Global flux of perfluoroalkyl acids from glaciers in a warming climate

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SUMMARY

Climate warming is accelerating glacier melting, releasing human-made chemicals that have been trapped in glaciers for decades. Among these are perfluoroalkyl acids (PFAAs), highly persistent and toxic pollutants that threaten aquatic ecosystems, fisheries, and human health. Despite global efforts to curb PFAA emissions, their continued release from melting glaciers represents a legacy source that remains unquantified on a global scale. Here we combine field and literature data with machine learning and glacial mass balance model to estimate current and future PFAA fluxes via both dissolved and particle-bound phases. We find that global glaciers release approximately 3,500 kg of PFAAs annually, with suspended particles contributing around 12% of this amount. Projected trends suggest future release potential will rapidly boom through 2040 under extreme climate warming. These findings fill a critical gap in the global PFAA budget and underscore the urgency of coordinated action on both legacy pollutant management and climate mitigation.

KEYWORDS

perfluoroalkyl acids; glacier melt; release flux; machine learning; future trend

INTRODUCTION

In the Anthropocene, chemical pollution has become a defining challenge as novel entities for planetary health.[1-3] Among these, per- and polyfluoroalkyl substances (PFAS), known as "forever chemicals" due to their extreme persistent, have attracted widespread attention.[4,5] PFAS are a large class of human-made chemicals that have been widely used in industrial and consumer products since the mid-20th century.[6] Perfluoroalkyl acids (PFAAs) are the best-studied subgroup of PFAS, including compounds listed for phase-out under Stockholm Convention due to a series of adverse effects.[7,8] Alarmingly, even in remote regions, the concentrations of perfluorooctanoic acid (PFOA) in rainwater greatly exceed health advisory levels (4 pg L^{-1}),[9] indicting the planetary boundary for PFAA pollution has been exceeded worldwide.[10]

Glaciers in the remote cryosphere are critical reservoirs for PFAAs. PFAAs can undergo long-range atmospheric transport and subsequently deposit onto glacial surfaces through both dry and wet deposition processes due to cold-trapping effect.[11] Measurable concentrations of PFAAs have been detected in glaciers in the Arctic,[12] Antarctica,[13] and high-altitude alpine regions,[14,15] ranging from hundreds to thousands of picograms per liter. As forever chemicals, PFAAs can persist in glaciers for decades, even after their primary emissions are controlled,[16,17] posing long-term threats to fragile ecosystems, particularly in sensitive regions such as the Arctic and the Tibetan Plateau.

Previously trapped PFAAs in glaciers are being released under the warming climate,[18,19] creating an emerging threat to proglacial ecosystems. Signals of PFAA meltwater sources have been identified in the contaminant profiles of sediment cores and in the biota from proglacial environments,[20,21] indicating the re-release of these previously accumulated chemicals. Once released, PFAAs can undergo biomagnification via food chain from benthic invertebrates to top predators,[22,23] thereby threatening aquatic diversity, fisheries and even human health. For example, high concentrations (~500 ng mL^{-1}) were found in blood serum from East Greenland Inuit who rely on traditional marine food, despite relatively low environmental concentrations (0.0005 ng mL^{-1}).[24]

Despite growing recognition of this emerging threat, several knowledge gaps remain. Most notably, we lack a comprehensive estimate of the magnitudes and spatial patterns of PFAA fluxes from glaciers on a global scale. Existing studies are limited to a few sampling sites. To date, only two studies report the release flux of PFAAs to the downstream: one reporting an annual flux of 1.6±0.7 kg in the Canadian High Arctic,[25] and another estimating of about 0.5 kg year^{-1} from a single glacier on the central Tibetan Plateau.[26] The lack of global flux data limits our understanding of how glacial melt contributes to global PFAA budget and hinders the identification of pollution hotspots.

Furthermore, current assessments of PFAA transport focus on dissolved phases while overlooking the contribution of suspended particles generated through glacial erosion and permafrost thawing.[17,18] These suspended particles, mobilized at increasing rates under accelerated glacial melting, may serve as important vectors for PFAAs, especially for more toxic long-chain compounds.[19,20] As climate warming accelerates erosion and sediment mobilization, the omission of particle-bound transport may result in underestimation of total PFAA fluxes and associated health risks.

Here we address these critical knowledge gaps by quantifying current and future flux of PFAAs released from glaciers worldwide via both dissolved and particle-bound particles. Our analysis includes a global dataset of field data from Tibetan glaciers and literature data from global glaciers, the application of machine learning and glacial mass balance model, and the prediction of release fluxes through the end of the 21st century. Our findings reveal that approximately 3,500 kg of PFAAs are released from global glaciers per year with Arctic Canada and South and Central Asia identified as major export regions. Suspended particles contribute around 12% of the total flux, highlighting their non-negligible impact. The release flux is projected to increase rapidly through 2040, leaving a narrow time window for effective actions. Our estimates and predictions are crucial for a better understanding of the role of glacial melting on PFAA cycling in the global cryosphere.

RESULTS

Methods summary

To evaluate the global flux of PFAAs from glaciers, we posed three research questions: (1) What are the magnitudes and spatial patterns of PFAA release fluxes from glaciers on a global scale? (2) What is the role of the particle-bound phase in total PFAA export? (3) How might these fluxes change under future climate scenarios?

To answer these questions, we first conducted field sampling on seven glaciers across the Tibetan Plateau, measuring 13 individual PFAAs in both dissolved phase and suspended particles. These field data were integrated into a global dataset comprising 739 samples from 49 glaciers across eight major glacial regions worldwide. Due to the scarcity of concentrations in suspended particles, we developed predictive models for log-transformed particle–water partition coefficients (logK_d), using both traditional curve-fitting and machine learning approaches. LogK_d were predicted based on environmental parameters (e.g., water temperature, particulate organic carbon) and molecular descriptors of PFAAs. The best-performing machine learning model was finally selected from multiple candidates based on its accuracy and stability.

We then coupled the predicted logK_d with glacial runoff volumes derived from glacial mass balance model to quantify annual release flux of PFAAs via both dissolved phase and suspended particles. For regions with high export fluxes, we further identified pollution hotspots using threshold-based spatial analysis of PFAA concentrations in water and sediment. Finally, we integrated climate projections under three Shared Socioeconomic Pathways (SSP126, SSP245, and SSP585) to simulate global glacial PFAA exports from 2020 to 2100. This integrative framework enables a comprehensive assessment of current and future glacier-sourced PFAA fluxes on a global scale.

