Environmental Science & Technology

pubs.acs.org/est

Perspective

Opposing Effects of Climate Change on the Fate of Persistent and Mobile Contaminants in the Environment

Published as part of Environmental Science & Technology special issue "From Silos to Interconnected Systems: Tackling Complex Environmental Problems Holistically".

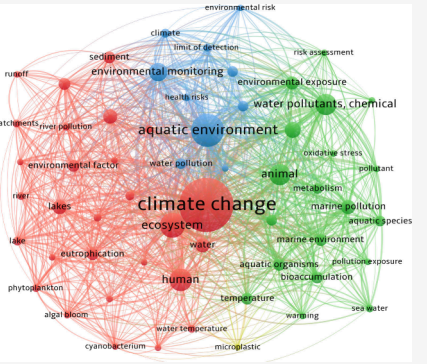
Sanjeeb Mohapatra* and Juliane Hollender

Cite This: *Environ. Sci. Technol.* 2026, 60, 96−105

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: This work reviews the complex interplay between climate change and the fate of persistent mobile (PM) and very persistent very mobile (vPvM) substances, with a particular focus on how rising temperatures, changing precipitation patterns, shifts in pH, and changes in how organic matter concentrations impact these contaminants in the aquatic environment. According to literature research, climate change exerts opposing effects on the persistence (P) and mobility (M) of these substances in the environment. The high uncertainties discussed here underscore the need for comprehensive monitoring, improved process understanding, and appropriate modeling strategies to assess the climate change impacts on PM and vPvM substances.



KEYWORDS: *Climate change, Temperature, Precipitation, Emerging contaminants, PMs, Sorption, Organic matter*

1. INTRODUCTION

Since the 1800s, anthropogenic activities have been the main drivers of climate change,[1] leading to significant environmental consequences as well as impacts on human health, including extreme heat-related mortality in Europe.[2] Concurrently, human activities have contributed to the emergence of emerging micropollutants. Among these, persistent and mobile (PM) substances and very persistent and very mobile (vPvM) substances are particularly concerning due to their long half-life and rapid spread in the environment. A substance is called persistent (P) in fresh or estuarine water if its half-life at 12 °C and pH 4−9 is more than 40 days.[3] For vP compounds, the half-life is 180 days under similar conditions.[3] Similarly, a substance is considered mobile (M) or very mobile (vM) if its organic carbon to water partition coefficient (log K_{OC}) over the pH range of 4−9 is less than 3 or 2, respectively.[4,5] Once released, these substances can travel long distances, recirculate within the water cycle, and even infiltrate drinking water resources.[6] One such PM substance is trifluoroacetic acid (TFA), which has recently gained significant attention due to its persistence and mobility as well as its potential reproductive toxicity.[7,8] Due to their persistence and mobility, forecasting the long-term effects of PM substances is challenging, as their environmental entry and subsequent impacts on ecosystems and human health are often separated by time and distance. Consequently, negative effects may manifest long after and far from the original discharge point, highlighting the need for increased attention to these contaminants, including some substances of very high concern (SVHC), in the context of climate change.

Extensive reviews on the toxic effects of certain PMs, especially for the per- and polyfluoroalkyl substances (PFAS)[9] as well as other notable PMs on human health[10] concluded their toxic effect at concentrations of only a few μg/L or lower. Furthermore, PMs and vPvM substances, including perfluorobutanesulfonic acid (PFBS) and 1,4-dioxane, are regarded under the EU REACH regulation (EC 1907/2006) as posing a level of concern comparable to that of persistent, bioaccumulative, and toxic (PBT) or very persistent and very bioaccumulative (vPvB) substances.[11] However, chronic studies on short-chain PFAS compounds, such as TFA, are rare. The available toxicity data, such as 35-day studies in fish, 21-day studies in *Daphnia*, 90-day studies in rats, and 36-day studies in crop plants, are considered insufficient to extrapolate the potential impacts of lifetime exposure to TFA.[8,12] Similarly, mechanistic data on the toxicity of short-chain perfluorohex-

Received: July 16, 2025
Revised: December 4, 2025
Accepted: December 5, 2025
Published: December 29, 2025

Table 1. Impacts of Opposing Climate Change Effects on the Occurrence, Fate, and Distribution of PMs

	Contaminated-related processes potentially affected			
Climate change impacts	Persistence (Increase)	Mobilty (Increase)	Persistnce (Decrease)	Mobility (Decrease)
		Direct Impacts		
Increased temperature (water, land, atmosphere), frequent heatwaves, longer and more intense summer radiation	Increased persistence in drier soils[57]	Increased contaminant remobilization due to increased solubility in water and release of organic matter-bound trapped contaminants[41,68,80] Long-range transport through increased volatilization[43,66]	Decreased persistence due to increased (biotic, abiotic, photo) degradation of contaminants, but potentially more transformation products.[42,93]	Reduced mobility in drier soils.
Extreme weather events (e.g., floods caused by heavy precipitation)	Dilution of contaminants due to increased translocation and redistribution during heavy precipitation events[63,64,68]	Higher concentrations in water and sediment due to re-mobilization of contaminants in floodplains or low-lying areas as well as input from urban runoff, sewer overflow and flooding of industrial sites, landfills, and farming lands[44,46,63,64]	–	–
Sea level rise combined with wind speed	–	Transfer of contaminants between terrestrial and marine environments, potentially dispersing them and lowering concentrations[51,52] Spreading contaminants over larger areas, whether adsorbed onto plastics or not, to enter previously unaffected areas[51,53]	Decreased persistence due to increased DO level driven by windspeed, leading to accelerated aerobic degradation	–
		Indirect impacts		
Decreased dissolved oxygen levels due to increased temperature	Lake stratification and the creation of more anaerobic conditions decrease aerobic contaminant degradation[42]	–	Increased degradation of substances only degradable under anoxic conditions.	–
Soil/water acidification and alkalinization	–	Remobilization of negatively charged contaminants occurs in an alkaline medium (increased pH) due to reduced sorption[4,59,61]	–	Reduced mobilization of negatively charged contaminants occurs in an acidic medium (reduced pH) due to increased sorption[4,61]
Altered soil/sediment organic matter composition	–	Increased mobilization of contaminants in low organic content medium[59,61]	–	Decreased mobilization of contaminants in high organic content medium[59,61]
Phytoplankton growth due to increased nutrient load and longer light duration	–	Increased mobilization in deeper water layers during seasonal transfer[70,71,73,74]	Decreased persistence through uptake, and biotransformation[8,39]	Decreased mobilization of contaminants due to sorption[72]
Increased forest fires	Formation of more persistent contaminants as well as increased use of persistent firefighting agents[32,34]	(Re-)mobilization and (re)-distribution[34]	Decreased persistence due to thermal degradation of soil organic matter[75]	–
Land degradation (e.g., increased soil erosion)	Increased persistence because erosion reduces microbial degradation and sorption capacity	Re-mobilization and reemission of contaminants between terrestrial and aquatic environments[46]	–	–
Increased agricultural diseases and pests	Increased persistent pesticide and pest control agent use and subsequent emission into the environment[2627]	Increased mobility due to greater chemical loading, runoff, leaching, and cropmediated cycling of residues[26,46]	–	–
Behavioral pattern changes (e.g., animal migration)	Different contaminant exposure changed bioaccumulation and different biovector-based transport of contaminants[29,30,33]	Increased mobility through long-distance transport, trophic transfer, and ecosystem disturbance by animal movement[38,39]	–	–
Human socioeconomic changes and new economic situation	Increased use of new sources of persistent contaminants such as electronic vehicles[35−37]	Re-mobilization and new exposure routes[34,38]	–	–

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

anoic acid (PFHxA) are generally limited, but computational studies suggest that PFHxA may disrupt the endocrine and nervous systems and is associated with changes in kidney and liver weight.[13] For the persistent and mobile azole fungicide, fluconazole (predicted log K_{OC} 1.7[14]), recent research has shown that its indirect photodegradation generates even more persistent transformation products with uncertain health effects.[15]

The inclusion of new hazard classes for PM/vPvM substances in the European Classification Labeling and Packaging (CLP) regulation marks an important first step.[16] However, many PM substances are transformation products and are often not registered.[17] Therefore, suspect screening and nontarget analysis will be particularly important for their ability to detect unknown PM substances and their transformation products. These techniques, when combined with machine learning,[18−20] have already been applied to identify PMs in surface water,[21−23] first-flush urban stormwater,[18] and drinking water.[24] Concentrations up to 2300 ng/L for perfluorobutanoic acid (PFBA) and 2900 ng/L for hexafluorophosphate ion (PF6-) have also been reported in wastewater effluent samples, based on suspect screening conducted across 15 European countries using supercritical fluid chromatography−high-resolution mass spectrometry.[25]

The fate of PM substances in the environment is directly influenced by temperature, pH, and log K_{OC} values, which are all subject to alteration due to climate change. However, a simple search in SCOPUS with the keywords "climate AND change AND impact AND emerging OR persistent OR mobile OR toxic OR contaminants AND aquatic AND environment" resulted in 310 papers, of which only seven contained the word "persistent" (please refer to the graphical abstract and Supporting Information), highlighting knowledge gaps between climate change and PM substances.

