and sampling sites (F1: Qinghai; F2: Keluke; F3: Co Na; F4: Nam Co; F5: Yamdro; F6: Basum; F7: Manasarovar; F8: Palgon).](image-url)
injected in splitless mode. DB-5 capillary columns (60 m x 0.25 mm, 0.25 μm film thickness) were used for separation. Helium was used as carrier gas with flow rate of 1.2 mL/min. Each batch of 11 samples includes one procedural blank. The mean concentration of the PCBs was 0.01 ng/sample and the dominant congener was CB28. The mean recoveries for 13C-labeled surrogate PCBs were 60–115%.

3. Results and discussion

3.1. Fish characteristics

Average age of fish in each lake ranges between 6.3 (Manasarovar) and 10.4 yr (Nam Co) (Table 1). Length of individual fish ranged from 200 to 470 mm, and weighed between 65 and 899 g. The lake average fish conditioning factor ranged from 1.01 to 1.47 cg/cm³ (mean 1.12 cg/cm³), while lake-averaged fish lipid content varied from 1.58% to 4.94% (Table 1) and was not correlated with elevation of the locations. There was no correlation between age, conditioning factor or lipid content and elevation (P > 0.05).

3.2. Concentrations and patterns

Dry weight (dw) based lake average concentrations of the POPs in fish muscle are summarized in Table 2. Lipid normalized concentrations and composition profiles at different sampling sites are presented in Fig. 2.

Average concentrations of ∑HCH and HCB are 2.5 ± 1.4 ng/g dw and 1.1 ± 1.0 ng/g dw, respectively. The concentrations of α-, γ- and β-HCH were from 0.34 to 1.8 ng/g dw (mean 0.88 ng/g dw), from 0.37 to 1.6 ng/g dw (mean 0.82 ng/g dw), and from 0.35 to 1.1 ng/g dw (mean 0.70 ng/g dw), respectively. The concentrations of contaminants were transformed to wet weight basis in order to have a direct comparison with other remote mountain fish (Table 3). HCB concentrations in Tibetan fish were similar to Western US Parks (Ackerman et al., 2008) or slightly lower than the Canada Rocky (Demers et al., 2007) and European mountain fish (Vives et al., 2004; Blais et al., 2006; Schmid et al., 2007). ∑HCH in Tibetan fish were similar to European and Canada Rocky mountain fish, but higher than Western US mountain fish. Technical HCH usually contains 55–80% of α-HCH, 5–14% of β-HCH, 8–15% of γ-HCH and 2–16% of δ-HCH (Willett et al., 1998). In our samples, the lake-averaged concentration of α-, γ-, β- and δ-HCH were found to