PFAAs in glacial meltwaters of the Tibetan Plateau

To characterize the current status of PFAAs in high-altitude glacial regions, we measured 13 individual PFAAs (Table S1) in meltwater and associated suspended

particles from seven glacier regions across the Tibetan Plateau. Figure 1 illustrates the upstream-to-downstream arrangement of sampling sites, along with average concentrations and compositions of Σ_{13}PFAAs. The highest concentration (5430 pg L^{-1}) was observed in the Rongbuk glacial region of Mt. Everest (Figure 1B), while concentrations at the other sites were generally below 1200 pg L^{-1}. Across all sites, short-chain PFAAs, consisting of <C8 perfluoroalkyl carboxylic acids (PFCAs) and <C6 perfluoroalkyl sulfonic acids (PFSAs), dominated the PFAA profiles, accounting for 68–96% of the total concentrations (Figure 1C).

PFAAs released through glacier ablation can be transported downstream either in the dissolved phase or adsorbed onto suspended particles. We found that concentrations of most short-chain PFAAs in the dissolved phase increased from upstream to downstream sites (Figure S1), likely due to their higher solubility and mobility in water. In contrast, long-chain PFAAs (≥C8 PFCAs and ≥C6 PFSAs) adsorbed onto suspended particles exhibited the opposite trend, with their concentrations decreasing from upstream to downstream (Figure S1). In other words, long-chain PFAAs associated with suspended particles tend to accumulate in the headwater regions. The opposing spatial trends of PFAA concentrations during transport (Figure S1) indicate the crucial need for accurate PFAA concentrations in both dissolved and particle-bound phase in glacier-fed systems.

Occurrence of PFAAs in global glacial regions

To place Tibetan data in a broader context, we compiled a global database of Σ_{13}PFAA concentrations from more than 49 glaciers, including field data from this study (n=59) and previous research (n=680) (Table S2). Figure 2 presents the locations of these glacial sites across eight major glacial regions, and corresponding average Σ_{13}PFAA concentrations (bold numbers) at each region. Pie charts depict the relative composition of individual PFAAs at each region.

Across the global dataset, PFAA concentrations in glacial meltwater (Table S3) ranged from several hundred to several thousand picograms per liter, exhibiting distinct

regional variation (Figure 2). Although the data exhibited fluctuations, the average concentrations of Σ_{13}PFAAs were relatively high (4486 pg L^{-1}) in glacial regions in Arctic Canada (ACG) (Figure 2) [i.e., Lake Hazen watershed, see Table S2], and those near the Greenland Sea exhibited much lower levels (297 pg L^{-1}). Similar to the Tibetan Plateau, short-chain PFAAs predominated in most regions, accounting for 62–80% of the total concentrations in areas such as ACG, Central Europe (CEG), and South and Central Asia (SCAG) (Figure 2, pie charts).

However, field data on PFAAs associated with suspended particles remain scarce in global glacial regions. To overcome this limitation, we applied particle-water partition coefficient (K_d) to bridge the field-measured dissolved PFAA concentrations to particle-bound concentrations.

Predicting particle–water partition coefficient

The K_d describes the distribution of PFAAs between the dissolved and particle-bound phases. However, K_d values are highly variable and influenced by environmental parameters and molecular descriptors of PFAAs. Therefore, we selected key influencing factors, including temperature (T_w), particulate organic carbon (POC), log$K_{ow\text{-}ionic}$, and PFAA type, for predicting logK_d. Details on selecting these factors and model validation procedures are provided in the Methods section.

Initial attempts to predict logK_d using curve-fitting models yielded limited performance, with coefficients of determination (R^2) ranging from 0.48 to 0.64 (Note S1). To improve prediction accuracy, we developed several machine learning (ML) models, including support vector machines (SVM), decision trees (DT), random forests (RF), and extreme gradient boosting (XGBoost). Among these, the XGBoost model (XGBoost-ML) outperformed others in both explanatory power and stability (R^2=0.95 for the training set and Q^2=0.85 for the test set). The best-performing XGBoost-ML showed strong agreement with field-measured logK_d for all individual PFAAs in the training set (Figure 3A). Almost all of the predicted logK_d in the test set fell within an order of

magnitude (±1 range) of the measured values, except one outlier (Figure 3B, white squares), which was measured with high POC values (up to 10%) (Table S4).

In summary, the XGBoot-ML outperforms traditional curve-fitting methods and other ML models in predicting logK_d. With the combination of model-predicted logK_d with field-measured dissolved PFAA concentrations (Table S2), the concentrations of PFAAs on suspended particles across the eight global glacial regions were calculated. The results are provided in Table S5.

Global fluxes of PFAAs from glaciers

Using dissolved and estimated particle-bound concentrations (Tables S3 and S6), combined with modeled glacial runoff volumes, we quantified the annual release fluxes of individual PFAAs from eight major glacial regions worldwide, with data listed in Table S6. Table 1 summarizes the release fluxes of Σ_{13}PFAAs via the dissolved phase and suspended particles for each region.

The total estimated global flux of Σ_{13}PFAAs was 3,547±375 kg year^{-1}, with the dissolved phase contributing 3,117±165 kg year^{-1} (~88%) and suspended particles accounting for the remaining 430±210 kg year^{-1} (~12%) (Table 1). In most glacial regions, the contribution of suspended particles remained less than 15%. However, in sediment-rich systems such as the Greenland ice sheet (GIS), suspended particles contributed up to 51% of the total flux, likely due to high particle loads in glacial outflows.

Differences in the chain length of PFAAs influenced release fluxes in dissolved and particle-bound phases. In the dissolved phase, short-chain PFAAs dominated, with an estimated flux of 1,823±97 kg year^{-1}, compared to 1,129±61 kg year^{-1} for long-chain compounds (Table 7). In contrast, the particle-bound phase was enriched in long-chain PFAAs, which contributed 238±63 kg year^{-1}, nearly three times the flux of short-chain compounds (87±14 kg year^{-1}) (Table 7), consistent with their stronger sorption affinities.

Substantial regional variations in total PFAA fluxes were also observed (Table 1). The SCAG region contributed the highest load, with an estimated flux of 1394±86 kg year^{-1}, accounting for nearly 40% of global glacial PFAA export. This was followed by the ACG (698±48 kg year^{-1}), Arctic Europe (AEG) (564±25 kg year^{-1}), Western Canada and the USA (WCUG) (426±15 kg year^{-1}), and GIS (316±190 kg year^{-1}). Collectively, these five regions represented over 95% of the total global flux. High glacial runoff volumes, ranging from 212 to 547 km^3 year^{-1} (Table 1), and relatively high PFAA concentrations (Figure 1) contributed to their dominant role.

In contrast, smaller glaciers such as those in North Asia (NAG) and Central Europe (CEG) exhibited limited annual PFAA fluxes (< 20 kg year^{-1}), due to both lower glacial runoff volumes (Table 1) and moderate PFAA levels (Figure 2). The Antarctic and Subantarctic Ice Sheet (AIS) also contributed modestly (118±10 kg year^{-1}), consistent with its relatively isolated location from PFAA emission sources.

