Current-use and legacy pesticides' multi-annual trends in air in central Europe: primary and unidentified secondary sources

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Abstract. This study investigated 48 current-use pesticides (CUPs) and 30 organochlorine pesticides (OCPs) in ambient air at a rural-agricultural site in the Czech Republic, with biweekly sampling over three and 10 years, respectively. Despite being banned decades ago, OCPs persist in the atmosphere, with revolatilisation from surfaces apparent in summer. Temporal trend analysis revealed decreasing atmospheric concentrations for several OCPs, which indicate long-term diminishing reservoirs in environmental compartments, especially soil. For *β*- and *γ*-HCH, *o,p'*- and *p,p'*-DDE, *o,p'*-DDD, *o,p'*- and *p,p'*-DDT, *α*-chlordane, and mirex, levelling off is observed, which points to recently enhanced secondary sources in the region or beyond, related to reversal of the direction of air-surface exchange in response to historic atmospheric depositions or recent mobilisation from ground compartments, such as water bodies, the cryosphere, or soils heated by wildfires.

CUP concentrations peaked during application seasons, with multi-annual trends either insignificant or declining. For compounds like chlorpyrifos and fenpropimorph, declining trends aligned with regulatory bans, though their presence in the atmosphere was evident one-year after the bans, suggesting persistence.

1 Introduction

The wide use of organochlorine pesticides (OCPs) started in the 1940s for agricultural and vector disease control purposes. Because of long residence time in ground compartments and air, these substances cycle globally, enhanced by semivolatility, which allows for several cycles of volatilisation and deposition (Wania and Mackay, 1993; Semeena and Lammel, 2005). Due to their severe health and environmental effects, OCPs have been restricted in most countries (UNEP, 2001). For DDT and HCH this was consistently reflected in declining concentrations in air (UNEP, 2003; Becker et al., 2008; Gao et al., 2010; Venier and Hites, 2010; Shunthirasingham et al., 2016; Wöhrnschimmel et al., 2016). Without primary emissions, re-volatilisation from soils and surface waters, triggered by the reversal of the direction of air-surface exchange under declining levels in air (Bidleman et al., 1995; Lakaschus et al., 2002; Semeena et al., 2006; Stemmler and Lammel, 2009;

Wöhrnschimmel et al., 2012, 2016; O'Driscoll, 2014; Lammel et al., 2018; Li et al., 2020) should be the only remaining source for banned OCPs in air (Salamova et al., 2015; Wong et al., 2021). Most of the total environmental burdens of OCPs are stored in surface compartments, while only a minor fraction is cycling in air (Semeena et al., 2006; Wöhrnschimmel et al., 2012; 2013; Mackay and Parnis, 2020).

Newer types of pesticides, called current-use pesticides (CUPs), have since been developed and have been extensively used worldwide (Alexandratos and Bruinsma, 2012; Sharma et al., 2019; FAOSTAT, 2024). CUPs, covering more than 30 substance classes such as organophosphates, pyrethroids, and neonicotinoids, are chemically varied and accordingly subject to different environmental fates (van Pul et al., 1999; Lewis et al., 2016; Carvalho, 2017). CUPs have been detected in many environmental matrices worldwide (Tang et al., 2021) and are capable of long-range transport (Balmer et al., 2019; Mayer et al., 2024). CUPs can enter the atmosphere during application, where up to 90% of the mass applied can be released directly into the atmosphere (van den Berg et al., 1999). CUPs can volatilise from surfaces such as soil, plants and surface water over longer periods of time following application (Bedos et al., 2002), and can be mobilised through wind erosion of soil particles containing CUPs (Glotfelty et al., 1989). Moreover, like OCPs, CUPs can also re-volatilise from soils and surface waters. For both banned and authorised chemicals, it is generally possible to distinguish between primary (e.g., application for pesticides) and secondary sources (e.g., re-volatilisation) by examining the seasonal temperature variations, application, and concentrations in air (Hoff et al., 1998; van den Berg et al., 1999). OCP sources and atmospheric concentrations have been monitored for decades at continental sites (Bidleman, 1999; Sofuoglu et al., 2004; Holoubek et al., 2007; Cindoruk, 2011; Salamova et al., 2015; White et al., 2021; Kalina et al., 2022; Hites and Venier, 2023) and remote sites (Hung et al., 2005, 2010, 2016; Wong et al., 2021). Monitoring of CUPs in air has been reported from a few European countries (Duyzer, 2003; Coscollà et al., 2010, 2017; Degrendele et al., 2016; Villiot et al., 2018; LCSQA, 2019; IVL, 2021; Kruse-Plaß et al., 2021; Debler et al., 2024; Habran et al., 2024), and CUP regional distributions have become an increasing focus of research in recent years (Wang et al., 2021; Mayer et al., 2024).

Multi-annual observations of these compounds are essential not only for assessing the effectiveness of policy decisions (e.g., the immediate effects of banning certain pesticides) and evaluating the overall atmospheric pesticide load, but also for identifying their sources in the atmospheric environment. In this study, biweekly samples of OCPs and CUPs were collected in both the gas and particulate phases at a rural site in an agricultural region of central Europe, spanning 2013-22 for OCPs and 2019-21 for CUPs, , allowing for the assessment of seasonal variations and time trends.

2 Methodology

2.1 Pesticide selection

Forty-eight CUPs (21 herbicides, 16 insecticides and 11 fungicides) encompassing 24 chemical classes were selected (Table S1) based on previous studies (Degrendele et al., 2016; Désert et al., 2018; Mayer et al., 2024), national and global pesticides usage trends (Maggi et al., 2019; ÚKZÚZ, 2024) and their potentially harmful effects on the environment and human health (Jepson et al., 2020; Hulin et al., 2021). In addition, 30 OCPs and related metabolites were also measured (Table S2).

2.2 Site location

The National Atmospheric Observatory Košetice, Czech Republic (NAOK), is a regional background site of the Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), Global Atmosphere Watch (GAW) and Integrated Carbon Observation System (ICOS) networks, and contributes to the Aerosols, Clouds and Trace Gases (ACTRIS) research infrastructure (Holoubek et al., 2007; Lammel et al., 2010; Váňa et al., 2020). However, as this site is located in an agricultural area (Figure S1) and in close vicinity to fields (samplers distanced <20 m from fields; Figure S2), the site is a rural site and not representative of background conditions with regards to emissions from agriculture.

2.3 Sample collection

A high-volume air sampler (Digitel DH77; Digitel, Volketswil, Switzerland), equipped with a PM_{10} pre-separator sampling head, was used to collect week-long samples every second week from January 2013 to December 2022 for OCPs alongside another high-volume air sampler (Baghirra, Baghirra s.r.o., Prague, Czech Republic) and from February 2019 to August 2021 for CUPs. For OCPs, the sampling volume was on average 5167 ± 518 m^3, while it was 3124 ± 491 m^3 for CUPs. Particles were collected on quartz fibre filters (QFFs) (QM-A, 150 mm, Whatman, UK) for both OCPs and CUPs, while gaseous OCPs were collected on polyurethane foam (PUF) plugs (two in sequence, T3037, 110×50 mm, 0.030 g cm^{-3}, Molitan, Břeclav, Czech Republic) and gaseous CUPs on a sandwich sorbent consisting of a PUF plug, a layer of XAD resin (Supelpak-2, Merck, Darmstadt, Germany), and another PUF plug, separated by cotton wool (i.e., PUF/XAD2/PUF sandwich). This configuration has been shown to be the most efficient for the collection of gaseous CUPs (Dobson et al., 2006; López et al., 2018) and has been applied and optimized previously for CUPs and OCPs (Degrendele et al., 2016). Prior to sampling, PUFs used for OCP sampling were precleaned via Soxhlet extraction with acetone and dichloromethane for 8 hours each, and both PUFs and XAD2 used for CUP collection were precleaned via Soxhlet extraction with acetone and methanol for 8 hours each.

In total, 252 air samples were collected for OCP analysis, while 107 samples were collected for CUP analysis. Six samples from early January to March 2016 were removed from the dataset due to road reconstruction in the vicinity of the sampling, which prompted a strong resuspension of soil particles. After collection, samples were wrapped in aluminium foil, sealed in a plastic bag, stored at -18 °C on site until transport to the RECETOX Trace Analytical Laboratories, and stored at -18 °C until extraction and analysis.

2.4 Sample preparation and analysis

Air samples were first spiked with isotopically-labelled standards (Table S3) and then underwent extraction using an automated extractor (E-800, Büchi Extraction System, Flawil, Switzerland), with 150 mL of methanol and 5 mM of ammonium acetate for CUPs and 150 mL of dichloromethane for OCPs. CUPs extract clean-up was done by filtration through a 0.22 μm pore size cellulose acetate membrane (Corning Costar Spin-X, United States) and concentrated under a gentle stream of nitrogen to a final volume of 500 μL. 100 μL of MilliQ water were then added to a 100 μL aliquot of the extract which was then used for analysis. After extraction, OCPs extracts were transferred to a glass column (30 mm i.d.) filled with 0.5 g of activated silica, 30 g of H_2SO_4 modified activated silica and 1 g of non-activated silica and were eluted with 40 mL of DCM:hexane (1:1). 50 μL of n-nonane was added as a keeper solvent, and the extract was then concentrated under a gentle stream of nitrogen to a final volume of 100 μL.

CUPs were analysed using a high-performance liquid chromatograph (HPLC, Agilent 1290, Agilent, Santa Clara, USA) coupled to a mass spectrometer (QTRAP 5500, AB Sciex, Framingham, USA) using four different methods previously developed and described (Mayer et al., 2024). The precursor to product ions were monitored in scheduled multiple reaction monitoring mode (MRM) (Table S4). The identification of individual pesticides was based on the comparison of intensity ratios of ions and retention times with standards and quantification was done using internal calibration with isotopically labelled standards (Table S4).

OCPs were analysed by gas chromatography-mass spectrometry (GC-MS/MS). Detailed information on the methods employed is available in the Supplementary Information (SI Methodology and Table S5).

2.5 Quality assurance and quality control

Twenty-three and eight field blanks were collected and treated alongside the collected samples for OCPs and CUPs, respectively. They were placed in the sampler without pumping air for several seconds (Table S6). Instrumental limits of detection (iLODs) and quantification (iLOQs) were determined by distinguishing the intensity of analytes with a signal-to-noise ratio of 3:1 and 10:1, respectively. Field blanks were used to determine method detection limits (MDLs) based on the average of the analyte concentrations in field blanks plus three times their standard deviation. If field blanks levels were below iLOQ, then iLOQs were used as MDL.

The recoveries of individual pesticides were assessed by spiking sampling media (i.e., QFFs and PUF/XAD2/PUF sandwiches for CUPs and PUFs for OCPs) with the native standards and their corresponding isotopically-labelled standards, which were then processed in the same way as the samples. With a few exceptions, most analyte recoveries were in the range of 60–120 % and had standard deviations lower than 20 %. For the 48 CUPs analysed using the HPLC-MS/MS, the method recoveries of individual analytes ranged from 68 ± 14 % (carbaryl) to 153 ± 22 % (iprovalicarb) for QFFs and from 61 ± 3 % (kresoxim-methyl) to 132 ± 10 % (iprovalicarb) for PUF/XAD2/PUF (Table S7a), while for OCPs, recoveries ranged from 47 ± 8 % (PeCB) to 100 ± 9 % (*p,p'*-DDD) for QFFs and from 49 ± 6 % (PeCB) to 103 ± 10 % (*p,p'*-DDD) for PUFs for all samples from 2013 to 2022 (Table S7b).

