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Distribution and sources of polycyclic aromatic hydrocarbons in the water column of Kongsfjorden, Arctic

Ruijing Li¹, Hui Gao¹, Zhongqiang Ji², Shuaichen Jin¹, Linke Ge¹,
Humin Zong¹, Liping Jiao³, Zhifeng Zhang¹, Guangshui Na^{1,4,*}

¹National Marine Environmental Monitoring Center, Dalian 116023, China

²Key Laboratory of Marine Ecosystems and Biogeochemistry, Second Institute of Oceanography, Ministry of Nature Resources, Hangzhou 310012, China

³Key Laboratory of Ocean-Atmospheric Chemistry and Global Change, Third Institute of Oceanography, Ministry of Nature Resources, Xiamen 361005, China

⁴Hainan Tropical Ocean University, Key Laboratory of Utilization and Conservation for Tropical Marine Bioresources, Ministry of Education, China

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ABSTRACT

Kongsfjorden is known for its characteristic multi-layer water mass formed by the convergence of freshwaters from nearby glaciers and rivers and saline water from the Atlantic and Arctic. The distribution of polycyclic aromatic hydrocarbons (PAHs) in the water column of Kongsfjorden was investigated and their potential sources were analyzed. The total concentrations of 16 PAHs in the surface seawater and river water were in the range of 33.4–79.8 ng/L (mean 48.5 ng/L) and 2.3–201.4 ng/L (mean 126.1 ng/L), respectively. Horizontally, PAHs were mainly concentrated around river estuaries and the glacier front in the dissolved phase. Vertically, the PAHs in the particulate phase followed surface-enrichment and depth-depletion patterns in most stations, with the maximum concentration found at 50 m depth in the central area of Kongsfjorden. The compositions of PAHs in seawater and rivers were similar, with two-ring and tricyclic PAHs comprising the majority of the dissolved and particulate phases. PAHs found in Kongsfjorden waters appeared to be derived from multiple sources such as petroleum and coal combustion. PAHs in the bay mouth of Kongsfjorden were mainly introduced by the West Spitsbergen Current and the Arctic waters, while in the inner bay, atmospheric deposition and local sources were the major contributors. The distribution of PAHs was mainly attributed to the suspended particulate distribution.

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Introduction

The Arctic environment has been suffering from increasing anthropogenic pressures (Barbante et al., 2017; Kallenborn et al., 2018), with the Svalbard Archipelago becoming an especially vulnerable area (Kozak et al., 2013). Kongsfjorden is a typi-

* Corresponding author.

E-mail: gsna@nmemc.org.cn (G. Na).

cal fjord marine system in the northwest of Svalbard; Ny-Ålesund is one of the northernmost permanent settlements of Svalbard and is located adjacent to Kongsfjorden. As the outer ends open into the sea and the inner ends near the glaciers, Kongsfjorden is regarded as a sensitive indicator of climate change (Svendsen et al., 2002). Tourism (Kozak et al., 2013), local human settlements (Kallenborn et al., 2018) and research stations (Cabrerizo et al., 2016; Vecchiato et al., 2015) constitute the sources of contamination in the polar environment. In addition, pollution from lower latitudes has been shown to threaten the local ecosystem. A large variety of contaminants have been detected in the Kongsfjorden environment; these include polycyclic aromatic hydrocarbons (PAHs) (Jiao et al., 2009; Vecchiato et al., 2015), organochlorinated pesticides (OCPs) and brominated diphenyl ethers (PBDEs) (Ma et al., 2015), DPs (Na et al., 2015). Many of these pollutants, such as polychlorinated biphenyls (PCBs) and OCPs, have accumulated in marine animals and birds to the detriment of their health (Hop et al., 2002).

PAHs are a class of typical persistent toxic substances (PTS) known for their carcinogenicity and mutagenicity. Some PAHs have been listed as priority pollutants by both the US EPA and the European Community (Luo et al., 2004). PAHs mainly originate from incomplete combustion of fossil fuels and biomass. Besides the direct discharge sources (e.g., sewage outflows and continental runoff), PAHs can enter into the marine environment through indirect pathways (e.g., atmospheric deposition, air-sea gas exchange) (Cai et al., 2016; Zhang and Tao, 2009). Due to their semi-volatile characteristics and ease of migration within the atmosphere, PAHs can disperse over long distances to remote polar regions. This phenomenon has been called the "global distillation" effect (also known as the "bounce" effect) (Blais et al., 1998; Gouin et al., 2004; Wania and Mackay, 1996). In the context of global warming, ice, as an important barrier to further pollutant movement in the environment, is now receiving increasing attention as a temporary repository of contaminants. Previous studies have shown the potential for polar regions to become secondary atmospheric sources of contaminants as a result of climate change (Ma et al., 2011), particularly in the Arctic, where recent evidence indicates the net volatilization of contaminants from local (i.e., secondary) sources (Bidleman et al., 2015). Therefore, PAHs have the potential to enter into the polar marine environment through atmospheric deposition, from continental runoff from glaciers and via ocean currents. It was reported that the North Atlantic/West Spitsbergen oceanic current around Kongsfjorden dominates the transport and input of legacy OCPs, whereas atmospheric deposition and meltwater runoff from the glaciers influence the inner fjord sediments regarding endosulfan (Ma et al., 2015). With so many sources and influencing factors, it is necessary to identify the controlling water masses in Kongsfjorden in order to understand the distribution of PAHs and identify their source and ultimate fate in the marine environment.

