SCIENCE CHINA
Earth Sciences

• REVIEW •

October 2016 Vol.59 No.10: 1899–1911
doi: 10.1007/s11430-016-5073-0

Climate change and global cycling of persistent organic pollutants: A critical review

WANG XiaoPing[1,2*], SUN DianChao[1,3] & YAO TanDong[1,2]

[1] *Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China;*
[2] *Chinese Academy of Sciences Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China;*
[3] *University of Chinese Academy of Sciences, Beijing 100049, China*

Received March 3, 2016; accepted June 30, 2016; published online September 1, 2016

Abstract Climate warming, one of the main features of global change, has exerted indelible impacts on the environment, among which the impact on the transport and fate of pollutants has aroused widespread concern. Persistent organic pollutants (POPs) are a class of pollutants that are transported worldwide. Determining the impact of climate warming on the global cycling of POPs is important for understanding POP cycling processes and formulating relevant environmental policies. In this review, the main research findings in this field over the past ten years are summarized and the effects of climate warming on emissions, transport, storage, degradation and toxicity of POPs are reviewed. This review also summarizes the primary POP fate models and their application. Additionally, research gaps and future research directions are identified and suggested. Under the influence of climate change, global cycling of POPs mainly shows the following responses. (1) Global warming directly promotes the secondary emission of POPs; for example, temperature rise will cause POPs to be re-released from soils and oceans, and melting glaciers and permafrost can re-release POPs into freshwater ecosystems. (2) Global extreme weather events, such as droughts and floods, result in the redistribution of POPs through intense soil erosion. (3) The changes in atmospheric circulation and ocean currents have significantly influenced the global transport of POPs. (4) Climate warming has altered marine biological productivity, which has changed the POP storage capacity of the ocean. (5) Aquatic and terrestrial food-chain structures have undergone significant changes, which could lead to amplification of POP toxicity in ecosystems. (6) Overall, warming accelerates the POP volatilization process and increases the amount of POPs in the environment, although global warming facilitates their degradation at the same time. (7) Various models have predicted the future environmental behaviors of POPs. These models are used to assist governments in comprehensively considering the impact of global warming on the environmental fate of POPs and therefore controlling POPs effectively. Future studies should focus on the synergistic effects of global changes on the cycling of POPs. Additionally, the interactions among global carbon cycling, water cycling and POP cycling will be a new research direction for better understanding the adaptation of ecosystems to climate change.

Keywords Global and regional warming, POPs, Primary and secondary emission, Global cycling

Citation: Wang X P, Sun D C, Yao T D. 2016. Climate change and global cycling of persistent organic pollutants: A critical review. Science China Earth Sciences, 59: 1899–1911, doi: 10.1007/s11430-016-5073-0

1. Introduction

The basic characteristics of regional and global climate can be described as cold, warm, dry and wet. The temperature over the past 100 years has gradually increased, which has been proved by large numbers of observations (Meinshausen et al., 2009; IPCC, 2013, 2014), and lake (Wang et al., 2007b) and ice-core records (Thompson et al., 1997;

*Corresponding author (email: wangxp@itpcas.ac.cn)

Petit et al., 1999; Thompson et al., 2003). The fifth Intergovernmental Panel on Climate Change (IPCC) assessment report addressed the fact that global warming is undoubted and unprecedented (Sheng et al., 2013). The temperature during 1983–2012 was the highest since 1400 years ago, particularly in the Northern Hemisphere (IPCC, 2013, 2014). Global warming is therefore the main characteristic of climate change at present. Scientists have reached a consensus that global warming has mainly been caused by greenhouse gas emissions since the industrial revolution.

Global warming has already triggered a series of environmental problems. For example, the increase in glacier melting rates driven by climate warming has resulted in the rise of sea levels, which has initiated changes in global water cycling (Meehl et al., 2005; Vermeer and Rahmstorf, 2009). Another example is the large amount of carbon released into the environment from fossil fuel combustion, which directly causes global warming, has broken the original carbon balance in ecosystems, leading to changes in the global carbon cycle (Cox et al., 2000). Therefore, the relationships between climate change and water and carbon cycling, and their effects and response mechanisms are research hotspots in the field of global environment change (Cao and Woodward, 1998), and large numbers of related review papers have been published (Cao and Woodward, 1998; Huntington, 2006; Luo, 2007). In addition, climate warming also has complex and significant effects on the biosphere, especially in phenology (Hughes, 2000; Parmesan, 2007), food-chain structure (Petchey et al., 1999), biological diversity (Botkin et al., 2007) and the agriculture and animal husbandry industries (Mendelsohn et al., 1994).

There are also close relationships between climate change and pollutant emissions, distribution and toxicity (Bridgman, 1991; Noyes et al., 2009; Seinfeld and Pandis, 2012). Both the IPCC report and the United Nations Environment Programme (UNEP) annual report emphasized that we should pay attention to the problem of environmental pollution, especially under the influence of global warming (UNEP, 2010; IPCC, 2013). So far, persistent organic pollutants (POPs) have drawn special attention. Considering the persistence, volatility, toxicity, bioavailability and long-distance atmospheric transport of POPs, more than 150 countries worldwide signed the Stockholm Convention on POPs to jointly protect the environment (Zheng, 2013). Similar to the influence of climate warming on the carbon and water cycles, the distribution, behavior and transport of POPs are also global-scale problems (Figure 1) and all these global environmental problems are interrelated. POP cycling is closely associated with biological material cycling and energy flow (Figure 2). In fact, emission, transport, sources and sinks, bioavailability, degradation, food-chain transfer and toxicity of POPs are all closely related to climate change. But how does climate change affect the global cycling of POPs? In this paper, the research progress regarding this scientific problem is summarized and reviewed, and existing problems and future research direction are highlighted.

2. Changes in POP emission sources

POPs are a series of pollutants that are persistent, toxic, bioavailable and semi-volatile in the environment (O'Sullivan and Megson, 2014). The Stockholm Convention lists several precedent-controlled POPs, including organochlorine pesticides (OCPs, representative compounds include dichlorodiphenyltrichloroethane (DDT)), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers

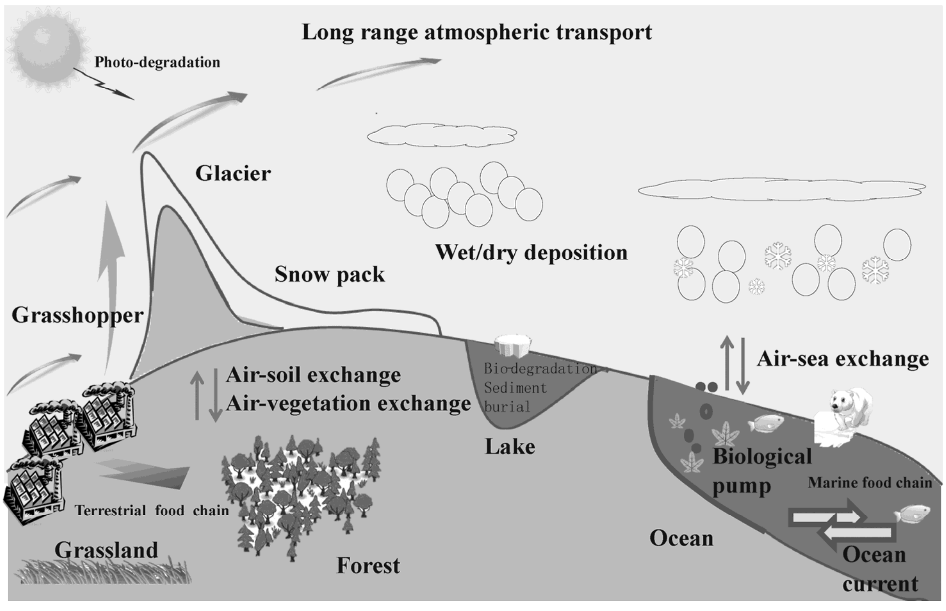

Figure 1 Transport processes for persistent organic pollutants.

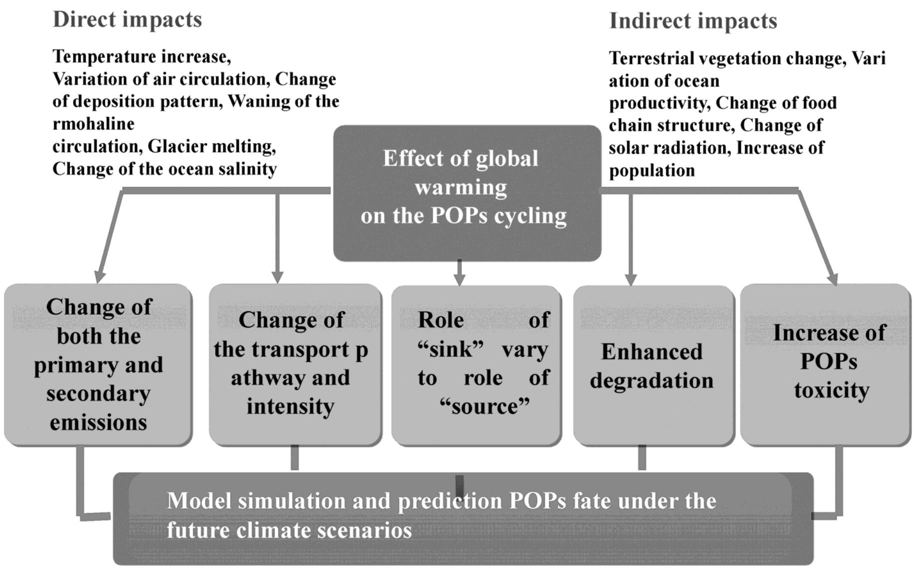

Figure 2 Direct and indirect impacts of climate change on the behavior and fate of persistent organic pollutants.

