

Impacts of PFAS-Enriched Sea Spray Aerosol on Coastal Regions

Ian T. Cousins

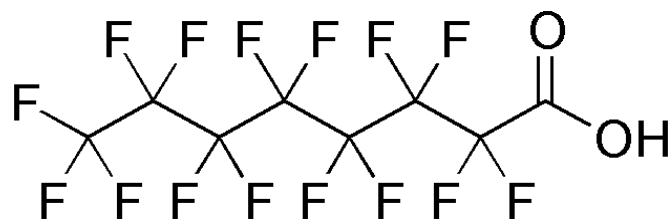
**Department of Environmental Science,
Stockholm University, Sweden**

NORDROCS 2026, Helsinki, September 15

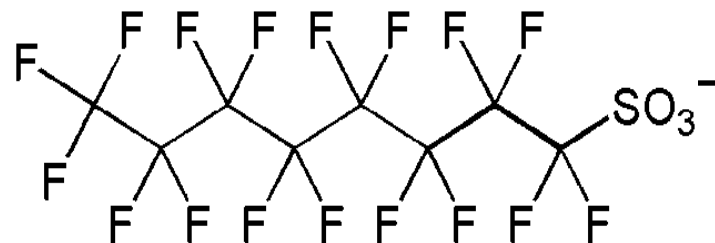
Outline

- Brief introduction to PFAS, and PFAS in the atmosphere
- Theory: why are PFAS enriched on sea spray aerosols?
- Laboratory chamber experiments
- Field evidence for sea spray aerosol transport of PFAS
 - Air sampling
 - Surface media and deposition samples
 - Groundwater data
- Conclusions
- Implications

Brief introduction to PFAS



Perfluorooctanoic acid - PFOA



Perfluorooctane sulfonate - PFOS

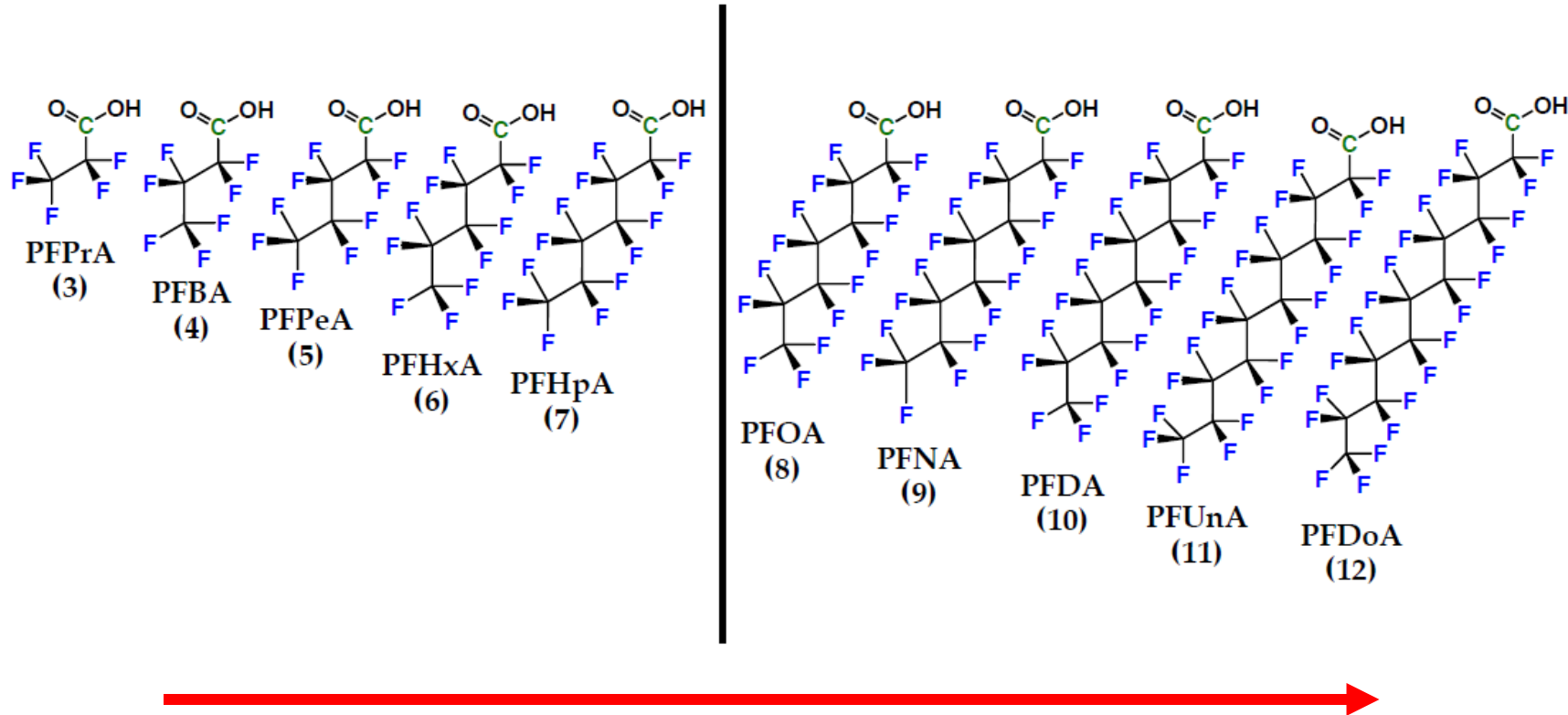


Tail

Head

PFOA and PFOS are persistent, bioaccumulative and toxic
Listed on Stockholm Convention..

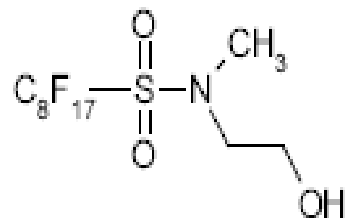
Properties versus chain length



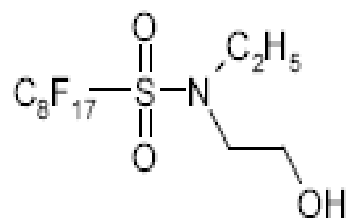
More hydrophobic/bioaccumulative/less mobile

More surface active

Volatile and Semi-Volatile Precursors

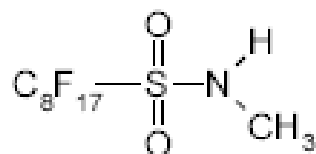


Methyl FOS Alcohol

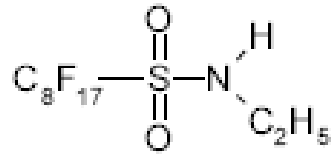


Ethyl FOS Alcohol

Perfluoroalkyl
sulfonamido ethanols

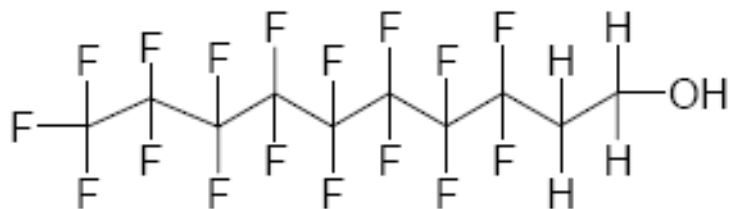


Methyl FOS Amide



Ethyl FOS Amide

Perfluoroalkyl sulfonamides

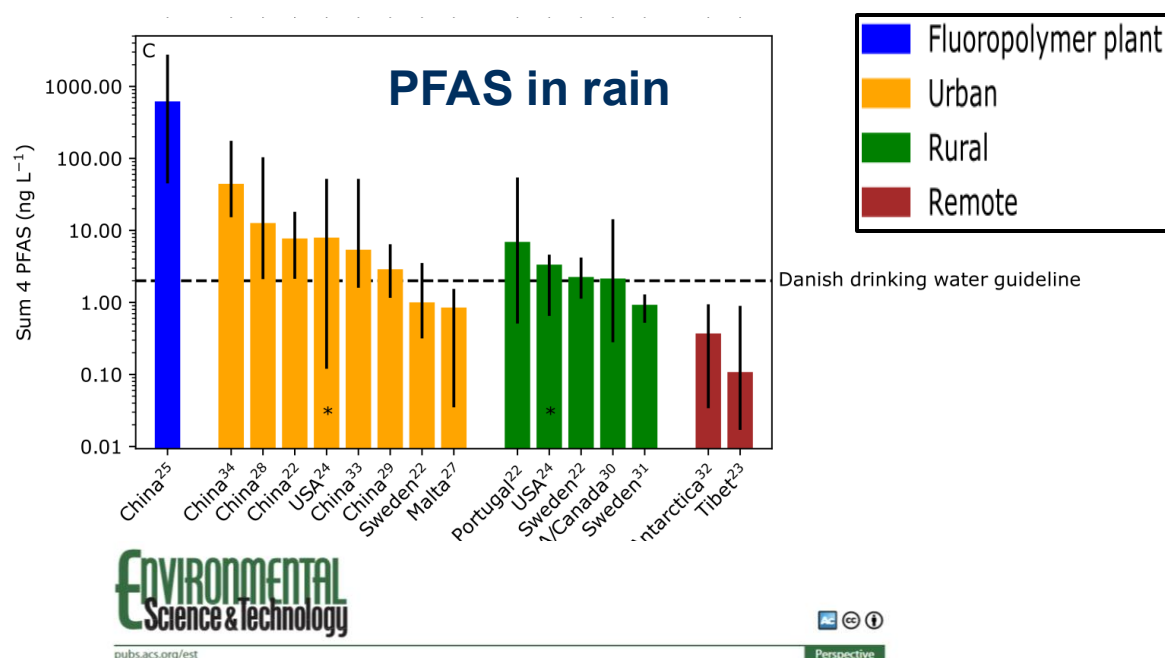


Fluorotelomer alcohols

8:2 FTOH

Danish drinking water guideline

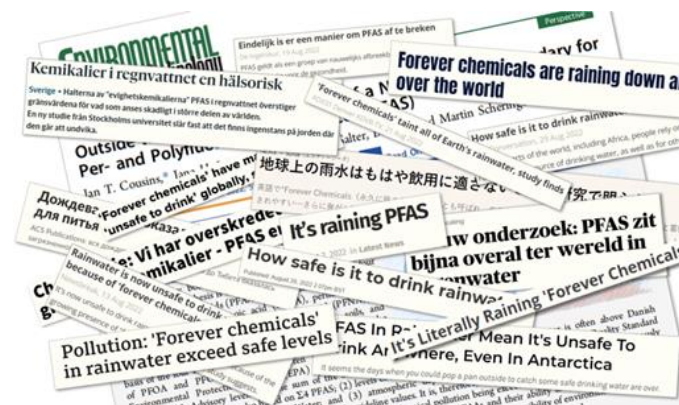
- $\Sigma 4$ PFAS (PFOS, PFHxS, PFOS, PFNA) < 2 ng/L
- These 4 PFAS no longer used (apart from PFOA in Asia)
- All still present in the environment and will cycle in the hydrosphere indefinitely