Kongsfjorden is mainly affected by two water masses, Atlantic Water (AW) and Arctic Water (ArW), that intermingle in the fjord during northward movement along the shelf (Appendix A Fig. S1). The entry of warm and saline AW and the cold and relatively fresh ArW into the Kongsfjorden often affects the Kongsfjorden system. Moreover, the input of glacial meltwater will also inject a large amount of pollutants that have been transported to the Arctic glaciers through the atmosphere and into the Kongsfjorden marine system. Melting of the glaciers will change the run-off pattern, and temperature and/or salinity changes in the adjacent Atlantic and Arctic water will cause changes in the fjords through exchange processes (Svendsen et al., 2002). The distributions of PAHs among different environments will reflect their inherent physico-chemical properties and biogeochemical characteristics (Parinos and Gogou, 2016). Therefore, the spatial distribution of PAHs in the water mass of Kongsfjorden is an important

indicator of the transport pattern and source of global pollutants.

Several studies have identified PAHs in different compartments of the Svalbard environment; these sources include aerosols (Cecinato et al., 2000), snow (Abramova et al., 2016; Kozioł et al., 2017; Vecchiato et al., 2018; Vehviläinen et al., 2002), rainfall (Krawczyk and SKRĘT, 2005), surface water (Kosek et al., 2018; Polkowska et al., 2011), soil (Marquès et al., 2017), sediment (Jiao et al., 2009; Kim et al., 2011; Pouch et al., 2017) and biota (Szczypiński et al., 2016). However, studies on both the horizontal and vertical distribution and the partition of PAHs related to the water mass composition in the Kongsfjorden waters are still limited. The present study collected seawater at different depths and runoff water from adjacent terrestrial glaciers in the Kongsfjorden for PAH detection. The temperature and salinity of all seawater samples was analyzed to define the water mass composition in Kongsfjorden in order to examine the distribution characteristics and sources of PAHs in multi-layer waters. Our goal was to achieve a better understanding of the sources and fate of PAHs in Kongsfjorden under the movement of currents and surface freshwater input. This knowledge would reveal the potential influence of PAHs on the Kongsfjorden environment.

1. Materials and methods

1.1. Sampling sites

Kongsfjorden lies on the northwestern coast (79°N, 12°E) of Spitsbergen, the largest island in the Svalbard archipelago. The fjord is approximately 20 km long and 5 km wide and has an unusually mild regional climate for this latitude, with an average annual temperature of approximately -6°C (Takeuchi et al., 1995). There are five tidewater glaciers directly entering the bay around Kongsfjorden; this is the main source of fresh water. Oceanographic conditions on the western Spitsbergen fjords are strongly related to the characteristics of the currents flowing around the Svalbard Archipelago. AW, with a salinity near 35.4, flows northward over the Scottish continental slope; the ArW, with a salinity lower than 34.8, flows northwards in a coastal current. The two main water masses AW and ArW outside the bay in coastal streams are mixed and form the transformed Atlantic waters (TAW). Surface water is formed during glacial ablation and dominates in late spring and summer, and the layer thickness gradually decreases toward the bay mouth. The annual average total flux of freshwater into Kongsfjorden, including glaciers, snow melt water, precipitation, runoff and groundwater, accounts for approximately 5% of the water quantity of the fjord (Cottier et al., 2005).

1.2. Sampling

Samples were collected over a two-week period during the summer in July in Kongsfjorden. Rather than a sill in the mouth, there is a prominent trench of decreasing depth towards a shallow shelf (Svendsen et al., 2002). Multi-layer seawater sampling was conducted at depths of 0, 20, 30, 50, 100, and 200 m at five seawater sites (K1, K2, K3, K4, and K5) spreading from the bay mouth to the inner bay of Kongsfjorden ($n=15$), and surface fresh water sampling was conducted at five river water sites (R1, R2, R3, R4, and R5) ($n=5$) near the glaciers of Ny-Ålesund. Owing to the seabed topography characteristics of the inner bay, the sampling depth at K4 was < 100 m and at K5 was < 30 m. The temperature and salinity of seawater were analyzed in situ with a CTD (SD204, SAIV A/S, Norway). The sampled water was filtered with glass fiber filters (GFF, 1825-047, GE Healthcare Life Sciences, USA) to collect the particulate components. According to Cao's report (Cao et al., 2018), a mixture of 100 ng/L deuterated PAH standards (naphthalene-d8, acenaphthene-d10,