Direct climate change impacts such as rising temperatures influence marine and atmospheric temperatures, which lead to extreme weather events, such as floods after heavy precipitation or droughts, decreased ice coverage, and sea level rise (Table 1). Indirect climate change impacts stem from the direct effects and involve environmental parameters such as a changed carbon cycle and erosion but also socio-economic factors. The most relevant ones are listed in Table 1. Both direct and indirect impacts can change the contamination profile of aquatic environments through several processes, complicating the understanding of the fate of PM and vPvM substances. This perspective aims to summarize and structure how climate change can affect the fate of PMs and vPvMs in the aquatic environment through their intrinsic properties and environmental conditions. Based on the identified knowledge gaps, future research needs, including modeling approaches, are suggested in the final section.

2. PM SUBSTANCES EMITTED TO THE ENVIRONMENT AND THEIR BIOACCUMULATION

2.1. Accelerated Emission of PM Substances. As of 2019, the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) database registered 22,400 contaminants, with unique chemical structures identified for 13,405 substances. Among these unique substances, 421 met the PM criteria and 343 met the vPvM criteria.[4] Due to insufficient data, a significant portion, 67%, i.e., 9047 substances in the REACH database, cannot yet be classified under PMT/vPvM criteria.[4] However, many countries have yet to address PM substances adequately. In addition to REACH chemicals, substances that fall under other regulations, such as plant protection products or pharmaceuticals, also fulfill the PM criteria. PM substances belong to various classes, each with various functions: fire retardants (e.g., melamine derivatives), pharmaceuticals (e.g., dapsone, methenamine, diclofenac, ibuprofen), personal care products (e.g., benzophenone), pesticides (e.g., atrazine metabolites, imidacloprid), tire wear chemicals (e.g., 1,3-diphenylguandine), and industrial chemicals (e.g., including many PFAS, benzotriazole, hexafluorophosphate). Further, transformation products are often more polar than their parent compounds and therefore, often also meet PM criteria.[17]

Climate change-induced shifts in temperature and precipitation patterns can create favorable conditions for more frequent and severe pest outbreaks, broader pest distributions, and increased survival rates of insect pests, plant diseases, and invasive species (Figure 1). These escalating threats to

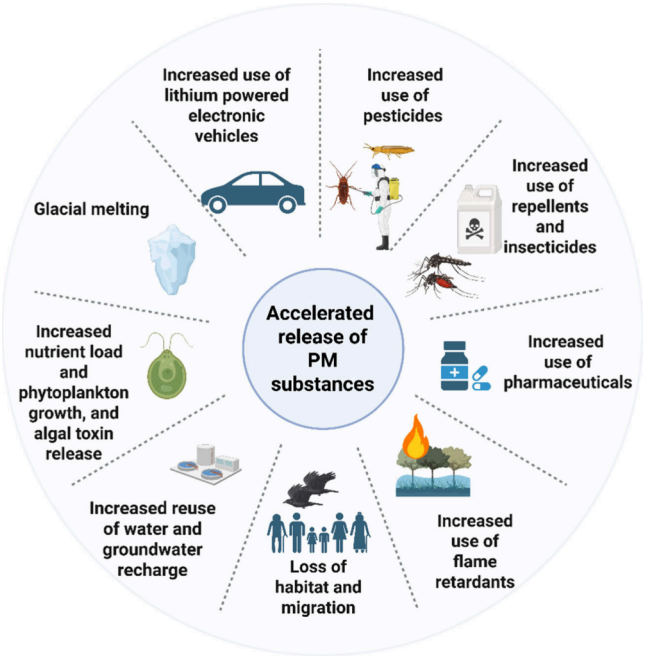


Figure 1. Accelerated use and release of PM substances in various sectors due to climate change.

agriculture, particularly in temperate and subtropical regions, are expected to drive greater reliance on chemical controls,[26] potentially including increased use of restricted or legacy pesticides where effective alternatives remain unavailable, as well as increased reliance on fungicides.[26] Moreover, C−CF_3-containing pesticides can act as precursors of TFA, thereby contributing to its increased release into the environment.[27] Climate-related changes in disease vectors, such as mosquitoes, lice, and mites,[28] may heighten demand for repellents and insecticides. There might also be possibilities of demand for certain pharmaceuticals due to increase in viral diseases driven by climate change.[29] For example, the demand for the antifungal pharmaceutical fluconazole is expected to rise as climate change drives an increase in fungal infections.[30]

In parallel, the rising frequency and severity of wildfires, closely linked to climate change,[31,32] may amplify the demand for flame retardants in building materials, electronics, and firefighting foams (Figure 1). Notably, PFAS-based formula-

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

tions are extensively employed in firefighting foams, with significant surges in application documented during extreme fire events.[33,34] Additional drivers, including stringent fire-safety regulations and infrastructure expansion in fire-prone areas, are expected to sustain or even increase the use of these substances despite regulatory restrictions.[35] Climate change necessitates the shift to clean and sustainable energy infrastructure, such as lithium-powered battery vehicles; however, this transition has also raised concerns about the potential release of certain PFAS compounds like bis-perfluoroalkyl sulfonimides and hexafluorophosphate that are used as electrolytes.[36,37] Ultimately, these PM substances can be released into the environment, further compounding their ecological and human health risks.

2.2. Bioaccumulation of PM Substances. As climate change intensifies water stress, treated wastewater is increasingly being considered for nonpotable applications, such as agricultural irrigation and groundwater recharge. In this context, the accumulation of PM substances in crops and their subsequent transfer through the food chain are of particular concern. Although these substances generally have low bioaccumulation potential, their mobility in water allows them to be taken up by plants and enter the food chain. A recent plant uptake study involving 61 PM substances reported relative uptake into rocket exceeding 10% for 18 compounds, including perfluoropropionic acid (72%), TFA (67%), and tetrafluoroborate (40%).[38] While extensive reviews of PFAS bioaccumulation are available elsewhere,[9,39] climate change-induced water stress, coupled with the increasing use of treated wastewater for agricultural irrigation and groundwater recharge, is likely to elevate the risks of PM accumulation in plants and aquatic organisms, ultimately posing threats to human health at the highest trophic levels. In this regard, despite less classic bioaccumulation in lipid-rich organisms, PM substances can lead to high and continuous concentrations in human bodies.[11]

3. IMPACT OF CLIMATE CHANGE ON THE FATE OF PM SUBSTANCES

3.1. Impact on Persistence. The environmental fate of persistent contaminants is closely linked to their travel time from emission points to water resources. If a contaminant does not persist long enough to endure this travel time, then it is unlikely to pose a major risk. Rising temperatures and heat waves, direct consequences of climate change observed in Europe[40] and beyond, can accelerate the degradation of contaminants by shortening their half-lives, thereby potentially reducing associated risks.[41] In contrast, rising air temperatures, which can decrease dissolved oxygen (DO) levels in water bodies, create more anaerobic conditions that exclude aerobic degradation and increase contaminant persistence. For example, a 5 °C increase in air temperature can reduce DO levels by 1−2 mg/L[42] and subsequently degradation rates. Global simulations indicate that rising temperatures, altered circulation, and sea-ice loss between 1992 and 2015 increased losses of the lighter polychlorinated biphenyl (PCB)-28 from the Arctic, while heavier PCB-153 showed greater stability, likely due to particle sorption.[43] A similar phenomenon is also expected for volatile PM substances, such as 6:2 fluorotelomer alcohol. In general, persistent substances released in temperate and tropical regions undergo global distillation across latitudinal gradients, driven by air−water exchange and deposition processes that are strongly influenced by their volatility and prevailing local temperatures.