In 2018, the analytical instrument and internal standards were changed for OCPs only. As a consequence, the chromatographic results from 2018 onward, for both OCPs and CUPs, have been adjusted by the recoveries (SI S1.1.2.), while results for OCPs prior to 2018 were not recovery corrected (SI S1.1.1.). Therefore, the time trends are determined separately for the two periods: (1) from 2013 to 2017 and (2) from 2018 to 2022. The different treatment of recoveries is clearly visible in some of the OCP time series (e.g., PeCB, HCB and HCHs).

2.6 Data processing and statistical analysis

As relaxation to phase equilibrium is fast on the time scale addressed (weeks), and both phases were analysed separately, the data analysis was based on the total concentration, i.e., the sum of particulate and gaseous concentration. Individual pesticide temporal trends were investigated using a multiple regression equation accounting for seasonality. For OCPs, with expected one annual amplitude, Equation (1) is used, which has been widely applied for trend analysis of OCPs (Venier et al., 2012; Wang et al., 2018), as well as for other semivolatile organic compounds (SVOCs) which are dominated by secondary emissions, such as polychlorinated biphenyls (PCBs; Degrendele et al., 2020) and polybrominated diphenyl ethers (PBDEs; Ma et al., 2013; Li et al., 2016; Degrendele et al., 2018), halogenated flame retardants (Liu et al., 2016), per- and polyfluoroalkyl substances (Paragot et al., 2020) and organophosphate esters (Wang et al., 2020).

$$\ln C_{air} = a_0 + a_1 \sin(zt) + a_2 \cos(zt) + a_3 t \qquad (1)$$

where C_{air} equals the total (particulate + gaseous) concentration of a compound (pg m^{-3}), t is the time (in years) when the samples were collected; z equals (2π/365.25) to fix the periodicity to a year; a_0 is an intercept to rectify the units, a_1 and a_2 are harmonic coefficients describing seasonal variations, and a_3 is a first-order rate constant and the long-term exponential component (yr^{-1}). The parametric F-test was used in order to assess the significance of each of these coefficients, while the coefficient of determination R^2 reflects the fit of equation (1).

Since at rural sites, CUPs in air sites will be dominated by primary emissions (i.e., application on agricultural land), long-term trends were analysed using Eq. (2), which captures up to two annual amplitudes and their application periodicity.

$$ln\, C_{air} = a_0 + a_1 \cos(a_2 zt + a_4) + a_3 t \qquad (2)$$

with a_1 being a harmonic coefficient describing seasonal variation, a_2 allowing for other periods than one year, a_3 is the long-term exponential component (yr^{-1}) and a_4 defines a phase shift deviating from the seasons. The initial guess for the value of a_4 was chosen according to the recommended timing of application (e.g., 2.32 in units of 2π for mid-May) and was later fine-tuned during the regression.

For both equations (1) and (2), the coefficient a_3 is used to calculate the halving (< 0) or doubling time (> 0) for a given compound according to Equation 3:

$$\tau_{1/2} = (\frac{\ln(2)}{a_3})/365.25 \qquad (3)$$

The apparent halving or doubling time (τ; in years) describes the time for concentrations of a compound to decrease by 50% or to increase by 100%. These halving or doubling times should not be confused with half-lives associated with degradation processes.

Non-parametric Mann-Whitney tests were applied to compare atmospheric concentrations with previous CUP measurements conducted at the same site in 2012-13 (Degrendele et al., 2016).

2.7 Clausius-Clapeyron equation

The influence of the near-ground air temperature on volatilisation of pesticides from soil can be represented using the Clausius-Clapeyron equation (Hoff et al., 1998; Equation 4):

$$\ln p = (\Delta H_{exp}/R)\,(1/T_a) + constant \qquad (4)$$

with partial pressure p (Pa), near-ground air temperature T_a (K), experimentally-based enthalpy of the soil-air exchange ΔH_{exp} (kJ mol^{-1}) and the universal gas constant R (8.314 Pa m^3 K^{-1} mol^{-1}). Firstly, the partial pressures of individual pesticides were calculated following Equation 5,

$$p = (c_{tot}\; R\; T_a)/M_g \qquad (5)$$

using the ideal gas law, air temperature T_a, molecular weight M_g (g mol^{-1}). and total concentrations $c_{tot} = c_g + c_p$ (in g m^{-3}) for OCPs and CUPs. c_{tot} is more appropriate than c_g, because inherent to our sampling design (weekly samples, long-lived substances), the total concentration, $c_g + c_p$, is operationally conservative, unlike c_g. The pesticide vapour pressures were expressed as linear regressions of the natural logarithm of partial pressure versus inverse temperature (Hoff et al., 1998; Equation 6):

$$\ln p = \frac{m}{T_a} + b \qquad (6)$$

where m and b correspond to the slope and intercept of the linear regression, respectively.

3. Results and Discussion

3.1 Pesticides detection frequencies

Overall, 32 of the targeted 48 CUPs were observed in at least one sample. Eleven CUPs had detection frequencies (DF) greater than 80%, with two CUPs, pendimethalin and tebuconazole, being detected in all samples. Six CUPs had DF from 50% to < 80%, five CUPs from 20% to < 50%, while 10 CUPs had DF < 20% (Table S8). The CUPs included in this study represented 22%, 30% and 28% of all the pesticides used in agriculture in the Czech Republic during the years 2019, 2020 and 2021, respectively (Table S9). Among them, chlorotoluron, chlorpyrifos, metamitron, metazachlor, pendimethalin, prochloraz, spiroxamine, tebuconazole and terbuthylazine were used in the largest amount (> 50 t of active substances per year), and these CUPs were all quantified > 65 % of air samples, except for metamitron (2.8 % DF). Most of the CUPs quantified during the sampling period were applied as plant protection products in the Czech Republic, however, six compounds, acetochlor, atrazine, carbaryl, diazinon, isoproturon and mecoprop, had DFs ranging from 0.9% to 51 % and had no documented use. Cyprodinil and diuron were approved, but no use was reported in the Czech Republic, while the other compounds were prohibited for use in Europe.

During the 2013 to 2022 period, all targeted legacy OCPs and metabolites were detected in at least one sample. Six compounds were present in every sample, emphasizing their persistence in the environment: pentachlorobenzene (PeCB); hexachlorobenzene (HCB); two stereoisomers of hexachlorocyclohexane (HCH): *α*-HCH and *γ*-HCH; *p,p'*-dichlorodiphenyltrichloroethane (*p,p'*-DDT), as well as one of its associated metabolites *p,p'*-dichlorodiphenyldichloroethane (*p,p'*-DDE) (Table S8). Twelve additional compounds were present in more than 50% of the samples: *o,p'*-DDT, *o,p'*-DDE, *o,p'*-DDD, *p,p'*-DDD, *α*-chlordane, *γ*-chlordane and associated metabolite oxychlordane, *β*-HCH, *δ*-HCH, *cis*-heptachlor epoxide, *α*-endosulfan, and mirex. Aldrin, dieldrin, *β*-endosulfan, endrin, endrin aldehyde, endrin ketone, heptachlor, *trans*-heptachlor epoxide, isodrin and methoxychlor were all detected in less than 25% of the samples (Table S8).

3.2 Total concentrations

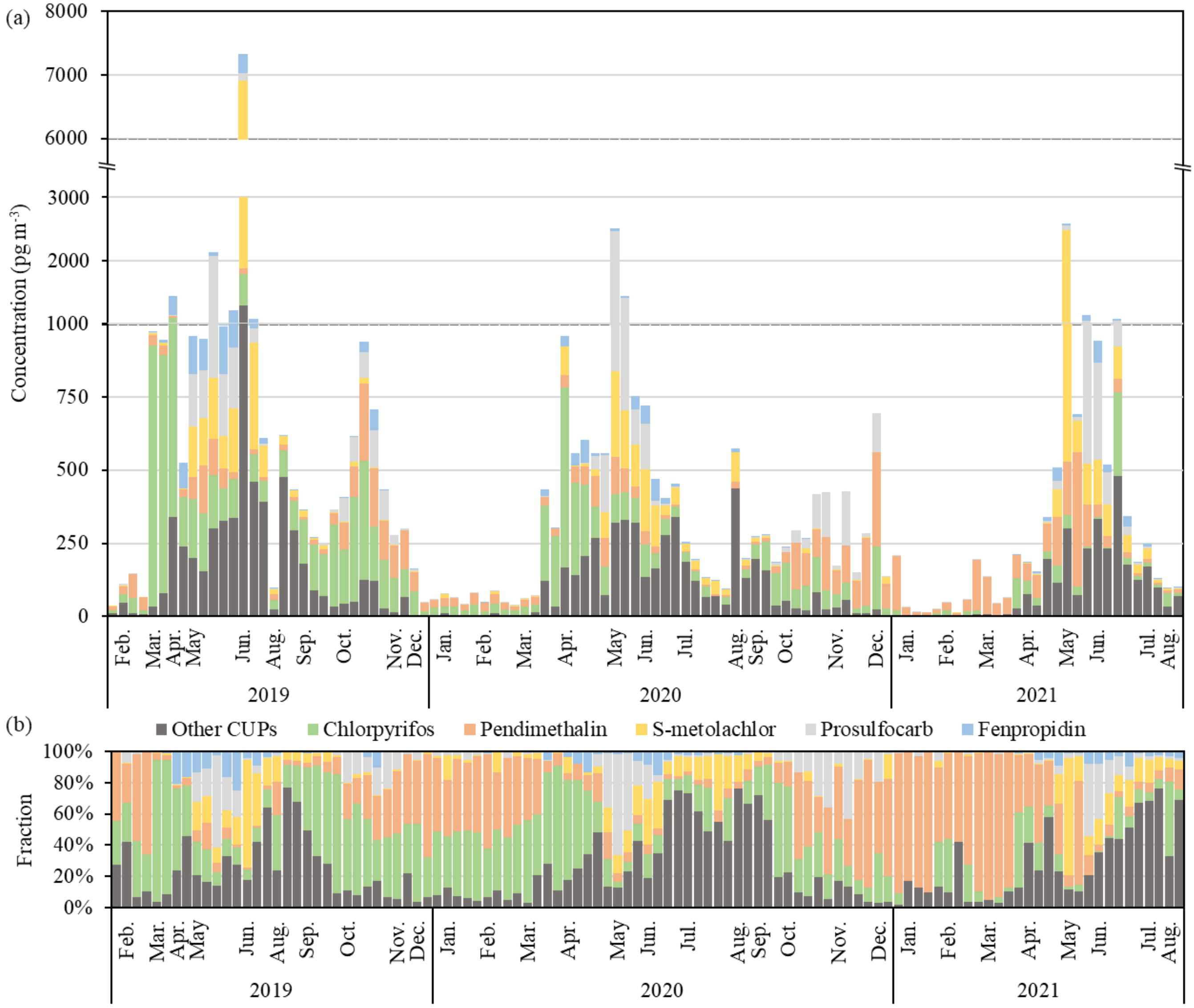
The concentrations of individual CUPs ranged over five orders of magnitude, from 40 fg m^{-3} (2,4-D) to 5 ng m^{-3} (s-metolachlor). Chlorpyrifos, fenpropidin, fenpropimorph, metalaxyl, metazachlor, pendimethalin, prosulfocarb, s-metolachlor, spiroxamine, tebuconazole and terbuthylazine were the only CUPs with total concentrations exceeding 100 pg m^{-3} on multiple occasions, while chlorotoluron exceeded that concentration only once during the sampling period (Figure 1a, b, Table S10). Previous observation at this site during the 2012-13 period also showcased the observation of chlorpyrifos, metazachlor and s-metolachlor, in addition to acetochlor and isoproturon in concentrations surpassing 100 pg m^{-3} (Degrendele et al., 2016). In this study, chlorpyrifos, s-metolachlor, and prosulfocarb were found most abundant (average concentrations of 116, 115, and 79.7 pg m^{-3}, respectively; Table S10a). As mentioned previously, some of those compounds (i.e., chlorpyrifos, metazachlor, pendimethalin, spiroxamine, tebuconazole and terbuthylazine) were applied on the Czech territory in more than 50 t of active substance per year, which would influence their high atmospheric concentration, notably during application periods (Table S9). Similarly, high concentrations of these compounds had previously been reported from rural environments (Debler et al., 2024; Habran et al., 2024; Mayer et al., 2024; Ni et al., 2024). Additionally, elevated levels of fenpropidin (0.42-307 pg m^{-3}), prosulfocarb (0.1-1631 pg m^{-3}), and s-metolachlor (0.06-5025 pg m^{-3}) have been previously observed in various European countries, including Germany, France, Belgium, and the Netherlands (Villiot et al., 2018; Kruse-Plaß et al., 2021; Debler et al., 2024; Habran et al., 2024) (Fig. 1a,b; Table S10).