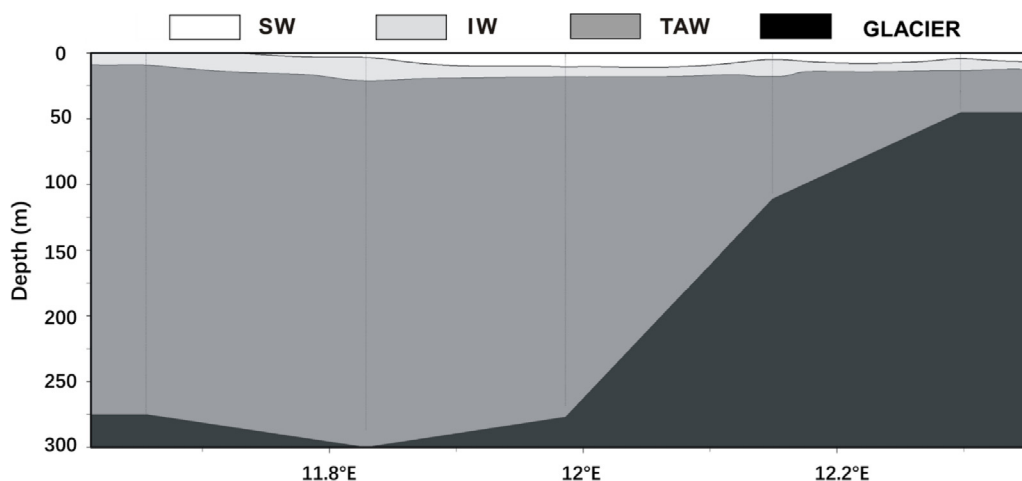


Fig. 1 – Distribution of water masses in Kongsfjorden. The Kongsfjorden waters were divided into three layers: SW (Surface Water), IW (Immediate Water) and TAW (Transformed Atlantic Waters).

phenanthrene-d10, chrysene-d12 and perylene-d12) (Z-014 J, AccuStandard, USA) was added into each 8 L of water as surrogate compounds after filtration, and then the dissolved component was concentrated in solid-phase extraction disks (2215-C18, 3M, USA).

1.3. Extraction and analysis

All samples were analyzed for 16 USEPA (United States Environment Protection Agency) priority compounds, namely naphthalene (Nap), acenaphthylene (Ace), acenaphthene (Acp), fluorene (Flu), phenanthrene (Phe), anthracene (Ant), fluoranthene (Flu), pyrene (Pyr), benzo[a]anthracene (BaA), chrysene (Chr), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[a]pyrene (BaP), indeno[1,2,3-cd]pyrene (InP), dibenz[a,h]anthracene (DbA), and benzo[ghi]perylene (BghiP). The extraction process and the analysis methods of all water samples were conducted in accordance with Cao's report (Cao et al., 2018).

1.4. Quality control

Laboratory and field blanks, recovery percentages and analytical limits were determined for each phase and individual sample. The sample extracts were tested three times to verify the relative standard deviation of the analyses. The recovery percentages of the surrogate compounds in C18 and GFF filters were 61% – 112% and 67% – 107%, respectively. The values of the method detection limits (MDLs) were derived as the mean plus three times the standard deviation of the concentrations. The relative standard deviations of the GFF and C18 samples ranged from 0.2% to 6.9%, and 1.3% to 7.3%, respectively, and the method detection limits were set as the lower limit of the calibration curve (0.01 ng for all compounds). The final PAH concentrations were corrected based on the recovery percentages.

2. Results

2.1. Hydrological characteristics of Kongsfjorden

In Kongsfjorden's inner basin, meltwater from glacier ablation results in the development of a freshened surface layer with a sharp vertical salinity gradient. The results of temperature and salinity measurements of Kongsfjorden waters and the classification standards are presented in **Appendix A Tables S1**

and **S2**, respectively, which serve to delineate the Kongsfjorden into three water masses. The section view in **Fig. 1** shows that the surface water (SW) occupies 10 m of the water column in the bay, but the layer decreases in thickness towards the fjord mouth. The vertical extent of SW is confined to the upper 2–3 m. The Intermediate Water (IW) water column was only 10 m thick, with salinity in the range 34.0–34.7 psu. The waters inside Kongsfjorden were mainly controlled by TAW, which could extend to a depth of more than 200 m.

2.2. Distribution of PAHs in multilayers of water in Kongsfjorden

2.2.1. Distribution of PAHs in the surface water of Kongsfjorden

The levels of 16 PAHs (dissolved + particulate) in the surface seawater (Σ_{16} [PAH] total) were between 33.4 and 79.8 ng/L (average 48.5 ng/L). Among these, the particulate PAH concentrations (Σ_{16} [PAH] par) were in the range of 4.4–6.7 ng/L (average 5.4 ng/L), and the dissolved (Σ_{16} [PAH] diss) were in the range of 26.8–74.1 ng/L (average 43.2 ng/L). The data indicated that most PAHs were inclined to exist in the dissolved phase. Compared with other studies, the PAH concentrations in the surface water of Kongsfjorden were higher than in the coastal area (0.6–6.3 ng/L) (Vecchiato et al., 2018) and lower than in the surface water of Fuglebekken basin, which is situated in the southern part of the island of Spitsbergen (4–603 ng/L, mean 90.26 ng/L) (Polkowska et al., 2011). The Σ_{16} [PAH] total in the surface river water was higher than in seawater (92.3–201.4 ng/L, average 126.1 ng/L), which had a Σ_{16} [PAH] par in the range of 5.1–13.6 ng/L, average 8.7 ng/L, while the Σ_{16} [PAH] diss was between 82.1–187.8 ng/L (average 117.3 ng/L). The distributions of PAHs in particulate and dissolved phases of surface water are shown in **Fig. 2**. The concentration of particulate PAHs in the outer bay was slightly higher than in the inner bay.