While accelerated degradation due to higher temperatures is beneficial, climate-induced increase in heavy precipitation and runoff can counteract this by facilitating more contaminant transport into drinking water sources, bypassing natural barriers, and reducing travel times.[44,45] This scenario is increasingly common, as seen in recent extreme weather events in Gulf Cooperation Council countries. Flooding and combined sewer overflow, coupled with sewage treatment plant failures, raise concerns about persistent substance contamination in drinking water, particularly through cracked pipes.[46,47] Larger seasonal variations in precipitation, expected with climate change, further complicate PM fate by altering their spatial and temporal distribution.[48,49]

Precipitation may not significantly affect DO levels directly; however, changes in wind patterns can have a substantial effect.[42] Shifting wind patterns, expected to vary seasonally on a global scale, will ultimately influence the distribution, fate, and transport of persistent contaminants.[50] For example, wind-driven long-range transport of plastics to the Singapore coast within 72 h of their release from neighboring countries highlights the role of wind in contaminant redistribution.[51−53] Consequently, adsorbed persistent substances may also be readily transported over long distances. Additionally, shifts in wind or temperature can alter lake stratification, impacting DO levels and PM distribution, especially if emissions occur within a single layer.

Beyond temperature, the persistence of substances in sediment or soil is also influenced by climate change-induced shifts in soil and sediment pH, both toward more alkaline and more acidic ranges.[54] For instance, soil acidification in alpine meadows and soil alkalinization in alpine steppes, driven by climate change, have already been documented.[55] Several factors can contribute to soil pH changes, with the biogeochemical cycle playing a key role. Intensified precipitation leads to increased leaching of soil nitrate and metal cations, which in turn causes soil acidification.[56] Additionally, the microbial communities responsible for nitrogen fixation and contaminant metabolism, along with soil temperature and moisture, are also significantly impacted by climate change.[57]

3.2. Impact on Mobility. Climate change also poses challenges to the mobility of contaminants, influenced by intrinsic properties such as log K_{OC}, which depends on pH and organic carbon.[4,58] Climate change is anticipated to cause pH shifts, affecting the mobility of these substances in soil by altering their speciation as well as organic carbon protonation/deprotonation.[59] An increase in pH can reduce the sorption of negatively charged contaminants due to electrostatic repulsion of the more negatively charged organic carbon. Conversely, a decrease in pH, could enhance the sorption of negatively charged contaminants such as anionic PFAS, reducing their mobility.[60] For example, in acidic conditions, variably charged tropical soils, perfluorooctanoic acid (PFOA), or perfluorohexane sulfonate (PFHxS) previously sorbed to soil particles may be mobilized when the soil pH increases.[61] However, log Koc values are not available in the literature for many PM substances and may also vary depending on the soil type. In the absence of K_{OC} values, contaminant mobility is often first approximated using pH-dependent octanol−water distribution (D_{OW}).

Climate-driven shifts in temperature and precipitation also alter sediment organic matter (SOM) characteristics, as

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

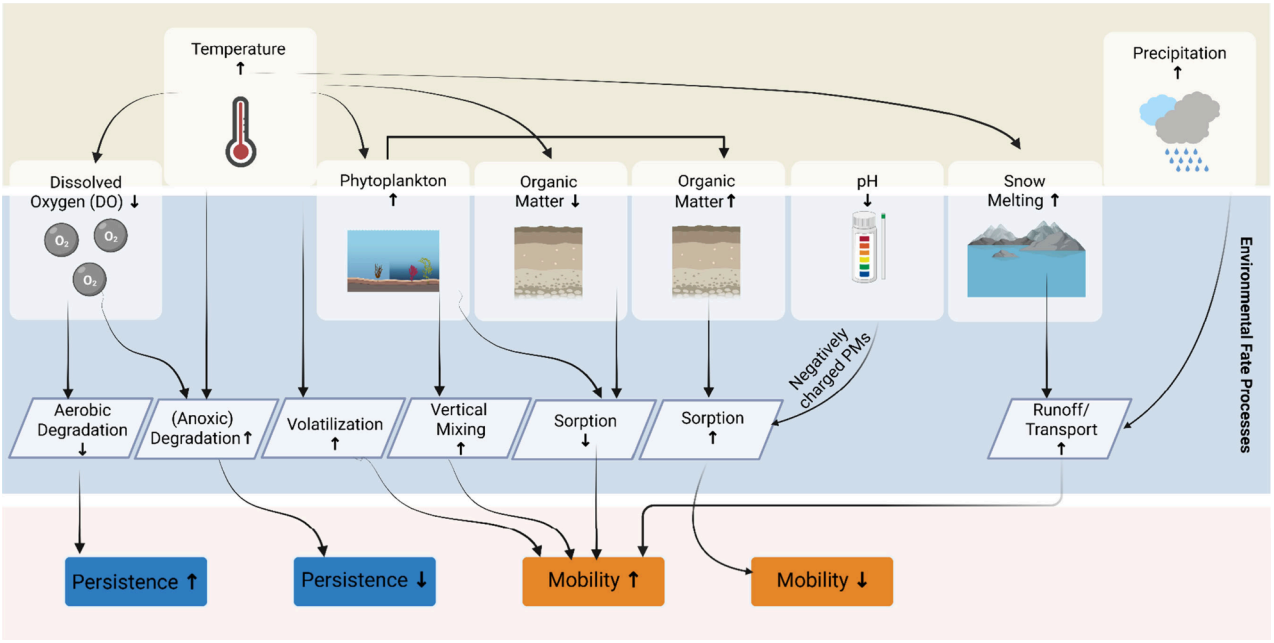


Figure 2. Opposing impact of climate change on PM substances in the aquatic environment as outlined in the text and Table 1 (↑ and ↓ arrows correspond to increase and decrease, respectively).

evidenced by increased total organic carbon, carbon stable isotopes, and fluorescence intensity of protein-like components in the water-extractable organic matter between 1920 and 2000.[62] Contaminants passing through high organic content media, like soil or sediment, sorb more effectively, slowing their mobility compared with low organic matter content. Climate change-induced environments with more anaerobic zones, eutrophication, and correspondingly higher organic fractions in soil and sediment tend to inhibit contaminant mobility. However, heavy precipitation events risk resuspending these contaminants, together with organic matter, redistributing them over previously uncontaminated areas.[63,64] Snowmelt contributes to mobile contaminant cycling. In high-latitude regions, snow deposition can release contaminants during snowmelt, increasing revolatilization and runoff, particularly in rocky, sparsely vegetated mountain areas.[65,66] The release of legacy persistent organic chemicals such as PCBs from melting Alpine glaciers has been shown,[67] but the relevance for PM compounds has not yet been sufficiently studied. This is particularly concerning if snow and lake water contamination in these regions affects pristine areas as well as drinking and agricultural water supplies downstream.[68,69]

Increased nutrient and light availability due to climate change has led to a rise in phytoplankton biomass, which plays a crucial role in biogeochemical cycles that can affect the long-range transport of PMs.[70,71] Phytoplankton biomass can reduce contaminant mobility through adsorption.[72] However, seasonal plankton transfer to deeper water layers can further transport adsorbed contaminants from surface water to deeper regions. Furthermore, rising water temperatures can stimulate primary productivity, which in turn accelerates the transport of contaminants from surface waters to deeper layers and sediments via the 'biological pump' process.[73] Rising water temperature, especially in the ocean, is projected to intensify mesoscale eddy activity, which facilitates the vertical mixing of heat, carbon, and nutrients within the water column, thereby enhancing the downward transport of contaminants into deeper marine environments.[74]