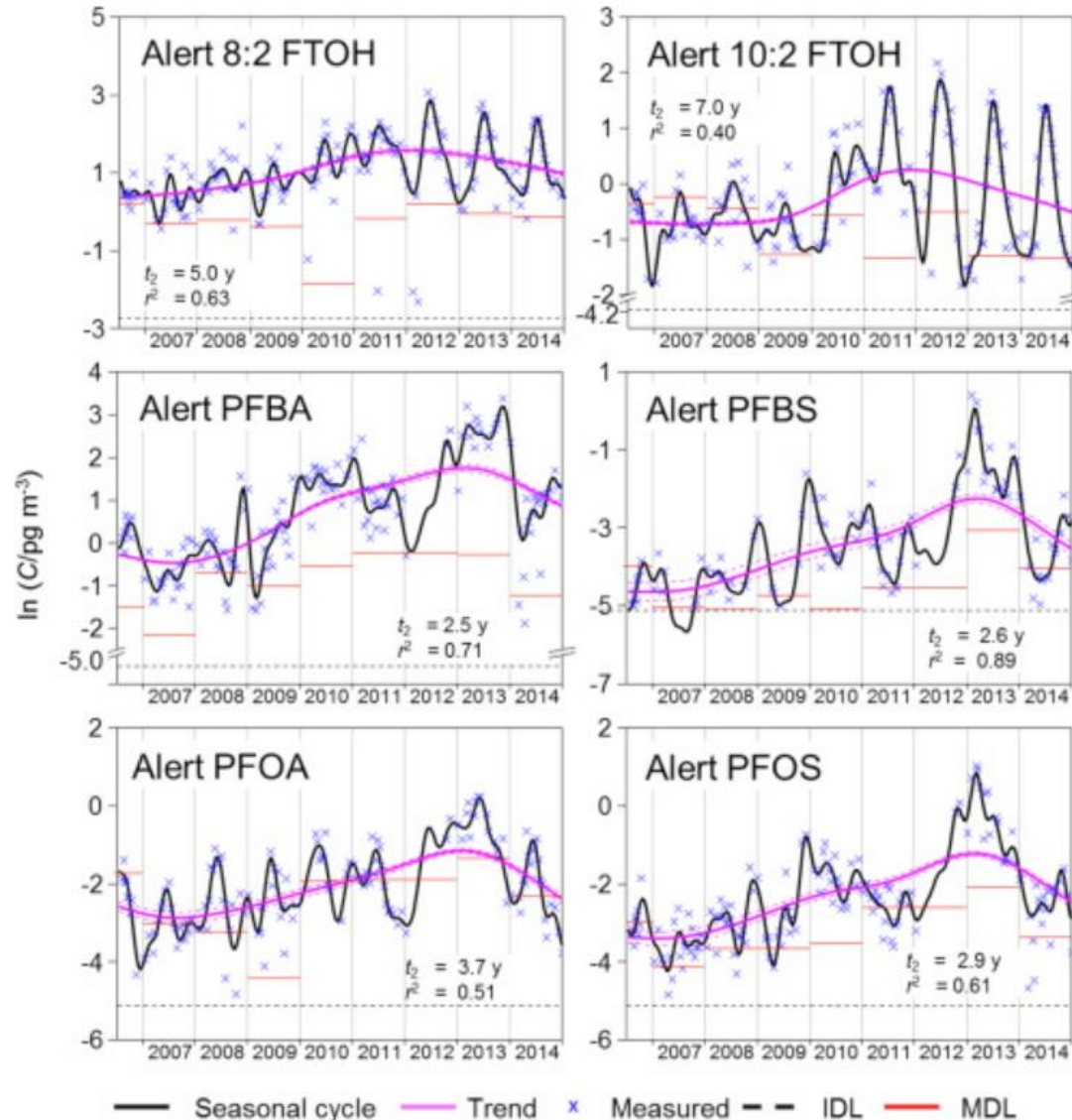
Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS)

Ian T. Cousins,* Jana H. Johansson, Matthew E. Salter, Bo Sha, and Martin Scheringer