According to the water mass distribution (**Fig. 1**), the surface water of the inner bay was contributed by the meltwater from glacier ablation. In contrast to the particulate part, the concentration of dissolved PAHs in surface water decreased from the inner bay to the bay mouth. The highest dissolved PAH concentration in surface water was found at K4, and the lowest concentration was at K1.

2.2.2. Vertical profile distribution of PAHs in Kongsfjorden

In this study, K2 and K3 had subsurface-enrichment and depth-depletion distribution patterns for PAHs, while the bay mouth

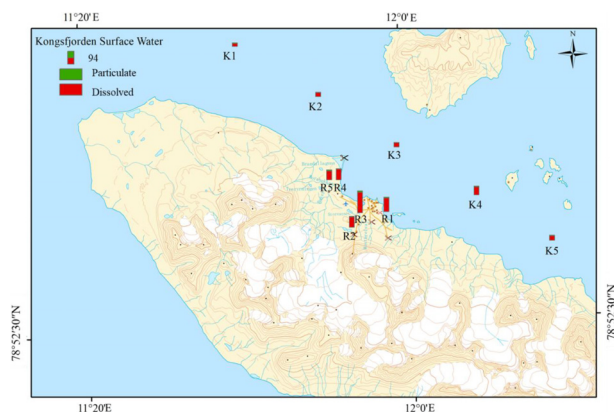


Fig. 2 – Spatial distribution of PAHs in the horizontal direction in Kongsfjorden. The red bar represents the PAH concentration in the dissolved phase and the green bar represents the PAH concentration in the particulate phase in the surface water of Kongsfjorden.

and inner bay showed a different situation, and the highest PAH concentration in the particulate phase was found in the sub-surface water of the central area of Kongsfjorden (14.3 ng/L) (Fig. 3a). Although the PAH concentration in the surface water of the bay mouth was higher than at other sites, it was decreased by half at the depth of 200 m, to the lowest level in Kongsfjorden waters (3.0 ng/L).

The values of Σ_{16} [PAH] diss were in the range of 26.6–50.5 ng/L (average 36.7 ng/L) under the surface water, and values of Σ_{16} [PAH] par were in the range of 3.0–14.3 ng/L (average 7.2 ng/L) (Fig. 3b). Similar to the spatial distribution in the surface water, Σ_{16} [PAH] diss at K4 was higher than at other stations in each studied layer, and the highest level was in the surface water. As with the particulate phase, PAHs in the dissolved phase presented surface-enrichment and depth-depletion patterns except at K1 and K5, with a concentration minimum at 200 m depth at K1 (26.6 ng/L). Referring to the water mass distribution in Fig. 1, the largest depth of surface water is in the central area, where the local input of meltwater acted as the main source of PAHs and caused PAHs to be concentrated.

2.3. Composition characteristics of PAHs in Kongsfjorden waters

With the influence of rivers and glacier meltwater input, the composition characteristics of PAHs at the sea water sampling sites were similar to those at river sites. Low-molecular-weight (MW) PAHs (2–4 rings) comprised the majority of the pollutants. Among these, 2- and 3-ring PAHs were the most abundant in the dissolved phase, responsible for 93.6% in seawater and 85.6% in river water, while 3- and 4-ring PAHs were the most abundant for the particulate phase, contributing 84.1% in seawater and 75.7% in river water (Fig. 4).

Moreover, the vertical profiles of 2- and 3-ring PAHs in the dissolved phase followed a similar trend in the bay mouth and the inner bay, with an increase from the surface water (mean 12.3, 18.9 ng/L) to the middle layer (mean 15.8, 22.5, 20.2 ng/L) and then decreasing at deeper depths (mean 11.9, 17.5 ng/L), while in the middle of Kongsfjorden, the same pollutants decreased sharply with increasing depth. Similarly, the principal components (3- and 4-ring PAHs) in the particulate phase both presented increasing trends from the surface water and then decreased to the end at K3, while their distributions in other sites were not consistent. Previous studies have reported that the maximum concentration of suspended particulate matter in front of glaciers was at 15 m depth, but at 20 m depth in the

central area (Hop et al., 2002; Svendsen et al., 2002). Due to their hydrophobic nature and relatively low solubility, PAHs tend to be adsorbed onto organic particles, resulting in their removal from surface water and subsequent transport to deep waters (Dachs et al., 1996; Lipiatou and Salot, 1991), which could be a result of upwelling of underlying water caused by meltwater input in the inner bay (Hop et al., 2002; Svendsen et al., 2002). It was inferred that the relatively stable suspended particulate mass may be an important reason for PAHs concentrating in the middle layer of Kongsfjorden center.

