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Relating (oxygenated) Polycyclic Aromatic Hydrocarbon concentrations in East Antarctic summer to air mass origin characteristics

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Abstract. Antarctica is the most remote region on Earth, and the presence of organic pollutants in its environment is of significant concern. To assess the role of atmospheric transport in the temporal variability of Polycyclic Aromatic Hydrocarbons (PAHs), backward trajectories were calculated using the FLEXTRA model for the Belgian Princess Elisabeth Station (PES; 71.95°S, 23.34°E, 1380 m a.s.l.) over the period January 2010 to February 2021. A k-means cluster analysis based on latitude, longitude, and altitude identified four distinct air mass origin clusters, with the dominant cluster representing Antarctic continental air masses from higher altitudes. The results reveal a strong seasonal pattern, with a more localized atmospheric circulation during summer in this region of East Antarctica, differing from other seasons. During four austral summer seasons from 2017/18 to 2020/21, atmospheric samples were collected by high-volume sampling and analysed for (oxygenated) PAHs ((oxy-)PAHs). Atmospheric backward trajectories were analysed for each of the collected samples to investigate the influence of air mass origin on (oxy-)PAH variability. However, no clear relationship could be established between PAH levels and atmospheric air mass origin parameters such as air mass origin cluster, temperature, distance to the station, and marine contribution. Phenanthrene was identified as the most abundant PAH at Princess Elisabeth Station, and it is suggested that its presence is governed by a seasonally distinct interplay of long-range transport and local remobilization from snow rather than by simple source-to-sink mechanisms.

1 Introduction

Polycyclic Aromatic Hydrocarbons (PAHs) are a group of semi-volatile organic compounds (sVOC) (Keyte et al. 2013; Cabrerizo et al. 2014) that are mainly formed by incomplete combustion of fossil fuels or biomass (Dat & Chang 2017). Anthropogenic sources such as vehicle exhaust and industrial burning are dominant (Abdel-Shafy & Mansour 2016). PAH are sometimes counted alongside persistent organic pollutants (POPs) (Keyte et al. 2013;

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Giannarelli et al. 2019), but they are not POPs *sensu stricto* (Secretariat of the Stockholm Convention (SSC) 2023). They partition between gas and particle phase, and long-range transport potential increases with association to particles (Lohmann & Lammel 2004; Lammel et al. 2009). They can be removed from the atmosphere through dry or wet deposition, or degrade in the atmosphere (Abdel-Shafy & Mansour 2016).

Phenanthrene has previously been recovered as one of the most abundant PAH in Antarctica (Cabrerizo et al. 2014; Xie et al. 2020), followed by its derivate phenanthrene-9-carboxaldehyde, naphthalene and fluoranthene (Fig. S4). Total PAH concentrations including oxygenated PAH (oxy-PAH) both in gas and particle phase at PES range from 30 to 250 pg/m³, although elevated concentrations could be traced back to volcanic eruptions and the baseline Antarctic concentrations are likely around 50 pg/m³ (Van Overmeiren et al. 2024). PAH are most abundant in gaseous phase and only rarely as particles, while oxy-PAH have a larger share in particle phase (Fig. S4).

It is debated whether the sources of PAH such as phenanthrene in remote polar areas are mainly determined by local sources such as oil spills and combustion at research stations (Vecchiato et al. 2015; Yao et al. 2016; Na et al. 2020; Wu et al. 2023), long-range atmospheric transport (Lammel et al. 2009; Cabrerizo et al. 2014), or a mixed origin (Cao et al. 2018; Szopińska et al. 2019; Jin et al. 2023). The main mechanism that governs atmospheric concentrations of sVOC is the exchange between surfaces and the atmosphere (Wania et al. 1998). A strong relationship between temperature and particulate sVOC levels can be interpreted as temperature-dependent release of PAH from the surrounding areas, while long-range atmospheric transport would be less temperature dependent (Cabrerizo et al. 2014; Na et al. 2020). In Antarctic snow samples, there is a clear trend in decreasing PAH values with increasing distance from the sea and increasing altitude (Giannarelli et al. 2019). If long-range transport governs (oxy-)PAH concentrations at PES, these concentrations should therefore co-vary with air-mass origin parameters along backward trajectories, while station temperature dependence would indicate more local processes.