Overall, concentrations of OCPs were found to be significantly lower than CUP concentrations. The average weekly concentration of Σ_{30}OCPs was 44.3 pg m^{-3}, with HCB, *p,p'*-DDE and *γ*-HCH accounting on average for 38, 29 and 8.1% of Σ_{30}OCPs and found at highest concentrations (Figure 1c,d and Table S10). These three OCPs have also been previously observed as the dominant atmospheric OCPs (Gevao et al., 2018; Wang et al., 2018; Wong et al., 2021; Mamontova and Mamontov, 2022; Khuman et al., 2023; Lunder-Halvorsen et al. 2023).

The ratio of (*p,p'*-DDT)/(*p,p'*-DDE + *p,p'*-DDD) can be used as an indicator of aged technical DDT, as over time, DDT is converted into both DDE and DDE (Bidleman, 1999). A lower ratio is indicative of aged DDT, while a ratio > 1 implies fresh application (Sari et al., 2020). In this study, the ratio ranged 0.03-0.53, indicating aged DDT, as would be expected considering Czechoslovak restrictions on DDT in the 1970s. Moreover, the (*o,p'*-/(*o,p'*-+*p,p'*-) ratios for each DDX substance were compared (Figure S3). In general, technical DDT contains a higher fraction of *p,p'*-DDT, while dicofol contains a higher fraction of *o,p'*-DDT (Qiu et al., 2005). For both DDT and DDD, this ratio decreased over time and remained low (0.37 and 0.31 for DDT and DDD, respectively), indicating that dicofol was seemingly not a viable source for presence of DDT in the atmosphere, not during years of declining concentration nor later (Ricking and Schwarzbauer, 2012). For DDE, however, the ratio remained stable and low (i.e., average ratio = 0.02), indicating great environmental persistence, as the more stable *p,p'*-DDE isomer predominates, leading to prolonged contamination and potential bioaccumulation in ecosystems.

Additionally, the ratio β-HCH/(α-HCH+γ-HCH) which ranged 0.01-0.16 can be used to distinguish between technical HCH (β-HCH/(α-HCH + γ-HCH) ≥ 0.5) and lindane (β-HCH/(α-HCH + γ-HCH) < 0.5) (Li and Macdonald, 2005), as sources of environmental contamination.

The overall low level of β-HCH and the β-/(α-+γ-) HCH ratios confirm the use of lindane, which was banned more recently (1995), as the dominant HCH source (Sari et al., 2020). Similar results have been recently observed in Turkey, Peru, South Korea and Argentina (Sari et al., 2020; Miglioranza et al., 2021; Lee et al., 2022). Similarly, the ratio α-HCH/γ-HCH has been previously used to infer sources of HCHs. A recent study in Europe highlighted a distinction between the northern and southern regions: in the north, high α-HCH/γ-HCH values were observed, indicating the dominance of long-range atmospheric transport and re-suspension of α-HCH, whereas in the south, lower α-HCH/γ-HCH values suggested historical use of γ-HCH (lindane; Lunder-Halvorsen et al., 2023). In our study, the ratio α-HCH/γ-HCH ranged from 0.12 to 1.7, aligning with values reported in southern Europe.


(a)
Concentration (pg m-3)
8000
7000
6000
3000
2000
1000
750
500
250
0
Feb.
Mar.
Apr.
May
Jun.
Aug.
Sep.
Oct.
Nov.
Dec.
Jan.
Jul.
2019
2020
2021
(b)
Other CUPs
Chlorpyrifos
Pendimethalin
S-metolachlor
Prosulfocarb
Fenpropidin
Fraction
100%
80%
60%
40%
20%
0%

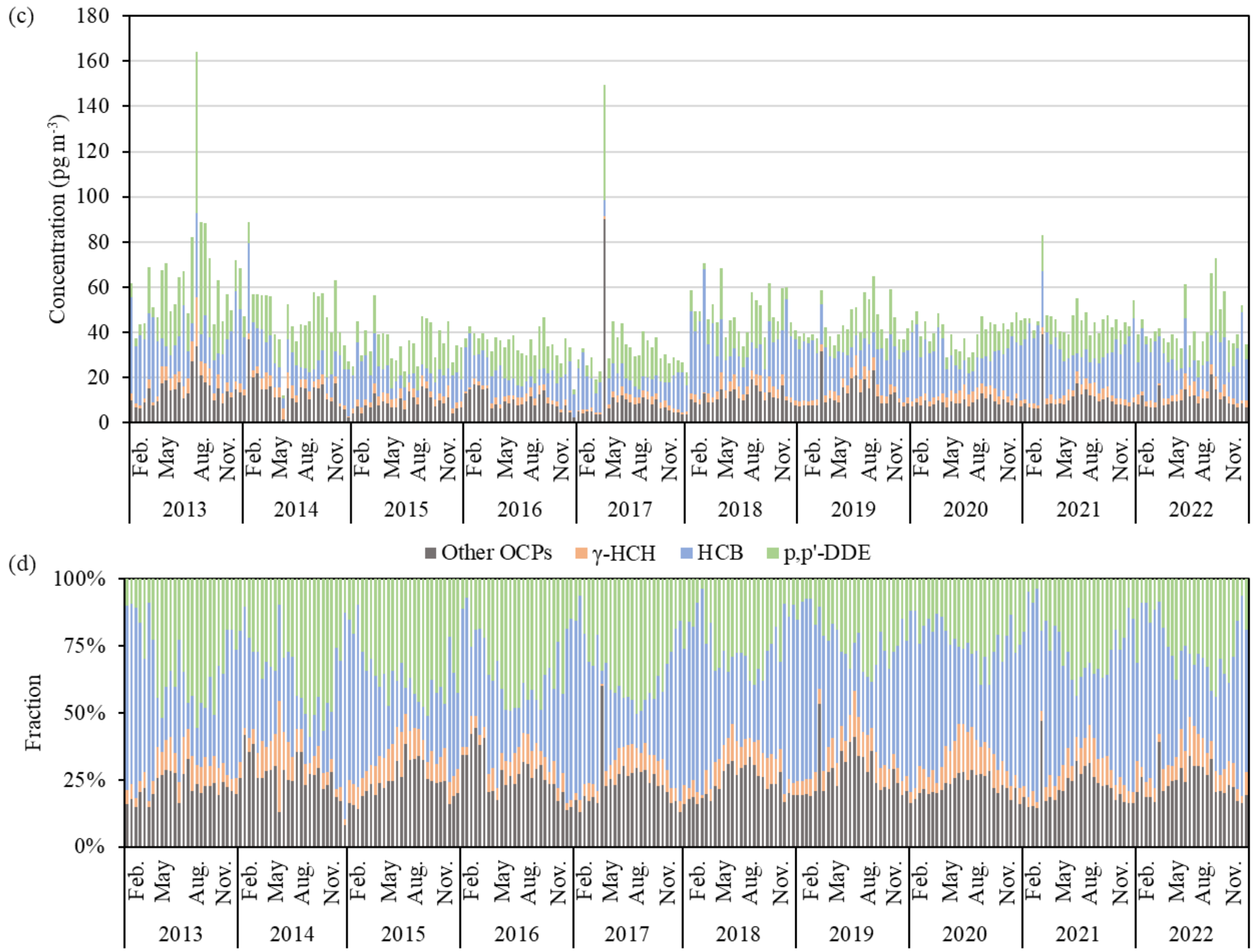


Figure 1. Time series of absolute (a, c; pg m^{-3}) and relative (b, d; %) abundances of Σ_{48}CUP (a,b) and Σ_{30}OCP (c,d) in air (total = sum of gaseous and particulate phases).

CUPs have previously been monitored at this site from 2012 to 2013 (Degrendele et al., 2016). Total concentrations were compared for compounds with sufficient data (DF>20%) in both this study and the previous one. Overall, eight CUPs were compared. The 2019-21 concentrations were significantly higher for chlorotoluron, chlorpyrifos, prochloraz and s-metolachlor, for which approvals existed during the entire study period, 2012-21. The 2012-13 concentrations were higher for isoproturon, banned as a plant protection product since 2016, and metazachlor, approved during the entire study period. No significant differences were observed for fenpropimorph and terbuthylazine (Table S11).

3.3 Seasonal variations

Out of the 22 CUPs with DF > 20%, the total atmospheric concentration for 16 peaked in spring (Table S12), aligned with the application season. The typical shape of applications during an application season is reflected as a fast increase in concentration followed by a slow decrease. Similar patterns have been previously observed for CUPs such as chlorpyrifos, fenpropidin, metazachlor, prosulfocarb and pendimethalin (Hayward et al., 2010; Degrendele et al., 2016; Carratalá et al., 2017; Villiot et al., 2018; Wang et al., 2021). Five CUPs, i.e., chlorotoluron, chlorpyrifos, isoproturon, pendimethalin and prosulfocarb, had atmospheric concentrations that peaked in both spring and autumn (Figure S4; Table S12). For pendimethalin, as a pre-emergence herbicide, an early winter/late spring application is also seen in 2019 and 2020. The autumn peak is likely due to direct application of pesticides for winter cereals (Garthwaite et al., 2014; Degrendele et al., 2016). However, it is also possible that volatilisation from surfaces such as soil, plants and pre-treated seed (Nuyttens et al., 2013) as well as tillage practices (Alletto et al., 2010) occurring at this time may contribute to the levels in air (Alletto et al., 2010). This is most likely the case for isoproturon, which has been banned since 2016, and therefore, application is unlikely. In general, during winter months, pesticide application are not expected due to low soil temperature (frozen or near), CUPs occurrence in ambient air indicates low degradability. During December to February, chlorpyrifos, isoproturon, and prosulfocarb were the dominant CUPs (with atmospheric concentrations > 100 pg m^{-3}), which have been indicated to be persistent previously (Debler et al., 2024; Mayer et al., 2024). Lastly, metazachlor peak in summer was particularly pronounced (Table S12, Figure S4), as observed previously (Mai et al., 2013; Degrendele et al., 2016). It was highest in August. This can be explained by coincidence of application, as metazachlor is most used for seed oil plants, usually applied in August for weed control of winter cereals (Wijewardene et al., 2021).