Focusing on the individual PAH compounds, Nap was the most abundant, contributing 68% in seawater and 55.7% in river water for the dissolved phase (Fig. 5). This result was consistent with previous studies (Jiao et al., 2009; Polkowska et al., 2011; Vehviläinen et al., 2002). However, Fl (24%) and Phe (21%) were the main compounds in seawater for the particulate phase, while Nap was the most abundant compound in river water samples (51%). This distribution patterns of particulate PAHs in seawater and river water is consistent with those in the Baier-tang and Macao water columns in South China (Luo et al., 2004), respectively.

2.4. Source of PAHs in Kongsfjorden waters

To describe the PAH sources in Kongsfjorden, we used Cross plots examining the (Flu/Flu + Pyr) and Inp/(BghiP + InP) ratios. In this study, both ratios in sea water strongly indicated a petrogenic origin of PAHs: Flu/(Flu + Pyr) and Inp/(BghiP + InP) ratios were in the range of 0.17–23 and 0.12–4.12 (Fig. 6). Among these, dissolved PAHs in all the river water samples were from grass/wood/coal combustion (Flu/(Flu + Pyr): 2.45–9.67, Inp/(BghiP + InP): 1.78–4.12), and the same sources were found for the particulate PAHs in R5. All detected river waters were from glacier meltwater, which inferred that earlier grass/wood/coal combustion activities were the main sources for glaciers in Ny-Ålesund. Recent human activities such as traveling and scientific research activities were important sources for petrogenic PAHs.

3. Discussion

The Kongsfjorden waters were delineated into three water masses according to Cottier and Payne's research (Cottier et al., 2005; Payne and Roesler, 2015). Due to the significant freshwater input, the SW in the fjord system is characterized by lower salinity compared to the typical Arctic SW found in the coastal area (Svendsen et al., 2002). The mixed water of SW in the upper layer and AW or TAW in the lower layer is called Intermediate Water (Ji et al., 2014). A recent study found that the TAW showed a gradual increase in temperature (Payne and Roesler, 2015). A study from 1990 defined TAW as $T = 5.5\text{--}7^\circ\text{C}$, $S > 34.7$ psu (Tislenko and Ivanov, 2015).

The distribution pattern of particulate PAHs in the surface water was consistent with OCPs in the surface sediment of Kongsfjorden (Ma et al., 2015). Generally, glacier concentrations would be lower than those in the seawater without additional input. Glaciers may however receive inputs of POPs from compounds entrained in snow or from wet and dry deposition. In this study, the concentration of particulate PAHs in front of the glaciers was higher than in the central area, which may be a result of the melt water from glaciers acting as a secondary source of POPs. In addition, the bay mouth surface water was from the intersection of WSC and AW off the coast of western Spitsbergen, which carried a lower level of PAHs (Lohmann et al., 2009; Nizzetto et al., 2008). Moreover, as the nearest station to rivers, K3 was prone to be influenced by the high level of PAHs from river water and expected to be the most concentrated station for PAHs. All the 5 rivers were formed by meltwater from glacier ablation, and many studies have found

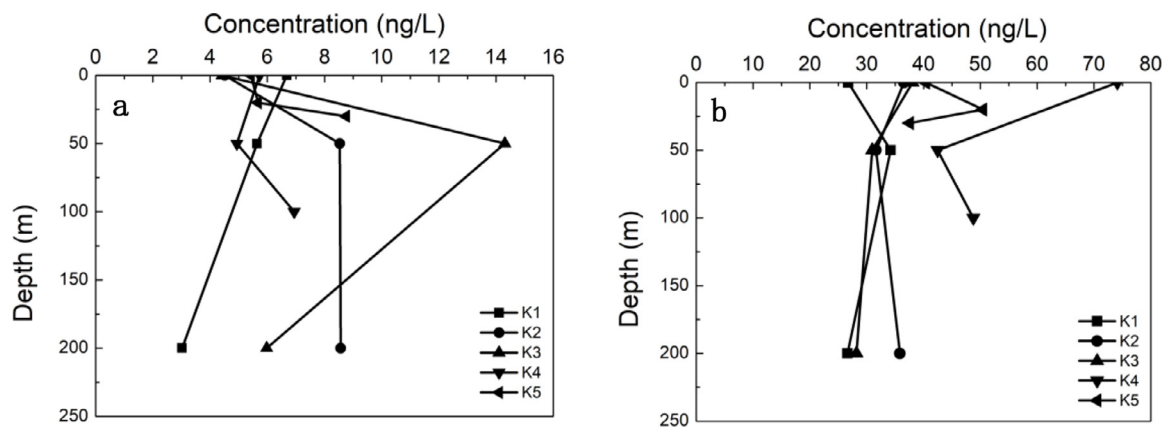


Fig. 3 – Distribution of particulate PAHs (a) and dissolved PAHs (b) in the Kongsfjorden water column.