PAH are relevant in an ecological context due to their toxicity. Many compounds are carcinogenic, disrupt development and metabolism (Honda & Suzuki 2020). Given their rapid metabolization in animals, it has been found that PAH concentrations actually decrease throughout the food web in the South Shetland Islands (Jin et al. 2023), unlike heavy metals or POPs which do bioaccumulate (Trevizani et al. 2016; Pala et al. 2023). Numerous phenanthrene-degrading soil bacteria have been found in Antarctica, which is interesting for bioremediation of fuel polluted soils using native organisms (Gran-Scheuch et al. 2017). The bacteria use a large array of metabolic pathways to degrade sVOC, and they are well adapted to both marine and terrestrial environments and can be both solitary or associated with plants (Egas et al. 2023). Even penguins are exposed to PAHs (Montone et al. 2016), as are many other species.

The Antarctic climate is very relevant to global climate, and it is highly connected to the global climate system (Turner et al. 2014). The Antarctic atmospheric circulation is dominated by a high-pressure system over the continent, driven by cold, dense air over the high East Antarctic plateau, and a surrounding, intense low-pressure, cyclonic, and westerly wind belt (the circumpolar trough). During the dark Austral winter, temperatures reach extreme minima, leading to the formation of a strong, stable high-pressure system over the continent, and enabling the formation of the so-called Polar Vortex, strong westerly winds in the upper atmosphere (Stohl & Sodemann 2010). This gradient between the circumpolar trough and the Antarctic interior high-pressure system weakens

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during austral summer. Due to the subsidence of cold air, upper tropospheric and also stratospheric air can reach the Antarctic lower troposphere.

The zero-emission Belgian Princess Elisabeth station (PES; 71.95°S, 23.34°E, 1380 m a.s.l.) is located on the Utsteinen Ridge in East Antarctica at an altitude of 1382 meters, around 220 km from the sea and 50 km to the Antarctic plateau. At PES a great variety of research has been or is being undertaken, like on glaciology, surface mass balance (Souverijns et al. 2018; Wauthy et al. 2024), microbiology (Peeters et al. 2011), atmospheric composition (Van Overmeiren et al. 2023; Van Overmeiren et al. 2024) and meteorology (Gorodetskaya et al. 2015; Sauerland et al. 2024). Therefore, a detailed characterization of the long-range atmospheric transport and of air mass origin is relevant for all the before-mentioned research at PES.

During four austral summer seasons (2017/18 to 2020/21), atmospheric samples were collected by high-volume sampling and analysed for (oxy-)PAH (Van Overmeiren et al. 2024). That study constituted the first investigation of atmospheric PAHs in East Antarctica outside the immediate influence of seawater-air exchange, and its dataset forms the basis of the present analysis. To investigate the variability in (oxy-)PAH concentrations, atmospheric backward trajectories were computed for each sample, which assesses the origin and characteristics of the air masses. This study aims to quantify the relationship of air mass origin parameters such as distance to the station, temperature across the backward trajectories or marine contribution to the concentration of PAH and oxy-PAH at PES. This objective is embedded in an overarching characterization of the general atmospheric transport pathways for this region in East Antarctica and identification of their seasonal and regional patterns.

2 Material and Methods

The data used in this study was collected within the Belgian Antarctic research project CHASE (*Unravelling Particle Chemistry in Dronning Maud Land: from Atmosphere to Surface*; 2017-2022; Mangold et al., (2022)). That research project investigated the sources, chemical composition, and atmospheric transport of particles and (semi-)volatile organic compounds, using chemical analyses and atmospheric transport modelling to better constrain natural and anthropogenic influences in this remote region. We use PAH data from the entire sampling period of the austral summer seasons 2017/18-2020/21 with a resolution of 7-8 days per sample filter. This dataset contains concentrations of 16 PAHs and 13 oxy-PAHs. Datapoints lower than the detection limit were coded as 0. An overview of the dataset, including description of the sampling, analysis, and results can be found in Van Overmeiren et al. (2024) and Fig. S4. For PAH and oxy-PAH data, samples were taken with a Digitel high-volume sampler sampling both gaseous and particle-bound PAH and extracted by pressurized liquid extraction. The extract was analysed by gas chromatography high-resolution mass spectrometry. The detection limits are around 0.5 pg/m³ for most PAHs and typical concentrations range around a few pg/m³ (Van Overmeiren et al. 2024). PES is designed as a zero-emission facility, with power primarily from wind, photovoltaics, and batteries, which strongly limits local emissions. Additionally, the sampling system had an automatic shut-off system in case the wind direction came from the station, which further prevented contamination directly from station activities. This setup aimed to minimize the effect of local sources such as oil spills or vehicle combustion.