Guideline close to ambient rainwater levels



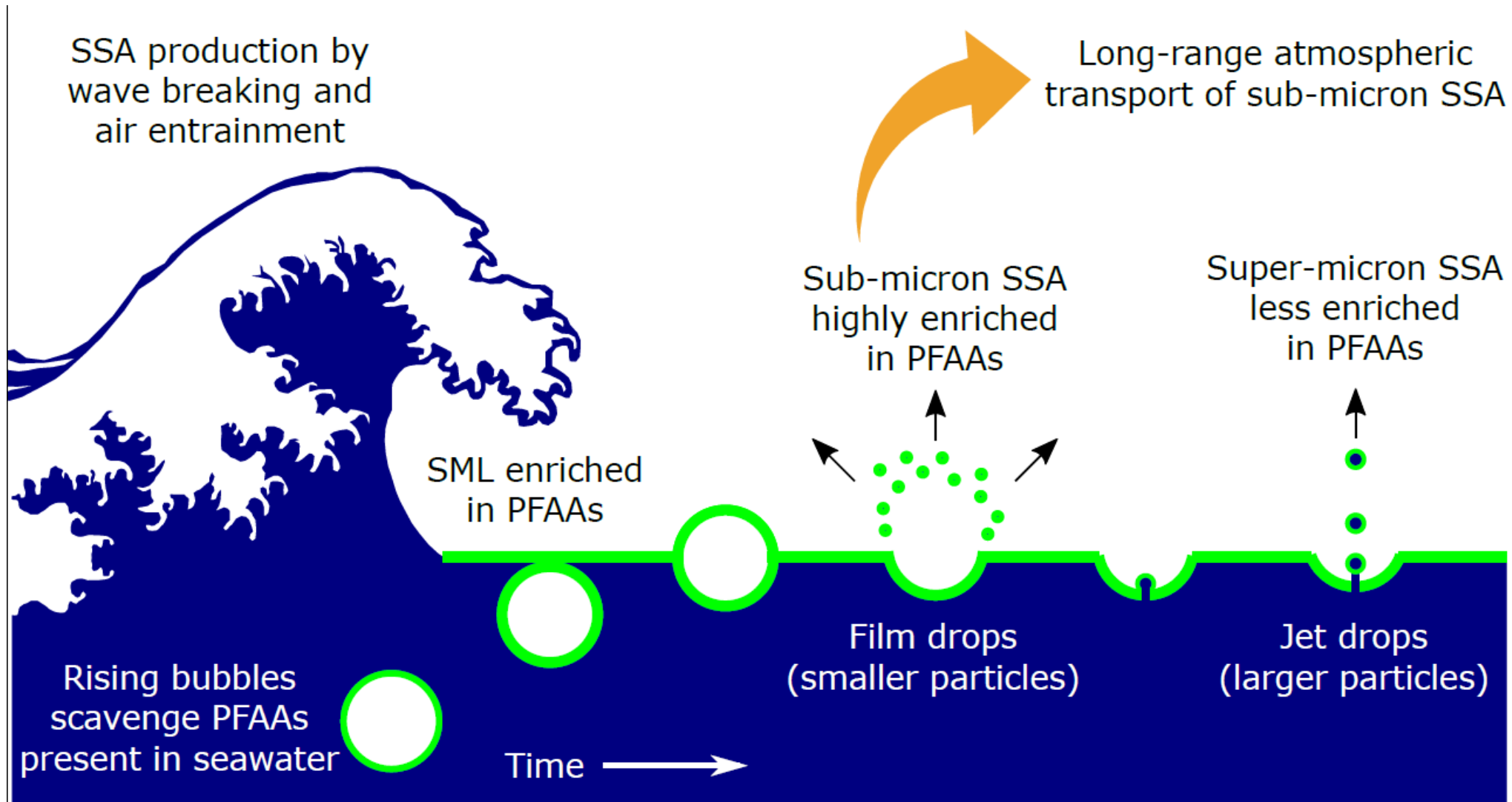
PFAS time trends in atmosphere stable



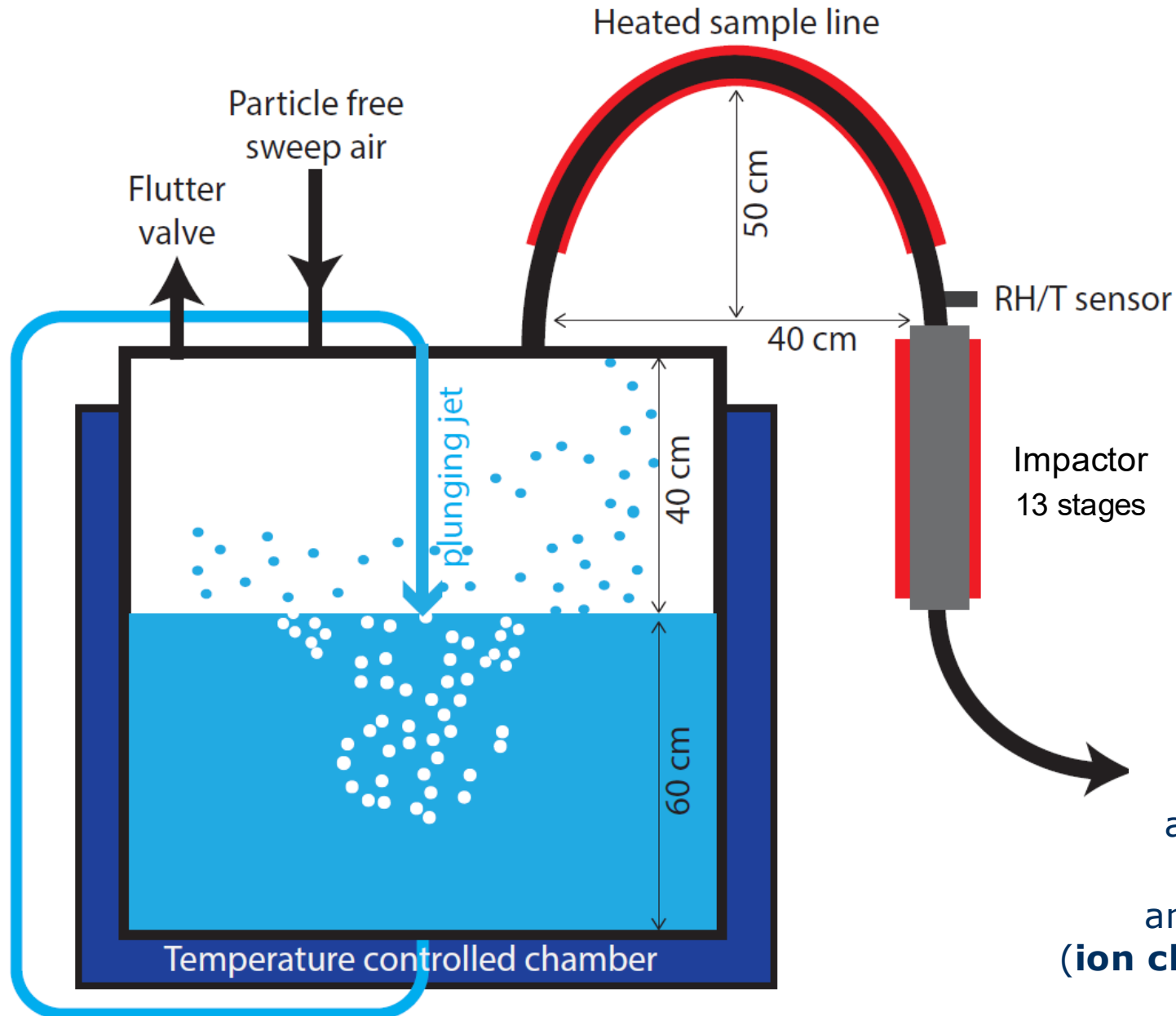
Assessing temporal trends and source regions of per- and polyfluoroalkyl substances (PFASs) in air under the Arctic Monitoring and Assessment Programme (AMAP)

Fiona Wong^a, Mahiba Shoeib^a, Athanasios Katsoyiannis^b, Sabine Eckhardt^c, Andreas Stohl^c, Pernilla Bohlin-Nizzetto^c, Henrik Li^d, Phil Fellin^d, Yushan Su^{a,c}, Hayley Hung^{a,e}

Sea spray aerosol: theory



Chamber experiments



PFAAs spiked to
solution of artificial **sea
salt** (35 psu).

Aerosol and water
analysed for PFAAs
(**UPLC-MS/MS**)
and sea salt content
(**ion chromatography**).

Similar application to cleanup of wastewater - SAFF

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

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Efficient removal of perfluorooctane sulfonate from aqueous film-forming foam solution by aeration-foam collection

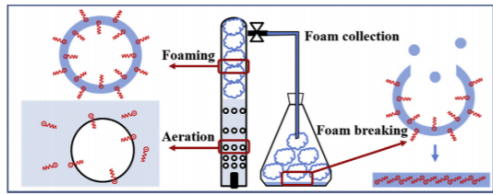
Pingping Meng^a, Shubo Deng^{a,*}, Ayiguli Maimaiti^a, Bin Wang^a, Jun Huang^a, Yujue Wang^a, Ian T. Cousins^b, Gang Yu^a

^a State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, POPs Research Center, Tsinghua University, Beijing, 100084, China
^b Department of Environmental Science and Analytical Chemistry (ACES), Stockholm University, SE-106 91, Stockholm, Sweden

HIGHLIGHTS

- PFOS removal reached 96% after 2 h with an aeration flow rate of 75 mL/min.
- PFOS enrichment factor exceeded 8400 with the assistance of APG.
- High ionic strength accelerated the PFOS removal by aeration-foam collection.
- Aeration-foam collection is suitable for PFOS recovery from AFFF wastewater.

GRAPHICAL ABSTRACT



- We don't want to generate foam in our chambers
- We want to generate sea spray aerosols in the same way as in the oceans

SAFF = Surface Active
Foam Fractionation

High levels of PFAS in sea foams in Denmark worldwide



Still no answers from sampling of PFAS-laden foam

03/04/2022 by Trista Tabon



E.g. Thyborøn:
1 700 000 ng/L
 Σ 4 PFAS

Compared to
9 ng/L Σ 4 PFAS in
seawater

Enriched
190 000 times in foam

PFAS-contaminated foam found at Caswell Beach, Oak Island

BY LISA SORO - OCTOBER 18, 2021 8:00 AM



PFAS i danskt havsskum för-giftade betande kor



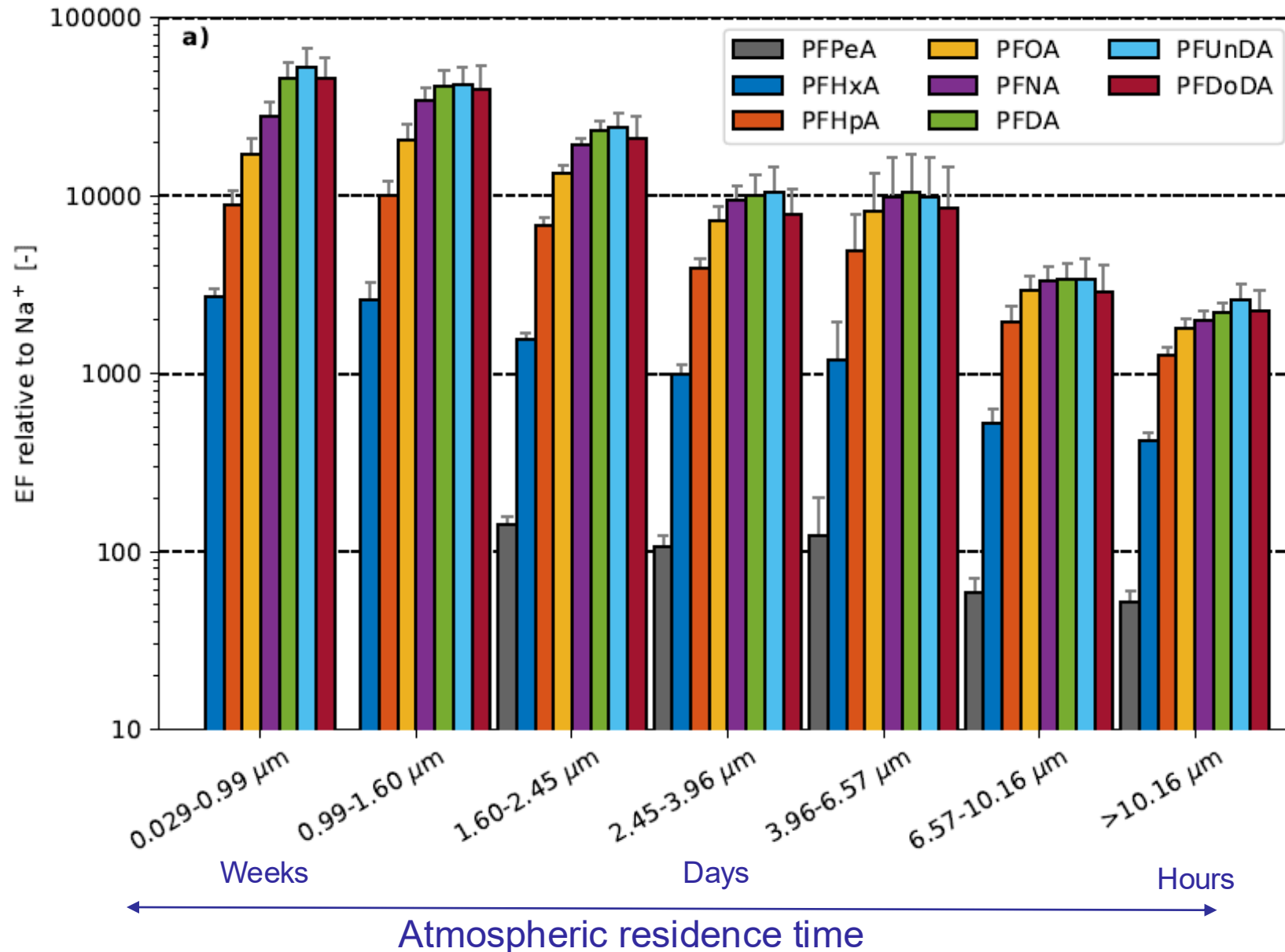
PFAS aangetroffen in zeeschuim in Knokke en De Haan, Agentschap Zorg en Gezondheid: "Beperk het contact"



▶ PFAS i vågskum kan vara ett hot mot danska surfare

Measured aerosol enrichment factors

Normalised to mass of sea salt tracer Na⁺



PFAAs enriched up to 60 000 times in aerosol.