Wildfires can also modify soil organic matter and structure, thereby influencing erosion processes and the transport of PM substances. At elevated temperatures of 600−700 °C, thermal degradation of soil organic carbon[75] will reduce the sorption capacity of soils, thereby increasing the mobility of PM substances. Sediment and water organic matter are even more vulnerable to changes when influenced by runoff with contaminants following wildfires, which are becoming more frequent due to climate-induced temperature increases.[76,77]

Few studies have documented PFAS remobilization associated with ice melt,[78,79] with sediment cores from the Canadian Arctic showing increasing PFAS levels in response to cryosphere melting.[80] Interestingly, a 1 °C rise in Antarctic temperatures is projected to increase soil−vegetation organic carbon pools, along with associated contaminants, by about 25%, effectively turning the region into a significant sink capable of sequestering up to 70 times more contaminants than those remobilized to the atmosphere.[81] This suggests that climate-driven shifts in soil biogeochemistry may enhance the soil storage capacity for the contaminants. In another study, when the temperature rose from 20 to 40 °C, the soil−air partitioning coefficient (K_{SA}) values of volatile PFAS including PFHxS decreased.[82] An increase in relative humidity from 30% to 100% led to approximate 90% reduction in K_{SA} values. By contrast, raising the soil organic carbon content (f_{OC}) from 2% to 8% enhanced K_{SA} values by 4 to 5 times. Overall, higher temperatures, elevated relative humidity, and lower soil organic carbon levels promote the faster diffusion of volatile PFAS such as the 6:2 fluorotelomer alcohol. Future studies should investigate this complex interplay and quantify these remobilization fluxes and sink dynamics for PM substances.

3.3. Modeling the Impact of Climate Change on PM Substances. The occurrence and fate of PMs can be modeled using either process-based or data-driven modeling approaches. Process-based models primarily rely on empirical

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

equations derived from the intrinsic properties of PMs and relevant environmental parameters. In contrast, data-driven models are developed using large data sets and employ machine learning or statistical methods. Comprehensive reviews of modeling techniques addressing the fate and multimedia distribution of emerging contaminants are available.[83,84] While some of these modeling approaches focus on persistent substances in arctic and subarctic regions,[85,86] studies explicitly linking climate change impacts to the fate of PM substances in the aquatic environment remain scarce. This can be attributed to significant uncertainties in key physicochemical properties, such as the acid dissociation constant (pK_a) and log K_{OC}, which play a crucial role in modeling outcomes. Since many PM substances occur in ionized forms, these uncertainties can markedly influence their mobility predictions. Importantly, experimental determinations of pK_a values for PFAS have only recently become available.[87] Recently, Tong et al. proposed a holistic modeling framework that integrates climate data with multiple models, including a rainfall−runoff model, hydrodynamic models for rivers, emission models, and water quality models, to study the impact of climate change on the fate and transport of contaminants.[88] Catchment-scale models that couple 1D hydrological−emission and 3D hydrodynamic−water quality components and take into account climate variables such as precipitation and temperature will be particularly effective in projecting the fate of PM under climate change scenarios if their intrinsic substance properties are also considered.[89] Factors to be considered in a modeling framework mapping the impact of climate change on persistent substances are shown in Figure 2.

4. IMPLICATIONS

As discussed above, the fate of PMs is influenced not only by direct changes of physical processes such as air and water temperature fluctuations and precipitation rates but also significantly by indirect changes of pH, organic carbon, and other parameters discussed above. Additionally, short-term and interannual climatic variability, such as seasonal or year-to-year changes, can have opposing effects on the fate of PMs. An additional component, which was mentioned under section 2.1 but is even more difficult to predict, is socio-economic changes associated with climate change, such as changes in land use with different agricultural crops and different pests,[26] resulting in increased or different pesticide applications (Table 1). Such changes might have an even higher impact on PM occurrence in aquatic systems than the changed fate behavior.

Modeling tools provide a way to navigate these complexities by simulating different scenarios and evaluating potential impacts; however, they suffer from high uncertainties in the input parameters. Rather than modeling each PM individually, representative PM substances can be used to assess how climate change affects their distribution and fate.[90−92] Given the complexity and interconnectivity of these parameters, accurately predicting climate change risks is challenging. Increased monitoring of PMs alongside environmental parameters, as well as targeted laboratory experiments on specific processes, are needed to parametrize the models, verify model results, and finally provide data for more accurate forecasts of the impact of climate change on the fate of PMs.

In conclusion, several key research questions must be addressed to better understand the fate of PMs in the context of climate change: What are the critical physicochemical and biochemical processes that influence the fate of PMs? What are the thresholds for environmental parameters beyond which the persistence and mobility of PM substances are significantly altered? What modeling approaches are most effective for predicting PM fate and transport under different climate scenarios, and which PM substances can be representatively used in such models for different substance classes? Finally, what regulatory frameworks are needed to integrate climate resilience into existing guidelines for the monitoring, safe handling and disposal of PMs,[5] considering especially the long-term effects of PMs in previously pristine or low-impact areas?

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c09667.

A network analysis of literature based on the SCOPUS database (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Sanjeeb Mohapatra − *Department of Water Management, Delft University of Technology, 2628 CN Delft, The Netherlands*; Email: s.mohapatra@tudelft.nl

Author

Juliane Hollender − *Swiss Federal Institute of Aquatic Science and Technology, 8600 Dübendorf, Switzerland; Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, 8092 Zurich, Switzerland*; orcid.org/0000-0002-4660-274X

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.5c09667

Notes

The authors declare no competing financial interest.

Biographies

Sanjeeb Mohapatra is a Marie Skłodowska-Curie Postdoctoral Fellow at Delft University of Technology (TU Delft) in the Department of Water Management. After completing a Ph.D. in Environmental Science and Engineering at the Indian Institute of Technology Bombay (IITB), India, he worked as a postdoctoral research fellow at the National University of Singapore, where he conducted extensive research on targeted and nontargeted analysis of organic micropollutants. His research focuses on the fate, transformation, and treatment of organic micropollutants in natural and engineered aquatic environments, with an emphasis on applications for water reuse. He is particularly interested in the characterization of organic

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

matter, the roles of reactive oxygen species, and radical-driven oxidation−reduction reactions in complex water matrices.

Juliane Hollender is a senior scientist at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) and an adjunct professor for environmental chemistry at the ETH Zürich in the Department Environmental Systems Science. After a Ph.D. in environmental engineering from the Technical University of Berlin (1994), she worked at the RWTH Aachen in Germany before moving to Switzerland in 2005. Her research focuses on the fate of polar organic contaminants in the natural and engineered aquatic environment, using liquid chromatography coupled to high-resolution mass spectrometry as an important methodological tool. She is particularly interested in nontarget screening to get a more comprehensive picture of environmental contamination as well as biological processes that link exposure and effects. Since 2013, she has been a member of the steering committee of the NORMAN network and an associated editor for the journal Environmental Science and Technology since 2023.

■ ACKNOWLEDGMENTS

The first author is supported by the European Union (Grant agreement ID: 101108414). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible.

■ REFERENCES

(1) Lynas, M.; Houlton, B. Z.; Perry, S. Greater than 99% Consensus on Human Caused Climate Change in the Peer-Reviewed Scientific Literature. *Environmental Research Letters* **2021**, *16* (11), No. 114005.

(2) Gallo, E.; Quijal-Zamorano, M.; Méndez Turrubiates, R. F.; Tonne, C.; Basagaña, X.; Achebak, H.; Ballester, J. Heat-Related Mortality in Europe during 2023 and the Role of Adaptation in Protecting Health. *Nature Medicine 2024* **2024**, *30*, 3101−3105.