### Table 1

Geographical position and related information to the samples.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Altitude (m)</th>
<th>Temp. (°C)</th>
<th>Precipitation (mm/y)</th>
<th>No. of fish</th>
<th>Species</th>
<th>Age</th>
<th>Conditioning factor (cg/cm³)</th>
<th>Lipid in muscle (%)</th>
<th>Water in muscle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qinghai</td>
<td>36°43.022'</td>
<td>100°15.101'</td>
<td>3225</td>
<td>1.2</td>
<td>337</td>
<td>7</td>
<td>Gymnocyris przewalskii</td>
<td>—</td>
<td>2.70 ± 1.91</td>
<td>75.9 ± 2.2</td>
<td></td>
</tr>
<tr>
<td>Co Na</td>
<td>37°17.162'</td>
<td>96°52.926'</td>
<td>2813</td>
<td>3.7</td>
<td>176</td>
<td>3</td>
<td>Carassius auratus</td>
<td>—</td>
<td>1.47 ± 0.04</td>
<td>1.69</td>
<td>79.9</td>
</tr>
<tr>
<td>Nam Co</td>
<td>32°02.021'</td>
<td>91°30.085'</td>
<td>4595</td>
<td>— to 4</td>
<td>400</td>
<td>3</td>
<td>Gymnocyris microcephalus</td>
<td>—</td>
<td>1.05 ± 0.13</td>
<td>2.59</td>
<td>80.0</td>
</tr>
<tr>
<td>Yandro</td>
<td>55°49.757'</td>
<td>92°28.351'</td>
<td>4441</td>
<td>2.4</td>
<td>373</td>
<td>17</td>
<td>Gymnocyris waddelli</td>
<td>—</td>
<td>1.30 ± 0.12</td>
<td>1.62 ± 0.80</td>
<td>81.5 ± 2.1</td>
</tr>
<tr>
<td>Basum</td>
<td>30°00.210'</td>
<td>93°54.376'</td>
<td>3538</td>
<td>6.0</td>
<td>600–700</td>
<td>6</td>
<td>Racoma bidulphita Gunther</td>
<td>—</td>
<td>1.06 ± 0.14</td>
<td>4.94 ± 2.26</td>
<td>77.9 ± 3.0</td>
</tr>
<tr>
<td>Manasarovar</td>
<td>30°43.017</td>
<td>81°27.670'</td>
<td>4588</td>
<td>2.0</td>
<td>169</td>
<td>7</td>
<td>Gymnocyris waddelli</td>
<td>—</td>
<td>1.07 ± 0.18</td>
<td>1.58 ± 0.70</td>
<td>83.2 ± 1.0</td>
</tr>
<tr>
<td>Palgon</td>
<td>33°31.191'</td>
<td>79°52.881'</td>
<td>4242</td>
<td>— to 2</td>
<td>61</td>
<td>7</td>
<td>Racoma tibetanus</td>
<td>—</td>
<td>1.01 ± 0.09</td>
<td>2.64 ± 1.55</td>
<td>80.6 ± 1.9</td>
</tr>
</tbody>
</table>

- a Meters above sea level.
- b Average annual temperature.
- c Data from reference (Xiang and Zheng, 1989).
- d Average value (±SD) of the fish analyzed in each lake.
- e Not determined.

### Table 2

Lake average concentration (ng/g dry weight) in fish muscle (mean ± standard deviation).

<table>
<thead>
<tr>
<th>Lakes</th>
<th>HCB</th>
<th>∑HCH</th>
<th>∑DDTs</th>
<th>∑PCBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qinghai</td>
<td>1.07 ± 0.73</td>
<td>1.61 ± 0.23</td>
<td>10.02 ± 0.79</td>
<td>4.04 ± 1.68</td>
</tr>
<tr>
<td>Co Na</td>
<td>0.60</td>
<td>1.34</td>
<td>4.19</td>
<td>0.44</td>
</tr>
<tr>
<td>Nam Co</td>
<td>3.64</td>
<td>3.91</td>
<td>—</td>
<td>0.91</td>
</tr>
<tr>
<td>Yandro</td>
<td>0.77 ± 0.73</td>
<td>4.03 ± 1.71</td>
<td>20.66 ± 7.25</td>
<td>2.01 ± 0.96</td>
</tr>
<tr>
<td>Basum</td>
<td>0.64 ± 0.23</td>
<td>2.75 ± 1.03</td>
<td>14.38 ± 7.08</td>
<td>0.32 ± 0.18</td>
</tr>
<tr>
<td>Manasarovar</td>
<td>1.11 ± 0.38</td>
<td>4.17 ± 1.64</td>
<td>34.55 ± 5.43</td>
<td>2.41 ± 1.18</td>
</tr>
<tr>
<td>Palgon</td>
<td>0.66 ± 0.30</td>
<td>2.09 ± 1.16</td>
<td>12.60 ± 19.73</td>
<td>0.34 ± 0.27</td>
</tr>
</tbody>
</table>