Aerosol enrichment increases with PFAA chain length and with decreasing aerosol size.

Environmental Science Processes & Impacts



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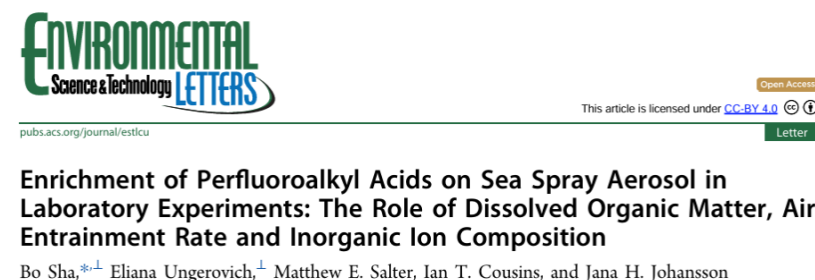
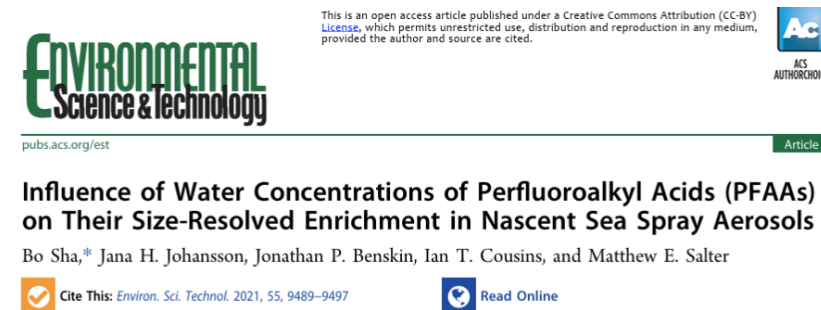
Cite this: Environ. Sci.: Processes Impacts, 2019, 21, 635

Global transport of perfluoroalkyl acids via sea spray aerosol†

J. H. Johansson,^{†*} M. E. Salter,^{†*} J. C. Acosta Navarro,^{†*} C. Leck,^{bc} E. D. Nilsson^{ab} and I. T. Cousins^{†*}

More chamber experiments

- Enrichment insensitive to changes in PFAS water concentration (0.3 – 150 ng/L)
- Higher enrichment when dissolved organic matter added to artificial seawater (enrichments exceed 100,000 times)
- Enrichment increases with increasing jet flow, especially in submicron particles
 - Increased SSA emission under stormy conditions



Chamber experiments in the field

The 29th Atlantic Meridional Transect (AMT) cruise

Oct 13th – Nov 25th , 2019

- Distribution of PFAAs in the Atlantic Ocean
- Field-based EFs at conditions representative for the global oceans



ENVIRONMENTAL
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Letter

Horizontal and Vertical Distribution of Perfluoroalkyl Acids (PFAAs)
in the Water Column of the Atlantic Ocean

Eleni K. Savvidou,^{*} Bo Sha, Matthew E. Salter, Ian T. Cousins, and Jana H. Johansson

Cite This: *Environ. Sci. Technol. Lett.* 2023, 10, 418–424

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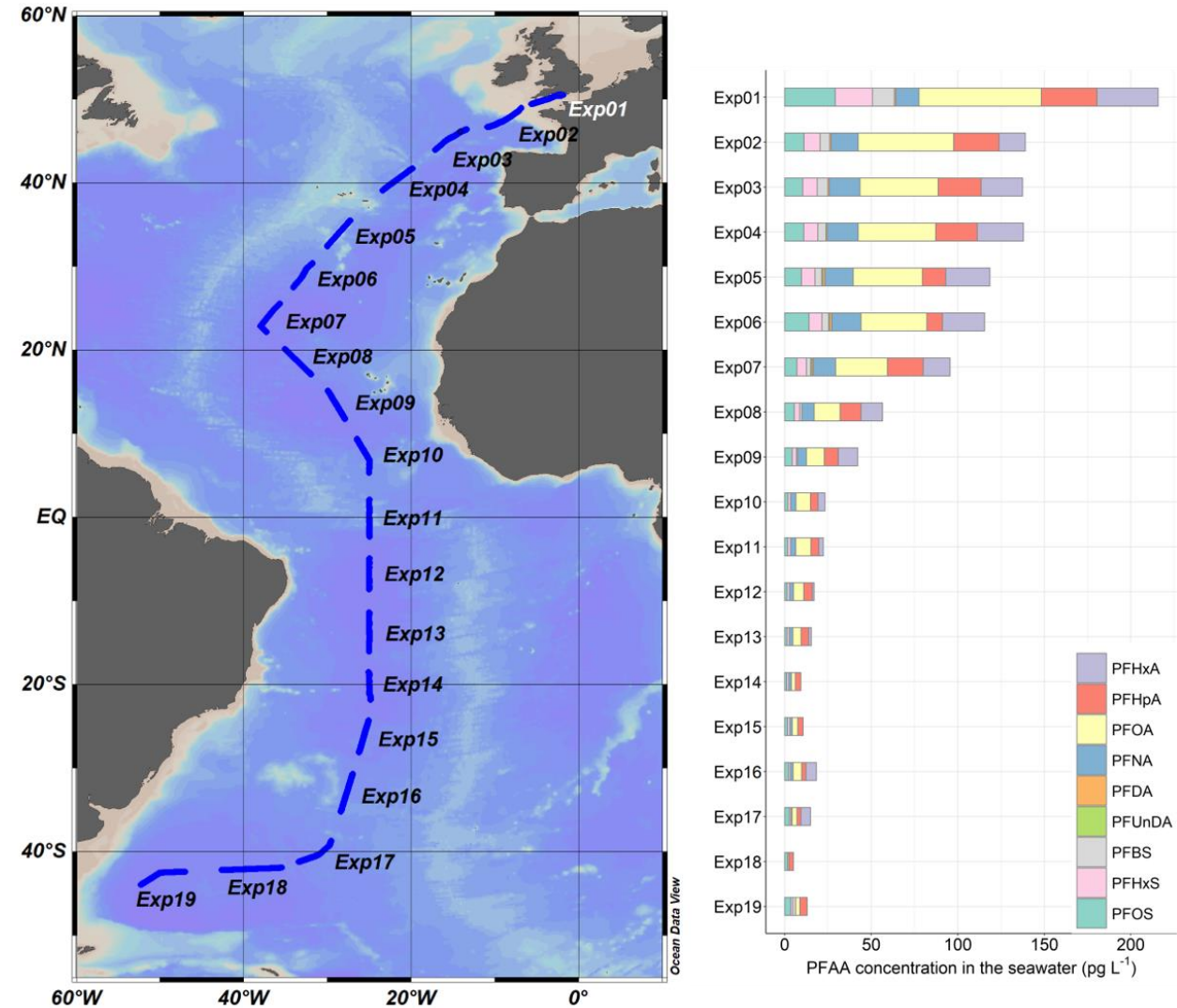
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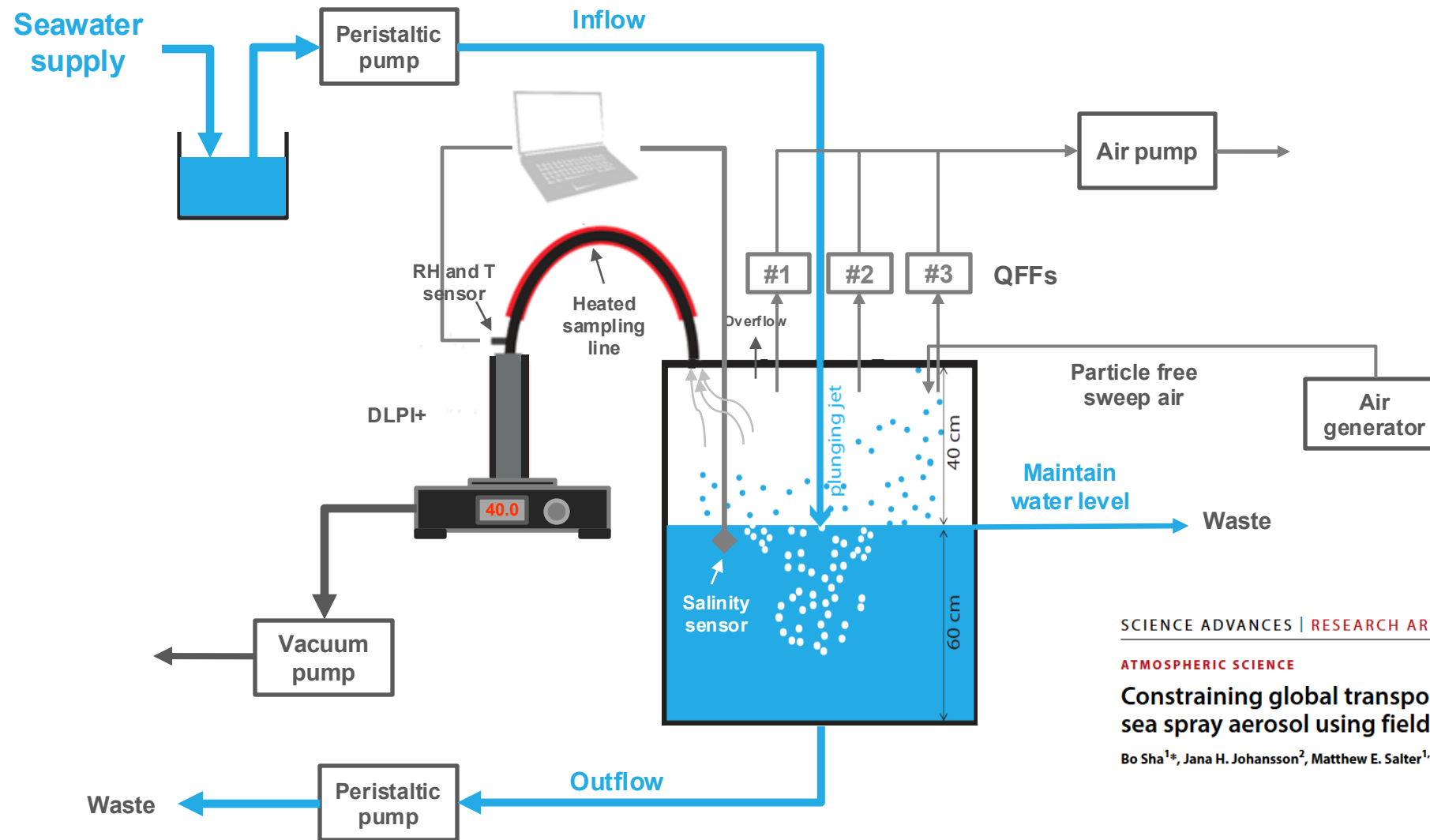
Constraining global transport of perfluoroalkyl acids on
sea spray aerosol using field measurements