(PBDEs) and perfluorinated substances (Wang et al., 2009; Wang et al., 2010b). These pollutants are intentionally made synthetic chemicals, and industrial and agricultural activities are their main emission sources. In addition, some unintentional discharged byproducts (i.e. polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) generated by metal smelting and waste incineration) and polycyclic aromatic hydrocarbons (PAHs) are also included in the Stockholm Convention control list and the long-range atmospheric transport draft (Wania, 2003; Liu and Zheng, 2013; Zheng, 2013). Whether intentional or unintentional, the direct emission of POPs through human activities is regarded as the primary emission. In addition, owing to their semi-volatility, elevated environmental temperatures result in the re-evaporation of POPs from surface media, which is called the secondary emission. Obviously, global warming will affect industrial and agricultural production and the secondary emission of chemicals, leading to changes in POP emission sources (Figure 2).

Global warming has triggered droughts and rising sea levels, which has resulted in the reduction of global arable land (Parry and Ruttan, 1991). The fourth IPCC report indicated that under the influence of global warming, the northern boundary for crops will continue to move to higher latitudes (IPCC, 2013; Wöhrnschimmel et al., 2013). Overall, the influence of global warming on crop production is complicated and shows strong regional differences. In general, the impact of climate warming on agriculture is more negative than positive. One of the main negative influences is the agricultural pest problem. The distribution, growth and reproduction of crop pests are closely related to temperature. Low temperatures prohibit pest growth and reproduction. With the increase in temperature, the distribution area of crop pests is expected to expand (Porter et al., 1991; Rosenzweig et al., 2001). Both changes in agricultural planting areas and the ravage of pests will require changes to the pesticide type and dosage. Therefore, from the perspective of global warming, this would likely result in massive emission of pesticidal POPs, including some that have been listed in the Stockholm Convention, such as endosulfan and lindane, as well as some new pesticides.

The IPCC's fifth report states that it is very likely that the frequency of heatwaves and rainstorms will increase with global warming. This means that global warming prompts extreme climatic events such as droughts, floods and hurricanes (Shen and Wang, 2013) and it is generally acknowledged that malaria is widespread after flooding (Easterling et al., 2000; Rosenzweig et al., 2001). Furthermore, with the expansion of climate warming, the malaria-affected area might also extend from the tropics to the Polar Regions (Githeko et al., 2000). Studies predict that the number of malaria patients will double in the tropical regions by 2100 and increase tenfold in temperate zones. In the next century, 45–60% of the global population may live in the potential transport area of malaria (Martens et al., 1995; Lindsay and Birley, 1996). DDT, one kind of POP, is a powerful chemical used to control the spread of malaria and has been widely used to fight the malaria parasite *Plasmodium* in many countries (Roberts et al., 2000; Stapleton, 2004). Owing to its toxicity, DDT has been banned since the 1970s. However, due to its low cost and high efficiency in terms of anti-malarial activity, in 2006, the World Health Organization (WHO) suggested the re-use of indoor spraying of DDT to block malaria transport (Sadasivaiah et al., 2007). Malaria-vulnerable countries, such as India and South Africa, also applied to the Stockholm Convention for exemption of DDT (Sharma et al., 2005; Channa et al., 2012). Consequently, global use of DDT is expected to increase due to the impact of climate warming.

Owing to their semi-volatility, POPs widely exist in all kinds of media in the world. They continuously undergo dynamic distribution between the atmosphere and the land surface, e.g. soil, water, vegetation and so on. (Bidleman, 1999). The physicochemical parameters of POPs, such as saturated vapor pressure, Henry's law constant, gas-water partition constant and octanol-air partition coefficient, are all temperature-dependent constants (Paasivirta et al., 1999). Therefore, the constantly rising temperatures will significantly affect the distribution of POPs between different phases, and promote POPs to migrate from the land surface to the atmosphere. Consequently, there are more active POPs in atmosphere (Hung et al., 2010; Ma and Cao, 2010). This process is called the secondary emission of POPs. Studies have shown that most European soils are a secondary source of low-molecular-weight PCBs (Meijer et al., 2003; RůŽičková et al., 2007), and Indian soils are a secondary source of DDT (Sharma et al., 2014). The elevated PCB concentrations in the Arctic atmosphere have been mainly attributed to the gradual rise in environmental temperature driven by global warming (Becker et al., 2006). Although the use of hexachlorocyclohexane (HCH) had been banned for more than 30 years, the current HCH concentration in the Arctic atmosphere is not decreasing, but slightly increasing. Ma et al. (2011) reported that secondary release of HCH caused by climate warming has buffered the effect of HCH prohibition.

3. Changes in the long-range transport of POPs

Atmospheric circulation and ocean currents are two major ways in which POPs are globally transported. POPs can exist in the atmosphere in both gas and particulate phases. Hence, with the help of atmospheric circulation, gaseous and particulate POPs in atmosphere can be globally spread (Jones and De Voogt, 1999). During the atmospheric transport process, POPs are likely to be deposited on the land surface when the temperature decreases, while they will evaporate into the atmosphere to migrate again when the temperature rises. This process continually occurs, so POPs can be transported and deposited to remote areas. This is the so-called grasshopper effect (Gouin et al., 2004). In addition, some POPs with relatively higher solubility, such as HCH (Kucklick et al., 1991) and perfluorooctane sulfonates (PFOS) (Giesy and Kannan, 2002), can also enter into surface waters, and then feed into ocean currents and undergo global ocean transport (Yamashita et al., 2008). Climate warming leads to changes in climatic factors, such as temperature, wind speed, wind direction and precipitation. The variation of these factors will certainly alter both the air and ocean transport intensity and pathways of POPs.

The global temperature gradient decreases with increasing latitude. The emission sources of POPs are mostly distributed in low-latitude areas with relatively warm temperatures. Accordingly, chemicals with high volatility will undergo multi-hopping, and will be easily transported to the high-latitude Polar Regions, while less-volatile compounds undergo less or single hopping. This leads to global chemical fractionation. This effect is termed the global distillation effect (Fernández and Grimalt, 2003). The global distillation effect of POPs is an important hypothesis to explain the global transport mechanism of POPs, which has been verified by numerous studies (Wania and Su, 2004; Blais, 2005; Yang et al., 2008). In this model, the ambient temperature is a decisive factor driving POP transport. If the ambient temperature increases by 1°C, the volatility of POPs increases by 10–15% (Lamon et al., 2009b; Wǒhrnschimmel et al., 2013).

The global atmospheric circulation shows obvious fluctuations with climate change. The major climate phenomena are the El Nino-Southern Oscillation (ENSO) in the Southeast Pacific and Indian oceans, the Northern Atlantic Oscillation (NAO) and the Pacific North American (PNA) teleconnection. Based on a 20-yearlong dataset of atmospheric POP observations in the Great Lakes region, Ma et al. (2003, 2004), Ma and Li (2006) assessed the relationship between POP levels and climate signals, and found that there was a significant correlation between variations in the hexachlorobenzene (HCB) concentration and ENSO fluctuations, and between variations in the HCH concentration and NAO fluctuations in winter and spring, respectively. Although various studies have shown that the primary emission of POPs has gradually decreased, HCB and HCH were found in elevated concentrations, which has been attributed to the increased temperature associated with the ENSO and NAO in the Great Lakes region. Temperature is a driving force for secondary emission of pollutants from soil and water, which is the reason for the increase in atmospheric concentration of HCB and HCH. Climate change will also affect the atmospheric transport of POPs in China. China was the main user of α-HCH and soils may have been contaminated with higher levels of residual chemicals. Tian et al. (2012) found that the output flux of α-HCH through the atmospheric circulation from Northeast China significantly increased under climate warming.

In addition, higher wind speeds will lead to the large-scale and more-effective intercontinental transport of POPs. During the positive phase of the NAO, strong westerly winds blow over the North Atlantic, which enhances the transport of used POPs in the Canadian prairies to the Great Lakes region (Gao et al., 2010; Christoudias et al., 2012). When the PNA pattern is enhanced, southwesterly winds from Canada are increased, which leads to POP transport to the north polar area (Hung et al., 2005). As another kind of climate system, monsoons can change the direction of the atmospheric circulation and precipitation intensity on the seasonal scale. The pathways and intensity of atmospheric transport of POPs is thus shifted seasonally. Previous studies have found that the monsoon enhances the vertical input of atmospheric POPs to the Arabian Sea (Dachs et al., 1999). Moreover, atmospheric transport driven by the monsoon continuously transports POPs of South Asia to the Tibetan Plateau (Sheng et al., 2013). Climate change influences not only the intensity of the monsoon, but also the direction of the wind at large spatial scales, both of which affect the global transport of POPs.

Atmospheric deposition is an important process in the global cycling of POPs. It plays an important role in scavenging. Temperature is the main factor that affects the form and the efficiency of atmospheric wet deposition (Lei and Wania, 2004). When the temperature reaches 0°C, rainfall has a greater removal efficiency of low-molecular-weight compounds existing in the gas phase, while snow has a higher removal efficiency of high-molecular-weight compounds and non-polar compounds (Lei and Wania, 2004). When the temperature is below 0°C, snow can more effectively remove compounds from the atmosphere (including both gaseous and particulate POPs); thus, this process can block POP transport to the atmosphere. There is a great difference in terms of atmospheric wet deposition for different compounds due to their different physical and chemical properties (Lei and Wania, 2004). From a global perspective, high POP deposition flux values in the intertropical convergence zone and high-latitude areas are expected due to high precipitation-induced wet deposition and low temperature-induced cold trapping, respectively (Jurado et al., 2005). In fact, the intertropical convergence zone will continue to move to northward under the influence of global warming (Frierson and Hwang, 2012), and the global precipitation patterns will be more varied (Philander et al., 1996; Held and Soden, 2006), which could possibly further change the global transport and distribution pattern of POPs.