(3) Hale, S. E.; Neumann, M.; Schliebner, I.; Schulze, J.; Averbeck, F. S.; Castell-Exner, C.; Collard, M.; Drmač, D.; Hartmann, J.; Hofman-Caris, R.; Hollender, J.; de Jonge, M.; Kullick, T.; Lennquist, A.; Letzel, T.; Nödler, K.; Pawlowski, S.; Reineke, N.; Rorije, E.; Scheurer, M.; Sigmund, G.; Timmer, H.; Trier, X.; Verbruggen, E.; Arp, H. P. H. Getting in Control of Persistent, Mobile and Toxic (PMT) and Very Persistent and Very Mobile (VPvM) Substances to Protect Water Resources: Strategies from Diverse Perspectives. *Environ. Sci. Eur.* **2022**, *34* (1), 1−24.

(4) Arp, H. P. H.; Hale, S. REACH: Guidance and Methods for the Identification and Assessment of PMT/VPvM Substances, 2023. *Umweltbundesamt*. https://www.umweltbundesamt.de/en/publikationen/reach-guidance-methods-for-the-identification (accessed 2024−08−27).

(5) *Guidance on the Application of the CLP Criteria*; ECHA: Helsinki, 2024.

(6) Neuwald, I. J.; Hübner, D.; Wiegand, H. L.; Valkov, V.; Borchers, U.; Nödler, K.; Scheurer, M.; Hale, S. E.; Arp, H. P. H.; Zahn, D. Occurrence, Distribution, and Environmental Behavior of Persistent, Mobile, and Toxic (PMT) and Very Persistent and Very Mobile (VPvM) Substances in the Sources of German Drinking Water. *Environ. Sci. Technol.* **2022**, *56* (15), 10857−10867.

(7) Adlunger, K.; et al. Reducing Chemical Inputs into Water Bodies − Trifluoroacetate (TFA) as a Persistent and Mobile Substance with Many Sources, 2021. Federal Environment Agency. https://www.umweltbundesamt.de/publikationen/chemikalieneintrag-in-gewaesser-vermindern (accessed 2025−09−24).

(8) Arp, H. P. H.; Gredelj, A.; Glüge, J.; Scheringer, M.; Cousins, I. T. The Global Threat from the Irreversible Accumulation of Trifluoroacetic Acid (TFA). *Environ. Sci. Technol.* **2024**, *58* (45), 19925−19935.

(9) Brunn, H.; Arnold, G.; Körner, W.; Rippen, G.; Steinhäuser, K. G.; Valentin, I. PFAS: Forever Chemicals—Persistent, Bioaccumulative and Mobile. Reviewing the Status and the Need for Their Phase out and Remediation of Contaminated Sites. *Environ. Sci. Eur.* **2023**, *35* (1), 1−50.

(10) Kim, D. H.; Ait Bamai, Y.; Belova, L.; Bessems, J.; Poma, G.; Covaci, A. Human Exposure to Persistent and Mobile Chemicals: A Review of Sources, Internal Levels and Health Implications. *Science of The Total Environment* **2023**, *893*, No. 164764.

(11) Hale, S. E.; Arp, H. P. H.; Schliebner, I.; Neumann, M. Persistent, Mobile and Toxic (PMT) and Very Persistent and Very Mobile (VPvM) Substances Pose an Equivalent Level of Concern to Persistent, Bioaccumulative and Toxic (PBT) and Very Persistent and Very Bioaccumulative (VPvB) Substances under REACH. *Environ. Sci. Eur.* **2020**, *32* (1), 1−15.

(12) Registration Dossier for Trifluoroacetic Acid. *ECHA*. https://echa.europa.eu/lv/registration-dossier/-/registered-dossier/5203/6/4/1 (accessed 2025−09−24).

(13) Kreychman, M.; Ivantsova, E.; Lu, A.; Bisesi, J. H.; Martyniuk, C. J. A Comparative Review of the Toxicity Mechanisms of Perfluorohexanoic Acid (PFHxA) and Perfluorohexanesulphonic Acid (PFHxS) in Fish. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology* **2024**, *279*, No. 109874.

(14) Fluconazole Env. Fate/Transport. *U.S. EPA*. https://comptox.epa.gov/dashboard/chemical/env-fate-transport/DTXSID3020627 (accessed 2025−09−24).

(15) Fahy, W. D.; Zhang, Z.; Wang, S.; Li, L.; Mabury, S. A. Environmental Fate of the Azole Fungicide Fluconazole and Its Persistent and Mobile Transformation Product 1,2,4-Triazole. *Environ. Sci. Technol.* **2025**, *59* (6), 3239−3251.

(16) Mohr, T.; Schliebner, I.; Neumann, M.; Oules, L.; Arp, H. P. H.; Hale, S. E. Progress in European Chemicals Policy to Support the Protection of the Environment and Human Health from Persistent, Mobile and Toxic and Very Persistent and Very Mobile Substances. *Environ. Sci. Eur.* **2024**, *36* (1), 1−11.

(17) Zahn, D.; Arp, H. P. H.; Fenner, K.; Georgi, A.; Hafner, J.; Hale, S. E.; Hollender, J.; Letzel, T.; Schymanski, E. L.; Sigmund, G.; Reemtsma, T. Should Transformation Products Change the Way We Manage Chemicals? *Environ. Sci. Technol.* **2024**, *58* (18), 7710−7718.

(18) Santana-Viera, S.; Labad, F.; Pintado-Herrera, M. G.; Montemurro, N.; Teixidó, M.; Lara-Martín, P. A.; Pérez, S. Comprehensive HRMS-Screening for Persistent, Mobile, and Toxic Compounds in First Flush Urban Stormwater. *NPJ. Clean Water* **2025**, *8* (1), 1−8.

(19) Wang, H.; Liu, W.; Chen, J.; Ji, S. Transfer Learning with a Graph Attention Network and Weighted Loss Function for Screening of Persistent, Bioaccumulative, Mobile, and Toxic Chemicals. *Environ. Sci. Technol.* **2025**, *59* (1), 578−590.

(20) Han, M.; Jin, B.; Liang, J.; Huang, C.; Arp, H. P. H. Developing Machine Learning Approaches to Identify Candidate Persistent, Mobile and Toxic (PMT) and Very Persistent and Very Mobile