Priority locations of concern

As mentioned above, the SCAG and Arctic regions present hotspot export zones for PFAA releases from melting glaciers. To further identify the locations of concern that should be prioritized for protection, we compiled the data on PFAAs in water and sediment from these regions (Tables S7 and S8).

The average concentration of Σ_{13}PFAAs in water (2 ng L^{-1}) and sediments (1 ng g^{-1}) were obtained and served as baselines for assessing priority locations of concern. Levels of concern are based on exceeding the average by 1, 2, and 3 times, respectively. Figure 4 illustrates priority locations of concern for PFAAs with relatively high concentrations in water or sediment in the Arctic and SCAG regions. Red circles on the map indicate sites influenced by water, while purple circles represent those influenced by sediment. The higher the concentration of PFAAs, the larger the buffer zone. Detailed locations of each site are available in Tables S7 and S8.

In the Arctic, locations of concern are categorized into four main regions: Svalbard,

Arctic Europe, the Canadian Arctic basins, and the Chukchi Sea (Figure 4A). Svalbard exhibits elevated PFAA levels in both water and sediment, indicating a significant overlap in environmental risk. In Arctic Europe, areas of high concern are identified in coastal sediments along the Norwegian Sea and the Barents Sea. Additionally, Northern Swedish glaciers are classified as high-concern sites due to high PFAA concentrations in glacial runoffs. In the Canadian Arctic basins, such as Lake Hazen and Lake B35, impacts on local wildlife, including polar bears and Arctic foxes, have been observed in surrounding areas like Grise Fjord and Arviat (Figure 4A, orange triangle). Meanwhile, sediments near the coast of the Chukchi Sea indicate relatively high environmental risk.

Future release potential under climate warming

Apart from regional impacts, understanding how the release of PFAAs from glaciers change under future climate warming is also imperative. Figures 5A and 5B illustrate the future release potential of Σ_{13}PFAAs from global glaciers in the 21st century via dissolved and suspended-particle phases under three shared socioeconomic pathway (SSP) scenarios, i.e., SSP126 (low emissions), SSP245 (intermediate emissions) and SSP585 (high emissions). The release potential refers to a predicted possibility of PFAA fluxes under future climate scenarios.

Under SSP126, the release potential of Σ_{13}PFAAs is expected to remain relatively stable by the end of the 21st century (Figures 5A and 5B, SSP126 scenario). In contrast, under SSP245—and especially under SSP585—the potential Σ_{13}PFAA fluxes exhibit increasing trends throughout the century. Under SSP585, the average release fluxes of Σ_{13}PFAAs via the dissolved phase could reach up to ~13,000 kg year^{-1}, and those via suspended particles may reach ~2,500 kg year^{-1}, which represents a 6-fold increase compared to 2020 levels (Figures 5A and 5B, SSP585 scenario). By 2040, the release potential is expected to be less than double those observed in 2020; however, after 2040, the rate of increase is projected to boom rapidly. These results identify the next 15 years as a critical window for global efforts to mitigate PFAA pollution and combat climate

change.

Regionally, under SSP 585, ACG and GIS are predicted to experience a nearly 10-fold increase in the release potential of dissolved PFAAs by the end of this century. In contrast, WCUG, AEG, SCAG and AIS are expected to have about a twofold increase (Figure S2). For the suspended-particle phase, the release potential in ACG and GIS is projected to increase by ~8-fold, while WCUG, AEG, SCAG and AIS are anticipated to experience about a twofold increase (Figure S3).

However, these estimates may be conservative, as they assume that the rate of sediment transport—and thus particle-associated PFAA flux—remains constant under future climate warming. Actually, glacial sediment export has already doubled over the past 30 years in regions such as the Arctic coastline and the Himalayas.[27] If this trend continues, doubling every 30 years, the release potential of Σ_{13}PFAAs associated with suspended particles in the Arctic (Greenland) region is expected to undergo an exponential increase, reaching approximately 50-fold above 2020 levels by 2100 under the SSP 585 scenario (Figure 5C). In the SCAG region, particle-bound PFAA fluxes are also projected to rise substantially, with a nearly tenfold increase over the same period (Figure 5D).

DISCUSSION

Although glaciers are increasingly recognized as secondary sources of pollutants, the magnitude and mechanisms of PFAA release, particularly via the particle-bound phase, have remained largely unresolved on a global scale. Our study addresses this gap by providing the first quantitative estimate of both dissolved and particle-bound PFAA releases from glaciers worldwide, revealing that glacial melt can export thousands of kilograms of legacy PFAAs to downstream ecosystems each year, with significant regional and chemical partitioning patterns.

In the following context, we first evaluate limitations of uncertainty in our global PFAA flux estimates. We then assess whether glaciers currently act as net sources or sinks of PFAAs by comparing the global patterns of release and depositional fluxes derived from the GEOS-Chem model. These glacial fluxes were further compared to global PFAA emission inventories to clarify their relative contribution and to identify locations of high concern. Beyond quantification, we explore the potential adverse effects of increased PFAA outflows, particularly the role of particle-bound transport. Finally, we discuss strategies for controlling future PFAA releases from glaciers under climate warming.

Limitations

Several sources of uncertainty may influence the accuracy of our global PFAA flux estimates. First, the limited number of sampled glaciers within each region may not fully capture spatial heterogeneity, potentially introducing bias when extrapolating to the regional scale. Temporal uncertainty also arises due to the seasonal variability of both meltwater runoff [28] and PFAA concentrations,[19] as most field campaigns were conducted during limited time windows. In some Arctic regions, the scarcity of glacial meltwater data led to the use of PFAA concentrations in adjacent seawater (Table S2), which may underestimate fluxes due to dilution effects. These factors likely contributed to the large standard deviations observed in both PFAA concentrations (Figure 2) and flux estimations (Table 1).

Second, data gaps in key regions remain. In particular, no observational data is currently available for Patagonia and the southern Andes. Glaciers in these regions are among the most rapidly retreating on Earth.[29] This lack of data would lead to an underestimation of global glacier-sourced PFAA fluxes. Moreover, geopolitical dynamics, such as international regulations on PFAA production, industrial substitution of legacy PFAAs, and the geographic relocation of manufacturing facilities, could alter emission patterns over time. However, due to the lack of reliable global models and transparent reporting,

316 the influence of these political and economic factors could not be quantitatively
317 assessed.

318 Finally, analytical uncertainties also exist. Perfluorobutanoic acid (PFBA), a prevalent
319 short-chain PFAA, has been inconsistently reported in previous studies due to analytical
320 challenges.[30,31] To assess the impact of its exclusion, we recalculated fluxes for Σ_{12}
321 PFAAs (excluding PFBA), with total fluxes of 2250±306 kg year^{-1}, with 18%
322 transported via the suspended particles (Table S6). The regional flux ranking remained
323 consistent—SCAG (536±39 kg year^{-1}), AEG (449±24 kg year^{-1}) and WCUG (426±15
324 kg year^{-1})—but the total global flux was substantially lower, underscoring the
325 importance of including PFBA in future assessments. Improved analytical techniques,
326 such as high-resolution mass spectrometry,[32] are essential for accurately quantifying
327 low-mass PFAAs and ensuring comparability across studies in the future.