Compared with the atmospheric transport (unit of speed: m s^{-1}) of POPs, ocean current transport (unit of speed: cm s^{-1}) is a relatively slow process. POPs enter into the ocean currents by both atmospheric deposition and surface runoff (Zingde, 2005; Zhang et al., 2011). A series of observation data from offshore has demonstrated that seawater of the European Mediterranean (Gómez-Gutiérrez et al., 2007; Castro-Jiménez et al., 2012), Baltic Sea (Theobald et al., 2011), North Sea (Ilyina et al., 2006), Bohai Sea (Chen et al., 2011), Yellow Sea (Lin et al., 2012; Zhong et al., 2014; Yang et al., 2003), South China Sea (Lin et al., 2012), Indian Ocean (Xie et al., 2011; Huang et al., 2013) and the Bay of Bengal (Sarkar et al., 2008) contain higher levels of POPs. These pollutants include compounds banned in the Stockholm Convention as well as some emerging POPs (Kallenborn et al., 2012). The sea itself is a huge circulation system: warm streams transfer tropical heat poleward, while ocean currents cool and sink in the Polar Regions, transferring matter and energy on the global scale (thermohaline circulation). Lohmann et al. (2006) calculated the sinking flux of PCBs on the basis of the sink rate of seawater. The results showed that the sinking flux of PCBs in the Norwegian Sea was larger than that in the Labrador Sea, the Ross Sea and Weddell Sea in the Southern Ocean. They also pointed out that PCBs can be used as tracers to track the movement of deep ocean currents. Currently, with global warming continuing, the temperature gradient that drives the thermohaline circulation is waning (Rühlemann et al., 1999). Thereby, the global ocean transport of POPs would be affected and needs to be investigated in future.

4. Effect of climate change on the fate of POPs

After transport, POPs eventually sink into the ocean, cryosphere, forest and soil (Figure 1). The ocean accounts for more than 70% of the global surface and is the largest sink of most pollutants (Sobek and Gustafsson, 2014). Seawater, zooplankton and particles contain measurable amounts of POPs, but most POPs are stored in ocean sediments (Nizzetto et al., 2010). Moreover, the forest canopy and soil organic matter can effectively accumulate atmospheric POPs. Therefore, the terrestrial ecosystem also stores a large amount of POPs (Ockenden et al., 2003; Nizzetto et al., 2010). As well as marine and terrestrial ecosystems, the cryosphere is another important destination for POPs. With wet deposition, atmospheric POPs can be scavenged by rain and snow and further stored in glaciers (Hermanson et al., 2005; Meyer and Wania, 2008). The cryosphere is extremely sensitive to climate change, so POPs stored in the cryosphere are prone to re-release under global or regional warming, and become secondary sources of POPs. Under the influence of global warming, the role (sink or source) of marine and terrestrial ecosystems and the cryosphere in POP global cycling will certainly change.

Owing to the hydrophobicity of POPs, they exist in the ocean in the particulate phase. Dissolved organic carbon, particulate matter, phytoplankton and so on all act as carriers of hydrophobic POPs in water. Maldonado et al. (1999) studied the vertical profile of PAHs in the Black Sea, and the results indicated that the highest value of PAHs appeared at a depth of 30 m, which was mainly attributed to the high biomass of phytoplankton at that depth. Phytoplankton plays an important role in the transport of POPs from water to sediment. On the one hand, phytoplankton absorb POPs, which decreases the POP concentration in water (Dachs et al., 2000). On the other hand, POPs associated with phytoplankton sink down the water column and finally accumulate in sediment. These two processes drive the flow of POPs from the atmosphere to the ocean, which is known as the biological pump (Dachs et al., 2002). Obviously, POPs in the atmosphere continuously enter into the deep-sea sediments through this effect. However, seawater temperature is rising as a consequence of global warming, which has reduced ocean primary productivity by 6% since the 1980s (Hoegh-Guldberg and Bruno, 2010; Galbán-Malagón et al., 2012). Therefore, climate warming indirectly affects the ocean's ability to absorb POPs by changing ocean primary productivity.

Soil with a high organic matter content has a higher POP storage capacity. Owing to the different distributions of soil temperature and organic matter content at different scales, the POP storage ability of soil varies. The POP storage ability in the Sahara Desert with a low soil organic matter content is relatively weak, while the POP storage ability in Siberia, Scandinavia, Canada and Alaska, which are characterized by a higher organic matter content, is much stronger (Dalla Valle et al., 2005).

Forest accounts for about 31% of the land area worldwide (Guan, 2003). The forest canopy provides an extensive organic surface for the partitioning of POPs in the atmosphere, and increases the net atmospheric deposition of POPs (Horstmann and McLachlan, 1998; McLachlan and Horstmann, 1998, Wania and McLachlan, 2001). Owing to vegetation renewal and litter fall, forest increases the atmospheric deposition of POPs. As a consequence, terrestrial forest ecosystems are important sinks for environmental POPs (Horstmann and McLachlan, 1998; McLachlan and Horstmann, 1998). It is well established that boreal forest can store 2–20% of global PCB emissions (Moeckel et al., 2009). From a global perspective, land cover has been transforming at a relatively high speed. Deforestation, agricultural reclamation and urbanization destroy the soil layer, so POPs that have accumulated in soil are re-released. These processes also reduce the POP retention capacity of soil (Komprda et al., 2013). In contrast, climate warming may also exert positive effects on the storage of POPs; for example, climate warming can extend the vegetation growing season and increase the content of soil organic carbon (Komprda et al., 2013), which may consequently increase the accumulation of POPs in terrestrial ecosystems.

Precipitation plays an important role in the deposition of POPs. POPs scavenged by atmospheric wet deposition can be stored in glaciers, snow pack and sea ice (Yao et al., 2002; Hermanson et al., 2005; Wang et al., 2007a; Meyer et al., 2008a, 2008b; Meyer and Wania, 2008; Wang et al., 2008, 2014; Guglielmo et al., 2012). Antarctica has the largest glacial area worldwide. Peterle et al. (1969) estimated the storage of DDT in Antarctica (2.4×10^6 kg) based on concentrations of DDT and Antarctic snow-ice reserves (24×10^7–$30\times10^7 m^3$) measured in 1966. Hofmann et al. (2012) calculated the storage of HCH and DDT in environmental medium and identified that approximately 8.4% of atmospheric γ-HCH and 10.4% of atmospheric DDT were deposited to snow and glaciers.

It is possible to evaluate the atmospheric concentration level, accumulation flux and historical accumulation trend of POPs based on dated ice cores (Hong et al., 2009). Currently, research regarding accumulation of POPs in ice cores is mainly focused on Arctic Svalbard (Hermanson et al., 2010), the Italian Alps (Villa et al., 2003, 2006; Maggi et al., 2006), China's Tibet (Wang et al., 2008, 2010a, 2014) and the Canadian Ellesmere Island (Veillette et al., 2012; Zhang et al., 2013). Ice cores are regarded as natural archives of pollutants as well as past climate. Global warming is having a remarkable impact on the cryosphere (Parry, 2007). The IPCC report states that during the past 30 years, global glaciers have continued to retreat in length, area and volume (Stocker, 2014). In addition, snow cover in the Northern Hemisphere has decreased, and the thickness and area of permafrost in Russia and northern Europe evidently reduced between 1975 and 2005 (IPCC, 2013). Melting of Arctic glaciers has released massive amounts of POPs back into atmosphere, leading to a slight increase in the concentration of a variety of POPs in the Arctic atmosphere during the past 20 years (Ma et al., 2011). Furthermore, the concentration of DDT in penguins from Antarctic has not decreased, which might be associated with the release of POPs from melting glaciers (Geisz et al., 2008). Melting glaciers may also increase the concentration of POPs in fresh water (Ma et al., 2011). Blais et al. (2001) found that 50–90% of POPs in Glacier Lake were sourced from glacial melt water. Under global warming, POPs can also migrate into the lakes through the water cycle and even accumulate in lake sediments (Bettinetti et al., 2008; Bogdal et al., 2009).

In summary, climate warming will alter the role (source or sink) of the land surface in the global cycling of POPs. Originally, glaciers, oceans and soil were sinks of POPs. However, the re-release of accumulated POPs under the influence of global or regional warming has resulted in glaciers, oceans and soil becoming sources of POPs (Bettinetti et al., 2008; Cabrerizo et al., 2011). As the primary emission of POPs has been regulated, secondary emission is now the main source of POPs in the atmospheric environment.

5. Effect of climate change on degradation, bioavailability and toxicity of POPs

The degradation of POPs in the environment is mainly divided into two types: photodegradation and biodegradation. The degradation rate of POPs is influenced by hydroxyl radical (·OH) and ozone (O_3) contents in the atmosphere (Klöpffer, 1992; Sinkkonen and Paasivirta, 2000; Wania and Daly, 2002). The microbial degradation of POPs primarily occurs in soils and sediments (Kawamoto and Urano, 1990; Hirano et al., 2007). The pH value of soil and sediment, organic carbon content and the amount and type of microorganisms affect the biodegradation rate of POPs. A higher organic carbon content can provide microorganisms with the energy to degrade POPs, thus speeding up the degradation process of pollutants (Hirano et al., 2007).

Global warming has led to an increased ozone concentration in the troposphere (Racherla and Adams, 2006; Stevenson et al., 2006 ; Cheng et al., 2007). In addition, model simulations have shown that the concentration of ozone will continue to rise from now to 2050 (Hogrefe et al., 2004). From this point of view, the scientific community generally believes that photodegradation of POPs will become more severe under the effect of global warming (Brubaker and Hites, 1998; Macdonald et al., 2003; Sweetman et al., 2005; Ma et al., 2004; Meyer and Wania, 2008).

Similarly, Dalla Valle et al. (2007) concluded that increasing temperatures will lead to the prosperity of the microbial community in Italy's Venice Lake, which should enhance the biodegradation of PCBs and chlorinated furan. The decomposition of organic carbon in terrestrial and aquatic ecosystems is an important biological process that affects the bioavailability of POPs. Research in Ontario revealed that drought and dissolved organic carbon decomposition associated with global warming increased the effective content of POPs, which meant the bioavailability of POPs increased (Magnuson et al., 1997; Schindler et al., 1997).