Atmospheric circulation was modelled using backward trajectories from the period January 2010 to February 2021. These trajectories were calculated with the FLEXTRA model, which simulates atmospheric transport using interpolated 3D wind fields (Stohl et al. 1995). FLEXTRA was driven by meteorological input data from the

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European Centre for Medium-Range Weather Forecasts (ECMWF), using the ERA-5 dataset at a grid of 0.5° x 0.5°. They were subsequently clustered with a non-hierarchical k-means algorithm, a less sensitive method (Kassomenos et al. 2010) that groups the data by normalized height, latitude and longitude. The backward trajectories originate on ground level of Princess Elisabeth station with the starting point being defined only by longitude and latitude. Each backward trajectory traces the air mass ten days back in time using three-hour time steps, with backward trajectories initiated at regular six-hour intervals.

Data analysis, including maps and clustering, was done in R version 4.5.2. Datapoints were classified as marine or continental using a medium-resolution shapefile of the Antarctic coastline (Gerrish et al. 2024). Marine contribution is defined as the percentage of points classified as marine during the 10-day period of the trajectory. Circular spline generalized additive modelling (GAM) was applied to analyse seasonal trends in marine contribution. Seasonal circulation patterns were determined by clustering the frequencies of the previously defined trajectory clusters across all seasons using k-means. Spring, summer, fall and winter refer to the austral meteorological seasons, starting on the 1st of September, December, March and June respectively.

Relationships between PAH concentrations and atmospheric parameters were evaluated using a range of models that included combinations and interactions of variables. (Table S1). Possible PAH sources were identified using diagnostic ratios following (Tobiszewski and Namieśnik, 2012).

PAHs were analysed at different levels of aggregation. “Full compounds” refer to individual compounds with additional distinction between gas and particulate phases. “Compounds” refer to individual PAH compounds without distinguishing between gas and particulate phases, while maintaining a distinction between PAHs and oxy-PAHs. “Compound aggregates” include PAH compounds together with their oxygenated derivatives.