328 ***Global patterns of release and depositional fluxes***

329 Based on the field measurements, predicted logK_d and modeled glacial runoffs, we
330 estimated that glaciers globally release approximately $3{,}547 \pm 375$ kg year^{-1} of
331 Σ_{13}PFAAs into downstream environments, with about 12% transported via suspended
332 particles. While previous studies have only quantified dissolved-phase fluxes at the
333 regional scale,[25,26] our study extends this assessment to the global scale and incorporates
334 the often-overlooked particle-bound phase.

335 To evaluate whether PFAA release is in balance with atmospheric inputs, we compared
336 regional glacial output fluxes with deposition fluxes estimated by the GEOS-Chem
337 global atmospheric chemistry model (Table 1),[33] and the estimates derived from ice
338 core records in the same glacial regions (Table S9).[14,15,34-36] Deposition fluxes showed
339 substantial regional variability, with AIS ≈ GIS ≈ SCAG > ACG ≈ WCUG > CEG ≈
340 NAG (Table 1). The high depositional fluxes in AIS and GIS were primarily due to their
341 large glacial surface areas. In contrast, the comparable flux in SCAG can be linked to
342 the high deposition concentration of PFAAs from nearby emission sources.[37,38]

Since GEOS-Chem model only include PFCAs, we focused on the comparison on Σ_{10}PFCAs (Table 1). Our results shows that the global average glacial release fluxes of Σ_{10}PFCAs (~2900 kg year^{-1}) were about 3 to 9 times higher than the modeled atmospheric deposition inputs (329–900 kg year^{-1}). Regionally, the glacial release flux exceeds the maximum depositional flux in all glacial regions, except for the AIS. This was obvious in ACG and SCAG, where the export fluxes of Σ_{10}PFCAs were 6 to 8 times higher than the maximum import fluxes (Table 1), followed by CEG and WCUG, due to rapid glacier ablation.[39] These findings indicated that under climate warming most glaciers were experiencing a net loss of PFAAs.

By contrast, the maximum depositional fluxes for the AIS were about twofold higher than the current release fluxes of Σ_{10}PFCAs, suggesting that the AIS may still act as a temporary sink for PFAAs.[36] Therefore, accumulation of PFAAs in the AIS should be continuously monitored,[36,40] particularly concerning their adverse effects on sensitive Antarctic wildlife like penguins.[41]

Intriguingly, based on results from the Devon, Meighen, Melville and Agassiz ice caps in 2005,[42] the total depositional flux of just four PFCAs, including PFOA, perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUdA), to the Arctic (north of 65° N) was approximately 2603 kg year^{-1}. This value is almost an order of magnitude higher than the estimated depositional fluxes for the Arctic regions (ACG+GIS+AEG = 128–390 kg year^{-1}) derived from the GEOS-Chem model for the period 2013–2015 (Table 1). The substantial decline in deposition flux during 2013-2015 may be attributed to the gradual phase-outs of PFAAs.[43] This discrepancy suggests that large amounts of PFAAs had already been deposited and stored in Arctic glaciers during earlier decades.

Known as “forever chemicals”, PFAAs deposited on snow/ice are likely to undergo minimal degradation,[11] resulting in their long-term storage within the glaciers for decades to centuries.[44] With continuous global warming, the previously stored PFAAs

in glaciers (aged ice) would be largely released at an increasing rate.[45,46]

Glacial fluxes compared to global PFAA emissions

While glaciers have been identified as secondary sources of PFAAs, their contribution remains limited in the context of global emissions. PFAAs have been widely used in industrial and household applications since the mid-20th century.[6] Under a high-emission scenario, global annual emissions of Σ_{10}PFCAs around 2020 were estimated at approximately 400 tonnes.[47] In comparison, the total glacial release fluxes of Σ_{10}PFCAs are approximately 2.9 tonnes per year (Table 1), representing only about 0.7% of annual global emissions and indicating a limited contribution. Similarly, the input of PFAAs to the Arctic via glacial meltwater is also minor compared to the hundreds of tonnes transported by sea spray aerosols.[31]

Nevertheless, the local impact of glacial release on PFAA distribution and wildlife in glacial regions remains significant. As observed in Figure 4A, PFAA concentrations in Arctic fjords are higher than in other locations. The deep and narrow structure of fjords can restrict water circulation, leading to slower mixing and flushing, which causes PFAAs to accumulate in the fjord waters for extended periods. Similarly, PFAA levels in high-latitude Arctic fjord sediments are higher than in lower latitudes.[20] The unique geomorphology of Arctic fjords, characterized by deep valleys and significant sediment deposits, allows for more effective trapping and accumulation of PFAAs. Importantly, many of these fjords also sustain vital fisheries.[48] Therefore, the Arctic fjords should be of high concern in the Arctic regions.

In the SCAG region, high level PFAA areas are predominantly located south of 33°N latitude (Figure 4B). The Khumbu and Rongbuk Glaciers have the largest PFAA risk buffer zones, followed by the Yulong Baishui No.1 glacier (Figure 4B). These glaciers are located in the monsoon-affected southern Tibetan Plateau (south of 33°N), where glacier melt rates are higher compared to the north.[49] Proglacial river sediments have been proven to be substantial sinks for PFAAs released by glacial meltwater,[18] acting

as important sources for the benthic food web. The export of PFAA by meltwater and suspended particles has led to PFAA being enriched in cold-water fish species in the Tibetan rivers (south of SCAG).[50] Consequently, particular attention should be given to headwater regions at glacier termini and adjacent catchment, as they are likely hotspots for PFAA contamination.

Adverse effects of increased PFAA outflows

With ongoing glacial retreat, the particle-bound fraction of PFAAs, especially bioaccumulative long-chain compounds, is expected to increase substantially. Our estimates suggest that fluvial suspended particles currently deliver 238±63 kg year^{-1} of long-chain PFAAs globally (Table S6), a figure likely to grow as glacier erosion and sediment fluxes intensify under warming conditions[27,51,52]. For example, projections for Greenland indicate that sediment transport could double every 30 years,[27] leading to a 20- to 60-fold increase in particle-bound Σ_{13}PFAAs releases by 2100 under different SSPs scenarios (Figure 5C). This sediment enrichment may eventually surpass meltwater as the dominant pathway of PFAA outflows, posing increasing risks to proglacial ecosystems.

