

**Exploiting Molecular Ions for Screening Hydrophobic Contaminants in
Sediments using Gas Chromatography-Atmospheric Pressure Chemical
Ionization-Ion Mobility-Mass Spectrometry**

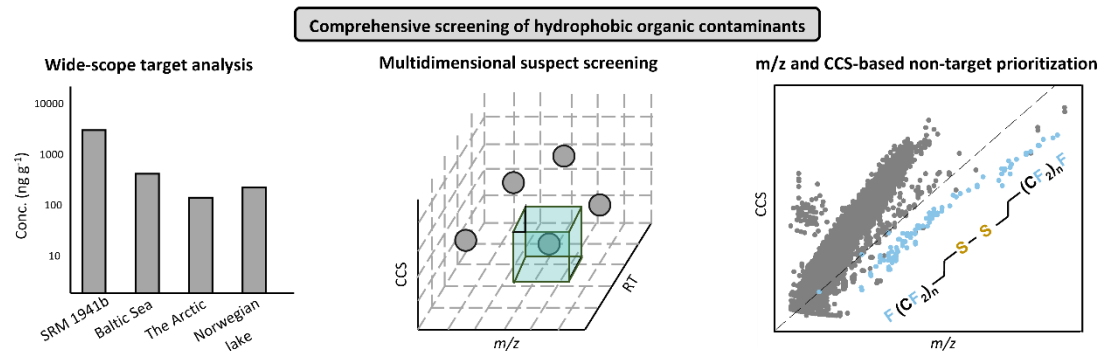
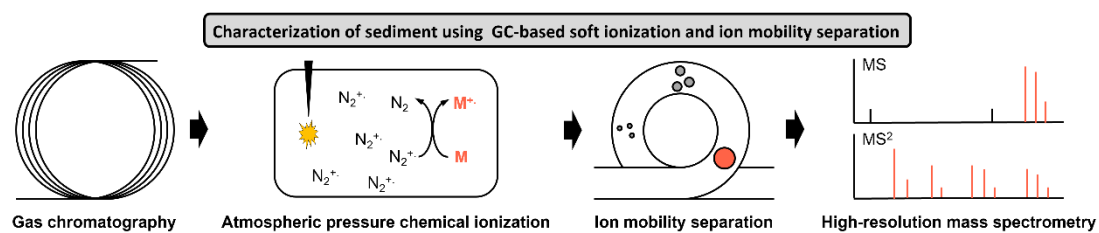
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15 GRAPHICAL ABSTRACT:



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ABSTRACT:

Hydrophobic organic compounds (HOCs) are conventionally screened by matching experimental- to reference electron ionization (EI) mass spectra acquired using gas chromatography-mass spectrometry (GC-MS). However, for identification of novel substances that are absent from EI databases, *de novo* structure elucidation using EI is hampered by extensive in-source fragmentation. To address this problem, a new method based on GC-atmospheric pressure chemical ionization (APCI) coupled to ion mobility-high resolution mass spectrometry (IM-HRMS) was developed for simultaneous target, suspect, and non-target screening of HOCs. Of 102 target chemicals, 85.3% produced (quasi-)molecular ions as base peaks, with 71.6% displaying method detection limits lower than those of GC-EI-low resolution MS. The optimized method was applied to standard reference sediment and sediments from the Baltic Sea, an Arctic shelf, and a Norwegian lake. In total, we quantified 56 target chemicals with concentrations ranging from 4.86 pg g⁻¹ dwt to 124 ng g⁻¹ dwt. Further, using a combination of exact mass, collision cross section (CCS), retention time, and MS² spectra, a total of 54 suspects were identified at Confidence Level (CL) 2. Among the remaining features, 169 were prioritized using a halogen-selective CCS cutoff (100 Å² + 20% mass), leading to annotation 54 substances (CL ≤ 3). Notably, a suite of fluorotelomer thiols, disulfides, and alkyl sulfones were identified in sediment (CL 1-2) for the first time. Overall, this work demonstrates the potential of GC-APCI-IM-HRMS as a next-generation technique for resolving complex HOC mixtures in environmental samples through exploitation of molecular ions.

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40 **SYNOPSIS:** Hydrophobic chemicals in sediment can be comprehensively screened
41 using a combination of soft ionization to preserve molecular ions and ion mobility to
42 derive collision cross sections.

43 **KEYWORDS:** Atmospheric pressure chemical ionization; Collision cross section;
44 Hydrophobic chemicals; Sediment; Neutral per- and polyfluoroalkyl substances.

INTRODUCTION

Chemical pollution is recognized as one of nine planetary boundaries which threatens the stability of Earth systems.¹ Between 700 and 1,700 new chemicals are registered in the United States and European Union every year,² and many more remain undocumented until they are discovered in the environment. Therefore, the need to comprehensively evaluate the occurrence and impact of chemicals challenges current monitoring frameworks to move beyond characterization and risk assessments of single chemicals, towards quantitative screening of as many known substances as possible, while simultaneously collecting non-target data suitable for identifying unknown compounds.³

Typically, hydrophobic organic contaminants (HOCs) are analyzed using gas chromatography-electron ionization-mass spectrometry (GC-EI-MS). The reproducible fragmentation obtained from EI at 70 eV enables annotation of known HOCs through matching of experimental- to reference mass spectra.⁴ However, the frequent absence of molecular ions in EI impedes *de novo* structural elucidation of unknown compounds.⁵ While electron capture negative ionization (ECNI) offers a partial solution to this problem, this technique tends to be too selective for broad screening, since only a small group of compounds with a resonance structure and high electron affinity can generate molecular ions.^{6,7} Therefore, an ionization technique for GC that is both universal and “soft” is critical for comprehensive screening of HOCs.