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

(VPvM) Substances Based on Molecular Structure. *Water Res.* **2023**, *244*, No. 120470.
(21) Fernández-García, A.; Martínez-Piernas, A. B.; Moreno-González, D.; Gilbert-López, B.; García-Reyes, J. F. Chemical Profiling of Organic Contaminants in Rural Surface Waters Combining Target and Non-Target LC-HRMS/MS Analysis. *Science of The Total Environment* **2024**, *954*, No. 176587.
(22) Zahn, D.; Mucha, P.; Zilles, V.; Touffet, A.; Gallard, H.; Knepper, T. P.; Frömel, T. Identification of Potentially Mobile and Persistent Transformation Products of REACH-Registered Chemicals and Their Occurrence in Surface Waters. *Water Res.* **2019**, *150*, 86−96.
(23) Neuwald, I.; Muschket, M.; Zahn, D.; Berger, U.; Seiwert, B.; Meier, T.; Kuckelkorn, J.; Strobel, C.; Knepper, T. P.; Reemtsma, T. Filling the Knowledge Gap: A Suspect Screening Study for 1310 Potentially Persistent and Mobile Chemicals with SFC- and HILIC-HRMS in Two German River Systems. *Water Res.* **2021**, *204*, No. 117645.
(24) Hartmann, J.; Rorije, E.; Wassenaar, P. N. H.; Verbruggen, E. Screening and Prioritising Persistent, Mobile and Toxic Chemicals: Development and Application of a Robust Scoring System. *Environ. Sci. Eur.* **2023**, *35* (1), 1−15.
(25) Tisler, S.; Zweigle, J.; Gotil, M. K.; Finckh, S.; Brack, W.; Braxmaier, E.-M.; Meyer, C.; Hollender, J.; Kosjek, T.; Schymanski, E. L.; Larsson, P.; Kärrman, A.; Selin, E.; Elabbadi, D.; Elliss, H.; Kasprzyk-Hordern, B.; Boogaerts, T.; Covaci, A.; Oberacher, H.; Quintana, H. F.; Lai, F. Y.; Ahrens, L.; Assoumani, A.; Béen, F.; Christensen, J. H. Nontarget and Suspect Screening of Fluorinated Ionic Liquids and PFAS in European Wastewaters Using Supercritical Fluid Chromatography. *Environ. Sci. Technol.* **2025**, *59*, 21300.
(26) Yang, Y.; Tilman, D.; Jin, Z.; Smith, P.; Barrett, C. B.; Zhu, Y. G.; Burney, J.; D'Odorico, P.; Fantke, P.; Fargione, J.; Finlay, J. C.; Rulli, M. C.; Sloat, L.; Jan van Groenigen, K.; West, P. C.; Ziska, L.; Michalak, A. M.; Lobell, D. B.; Clark, M.; Colquhoun, J.; Garg, T.; Garrett, K. A.; Geels, C.; Hernandez, R. R.; Herrero, M.; Hutchison, W. D.; Jain, M.; Jungers, J. M.; Liu, B.; Mueller, N. D.; Ortiz-Bobea, A.; Schewe, J.; Song, J.; Verheyen, J.; Vitousek, P.; Wada, Y.; Xia, L.; Zhang, X.; Zhuang, M. Climate Change Exacerbates the Environmental Impacts of Agriculture. *Science* **2024**, *385* (6713), No. eadn3747.
(27) Joerss, H.; Freeling, F.; van Leeuwen, S.; Hollender, J.; Liu, X.; Nödler, K.; Wang, Z.; Yu, B.; Zahn, D.; Sigmund, G. Pesticides Can Be a Substantial Source of Trifluoroacetate (TFA) to Water Resources. *Environ. Int.* **2024**, *193*, No. 109061.
(28) Rulli, M. C.; D'Odorico, P.; Galli, N.; John, R. S.; Muylaert, R. L.; Santini, M.; Hayman, D. T. S. Land Use Change and Infectious Disease Emergence. *Reviews of Geophysics* **2025**, *63* (2), No. e2022RG000785.
(29) Mohapatra, S.; Menon, N. G. Factors Responsible for the Emergence of Novel Viruses: An Emphasis on SARS-CoV-2. *Curr. Opin Environ. Sci. Health* **2022**, *27*, No. 100358.
(30) Seidel, D.; Wurster, S.; Jenks, J. D.; Sati, H.; Gangneux, J. P.; Egger, M.; Alastruey-Izquierdo, A.; Ford, N. P.; Chowdhary, A.; Sprute, R.; Cornely, O.; Thompson, G. R.; Hoenigl, M.; Kontoyiannis, D. P. Impact of Climate Change and Natural Disasters on Fungal Infections. *Lancet Microbe* **2024**, *5* (6), e594−e605.
(31) El Garroussi, S.; Di Giuseppe, F.; Barnard, C.; Wetterhall, F. Europe Faces up to Tenfold Increase in Extreme Fires in a Warming Climate. *NPJ. Clim Atmos Sci.* **2024**, *7* (1), 1−11.
(32) Chang, D. Y.; Jeong, S.; Park, C. E.; Park, H.; Shin, J.; Bae, Y.; Park, H.; Park, C. R. Unprecedented Wildfires in Korea: Historical Evidence of Increasing Wildfire Activity Due to Climate Change. *Agric For Meteorol* **2024**, *348*, No. 109920.
(33) Morrison, C.; Grogan, L. F.; Clemann, N.; Lanctôt, C. Impacts of Fire-Fighting Chemicals on Native Fauna and Ecosystems in Australia: Identification of Key Knowledge Gaps and Research Priorities. *Environ. Manage* **2025**, *75* (6), 1559−1570.
(34) Wang, M.; Kinyua, J.; Jiang, T.; Sedlak, M.; McKee, L. J.; Fadness, R.; Sutton, R.; Park, J. S. Suspect Screening and Chemical Profile Analysis of Storm-Water Runoff Following 2017 Wildfires in Northern California. *Environ. Toxicol. Chem.* **2022**, *41* (8), 1824−1837.
(35) Flame Retardant Chemicals Market is projected to grow from $6.1 billion in 2025. *BCC Research*. https://www.bccresearch.com/pressroom/chm/flame-retardant-chemicals-market-is-projected-to-grow-from-$61-billion-in-2025 (accessed 2025−09−13).
(36) Guelfo, J. L.; Ferguson, P. L.; Beck, J.; Chernick, M.; Doria-Manzur, A.; Faught, P. W.; Flug, T.; Gray, E. P.; Jayasundara, N.; Knappe, D. R. U.; Joyce, A. S.; Meng, P.; Shojaei, M. Lithium-Ion Battery Components Are at the Nexus of Sustainable Energy and Environmental Release of per- and Polyfluoroalkyl Substances. *Nat. Commun.* **2024**, *15* (1), 1−13.
(37) Rensmo, A.; Savvidou, E. K.; Cousins, I. T.; Hu, X.; Schellenberger, S.; Benskin, J. P. Lithium-Ion Battery Recycling: A Source of per- and Polyfluoroalkyl Substances (PFAS) to the Environment? *Environ. Sci. Process Impacts* **2023**, *25* (6), 1015−1030.
(38) Seelig, A. H.; Junghans, V.; Reemtsma, T.; Zahn, D. Plant Uptake of Persistent and Mobile Chemicals in Rocket (Eruca Sativa)—A Greenhouse Study on Agricultural Wastewater Reuse. *Environ. Sci. Technol.* **2025**, *59* (18), 9265−9274.
(39) Gkika, I. S.; Arie Vonk, J.; ter Laak, T. L.; van Gestel, C. A. M.; Dijkstra, J.; Groffen, T.; Bervoets, L.; Kraak, M. H. S. Strong Bioaccumulation of a Wide Variety of PFAS in a Contaminated Terrestrial and Aquatic Ecosystem. *Environ. Int.* **2025**, *202*, No. 109629.
(40) Khodayar Pardo, S.; Paredes-Fortuny, L. Uneven Evolution of Regional European Summer Heatwaves under Climate Change. *Weather Clim Extrem* **2024**, *43*, No. 100648.
(41) Brunn, H.; Arnold, G.; Körner, W.; Rippen, G.; Steinhäuser, K. G.; Valentin, I. PFAS: Forever Chemicals—Persistent, Bioaccumulative and Mobile. Reviewing the Status and the Need for Their Phase out and Remediation of Contaminated Sites. *Environmental Sciences Europe 2023 35:1* **2023**, *35* (1), 1−50.
(42) Koue, J. Assessing the Impact of Climate Change on Dissolved Oxygen Using a Flow Field Ecosystem Model That Takes into Account the Anaerobic and Aerobic Environment of Bottom Sediments. *Acta Geochimica* **2025**, *44*, 11−22.
(43) Wagner, C. C.; Amos, H. M.; Thackray, C. P.; Zhang, Y.; Lundgren, E. W.; Forget, G.; Friedman, C. L.; Selin, N. E.; Lohmann, R.; Sunderland, E. M. A Global 3-D Ocean Model for PCBs: Benchmark Compounds for Understanding the Impacts of Global Change on Neutral Persistent Organic Pollutants. *Global Biogeochem Cycles* **2019**, *33* (3), 469−481.
(44) Gray, L. C.; Zhao, L.; Stillwell, A. S. Impacts of Climate Change on Global Total and Urban Runoff. *J. Hydrol (Amst)* **2023**, *620*, No. 129352.
(45) Sun, P.; Zou, Y.; Yao, R.; Ma, Z.; Bian, Y.; Ge, C.; Lv, Y. Compound and Successive Events of Extreme Precipitation and Extreme Runoff under Heatwaves Based on CMIP6Models. *Science of The Total Environment* **2023**, *878*, No. 162980.
(46) Aga, D. S.; Samara, F.; Dronjak, L.; Kanan, S.; Mortula, M. M.; Vahapoglu, L. Rising Water, Rising Risks: The Hidden Dangers of Emerging Contaminants in Climate-Intensified Storms. *ACS ES and T Water* **2024**, *4* (7), 2785−2788.
(47) Mohapatra, S.; Sargaonkar, A.; Labhasetwar, P. K. P. K. Distribution Network Assessment Using EPANET for Intermittent and Continuous Water Supply. *Water Resources Management* **2014**, *28* (11), 3745−3759.
(48) Mohapatra, S.; Menon, N. G.; Padhye, L. P.; Tatiparti, S. S. V.; Mukherji, S. *Natural Attenuation of Pharmaceuticals in the Aquatic Environment and Role of Phototransformation*, 1st ed.; Kumar, M., Snow, D. D., Honda, R., Mukherjee, S., Eds.; Springer Singapore: Singapore, 2021. DOI: 10.1007/978-981-15-4599-3_3.
(49) Mohapatra, S.; Yutao, L.; Goh, S. G.; Ng, C.; Luhua, Y.; Tran, N. H.; Gin, K. Y.-H. Quaternary Ammonium Compounds of Emerging Concern: Classification, Occurrence, Fate, Toxicity and Antimicrobial Resistance. *J. Hazard Mater.* **2023**, *445*, No. 130393.