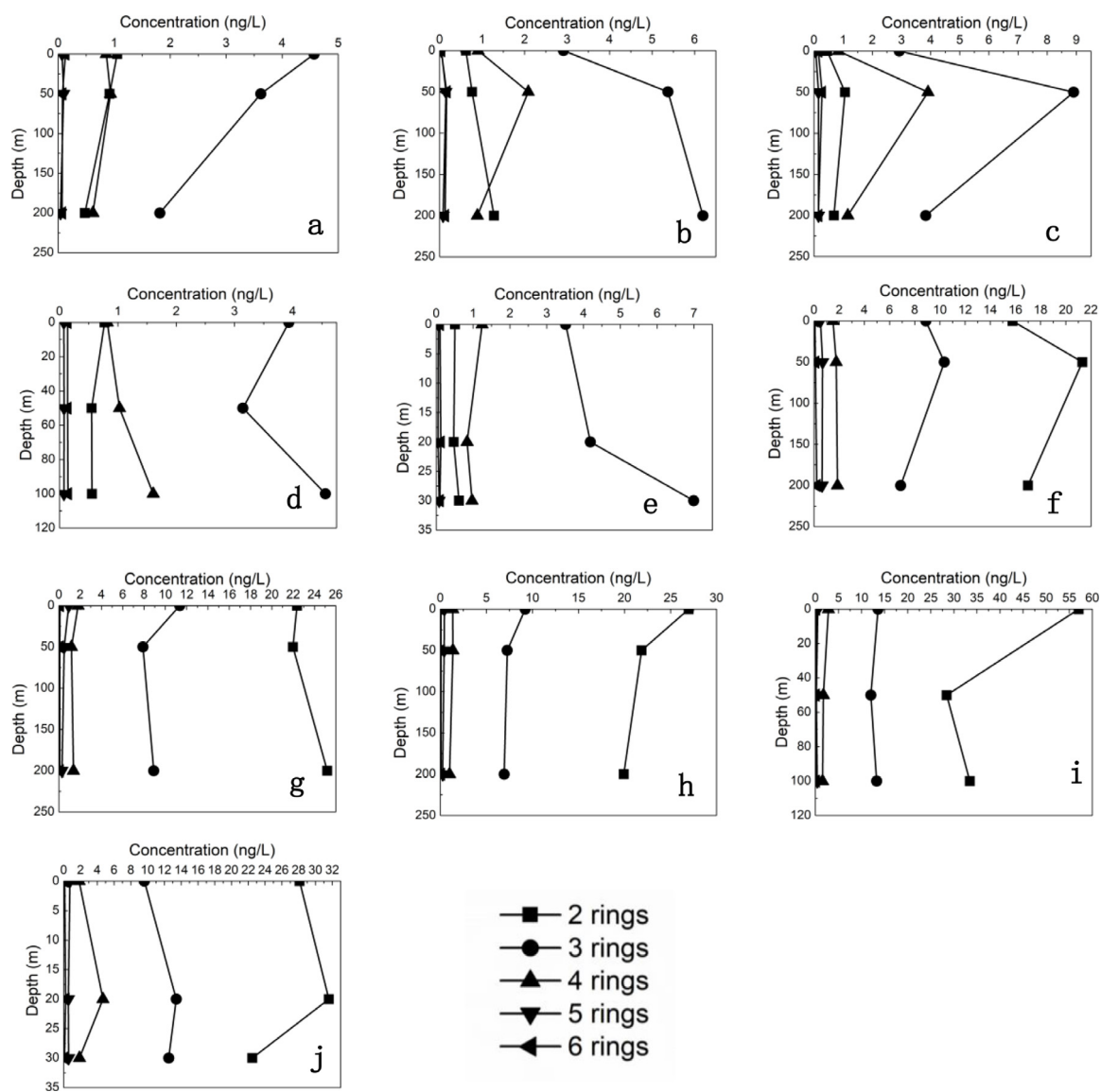


Fig. 4 – Composition characteristics of PAHs in the dissolved and particulate phases of Kongsfjorden sea water at multiple depths (K1, K2 and K3: surface, 50 m, 200 m; K4: surface, 50 m, 100 m; K5: surface, 20 m, 30 m). Particulate phase in K1-K5 (a-e), dissolved phase in K1-K5 (f-j).