Bo Sha^{1*}, Jana H. Johansson², Matthew E. Salter^{1,3}, Sara M. Blichner¹, Ian T. Cousins¹

Seawater measurements



SSA EFs for PFAS



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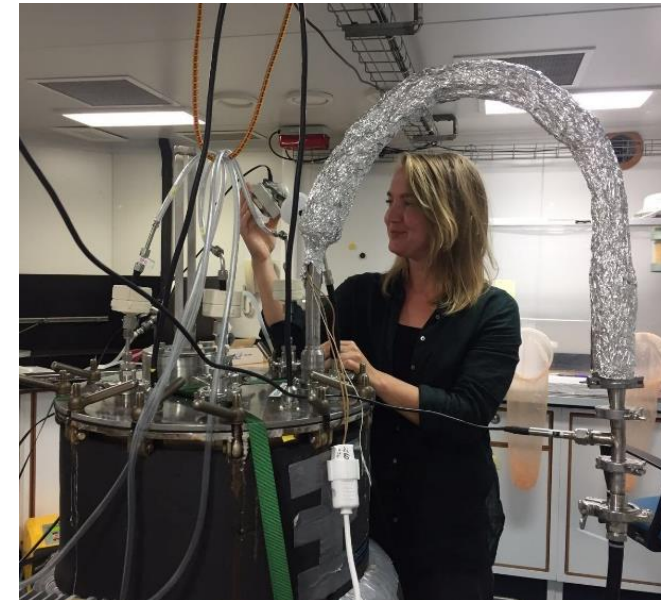
ATMOSPHERIC SCIENCE

Constraining global transport of perfluoroalkyl acids on sea spray aerosol using field measurements

Bo Sha^{1*}, Jana H. Johansson², Matthew E. Salter^{1,3}, Sara M. Blichner¹, Ian T. Cousins¹

SSA EFs for PFAS

- Field-derived EFs $> 100,000$, depending on chain length
- Very similar to in the lab
- Quite constant in experiments
 - Changes in seawater properties (e.g. ionic content and organic matter) did not affect the enrichment much



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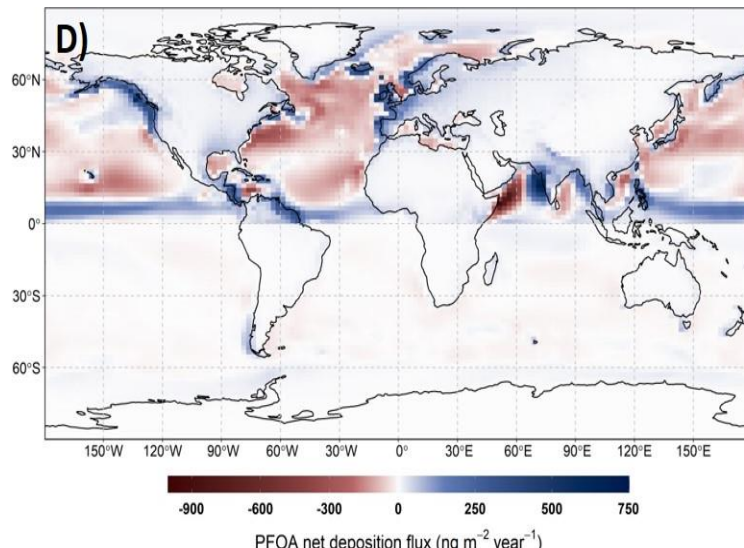
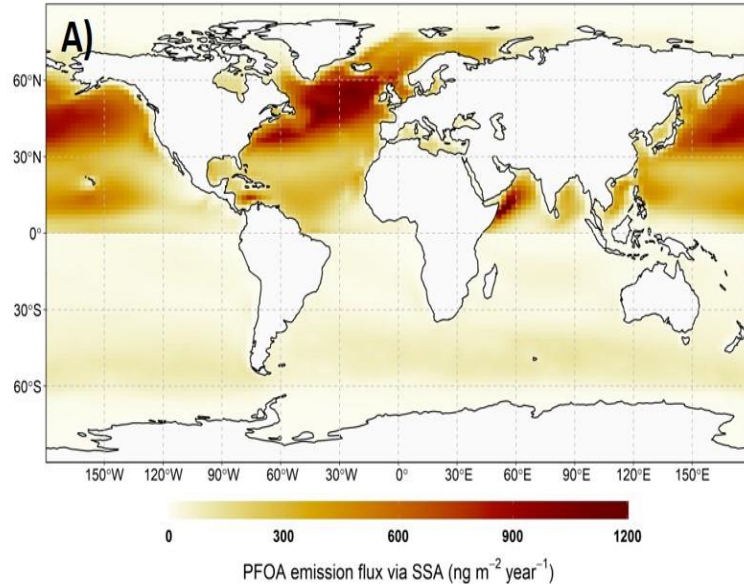
ATMOSPHERIC SCIENCE

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Global modelling

Norwegian Earth System Model version 2 (NorESM2)



- Global ocean emissions
 - 53 (40 – 62) tonnes of PFOA
 - 33 (28 – 35) tonnes of PFOS
- Comparable to other sources of PFOA to air & much greater than all other sources of PFOS
- Coastal areas impacted most by SSA

SCIENCE ADVANCES | RESEARCH ARTICLE

ATMOSPHERIC SCIENCE

Constraining global transport of perfluoroalkyl acids on sea spray aerosol using field measurements

Bo Sha^{1*}, Jana H. Johansson², Matthew E. Salter^{1,3}, Sara M. Blichner¹, Ian T. Cousins¹

Field evidence for SSA transport of PFAS?

- If SSA is an important PFAA source, correlations between SSA tracer ion concentration (Na^+) and PFAA concentration should be observed in aerosol samples collected from coastal areas.
- **Sampling sites**
 - **Andøya** – A remote sampling site located in the Arctic circle. Close to open water (<100 m).
 - **Birkenes** – Located close to populated coastal area in Norway. Far from open water (~20 km).



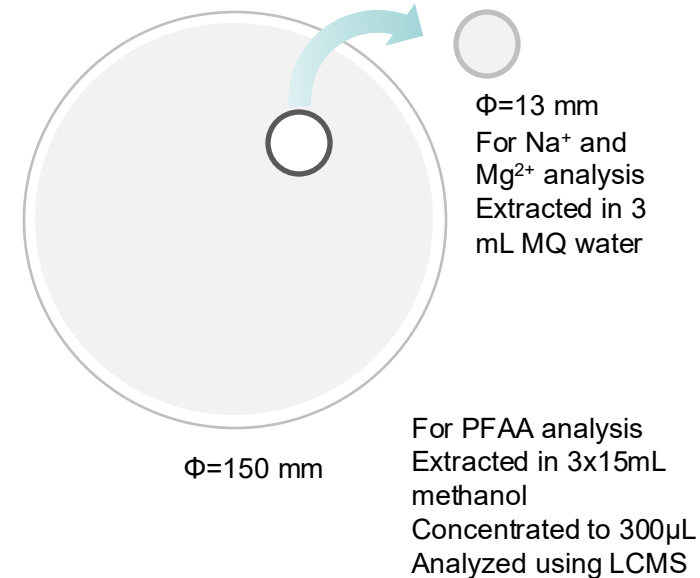
Aerosol sampling at in Norway

- **Sampling**

- Coordinated by colleagues at NILU
- Bulk aerosol sampling using quartz fiber filters (QFFs)
- 48 hours, $\sim 1500 \text{ m}^3$ per sample
- From 2018.04 to 2020.07
- 57 filters from Andøya, 58 filters from Birkenes