Numerous studies have concluded that the bioavailability and toxicity of POPs in wild organisms increases with the increase of temperature and salinity (Wang et al., 2001; Waring and Moore, 2004; Capkin et al., 2006; Jenssen, 2006; Schiedek et al., 2007). Possible mechanisms for this are as follows. (1) The dynamic toxicity effect of compounds increases with the increasing temperature (Buchwalter et al., 2003; Maruya et al., 2005). (2) Warming gives rise to a weak immune ability of wildlife to POPs (Broomhall, 2002, 2004; Patra et al., 2007), which results in increasing toxicity of POPs. (3) Studies in Seattle Bay identified that increasing water salinity led to acute toxicity of salmon as anticholinesterase metabolites increased (Schlenk and Lavado, 2011). (4) Compared with the above three mechanisms, structural changes in ecosystem food chains derived from global warming is the leading factor that increases the toxicity of POPs to whole ecosystems (Macdonald et al., 2005; Jenssen, 2006; Burek et al., 2008; Noyes et al., 2009; Borgå et al., 2010; Bustnes et al., 2011).

6. Model simulation and prediction of the environmental behavior of POPs

So far, plenty of models have been applied to simulate and predict the environmental behavior and transport trends of POPs under the influence of global warming (Huang et al., 2007; Shindell et al., 2008; Guglielmo et al., 2009; Lamon et al., 2009a, 2009b; Stemmler and Lammel, 2009, 2012; Lammel and Stemmler, 2012; Gouin et al., 2013; Kong et al., 2013, 2014). These models can be grouped into two general categories. One is multimedia models based on fugacity theory, which is simple and has been widely used (Mackay, 2001). The other is general circulation models (GCMs), which divides the world into different areas and focuses on the transfer processes of mass, energy and momentum of chemicals among the atmosphere, land surface and ocean (Ilyina et al., 2006). These models can not only predict the environmental behaviors of POPs, but also determine the key environmental factors that affect the global transport of POPs. The main characteristics of these models are summarized below and in Table 1.

The Berkeley-Trent Global Model (BETR-Global) is a global mass-balance model based on steady state (level III) or unsteady state (level IV) fugacity scenarios. It synthetically considers the influence of temperature, atmospheric stability, atmospheric boundary layer and photochemical reaction processes on the transport of POPs under different environmental conditions (MacLeod et al., 2005).

Globo-POP is an integrated model with a prediction function based on the level IV fugacity model. Compared with the differences between this model and other fugacity models, Globo-POP considers non-temporal resolved input parameters, including organic carbon, aerosol and suspended particulate matter (Wania and Mackay, 1995; Meyer and Wania, 2007). Globo-POP resolves inputs consisting of temperature, ice cover and hydroxyl radical concentration. In the improvement of the Globo-POP model by Stocker et al. (2007), the impact of glacier melting on POPs was also taken into consideration.

Table 1 The main multimedia fate and transport models cited in this paper

Model	Description	Features
BETR-Global	Level III-IV fugacity model. The world is divided latitudinally and longitudinally into 288 regions. Seven environmental compartments are considered (two atmospheric layers, soil, vegetation, coastal water, freshwater and sediments).	This model can be flexibly applied on different scales (local) or global simulation.
Globo-POP	Level IV fugacity model. Latitudinal resolution up to 10 regions. It takes into account 9 compartments (freshwater and sediment, four vertical atmospheric layers, upper ocean layer, cultivated and uncultivated soils).	This model can be used for assessing the POPs fate and under the influence of ice melting.
G-CIEMS	Level IV fugacity model. GIS-based models. Six environmental compartments are assumed in this model (atmosphere, freshwater - rivers and lakes, coastal water, sediments, soil).	It could be used for calculating the fate of persistent pollutants in a climate change perspective especially at high spatial resolution for the dry land areas, where this model allows to easily distinguish different environments.

Another possibility for POP fate modeling is the spatially resolved and geo-referenced dynamic multimedia environmental fate model, G-CIEMS (Grid-Catchment Integrated Environmental Modelling System). This model integrates a basic fugacity formulation following a level IV calculation, on a geographic information system (GIS) (Suzuki et al., 2004). Six compartments, namely air, freshwater (rivers and lakes), sediments, forest, seawater, soil, and advective transport are considered.

Given that POP fate models can predict the transport pathways, intensity and concentrations of POPs for future climate scenarios, the model results provide policy makers with scientific information for an early response to these changes. Recently, on the basis of the moderate intensity greenhouse gas emission scenario, Octaviani et al. (2015) used a GCM to study meridional transport of POPs under the present-day (1970–1999) and future (2070–2099) climate. POP transport channels into the Arctic were identified as (1) the Alaska-North America channel, (2) the Greenland channel, (3) the Norwegian Sea-West Russia channel (Europe) and (4) the Urals-Siberian channel (Asia). Moreover, ignoring the primary emission of POPs, the model also predicts that secondary volatilization of DDT caused by global warming will still be continuously transported to the north polar area. However, in contrast, the results also predicted that the net export of PCB 153 out of the Arctic will increase under future climate conditions (2070–2099, Octaviani et al., 2015).

In general, model application provides a view for evaluating the process and degree of the rise, cycling and fading away of POPs on the larger spatial and longer temporal scales. The current laws and regulations regarding environmental pollution do not consider the influence of climate change on the concentration of POPs in the environment. In fact, several studies have demonstrated that global warming could increase the long-range transport ability of POPs. As a result, it is necessary to consider the impact of climate warming on environmental loading of POPs in the formulation of relevant policies in future.

7. Research prospects

From the statistical results of the literature, studies related to climate change and the global transport of POPs were rarely reported until 2004. However, this research direction began to flourish from 2004 onwards and has made considerable progress during the past ten years. Both field observations and model simulations have proved that warming directly and indirectly affects the transport, distribution and final fate of POPs. Table 2 summarizes the response of POPs to global change for publicity and policy-making departments to understand and judge the factors.

Relevant research work in the Arctic is impressive. Scientists are conducting systematic studies in the following areas: (1) the effect of melting snow and ice on the secondary release of POPs; (2) the effect of secondary release of POPs on the temporal and spatial distribution of POPs in

Table 2 Environmental behavior of persistent organic pollutant in response to global change [a)]

Scenario	Environmental consequence	Response of POPs	Effect on POPs level	Reference
Glaciers melting	Fresh water was injected into the environment; chemicals stored in the glacier were released.	POPs were rereleased into the environment e.g. atmosphere and lakes	+	UNEP, 2010; Grannas et al., 2013
Permafrost degradation	Exacerbated surface erosion	Increased the second emission of POPs	+	Evans et al., 2005; Grannas et al., 2013
Sea level rise	Increased erosion	Increased the second emission of POPs	+	Kwok et al., 2009
Salinity of sea water changes	Two situation: salinity is decreased due to injection of glacier melting water; seawater salinity increase because of local drought	Change of the marine food chain structure, variation of metabolism of marine biota	±	Olsen et al., 2011
Flood	Severe erosion	Increased the second emission of POPs	+	Holoubek et al., 2007
Forest fire	Surface soil temperature rise up the non-intentional POPs	Increased both the primary and secondary discharge of POPs	+	Kim et al., 2003; Kallenborn et al., 2011
Changes of atmospheric circulation	Changed POPs transport intensity and direction of	Changed the environment distribution of POPs	±	Ma et al., 2004, 2011; Ma and Li, 2006
Ocean current change	Changed POPs transport intensity and direction of	Changed the environment distribution of POPs	±	Lohmann et al., 2006
Population increase	Increased use of pesticides, malaria outbreak, and worsened environmental pollution	Increased both the primary and secondary discharge of POPs	+	Noyes et al., 2009
Soil desertification	The reconstruction of the vegetation zone around the world	Changed the fate of POPs	+	Noyes et al., 2009
Variation of biodiversity	The components of regional biosphere changed	Changes on the biological enrichment of POPs at regional scale	±	Brander, 2007

a) +, positive; –, negative

multimedia of the Arctic; (3) changes in the accumulation characteristics of POPs in Arctic ecosystems (marine food chain and tundra food chain) under the background of climate warming; (4) long-distance transport potential of different POPs to enter into the Arctic under the condition of climate warming; (5) how POPs will be imported to and exported from the Arctic area in a warming future. However, there are still various research gaps:

(1) The POP emission inventory is relatively clear, but under the gradual decrease of primary source POPs and the increasing importance of secondary emission, caused by climate warming, from the soil and sea, how can the contribution of secondary emission of POPs be quantified ?

(2) It is necessary to study the effect of extreme weather, such as floods and storms, and soil sustainable desertification on migration of POPs on the global scale.

(3) It is necessary to carry out research on the relationship between emerging POPs and climate change.

(4) It is necessary to comprehensively assess the environmental and ecological impacts of POPs released from glaciers melting on global main mountain areas, e.g. the Alps, the Himalayas, and the Rocky Mountain.

(5) How can the relative contribution of secondary emission and degradation of POPs prompted by climate warming be measured?

In conclusion, the impacts of climate change on the global cycling of POPs are linked to the production and use of chemicals, temperature increases, variations in ocean and atmospheric circulation, change of land cover, biological absorption and metabolism, multiple photochemical reactions, multiple interface processes and other complex processes. The study of these impacts requires long time series observational data and large-scale research projects with international cooperation (Hung et al., 2010; Kallenborn et al., 2015; Pacyna et al., 2015), as well as collaborations of scientists from various disciplines (Nadal et al., 2015).