Sediments serve as an important pathway for the entry of PFAAs into the food web (i.e., sediment – phytoplankton – zooplankton – Arctic char – seals – polar bears).[22-24] Bioaccumulation factors for long-chain PFAAs are approximately 30-50 fold from sediment to Arctic char,[23] 10-30 fold from char to ringed seals,[53] and up to 10 fold from seal to polar bear.[54] Under the worst-case warming scenario (SSP585), PFAA concentrations in polar bear liver tissues could rise from current levels of several μg g^{-1} to potentially mg g^{-1} concentrations (Figure S4). Although no official safe thresholds have been established for PFAAs in polar bears, such extreme high concentrations would exacerbate their health risks.

Polar bears are already listed on the International Union for Conservation of Nature (IUCN) Red List.[55] Rising PFAA concentrations under future warming scenarios could

accelerate the decline of this keystone species, disrupt Arctic ecosystems, and contribute to broader biodiversity loss. Although the Arctic Monitoring and Assessment Programme (AMAP) has already warned of increasing PFAA-related toxicity in polar organisms,[56] our work provides a quantitative amplification of this trend, specifically in the increased concentrations found in the livers of polar bears (Figure S4). This is critical for understanding and mitigating the environmental impact of PFAAs released from glacial sources.

Compared to the Arctic, the Tibetan Plateau (southern SCAG) presents a lower risk profile. The aquatic food chain in the plateau is generally shorter than that of the Arctic marine ecosystem, which limits the biomagnification of PFAAs.[50] However, glaciers on the Tibetan Plateau serve as the headwaters of major Asian rivers that support the livelihoods of over two billion people downstream.[49] Under future warming scenarios, accelerated glacial melt and enhanced sediment transport may increase the release of particle-bound PFAAs into these headwater systems. This could pose adverse impacts on ice-dwelling headwater species at the base of the food web, such as algae, copepods, and amphipods.[57] Such upstream ecological disturbances may cascade downstream, threatening water quality and aquatic biodiversity in major Asian rivers.

Controlling future PFAA releases from glaciers

To mitigate adverse impacts of future PFAA releases from glaciers, coordinated and immediate global actions are essential. Reducing greenhouse gas emissions remains the most critical step, as slowing the rate of climate warming directly reduces glacial melt rates and the remobilization of legacy PFAAs stored in ice. Lower emissions will not only stabilize climatic systems but also protect ecosystems from accelerated degradation due to rising temperatures.

In parallel, stronger global regulations on PFAS production and use are urgently needed. Current policies have largely targeted long-chain PFAAs and their precursors, but short-chain and emerging PFAS—many of which are poorly regulated or still unknown—are

now dominant in the environment. Expanding regulatory frameworks to include these compounds is essential for protecting sensitive ecosystems, particularly polar and alpine regions where bioaccumulation risks remain high.

Policy oversight must also account for unintended consequences. For instance, the global transition from chlorofluorocarbons (CFCs) to short-lived substitutes under the Montreal Protocol has inadvertently accelerated atmospheric deposition of ultra-short-chain PFAAs, such as trifluoroacetic acid (TFA).[44,58] These substitutes, while beneficial for ozone protection, now contribute both to climate forcing and chemical contamination.[59] This underscores the need for integrated environmental governance, where solutions to one crisis do not amplify another.

As shown in Figures 5A and 5B, the world faces a narrow window of approximately 15 years to effectively curb glacier-derived PFAA release. A combined strategy of emissions reduction, PFAS regulation, and careful chemical substitution is essential. Without coordinated intervention, PFAA discharges from glaciers are projected to rise sharply, with long-term consequences for freshwater security, fisheries, biodiversity, and global pollutant burdens.

Finally, establishing long-term environmental and wildlife monitoring programs is crucial. These systems serve as early-warning networks, enabling the detection of rising PFAA levels and other ecological stress signals in fragile regions. Proactive monitoring not only informs risk assessment and response but also supports evidence-based policy decisions aimed at preventing irreversible ecological damage to the most fragile cryosphere on our planet.

METHODS

Study area and field sampling

Seven glaciers on the Tibetan Plateau (affiliated to part of SCAG) were investigated in

the field, including the Rongbuk (RB), Qiangyong (QY) and Rijie Cojia (RC) glaciers in the Himalayan Mountains, the Korchung Gangri (KG) and Zhadang (ZD) glaciers in the Gangdise–Nyainqêntanglha Mountains, and the Galongla (GL) and Parlung No. 4 (PL) glaciers in the Hengduan Mountains (Figure 1). Among them, RB, ZD, KG, QY, and RC are continental valley glaciers, whereas the GL and PL are typical temperate glaciers. Details of these glacial regions, among which there are significant geographical, hydrological, and meteorological differences, are summarized in Table S10.

Meltwater sampling was conducted from July to August 2020, corresponding to the peak melting season. At each glacier, surface runoff samples (0–30 cm) were collected at three sites from the upstream to the downstream (Figure 1A). Approximately 20 L of water was collected at each site using pre-cleaned polypropylene bottles. Prior to use, all sampling bottles were rinsed three times with methanol and Milli-Q water. To minimize contamination, sampling materials containing fluoropolymer coatings or PFAS-related components were strictly avoided. *In situ* measurements of basic water quality parameters, including water temperature (T_w), pH, conductivity (σ), and dissolved oxygen (DO), were conducted during the sampling at the same site.

Analysis of PFAAs

Glacial runoff samples from seven glacial catchments on the Tibetan Plateau were analyzed for 13 target PFAAs. Upon analysis, all water samples were filtered through Whatman 0.7 μm glass fiber filters (GFFs) to separate suspended particles. The filtrates (2L each) were subjected to solid-phase extraction (SPE) using Waters Oasis WAX cartridges (150 mg, 6 cm^3, 30 μm), while the retained GFFs were extracted by ultrasonic agitation using methanol to measure particle-bound PFAAs. Detailed extraction procedures are described in Notes S2 and S3.

Quantification of 13 PFAAs and internal standards (Table S11) were performed using high-performance liquid chromatography coupled with tandem mass spectrometry

(HPLC–MS/MS; ThermoFisher UltiMate 3000 and TSQ Quantiva triple quadrupole system), as described in Note S4. POC on the GFFs (the suspended particle samples) was measured using a Shimadzu 5000-A total organic carbon analyzer to support subsequent partitioning analysis.

All analytical procedures were conducted under strict quality assurance and quality control measures (Note S5). Field and procedural blanks prepared with Milli-Q water yielded concentrations below the method quantification limits (Table S12), confirming that sample contamination was negligible. Matrix spiked recoveries, obtained by spiking with 2000 pg of internal standards, ranged from 52% to 81% for water samples and 42% to 70% for suspended particle samples, with detailed values listed in Table S13.

Identification of glacial regions and data compilation

The identification of glacial regions was undertaken using version 6.0 of the RGI (http://www.glims.org/RGI/). Eight major glacial regions were included in this study (Figure 2): ①West Canada and USA (WCUG), ②Arctic Canada (ACG), ③Greenland Ice Sheet (GIS), ④Arctic Europe (AEG), ⑤North Asia (NAG), ⑥Central Europe (CEG), ⑦South and Central Asia (SCAG), and ⑧Antarctic and Subantarctic Ice Sheet (AIS).