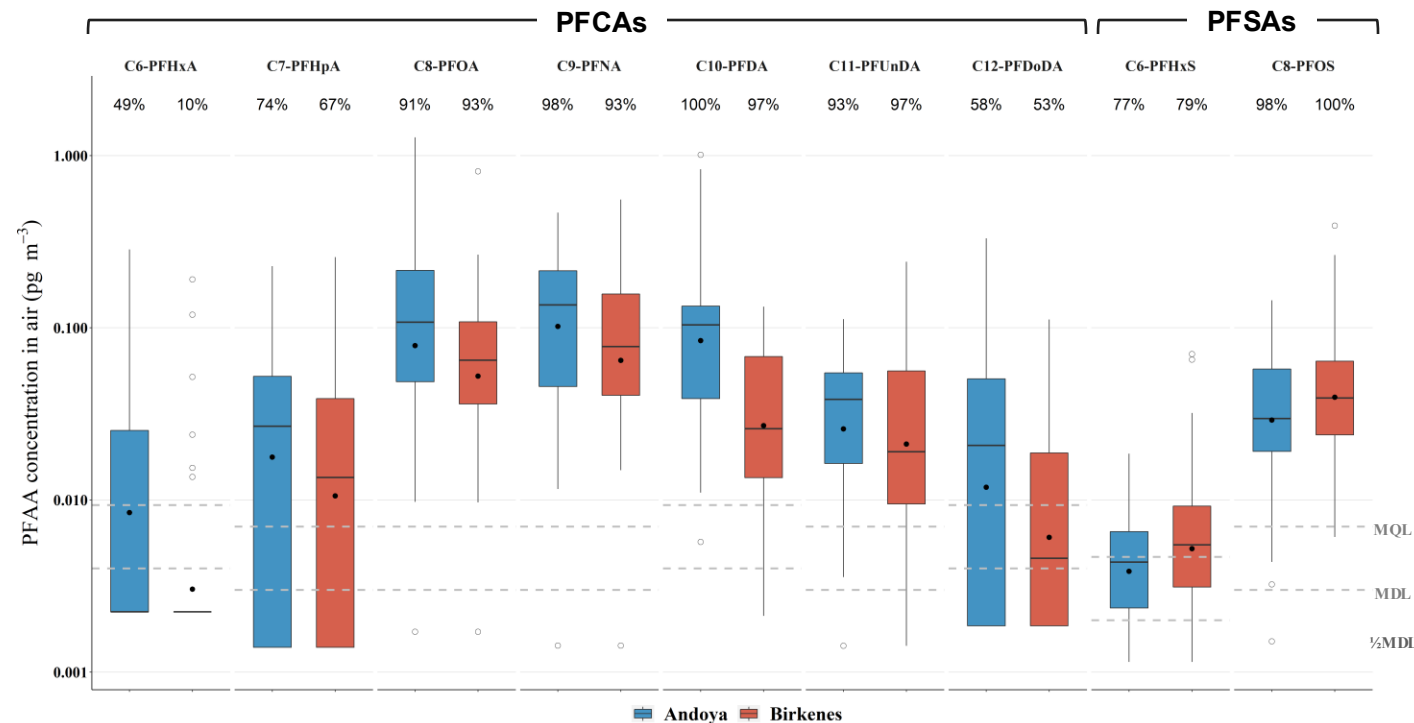
- **Analysis**

- A punch was taken from the filter for Na^+ and Mg^{2+} analysis
- The rest of the filter was analyzed for PFAAs using LC-MS/MS
 - C5 – C12 PFCAs
 - C4, C6 and C8 PFSA



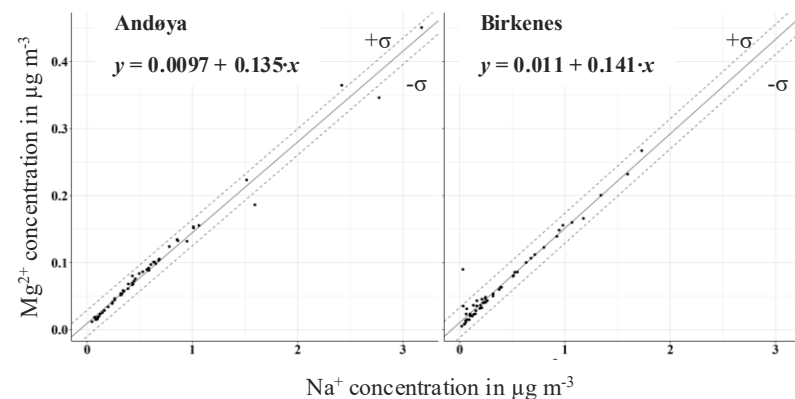
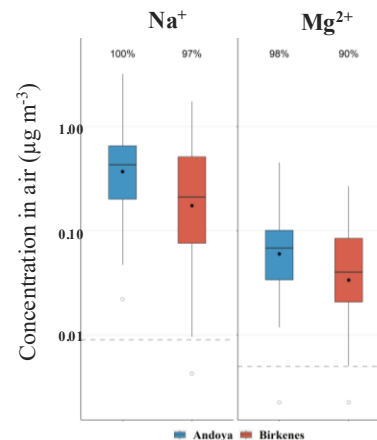
Results – PFAAs

- **ΣPFCAs** median (min – max)
 - Andøya: 0.46 (0.045 – 3.4) pg m^{-3}
 - Birkenes: 0.22 (0.012 – 2.0) pg m^{-3}
- **ΣPFSA**s median (min – max)
 - Andøya: 0.033 (<0.005 – 0.16) pg m^{-3}
 - Birkenes: 0.045 (0.007 – 0.46) pg m^{-3}



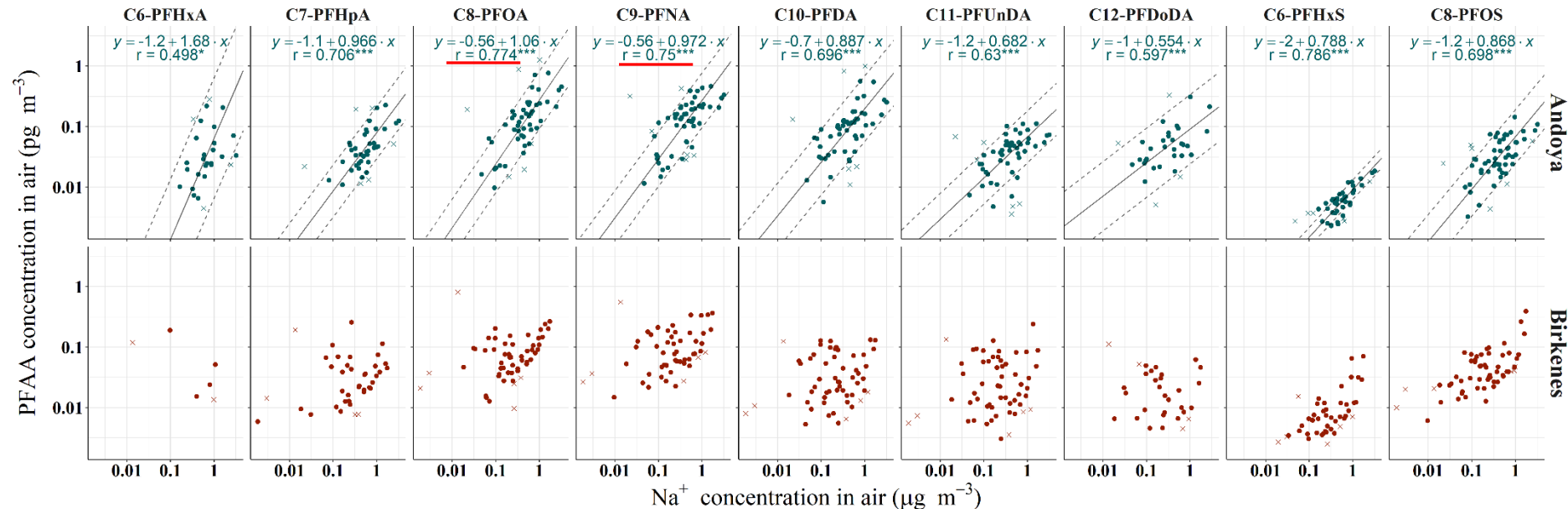
Results – Na⁺ and Mg²⁺

- Na⁺ concentration median (min – max)
 - Andøya: 0.37 (0.02-3.2) $\mu\text{g m}^{-3}$
 - Birkenes: 0.23 (<0.009-1.7) $\mu\text{g m}^{-3}$
- Andøya is more influenced by SSA than Birkenes (higher Na⁺ concentration at Andøya $p < 0.01$)
- Good correlation between Na⁺ and Mg²⁺ concentration ($r > 0.99$, $p < 0.001$)
- Na⁺/Mg²⁺ ratio close to the ratio in seawater (0.119)