Atmospheric pressure chemical ionization (APCI) can efficiently preserve (quasi-)molecular ions of GC-amenable compounds through charge/proton transfer.⁸ Its

potential for harnessing molecular ions has been demonstrated in studies involving wide-scope quantification of emerging contaminants and even identification of unknown compounds.⁹⁻¹² When coupled to ion mobility (IM), instrument-independent and reproducible collision cross section (CCS) values can be acquired to provide additional structure information, improving confidence in identification.¹³ A number of pioneering studies have already begun developing HOC databases and non-target prioritization strategies based on CCS,^{14,15} highlighting the great potential of this technique for both screening and discovery of environmental contaminants.

As a sink for organic carbon (OC), sediment is a complex matrix containing a diverse range of HOCs, making it ideally suited for testing the performance of new analytical methods. In this study, we developed and validated a new analytical workflow for simultaneous target, suspect, and non-target screening of HOCs in sediment samples using multi-dimensional information obtained from (quasi-)molecular ions. Testing the new method on a diverse range of sediment samples demonstrated its widespread applicability and generated new quantitative and qualitative information on legacy, emerging, and even unknown substances in both remote and impacted sediment samples.

MATERIALS AND METHODS

Instrumental analysis. A Waters quadrupole-cyclic ion mobility-time-of-flight mass spectrometer (Q-cIM-ToF; Waters Corp., Wilmslow, U.K.) coupled to an Agilent 8890 GC (Agilent Technologies, Santa Clara, CA, U.S.A) via an APCI source was employed

for analysis. Sample volumes of 1 μL were injected in pulse splitless mode with a programmed inlet temperature for vaporization: initially 100 $^{\circ}\text{C}$ for 0.15 min, then increased at 600 $^{\circ}\text{C min}^{-1}$ to 280 $^{\circ}\text{C}$, and then held for 1 min. Analytes were separated using a 30-m DB-5MS Ultra Inert column (i.d., 0.25 mm; film thickness, 0.25 μm ; Agilent Technologies) with helium carrier gas at a constant flow of 1.5 mL min^{-1} . The GC oven temperature program was as follows: held at 70 $^{\circ}\text{C}$ for 1 min, increased at 10 $^{\circ}\text{C min}^{-1}$ to 310 $^{\circ}\text{C}$, and then held for 15 min.

The GC-MS interface and ion source were maintained at 290 and 150 $^{\circ}\text{C}$, respectively. The corona discharge and cone voltage were set at 2 μA and 30 V, separately. N_2 was used as the makeup gas, auxiliary gas, and cone gas at flow rates of 200 mL min^{-1} , 350 L h^{-1} , and 250 L h^{-1} , respectively, in the dry condition. An uncapped bottle of water was placed in the ionization enclosure to achieve wet conditions. Auxiliary and cone gas flow rates were reduced to 150 and 200 L h^{-1} , respectively, under wet conditions. The ion source was conditioned overnight before use.

The MS was operated in high-definition MS^{E} mode with a mass range of 100-1200 Da. Collision energy was fixed at 6 eV in low energy mode and ramped between 15-50 eV in high energy mode, with a scan time of 0.3 s for each mode. The cIM cell was operated in one pass mode with 3 pushes per bin at a traveling wave height of 22 V. Both drift and collision gases were N_2 . Column bleeding ($\text{C}_9\text{H}_{27}\text{O}_5\text{Si}_5^{+}$: mass-to-charge ratio 355.0705) was measured every 2 min for internal mass correction. CCS was calibrated using a mixture of 22 compounds supplied by Waters Corp., following their standard procedure. Tuning parameters are listed in the Table S1 in the Supporting

Information (SI).

Optimization of instrumental parameters. For the above method, APCI source parameters were optimized to minimize in-source fragmentation and enhance sensitivity. Various settings were tested for auxiliary gas, cone gas, makeup gas, corona current, and cone voltage under both wet and dry conditions. Given that HOCs often contain halogen atoms which increase their molecular weight, tuning parameters were optimized based on ions generated from column bleeding at 70 °C to increase intensities of ions with higher mass-to-charge ratios (m/z). Optimization results are shown in the Section A and Figure S1-3 in the SI.

Sample collection and preparation. To demonstrate the widespread applicability and robustness of our method, a diverse set of sediments were analyzed, each influenced by different sources of contamination and containing different concentrations of OC. Surface marine sediments from the Baltic Sea (9 sites; 0-2 cm; 1.6-7.7% OC) were impacted by both local sources and long-range transport. Surface lake sediment from Lake Tyrifjorden, Norway (1 site; 0-2 cm; 4.5% OC) received emerging contaminants (e.g., per- and polyfluoroalkyl substances [PFAS]) primarily from a local paper production plant.¹⁶ For marine sediments from the remote East Siberian Sea (2 sites; 0-1 cm; 0.94-1.4% OC), we expected low concentrations of pollutants, primarily associated with long-range transport and deposition. NIST standard reference material (SRM; 1941b-Organics in Marine Sediment; 2.99% OC) was included for method

validation.¹⁷ Detailed sampling information and total organic carbon content (TOC) for all sediment samples is provided in Section B and Table S2 of the SI.

The extraction method was modified from the U.S. EPA (Environmental Protection Agency) Method 3545A.¹⁸ Approximately 4 g of each freeze-dried sediment was fortified with 28 isotope-labeled internal standards (IS; listed in Table S3 in the SI) and extracted using an accelerated solvent extraction system (ASE 350; Dionex, U.S.A) three times with 20 mL of acetone/n-hexane (1:1 v/v) per cycle. The static state was held at 100 °C for 10 min. After rotary evaporation, sulfur was removed using activated copper. Because of reduced fragment ions and lowered base line using APCI and HRMS, no further cleanup was conducted in order to enhance throughput and avoid inadvertent removal of nontarget substances. Finally, extracts were concentrated to approximately 200 µL under a nitrogen stream. Further details on the sample preparation method are provided in Section C of the SI. All glassware was burned at 450 °C for 4 h, and metal parts were ultrasonicated for 20 min using acetone. To prevent potential photolysis, containers were either wrapped in aluminum foil or amber glassware was used.

