LONG-RANGE TRANSPORT OF INDUSTRIAL-USE ORGANIC CONTAMINANTS WITH E-WASTE: POSSIBLE IMPLICATIONS FOR EMISSIONS, TRANSPORT AND ENVIRONMENTAL EXPOSURE

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Introduction

Some industrial-use organic contaminants (IUOCs), such as polychlorinated biphenyls (PCBs) and various halogenated flame retardants (HFRs), have in common that they have been deliberately produced and used for a wide range of industrial purposes including, but not limited to, electrical and electronic equipment. The perception has been that the major source regions of IUOCs have mainly been industrialized countries in the northern hemisphere where these chemicals have been manufactured and more extensively used, such as North America, central parts of Europe and Japan in the case of PCBs[1]. Developed countries are also regions where significant reductions in environmental and human burdens are now often reported, following regulations such as bans on production and use of IUOCs[2,3]. As regulated IUOCs are approaching the end of their life-cycle and environmental agreements are coming into effect, it is prudent to ask whether there remain any significant sources and source regions for IOCs on a global scale which remains to be identified and controlled.

Recent studies have shown that concentrations in air, and hence emissions of some IUOCs remain surprisingly high in some regions of West Africa and parts of Asia, which are implicated as recipients of obsolete products and wastes containing IUOCs from rich countries [4]. Divergent patterns and trends between some developed and developing regions[3,5] led us to hypothesize that transboundary export of wastes containing IUOCs may have caused a shift in global sources and source regions, due to a final transition in the life-cycle towards the recycling and disposal stages[4]. It was further hypothesized that this shift may have significant implications in terms of spatial and temporal trends on a regional and possibly even global scale[4].

The objectives of this work were

(i) to develop an inventory of the global generation and transboundary flows of e-waste (discarded electronic and electrical equipment) towards non-OECD countries,

(ii) to develop generic global scale atmospheric emission scenarios from wastes for hypothetical IUOCs (with and without consideration of exports),

(iii) to explore the potential implications of e-waste flows for global transport and exposure of IUOCs using a global multimedia fate and transport model.

Materials and methods

E-waste inventory

The net amount (M_{NET} in kt) of e-waste processed annually in any given country is calculated as

$M_{NET} = M_{GEN} + M_{IMP} - M_{EXP}$

where M_{GEN} is the amount of e-waste generated domestically by its own population, M_{IMP} and M_{EXP} are the amounts of e-waste imported to and exported from the country.

M_{GEN} was derived using a top-down approach, based on an estimated global generation of e-waste of 35,000 kt (20,000-50,000) in 2005 by UNEP[6]

Gross Domestic Product [GDP(PPP)][7] was used as a proxy for distributing the UNEP estimate by country, taking advantage of the often tight relationship seen between the generation of e-waste and key economic indicators[8].

M_{IMP} to non-OECD was derived on the basis of a review of data on e-waste imports available and/or derived for China, India and five West African countries.

M_{EXP} from any OECD country was back-calculated as a fixed percentage ($\Sigma_{non\text{-}OECD}M_{IMP}$ / $\Sigma_{OECD}M_{GEN}$) of M_{GEN}

The national data were spatially distributed and mapped on a 1°x1° longitude and latitude basis, using population densities within individual countries as proxies (https://na.unep.net/metadata/unep/GRID/GLPOP90.html).

Generic emission scenarios

E-waste inventory estimates on a 1°x1° basis were first aggregated to match the spatial resolution of the fate/transport model employed in this study (the BETR Global 2.0 model[9], 15°x15°, 288 zones). Atmospheric emissions in each zone were then assumed to be a function of i) the amount of e-waste generated normalized to Central Europe (Zone 61) and ii) a passive volatilization emission factor (PVEF) also normalized to Zone 61 (based on monthly average temperatures). PVEFs are calculated using the following assumed relationship[10]:

$$\frac{E_2}{E_1} = \exp\left[\frac{\Delta U_A}{R} \cdot \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

where ΔU_A is the internal energy of vaporization, R is the gas law constant, T_1 is the temperature in Zone 61, T_2 is the temperature in other zones.

Model simulations

Simulations were conducted for four hypothetical IUOCs, assigned the physical-chemical property values shown in Table 1. For each IUOC, atmospheric emissions were estimated for the M_{GEN} scenario and the M_{NET} scenario. Model output assuming steady-state conditions was then produced for each IUOC and emission scenario (i.e., 4 IUOCs x 2 emission scenarios each). Concentration ratios (e.g., C_{AIR}, M_{NET} / C_{AIR}, M_{GEN}) for each zone were then calculated for each IUOC to characterize the relative changes in model output associated with the transboundary flows of e-waste.