Bans on chlorpyrifos, fenpropimorph, propiconazole and thiacloprid became effective during the sampling period and an indication of these bans were apparent in the data (Table S1). During 2019, high concentrations were due to clearly evident applications, but these maxima were six times lower during the same period in the following years, highlighting the immediate effect of the legislation (Figure 1). In addition, based on the simulated concentrations distribution encountered derived from Eq. (2) (Table S12), we found that pesticide application was done from February until November, with the spring being quite broad, ranging from mid-March to end of June, while the autumn one ranged from mid-October to end of October.

3.4 Influence of temperature on pesticide re-volatilisation

The influence of local secondary emissions of pesticides via re-volatilisation from soils was examined using the Clausius-Clapeyron equation (Table S13) (Hoff et al., 1998). For the 2013-22 OCPs collection period, the temperature ranged from -9.5 to 23.7 °C while for the 2019-21 CUPs collection period, it ranged from -5.8 to 22.1°C.

A statistically significant correlation between the natural logarithm of partial pressure and the inverse ambient temperature was found for all OCPs with DF > 20%, except γ-chlordane (Table S13b). In addition, slopes were negative for 17 OCPs (Table S13b) and ranged from -7768 (ε-HCH) to -2879 (endosulfan sulfate). This indicates that those pesticides' atmospheric concentration increased with increasing air temperature (Figure S6). Previous studies noted that a steep slope and high R^2 values (> 0.6) are synonymous with temperature-controlled air–surface cycling and may indicate significant influence of short-range transport on the ambient concentrations (Hoff et al., 1998; Wania et al., 1998; Degrendele et al., 2016). This was observed for two OCPs: *o,p'*-DDT and *p,p'*-DDT, with respective slopes of -7221 and -6112, while respective R^2 values were 0.65 and

0.68 (Table S13b). The results from the Clausius-Clapeyron analysis suggest that soil temperatures play a significant role in influencing DDD levels at this site, as indicated by only little scatter, also in the DDD sinusoidal time series ($R^2 = 0.34$, Table S13b, Figure S8). In contrast, the bigger scatter for DDE ($R^2 = 0.46$, Table S13b, Figure S9), suggests that DDE is more influenced by secondary sources located far from the sampling area (Hoff et al., 1998).

In general, the Clausius-Clapeyron relationships suggest that atmospheric concentrations of most OCPs in this study were controlled by the exchange between soil and air and therefore, by revolatilisation from surfaces close to the sampling site. This observation agrees with other studies (Cabrerizo et al., 2011; Degrendele et al., 2016; Zhan et al., 2017). For the less temperature-dependent compounds, it is suggested that atmospheric concentrations were more influenced by long-range atmospheric transport (LRAT; Table S13b).

According to the Clausius-Clapeyron relationship, 18 CUPs were found to be temperature dependent (Table S13a; p-value < 0.05). Previously, terbuthylazine and s-metolachlor have been found to have significant temperature dependency (Degrendele et al., 2016). Unlike for OCPs, CUP maximum concentrations were not encountered during the warmest period (summer) but during their application periods (Figure S6 and Table S11).

The overall results emphasize the differences between OCPs and CUPs. For OCPs, temperature-dependent volatilisation is the main influence on OCP atmospheric concentration. For authorised CUPs, atmospheric concentrations were mainly influenced by application, while temperature-dependent resuspension and LRAT determined CUP atmospheric levels for banned compounds.

3.5 Multi-annual variations

Long-term annual variations in atmospheric concentrations were assessed for 22 CUPs with sufficient concentration data (DF > 20%) using Eq. (2) and Eq. (1) for CUPs and OCPs, respectively. Values below MDL were substituted by MDL/2. Eq. (1) was tested for CUPs trends, too, which led to lower R^2 values as compared to using Eq.(2) (Tables S15-S16), not only for CUPs with 2 concentration maxima per year, but also for CUPs with only one.

A decrease of total atmospheric concentrations is found for 14 CUPs over the period 2019-21 (Eq. 2, Table S15). Nine of these were approved pesticides: 2,4-D, chlorotoluron, cyprodinil, fenpropidin, metazachlor, pirimicarb, prochloraz, s-metolachlor and terbuthylazine. National usage of these pesticides in the Czech Republic was almost constant during 2019-21, except for fenpropidin and prochloraz, for which annual amounts decreased by approximately 40% during this period. Decreasing trends were also observed for recently banned pesticides (chlorpyrifos, fenpropimorph, and thiacloprid), as well as the earlier banned CUPs isoproturon and propiconazole. This reflects the immediate and long-term effects of legislation. Generally, for the CUPs with decreasing concentrations, the estimated halving times $\tau_{1/2}$ ranged from 0.62 to 1.37 yr for the approved pesticides, while for the banned pesticides halving times were expectedly lower (i.e., $\tau_{1/2} \approx$ 0.38-0.48 yr), except for thiacloprid ($\tau_{1/2} \approx 0.91$ yr) (Figure 2; Table S15). Seven CUPs showed no significant change of their atmospheric concentration over time. These compounds are all approved for use and applied in the Czech Republic with stable or increasing usage. Boscalid was the only in-use CUP in the Czech Republic that was decreasing (ÚKZÚZ, 2024).

For chlorpyrifos and fenpropimorph, the usage was reduced by 30-50% from 2019 to 2020 in the Czech Republic and was reported to approach zero or very low amounts in 2021 (Table S9). The observed decline was accelerated from 2020-21 compared to the 2019-20 period, reflecting the combination of these applications and degradation in the total environment after the ban (total environmental residence time $\tau_{overall}$ up to many months, BCPC, 2012).

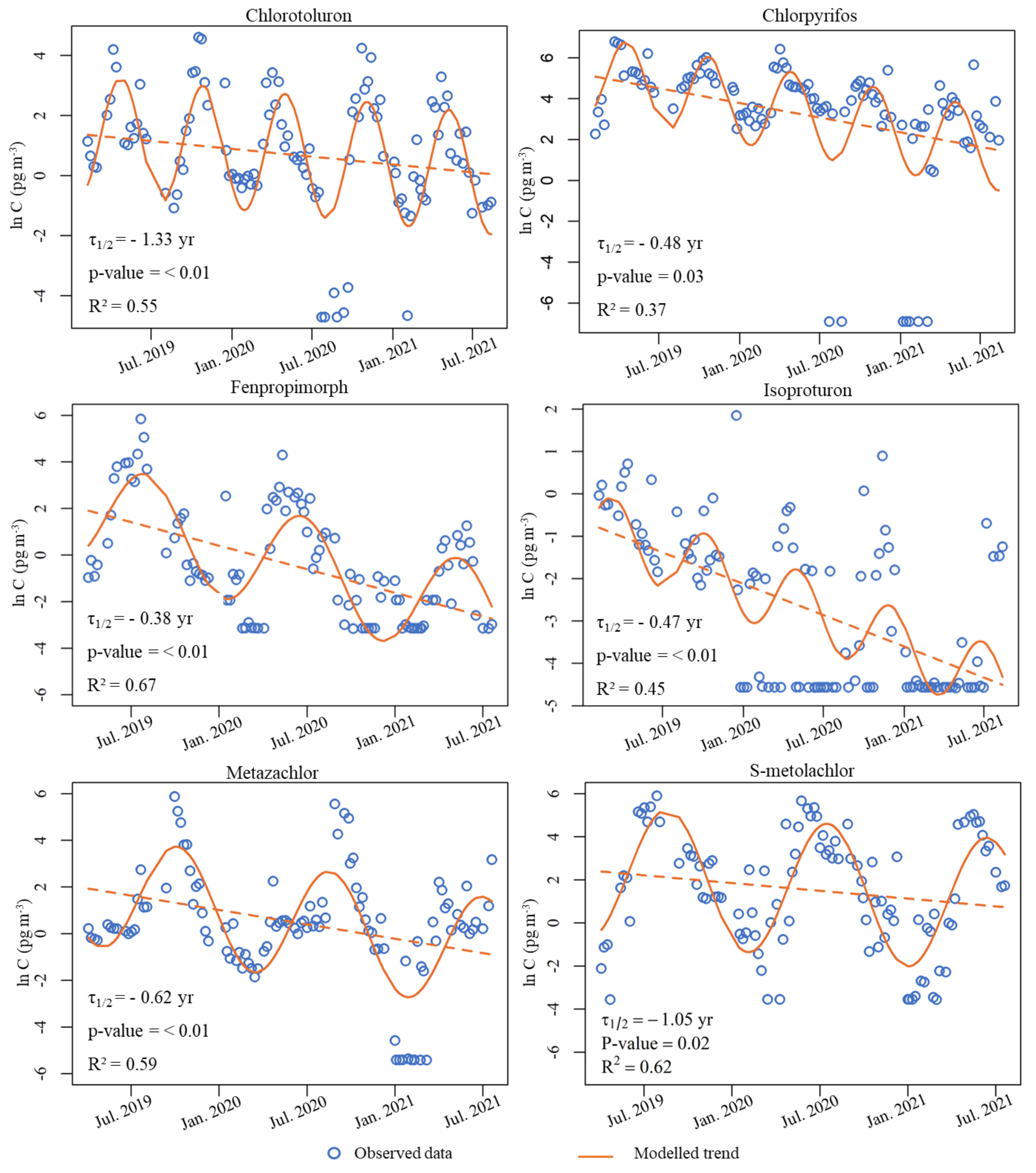


Figure 2. Multi-annual variations of selected CUPs with significantly negative trends. Values < MDL were substituted by MDL/2.