Method validation and quality control. Analytical performance of the method was evaluated using 102 standards for environmental contaminants ($1.44 < \log K_{ow} < 16.8$; $9.31 < \log K_{aw} < 11.3$; Table S3 in the SI), including polycyclic aromatic hydrocarbons (PAHs), organophosphate esters (OPEs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), per- and polyfluoroalkyl substances (PFAS) and other halogenated compounds.

Accuracy and precision of target HOC analysis was evaluated in two ways: Firstly, by comparing triplicate measurements of SRM 1941b to certified concentrations; and secondly, via spike/recovery experiments with Baltic sea sediment (58.26° N, 16.91° E), which was fortified in triplicate to $\sim 1 \text{ ng g}^{-1}$ dwt with a standard of each target. Recoveries were calculated after subtracting background intensities obtained from unfortified sediment. Lab contamination was monitored via procedural blanks (one per batch) using diatomaceous earth (DE; Dionex, Thermo Scientific), which underwent the same extraction process as sediments. Since intensities in blanks were negligible compared to those in real samples, blank subtraction was not performed. Instrumental detection limits (IDLs) were estimated based on standard deviations of peak area from five replicate measurements of contaminant mixtures at the lowest detectable concentrations, while method detection limits (MDLs) were the sum of concentrations in procedural blanks and standard deviations of peak area using triplicates of fortified sediment. Concentrations lower than MDLs were flagged in the target analysis. For suspect and unknown compounds, relative intensities in samples lower than the average plus three times the standard deviation of those in procedural blanks were considered not detected.

For comparison of method sensitivity, IDLs and MDLs were also determined using a low-resolution ISQLR GC-EI-MS (Thermo Scientific, U.S.A) and an 8890 GC-ECNI-5977B MS (Agilent Technologies), both in selected ion monitoring (SIM) mode. Details of these methods are provided in Section D and Table S3 in the SI.

Target analysis. We quantified 102 HOCs using reference standards. The most intense isotopic ion under either dry (typically M^+) or wet (typically $[M+H]^+$) conditions was selected as the quantitative ion, all of which are listed in Table S3 of the SI, along with their preferred source conditions. After integration using Masslynx (version 4.2, Waters Corp.), target compounds were quantified using the IS method with 1/x weighted regression.

Suspect analysis. MS and MS² data were exported separately from Progenesis QI (version 3.0, Waters Corp.), following lockmass correction, pairing of precursor and product ions, peak picking, and alignment. We retained peaks with maximum areas >3 times higher than that in procedural blanks for screening. Software parameters are provided in Section E in the SI.

A multidimensional-constrained suspect screening method was employed as previously described.¹⁹ Briefly, two suspect lists were compiled with information on identity, exact mass, CCS, and retention time (RT). The first comprised 1,060 GC-amenable compounds with experimentally-derived CCS values, previously reported in the literature.^{13,20} The second included 530 chemicals derived from the Arctic Monitoring and Assessment programme's (AMAP's) list of chemicals of emerging Arctic concern and the European Chemical Agency's (ECHA's) list of substances of very high concern.^{21,22} Peaks were matched against suspect lists by m/z , RT, and CCS. MS² similarity scores of candidates with matches in all three dimensions were further evaluated using SIRIUS+CSI:FingerID (version 5.8.6).²³ Eventually, multidimensional

scores were calculated using E1-4.

$$\Delta RT \text{ (min)} = RT_{\text{measured}} - RT_{\text{reference}} \quad \text{E1}$$

$$\Delta CCS \text{ (\%)} = \frac{CCS_{\text{measured}} - CCS_{\text{reference}}}{CCS_{\text{reference}}} \times 100\% \quad \text{E2}$$

$$Score \text{ (\%)} = \begin{cases} 100 & , \Delta RT \text{ or } \Delta CCS \leq THR_{\text{high}} \\ 100 - \frac{(\Delta - THR_{\text{high}}) \times 100}{(THR_{\text{low}} - THR_{\text{high}})}, & THR_{\text{high}} < \Delta RT \text{ or } \Delta CCS < THR_{\text{low}} \\ 0 & , \Delta RT \text{ or } \Delta CCS \geq THR_{\text{low}} \end{cases} \quad \text{E3}$$

$$Score \text{ (\%)} = W_{RT} \times Score_{RT} + W_{CCS} \times Score_{CCS} + W_{MS^2} \times Score_{MS^2} \quad \text{E4}$$

High- and low-confidence thresholds (THR_{high} and THR_{low}) were selected base on the quality of suspect lists. W denotes the weight for each dimension. Score calculation was explained in detail previously.¹⁹ Peaks with a multidimensional score >60% were potential candidates, among which, the highest scoring peak was reported as putatively identified (Confidence Level 2 according to the Schymanski scale^{24,25}).

Non-target analysis. Halogenated organic compounds are distinguished by their smaller size compared to non-halogenated compounds with similar mass, due to the greater mass density of halogen atoms. In this study, peaks with CCS values lower than a proposed CCS boundary (i.e., $100 \text{ \AA}^2 + 20\% \text{ mass}$) were preliminarily prioritized as halogenated compounds.¹⁴ Molecular compositions were determined with the number of halogen atoms constrained by isotopic patterns. Compounds at Confidence Level 1 were confirmed with a standard, while compounds classified as Confidence Level 2 were putatively identified with multidimensional and diagnostic information, according to the Schymanski scale.^{24,25} SIRIUS+CSI:FingerID was used for *in silico* interpretation.²³ The candidate with the highest CSI:Finger ID score for each peak was

retained and categorized as Confidence Level 3. Remaining peaks were considered Confidence Level 4.