Table 1: *Physical-chemical property values selected for four hypothetical IUOCs.*

	ΔU_A (kJ/mol)	$t_{1/2}$ in air (d) (Global average)	log K_{OW}	log K_{AW}	Analog
IUOC-1	74.8	6.7	5.66	-1.93	PCB-28
IUOC-2	94.8	31	6.86	-2.13	PCB-153
IUOC-3	97.0	11	6.53	-3.12	PBDE-47
IUOC-4	145	318	9.97	-4.81	PBDE-209

Results and discussion

The overall results for the e-waste inventory for 2005 is mapped in Figure 1.

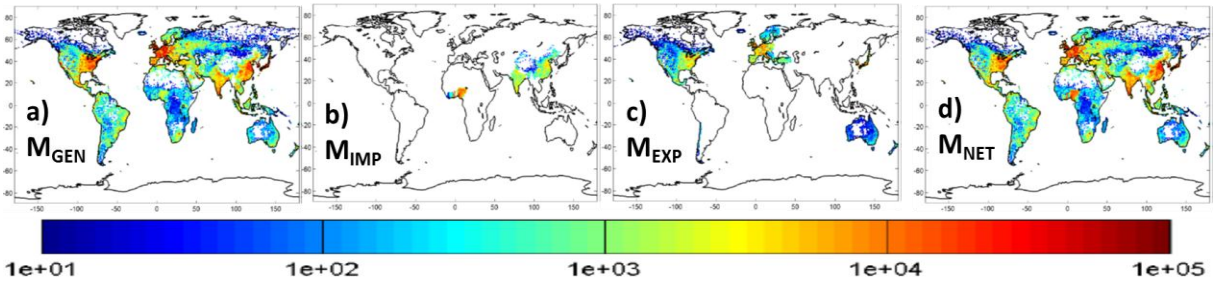

Figure 1: *Estimated domestic generation (a), import to non-OECD (b), exports from OECD (c) and net amount (d) of e-waste around 2005 with 1°x1° longitude and latitude resolution (in tonnes)*.

Our top-down estimates for M_{GEN} (Fig 1a) compare favorably with independent data for individual countries (*data not shown*), while the budget for total import of e-waste to selected non-OECD countries (Fig 1b) accounts for 5,023 kt (3,642 kt - 7,331 kt). This amount represents 23% (16.7% - 33.5%) of the e-waste generated within the OECD. However, available estimates of transboundary exports of e-waste out of the OECD in the literature are highly variable, and often at the lower end of estimates of imports to non-OECD. Uncertainties in our understanding of global flows of e-waste remain and are likely to persist because of the lack of activity data on illicit exports, which calls for complementary approaches to track the sources, flows and destinations of e-wastes, such as by use of GPS-based monitoring as well as contaminant forensics and chemical fingerprinting techniques.

The generic emission scenarios from e-waste alone, developed on the basis of M_{GEN} (Fig 1a) and M_{NET} (Fig 1d) are shown in Figure 2. These results suggest that global emissions from e-waste may increase ~ 30 (IUOC-1) up to almost 50% (IUOC-4) under the current assumptions due to enhanced passive volatilization following

transport of e-waste to warmer regions. Informal recycling practices (e.g., open burning) in e-waste import regions are likely to exacerbate the quantitative changes in emissions (M_{GEN} –> M_{NET}) depicted here. However, more realistic emission scenarios would require more specific knowledge on the actual emissions occurring from various informal recycling and disposal practices at recycling sites in developing regions. Furthermore, passive volatilization may not realistically reflect the mehanism for atmospheric emissions for IUOCs which are strongly sorbed to particles (high K_{OA}, i.e. IUOC-4).

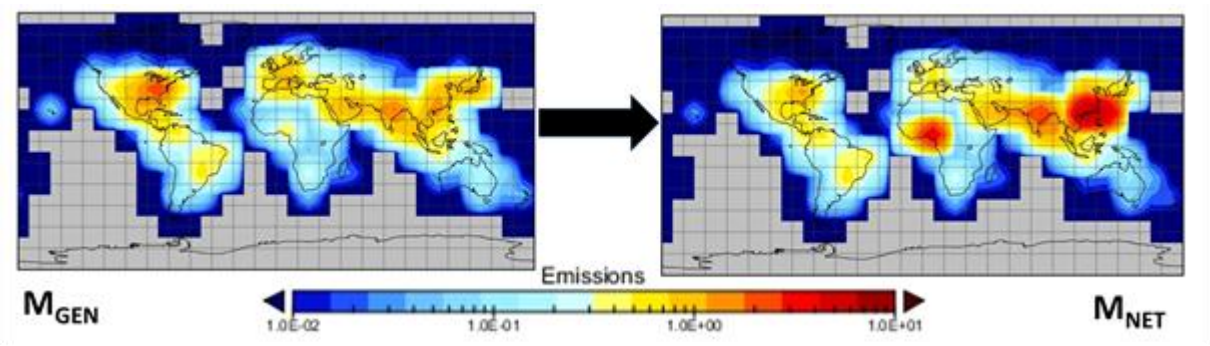

Figure 2: *Generic emission scenarios developed for M_{GEN} and M_{NET}, assuming temperature dependent passive volatilisation.*