Acknowledgements *We thank Dr. Gong Ping, Dr. Wang Chuanfei, Dr. Xue Yonggang, Dr. Ren Jiao and Dr. Balram Pokhrel for their advice during the preparation of this review. This paper was financially supported by the National Natural Science Foundation of China (Grant Nos. 41222010, 41571463) and the Youth Innovation Promotion Association, Chinese Academy of Sciences (Grant No. 2011067).*

References

Becker S, Halsall C J, Tych W, Hung H, Attewell S, Blanchard P, Li H, Fellin P, Stern G, Billeck B. 2006. Resolving the long-term trends of polycyclic aromatic hydrocarbons in the Canadian Arctic atmosphere. Environ Sci Technol, 40: 3217–3222

Bettinetti R, Quadroni S, Galassi S, Bacchetta R, Bonardi L, Vailati G. 2008. Is meltwater from Alpine glaciers a secondary DDT source for lakes? Chemosphere, 73: 1027–1031

Bidleman T F. 1999. Atmospheric Transport and Air-Surface Exchange of Pesticides, Fate of Pesticides in the Atmosphere: Implications for Environmental Risk Assessment. Amsterdam: Springer Netherlands. 115–166

Blais J M, Schindler D W, Muir D C, Sharp M, Donald D, Lafreniere M, Braekevelt E, Strachan W M. 2001. Melting glaciers: A major source of persistent organochlorines to subalpine Bow Lake in Banff National Park, Canada. Ambio, 30: 410–415

Blais J. 2005. Biogeochemistry of persistent bioaccumulative toxicants: Processes affecting the transport of contaminants to remote areas. Can J Fish Aquat Sci, 62: 236–243

Bogdal C, Schmid P, Zennegg M, Anselmetti F S, Scheringer M, Hungerbühler K. 2009. Blast from the past: Melting glaciers as a relevant source for persistent organic pollutants. Environ Sci Technol, 43: 8173–8177

Borgå K, Saloranta T M, Ruus A. 2010. Simulating climate change-induced alterations in bioaccumulation of organic contaminants in an Arctic marine food web. Environ Toxicol Chem, 29: 1349–1357

Botkin D B, Saxe H, Araujo M B, Betts R, Bradshaw R H, Cedhagen T, Chesson P, Dawson T P, Etterson J R, Faith D P. 2007. Forecasting the effects of global warming on biodiversity. Bioscience, 57: 227–236

Brander K M. 2007. Global fish production and climate change. Proc Natl Acad Sci USA, 104: 19709–19714

Bridgman H A. 1991. Global air Pollution: Problems for the 1990's. Devon: Belhaven Press

Broomhall S. 2002. The effects of endosulfan and variable water temperature on survivorship and subsequent vulnerability to predation in Litoria citropa tadpoles. Aquat Toxicol, 61: 243–250

Broomhall S D. 2004. Egg temperature modifies predator avoidance and the effects of the insecticide endosulfan on tadpoles of an Australian frog. J Appl Ecol, 41: 105–113

Brubaker W W, Hites R A. 1998. OH reaction kinetics of polycyclic aromatic hydrocarbons and polychlorinated dibenzo-p-dioxins and dibenzofurans. J Phys Chem A, 102: 915–921

Buchwalter D B, Jenkins J J, Curtis L R. 2003. Temperature influences on water permeability and chlorpyrifos uptake in aquatic insects with differing respiratory strategies. Environm Toxicol Chem, 22: 2806–2812

Burek K A, Gulland F M, O'Hara T M. 2008. Effects of climate change on Arctic marine mammal health. Ecol Appl, 18: 126–134

Bustnes J O, Yoccoz N G, Bangjord G, Herzke D, Ahrens L, Skaare J U. 2011. Impacts of climate and feeding conditions on the annual accumulation (1986–2009) of persistent organic pollutants in a terrestrial raptor. Environ Sci Technol, 45: 7542–7547

Cabrerizo A, Dachs J, Moeckel C, Ojeda M J, Caballero G, Barceló D, Jones K C. 2011. Factors influencing the soil-air partitioning and the strength of soils as a secondary source of polychlorinated biphenyls to the atmosphere. Environ Sci Technol, 45: 4785–4792

Cao M, Woodward F I. 1998. Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. Nature, 393: 249–252

Capkin E, Altinok I, Karahan S. 2006. Water quality and fish size affect toxicity of endosulfan, an organochlorine pesticide, to rainbow trout. Chemosphere, 64: 1793–1800

Castro-Jiménez J, Berrojalbiz N, Wollgast J, Dachs J. 2012. Polycyclic aromatic hydrocarbons (PAHs) in the Mediterranean Sea: Atmospheric occurrence, deposition and decoupling with settling fluxes in the water column. Environ Pollut, 166: 40–47

Channa K, Röllin H B, Nøst T H, Odland J Ø, Sandanger T M. 2012. Prenatal exposure to DDT in malaria endemic region following indoor residual spraying and in non-malaria coastal regions of South Africa. Sci Total Environ, 429: 183–190

Chen C, Wang T, Naile J E, Li J, Geng J, Bi C, Hu W, Zhang X, Khim J S, Feng Y. 2011. Perfluorinated compounds in aquatic products from Bohai Bay, Tianjin, China. Hum Ecol Risk Assess, 17: 1279–1291

Christoudias T, Pozzer A, Lelieveld J. 2012. Influence of the North Atlantic oscillation on air pollution transport. Atmos Chem Phy, 12: 869–877

Cox P M, Betts R A, Jones C D, Spall S A, Totterdell I J. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 408: 184–187

Cheng C S, Campbell M, Li Q, Li G, Auld H, Day N, Pengelly D, Gingrich S, Yap D. 2007. A synoptic climatological approach to assess climatic impact on air quality in south-central Canada. Part II: Future estimates. Water Air Soil Pollut, 182: 117–130