For confirmation, 8:2/8:2 fluorotelomer disulfide was purchased from AKos GmbH (Lörrach, Germany). Its ^1H nuclear magnetic resonance (NMR) spectrum is provided in the Figure S4 in the SI. 10:2 and 12:2 fluorotelomer methyl sulfones were custom synthesized from Chiron (Trondheim, Norway).²⁶

Semi-quantification. Fluorotelomer thiols and disulfides were semi-quantified using the mole ionization efficiency of 8:2/8:2 fluorotelomer disulfide. Average mole ionization efficiencies of 10:2 and 12:2 fluorotelomer methyl sulfones were used to semi-quantify other fluorotelomer alkyl sulfones. For suspect and unknown compounds, relative intensities ($\text{g}^{-1} \text{dwt}$) were calculated by normalizing the area of the compound to the dry weight of the extracted sediment and the area of 1-ng IS (i.e., PCB47- $^{13}\text{C}_{12}$ and triphenylphosphate- d_{15} for the dry and wet conditions, respectively).

Estimation of long-range transport potential (LRTP). Physical-chemical properties and half-lives in different compartments for chemicals of interest were derived from Estimation Programs Interface Suite™ for Microsoft® Windows, v 4.11 and thereafter imported to the OECD (Organization for Economic Cooperation and Development) screening model to predict overall persistence, transfer efficiency, and characteristic travel distance.²⁷

RESULTS AND DISCUSSION

Method performance. Among 102 target chemicals, 85.3% produced (quasi-)molecular ions (i.e., M^+ , $[M+H]^+$, $[M-H]^+$, and $[M-X]^+$) as base peaks (Figure 1A), indicating the softness of this technique for HOCs. Specifically, aromatic compounds, such as PAHs, PCBs, PBDEs, and halogenated benzenes, were ionized through charge transfer without fragmentation. Under wet conditions, $[M+H]^+$ was predominantly the base ion for oxidized compounds and OPEs. In comparison, only molecular ions of aromatic compounds were quantitative ions using EI, while only 68 halogenated compounds were ionized using ECNI, primarily with halogen ions as base ions (Table S3 in the SI). These results suggest that APCI is a universal ionization technique for a wide range of known HOCs and also preserves molecular ions necessary for unknown identification.

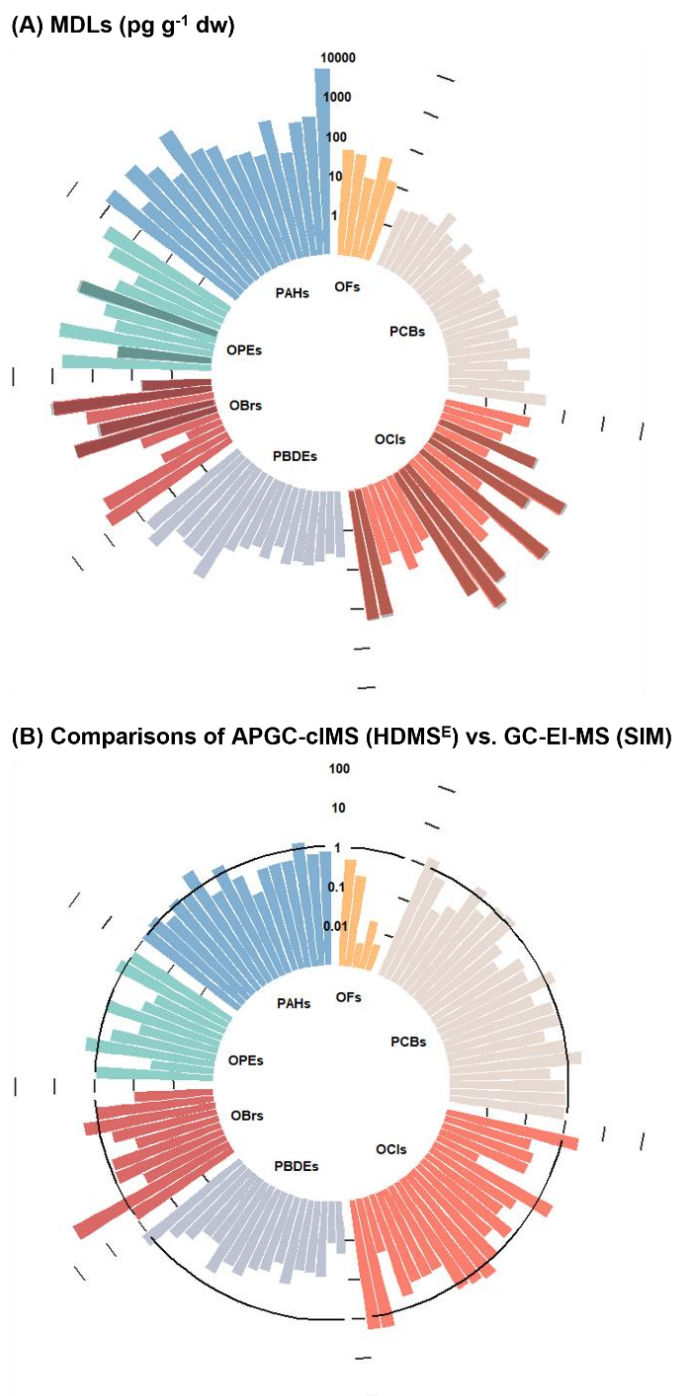


Figure 1. (A) Method detection limits (MDLs) using gas chromatography-atmospheric pressure chemical ionization-cyclic ion mobility-mass spectrometry (APGC-cIMS) at high definition MS^E mode (HDMS^E) and (B) its comparison with gas chromatography-electron ionization-mass spectrometry (GC-EI-MS) at selective ion monitoring mode (SIM). Light bars in the panel A indicates (quasi-) molecular ions (i.e., M⁺, [M+H]⁺, [M-H]⁺, and [M-X]⁺) as base peaks. Bars within the circle in the panel B indicates better sensitivity using the current method. OFs: organofluorines, PCBs: polychlorinated biphenyls, OCIs: organochlorines, PBDEs: polybrominated diphenyl ethers, OBrS: organobromines, OPEs: organophosphates, and PAHs: polycyclic aromatic hydrocarbons.