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3 Results

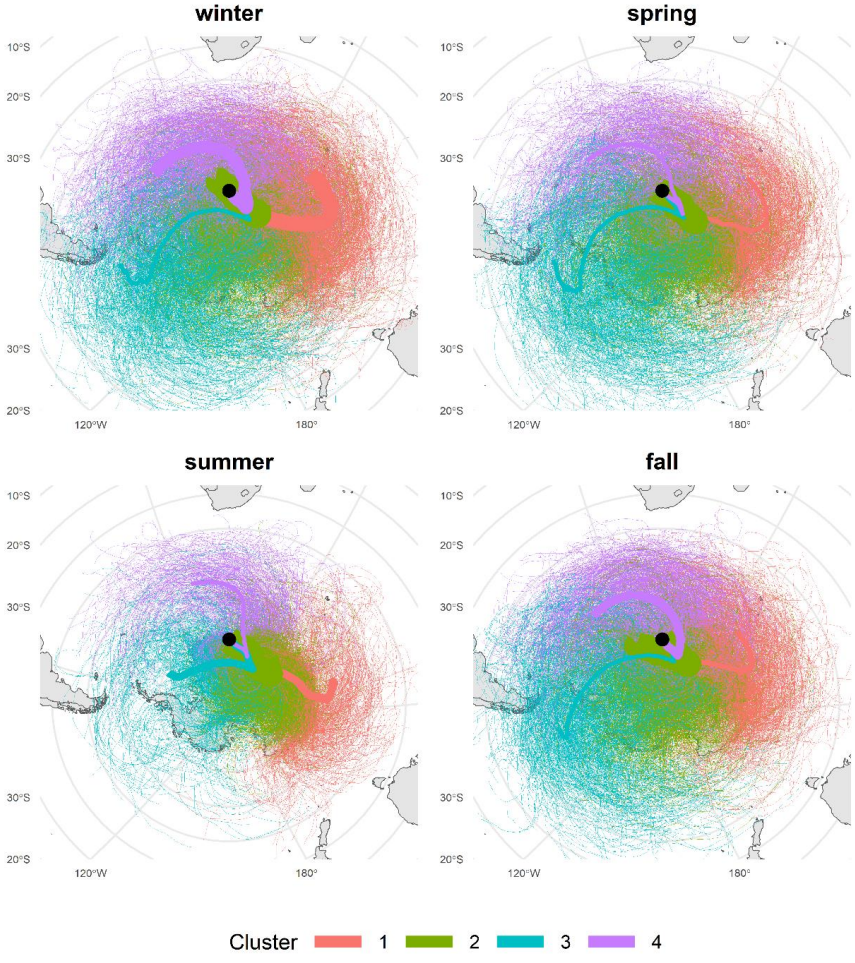

Figure 1: Clustered seasonal air mass trajectories (2010–2021). Individual trajectories are shown as coloured lines corresponding to different clusters. The average trajectory for each cluster is indicated by a bold line, with line width proportional to the cluster's relative frequency. PES is marked with a black dot.

The trajectory clusters move in different directions: Cluster 1 originates in the Indian ocean, cluster 3 originates from South America or the Weddell Sea and cluster 4 originates in the Atlantic region (Fig. 1). Cluster 2 is confined to the Antarctic continent (Fig. 1). Air mass backward trajectories rarely follow a direct meridional path from the ocean to the station; instead, their movement typically involves a significant zonal component, reflecting a more curved trajectory, following the main synoptic circulation.

The seasonal distribution of clusters varies significantly in terms of spatial coverage and relative frequency (Fig. 1). Five main seasonal circulation patterns were distinguished by k-means clustering of trajectory cluster

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frequencies for each season (Table I) and subsequently described according to their air mass origin. Summer seasons generally show a highly dominant Antarctic continental air mass origin with only minor contributions from adjacent oceans. Other seasons can show more distinct patterns, often related to varying contributions of the different oceans (Table I).

Table I: Seasonal circulation patterns summary; note that 'continental' refers to the Antarctic continent

Pattern	Description	Main Seasons
A	Comparatively low continental input, comparatively strong contribution of Southern Indian Ocean air masses, average contribution of Atlantic air masses and Weddell Sea air masses	Winter
fall2017, winter2010, winter2016, winter2018, winter2019, winter2020		
B	Highly dominant continental air mass origin with above-average contributions from the Southern Indian Ocean and very low contributions from the Atlantic and the Weddell Sea	Summer
spring2014, spring2020, summer2010/11, summer2011/12, summer2013/14, summer2014/15, summer2015/16, summer2016/17, summer2017/18		
C	Highly dominant continental air mass origin with above-average contributions from the Weddell Sea and very low contributions from the Southern Indian Ocean and the Atlantic	Summer
spring2011, summer2012/13, summer2018/19, summer2019/20, summer2020/21		
D	Average continental input, high Atlantic input	Spring, fall
spring2012, spring2013, spring2016, spring2018, spring2019, fall2011, fall2013, fall2015, fall2016, fall2018, fall2019		
E	Comparatively low continental air mass origin, significant contributions from Atlantic and Weddell Sea air masses	Winter, spring, fall
spring2010, spring2015, spring2017, fall2010, fall2012, fall2014, fall2020, winter2011, winter2012, winter2013, winter2014, winter2015, winter2017		

In all clusters, the air masses begin descending onto the station from a height of around 2 km above the ground level of the station within 24 hours before arrival (Fig. S1). Even air masses that come from nearby marine areas first ascend from the ground level before descending onto the station from a greater height. Earlier on, the average cluster 1, 3 and 4 backward trajectories came from a constant level of 1500 m which could have ascended from sea level at various moments. In contrast, the average cluster 2, and in summer also cluster 3 backward trajectories, remained at a height of 4500 m during the entire 10-day period preceding the arrival at the station (Fig. S1).