Dachs J, Bayona J M, Ittekkot V, Albaigés J. 1999. Monsoon-driven vertical fluxes of organic pollutants in the western Arabian Sea. Environ Sci Technol, 33: 3949–3956
Dachs J, Eisenreich S J, Hoff R M. 2000. Influence of eutrophication on air-water exchange, vertical fluxes, and phytoplankton concentrations of persistent organic pollutants. Environ Sci Technol, 34: 1095–1102
Dachs J, Lohmann R, Ockenden W A, Méjanelle L, Eisenreich S J, Jones K C. 2002. Oceanic biogeochemical controls on global dynamics of persistent organic pollutants. Environ Sci Technol, 36: 4229–4237
Dalla Valle M, Jurado E, Dachs J, Sweetman A J, Jones K C. 2005. The maximum reservoir capacity of soils for persistent organic pollutants: Implications for global cycling. Environ Pollut, 134: 153–164
Dalla Valle M, Codato E, Marcomini A. 2007. Climate change influence on POPs distribution and fate: A case study. Chemosphere, 67: 1287–1295
Easterling D R, Meehl G A, Parmesan C, Changnon S A, Karl T R, Mearns L O. 2000. Climate extremes: Observations, modeling, and impacts. Science, 289: 2068–2074
Evans M S, Muir D, Lockhart W L, Stern G, Ryan M, Roach P. 2005. Persistent organic pollutants and metals in the freshwater biota of the Canadian Subarctic and Arctic: An overview. Sci Total Environ, 351: 94–147
Fernández P, Grimalt J O. 2003. On the global distribution of persistent organic pollutants. Chimia Int J Chem, 57: 514–521
Frierson D M, Hwang Y T. 2012. Extratropical influence on ITCZ shifts in slab ocean simulations of global warming. J Clim, 25: 720–733
Gao H, Ma J, Cao Z, Dove A, Zhang L. 2010. Trend and climate signals in seasonal air concentration of organochlorine pesticides over the Great Lakes. J Geophys Res, 115: D15307
Galbán-Malagón C, Berrojalbiz N, Ojeda M J, Dachs J. 2012. The oceanic biological pump modulates the atmospheric transport of persistent organic pollutants to the Arctic. Nat Commun, 3: 862
Geisz H N, Dickhut R M, Cochran M A, Fraser W R, Ducklow H W. 2008. Melting glaciers: A probable source of DDT to the Antarctic marine ecosystem. Environ Sci Technol, 42: 3958–3962
Gómez-Gutiérrez A, Garnacho E, Bayona J M, Albaigés J. 2007. Assessment of the Mediterranean sediments contamination by persistent organic pollutants. Environ Pollut, 148: 396–408
Giesy J P, Kannan K. 2002. Peer reviewed: Perfluorochemical surfactants in the environment. Environ Sci Technol, 36: 146–152
Githeko A K, Lindsay S W, Confalonieri U E, Patz J A. 2000. Climate change and vector-borne diseases: A regional analysis. B World Health Organ, 78: 1136–1147
Gouin T, Mackay D, Jones K C, Harner T, Meijer S N. 2004. Evidence for the "grasshopper" effect and fractionation during long-range atmospheric transport of organic contaminants. Environ Pollut, 128: 139–148
Gouin T, Armitage J M, Cousins I T, Muir D C, Ng C A, Reid L, Tao S. 2013. Influence of global climate change on chemical fate and bioaccumulation: The role of multimedia models. Environ Toxicol Chem, 32: 20–31
Grannas A, Bogdal C, Hageman K, Halsall C, Harner T, Hung H, Kallenborn R, Klán P, Klánová J, Macdonald R. 2013. The role of the global cryosphere in the fate of organic contaminants. Atmosph Chem Phys, 13: 3271–3305
Guan B J 2003. The present situation and analysis of world forest resources (in Chinese). World Forest Res, 16: 1–5
Guglielmo F, Lammel G, Maier-Reimer E. 2009. Global environmental cycling of γ-HCH and DDT in the 1980s–A study using a coupled atmosphere and ocean general circulation model. Chemosphere, 76: 1509–1517
Guglielmo F, Stemmler I, Lammel G. 2012. The impact of organochlorines cycling in the cryosphere on their global distribution and fate–1. Sea ice. Environ Pollut, 162: 475–481
Held I M, Soden B J. 2006. Robust responses of the hydrological cycle to global warming. J Clim, 19: 5686–5699
Hermanson M H, Isaksson E, Teixeira C, Muir D C, Compher K M, Li Y, Igarashi M, Kamiyama K 2005. Current-use and legacy pesticide history in the Austfonna ice cap, Svalbard, Norway. Environ Sci Technol, 39: 8163–8169
Hermanson M H, Isaksson E, Forsström S, Teixeira C, Muir D C, Pohjola V A, Van de Wal R S. 2010. Deposition history of brominated flame retardant compounds in an ice core from Holtedahlfonna, Svalbard, Norway. Environ Sci Technol, 44: 7405–7410
Hirano T, Ishida T, Oh K, Sudo R. 2007. Biodegradation of chlordane and hexachlorobenzenes in river sediment. Chemosphere, 67: 428–434
Hoegh-Guldberg O, Bruno J F. 2010. The impact of climate change on the world's marine ecosystems. Science, 328: 1523–1528
Hofmann L, Stemmler I, Lammel G. 2012. The impact of organochlorines cycling in the cryosphere on global distributions and fate–2. Land ice and temporary snow cover. Environ Pollut, 162: 482–488
Hogrefe C, Lynn B, Civerolo K, Ku J Y, Rosenthal J, Rosenzweig C, Goldberg R, Gaffin S, Knowlton K, Kinney P. 2004. Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. J Geophys Res, 109: D22301
Holoubek I, Klanova J, Jarkovský J, Kohoutek J. 2007. Trends in background levels of persistent organic pollutants at Kosetice observatory, Czech Republic. Part I. Ambient air and wet deposition 1996–2005. J Environm Monit, 9: 557–563
Hong S, Lee K, Hou S, Hur S D, Ren J, Burn L J, Rosman K J, Barbante C, Boutron C F. 2009. An 800-year record of atmospheric As, Mo, Sn, and Sb in central Asia in high-altitude ice cores from Mt. Qomolangma (Everest), Himalayas. Environ Sci Technol, 43: 8060–8065
Horstmann M, Mclachlan M S. 1998. Atmospheric deposition of semivolatile organic compounds to two forest canopies. Atmos Environ, 32: 1799–1809
Huang P, Gong S, Zhao T, Neary L, Barrie L. 2007. GEM/POPs: A global 3-D dynamic model for semi-volatile persistent organic pollutants–Part 2: Global transports and budgets of PCBs. Atmos Chem Phys, 7: 4015–4025
Huang Y, Xu Y, Li J, Xu W, Zhang G, Cheng Z, Liu J, Wang Y, Tian C. 2013. Organochlorine pesticides in the atmosphere and surface water from the equatorial Indian Ocean: Enantiomeric signatures, sources, and fate. Environ Sci Technol, 47: 13395–13403
Hughes L. 2000. Biological consequences of global warming: Is the signal already apparent? Trends Ecol Evol, 15: 56–61
Hung H, Blanchard P, Halsall C J, Bidleman T, Stern G, Fellin P, Muir D, Barrie L, Jantunen L, Helm P. 2005. Temporal and spatial variabilities of atmospheric polychlorinated biphenyls (PCBs), organochlorine (OC) pesticides and polycyclic aromatic hydrocarbons (PAHs) in the Canadian Arctic: Results from a decade of monitoring. Sci Total Environ, 342: 119–144
Hung H, Kallenborn R, Breivik K, Su Y, Brorström-Lundén E, Olafsdottir K, Thorlacius J M, Leppänen S, Bossi R, Skov H. 2010. Atmospheric monitoring of organic pollutants in the Arctic under the Arctic Monitoring and Assessment Programme (AMAP): 1993–2006. Sci Total Environ, 408: 2854–2873
Huntington T G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. J Hydrol, 319: 83–95
Ilyina T, Pohlmann T, Lammel G, Sündermann J. 2006. A fate and transport ocean model for persistent organic pollutants and its application to the North Sea. J Mar Syst, 63: 1–19
IPCC. 2013. Climate change 2013. In: Stocker T F, Qin D H, Plattner G K, Tignor M, Allen S K, Boschung J, Nauels A, Xia Y, Bex V, Midgley P M, eds. Working Group I Contribution to the IPCC Fifth Assessment Report: The Physical Science Basis: Summary for Policymakers. Cambridge: Cambridge University Press. 1–28
IPCC. 2014. Climate change 2014. In: Core Writing Team, Pachauri R K, Meyer L A, eds. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Switzerland: IPCC. 151
Jenssen B M. 2006. Endocrine-disrupting chemicals and climate change: A worst-case combination for arctic marine mammals and seabirds? Environ Health Perspect, 114: 76–80
Jones K C, De Voogt P. 1999. Persistent organic pollutants (POPs): State of the science. Environ Pollut, 100: 209–221
Jurado E, Jaward F, Lohmann R, Jones K C, Simó R, Dachs J. 2005. Wet deposition of persistent organic pollutants to the global oceans. Environ

Sci Technol, 39: 2426–2435

Kallenborn R, Borgå K, Christensen J, Dowdall M, Evenset A, Odland J, Ruus A, Aspmo Pfaffhuber K, Pawlak J, Reiersen L. 2011. Combined effects of selected pollutants and climate change in the Arctic environment. In: Arctic Monitoring and Assessment Programme. Oslo

Kallenborn R, Halsall C, Dellong M, Carlsson P. 2012. The influence of climate change on the global distribution and fate processes of anthropogenic persistent organic pollutants. J Environ Monit, 14: 2854–2869

Kallenborn R, Hung H, Brorström-Lundén E. 2015. Chapter 13-Atmospheric Long-Range Transport of Persistent Organic Pollutants (POPs) into Polar Regions. In: Eddy Y Z, ed. Comprehensive Analytical Chemistry, Persistent Organic Pollutants (POPs): Analytical Techniques, Environmental Fate and Biological Effects. Amsterdam: Elsevier. 411–432

Kawamoto K, Urano K. 1990. Parameters for predicting fate of organochlorine pesticides in the environment (III) Biodegradation rate constants. Chemosphere, 21: 1141–1152

Kim E J, Oh J E, Chang Y S. 2003. Effects of forest fire on the level and distribution of PCDD/Fs and PAHs in soil. Sci Total Environ, 311: 177–189

Klöpffer W. 1992. Photochemical degradation of pesticides and other chemicals in the environment: A critical assessment of the state of the art. Sci Total Environ, 123: 145–159

Komprda J í, Komprdová K r, Sáňka M, Možný M, Nizzetto L. 2013. Influence of climate and land use change on spatially resolved volatilization of persistent organic pollutants (POPs) from background soils. Environ Sci Technol, 47: 7052–7059

Kong D, MacLeod M, Li Z, Cousins I T. 2013. Effects of input uncertainty and variability on the modelled environmental fate of organic pollutants under global climate change scenarios. Chemosphere, 93: 2086–2093

Kong D, MacLeod M, Cousins I T. 2014. Modelling the influence of climate change on the chemical concentrations in the Baltic Sea region with the Popcycling-Baltic model. Chemosphere, 110: 31–40

Kucklick J R, Hinckley D A, Bidleman T F. 1991. Determination of Henry's law constants for hexachlorocyclohexanes in distilled water and artificial seawater as a function of temperature. Mar Chem, 34: 197–209

Kwok R, Cunningham G, Wensnahan M, Rigor I, Zwally H, Yi D. 2009. Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. J Geophys Res, 114: C07005

Lammel G, Stemmler I. 2012. Fractionation and current time trends of PCB congeners: Evolvement of distributions 1950–2010 studied using a global atmosphere-ocean general circulation model. Atmos Chem Phys, 12: 7199–7213

Lamon L, Dalla Valle M, Critto A d, Marcomini A. 2009a. Introducing an integrated climate change perspective in POPs modelling, monitoring and regulation. Environ Pollut, 157: 1971–1980

Lamon L, von Waldow H, MacLeod M, Scheringer M, Marcomini A, Hungerbühler K. 2009b. Modeling the global levels and distribution of polychlorinated biphenyls in air under a climate change scenario. Environ Sci Technol, 43: 5818–5824

Lei Y D, Wania F. 2004. Is rain or snow a more efficient scavenger of organic chemicals? Atmos Environ, 38: 3557–3571

Lin T, Li J, Xu Y, Liu X, Luo C, Cheng H, Chen Y, Zhang G. 2012. Organochlorine pesticides in seawater and the surrounding atmosphere of the marginal seas of China: Spatial distribution, sources and air-water exchange. Sci Total Environ, 435: 244–252

Lindsay S, Birley M. 1996. Climate change and malaria transmission. Ann Trop Med Parasit, 90: 573–588

Liu G R, Zheng M H. 2013. Progress in the studies associated with formation and emission of unintentionally produced persistent organic pollutants (in Chinese). Sci Sin Chim, 43: 265–278

Lohmann R, Jurado E, Pilson M E, Dachs J. 2006. Oceanic deep water formation as a sink of persistent organic pollutants. Geophys Res Lett, 33: L12607

Luo Y. 2007. Terrestrial carbon-cycle feedback to climate warming. Ann Rev Ecol Evolu Syst, 38: 683–712

Ma J, Venkatesh S, Jantunen L. 2003. Evidence of the impact of ENSO events on temporal trends of hexachlorobenzene air concentrations over the Great Lakes. Sci Total Environ, 313: 177–184

Ma J, Cao Z, Hung H. 2004. North Atlantic oscillation signatures in the atmospheric concentrations of persistent organic pollutants: An analysis using integrated atmospheric deposition network-Great Lakes monitoring data. J Geophys Res, 109: D12305

Ma J, Li Y F. 2006. Interannual variation of persistent organic pollutants over the Great Lakes induced by tropical Pacific sea surface temperature anomalies. J Geophys Res, 111: D04302

Ma J, Cao Z. 2010. Quantifying the perturbations of persistent organic pollutants induced by climate change. Environ Sci Technol, 44: 8567–8573