Owing to reduced fragmentation and lower base lines using APCI and HRMS, MDLs for 71.6% of target compounds using the current technique were better than those achieved with GC-EI-MS in SIM mode (Figure 1B). Notably, semi-fluorinated alkanes and OPEs displayed orders of magnitude lower MDLs using GC-APCI compared to GC-EI, likely due to reduced fragmentation using the former approach. IDLs and MDLs using different methods for each compound are listed in the Table S3 in the SI.

IS-corrected recoveries for 67.6% of the target chemicals fell within the range of 70-130% with a standard deviation (STD) <30% (for compound-specific recoveries, see Table S3 in the SI). The remaining compounds were mostly comprised of semi-fluorinated alkanes and PBDEs. Low recoveries for these substances are likely associated with the high volatility of the former and the susceptibility of the latter to thermal degradation.

Among our target compounds, concentrations of 15 PAHs, 14 PCBs, and 3 organochlorine pesticides were consistent with certified concentrations in SRM 1941b, with an average accuracy of $103\% \pm 31.6\%$ (Figure S5 in the SI). Overall, the high sensitivity, recovery, and accuracy of the method for a diverse range of HOCs demonstrate its potential as a reliable technique for comprehensive contamination assessment in sediments.

Wide-scope quantification of chemicals in sediment. Application of the optimized method to unfortified marine and lake sediments revealed 56 quantifiable substances

287 observed in at least 1 sample, including PAHs, PCBs, PBDEs, organochlorines, and
288 OPEs (Figure 2). Concentrations for individual compounds cover five orders of
289 magnitude, ranging from 4.86 pg g⁻¹ dw to 124 ng g⁻¹ dw (concentrations are provided
290 in Table S4 of the SI). Sediment from the Baltic Sea contained the highest level of
291 contamination with average sum concentration of 403 ng g⁻¹ dw (Figure 2). In contrast,
292 contamination in the Arctic sediment, representing a remote area with little human
293 activity, is about six and three times lower than those in sediment from the Baltic Sea
294 and Lake Tyrifjorden, respectively.

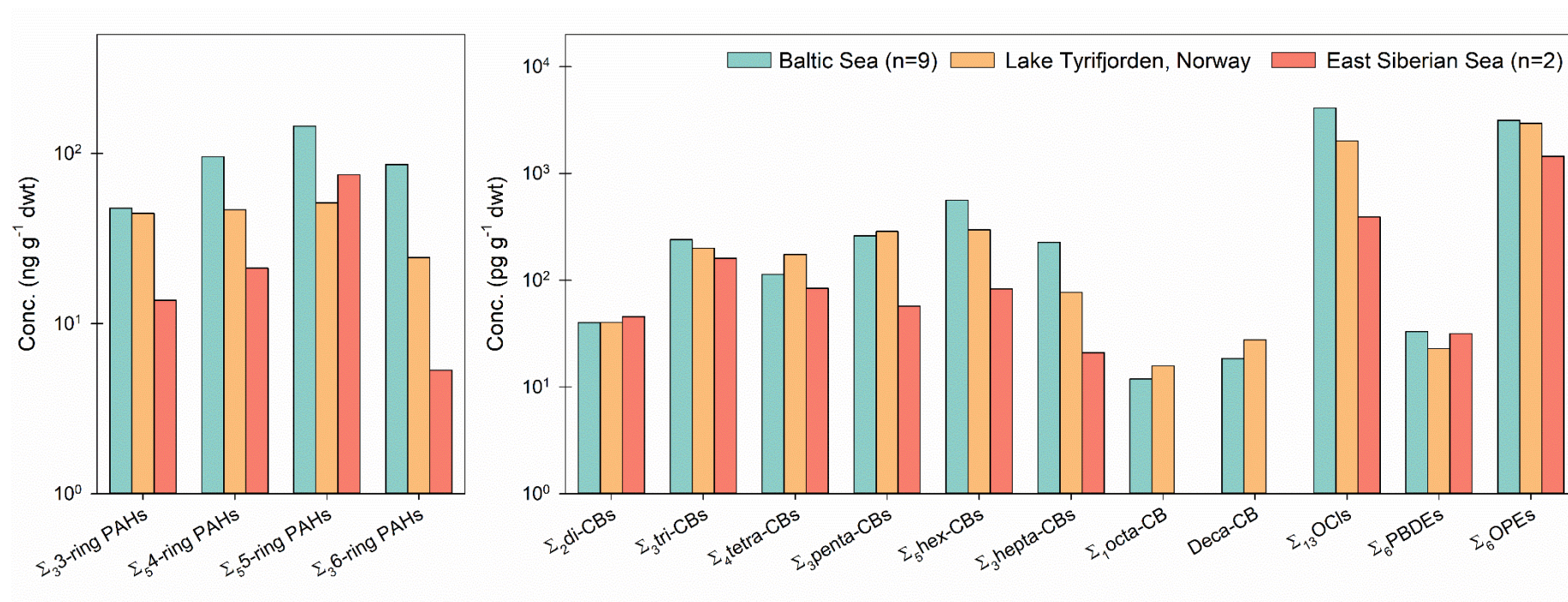


Figure 2. Average concentrations of contaminants in sediments from different locations. PAHs: polycyclic aromatic hydrocarbons, CB: chlorinated biphenyls, OCls: organochlorines, PBDEs: polybrominated diphenyl ethers, and OPEs: organophosphate esters.