In contrast to the distinct height patterns, the backward trajectories gradually approach the station in terms of distance (Fig. S2). This is not the case for cluster 1 which, except for during summer, first increased in distance before revisiting the station (Fig. S2). In all seasons except for summer, cluster 3 backward trajectories came from the greatest distances (~5000 km), while cluster 2 and 4 have a very similar distance history around 3000 km (Fig. S2). In summer, cluster 2, 3 and 4 have a very similar distance history around 2300 km, indicative of the Antarctic continental dominance. Only cluster 1 came from distances around 4500 km during summer.

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There is a clear seasonal trend in marine contributions in addition to geographic origin (Table I). Although Cluster 2 is the most common across all seasons, it is only during summer that its frequency exceeds the combined frequency of all other clusters (Fig. 2). During the other seasons, clusters 1, 3 and 4 are rather equally frequent (Fig. 2). All clusters contain less marine contribution in summer compared to other seasons, even if some clusters are generally more marine than others (Fig. 2).

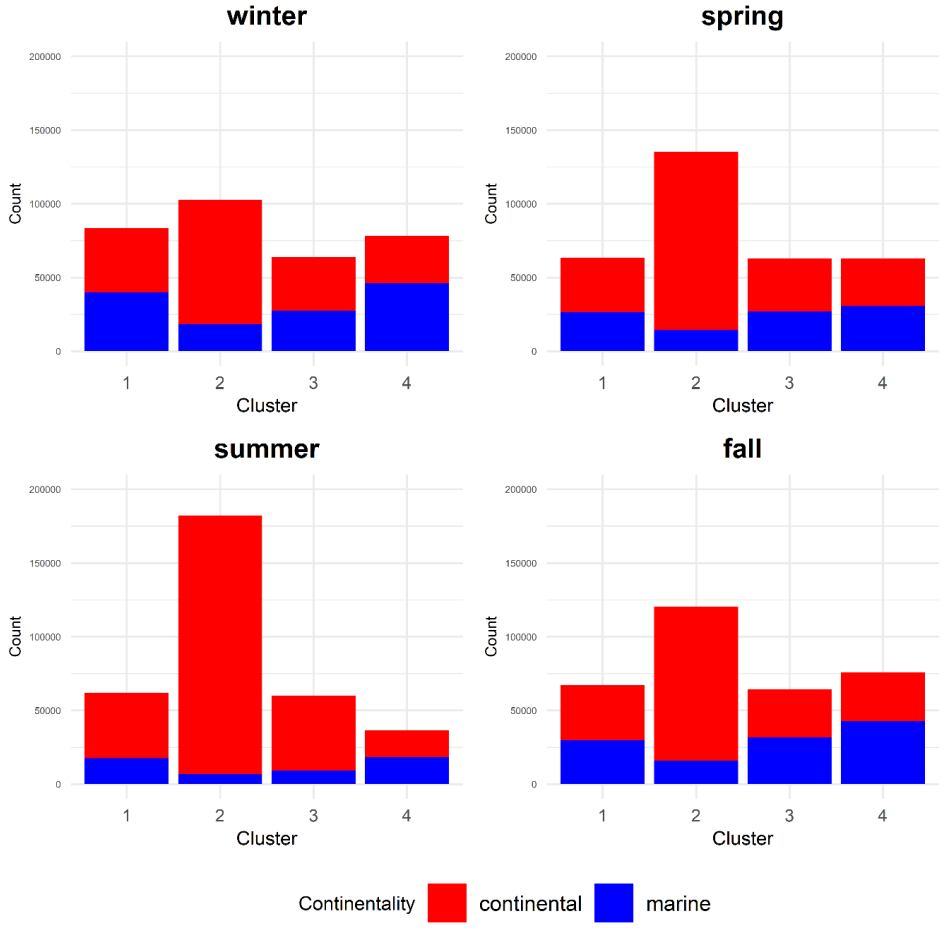

Figure 2: Distribution of continental and marine contributions by season and cluster (2010-21). Bars show the proportion of continental (red) and marine (blue) air masses for each cluster on the x-axis, with separate panels for each season.