- a Pooled sample analysis.
- b Sum concentration of α-, β-, γ- and δ-HCH.
- c Sum concentration of p,p’-DDE, p,p’-DDE, p,p’-DDD, p,p’-DDT and p,p’-DDE.
- d Sum concentration of CBs 3, 15, 19, 28, 52, 77, 81, 101, 105, 114, 118, 123, 126, 138, 156, 153, 157, 167, 169, 180, 189, 202, 205, 208 and 209.
contribute 20—49%, 17—49%, 15—49% and 0—28%, respectively, to \( \Sigma \)HCH. The contribution of \( \beta \)-HCH was elevated about 3 times compared to the composition of the technical HCH. \( \beta \)-HCH is more stable and resistant to microbial degradation compared with other isomers. In addition, the \( \alpha \)- and \( \gamma \)-HCHs may be transformed to \( \beta \)-HCH in the environment (Walker, 1999). The ratio of \( \alpha \)/\( \gamma \)-HCH isomers ranges between 0.7 and 2.1, significantly lower than the range of 4—15 in technical HCH. Considering lindane (\( >90\% \gamma \)-HCH) is still being used in regions surrounding the plateau, the present low \( \alpha \)/\( \gamma \)-HCH ratio indicates the use of lindane as a potential main source.

Concentrations of \( \Sigma \)DDT were much higher than \( \Sigma \)HCH in the fish muscle, with a mean of 18 ± 14 ng/g dw. \( \gamma \)-DDT in Tibetan fish were, on average, comparable to Western US Parks and Canada Rocky mountain fish, but 3—5 times lower than the Europe a mountain fish (Table 3). Technical DDT usually contains about 85%
### Table 3
Comparison of contaminants concentrations in fish muscle from remote mountain lakes (ng/g ww).

<table>
<thead>
<tr>
<th>Location</th>
<th>Concentration (average, range)</th>
<th>N</th>
<th>Altitude (m)</th>
<th>Year</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibetan Plateau</td>
<td>0.21 (0.08–0.55)</td>
<td>62</td>
<td>2813–4718</td>
<td>2006–2007</td>
<td>This study</td>
</tr>
<tr>
<td>European mountains</td>
<td>0.42 (0.14–1.0)</td>
<td>163</td>
<td>436–2799</td>
<td>2000–2001</td>
<td>Vives et al. (2004)</td>
</tr>
<tr>
<td>French Pyrénées</td>
<td>0.26</td>
<td>37</td>
<td>450–2492</td>
<td>2001</td>
<td>Biasi et al. (2006)</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0.43 (0.15–1.1)</td>
<td>79</td>
<td>2062–2631</td>
<td>2003</td>
<td>Schmid et al. (2007)</td>
</tr>
<tr>
<td>Canada Rocky mountain</td>
<td>0.35 (0.014–1.9)</td>
<td>91</td>
<td>760–2360</td>
<td>1997, 2001, 2003</td>
<td>Demers et al. (2007)</td>
</tr>
<tr>
<td>Western US Parks</td>
<td>0.26 (0.01–1.3)</td>
<td>136</td>
<td>430–3030</td>
<td>2003–2005</td>
<td>Ackerman et al. (2008)</td>
</tr>
<tr>
<td>US Nevada</td>
<td>na</td>
<td>8</td>
<td>2384</td>
<td>1995</td>
<td>Datta et al. (1998)</td>
</tr>
</tbody>
</table>

*p* 25-DDE and 15% *p* 25-DDT (15% *p* 25-DDT; *p* 25-DDT = 0.18). In this work, *p* 25-DDT was detected at much higher percentage (*p* 25-DDT; *p* 25-DDT = 0.81 ± 0.55) compared with the original technical DDT composition. Recent research indicated pesticide dicofol is characterized by high ratio of *p* 25-DDT to *p* 25-DDT (about 7.0) (Qiu et al., 2005). The current use of dicofol in regions surrounding the Plateau (such as India and China) may have contributed to the current DDT profiles found in the fish. The dechlorination products p’25-DDT and o’25-DDT are p’25-DDT and o’25-DDT under reducing conditions, and *p* 25-DDE and *o* 25-DDE under aerobic conditions (Garrison et al., 2000). In this work, *p* 25-DDE was found to be the most abundant in the DDT family (Fig. 2B), and the observed ratio of p’25-DDE/ (DDE + DDD) is low (mean 0.20), indicating aged DDT pollution. According to the available concentration of DDTs in Yamdro lake water (Zhang et al., 2003), the biocorrelation factor of DDT by fish according to our result was estimated to be as high as 100%. The accumulation of persistent and lipophilic contaminants is likely to be exacerbated by fish in alpine lakes due to their higher lipid storage, longer lives and slower growth rate.