HOC concentrations observed in sediments from the present work are comparable to previously reported concentrations. For example, average concentrations of Σ_{16} PAHs and Σ_7 PCBs in sediment from the Swedish Baltic Sea coast (336 and 0.95 ng g⁻¹ dwt, respectively) are consistent with prior measurements from nearby locations (i.e., Σ_{16} PAHs: 157-502 ng g⁻¹ dwt and Σ_7 PCBs: 0.73-2.48 ng g⁻¹ dwt).²⁸ Similarly, for the Arctic samples, average concentrations of Σ_{16} PAHs (45.0 ng g⁻¹ dwt) and Σ_7 PCBs (209 pg g⁻¹ dwt) align with prior reports from the Chukchi Sea (14.4-218 ng g⁻¹ dwt for Σ_{16} PAHs; 40.2 pg g⁻¹ dwt Σ_7 PCBs)²⁹ and East Siberian rivers (Σ_7 PCBs: 214-328 pg g⁻¹ dwt).^{30,31}

OPEs, used as flame retardants, plasticizers, and additives, have become an emerging concern due to their increasing production after the effective regulation of PBDEs.³² Their concentrations and composition varies with usage and proximity to source. In this study, average concentrations of Σ_5 OPEs were 3.17 and 2.95 ng g⁻¹ dwt in Baltic Sea and Lake Tyrifjorden sediment, respectively, with tris(2-ethylhexyl) phosphate as the predominant compound. Triphenylphosphate, tris(2-butoxyethyl) phosphate, and 2-ethylhexyl diphenyl phosphate were quantified in the Arctic sediment and also previously reported in different matrices in the Arctic.³³ Particularly, the concentration of triphenylphosphate is close to those in a previous study in the Chukchi Sea.³⁴ Overall, these results further highlight the sensitivity and robustness of the current method for a wide range of contaminants and concentration levels thereof.

Multidimensional-constrained suspect screening. In addition to quantification, the

320 technique presented here based on soft ionization and ion mobility mass spectrometry
321 offers valuable multidimensional information (i.e., MS, RT, CCS, and MS²) for
322 screening and structure elucidation. We screened 54 suspect compounds with
323 multidimensional scores >60% (Confidence Level 2 according to the Schymanski
324 scale), 28 of which are listed as chemicals of concern by AMAP or ECHA (Figure
325 3).^{24,25} Detailed identities, scores, and relative intensities are listed in the Table S5 in
326 the SI.

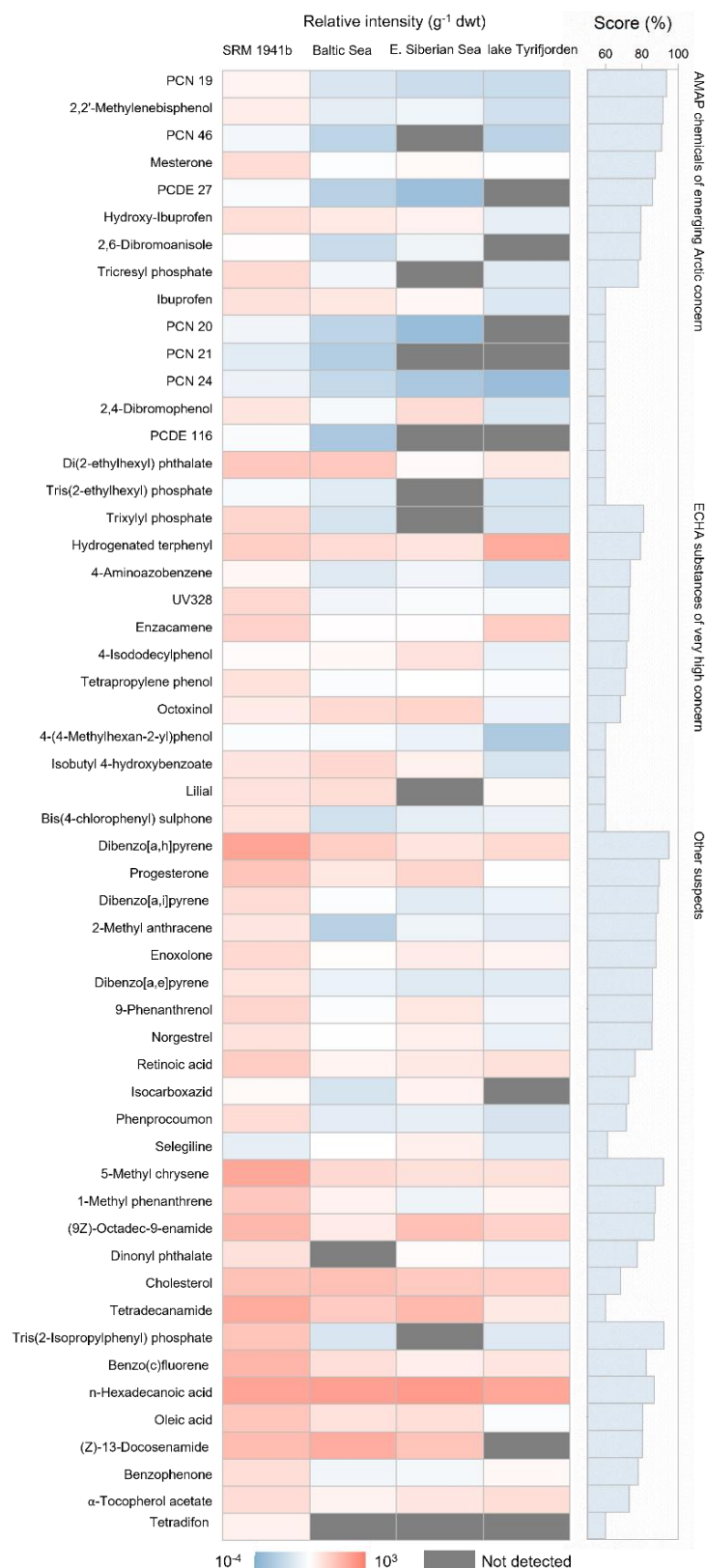


Figure 3. Relative intensities (g⁻¹ dwt) and multidimensional scores (%) of suspect contaminants in sediment samples from different locations. PCN: polychlorinated naphthalene, PCDE: polychlorinated diphenyl ether, AMAP: Arctic monitoring & assessment programme, and ECHA: Europe chemical agency.