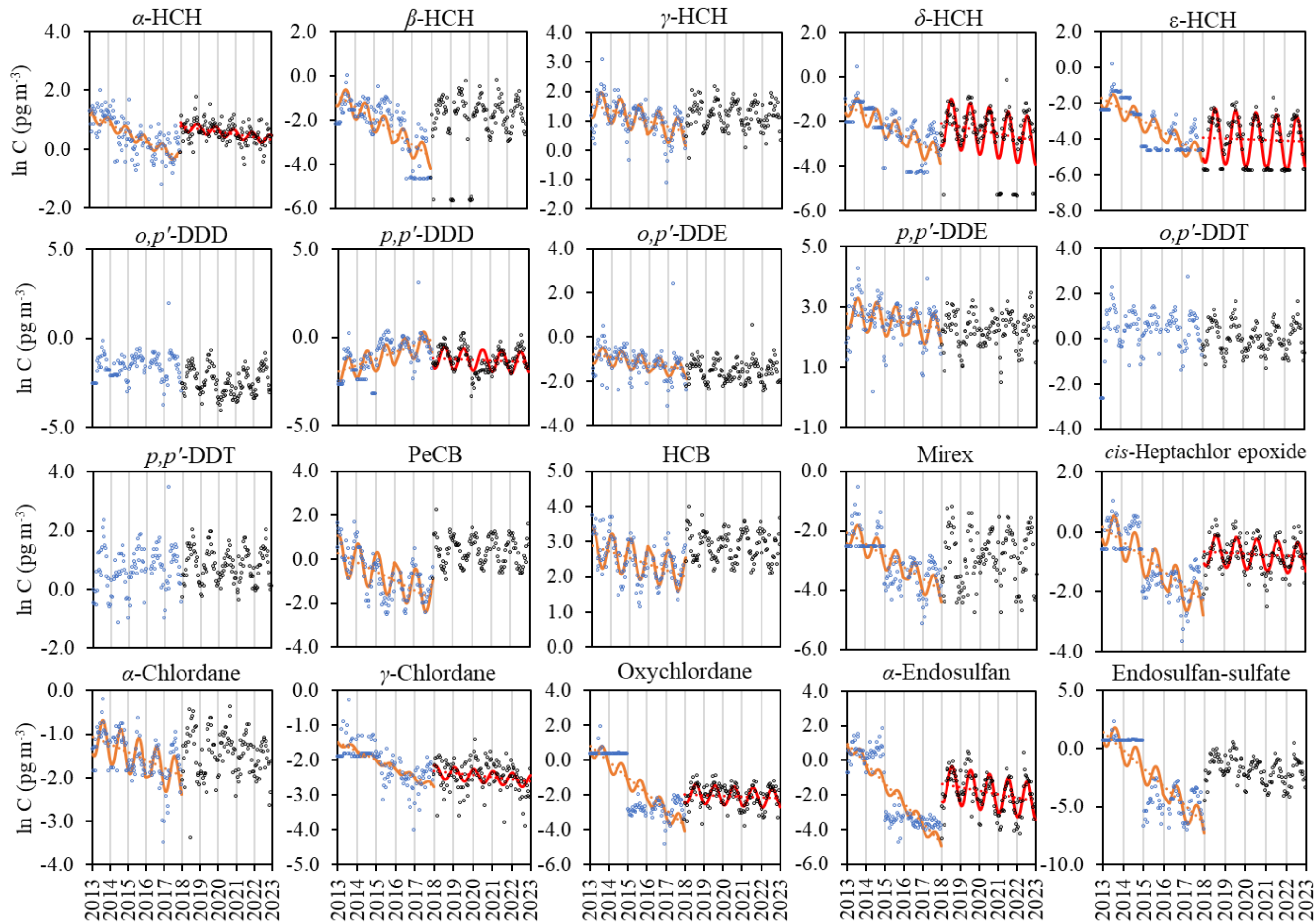


Figure 3. Multi-annual variations of OCPs (DF > 20%). Blue and black dots represent data from the 2013-17 and 2018-22 periods, respectively. The orange and red lines represent the modelled variation, whenever the trend was significant. Values < MDL were substituted by MDL/2.

The time trend analyses of the OCPs were assessed separately for the time periods 2013-17 and 2018-22 (Eq. (1), Table S16). A significant decrease in total atmospheric concentration is observed in both periods for *α*-, *δ*- and *ε*-HCH, *cis*-heptachlor epoxide, *γ*-chlordane, oxychlordane, and *α*-endosulfan (Figures 3 and S6). *p,p'*-DDD shows an increasing trend in the 2013-17 period, but a decreasing one in the 2018-22 period (Figures 3 and S7, Table S16), for unknown reason. The decreasing trends in 2018-22 range -7.3% ± 5.1% yr^{-1}, with the steepest slope, -16.7% yr^{-1}, found for *α*-endosulfan. Consistently, this steepest slope of *α*-endosulfan corresponds with the shortest time passed since restriction (2013) among these eight OCPs (Alarcón et al., 2023). Twelve OCPs, i.e., PeCB, HCB, *β*- and *γ*-HCH, *o,p'*- and *p,p'*-DDE, *o,p'*-DDD, *o,p'*- and *p,p'*-DDT, *α*-chlordane, mirex and endosulfan sulfate show non-significant trends in the 2018-22 period (Figures 3 and S8, Table S16b). Among these, eight substances were found to be significantly decreasing during the 2013-17 period, while four (namely *o,p'*-DDD, *o,p'*- and *p,p'*-DDT, and endosulfan sulfate) had non-significant trends (Figures 3 and S8, Table S16a). The trend of these 12 substances suggests that the total environmental burdens cycling across environmental compartments have been levelling off in the region in recent years. Compared to CUPs with insignificant trends, these 12 OCPs levelled-off on a shorter time scale (i.e., longer half-life than for CUPs), highlighting the persistence of these compounds. For DDT compounds, the ratio of the pesticide over its metabolites, DDT/(DDE+DDD), ranged from 0.27 to 0.34 during the 2013-22 period, which does not indicate any influence of fresh inputs of the pesticide, as generally a ratio <1 imply aged DDT (Yang et al., 2008). For chlordane, the isomeric ratio shifted from $\alpha/\gamma \approx 2.2$ during 2013-17 to $\alpha/\gamma \approx 2.8$ during 2018-22. With α/γ <1 indicating fresh inputs (Liu et al., 2009), this observed trend indicates that eventually recently enforced sources are from old storage of the pollutant.

The negative trends found are consistent with trends reported from the region for the years 1996-23 (UNEP, 2023; EMEP, 2024), namely for chlordane, α-, β- and γ-HCH, DDT and DDE. For HCB, a long-term increase was reported in European background air for the years 2016 to 2019 compared to the previous decade (Fiedler et al., 2023; Lunder Halvorsen et al., 2023). Even one decade earlier, higher HCB had been observed at the site in 2004-06 as compared to 1997-99 (Dvorská et al., 2009). However, for Iceland, Germany, Norway and Sweden decreasing HCB was reported during 2016-23 (Lunder Halvorsen et al., 2023). For PeCB both negative as well as insignificant trends were reported in the region (UNEP, 2023). PeCB and HCB are long phased-out from agricultural usage, but are unintentionally released by industries and combustion processes, such as waste incineration (Thomsen et al., 2009; Gong et al., 2017; UNEP 2024). Levelling off of α-, β- and γ-HCH, *o,p'*- and *p,p'*-DDE, and α-chlordane concentrations has not been observed before, but declining levels of these pollutants have been reported until 2023 for α-, β- and γ-HCH, PeCB, α-chlordane, and DDX substances in the region (central and eastern Europe; Ilyin et al., 2022; UNEP, 2023), for DDX substances, α- and γ-HCH in Germany, Denmark, Finland, Sweden, Norway and Iceland, and for β-HCH in Denmark and Iceland (Lunder Halvorsen et al., 2023). Levelling off of α- and γ-HCH, *p,p'*-DDE, *p,p'*-DDT and α- and γ-chlordane since ≈2014 has been reported in some but not all Arctic air monitoring stations, including in the European Arctic ($\tau_{1/2} \gtrsim 10$ yr; Wong et al., 2021). No mirex monitoring data were recently reported in Europe.

Long-term chemodynamics and air-surface exchange of OCPs has been addressed in only few large-scale multicompartment modelling studies. Based on global multicompartment modelling, net volatilisation of DDT and β-HCH from soils and the marginal seas of the region are expected since at least the early 2000s (Stemmler and Lammel, 2009; Wöhrnschimmel et al., 2012). Unlike for the other OCPs, the influence of recent intentional primary emissions cannot be excluded for DDT, as India and some African countries have been reporting DDT applications throughout the last decade for vector disease control purposes (van den Berg et al., 2017; UNEP, 2024). In the case of endosulfan sulfate, lack of significant trends is inconclusive due to low detection frequency (Figure S9). In general, the atmospheric levels of banned OCPs could be sustained by reversal of the direction of air-surface exchanges driven by historic contamination and chemical equilibria (Bidleman et al., 1995; Mackay and Parnis, 2020) or by mobilisation from surface compartments driven by climate events, such as melting of glaciers, permafrost soils or polar ice, flooding or heating of soils by wildfires (Holoubek et al., 2007; Bogdal et al., 2009; Nadal et al., 2015; Jiang et al., 2023). However, for only few OCPs (HCH, DDT) historic primary emissions, needed for modelling the large-scale chemodynamics are available (Hansen et al., 2004; Semeena and Lammel, 2005; Stemmler and Lammel, 2009;

Wöhrnschimmel et al., 2012) and mobilisation processes have hardly been described beyond case studies (Bogdal et al., 2009; Nizzetto et al., 2010; Christensen, 2024). In recent years, the influence of such mobilisation processes on OCP cycling in the study region has not become evident, but cannot be excluded, considering on-going climate change and its global impacts. Note, that the pesticide concentration in air summer maximum may indicate local sources (Hoff et al., 1998; Wania et al., 1998), but could also be explained by sources located upwind under co-varying temperature, such as the larger region (e.g., Zhan et al., 2024). Using a global chemistry-transport model with air-soil exchange parameterisations for land and water surfaces, seasonal HCH and DDT secondary source areas were mapped and identified as regional and global scale phenomena (Semeena and Lammel, 2005; Semeena et al., 2006). In conclusion, current knowledge cannot assess the significance of these two types of secondary sources for long-term trends in the region, hence, cannot identify the sources, even not for HCH and DDT.

One aspect that was not investigated in this study is determining the CUP gas-particle partitioning (GPP) and related temporal trends. GPP models tested successfully for other semi-volatile organic compounds (SVOCs e.g., polycyclic aromatic compounds and PBDEs (Shahpoury et al., 2016; Qin et al., 2021) could not yet be adopted for testing CUPs' GPP, because of a lack of field (PM chemical composition) and laboratory data (GPP model parameters).

4 Conclusions

Overall, this study provided long-term data series for OCPs and CUPs at a central European site. As this study focuses on a single agricultural site, the findings cannot capture the variability across the entire CUP source area i.e., rural central Europe. However, the observations were consistent with the perception of semivolatile compounds degrading slowly in soils, the Clausius-Clapeyron analysis showed that re-volatilisation is a source for all OCPs and most CUPs in air in summer in rural central Europe.

Although OCPs were banned decades ago, their occurrence in the rural atmosphere demonstrates their persistence in the environment. For the OCPs α-HCH, *cis*-heptachlor epoxide, γ-chlordane, oxychlordane, and α-endosulfan significant negative trends are found until 2023, which were consistent with previous findings in the region. Additionally, similar trends were found for δ- and ε-HCH. However, the trends during 2018-23 are no longer significantly negative for PeCB, HCB, β- and γ-HCH, *o,p'*- and *p,p'*-DDE, *o,p'*-DDD, *o,p'*- and *p,p'*-DDT, α-chlordane, and mirex. This suggests a levelling off of these pollutant levels in air in the region and possibly beyond. Except for PeCB and HCB, whose atmospheric levels may be sustained by unintended releases, the levelling off of these OCPs results from enhanced secondary sources, i.e., reversal of the direction of air-surface exchange or recent mobilisation of their reservoirs in soils, water bodies or the cryosphere. Current knowledge cannot assess the significance of these two types of secondary sources or locate their distributions. Longer time trends, experimental verification of the direction of air surface exchange and large-scale multicompartment model simulations are needed to comprehensively investigate the chemodynamics of the globally cycling OCPs.

In addition, we observed that CUPs' temporal trends were apparently dominated by applications. They were generally negative or insignificant, while during our study period, CUP use in the Czech Republic increased for most of the compounds. For pesticides such as chlorpyrifos and fenpropimorph, the decreasing trends were directly related to their use authorisation being revoked. However, one year after their ban, these compounds were still present in the atmosphere at detectable concentrations, suggesting potential environmental or atmospheric persistence.

The long-term data presented in this study highlights the importance of continued research on these compounds to provide sufficient insights into their atmospheric fate and to further develop accurate models to predict key environmental processes such as transport, deposition, and GPP.