Average concentration of *Σ* 25PCB was 1.64 ± 1.35 ng/g dw, which was comparable with the concentration of HCB, but obviously lower than the concentration of *Σ* *HCH* and *Σ* DDT. The quantified congeners were quite different in the compared sites (Table 3). Although quantified congeners in our study were the most (*Σ* 25PCB), the *Σ* PCB in Tibetan fish were, on average, about 4–150 times lower than these compared mountain fish. PCB153 and PCB138 are the main congeners in most samples (Fig. 2C), varying from 14 to 34% and from 14 to 23% of *Σ* 25PCB, respectively. A strong linear relationship was found between indicator *Σ* 25PCB (CBs 28, 52, 101, 138, 153 and 180) and *Σ* 25PCB (coefficient *R* 2 = 0.91, *P* < 0.05). Penta and hexa-CBs were the predominant PCB congeners, ranging from 22 to 31% (mean 24%) and from 31 to 61% (mean 47%) of *Σ* 25PCB, respectively (see Supplementary Fig. S1). Although correlations between fish age and lake-wide average concentrations were not significant (*P* > 0.05) for most pollutants, positive linear correlations were observed between age and concentrations of heavier PCBs (octaPCBs: *R* 2 = 0.314; nonaPCBs: *R* 2 = 0.282, <0.05, *N* = 17) in individual fish in Lake Yamdro.

### 3.3. Spatial variations

Table 4 showed the multiple regressions for log-transformed concentrations (lipid wt, *N* = 56) with the temperature, precipitation, longitude and latitude of the sampling sites. The results indicated that the four parameters are major factors in explaining the variance in contaminant concentrations in fish sample and was correlated 11 of 14 contaminant class considered in Table 4 (*P* < 0.05).

Temperature was usually regarded as the predominant factor controlling the distribution of POPs in mountains (Wania and Westgate, 2008). Our results indicate HCHs and PCB concentrations correlate with the reciprocal of the absolute temperature (*P* < 0.05) or correlate with the elevations of the sampling sites (HCHs, Fig. 2A). Previous studies have shown that in the mountain slopes of the Plateau, such as Himalayas and southeast Tibet,
concentrations of some POPs in soil, pine needles and spruce needles increased with increasing altitude (Wang et al., 2006, 2009; Yang et al., 2008). Such a positive altitudinal gradient of concentrations points to the overlying atmosphere as the dominating input source for these pollutants, and suggests that the mountains in the Plateau act as a regional convergence zone, thus providing evidence of mountain cold trapping. Chen et al. (2008) also found the lighter PCBs and HCHs increased with the elevation in mountain soil samples in western Sichuan, China. However, for lighter PCBs (1–4Cl) in this study showed the different trend. The lakes situated at lower altitudes or higher temperature tends to have higher fractions of mono- and di-CBs congeners than the higher lakes (Table 4, Fig. S1). Such difference may be attribute to the locations of lakes of the plateau with very different meteorological conditions and proximity to sources. The heavier PCBs appear to be preferably enriched at higher elevation (Fig. S1). This result is consistent with the observation that less volatile congeners (with subcooled liquid vapor pressure ≤ 10−2.5 Pa) are preferentially trapped at higher locations (Grimalt et al., 2001) and the predictions by the Mountain-POP model simulations (Wania and Westgate, 2008). The lower tendency of heavier congener to re-evaporate from water into air during warm seasons may also result in their preferential accumulation downwind on lower temperature, which slows the metabolic dechlorination of PCBs in fish. Studies on mountain lakes across Europe revealed strong dependence of OCP concentration in fish on ambient air temperature of the sites as well as the proximity to sources in Central Europe (Daly and Wania, 2005; Gallego et al., 2007).