A total of 16 features tentatively matched to substances on the AMAP chemicals of emerging Arctic concern database. Among these substances, 11 were detected in the East Siberian Sea sediment, including trichloronaphthalenes, 2,3',6-trichlorodiphenyl ether, di(2-ethylhexyl) phthalate, and 2,2'-methylenebisphenol (Figure 3). Given the remoteness of the Arctic from major urban settlements and chemical use, these results emphasize the persistence and LRT of these substances. An additional 34 compounds were found in the Arctic, but not listed in the AMAP chemicals of emerging Arctic concern database (Figure 3). Some of these compounds showed similar relative intensities across samples, indicating potential natural sources. Notably, 13 substances exhibited relative intensities in Arctic sediment orders of magnitude lower than those in other samples, suggesting their potential origin from long-range transport. Particularly, estimated transfer efficiencies for dibenzopyrene isomers (5.38-8.77%), bis(4-chlorophenyl) sulphone (6.42 %), and UV-328 (12.4%) were above reference LRTP criteria (2.25%). Bis(4-chlorophenyl) sulphone is used in high temperature plastics, while is a UV absorber in plastic applications. Both were identified as persistent, bioaccumulative and toxic substances by ECHA, and UV-328 is under investigation for inclusion in the United Nations Stockholm Convention on Persistent Organic Pollutants. Additionally, high relative intensities of enzacamene, octoxinol, tetrapropylene phenol, and isobutyl 4-hydroxybenzoate were observed in this study (Figure 3). All of these are listed as ECHA substances of very high concern, due to their potential endocrine disrupting properties.

CCS and m/z -based prioritization of halogenated compounds. In addition to screening of compounds with a known structure, IM-derived CCS is a novel size dimension for prioritization of unknown compounds, especially halogenated organic compounds. The top 50 potential halogenated compounds with the highest intensity in each region and condition were investigated after prioritization. In total, we obtained the elemental composition of 192 peaks, detailed in Table S6 in the SI. For those peaks, 23 were validated by reference chemical standards. Structures of 22 compounds were assigned considering multidimensional or diagnostic information. We annotated 32 peaks using an *in silico* tool.

Specifically, the major halogenated compounds detected in the SRM 1941b were anthropogenic chlorinated compounds. In addition to PCB congeners and chlorinated benzenes, higher relative intensities of potential dichlorodiphenyl sulfone isomers and polychloronaphthalene congeners were observed. In contrast, halogenated compounds in the Arctic sediment were primarily natural compounds, such as bromophenolic compounds and halogenated carbazoles. These naturally occurring compounds share similar structures with anthropogenic bioaccumulative contaminants and could pose a risk to biota.³⁵ The sediment from the Baltic Sea contained a mixture of anthropogenic and natural halogenated compounds.

Notably, 34 unknown fluorinated features with high relative intensities were prioritized in Lake Tyrifjorden sediments (Figure 4A). Among them, 15 were in-source fragments, while the remaining were molecular ions. The elemental composition of potential neutral PFAS included $F(CF_2)_n(CH_2)_xSH$ ($x=2$, $n=10, 12, 14$, and 16 ; $x=3$, $n=8$), $F_2(CF_2)_n(CH_2)_xS_2$ ($x=4$, $n=14, 16, 18$, and 20 ; $x=6$, $n=16$ and 18), $F(CF_2)_nC_5H_9S_2O$ ($n=8, 10$, and 12), $F(CF_2)_nC_3H_7SO_2$ ($n=8, 10, 12$, and 14) and $F(CF_2)_8C_4H_7SO_2$. A previous study in the same lake found high concentrations of

379 fluorotelomer sulfonate homologues (FTS) in sediment, due to the discharge from paper
380 production factories.¹⁶ All neutral PFAS detected the present work contain a
381 perfluorinated chain, a hydrocarbon chain with at least C2, and sulfur atom(s).
382 Therefore, we hypothesized that all of these unknown compounds have a fluorotelomer
383 structure.