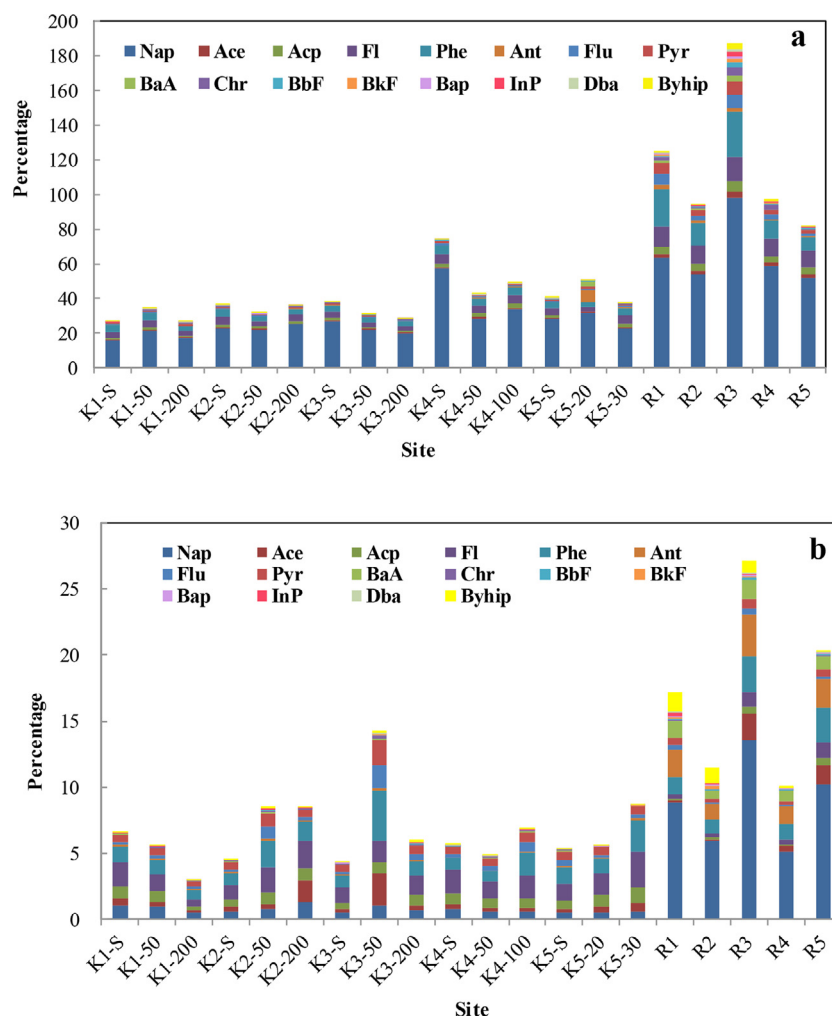


Fig. 5 – Composition characteristics of PAHs in dissolved (a) and particulate (b) phases of seawater and river water.

high input of fine-grained sediments transported in suspension from the glacier front. PAHs are hydrophobic and easily adsorb on particulate matter, so we deduced that PAHs were efficiently exported from surface waters to deeper waters by particle-mediated scavenging in the water column. Therefore, dissolved concentrations in the surface water at K3 and K5 were lower than at K4 due to the sedimentation of particulates in front of the glaciers. Svendsen et al. (2002) found that particles exported by the glacier were mainly trapped in the inner bay, where the sediment accumulation rate was one order of magnitude higher than in the middle of fjord and two orders of magnitude higher than in the outer shelf area. Moreover, the total suspended solids begins to increase in April and reaches its maximum in July, which will last about one month and end in mid-September (Svendsen et al., 2002). Therefore, suspended particulate matter was an important factor for PAH transport in Kongsfjorden summer. Niu et al. (2018) found that suspended sediment was a determining factor controlling the transport and distribution of PAHs in the water column of Pearl River estuary in China.

Settling particulate organic matter is an important carrier for vertical transport of POPs from surface water to deep waters (Carrizo et al., 2017). Our research found subsurface-enrichment and depth-depletion distribution patterns for particulate PAHs, and surface-enrichment and depth-depletion patterns for the dissolved phase only in the central area of Kongsfjorden. Cai et al. (2018) had reported surface-enrichment

and depth-depletion patterns in the vertical direction for PAHs in the particulate phase in the northern South China Sea, while the dissolved PAHs presented reverse trends. It was inferred that this vertical distribution of PAHs was strongly related to the relatively stable water column of the central bay.

Low-MW semi-volatile organic compounds can more easily undergo long distance air-sea transport (Lipiatou et al., 1997) and deposition into water. Data from the North Pacific Ocean and the Arctic area (Ding et al., 2007) showed that 2–4 ring PAHs dominated the atmospheric environment, contributing almost 50% to the Σ_{15} [PAH] diss. The PAH composition characteristics in this study could be attributed to the higher octanol-water partition coefficient (K_{ow}) of 3- and 4-ring PAHs and their proneness to adsorb onto suspended particulates. As the lowest weight PAH, Nap is semi-volatile and can transport in the atmosphere over a long range and deposit in the Arctic snow or ice gap (Vehviläinen et al., 2002). Our research indicated that atmospheric deposition was a source of PAHs both in seawater and river water, while the PAH composition characteristics in seawater may be affected by local sources.

Molecular diagnostic ratios (MDRs) were calculated to estimate the sources of PAHs in Kongsfjorden. The US EPA (U.S. EPA, 1998) has collected several hundred source-specific emission factors for PAH emission examination, and diagnostic ratios for four commonly examined isomer pairs were recommended: Phe-and Ant, Flu and Pyr, BaA and Chr, and InP and BghiP. Among these, Flu/(Flu+Pyr) is used to discriminate