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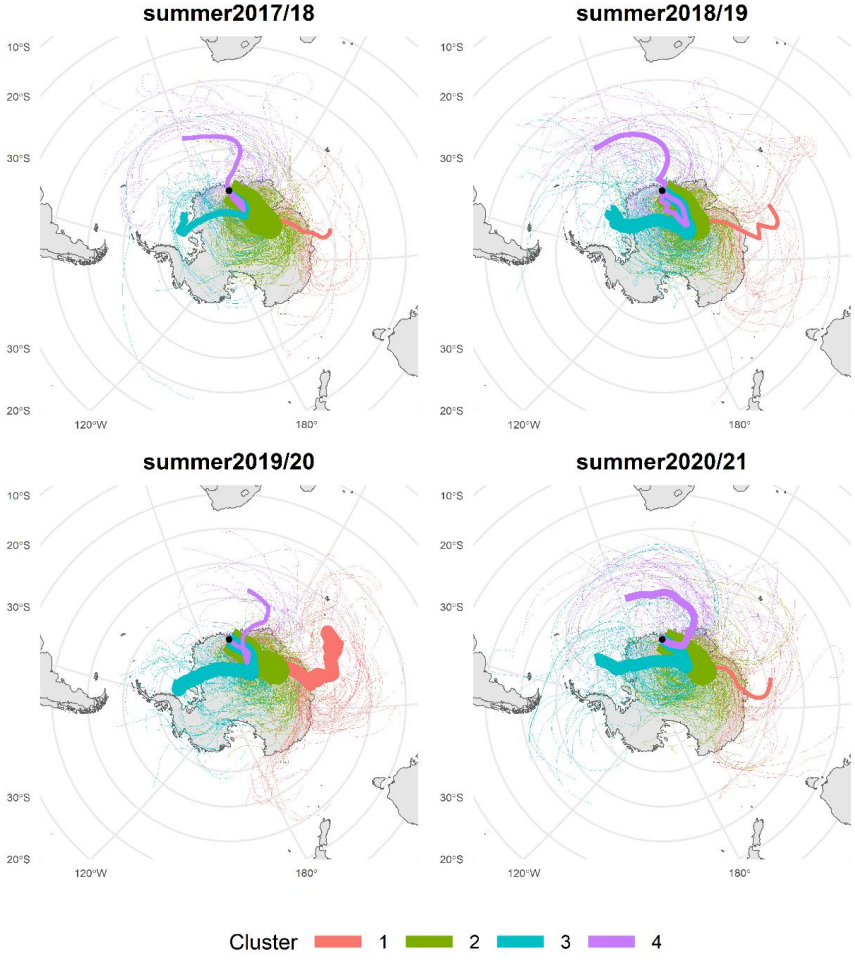

Figure 3: Clustered seasonal air mass trajectories for the four summer sampling seasons. Individual trajectories are shown as coloured lines corresponding to different clusters. The average trajectory for each cluster is indicated by a bold line, with line width proportional to the cluster's relative frequency. PES is marked with a black dot.

During the four sampling seasons, the circulation pattern is broadly similar (Fig. 3). Summer 2017/18 corresponds to type B, while the other three summers are type C (Table I). This difference is most apparent in the very low proportion of Weddell Sea air masses during the first season compared to the following three. In summer 2019/20, there is an apparent increase in cluster 1 contribution; however, this remains within the range of the other seasons and is not statistically significant. Additionally, the first sampling season shows higher overall PAH concentrations, which can be attributed to volcanic eruptions (Van Overmeiren et al., 2024) (Fig. S4). Antarctic continental origins are dominant across all filters and marine origins are minor, almost completely absent in several filters (Fig. 4). Cluster 2 is clearly dominant during the sampling seasons, followed by cluster 3 (Figs. 3, 4).

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The GAM modelling technique reveals that the most rapid decline in marine contribution is robustly recovered at the end of October/beginning of November, about one month before the start of meteorological summer (Fig. S3). The most rapid increase in marine contribution takes place in accordance with the transition between meteorological summer and autumn (Fig. S3).