Author contributions

LuM: Investigation, Formal analysis, Data Curation, Writing – Original Draft. LiM: Data Curation. AHŠ: Investigation. JK: Methodology. PK: Validation. JM: Validation. PP: Validation, Funding Acquisition. PS: Data Curation. GL: Conceptualization, Funding Acquisition, Supervision, Data Curation. All authors: Writing – Review and Editing, Approval of final manuscript.

Competing interest

The authors declare that they have no conflict of interest.

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References

Alarcón, P. C., Kitanovski, Z., Padervand, M., Pöschl, U., Lammel, G., and Zetzsch, C.: Atmospheric hydroxyl radical reaction rate coefficient and total environmental lifetime of α-endosulfan, Environ. Sci. Technol., 57, 15999–16005, 2023.

Alexandratos, N. and Bruinsma, J.: World agriculture towards 2030/2050: the 2012 revision, Food and Agriculture Organization (FAO), Rome, Italy, www.fao.org /docrep/016/ap106e/ap106e.pdf (last accessed online: 15 Nov 2023).

Alletto, L., Coquet, Y., Benoit, P., Heddadj, D., and Barriuso, E.: Tillage management effects on pesticide fate in soils. A review, Agron. Sustain. Dev., 30, 367–400, 2010.

Balmer, J. E., Morris, A. D., Hung, H., Jantunen, L., Vorkamp, K., Rigét, F., Evans, M., Houde, M., and Muir, D. C. G.: Levels and trends of current-use pesticides (CUPs) in the arctic: An updated review 2010–2018, Emerg. Contam., 5, 70–88, 2019.

Becker, S., Halsall, C. J., Tych, W., Kallenborn, R., Su, Y., and Hung, H.: Long-term trends in atmospheric concentrations of α- and γ-HCH in the Arctic provide insight into the effects of legislation and climatic fluctuations on contaminant levels, Atmos. Environ., 42, 8225–8233, 2008.

Bedos, C., Cellier, P., Calvet, R., Barriuso, E., and Gabrielle, B.: Mass transfer of pesticides into the atmosphere by volatilization from soils and plants: Overview, Agronomie, 22, 21–33, 2002.

Bidleman, T.F.: Atmospheric transport and air-surface exchange of pesticides, in: Fate of Pesticides in the Atmosphere: Implications for Environmental Risk Assessment (van Dijk, H. F. G., van Pul, W. A. J., and de Voogt, P., eds.), Springer, Dordrecht, Netherlands, pp. 115–166, 1999.

Bidleman, T.F., Jantunen, L.M., Falconer, R.L., Barrie, L.A., and Fellin, P.: Decline of hexachlorocyclohexane in the Arctic atmosphere and reversal of air-sea gas exchange, Geophys. Res. Lett., 22, 219–222, 1995.

BCPC: British Crop Protection Council.: The pesticide manual : A world compendium., 16th ed., MacBean, C. ed., BCPC Publications, Alton, United Kingdom, 2012.

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

Cabrerizo, A., Dachs, J., Jones, K.C., and Barceló, D.: Soil-air exchange controls on background atmospheric concentrations of organochlorine pesticides, Atmos. Chem. Phys., 11, 12799–12811, 2011.

Carratalá, A., Moreno-González, R., and León, V.M.: Occurrence and seasonal distribution of polycyclic aromatic hydrocarbons and legacy and current-use pesticides in air from a Mediterranean coastal lagoon (Mar Menor, SE Spain), Chemosphere, 167, 382–395, 2017.

Carvalho, F.P.: Pesticides, environment, and food safety, Food Energy Secur., 6, 48–60, 2017.

Christensen, K.: Thawing permafrost releases industrial contaminants into Arctic communities. Environ. Health Persp., 132, 032001, 2024.

Cindoruk, S.S.: Atmospheric organochlorine pesticide (OCP) levels in a metropolitan city in Turkey, Chemosphere, 82, 78–87, 2011.

Coscollà, C., Colin, P., Yahyaoui, A., Petrique, O., Yusà, V., Mellouki, A., and Pastor, A.: Occurrence of currently used pesticides in ambient air of Centre Region (France), Atmos. Environ., 44, 3915–3925, 2010.

Coscollà, C., López, A., Yahyaoui, A., Colin, P., Robin, C., Poinsignon, Q., and Yusà, V.: Human exposure and risk assessment to airborne pesticides in a rural French community, Sci. Total Environ., 584–585, 856–868, 2017.

Debler, F., Abrantes, N., Harkes, P., Campos, I., and Gandrass, J.: Occurrence and distribution of pesticides and transformation products in ambient air in two European agricultural areas, Sci. Total Environ., 940, 173705, 2024.

Degrendele, C., Okonski, K., Melymuk, L., Landlová, L., Kukučka, P., Audy, O., Kohoutek, J., Čupr, P., and Klánová, J.: Pesticides in the atmosphere: a comparison of gas-particle partitioning and particle size distribution of legacy and current-use pesticides, Atmos. Chem. Phys., 16, 1531–1544, 2016.

Degrendele, C., Wilson, J., Kukučka, P., Klánová, J., and Lammel, G.: Are atmospheric PBDE levels declining in central Europe? Examination of the seasonal and semi-long-term variations, gas-particle partitioning and implications for long-range atmospheric transport, Atmos. Chem. Phys., 18, 12877–12890, 2018.

Degrendele, C., Fiedler, H., Kočan, A., Kukučka, P., Přibylová, P., Prokeš, R., Klánová, J., and Lammel, G.: Multiyear levels of PCDD/Fs, dl-PCBs and PAHs in background air in central Europe and implications for deposition, Chemosphere, 240, 2020.

Désert, M., Ravier, S., Gille, G., Quinapallo, A., Armengaud, A., Pochet, G., Savelli, J. L., Wortham, H., and Quivet, E.: Spatial and temporal distribution of current-use pesticides in ambient air of Provence-Alpes-Côte-d'Azur Region and Corsica, France, Atmos. Environ., 192, 241–256, 2018.

Dobson, R., Scheyer, A., Rizet, A.L., Mirabel, P., and Millet, M.: Comparison of the efficiencies of different types of adsorbents at trapping currently used pesticides in the gaseous phase using the technique of high-volume sampling. Anal. Bioanal. Chem., 386, 1781-1789, 2006.

Dvorská, A., Lammel, G. and Holoubek, I.: Recent trends of persistent organic pollutants in air in Europe - Air monitoring in combination with air mass trajectory statistics as a tool to study the effectivity of regional chemical policy. Atmos. Environ., 43, 1280-1287, 2009.

Duyzer, J.: Pesticides in Perspective Pesticide concentrations in air and precipitation in the Netherlands, J. Environ. Monit., 5, 77N-80N, 2003.

FAOSTAT: Pesticides use. UN Food and Agriculture Organisation (FAO), http://www.fao.org/faostat/en/#data/RP (last accessed online 21/03/2024).

Fiedler, H., Abad, E., and de Boer, J.: Preliminary trends over ten years of persistent organic pollutants in air - Comparison of two sets of data in the same countries, Chemosphere, 324, 138299, 2023.

Gao, H., Ma, J., Cao, Z., Dove, A., and Zhang, L.: Trend and climate signals in seasonal air concentration of organochlorine pesticides over the Great Lakes, J. Geophys. Res., 115, 2010.

Garthwaite, D. G., Hudson, S., Barker, I., Parrish, G., Smith, L., and Pietravalle, S.: Pesticide usage survey report 250: Arable crops in the United Kingdom 2012 (including aerial applications 2012), Food and Environment Research Agency, York, UK, https://pusstats.fera.co.uk/upload/kxZtSlyLVGQl5Wj0oFpHmPtX3PI3i6ZOF7L8Ep8Q.pdf (last accessed online 3 Jan. 2025), 2012.

Gevao, B., Porcelli, M., Rajagopalan, S., Krishnan, D., Martinez-Guijarro, K., Alshemmari, H., Bahloul, M., and Zafar, J.: Spatial and temporal variations in the atmospheric concentrations of "Stockholm Convention" organochlorine pesticides in Kuwait, Sci. Total Environ., 622–623, 1621–1629, 2018.

Glotfelty, D.E., Leech, M.M., Jersey, J., and Taylor, A. W.: Volatilization and wind erosion of soil surface applied atrazine, simazine, alachlor and toxaphene, J. Agric. Food Chem., 37, 546–551, 1989.

Gong, W.W., Fiedler, H., Liu, X.T., Wang, B., Yu, G.: Emission factors of unintentional HCB and PeCBz and their correlation with PCDD/PCDF. Environ. Pollut., 230, 516-522, 2017.

Habran, S., Giusti, A., Galloy, A., Gérard, G., Delvaux, A., Pigeon, O., and Remy, S.: Spatial and temporal variations of currently used pesticides (CUPs) concentrations in ambient air in Wallonia, Belgium, Chemosphere, 351, 141241, 2024.

Hansen, K.M., Christensen, J.H., Brandt, J., Frohn, L.M., and Geels, C.: Modelling atmospheric transport of persistent organic pollutants in the northern hemisphere with a three-dimensional dynamic model: DEHM-POP, Atmos. Chem. Phys., 4, 1125–1137, 2004.

Hayward, S.J., Gouin, T., and Wania, F.: Comparison of four active and passive sampling techniques for pesticides in air, Environ. Sci. Technol., 44, 3410–3416, 2010.

Hites, R.A. and Venier, M.: Good news: Some insecticides have been virtually eliminated in air near the Great Lakes, Environ. Sci. Technol., 57, 2199–2204, 2023.

Hoff, R.M., Brice, K.A., and Halsall, C.J.: Nonlinearity in the slopes of Clausius−Clapeyron plots for SVOCs, Environ. Sci. Technol., 32, 1793–1798, 1998.

Holoubek, I., Klánová, J., Jarkovský, J., and Kohoutek, J.: Trends in background levels of persistent organic pollutants at Kosetice observatory, Czech Republic. Part I. Ambient air and wet deposition 1996-2005, J. Environ. Monit., 9, 557–563, 2007.

Hulin, M., Leroux, C., Mathieu, A., Gouzy, A., Berthet, A., Boivin, A., Bonicelli, B., Chubilleau, C., Hulin, A., Leoz Garziandia, E., Mamy, L., Millet, M., Pernot, P., Quivet, E., Scelo, A. L., Merlo, M., Ruelle, B., and Bedos, C.: Monitoring of pesticides in ambient air: Prioritization of substances, Sci. Total Environ., 753, 141722, 2021.

Hung, H., Blanchard, P., Halsall, C.J., Bidleman, T.F., Stern, G.A., Fellin, P., Muir, D.C.G., Barrie, L.A., Jantunen, L.M., Helm, P.A., Ma, J., and Konoplev, A.: 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, 2005.

Hung, H., Kallenborn, R., Breivik, K., Su, Y., Brorström-Lundén, E., Olafsdottir, K., Thorlacius, J. M., Leppänen, S., Bossi, R., Skov, H., Manø, S., Patton, G. W., Stern, G., Sverko, E., and Fellin, P.: Atmospheric monitoring of organic pollutants in the Arctic under the Arctic Monitoring and Assessment Programme (AMAP): 1993-2006, Sci. Total Environ., 408, 2854–2873, 2010.

Hung, H., Katsoyiannis, A. A., Brorström-Lundén, E., Olafsdottir, K., Aas, W., Breivik, K., Bohlin-Nizzetto, P., Sigurdsson, A., Hakola, H., Bossi, R., Skov, H., Sverko, E., Barresi, E., Fellin, P., and Wilson, S.: Temporal trends of Persistent Organic Pollutants (POPs) in Arctic air: 20 years of monitoring under the Arctic Monitoring and Assessment Programme (AMAP), Environ. Pollut., 217, 52–61, 2016.