Precipitation is often believed to be efficient at capturing both particle-bound and gaseous POPs from air (Daly and Wania, 2005). F. Wang et al. (2007) also observed ten kinds of OCPs in newly deposited snow from the Mt. Everest region. However, in this study, only γ-HCH, 1–4 Cl, 6–10Cl and sum of PCB were correlated with precipitation ($P < 0.05$, Table 4) and most of OCP contaminants didn’t pass the significant test ($P > 0.05$). The transport and fate of POPs can be significantly complicated by other influencing factors such as the proximity to sources and the directions of seasonal airflow, which could be reflected by the latitudinal and longitudinal trends of pollutant concentrations. In this work, a negative correlation between logarithm of concentrations for most OCPs in fish and latitude or longitude was found (Table 4). The positive correlation of PCB with latitude suggests the lack of significant atmospheric transport of these industrial chemicals from the agriculture dominated areas south of the Plateau and also may be affected by other sources from north china (e.g. the highest PCB concentration was found in Lake Qinghai). The pathways of air mass to each sampling site were determined to assess potential source regions using backward trajectories from the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model (www.arl.noaa.gov/ready/hysplit4.html) (see Supplementary Fig. S2). During summer (June–September), high temperature over the Indian subcontinent and the Plateau causes a low-pressure front which induces a supply of air mass over the Indian subcontinent to move into the mountain ranges of the Plateau and results in significant precipitation events (Yanai and Wu, 2005). Air mass movement in the southern Plateau is controlled by the southeast wind (Sites F4–F6) and southwest wind (Site F7) arriving from the Indian continent. In contrast, in the northern (Sites F1 and F2) and northwest (Site F8) of the Plateau are prevailed by the westerly wind (Fig. S2a). During winter time the continent cools down and high-pressure drives the wind away from the Plateau and splits the westerly jet stream into two currents flowing south and north of the Plateau, and air mass movement to all the sampling sites is predominated by the westerly wind (Fig. S2b).

Sources of OCPs to the Plateau are likely to be significantly affected by the southwest or southeast air mass from Indian subcontinent. Our previous work showed a summer monsoon-controlled distribution pattern of OCPs in conifer needles in southeast Tibet (Yang et al., 2008). Zhu et al. (2004) have shown that there is a strong seasonal variation in the concentration of OCPs in an ice core from the Mt. Qomolangma region, resulted from the effects of the Indian monsoon. It is estimated that about $5 \times 10^{3}$ tons of DDT and more than $10^{4}$ tons of technical HCH have been used in India. China used about $2.7 \times 10^{5}$ tons of DDT as well as $4.9 \times 10^{5}$ tons of technical HCH from the 1950s until its ban in 1983 (Li et al., 1998). DDT and lindane are still being used to control certain insects in some tropical and subtropical countries including India, although in lower amount than in the past (Li et al., 1998). The effect of the monsoon on air pollution in this region has been documented in other studies (Valsecchi et al., 1999; Hindman and Upadhyay, 2002), providing additional evidence of region-specific meteorological influence. These findings combined suggest that OCPs transported by air to the Plateau might mainly originate from the Indian subcontinent.

4. Conclusion

This work provided evidence for atmospheric transport and deposition of POPs to higher-altitude lakes in the Tibetan Plateau. The accumulation pattern of POPs by alpine lake fish and some influencing factors on spatial variations were examined. The specific mechanism for transport of POPs to the Plateau is at present not completely understood due to the limited data. Future studies on the role played by the Plateau in the global distribution, long-range transport and the fate of persistent and toxic chemicals are warranted.

Acknowledgements

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Appendix Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envpol.2010.02.004.