Ma J, Hung H, Tian C, Kallenborn R. 2011. Revolatilization of persistent organic pollutants in the Arctic induced by climate change. Nat Clim Change, 1: 255–260

Maldonado C, Bayona J M, Bodineau L. 1999. Sources, distribution, and water column processes of aliphatic and polycyclic aromatic hydrocarbons in the northwestern Black Sea water. Environ Sci Technol, 33: 2693–2702

Macdonald R W, Mackay D, Li Y F, Hickie B. 2003. How will global climate change affect risks from long-range transport of persistent organic pollutants? Hum Ecol Risk Assess, 9: 643–660

Macdonald R, Harner T, Fyfe J. 2005. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. Sci Total Environ, 342: 5–86

Mackay D. 2001. Multimedia environmental models: The fugacity approach. Boca Raton: CRC Press

MacLeod M, Riley W J, Mckone T E. 2005. Assessing the influence of climate variability on atmospheric concentrations of polychlorinated biphenyls using a global-scale mass balance model (BETR-Global). Environ Sci Technol, 39: 6749–6756

Maggi V, Villa S, Finizio A, Delmonte B, Casati P, Marino F. 2006. Variability of anthropogenic and natural compounds in high altitude-high accumulation alpine glaciers. Hydrobiologia, 562: 43–56

Magnuson J, Webster K, Assel R, Bowser C, Dillon P, Eaton J, Evans H, Fee E, Hall R, Mortsch L. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian shield region. Hydrol Process, 11: 825–871

Martens W, Jetten T, Rotmans J, Niessen L. 1995. Climate change and vector-borne diseases: A global modelling perspective. Glob Environ Change, 5: 195–209

Maruya K A, Smalling K L, Vetter W. 2005. Temperature and congener structure affect the enantioselectivity of toxaphene elimination by fish. Environ Sci Technol, 39: 3999–4004

McLachlan M S, Horstmann M. 1998. Forests as filters of airborne organic pollutants: A model. Environ Sci Technol, 32: 413–420

Meehl G A, Washington W M, Collins W D, Arblaster J M, Hu A, Buja L E, Strand W G, Teng H. 2005. How much more global warming and sea level rise? Science, 307: 1769–1772

Meijer S, Ockenden W, Steinnes E, Corrigan B, Jones K. 2003. Spatial and temporal trends of POPs in Norwegian and UK background air: Implications for global cycling. Environ Sci Technol, 37: 454–461

Meinshausen M, Meinshausen N, Hare W, Raper S C, Frieler K, Knutti R, Frame D J, Allen M R. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature, 458: 1158–1162

Mendelsohn R, Nordhaus W D, Shaw D. 1994. The impact of global warming on agriculture: A Ricardian analysis. Am Econ Rev, 84: 753–771

Meyer T, Wania F. 2007. What environmental fate processes have the strongest influence on a completely persistent organic chemical's accumulation in the Arctic? Atmos Environ, 41: 2757–2767

Meyer T, Wania F. 2008. Organic contaminant amplification during snowmelt. Water Res, 42: 1847–1865

Meyer T, Lei Y D, Muradi I, Wania F. 2008a. Organic contaminant release from melting snow. 1. Influence of chemical partitioning. Environ Sci Technol, 43: 657–662

Meyer T, Lei Y D, Muradi I, Wania F. 2008b. Organic contaminant release from melting snow. 2. Influence of snow pack and melt characteristics. Environ Sci Technol, 43: 663–668

Moeckel C, Nizzetto L, Strandberg B, Lindroth A, Jones K C. 2009. Air-Boreal forest transfer and processing of polychlorinated biphenyls.

Environ Sci Technol, 43: 5282–5289
Nadal M, Marquès M, Mari M, Domingo J L. 2015. Climate change and environmental concentrations of POPs: A review. Environ Res, 143: 177–185
Nizzetto L, Macleod M, Borgå K, Cabrerizo A, Dachs J, Guardo A D, Ghirardello D, Hansen K M, Jarvis A, Lindroth A. 2010. Past, present, and future controls on levels of persistent organic pollutants in the global environment. Environ Sci Technol, 44: 6526–6531
Noyes P D, McElwee M K, Miller H D, Clark B W, Van Tiem L A, Walcott K C, Erwin K N, Levin E D. 2009. The toxicology of climate change: Environmental contaminants in a warming world. Environ Int, 35: 971–986
O'Sullivan G, Megson D. 2014. Chapter 1-brief overview: Discovery, regulation, properties, and fate of POPs. In: Sandau G O S, ed. Environmental Forensics for Persistent Organic Pollutants. Amsterdam: Elsevier. 8–20
Ockenden W A, Breivik K, Meijer S N, Steinnes E, Sweetman A J, Jones K C. 2003. The global re-cycling of persistent organic pollutants is strongly retarded by soils. Environ Pollut, 121: 75–80
Octaviani M, Stemmler I, Lammel G, Graf H F. 2015. Atmospheric transport of persistent organic pollutants to and from the Arctic under present-day and future climate. Environ Sci Technol, 49: 3593–3602
Olsen M, Callaghan T, Reist J, Reiersen L, Dahl-Jensen D, Granskog M, Goodison B, Hovelsrud G, Johansson M, Kallenborn R. 2011. The changing Arctic cryosphere and likely consequences: An overview. Ambio, 40: 111–118
Paasivirta J, Sinkkonen S, Mikkelson P, Rantio T, Wania F. 1999. Estimation of vapor pressures, solubilities and Henry's law constants of selected persistent organic pollutants as functions of temperature. Chemosphere, 39: 811–832
Pacyna J M, Cousins I T, Halsall C, Rautio A, Pawlak J, Pacyna E G, Sundseth K, Wilson S, Munthe J. 2015. Impacts on human health in the Arctic owing to climate-induced changes in contaminant cycling-The EU ArcRisk project policy outcome. Environ Sci Pollut Res, 50: 200–213
Parmesan C. 2007. Influences of species, latitudes and methodologies on estimates of phenological response to global warming. Glob Change Biol, 13: 1860–1872
Parry M L, Ruttan V W. 1991. Climate change and world agriculture. Environ Sci Policy Sustain Dev, 33: 25–29
Parry M L. 2007. Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC. Cambridge: Cambridge University Press
Patra R W, Chapman J C, Lim R P, Gehrke P C. 2007. The effects of three organic chemicals on the upper thermal tolerances of four freshwater fishes. Environ Toxicol Chem, 26: 1454–1459
Petchey O L, McPhearson P T, Casey T M, Morin P J. 1999. Environmental warming alters food-web structure and ecosystem function. Nature, 402: 69–72
Peterle T J. 1969. DDT in Antarctic snow. Nature, 224: 620–625
Petit J R, Jouzel J, Raynaud D, Barkov N I, Barnola J M, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G. 1999. Climate and atmospheric history of the past 420000 years from the Vostok ice core, Antarctica. Nature, 399: 429–436
Philander S, Gu D, Lambert G, Li T, Halpern D, Lau N, Pacanowski R. 1996. Why the ITCZ is mostly north of the equator. J Clim, 9: 2958–2972
Porter J, Parry M, Carter T. 1991. The potential effects of climatic change on agricultural insect pests. Agric For Meteorol, 57: 221–240
Racherla P N, Adams P J. 2006. Sensitivity of global tropospheric ozone and fine particulate matter concentrations to climate change. J Geophys Res, 111: D24103
Roberts D R, Manguin S, Mouchet J. 2000. DDT house spraying and re-emerging malaria. Lancet, 356: 330–332
Rosenzweig C, Iglesias A, Yang X, Epstein P R, Chivian E. 2001. Climate change and extreme weather events: Implications for food production, plant diseases, and pests. Glob Change Hum Health, 2: 90–104
Rühlemann C, Mulitza S, Müller P J, Wefer G, Zahn R. 1999. Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation. Nature, 402: 511–514
RůŽičková P, Klánová J, Cupr P, Lammel G, Holoubek I. 2007. An assessment of air-soil exchange of polychlorinated biphenyls and organochlorine pesticides across Central and Southern Europe. Environ Sci Technol, 42: 179–185
Sadasivaiah S, Tozan Y, Breman J G. 2007. Dichlorodiphenyltrichloroethane (DDT) for indoor residual spraying in Africa: How can it be used for malaria control? Am J Trop Med Hyg, 77: 249–263
Sarkar S, Bhattacharya B, Bhattacharya A, Chatterjee M, Alam A, Satpathy K, Jonathan M. 2008. Occurrence, distribution and possible sources of organochlorine pesticide residues in tropical coastal environment of India: An overview. Environ Int, 34: 1062–1071
Schiedek D, Sundelin B, Readman J W, Macdonald R W. 2007. Interactions between climate change and contaminants. Mar Pollut Bull, 54: 1845–1856
Schindler D W, Curtis P J, Bayley S E, Parker B R, Beaty K G, Stainton M P. 1997. Climate-induced changes in the dissolved organic carbon budgets of boreal lakes. Biogeochemistry, 36: 9–28
Schlenk D, Lavado R. 2011. Impacts of climate change on hypersaline conditions of estuaries and xenobiotic toxicity. Aquat Toxicol, 105: 78–82
Seinfeld J H, Pandis S N. 2012. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. Hoboken: John Wiley & Sons. 25
Sharma S, Shukla R, Raghavendra K, Subbarao S K. 2005. Impact of DDT spraying on malaria transmission in Bareilly District, Uttar Pradesh, India. J Vector Borne Dise, 42: 54
Sharma B M, Bharat G K, Tayal S, Nizzetto L, Čupr P, Larssen T. 2014. Environment and human exposure to persistent organic pollutants (POPs) in India: A systematic review of recent and historical data. Environ Int, 66: 48–64
Shen Y P, Wang G Y. 2013. Key findings and assessment results of IPCC WGI Fifth Assessment Report (in Chinese). J Glaciol Geocryol, 35: 1068–1076
Sheng J, Wang X, Gong P, Joswiak D R, Tian L, Yao T, Jones K C. 2013. Monsoon-driven transport of organochlorine pesticides and polychlorinated biphenyls to the Tibetan Plateau: Three year atmospheric monitoring study. Environ Sci Technol, 47: 3199–3208
Shindell D, Chin M, Dentener F, Doherty R, Faluvegi G, Fiore A M, Hess P, Koch D, MacKenzie I, Sanderson M. 2008. A multi-model assessment of pollution transport to the Arctic. Atmos Chem Phys, 8: 5353–5372
Sinkkonen S, Paasivirta J. 2000. Degradation half-life times of PCDDs, PCDFs and PCBs for environmental fate modeling. Chemosphere, 40: 943–949
Sobek A, Gustafsson O R. 2014. Deep water masses and sediments are main compartments for polychlorinated biphenyls in the Arctic Ocean. Environ Sci Technol, 48: 6719–6725
Stapleton D H. 2004. Lessons of history? Anti-malaria strategies of the international health board and the Rockefeller Foundation from the 1920s to the era of DDT. Public Health Rep, 119: 206
Stemmler I, Lammel G. 2009. Cycling of DDT in the global environment 1950–2002: World ocean returns the pollutant. Geophys Res Lett, 36: L24602
Stemmler I, Lammel G. 2012. Long-term trends of continental-scale PCB patterns studied using a global atmosphere-ocean general circulation model. Environ Sci Pollut Res, 19: 1971–1980
Stevenson D, Dentener F, Schultz M, Ellingsen K, Van Noije T, Wild O, Zeng G, Amann M, Atherton C, Bell N. 2006. Multimodel ensemble simulations of present-day and near-future tropospheric ozone. J Geophys Res, 111: D08301
Stocker J, Scheringer M, Wegmann F, Hungerbühler K. 2007. Modeling the effect of snow and ice on the global environmental fate and long-range transport potential of semivolatile organic compounds. Environ Sci Technol, 41: 6192–6198
Stocker T F. 2014. Climate change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