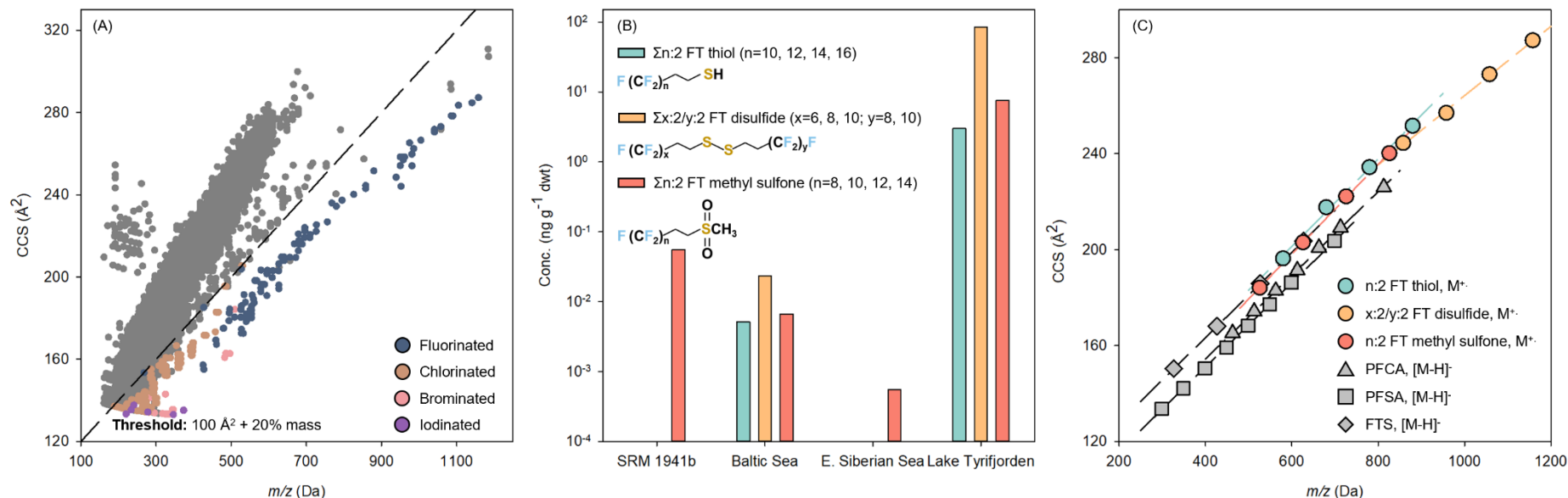


Figure 4. (A) Mass-to-charge ratios (m/z) and collision cross section (CCS) values of peaks detected in Lake Tyrifjorden, Norway to prioritize halogenated organic compounds. (B) Semi-quantified concentrations of neutral fluorotelomer (FT) substances in sediments from different locations. (C) Trends between m/z and CCS values of organofluorines. In the panel A, peaks with a CCS value under the threshold ($100 \text{ Å}^2 + 20\% \text{ mass}$) were preliminarily prioritized as potential halogenated compounds.¹⁴ In panel C, CCS values for perfluoroalkyl carboxylic acids (PFCA), perfluoroalkyl sulfonate acids (PFSA), and fluorotelomer sulfonates (FTS) were obtained from Dodds et al.³⁷

Structures of these compounds were tentatively deduced, based on the in-source fragments. Due to the presence of $[M-F-SH_2]^+$ (Figure S6A in the SI), $F(CF_2)_n(CH_2)_xSH$ were likely fluorotelomer thiols. Based on the cleavage of S-S bond (Figure S6B), $F_2(CF_2)_n(CH_2)_xS_2$ was tentatively identified as fluorotelomer disulfides, and later confirmed with an authentic standard (i.e., 8:2/8:2 fluorotelomer disulfide). $F(CF_2)_nC_3H_7SO_2$ and $F(CF_2)_8C_4H_7SO_2$ were identified as potential fluorotelomer alkyl sulfones, based on the loss of alkyl group (Figure S6C-D). We confirmed 10:2 and 12:2 fluorotelomer methyl sulfones with reference chemical standards. In summary, we identified novel thiol, disulfide, and alkyl sulfone forms of fluorotelomers.

Fluorotelomer thiols are a precursor of fluorotelomer mercaptoalkyl phosphate esters (FTMAP), also known as S-diPAP marketed under the tradename Lodyne P208E.³⁶ These compounds were used as fluorinated surfactants in food packaging since 1995. Detection of these neutral PFAS aligns with previous hypotheses regarding the application of mixtures of FTS precursors, such as FTMAP and 3-[2-(perfluoroalkyl)ethylthio] propionate (marketed as Zonyl FSA) in the factories upstream of the sampling site.¹⁶

The semi-quantified concentrations are provided in Table S4 in the SI. The sum concentrations of neutral PFAS in the Norwegian lake sediment was $96.1 \text{ ng g}^{-1} \text{ dwt}$ with 88.3% attributed to fluorotelomer disulfides (Figure 4B). This value is three times higher than the total concentration of FTS ($30.9 \text{ ng g}^{-1} \text{ dwt}$).¹⁶ Only 12:2 fluorotelomer thiol and 8:2/8:2 fluorotelomer disulfide were detected in the Baltic Sea sediment, while fluorotelomer methyl sulfones appeared in almost all samples. Notably, 8:2

fluorotelomer methyl sulfone was detected in one of the Arctic sediment samples (Figure 4B). Its 10:2 and 12:2 homologues were previously detected in the blubber of killer whales from Greenland.²⁶ Therefore, these results underscore the widespread environmental distribution and persistence of these substances.

CCS values of neutral PFAS observed here are linearly associated with their m/z , which has also been observed for polar PFAS measured with LC-ESI systems (Figure 4C).³⁷ Due to the instrument-independence of both CCS values and m/z , these class-specific trends can be leveraged to comprehensively prioritize and identify these groups of compounds across different sample types, facilitating further investigation of their sources and health effects.

Implications. Using GC-APCI-IM-HRMS, a powerful workflow for screening of HOCs in environmental samples was established and enabled us to detect and/or quantify 56 target, 54 suspect, and 56 unknown compounds with $CL \leq 3$ in sediment samples. A series of novel neutral fluorotelomer thiols, disulfides, and alkyl sulfones were identified in sediment for the first time with their m/z and CCS trends reported for further comprehensive screening. GC-APCI can effectively preserve (quasi-) molecular ions for HOCs, and IM-HRMS can acquire confirmatory CCS as a semi-orthogonal dimension. In addition to wide-scope quantification and highly specific suspect screening, their combination has great potential for *de novo* elucidation of unknown halogenated compounds and transplantation of *in silico* technique. Therefore, GC-APCI-IM-HRMS could be a next-generation technique for analyzing HOCs in complex

matrices through a thorough exploitation of molecular ions.

ASSOCIATED CONTENT

Supporting Information

Additional information as noted in the text is available.

Tuning parameters (Table S1); optimization of source and tuning parameters (Section A); optimization using dieldrin for the dry condition (Figure S1); optimization for the wet condition (Figure S2); intensity fold changes using optimized and default parameters (Figure S3); sampling procedure and analysis of TOC (Section B); sampling and TOC information (Table S2); qualitative and quantitative information of target compounds (Table S3); sample preparation (Section C); instrumental method of GC-low resolution MS (Section D); software parameters (Section E); ¹H NMR spectrum of 8:2/8:2 fluorotelomer disulfide (Figure S4); comparison of measured and certificated concentrations of contaminants in SRM 1941b (Figure S5); (semi)quantified concentrations of contaminants (Table S4); scores and relative intensities of suspected compounds (Table S5); qualitative information and relative intensities of non-target compounds (Table S6); representative in-source fragments of fluorotelomer thiols, disulfides, and alkyl sulfones (Figure S6).

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGEMENTS

We thank Gastón Alurralde, Elena Gorokhova, and Örjan Gustafsson (all at Department of Environmental Science, Stockholm University) for providing samples. This research was supported by the Marie Skłodowska-Curie postdoctoral fellowship under Horizon Europe (Grant agreement number: 101150779), Ymer-80 foundation, and faculty funding of Department of Environmental Science, Stockholm University.

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