(50) Chemke, R.; Coumou, D. Human Influence on the Recent Weakening of Storm Tracks in Boreal Summer. *NPJ. Clim Atmos Sci.* **2024**, *7* (1), 1−8.
(51) Tong, X.; Jong, M. C.; Zhang, J.; You, L.; Gin, K. Y. H. Modelling the Spatial and Seasonal Distribution, Fate and Transport of Floating Plastics in Tropical Coastal Waters. *J. Hazard Mater.* **2021**, *414*, No. 125502.
(52) Tong, X.; Mohapatra, S.; Zhang, J.; Tran, N. H.; You, L.; He, Y.; Gin, K. Y. H. Source, Fate, Transport and Modelling of Selected Emerging Contaminants in the Aquatic Environment: Current Status and Future Perspectives. *Water Res.* **2022**, *217*, No. 118418.
(53) Rai, P. K.; Sonne, C.; Brown, R. J. C.; Younis, S. A.; Kim, K. H. Adsorption of Environmental Contaminants on Micro- and Nano-Scale Plastic Polymers and the Influence of Weathering Processes on Their Adsorptive Attributes. *J. Hazard Mater.* **2022**, *427*, No. 127903.
(54) Saalidong, B. M.; Aram, S. A.; Otu, S.; Lartey, P. O. Examining the Dynamics of the Relationship between Water PH and Other Water Quality Parameters in Ground and Surface Water Systems. *PLoS One* **2022**, *17* (1), e0262117.
(55) Sun, W.; Li, S.; Zhang, G.; Fu, G.; Qi, H.; Li, T. Effects of Climate Change and Anthropogenic Activities on Soil PH in Grassland Regions on the Tibetan Plateau. *Glob Ecol Conserv* **2023**, *45*, No. e02532.
(56) Lucas, R. W.; Klaminder, J.; Futter, M. N.; Bishop, K. H.; Egnell, G.; Laudon, H.; Högberg, P. A Meta-Analysis of the Effects of Nitrogen Additions on Base Cations: Implications for Plants, Soils, and Streams. *For Ecol Manage* **2011**, *262* (2), 95−104.
(57) Wen, J.; Qin, R.; Zhang, S.; Yang, X.; Xu, M. Effects of Long-Term Warming on the Aboveground Biomass and Species Diversity in an Alpine Meadow on the Qinghai-Tibetan Plateau of China. *J. Arid Land* **2020**, *12* (2), 252−266.
(58) Arp, H. P. H.; Hale, S. REACH: Guidance and Methods for the Identification and Assessment of PMT/VPvM Substances, 2019. *Umweltbundesamt*. https://www.umweltbundesamt.de/en/publikationen/reach-guidance-methods-for-the-identification (accessed 2024−08−27).
(59) Tülp, H. C.; Fenner, K.; Schwarzenbach, R. P.; Goss, K. U. PH-Dependent Sorption of Acidic Organic Chemicals to Soil Organic Matter. *Environ. Sci. Technol.* **2009**, *43* (24), 9189−9195.
(60) Liu, P.; Wu, X.; Liu, H.; Wang, H.; Lu, K.; Gao, S. Desorption of Pharmaceuticals from Pristine and Aged Polystyrene Microplastics under Simulated Gastrointestinal Conditions. *J. Hazard Mater.* **2020**, *392*, No. 122346.
(61) Oliver, D. P.; Li, Y.; Orr, R.; Nelson, P.; Barnes, M.; McLaughlin, M. J.; Kookana, R. S. The Role of Surface Charge and PH Changes in Tropical Soils on Sorption Behaviour of Per- and Polyfluoroalkyl Substances (PFASs). *Science of The Total Environment* **2019**, *673*, 197−206.
(62) Wang, W.; Zhao, L.; Li, W.; Chen, J.; Wang, S. Response Mechanism of Sediment Organic Matter of Plateau Lakes in Cold and Arid Regions to Climate Change: A Case Study of Hulun Lake, China. *Environmental Science and Pollution Research* **2023**, *30* (10), 26778−26790.
(63) Matej-Łukowicz, K.; Wojciechowska, E.; Kolerski, T.; Nawrot, N.; Kuliński, K.; Winogradow, A. Sources of Contamination in Sediments of Retention Tanks and the Influence of Precipitation Type on the Size of Pollution Load. *Scientific Reports 2023 13:1* **2023**, *13* (1), 1−19.
(64) Zheng, W.; Chen, Y.; Pang, W.; Gao, J.; Li, T. Riverine Seasonal Rainfall Event Tracing of Organic Pollution Sources Using Fluorescence Fingerprint Difference Spectrum. *Science of The Total Environment* **2024**, *949*, No. 175024.
(65) Zhang, X.; Peng, Z.; Hou, S.; Sun, Q.; Yuan, H.; Yin, D.; Zhang, W.; Zhang, Y.; Tang, J.; Zhang, S.; Cai, Z. Ubiquitous Occurrence of P-Phenylenediamine (PPD) Antioxidants and PPD-Quinones in Fresh Atmospheric Snow and Their Amplification Effects on Associated Aqueous Contamination. *J. Hazard Mater.* **2024**, *465*, No. 133409.
(66) Hung, H.; Halsall, C.; Ball, H.; Bidleman, T.; Dachs, J.; De Silva, A.; Hermanson, M.; Kallenborn, R.; Muir, D.; Sühring, R.; Wang, X.; Wilson, S. Climate Change Influence on the Levels and Trends of Persistent Organic Pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEACs) in the Arctic Physical Environment − a Review. *Environ. Sci. Process Impacts* **2022**, *24* (10), 1577−1615.
(67) Bogdal, C.; Schmid, P.; Zennegg, M.; Anselmetti, F. S.; Scheringer, M.; Hungerbühler, K. Blast from the Past: Melting Glaciers as a Relevant Source for Persistent Organic Pollutants. *Environ. Sci. Technol.* **2009**, *43* (21), 8173−8177.
(68) Muir, D.; Gunnarsdóttir, M. J.; Koziol, K.; von Hippel, F. A.; Szumińska, D.; Ademollo, N.; Corsolini, S.; De Silva, A.; Gabrielsen, G.; Kallenborn, R.; Polkowska, Ż.; Krümmel, E.; Vorkamp, K. Local Sources versus Long-Range Transport of Organic Contaminants in the Arctic: Future Developments Related to Climate Change. *Environmental Science: Advances* **2025**, *4* (3), 355−408.
(69) Gander, M. J. Climate Change and the Water Quality Threats Posed by the Emerging Contaminants Per- and Polyfluoroalkyl Substances (PFAS) and Microplastics. *Water Int.* **2025**, *50* (3−4), 306−328.
(70) Thomalla, S. J.; Nicholson, S. A.; Ryan-Keogh, T. J.; Smith, M. E. Widespread Changes in Southern Ocean Phytoplankton Blooms Linked to Climate Drivers. *Nature Climate Change 2023 13:9* **2023**, *13* (9), 975−984.
(71) Ferreira, A.; Mendes, C. R. B.; Costa, R. R.; Brotas, V.; Tavano, V. M.; Guerreiro, C. V.; Secchi, E. R.; Brito, A. C. Climate Change Is Associated with Higher Phytoplankton Biomass and Longer Blooms in the West Antarctic Peninsula. *Nature Communications 2024 15:1* **2024**, *15* (1), 1−11.
(72) Xin, X.; Chen, B.; Yang, M.; Gao, S.; Wang, H.; Gu, W.; Li, X.; Zhang, B. A Critical Review on the Interaction of Polymer Particles and Co-Existing Contaminants: Adsorption Mechanism, Exposure Factors, Effects on Plankton Species. *J. Hazard Mater.* **2023**, *445*, No. 130463.
(73) Galbán-Malagón, C.; Berrojalbiz, N.; Ojeda, M. J.; Dachs, J. The Oceanic Biological Pump Modulates the Atmospheric Transport of Persistent Organic Pollutants to the Arctic. *Nat. Commun.* **2012**, *3* (1), 1−9.
(74) Martínez-Moreno, J.; Hogg, A. M. C.; England, M. H.; Constantinou, N. C.; Kiss, A. E.; Morrison, A. K. Global Changes in Oceanic Mesoscale Currents over the Satellite Altimetry Record. *Nat. Clim Chang* **2021**, *11* (5), 397−403.
(75) Kirschbaum, M. U. F. The Temperature Dependence of Soil Organic Matter Decomposition, and the Effect of Global Warming on Soil Organic C Storage. *Soil Biol. Biochem* **1995**, *27* (6), 753−760.
(76) Westerling, A. L. R. Increasing Western US Forest Wildfire Activity: Sensitivity to Changes in the Timing of Spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* **2016**, *371* (1696), 20150178.
(77) Kumar, M.; Upadhyay, R.; Mohapatra, S.; Dhangar, K. Transport of Black Carbon in the Presence of Perchlorate in Aquatic Environment: A Perspective of Cogenerated Species in the Gangetic Plain of India. *Case Studies in Chemical and Environmental Engineering* **2021**, *3*, No. 100065.
(78) Garnett, J.; Halsall, C.; Thomas, M.; Crabeck, O.; France, J.; Joerss, H.; Ebinghaus, R.; Kaiser, J.; Leeson, A.; Wynn, P. M. Investigating the Uptake and Fate of Poly- and Perfluoroalkylated Substances (PFAS) in Sea Ice Using an Experimental Sea Ice Chamber. *Environ. Sci. Technol.* **2021**, *55* (14), 9601−9608.
(79) Zhao, Z.; Xie, Z.; Möller, A.; Sturm, R.; Tang, J.; Zhang, G.; Ebinghaus, R. Distribution and Long-Range Transport of Polyfluoroalkyl Substances in the Arctic, Atlantic Ocean and Antarctic Coast. *Environ. Pollut.* **2012**, *170*, 71−77.
(80) MacInnis, J. J.; Lehnherr, I.; Muir, D. C. G.; Quinlan, R.; De Silva, A. O. Characterization of Perfluoroalkyl Substances in Sediment Cores from High and Low Arctic Lakes in Canada. *Science of The Total Environment* **2019**, *666*, 414−422.