To construct a global dataset of PFAA concentrations, we compiled published data for 13 PFAAs from 680 samples across 49 glaciers in these eight glacial regions (Figure 2). The dataset includes samples from glacial runoff, snow/ice, and seawater neighboring the glaciers. In addition, we combined our field measurements (n=59) from seven glaciers on the Tibetan Plateau with the above published data to produce a global dataset (n=739, Table S2). This integrated dataset offers the basis for the global-scale assessment of PFAA fluxes from glaciers.

Drivers of particle-water partition coefficient (K_d)

The K_d is defined as the ratio of a chemical's concentration in the particle-bound phase (C_p) to that in the dissolved phase (C_w) (i.e., $K_d = C_p/C_w$). The logK_d data obtained from measurements of 13 PFAA concentrations in runoff water and suspended particles from the Tibetan glaciers is presented in Table S4. While K_d values are variable, they often respond to environmental factors and chemical properties of PFAAs.

To explore the key drivers of PFAA partitioning, we analyzed the relationships between logK_d and several environmental parameters, including pH, T_w, POC, σ and DO, as well as molecular descriptors such as perfluorinated chain length and functional group type (i.e., carboxylates for PFCAs and sulfonates for PFSAs). Statistically significant correlations were observed between logK_d and both POC and T_w ($p<0.05$), while no significant correlations were found for pH, DO or σ (Table S14). These findings are consistent with previous studies highlighting the importance of organic carbon and water temperature in governing PFAS partitioning.[60]

In addition, we examined the influence of molecular hydrophobicity using theoretical ionic octanol–water partition coefficients (log$K_{ow\text{-}ionic}$), as reported by Hidalgo and Mora-Diez (2015).[61] Given that glacial meltwaters are commonly alkaline[62] and PFAAs possess low pK_a values (typically <1.0), these compounds are expected to be fully dissociated to their anionic forms.[63] The log$K_{ow\text{-}ionic}$ values , which vary by carbon chain length but are fixed for each compound, were significantly correlated with logK_d (p <0.01, Figure S5), which suggests that log$K_{ow\text{-}ionic}$ can be a useful model predictor of logK_d, especially if combined with the abovementioned POC and T_w.

To support model development, we compiled a comprehensive dataset (n=771), containing logK_d, T_w, POC, log$K_{ow\text{-}ionic}$, and PFAA type. These data were sourced from both glacial regions (n=191) and non-glacial environments (e.g., inland watersheds and coastal areas; n=580). All values were either directly measured or extracted from the previous literature, as listed in Table S4. Notably, T_w values were all below 19°C to

represent relatively low-temperature environments, with data screening criteria detailed in Note S1.

Prediction of K_d with machine learning models

Traditional curve-fitting methods showed limited performance in predicting logK_d. To overcome this limitation, we developed machine learning (ML) models to estimate logK_d, including the support vector machine (SVM), decision tree (DT), random forest (RF), and extreme gradient boosting algorithm (XGBoost).

All ML models were implemented in Python 3.9.7 using the *scikit-learn* module. Model performance was evaluated using multiple metrics: the coefficient of determination for the training set (R^2), the predictive Q^2 for the test set, and the mean absolute error (MAE) and mean squared error (MSE) for both sets. To ensure robustness and reproducibility, the dataset was randomly divided into training and test sets using sklearn.model_selection.train_test_split, with varying split ratios ranging from 5:95 to 50:50, and 10 replicates for each ratio.

Among all models, the XGBoost-ML (denoted as Xgb_A) exhibited the best overall performance, achieving the highest R^2 (0.95±0.01) and Q^2 (0.85±0.04), along with the lowest MAE and MSE for both the training set (0.138±0.016 and 0.034±0.008, respectively) and test set (0.241±0.032 and 0.105±0.030, respectively). Additionally, statistical analyses using Student's t-tests showed no significant variation in predictive accuracy when increasing the proportion of the test set from 5% to 45% of the total dataset (raw significant level α=0.05, Bonferroni-corrected significant level α=0.0011, number of tests =45).

Based on these results, the XGBoost-ML (Xgb_A) was selected as the best-performing model for predicting logK_d. Further details regarding ML model development and comparative performance are provided in Note S1.

Glacial mass balance model

Glacial runoff was calculated using a water balance approach adapted from Bliss et al.[39] Within each glacial region, there are several subregions characterized by different meteorological and geological characteristics. In addition, there are several different landforms in each subregion, which might influence the melting rate of snow or ice, i.e. the degree-day factor for snow/ice. Therefore, the estimation for the monthly glacier runoff needs to account for variations among different subregions and landforms. The monthly average glacier runoff of each glacial region (Q) was calculated using Equation 1 below.

$$Q = \sum_{i=1}^{n} S_i \times (a_i + P_{liq,i} - R_i) \quad \text{(Equation 1)}$$

where S_i (km^2) is the effective area of the glacial region, which is computed by the annual average area of subregion i, included by the glacial region. a_i is the snow/ice melt of each month, $P_{liq,i}$ (mm) is the net accumulated liquid precipitation of each month and R_i (%) is the potential of refreezing during melting of each month.

It was assumed that melting had a linear correlation with the monthly air temperature, a_i, if > 0°C, and thus a_i was calculated using Equation 2 below.

$$a_i = f_{snow/ice} \times \int \max(T_i, 0)dt \quad \text{(Equation 2)}$$

where $f_{snow/ice}$, the degree-day factor for snow/ice (mm w.e. d^{-1} °C^{-1}), is a constant that depends on the sample types, and T_i, the monthly air temperature (°C) above the glacier surface, is a random variable, which was computed using Equation 3 below:

$$T_i = T_{\text{annual average}} + (T_{\text{summer}} - T_{\text{annual average}}) \times \sin((i-4) \times \tfrac{2\pi}{12}) + \delta T_i \quad \text{(Equation 3)}$$

where the $T_{\text{annual average}}$ and T_{summer} were provided from previous studies.[39] The δT_i is a random variable following normal distributions, with a mean value of 0°C. When i referred to winter (December to February) or summer (June to August) time, the δT_i was the standard deviation of summer temperatures. Vice versa, when i referred to

606 Spring (March to May) or Autumn (September to November) time, the δT_i was the
607 standard deviation of annual average temperatures.

608 Fluxes contributed by liquid precipitations, $P_{liq,i}$, were calculated using the following
609 Equation 4.

610 $$P_{liq,i} = P_i \times \theta_{(T_i,0)} \quad \text{(Equation 4)}$$

611 where P_i is a random parameter following a normal distribution, with its mean value
612 and standard deviation cited from previous publications,[62] and $\theta_{(T_i,0)}$ is a Heaviside
613 function, which equals to 1 when T_i is greater than 0, and equals to 0 when T_i is
614 smaller or equals to 0.