Ilyin, I., Batrakova, N., Gusev, A., Kleimenov, M., Rozovskaya, O., Shatalov, V., Strizhkina, I., Travnikov, O., Vulykh, N., Breivik, K., Bohlin-Nizzetto, P., Pfaffhuber, K.A., Aas, W., Poupa, S., Wankmueller, R., Ullrich, B., Bank, M., Ho, Q.T., Vivanco, M.G., Theobald, M.R., Garrido, J.L., Gil, V., Couvidat, F., Collette, A., Mircea, M., Adani, M., Delia, I., Kouznetsov, R.D. and Kadancev, E.V.: Assessment of heavy metal and POP pollution on global, regional and national scales. Status Report

No. 2/2022, Meteorological Synthesizing Centre – East, Moscow, accessible online from. https://msc-east.org/wp-content/uploads/2024/08/2022_2.pdf, 2022.

Jepson, P. C., Murray, K., Bach, O., Bonilla, M. A., and Neumeister, L.: Selection of pesticides to reduce human and environmental health risks: a global guideline and minimum pesticides list, Lancet Planet. Health, 4, e56–e63, 2020.

Jiang, H.Y., Li, J., Zhang, R.J., Pansak, W., Zhong, G.C., Li, K.C., Zhao, S.Z., Bualert, S., Phewnil, O., and Zhang, G.: Mapping the contribution of biomass burning to persistent organic pollutants in the air of the Indo-China Peninsula based on a passive air monitoring network. Environ. Sci. Technol., 57, 2274-2285, 2023.

Kalina, J., White, K. B., Scheringer, M., Přibylová, P., Kukučka, P., Audy, O., Martiník, J., and Klánová, J.: Comparability of semivolatile organic compound concentrations from co-located active and passive air monitoring networks in Europe, Environ. Sci.: Proc. Impacts, 24, 898–909, 2022.

Khuman, S.N., Park, M.K., Kim, H.J., Hwang, S.M., Lee, C.H., and Choi, S. D.: Nationwide assessment of atmospheric organochlorine pesticides over a decade during 2008–2017 in South Korea, Sci. Total Environ., 877, 162927, 2023.

Kruse-Plass, M., Hofmann, F., Wosniok, W., Schlechtriemen, U., and Kohlschütter, N.: Pesticides and pesticide-related products in ambient air in Germany, Environ. Sci. Eur., 33, 114, 2021.

Lakaschus, S., Weber, K., Wania, F., Bruhn, R., and Schrems, O.: The air−sea equilibrium and time trend of hexachlorocyclohexanes in the Atlantic Ocean between the Arctic and Antarctica, Environ. Sci. Technol., 36, 138–145, 2002.

Lee, M., Lee, S., Noh, S., Park, K.S., Yu, S.M., Lee, S., Do, Y.S., Kim, Y.H., Kwon, M., Kim, H., and Park, M.K.: Assessment of organochlorine pesticides in the atmosphere of South Korea: spatial distribution, seasonal variation, and sources, Environ. Monit. Assess., 194, 754, 2022.

Lammel, G., Novák, J., Landlová, L., Dvorská, A., Klánová, J., Čupr, P., Kohoutek, J., Reimer, E., and Škrdlíková, L.: Sources and distributions of polycyclic aromatic hydrocarbons and toxicity of polluted atmosphere aerosols, in: Urban Airborne Particulate Matter: Origin, Chemistry, Fate and Health Impact (Zereini F., Wiseman C.L.S., eds), Springer, Berlin, pp. 39–62, 2010.

Lammel, G., Degrendele, C., Gunthe, S. S., Mu, Q., Muthalagu, A., Audy, O., Biju, C. V., Kukučka, P., Mulder, M. D., Octaviani, M., Příbylová, P., Shahpoury, P., Stemmler, I., and Valsan, A. E.: Revolatilisation of soil-accumulated pollutants triggered by the summer monsoon in India, Atmos. Chem. Phys., 18, 11031–11040, 2018.

LCSQA: Résultats de la campagne nationale exploratoire de mesure des résidus de pesticides dans l'air ambiant (2018-2019), 2019.

Lee, M., Lee, S., Noh, S., Park, K.S., Yu, S. M., Lee, S., Do, Y.S., Kim, Y. H., Kwon, M., Kim, H., and Park, M.K.: Assessment of organochlorine pesticides in the atmosphere of South Korea: spatial distribution, seasonal variation, and sources, Environ. Monit. Assess., 194, 754, 2022.

Lewis, K. A., Tzilivakis, J., Warner, D. J., and Green, A.: An international database for pesticide risk assessments and management, Hum. Ecol. Risk Assess. Int. J., 22, 1050–1064, 2016.

Li, Y. F. and Macdonald, R. W.: Sources and pathways of selected organochlorine pesticides to the Arctic and the effect of pathway divergence on HCH trends in biota: a review, Sci. Total Environ. 342, 87-106, 2005.

Li, W. L., Huo, C. Y., Liu, L.Y., Song, W.W., Zhang, Z.F., Ma, W.L., Qiao, L.N., and Li, Y.F.: Multi-year air monitoring of legacy and current-use brominated flame retardants in an urban center in northeastern China, Sci. Total Environ., 571, 633–642, 2016.

Li, Y., Lohmann, R., Zou, X., Wang, C., and Zhang, L.: Air-water exchange and distribution pattern of organochlorine pesticides in the atmosphere and surface water of the open Pacific Ocean, Environ. Pollut., 265, 2020.

Liu, X., Zhang, G., Li, J., Yu, L.L., Xu, Y., Li, X.D., Kobara, Y., and Jones, K.C.: Seasonal patterns and current sources of DDTs, chlordanes, hexachlorobenzene, and endosulfan in the atmosphere of 37 Chinese cities, Environ. Sci. Technol., 43, 1316–1321, 2009.

Liu, L. Y., Salamova, A., Venier, M., and Hites, R. A.: Trends in the levels of halogenated flame retardants in the Great Lakes atmosphere over the period 2005-2013, Environ. Int., 92–93, 442–449, 2016.

López, A., Coscollà, C., and Yusà, V.: Evaluation of sampling adsorbents and validation of a LC-HRMS method for determination of 28 airborne pesticides, Talanta, 189, 211–219, 2018.

Lunder Halvorsen, H., Bohlin-Nizzetto, P., Eckhardt, S., Gusev, A., Moeckel, C., Shatalov, V., Skogeng, L.P., and Breivik, K.: Spatial variability and temporal changes of POPs in European background air, Atmos. Environ., 299, 2023.

Ma, Y., Salamova, A., Venier, M., and Hites, R.A.: Has the phase-out of PBDEs affected their atmospheric levels? Trends of PBDEs and their replacements in the Great Lakes atmosphere, Environ. Sci. Technol., 47, 11457–11464, 2013.

Mackay, D. and Parnis, J.M.: Multimedia environmental models: The fugacity approach, 3rd ed., CRC Press, Boca Raton, USA., 2020.

Maggi, F., Tang, F.H.M., la Cecilia, D., and McBratney, A.: PEST-CHEMGRIDS, global gridded maps of the top 20 crop-specific pesticide application rates from 2015 to 2025, Sci. Dat., 6, 170–190, 2019.

Mai, C., Theobald, N., Lammel, G., and Hühnerfuss, H.: Spatial, seasonal and vertical distributions of currently-used pesticides in the marine boundary layer of the North Sea, Atmos. Environ., 75, 92–102, 2013.

Mamontova, E.A. and Mamontov, A.A.: Air monitoring of polychlorinated biphenyls and organochlorine pesticides in Eastern Siberia: Levels, temporal trends, and risk assessment, Atmosphere, 13, 1971, 2022.

Mayer, L., Degrendele, C., Šenk, P., Kohoutek, J., Přibylová, P., Kukučka, P., Melymuk, L., Durand, A., Ravier, S., Alastuey, A., Baker, A. R., Baltensperger, U., Baumann-Stanzer, K., Biermann, T., Bohlin-Nizzetto, P., Ceburnis, D., Conil, S., Couret, C., Degórska, A., Diapouli, E., Eckhardt, S., Eleftheriadis, K., Forster, G. L., Freier, K., Gheusi, F., Gini, M. I., Hellén, H., Henne, S., Herrmann, H., Holubová Šmejkalová, A., Hõrrak, U., Hüglin, C., Junninen, H., Kristensson, A., Langrene, L., Levula, J., Lothon, M., Ludewig, E., Makkonen, U., Matejovičová, J., Mihalopoulos, N., Mináriková, V., Moche, W., Noe, S. M., Pérez, N., Petäjä, T., Pont, V., Poulain, L., Quivet, E., Ratz, G., Rehm, T., Reimann, S., Simmons, I., Sonke, J. E., Sorribas, M., Spoor, R., Swart, D. P. J., Vasilatou, V., Wortham, H., Yela, M., Zarmpas, P., Zellweger Fäsi, C., Tørseth, K., Laj, P., Klánová, J., and Lammel, G.: Widespread pesticide distribution in the European atmosphere questions their degradability in air, Environ. Sci. Technol., 58, 3342–3352, 2024.

Miglioranza, K. S. B., Ondarza, P. M., Costa, P. G., de Azevedo, A., Gonzalez, M., Shimabukuro, V. M., Grondona, S. I., Mitton, F.M., Barra, R.O., Wania, F., and Fillmann, G.: Spatial and temporal distribution of Persistent Organic Pollutants and current use pesticides in the atmosphere of Argentinean Patagonia, Chemosphere, 266, 129015, 2021.

Nadal, M., Marquès, M., Mari, M., and Domingo, J. L.: Climate change and environmental concentrations of POPs: A review, Environ. Res., 143, 177-185, 2015.

Ni, J., Cai, M., Lin, Y. J., Li, T., and Ma, J.: Occurrence, seasonal variations, and spatial distributions of current-use organoamine pesticides in the atmosphere of Shanghai, China, Atmos. Pollut. Res., 15, 102187, 2024.

Nizzetto, L.,MacLeod, M., Borgå, K., Cabrerizo, A., Dachs, J., di Guardo, A., Ghirardello, D., Hansen, K.M., Jarvis, A., Lindroth, A., Ludwig, B., Monteith, D., Perlinger, J.A., Scheringer, M., Schwendenmann, L., Semple, K.T., Wick, L.Y., Zhang, G., and Jones, K.C.: Past, present, and future controls on levels of persistent organic pollutants in the global environment - Understanding the legacy of persistent organic pollutants requires studying the transition from primary to secondary source control. Environ. Sci. Technol., 44, 6526–6531, 2010.

Nuyttens, D., Devarrewaere, W., Verboven, P., and Foqué, D.: Pesticide-laden dust emission and drift from treated seeds during seed drilling: A review, Pest Manag. Sci., 69, 564–575, 2013.

O'Driscoll, K.: Air-sea exchange of legacy POPs in the North Sea based on results of fate and transport, and shelf-sea hydrodynamic ocean models, Atmosphere, 5, 156–177, 2014.

Paragot, N., Bečanová, J., Karásková, P., Prokeš, R., Klánová, J., Lammel, G., and Degrendele, C.: Multi-year atmospheric concentrations of per- and polyfluoroalkyl substances (PFASs) at a background site in central Europe, Environ. Pollut., 265, 114851, 2020.

