



Invited review article

# The influence of global climate change on the environmental fate of persistent organic pollutants: A review with emphasis on the Northern Hemisphere and the Arctic as a receptor



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## ABSTRACT

Following worldwide bans and restrictions on the use of many persistent organic pollutants (POPs) from the late 1970s, their regional and global distributions have become governed increasingly by phase partitioning between environmental reservoirs, such as air, water, soil, vegetation and ice, where POPs accumulated during the original applications. Presently, further transport occurs within the atmospheric and aquatic reservoirs. Increasing temperatures provide thermodynamic forcing to drive these chemicals out of reservoirs, like soil, vegetation, water and ice, and into the atmosphere where they can be transported rapidly by winds and then recycled among environmental media to reach locations where lower temperatures prevail (e.g., polar regions and high elevations). Global climate change, widely considered as global warming, is also manifested by changes in hydrological systems and in the cryosphere; with the latter now exhibiting widespread loss of ice cover on the Arctic Ocean and thawing of permafrost. All of these changes alter the cycling and fate of POPs. There is abundant evidence from observations and modeling showing that climate variation has an effect on POPs levels in biotic and abiotic environments. This article reviews recent progress in research on the effects of climate change on POPs with the intention of promoting awareness of the importance of interactions between climate and POPs in the geophysical and ecological systems.

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## 1. Introduction

Persistent organic pollutants (POPs) are toxic substances produced by industry and released to the environment either deliberately or unintentionally by human activities. Within the environment, POPs are resistant to degradation, and can, therefore, accumulate over long periods of time in solid, liquid or gas-phase reservoirs from which they enter food webs, posing risks to ecosystems and human health. These contaminants include industrial chemicals [such as polychlorinated biphenyls (PCBs)], pesticides [such as dichlorodiphenyltrichloroethane (DDT)], and unintentionally produced chemicals (such as dioxins and furans); among which are compounds with exceptional toxicity to human development [e.g., 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD)] (Berg et al., 2006). Owing to their persistence, POPs can transport long distances in the atmosphere and oceans, thence to accumulate in water, sediments, vegetation and in the cryosphere (snow, ice, permafrost) (Muir and Norstrom, 1994; Mackay and Wania, 1995; Wania and Mackay, 1996; Macdonald et al., 2005; Bailey et al., 2000; Grannas et al., 2013). Global thermodynamic forcing by temperature gradients has been proposed as a leading mechanism to enhance the accumulation of semivolatile chemicals in cold environments (Wania and Mackay, 1996). Ample evidence has been collected to demonstrate that remote, pristine locations, like the Arctic and high mountains, far from the predominant POPs sources, reflect this cold-trapping process and have been widely contaminated by POPs (Goldberg et al., 1975; Ottar, 1981; Meijer et al., 2003; Hung et al., 2010). Recently, the European Union instigated investigations into linkages among climate change, persistent toxic chemicals, and ecosystem risks in the Arctic through the ArcRisk (Arctic Health Risks) project, with the intent of furthering the understanding of POPs cycling in the environment and biota under a warming Arctic (<http://www.arcrisk.eu/about-us/>). The cycling of POPs is driven primarily by physicochemical properties of the chemicals (volatility, partitioning among phases) and environmental factors, such as temperature, precipitation, winds, and currents (Simonich and Hites, 1995; Dachs et al., 2002; Gobas and Maclean, 2003; Stemmler and Lammel, 2009; Meijer et al., 2009). In addition to these physical factors, biogeochemical cycles also play crucial roles because they provide transport pathways (e.g., Blais et al., 2001) and mechanisms to concentrate POPs (Lohmann et al., 2007; Nizzetto et al., 2010; Macdonald et al., 2002). Efforts have been made nationally and internationally to regulate or phase out POPs through domestic chemical control initiatives and international environmental treaties, such as the United Nations Environment Programme (UNEP) Stockholm Convention on Persistent Organic Pollutants and the United Nations Economic Commission for Europe (UNECE) POPs Protocol of the Convention on Long-range Transboundary Air Pollution. The Stockholm Convention on POPs, which came into effect in 2004, initially identified twelve chemicals or chemical groups (the so called Dirty Dozen) for regulation and elimination of production and use (<http://www.pops.int>). As a result of these and other control efforts, the environmental levels of legacy POPs have been declining worldwide, demonstrating some success of POPs regulations (Kong et al., 2014). On the other hand, the number of chemicals added to the list of POPs under the Stockholm Convention has been increasing, with 26 chemicals or chemical groups presently listed for elimination (<http://chm.pops.int/default.aspx>).