615 R_i was estimated according to the linear relationship between R_i and air temperature (T_i)
616 at different elevations, assuming that the snow meltwater frozen on the surface of the
617 glacier (R_i) does not flow away. The estimation was conducted using Equation 5 below.

618 $$R_i = -0.69 \times T_i + 0.0096 \quad \text{(Equation 5)}$$

619 For each of eight glacial regions, 2500 Monte Carlo simulations were conducted (Note
620 S6). For each simulation, glacier runoff fluxes in 12 months were computed using the
621 method stated above and then summed over to obtain the annual glacier runoff fluxes.
622 One glacial region may be composed of several glaciers, while each of them might have
623 a different composition of landforms: 3 types of landforms, namely the sample types,
624 were considered, having different degree-day factors: $f_{snow/ice}$ = 1 for *glacier runoff*,
625 $f_{snow/ice}$ = 2 for *snow/ice*, and $f_{snow/ice}$ = 4 for *seawater neighboring the glaciers*. Each
626 sample type was chosen randomly for the simulation of the whole year, without bias.

627 ***Released flux estimation of PFAAs (dissolved part).*** The annual fluxes of 13 PFAAs
628 in the dissolved phase were estimated for eight glacial regions using Monte Carlo
629 simulations (Note S6). For each region and each PFAA, 2500 simulations were

conducted. Because a glacial region can consist of multiple subregions of varying sizes, the number of simulations allocated to each subregion is determined based on the respective area sizes within the larger region. For each simulation, the PFAA concentrations discharged in a subregion (C_w) were those of a sample randomly chosen from one of three sample types (ice/snow, glacier runoff, and seawater) (Table S2), with equal probability.

The glacial meltwater fluxes of the subregion from each sample type in each month were determined in the above-mentioned glacial mass balance model, and the PFAA fluxes in dissolved phase of that month were the concentration of PFAAs times the corresponding runoff volume. Annual fluxes for each region were derived by summing monthly fluxes across all subregions.

Released flux estimation of PFAAs (suspended particle part). The annual fluxes of 13 PFAAs partitioned on suspended particles of the eight glacial regions were also estimated using Monte Carlo simulations (Note S6). Based on the predictions for $\log K_d$ by the XGBoost-ML and the reported mean PFAA concentrations in water of each glacial region, we obtained the concentration of PFAAs on suspended particles (C_p) (Table S5). The annual particulate PFAA fluxes from different glacial regions were then estimated by multiplying the mean C_p by the regional average glacial runoff and the mean suspended particle concentration (Table 1). The final flux estimates for all regions are presented in Table S6.

Future Release Potential of PFAAs

The project future release fluxes of 13 PFAAs in both dissolved and particle-bound phases were estimated with the support of shared socioeconomic pathways (SSPs), which provided estimates of precipitation and air temperature from 2020 to 2100 (Figures S6 and S7). The modeling assumed there would be sufficiently large amounts of historical storage of PFAAs in glaciers.

Three SSP scenarios, namely SSP126, SSP 245, and SSP585,[64,65] were utilized to represent low, intermediate, and high global warming scenarios, respectively. For each scenario, the annual and summer average air temperatures in each subregion were calibrated using the 2020 values as a baseline. This ensured that the projected temperature increases under different SSPs, relative to 2020, were maintained. Similarly, monthly precipitation values for each region were calculated based on the recorded data from 2020, such that changes in annual precipitation projected by the SSPs were consistently applied while preserving the seasonal distribution. Detailed calibration procedures are provided in Note S6.

The potential release fluxes of 13 PFAAs, both in the dissolved phase and on suspended particles, were estimated annually from 2020 to 2100 under the three climate warming scenarios (Figures 5A and 5B). For each year, 2,500 Monte Carlo simulations were conducted to account for variability and uncertainty. The modeling approach for 2021–2100 followed the same framework used for the baseline year 2020, ensuring methodological consistency across the entire simulation period.

Deposition and budget estimates of Σ_{10}PFCAs

Atmospheric deposition is the primary input pathway of PFAAs to glacier surfaces. As the GEOS-Chem model does not simulate PFSAs,[33] our analysis focuses on ten PFCAs with carbon chain lengths from C4 to C13 (Σ_{10}PFCAs). Using the atmospheric depositional fluxes of Σ_{10}PFCAs generated by the GEOS-Chem model,[33] long with glacier surface area data (Table 1), we estimated the deposition fluxes (input) of Σ_{10}PFCAs to global glaciers. By comparing this input with the predicted release fluxes (output) of Σ_{10}PFCAs, we evaluated the input-output budget of Σ_{10}PFCAs across the eight different glacial regions (Table 1).

The GEOS-Chem model (version 12.2) is a widely used, community-developed atmospheric chemistry model that incorporates reanalysis meteorological data to simulate the transport and deposition of pollutants. Σ_{10}PFCAs were included in the

GEOS-Chem model with a detailed set of chemical reactions, emission inventories, prescribed meteorology, and wet and dry deposition schemes.[33] The model was then run at a horizontal resolution of 4°×5°, with 46 vertical levels, using assimilated GEOS-FP meteorology data. This produced the modeled spatial distribution of the annual deposition of Σ_{10}PFCAs in 2013–2015 resulting from the inventory of degradation of precursor molecules and direct global emissions. Due to the observed long-term stability of atmospheric PFAA concentrations, e.g. perfluorooctane sulfonic acid (PFOS), in polar regions over recent decades (Note S7)[12,66], we assumed the annual deposition fluxes of Σ_{10}PFCAs from 2013 to 2020 are the same.

The GEOS-Chem estimation contains a few uncertainties. These include incomplete emission inventories of short-chain PFAA replacements[67,68] and precursors,[17,47] unquantified contribution of sources such as sea spray aerosols,[69,70] and limited understanding of atmospheric transformation mechanism.[71] Despite these limitations, GEOS-Chem model offers a valuable basis for estimating large-scale deposition patterns of PFAAs to compare their input-output budget in remote glacial environments.

RESOURCE AVAILABILITY

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Materials availability

This study did not generate new unique materials.

Data and code availability

The code and data needed for Monte Carlo simulation of PFAA glacial runoff volumes, logK_d estimation for each situation based on trained XGBoost model, and the estimated release fluxes of PFAAs via dissolve phase and suspended particles are available in

https://github.com/EssexHUBOYUAN/Glacial_runoff_PFAS_sims.

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AUTHOR CONTRIBUTIONS

Conceptualization, X.W. and J.F.; methodology, Y.Z., B.H., and M.C.; investigation, L.W., M.C., and S.R.; formal analysis, B.H. and M.C.; visualization, Y.Z., B.H., and M.C.; writing—original draft: Y.Z. and B.H.; writing—review and editing, X.W., J.F., I.C., X.B., C.W., H.D., Z.W., T.A, D.L., K.J., and D.M.; funding acquisition, X.W., J.F., and Y.Z.