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105

(81) Cabrerizo, A.; Dachs, J.; Barceló, D.; Jones, K. C. Climatic and Biogeochemical Controls on the Remobilization and Reservoirs of Persistent Organic Pollutants in Antarctica. *Environ. Sci. Technol.* **2013**, *47* (9), 4299−4306.
(82) Zhang, W.; Ma, L.; Chen, S.; Chen, C.; Bu, C.; Yu, J.; Zhang, R.; Wang, Y.; Zeng, H.; Han, Y. Effects of Temperature, Relative Humidity and Soil Organic Carbon Content on Soil-Air Partitioning Coefficients of Volatile PFAS. *Science of The Total Environment* **2024**, *955*, No. 176987.
(83) Christensen, E. R.; Wang, Y.; Huo, J.; Li, A. Properties and Fate and Transport of Persistent and Mobile Polar Organic Water Pollutants: A Review. *J. Environ. Chem. Eng.* **2022**, *10* (2), No. 107201.
(84) Tong, X.; Mohapatra, S.; Zhang, J.; Tran, N. H.; You, L.; He, Y.; Gin, K. Y. H. Source, Fate, Transport and Modelling of Selected Emerging Contaminants in the Aquatic Environment: Current Status and Future Perspectives. *Water Res.* **2022**, *217*, No. 118418.
(85) Noyes, P. D.; Miranda, D.; Oliveira de Carvalho, G.; Perfetti-Bolaño, A.; Guida, Y.; Barbosa Machado Torres, F.; Paulo Machado Torres, J.; Miglioranza, K. S. B.; Hatje, V.; Barra, R. O. Climate Change Drives Persistent Organic Pollutant Dynamics in Marine Environments. *Commun. Earth Environ* **2025**, *6* (1), 1−21.
(86) de Wit, C. A.; Vorkamp, K.; Muir, D. Influence of Climate Change on Persistent Organic Pollutants and Chemicals of Emerging Concern in the Arctic: State of Knowledge and Recommendations for Future Research. *Environ. Sci. Process Impacts* **2022**, *24* (10), 1530−1543.
(87) Balasuryia, D.; Queral-Beltran, A.; Vick, T.; Simpson, S.; Lacorte, S.; Aga, D. S.; Hoepker, A. C. Experimental Determination of PKa for 10 PFAS, Mono-, Di-, and Trifluoroacetic Acid by 19F-NMR. *Environ. Sci. Technol. Lett.* **2025**, *12* (9), 1238−1246.
(88) Tong, X.; Xiang, Z.; You, L.; Zhang, J.; Gin, K. Y.-H. Modeling Approach to Understanding the Nexus of Emerging Contaminants, Climate Change, and Water Security. *Curr. Opin Environ. Sci. Health* **2025**, *47*, No. 100650.
(89) Frederiksen, M.; Mosthaf, K.; Bøllingtoft, A. B.; Albers, C. N.; Christensen, B. S. B.; Christophersen, M.; Tuxen, N.; Tüchsen, P.; Clausen, L.; Janniche, G. A. S.; Bjerg, P. L. Predicting the Impact and Duration of Persistent and Mobile Organic Compounds in Groundwater Systems Using a Contaminant Mass Discharge Approach. *J. Environ. Manage* **2023**, *348*, No. 119199.
(90) Nagesh, P.; Edelenbosch, O. Y.; Dekker, S. C.; de Boer, H. J.; Mitter, H.; van Vuuren, D. P. Extending Shared Socio-Economic Pathways for Pesticide Use in Europe: Pest-Agri-SSPs. *J. Environ. Manage* **2023**, *342*, No. 118078.
(91) Desrousseaux, A.; Nagesh, P.; Gajraj, R.; Dekker, S.; Eitzinger, J.; Sallach, J. B.; Boxall, A.; Kok, K. A Shared Socio-Economic Pathway Based Framework for Characterising Future Emissions of Chemicals to the Natural Environment. *Futures* **2022**, *144*, No. 103040.
(92) Tong, X.; Goh, S. G.; Mohapatra, S.; Tran, N. H.; You, L.; Zhang, J.; He, Y.; Gin, K. Y. H. Predicting Antibiotic Resistance and Assessing the Risk Burden from Antibiotics: A Holistic Modeling Framework in a Tropical Reservoir. *Environ. Sci. Technol.* **2024**, *58* (15), 6781−6792.
(93) Mohapatra, S.; Menon, N. G.; Padhye, L. P.; Sarma, S.; Tatiparti, V.; Mukherji, S. Natural Attenuation of Pharmaceuticals in the Aquatic Environment and Role of Phototransformation. *Contaminants in Drinking and Wastewater Sources* **2021**, 65−94.

https://doi.org/10.1021/acs.est.5c09667
Environ. Sci. Technol. 2026, 60, 96−105