Results – Correlations between PFAAs and Na⁺

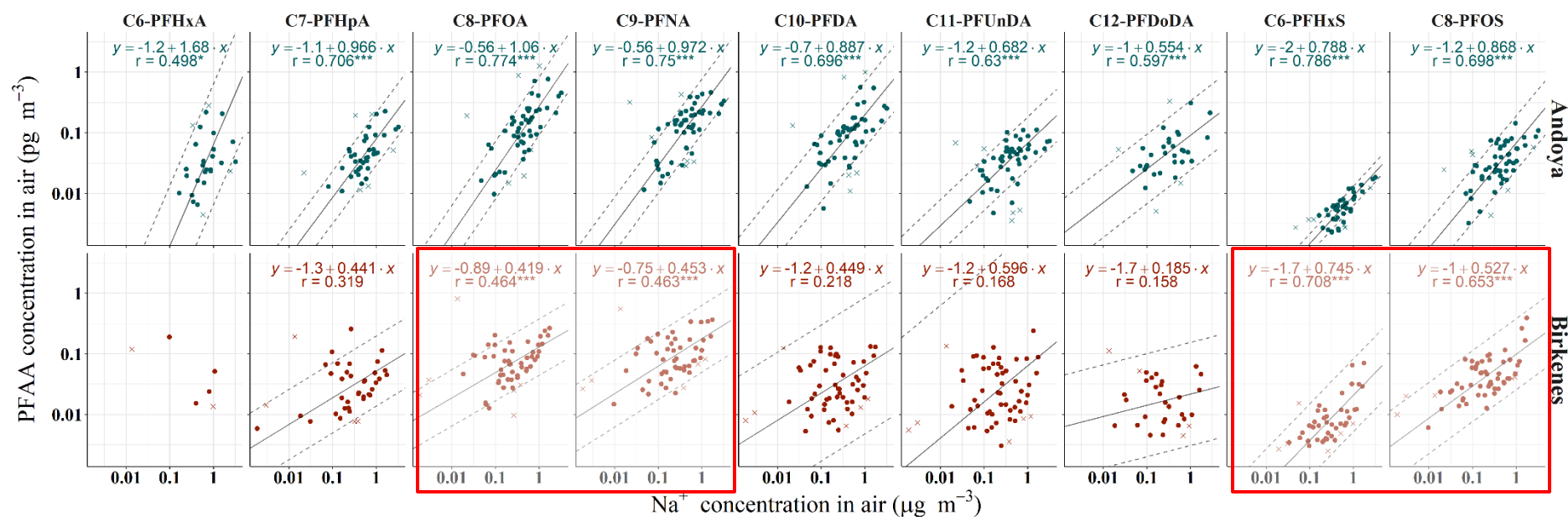
- Andøya
 - Significant correlations ($p < 0.05$) between PFAAs and Na⁺ were observed for both PFCAs and PFSAs
 - Among the PFCAs, PFOA and PFNA have the strongest correlation with Na⁺



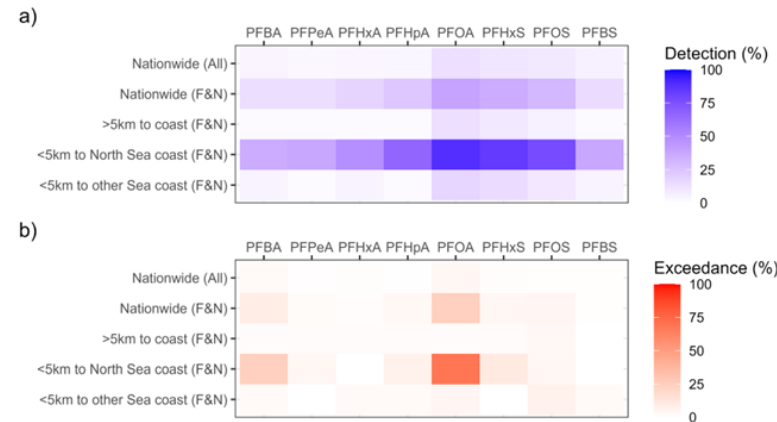
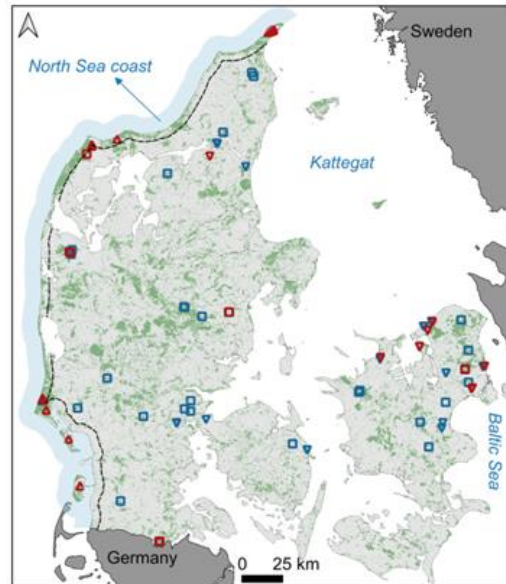
Results – Correlations between PFAAs and Na⁺

- Birkenes

- Correlations with Na⁺ were observed for PFOA, PFNA, PFHxS and PFOS ($p < 0.001$)
- Correlations were weaker than the Andøya samples
 - Less input from SSA (located farther away from coast than Andøya)



Data from Denmark: coastal aquifers



- Public waterworks in Hanstholm, Skagen and Fanø contaminated (2-5 km from sea)
- Groundwater <5 km from coast impacted by diffuse PFAS source
- Long-chain PFAAs dominate



Environmental Science
Advances



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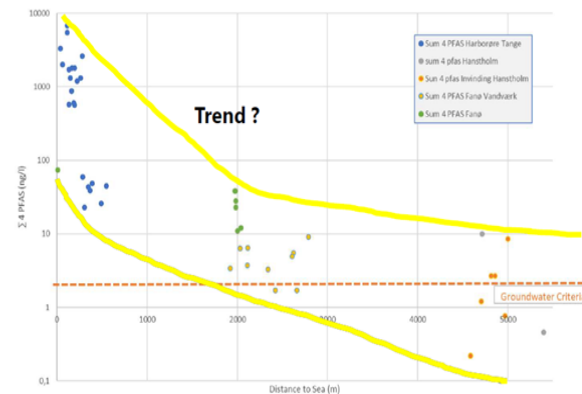
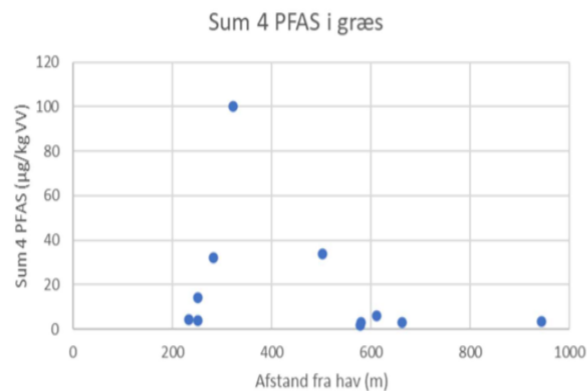
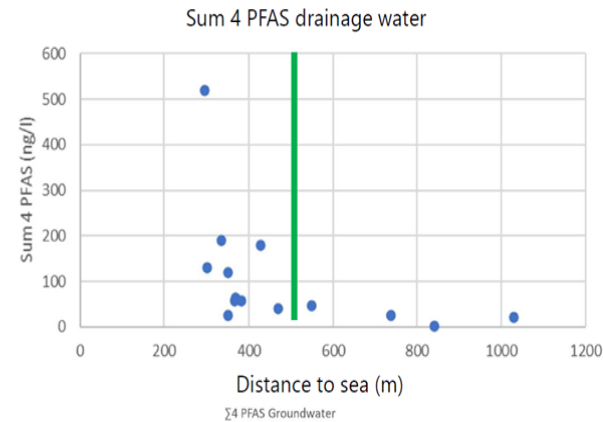
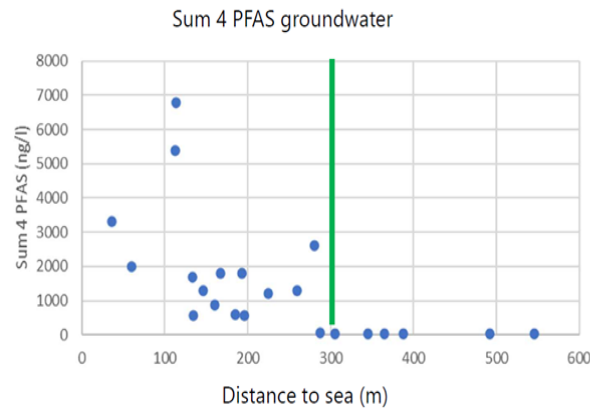
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Sea spray aerosols can be a source of PFAS pollution in coastal aquifers

Cite this: Environ. Sci.: Adv., 2025, 4, 2069

Danish monitoring at coast

- Strong gradient in PFAS in groundwater, drainage water and grass from the sea with distance inland