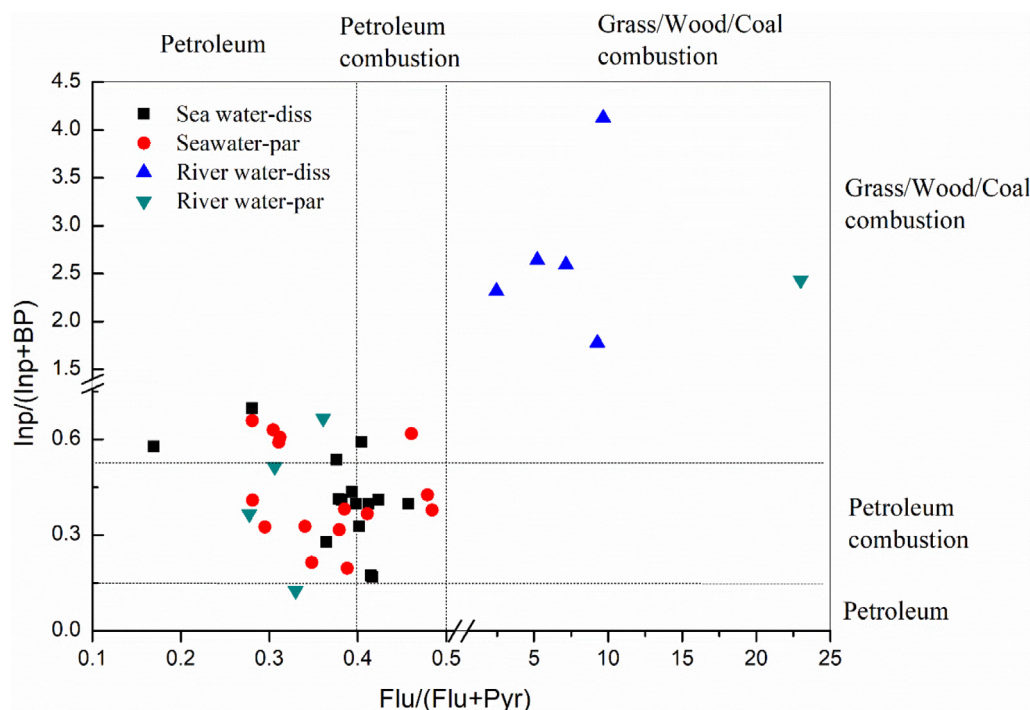


Fig. 6 – Source of PAHs in river surface water and multi-layer seawater of Kongsfjorden.

petroleum combustion from other types of combustion, and $\text{Inp}/(\text{Inp} + \text{BghiP})$ is used to corroborate the assignment of combustion sources (Yunker et al., 2002). In this study, $(\text{Flu}/\text{Flu} + \text{Pyr})$ and $\text{Inp}/(\text{BghiP} + \text{InP})$ were designated as indicators of potential sources. For mass 202, a fluoranthene to fluoranthene plus pyrene ($\text{Flu}/\text{Flu} + \text{Pyr}$) ratio of 0.5 is usually defined as the petroleum/combustion transition point (Budzinski et al., 1997), and ratios between 0.4 and 0.5 are most characteristic of liquid fossil fuel (vehicle and crude oil) combustion, whereas ratios > 0.5 indicate the characteristics of grass, wood or coal combustion. $\text{Inp}/(\text{BghiP} + \text{InP}) < 0.20$ likely implies petroleum and 0.20–0.50 indicates liquid fossil fuel (vehicle and crude oil) combustion, and ratios > 0.50 imply grass, wood and coal combustion (Yunker et al., 2002). Often, multiple sources of approximately equal weighting manifest themselves as scatter in PAH ratio plots, while ratios exhibiting less variation could provide a more accurate discrimination for one or two dominant sources (Yunker et al., 2002). Petroleum and its combustion products were the main source of PAHs for seawaters in our research, while coal combustion was the main source for river waters. Ny-Ålesund is a former coal-mining town, and post-deposition of local coal dust is an important source of PAHs for river water, as shown by findings from local lake sediments (Jiao et al., 2009). Along with the input of Atlantic and Arctic surface water, the local human activities are important sources of PAHs in seawater. This might include the nearby Arctic scientific stations at Ny-Ålesund as well as the influence of shipping, including large cruise vessels that operate in the fjord during ice-free periods (Ma et al., 2015).

4. Conclusions

This study showed the spatial distribution and sources of PAHs in Kongsfjorden. The surface water in Kongsfjorden was mainly formed by glacier meltwater, while the West Spitsbergen Current and the Arctic water were the main sources of PAHs in the bay mouth. A majority of PAHs in Kongsfjorden were concen-

trated in the TAW layer of the central area. The vertical profile of PAHs was characterized both by the suspended particulate distribution and melt water runoff. Low-molecular-weight (MW) PAHs (2–4 rings) were the most abundant components in both seawater and river water. The PAH concentration in river was higher as a whole than in seawater. PAHs in river water were mainly from local coal/biomass burning or long-range atmospheric deposition, whereas PAHs in seawater were mainly from petroleum associated with shipping transport. North Atlantic/West Spitzbergen oceanic currents influence the transport and input of the legacy PAHs, whereas atmospheric deposition and meltwater runoff from the glaciers dominate their occurrence in the inner fjord. This distribution pattern indicated the influence of ocean currents and glacier runoff on the PAH distribution in the Kongsfjorden marine system. The carrying capacity of the water mass for pollutants should be calculated in future research.

Declaration of Competing Interest

All the authors of JES_2019_1705 declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.jes.2020.04.024](https://doi.org/10.1016/j.jes.2020.04.024).

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