The predicted steady-state concentration ratios in lower air for the M_{NET} vs M_{GEN} emission scenarios are shown in Figure 3. These concentration ratios, representative for the surface compartments as well, shows that e-waste exporters in OECD regions gain a marginal reduction in environmental exposures, while e-waste importers in southeastern Asia and West Africa are predicted to suffer from a relatively high increase. Response to e-waste emission scenarios considered here depend on persistence of chemical in the environment; for chemicals with relatively low persistence (e.g., IUOC-1), negative consequences of trans-boundary e-waste exports may be more localized in recipient areas. On a global scale, the overall persistence of all IUOCs declines due to enhanced degradation of these chemicals at lower latitudes. Nevertheless, the net effect for all IUOCs considered is that the total global inventory of chemical is predicted to increase from ~5% (IUOC-1) up to ~38% (IUOC-4).

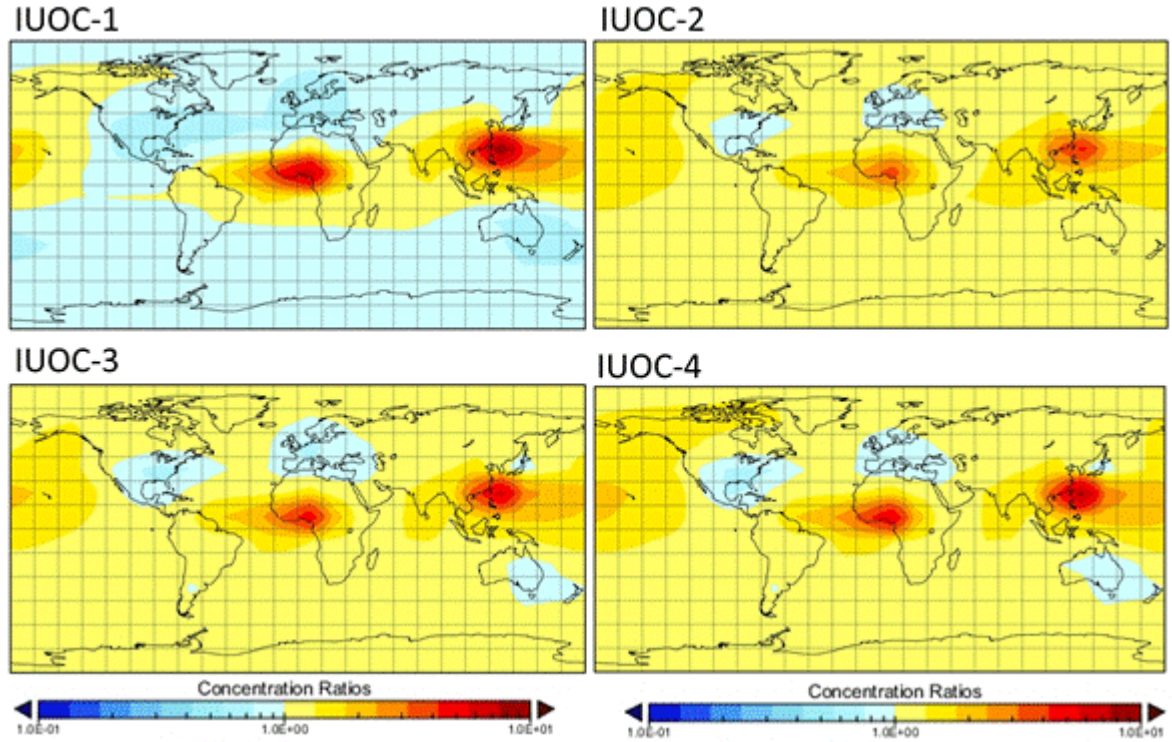

Figure 3: *Preidcted steady-state concentration ratios in lower air (M_{NET} / M_{GEN}).*

We caution that the results presented herein are affected by simplifying assumptions and therefore also significant uncertainties. However, the difference in terms of impact on environmental exposures in recipient versus exporting regions is to be considered as conservative as the "real" difference in emission potential are likely to be significantly underestimated (Figure 2). Further research to better characterize the actual emissions of IUOCs in e-waste areas of developing regions is therefore needed. It is finally our hope that these results are of interest to policy makers interested in improving control strategies to further reduce emissions of IUOCs to protect environmental and human health on a global scale.

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