Figure 4: Air mass contributions for each filter, grouped by cluster and continentality. Each bar represents a single 7–8 day filter sample on the x-axis, with colours indicating the relative contribution of each air mass cluster and whether it is marine or continental. Differences in bar height reflect varying sampling durations.

PAH concentrations measured in 7–8-day filter samples show that the relative contribution of air mass clusters varies between sampling periods (Fig. 4). However, neither time of most recent marine origin nor distance nor marine contribution nor average temperature have any significant effect on the PAH concentration measured during the summer seasons at PES. This is illustrated in Fig. 5, which shows the four main-effect plots (i.e the linear effect of the before-mentioned parameters) for phenanthrene gas (Fig. 5). Combinations and interactions in mixed and fixed effect models were also non-significant (Table S1). This is the case for full compounds, individual compounds, compound aggregates, compound ratios and total PAH concentrations (Fig. S5).

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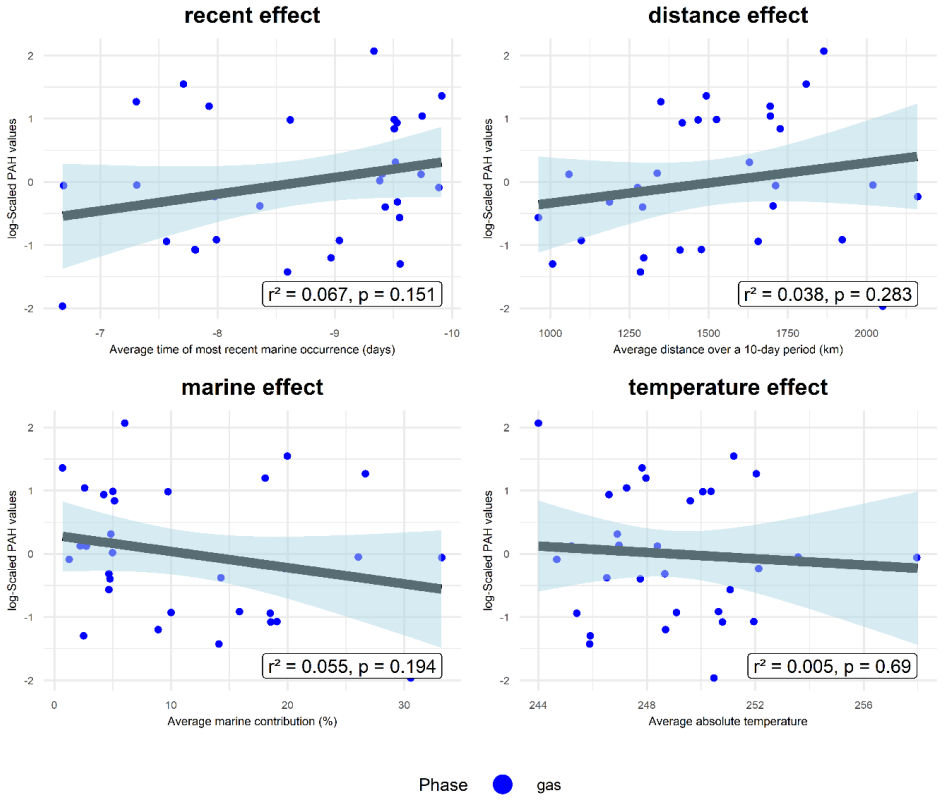

Figure 5: Effects of most recent marine occurrence, distance, marine contribution, and temperature on phenanthrene gas concentrations at PES. Points represent individual measurements, black lines show predicted effects from main-effect linear models, and shaded ribbons indicate 95% confidence intervals. Annotations display model r² and p-values. Phenanthrene is the most abundant PAH in East Antarctica. Individual effect plots for other PAHs are shown in Figure S5.