DECLARATION OF INTERESTS

The authors declare no competing interest.

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Figures and tables

Figure 1. Sampling sites from upstream to downstream (A) and average concentrations (B) and compositions (C) of 13 perfluoroalkyl acids (PFAAs) in seven glacial regions of the Tibetan Plateau. The seven glacial regions are: RB, the Rongbuk glacier; KG, the Korchung Gangri glacier; ZD, the Zhadang glacier; GL, the Galongla glacier; PL, the Parlung No. 4 glacier; QY, the Qiangyong glacier; and RC, the Rijie Cojia glacier. U, M, and D in part (A) represent upstream, midstream, and downstream sites, respectively.

Figure 2. Average concentrations and compositions of 13 perfluoroalkyl acids (PFAAs) in (A) eight glacial regions and sampling sites in the (B) Arctic and (C) Asian regions. The dots represent sample locations in different glacial regions. Glaciers are shown in blue, ice sheets in white, and the black lines indicate the outlines of glaciers from the Randolph Glacier Inventory. The eight glacial regions are: ①West Canada and USA (WCUG), ②Arctic Canada (ACG), ③Greenland ice sheet (GIS), ④Arctic Europe (AEG), ⑤North Asia (NAG), ⑥Central Europe (CEG), ⑦South and Central Asia (SCAG), ⑧Antarctic and Subantarctic ice sheet (AIS). The pie charts represent the composition of PFAAs in each glacial region, and bold numbers present the average concentration and standard deviation of PFAAs. The 13 PFAAs are perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUdA), perfluorododecanoic acid (PFDoA), perfluorotridecanoic acid (PFTrDA), perfluorobutane sulfonic acid (PFBS), perfluorohexane sulfonic acid (PFHxS), and perfluorooctane sulfonic acid (PFOS).

Figure 3. Comparison of the measured logK_d for perfluoroalkyl acids (PFAAs) in glacial and non-glacial regions with the predicted logK_d driven from the XGBoost algorithm: (A) Training set and (B) Test set. The red and green squares indicate the ratios of measured logK_d and predicted values that fall within ±1 log unit for samples from glacial and non-glacial regions, respectively. The white square represents the ratio of the measured logK_d and predicted logK_d that falls outside ±1 log unit, with only one data observed in the non-glacial regions.

Figure 4. Geographical distribution of perfluoroalkyl acids (PFAAs) concerned areas in the (A) Arctic and (B) the Tibetan Plateau. The red circle and purple circle represent the concerned sites for water and sediment, respectively. The orange triangles mark areas of potential biodiversity loss due to high PFAA levels found in polar bears and Arctic foxes, as reported in previous studies.[72] Detailed data for the buffer zone are provided in Tables S7 and S8, with average concentrations for water and sediment being approximately 2000 pg/L and 1000 pg/g, respectively. Buffer zones I, II, and III represent areas where PFAA concentrations in water and sediment exceed the regional average concentration by 1 time, 2 times, and more than 3 times, corresponding to impact zones of 100 km, 200 km, and 300 km, respectively.

Figure 5. Annual future release potential (kg year^{-1}) of perfluoroalkyl acids (PFAAs) from glaciers in eight glacial regions via the (A) dissolved phase and (B) suspended particles in 2020-2100 under three climate change scenarios (SSP126, SSP 245 and SSP 585). And the release potential (kg year^{-1}) of PFAAs via suspended particles from glaciers in the (C) Greenland Ice Sheet (GIS) and (D) South and Central Asia (SCAG). The release potential refers to a predicted possibility of PFAA fluxes under future climate scenarios. The solid line in parts (A) and (B) presents the average value with a window of one year and the shaded area indicates the range of minimum and maximum values. The line in the box of part (C) and (D) is median line, the edges of the boxes are the 5th and 95th percentile, and the whisker is range within the minimum and maximum values. The difference in the time scales on the horizontal axis in part (C, D) compared with (A, B) is due to the assumption that the release of glacier meltwater sediment doubles every 30 years.[27]

Table 1. Release fluxes of perfluoroalkyl acids (PFAAs) via the dissolved phase and suspended particles from glaciers in eight glacial regions globally compared with the depositional fluxes, with the glacial area, glacial runoff and average concentration of suspended particles.

Glacial region	Glacial area (km^2)	Glacial runoff (km^3 $year^{-1}$)	ACSP (mg L^{-1})	Release fluxes (kg $year^{-1}$)				Depositional fluxes of $\sum_{10}$PFCAs estimated by the GEOS-Chem model (kg $year^{-1}$) [33]	
				Dissolved phase[a]	Suspended particles[a]	$\sum_{13}$PFAAs	$\sum_{10}$PFCAs	Minimum	Maximum
WCUG	101,249	400	182	380±8.6 (89%)	46±6.0 (11%)	426±15	388±13	16.9	79.6
ACG	146,016	212	97	683±47 (98%)	14±1.3 (2%)	698±48	683±47	17.5	81.8
GIS	1,718,000	547	881	153±8.4 (49%)	162±181 (51%)	316±190	179±42	96.2	206
AEG	88,498	146	91	520±18 (92%)	44±7.3 (8%)	564±25	330±11	14.2	102
NAG	2410	7	91	9.1±0.5 (85%)	1.7±0.5 (15%)	11±0.9	8.3±0.6	0.39	2.89
CEG	2075	9	356	18±0.3 (88%)	2.6±0.1 (12%)	21±0.4	20±0.3	3.32	3.32
SCAG	97,604	352	500	1244±73 (89%)	151±13 (11%)	1394±86	1159±60	151	205
AIS	13,746,463	48	73	109±9.0 (93%)	8.2±1.1 (7%)	118±10	116±10	28.9	220
Total				3117±165 (88%)	430±210 (12%)	3547±375	2884±184	329	900

Notes: WCUG, Western Canada and USA; ACG, Arctic Canada; GIS, Greenland ice sheet; AEG, Arctic Europe; NAG, North Asia; CEG, Central Europe; SCAG, South and Central Asia; AIS, Antarctic and Subantarctic ice sheet; ACSP, average concentration of suspended particles in each glacial region reported previously. The areas of the GIS and AIS were obtained from Pfeffer et al.[73] and Liston et al.[74], respectively. The other data are available from the Randolph Glacier Inventory version 6.0 (http://www.glims.org/RGI/). The glacial runoffs of the GIS and AIS are available from Tedesco et al.[75] and Liston et al.[74], respectively, with the other data

collected from Bliss et al.[39]. The depositional fluxes of $\sum_{10}$PFCAs estimated by the GEOS-Chem model represent the average value for 2013-2015, the historical depositional fluxes might be much higher.

[a] Data presented as release fluxes (% of total fluxes).