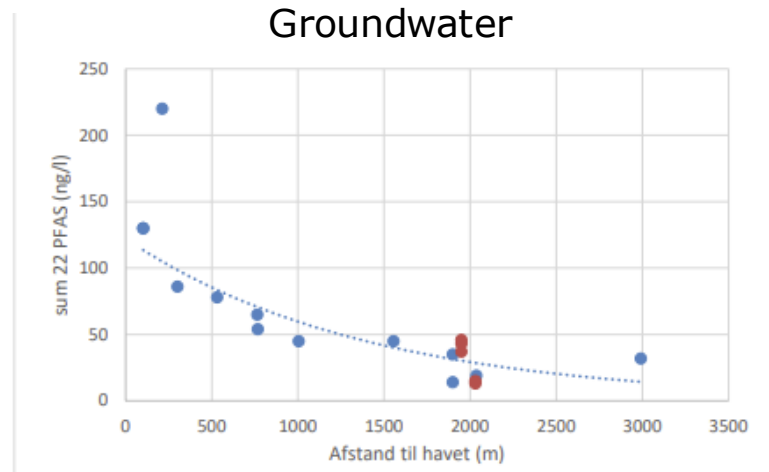


NIRAS

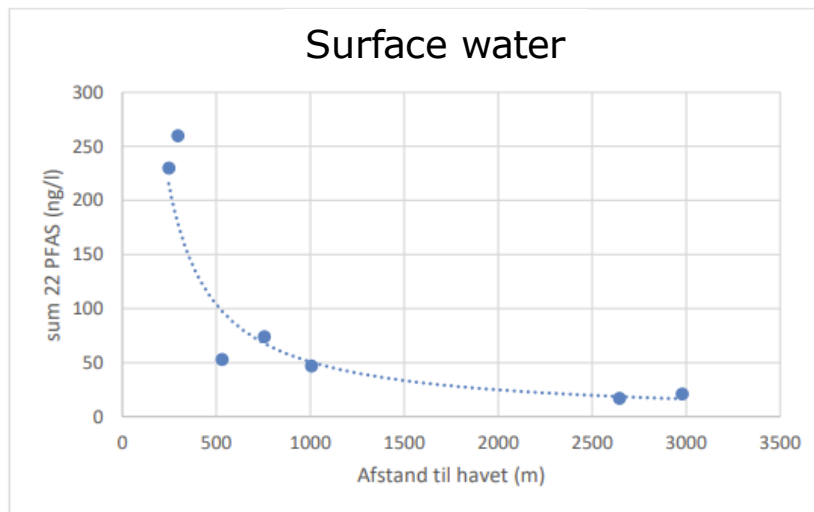


Thyborøn town
and Harboøre
Tange – Lemvig
Municipality-
Denmark

More data from Fanø



Figur 1.1: Indhold af sum af 22 PFAS (ng/l) som funktion af afstand til havet (m) for terrænnært grundvand. De røde prikker på graf med grundvand er målinger foretaget af COWI i 2022 /5/.

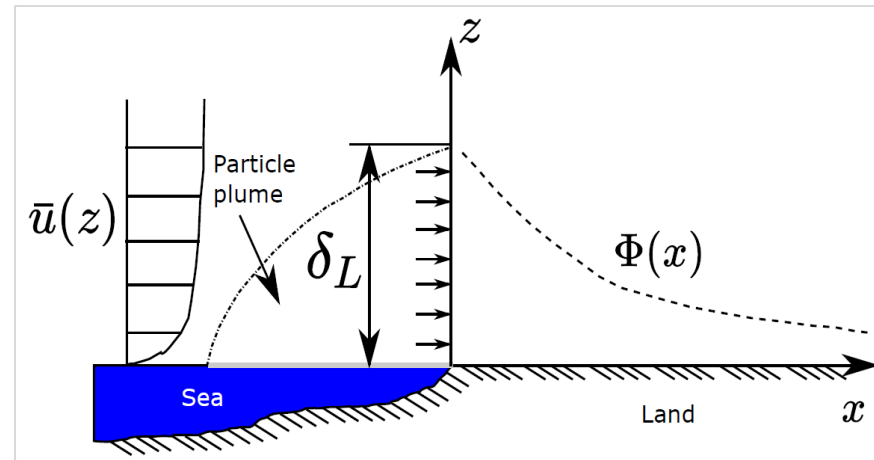
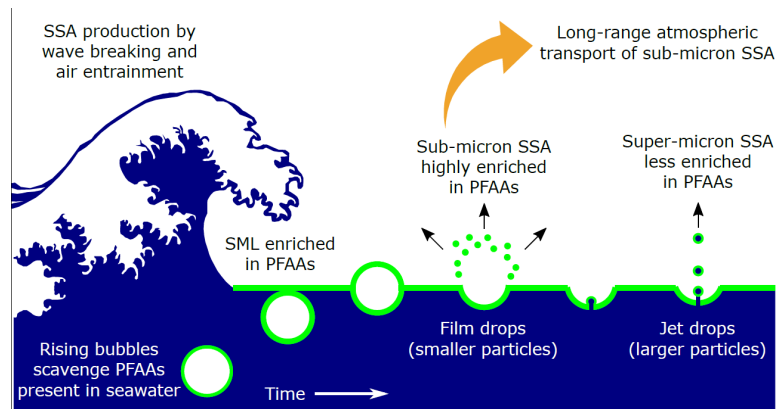


Figur 1.2: Indhold af sum af 22 PFAS (ng/l) som funktion af afstand til havet (m) for overfladevand.

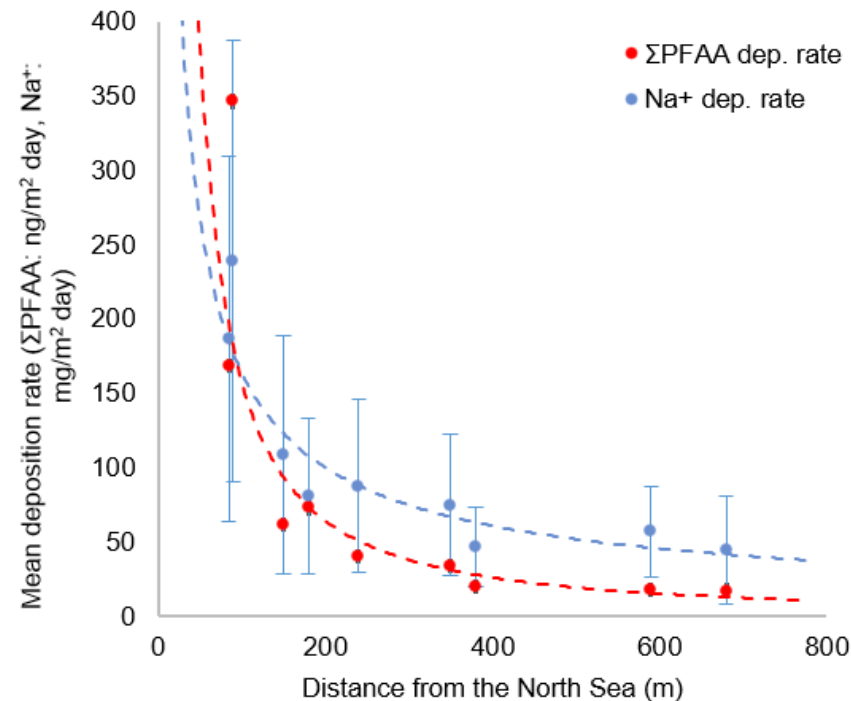
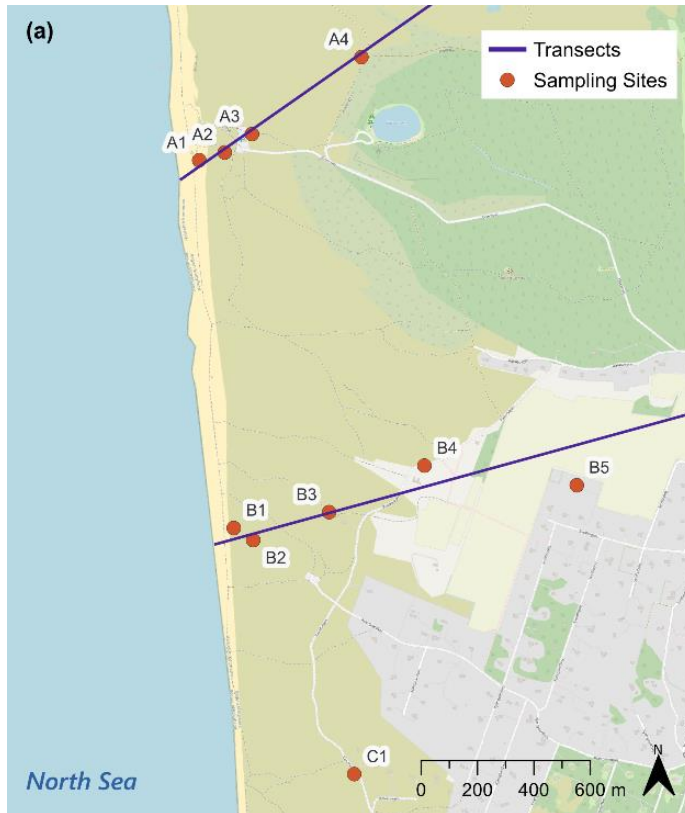


Sea spray aerosols responsible for transport of PFAS inland?

- Known that short-range transport of sea salt causes metal corrosion
- Large particles will be deposited relatively quickly whereas fine particles will be transported hundreds of kilometers inland



Evidence from our bulk deposition measurements



Sampled November 2024, and then continuously from July 2025 to January 2026

Unpublished work of Theresa Döring, PhD student

Conclusions

- Multiple lines of evidence that the sea is a secondary source of PFAAs to land
 - PFAAs highly enriched in foams and sea spray aerosols
 - Sea-inland gradient in PFAA concentrations in multiple media in Denmark
 - Unpublished data suggests similar in Halland, Belgium, Netherlands
 - Correlations between concentrations of PFAAs and seawater tracer ions in air
 - Quantified impacts with models

Implications

- Secondary source that cannot be stopped
 - Continuous cycle (PFAS “boomerang” back to land)
 - Can only wait until PFAS slowly dilute into deep oceans
- Coastal drinking water sources impacted (< 5 km)
 - Cleanup costs?
 - Dune infiltration (Netherlands)
- Coastal farming
 - Move grazing animals?
- Recommendations to avoid contact with contaminated sea foams
- Learn the lesson about persistent synthetic chemicals!

Thank you for your attention!

Acknowledgements

- The work behind this presentation has been performed by the scientists in my research group and at Norwegian Institute for Air Research (NILU)
- Thanks to past and present colleagues: Theresa Döring, Bo Sha, Jana Johansson, Matt Salter, Jon Benskin
- The Swedish Research Councils FORMAS and VR are acknowledged for providing funding