Suzuki N, Murasawa K, Sakurai T, Nansai K, Matsuhashi K, Moriguchi Y, Tanabe K, Kasugi O, Morita M. 2004. Geo-referenced multimedia environmental fate model (G-CIEMS): Model formulation and comparison to the generic model and monitoring approaches. Environ Sci Technol, 38: 5682–5693

Sweetman A J, Dalla Valle M, Prevedouros K, Jones K C. 2005. The role of soil organic carbon in the global cycling of persistent organic pollutants (POPs): Interpreting and modelling field data. Chemosphere, 60: 959–972

Theobald N, Caliebe C, Gerwinski W, Hühnerfuss H, Lepom P. 2011. Occurrence of perfluorinated organic acids in the North and Baltic seas. Part 1: Distribution in sea water. Environ Sci Pollut Res, 18: 1057–1069

Thompson L G, Yao T, Davis M, Henderson K, Mosley-Thompson E, Lin P N, Beer J, Synal H A, Cole-Dai J, Bolzan J. 1997. Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core. Science, 276: 1821–1825

Thompson L G, Mosley-Thompson E, Davis M E, Lin P N, Henderson K, Mashiotta T A. 2003. Tropical Glacier and Ice Core Evidence of Climate Change on Annual to Millennial Time Scales, Climate Variability and Change in High Elevation Regions: Past, Present & Future. Amsterdam: Springer Netherlands. 137–155

Tian C, Ma J, Chen Y, Liu L, Ma W, Li Y F. 2012. Assessing and forecasting atmospheric outflow of α-HCH from China on intra-, inter-, and decadal time scales. Environ Sci Technol, 46: 2220–2227

UNEP. 2010. Climate change and POPs: Predicting the impacts. Report of the UNEP/AMAP expert group. United Nations Environmental Programme Report. 65

Veillette J, Muir D C, Antoniades D, Small J M, Spencer C, Loewen T N, Babaluk J A, Reist J D, Vincent W F. 2012. Perfluorinated chemicals in meromictic lakes on the northern coast of Ellesmere Island, High Arctic Canada. Arctic, 65: 245–256

Vermeer M, Rahmstorf S. 2009. Global sea level linked to global temperature. Proc Natl Acad Sci USA, 106: 21527–21532

Villa S, Vighi M, Maggi V, Finizio A, Bolzacchini E. 2003. Historical trends of organochlorine pesticides in an Alpine glacier. J Atmos Chem, 46: 295–311

Villa S, Negrelli C, Maggi V, Finizio A, Vighi M. 2006. Analysis of a firn core for assessing POP seasonal accumulation on an Alpine glacier. Ecotox Environ Safe, 63: 17–24

Wang J, Grisle S, Schlenk D. 2001. Effects of salinity on aldicarb toxicity in juvenile rainbow trout (Oncorhynchus mykiss) and striped bass (Morone saxatilis× chrysops). Toxicol Sci, 64: 200–207

Wang F, Zhu T, Xu B Q, Kang S C. 2007a. Organochlorine pesticides in fresh-fallen snow on East Rongbuk Glacier of Mt. Qomolangma (Everest). Sci China Ser D-Earth Sci, 50: 1097–1102

Wang H, Yang Z, Saito Y, Liu J P, Sun X, Wang Y. 2007b. Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): Impacts of climate change and human activities. Glob Planet Change, 57: 331–354

Wang X, Xu B, Kang S, Cong Z, Yao T. 2008. The historical residue trends of DDT, hexachlorocyclohexanes and polycyclic aromatic hydrocarbons in an ice core from Mt. Everest, central Himalayas, China. Atmos Environ, 42: 6699–6709

Wang T, Wang Y, Liao C, Cai Y, Jiang G. 2009. Perspectives on the inclusion of perfluorooctane sulfonate into the Stockholm Convention on persistent organic pollutants 1. Environ Sci Technol, 43: 5171–5175

Wang X, Gong P, Zhang Q, Yao T. 2010a. Impact of climate fluctuations on deposition of DDT and hexachlorocyclohexane in mountain glaciers: Evidence from ice core records. Environ Pollut, 158: 375–380

Wang Y W, Cai Y Q, Jiang G B. 2010b. Research processes of persistent organic pollutants (POPs) newly listed and candidate POPs in Stockholm Convention (in Chinese). Sci Sin Chim, 40: 99–123

Wang X, Halsall C, Codling G, Xie Z, Xu B, Zhao Z, Xue Y, Ebinghaus R, Jones K. 2014. Accumulation of perfluoroalkyl compounds in Tibetan Mountain Snow: Temporal Patterns from 1980 to 2010. Environ Sci Technol, 48: 173–181

Wania F, Mackay D. 1995. A global distribution model for persistent organic chemicals. Sci Total Environ, 160: 211–232

Wania F, McLachlan M S. 2001. Estimating the influence of forests on the overall fate of semivolatile organic compounds using a multimedia fate model. Environ Sci Technol, 35: 582–590

Wania F, Daly G L. 2002. Estimating the contribution of degradation in air and deposition to the deep sea to the global loss of PCBs. Atmos Environ, 36: 5581–5593

Wania F. 2003. Assessing the potential of persistent organic chemicals for long-range transport and accumulation in polar regions. Environ Sci Technol, 37: 1344–1351

Wania F, Su Y. 2004. Quantifying the global fractionation of polychlorinated biphenyls. Ambio, 33: 161–168

Waring C P, Moore A. 2004. The effect of atrazine on Atlantic salmon (Salmo salar) smolts in fresh water and after sea water transfer. Aquat Toxicol, 66: 93–104

Wӧhrnschimmel H, MacLeod M, Hungerbuhler K. 2013. Emissions, fate and transport of persistent organic pollutants to the Arctic in a changing global climate. Environ Sci Technol, 47: 2323–2330

Xie Z, Mӧller A, Ahrens L, Sturm R, Ebinghaus R. 2011. Brominated flame retardants in seawater and atmosphere of the Atlantic and the Southern Ocean. Environ Sci Technol, 45: 1820–1826

Yamashita N, Taniyasu S, Petrick G, Wei S, Gamo T, Lam P K, Kannan K. 2008. Perfluorinated acids as novel chemical tracers of global circulation of ocean waters. Chemosphere, 70: 1247–1255

Yang Y L, Pan J, Li Y, Yin X C, Shi L. 2003. The polychlorinated naphthalenes and polybrominated diphenyl ethers in the sediments of Qingdao coastal area. Chin Sci Bull, 48: 2244–2251

Yang R, Yao T, Xu B, Jiang G, Zheng X. 2008. Distribution of organochlorine pesticides (OCPs) in conifer needles in the southeast Tibetan Plateau. Environ Pollut, 153: 92–100

Yao Z W, Jiang G B, Cai Y Q, Xu H Z, Ma Y A. 2002. Current status of persistent organic pollutants and heavy metal pollution in the surface waters of the Arctic. Chin Sci Bull, 47: 1196–1200

Zhang K, Zhang B Z, Li S M, Zeng E Y. 2011. Regional dynamics of persistent organic pollutants (POPs) in the Pearl River Delta, China: Implications and perspectives. Environ Pollut, 159: 2301–2309

Zhang X, Meyer T, Muir D C, Teixeira C, Wang X, Wania F. 2013. Atmospheric deposition of current use pesticides in the Arctic: Snow core records from the Devon Island Ice Cap, Nunavut, Canada. Environ Sci: Process Impacts, 15: 2304–2311

Zheng M H. 2013. Research progress of persistent organic pollutants (in Chinese). Sci Sin Chim, 43: 253–254

Zhong G, Tang J, Xie Z, Möller A, Zhao Z, Sturm R, Chen Y, Tian C, Pan X, Qin W. 2014. Selected current-use and historic-use pesticides in air and seawater of the Bohai and Yellow Seas, China. J Geophys Res, 119: 1073–1086

Zingde M. 2005. Inputs into the oceans from land/rivers and pollution. In: Gupta H K, ed. Oceanology. India: Universities Press. 92–117