Qin, M., Yang, P.F., Hu, P.T., Hao, S., Macdonald, R.W., and Li, Y.F.: Particle/gas partitioning for semi-volatile organic compounds (SVOCs) in level III multimedia fugacity models: Both gaseous and particulate emissions, Sci. Total Environ., 790, 148012, 2021.

Qiu, X., Zhu, T., Yao, B., Hu, J., Hu, S.: Contribution of dicofol to the current DDT pollution in China, Environ Sci. Technol., 39, 12, 4385-4390, 2005.

Ricking, M. and Schwarzbauer, J.: DDT isomers and metabolites in the environment: an overview, Environ. Chem. Lett., 10, 317–323, 2012.

Salamova, A., Venier, M., and Hites, R.A.: Revised temporal trends of persistent organic pollutant concentrations in air around the Great Lakes, Environ. Sci. Technol. Lett., 2, 20–25, 2015.

Sari, M.F., Córdova del Águila, D. A., Tasdemir, Y., and Esen, F.: Atmospheric concentration, source identification, and health risk assessment of persistent organic pollutants (POPs) in two countries: Peru and Turkey, Environ. Monit. Assess., 192, 655, 2020.

Semeena V.S., and Lammel G.: The significance of the grasshopper effect on the atmospheric distribution of persistent organic substances, Geophys. Res. Lett., 32, L07804, 2005.

Semeena, V.S., Feichter, J., and Lammel, G.: Impact of the regional climate and substance properties on the fate and atmospheric long-range transport of persistent organic pollutants-examples of DDT and γ-HCH, Atmos. Chem. Phys, 6, 1231–1248, 2006.

Shahpoury, P., Lammel, G., Albinet, A., Sofuoğlu, A., Dumanoğlu, Y., Sofuoğlu, S. C., Wagner, Z., and Ždimal, V.: Evaluation of a conceptual model for gas-particle partitioning of polycyclic aromatic hydrocarbons using polyparameter linear free energy relationships, Environ. Sci. Technol., 50, 12312–12319, 2016.

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., Kohli, S. K., Yadav, P., Bali, A. S., Parihar, R. D., Dar, O.I., Singh, K., Jasrotia, S., Bakshi, P., Ramakrishnan, M., Kumar, S., Bhardwaj, R., and Thukral, A.K.: Worldwide pesticide usage and its impacts on ecosystem, SN Appl. Sci., 1, 1446, 2019.

Shunthirasingham, C., Gawor, A., Hung, H., Brice, K. A., Su, K., Alexandrou, N., Dryfhout-Clark, H., Backus, S., Sverko, E., Shin, C., Park, R., and Noronha, R.: Atmospheric concentrations and loadings of organochlorine pesticides and polychlorinated biphenyls in the Canadian Great Lakes Basin (GLB): Spatial and temporal analysis (1992–2012), Environ. Pollut., 217, 124–133, 2016.

Sofuoglu, A., Cetin, E., Bozacioglu, S. S., Sener, G. D., and Odabasi, M.: Short-term variation in ambient concentrations and gas/particle partitioning of organochlorine pesticides in Izmir, Turkey, Atmos. Environ., 38, 4483–4493, 2004.

Stemmler, I. and Lammel, G.: Cycling of DDT in the global environment 1950–2002: World Ocean returns the pollutant, Geophys. Res. Lett., 36, 2009.

Tang, F.H.M., Lenzen, M., McBratney, A., and Maggi, F.: Risk of pesticide pollution at the global scale, Nat Geosci, 14, 206–210, 2021.

Thomsen, M., Nielsen, O.K., and Illerup, J.B.: Unintentional formation and emission of the persistent organic pollutants HCB and PCBs in the Nordic countries: Documentation of existing information regarding sources and emissions to air, water and soil, with focus on reporting obligations according to the Stockholm Convention, the UNECE POP protocol, and PRTR registers. Nordic Council of Ministers. TemaNord No. 518. http://norden.diva-portal.org/smash/get/diva2:700932/FULLTEXT01.pdf (last accessed online 5 Dec. 2024), 2009.

UNEP: United Nations Environment Programme (UNEP), Regionally Based Assessment of Persistent Toxic Substances, Global Rep. 2003, 211 pp., Geneva, Switzerland, 2003.

UNEP: Stockholm Convention on Persistent Organic Pollutants (POPs), United Nations Environment Programme, http://chm.pops.int/tabid/208/Default.aspx, 2001 (last accessed online, 5 Dec. 2024).

UNEP: United Nations Environment Programme (UNEP), Regionally Based Assessment of Persistent Toxic Substances, Global Rep., 211 pp., Geneva, Switzerland, 2003.

UNEP: Third global monitoring report. Global monitoring plan for persistent organic pollutants under the Stockholm Convention Article 16 on effectiveness evaluation. Secretariat of the Basel, Rotterdam and Stockholm conventions, United Nations Environment Programme, Geneva., 2023.

ÚZKÚZ: Consumption of plant protection products per individual years. 2024. Central Institute for Supervising and Testing in Agriculture (ÚZKÚZ), Prague, Czech Republic, https://eagri.cz/public/portal/ukzuz/pripravky-na-or/ucinne-latky-v-por-statistika-spotreba/spotreba-pripravku-na-or/spotreba-v-jednotlivych-letech, (last accessed online: 20 June 2024).

van den Berg, F., Kubiak, R., Benjey, W.G., Majewski, M.S., Yates, S.R., Reeves, G.L., Smelt, J.H., and van der Linden, A.M.A.: Emission of pesticides into the air, Water Air Soil Pollut., 115, 195–218, 1999.

van den Berg, H., Manuweera, G., and Konradsen, F.: Global trends in the production and use of DDT for control of malaria and other vector-borne diseases, Malar. J., 16, 401, 2017.

van Pul, W.A.J., Bidleman, T.F., Brorström-Lunden, E., Builtjes, P.J.H., Dutchak, S., Duyzer, J.H., Gryning, S.E., Jones, K.C., van Dijk, H.F.G., and van Jaarsveld, J.A.: Atmospheric transport and deposition of pesticide: an assessment of current knowledge, Water, Air Soil Pollut., 115, 245–256, 1999.

Váňa, M., Šmejkalová, A. H., Svobodová, J., and Machálek, P.: Long-term trends of air pollution at national atmospheric observatory Košetice (ACTRIS, EMEP, GAW), Atmosphere, 11, 537, 2020.

Venier, M. and Hites, R.A.: Time trend analysis of atmospheric POPs concentrations in the Great Lakes region since 1990, Environ. Sci. Technol., 44, 8050–8055, 2010.

Venier, M. and Hites, R.A.: DDT and HCH, two discontinued organochlorine insecticides in the Great Lakes region: Isomer trends and sources, Environ. Int., 69, 159–165, 2014.

Venier, M., Hung, H., Tych, W., and Hites, R.A.: Temporal trends of persistent organic pollutants: A comparison of different time series models, Environ. Sci. Technol., 46, 3928–3934, 2012.

Villiot, A., Chrétien, E., Drab-Sommesous, E., Rivière, E., Chakir, A., and Roth, E.: Temporal and seasonal variation of atmospheric concentrations of currently used pesticides in Champagne in the centre of Reims from 2012 to 2015, Atmos. Environ., 174, 82–91, 2018.

Wang, C., Wang, X., Gong, P., and Yao, T.: Long-term trends of atmospheric organochlorine pollutants and polycyclic aromatic hydrocarbons over the southeastern Tibetan Plateau, Sci. Total Environ., 624, 241–249, 2018.

Wang, C., Wang, P., Zhao, J., Fu, M., Zhang, L., Li, Y., Yang, R., Zhu, Y., Fu, J., Zhang, Q., and Jiang, G.: Atmospheric organophosphate esters in the Western Antarctic Peninsula over 2014–2018: Occurrence, temporal trend and source implication, Environ. Pollut., 267, 2020.

Wang, S., Salamova, A., and Venier, M.: Occurrence, spatial, and seasonal variations, and gas-particle partitioning of atmospheric current-use pesticides (CUPs) in the Great Lakes Basin, Environ. Sci. Technol., 55, 3539–3548, 2021.

Wania, F., Haugen, J.E., Lei, Y.D., and Mackay, D.: Temperature dependence of atmospheric concentrations of semivolatile organic compounds, Environ. Sci. Technol., 32, 1013–1021, 1998.

Wania, F., and Mackay, D.: Global fractionation and cold condensation of low volatility organochlorine compounds in polar regions, Ambio, 22, 10-18, 1993.

White, K.B., Kalina, J., Scheringer, M., Přibylová, P., Kukučka, P., Kohoutek, J., Prokeš, R., and Klánová, J.: Temporal trends of persistent organic pollutants across Africa after a decade of MONET passive air sampling, Environ. Sci. Technol., 55, 9413–9424, 2021.

Wijewardene, L., Wu, N.C., Hörmann, G., Messyasz, B., Riis, T., Hölzel, C., Ulrich, U. and Fohrer, N.: Effects of the herbicides metazachlor and flufenacet on phytoplankton communities – A microcosm assay. Ecotox. Environ. Safety, 228, 113036, 2021.

Wöhrnschimmel, H., Tay, P., von Waldow, H., Hung, H., Li, Y.F., MacLeod, M., and Hungerbühler, K.: Comparative assessment of the global fate of α- and β-hexachlorocyclohexane before and after phase-out, Environ. Sci. Technol., 46, 2047–2054, 2012.

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

Wöhrnschimmel, H., Scheringer, M., Bogdal, C., Hung, H., Salamova, A., Venier, M., Katsoyiannis, A., Hites, R.A., Hungerbühler, K., and Fiedler, H.: Ten years after entry into force of the Stockholm Convention: What do air monitoring data tell about its effectiveness? Environ. Pollut., 217, 149–158, 2016.

Wong, F., Hung, H., Dryfhout-Clark, H., Aas, W., Bohlin-Nizzetto, P., Breivik, K., Mastromonaco, M. N., Lundén, E. B., Ólafsdóttir, K., Sigurðsson, Á., Vorkamp, K., Bossi, R., Skov, H., Hakola, H., Barresi, E., Sverko, E., Fellin, P., Li, H., Vlasenko, A., Zapevalov, M., Samsonov, D., and Wilson, S.: Time trends of persistent organic pollutants (POPs) and chemicals of emerging arctic concern (CEAC) in Arctic air from 25 years of monitoring, Sci. Total Environ., 775, 145109, 2021.

Yang, Y., Li, D., Mu, D.: Levels, seasonal variations and sources of organochlorine pesticides in ambient air of Guangzhou, China, Atmos. Environ. 42, 677-687, 2008.

Zhan, L., Lin, T., Wang, Z., Cheng, Z., Zhang, G., Lyu, X., and Cheng, H.: Occurrence and air–soil exchange of organochlorine pesticides and polychlorinated biphenyls at a CAWNET background site in central China: Implications for influencing factors and fate, Chemosphere, 186, 475–487, 2017.

Zhan, F.Q., Li, Y.N., Shunthirasingham, C., Oh, J., Lei, Y.D., Lu, Z., ben Chaaben, A., Lee, K., Gobas, F.A.P.C., Hung, H., Breivik, K., and Wania, F.: Archetypes of spatial concentration variability of organic contaminants in the atmosphere: Implications for identifying sources and mapping the gaseous outdoor inhalation exposome. Environ. Sci. Technol., 58, 18273−18283, 2024.