While long-term POPs monitoring data show generally decreasing patterns during the past two decades for regulated (legacy) POPs, the influence of climate change (referred to as CC hereafter) on temporal and spatial distributions of POPs in biotic and abiotic environments poses a new challenge to governments and scientists. For many industrial POPs and pesticides, significant release to the environment started after World War II and peaked during 1970–1990 (Li and Macdonald, 2005). Once released at their sources, POPs were transported by winds and, following atmospheric circulation patterns, arrived within days at remote regions where they had never been used. In remote places like the Arctic, lower temperatures promoted the partitioning

of POPs from air to liquid or solid, and thus POPs were deposited in snow, ice, vegetation, and soil where prevailing cold temperatures helped to preserve them and, therefore, extend their residence time in the environment. The distribution of POPs in the global environment can be attributed largely to their physicochemical properties, which are temperature dependent and often parameterized by linear relationships with temperature. With warming, POPs that had been sequestered in water or terrestrial surfaces by low temperatures tend to return to the atmosphere. The thawing of permafrost or melting of sea-ice and glaciers due to warming provides another means for historically archived contaminants to mobilize into aquatic systems (e.g., Blais et al., 2001; Bogdal et al., 2010). Subsequent to entry into aquatic systems, released POPs may then enter the food chain and become biomagnified in top predators. There is a growing body of evidence that CC results in the release of POPs locally, regionally and globally from containment in historically-accumulated reservoirs. The CC-induced release of archived POPs, together with direct and indirect alterations in biogeochemical cycles, also due to CC, then provides opportunities for 'surprises' that could undermine global efforts to reduce environmental and human exposure to these toxic chemicals. The daunting complexity of the global environment into which POPs are released (Fig. 1, top panel, showing the Northern Hemisphere only) has been simplified by viewing the system as a series of arrows signifying fluxes, and boxes signifying reservoirs (Fig. 1, bottom panel). These fluxes (release, transport, degradation) and reservoirs (soil, vegetation, water, ice) are all vulnerable to CC, which then leads to the re-distribution of POPs.

Given the dramatic changes now unfolding in the cryosphere and elsewhere, an increasing number of observational and modeling studies over the past decade have focused on what climate change and variability imply for the transport, deposition and cycling of POPs (and other contaminants) in abiotic and biotic systems (e.g., Lucia et al., 2015; Manciooco et al., 2014; Armitage and Wania, 2013; McKinney et al., 2012; Kallenborn et al., 2012; Bidleman et al., 2012; Sumaila et al., 2011; Bustnes et al., 2010; Bogdal et al., 2009, 2010; McKinney et al., 2009; Becker et al., 2008, 2012; Geisz et al., 2008; Thies et al., 2007; Eckhardt et al., 2007; Garrett and Zhao, 2006; Stern et al., 2005; Ma et al., 2005, 2011; Ma and Li, 2006; Ma and Cao, 2010; MacLeod et al., 2005; Lamon et al., 2009; Wang et al., 2010a, 2010b; Komprda et al., 2013; Wöhrnschimmel et al., 2013; Rigét et al., 2010, 2013; Octaviani et al., 2015; Zhao et al., 2015). Likewise, reviews have highlighted the wide variety of potential CC-contaminant interactions (Noyes and Lima, 2015; Teran et al., 2012; UNEP/AMAP, 2011; Kallenborn et al., 2011; Rockström et al., 2009a, 2009b; Dauvin, 2007; Schindler and Smol, 2006; Watson et al., 2005; Macdonald et al., 2005; Schiedek et al., 2007; Noyes et al., 2009; Armitage et al., 2011; Kallenborn et al., 2012; Teng et al., 2012; Gouin et al., 2013; Grannas et al., 2013). Climate variability and climate change operate on almost every aspect of a POP's lifetime in the environment. However, due to knowledge gaps in understanding the complex dynamic exchange and transport, toxicological, and biological processes in POPs contamination to the environment, and the lack of sufficient monitoring data, many of the modeled or predicted effects of CC on POPs have not yet been confirmed (Zhao et al., 2015).

In the present article, we aimed to provide an overview of recent progresses in understanding the associations between POPs in biotic and abiotic environments and CC. The article is particularly aimed to inform geophysical and ecological scientists about the importance of climate variability and change to the cycling and fate of POPs in the environment.

## 2. How climate change interacts with POPs

### 2.1. Temperature-dependent physicochemical properties of POPs

Once released into the environment from applications in agriculture, commerce and industry, POPs immediately begin to distribute

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