4 Discussion

The overall dominance of the Antarctic continental origin of the air mass in all found clusters is coherent with the general characteristic of the Antarctic circulation that the air is fed by subsidence, the downward movement from the troposphere and stratosphere to the lower troposphere (Stohl and Sodemann, 2010). It has been found previously that air in the East Antarctic atmosphere in summer is more continental than in winter (Suzuki et al., 2013), coherent with our findings. This indicates that during austral summer, the Antarctic continent presents the main source region of air masses and that oceanic or lower-latitude source regions are less frequent than what would be expected from the weakened circumpolar trough and polar vortex during austral summer. The result that in all clusters, the air masses first show an ascending path before descending onto the station from a greater height (Fig. S1) can be understood by the pattern that warmer air masses, more likely to be marine in origin, slide on top

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of colder, more continental, air (Glawion et al., 2019), which is further amplified by the orographic gradient between the sea and the station.

The investigated parameters associated with atmospheric backward trajectories do not provide significant effects on PAH concentrations at PES. This means that a simple source-to-sink model that links the variability in PAH to the average parameters of their air mass origin does not sufficiently describe variability in PAH concentrations measured at this remote location.

In this regard, 10 days of backward trajectory modelling may not provide a long enough timeframe to trace back remote PAH sources to their origin beyond the Antarctic (Van Overmeiren et al., 2024; Virkkula et al., 2022). During the sampling period, most backward trajectories remained continental, with only limited marine influence (Fig. 4), indicating that longer trajectories would be required to reach potential source regions on other continents, which would be inherently less accurate due to increasing uncertainties in atmospheric transport (Delcloo and De Meutter, 2020). The persistence of clusters 1-3 at a nearly constant distance (~2000 km) from the station over several days during summer (Fig. S2) indicates circular air-mass motion around East Antarctica, with little direct meridional transport from the ocean to the station, a pattern that is much less pronounced in winter. This increases the travel time of long-range PAHs to the station, allowing more time for photochemical reactions.

Phenanthrene undergoes rapid photo degradation and reaction with OH radicals, resulting in an atmospheric lifetime of only a few hours (Ram and Anastasio, 2009). Field and laboratory measurements from Greenland indicate lifetimes of ~3–6 h under summer conditions (Ram and Anastasio, 2009). During the Antarctic summer, nearly continuous sunlight further enhances photochemical degradation, resulting in very short effective lifetimes for phenanthrene and other reactive PAHs. However, other factors stabilize PAH in polar regions, such as particle-associated shielding (Keyte et al., 2013) and stabilization through low temperatures (around −25°C in summer, based on air-mass trajectory data; Fig. S5.4) (Cao et al., 2018).

Resulting from the long transport duration and short-term chemical processes, the 7-8 day sampling period per filter presents a significant limitation on temporal resolution, which is lower than in some comparable studies, e.g. 24 h sampling of heavy metals (Marina-Montes et al., 2020) or 48 h sampling of PAHs (Cao et al., 2018), both in the South Shetland islands. Nevertheless, given that PAH concentrations are extremely low in this very remote location (in the range of several tens of pg/m³), shorter filter periods would likely fall below the analytical detection limit, reducing data reliability. Finally, the very low concentrations of individual PAHs introduce additional uncertainty. Because total PAH concentrations are calculated as the sum of individual compounds, and measurements below the detection limit are omitted, error propagation can be substantial if total PAH concentrations are used to assess transport effects. It should also be noted that the most rapid decrease in marine contribution occurs one month before the transition to meteorological summer (Fig. S3), which suggests an earlier shift in PAH transport that is not yet captured in concentration data. Despite these constraints, the dataset provides new insights into PAH occurrence in an environment with extremely low background levels.

While the role of local vs distant PAH sources is debated, local contributions are expected to be minimal in this remote inland region of Antarctica and were accounted for in the experimental design (Van Overmeiren et al., 2024). PAH source identification at PES is inconclusive, based on diagnostic ratios. The ΣLMW/ΣHMW ratio (1.25-29.70) and the Anthracene/(Anthracene + Phenanthrene) ratio (0.00-0.085) tend towards petrogenic sources at PES (Pies et al., 2008; Soclo et al., 2000), but the Fluoranthene/(Fluoranthene+Pyrene) ratio (0.31-0.72), does not sufficiently indicate petrogenic sources (De La Torre-Roche et al., 2009). There is no correlation of those

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diagnostic ratios across the same filters (r=0.218, p=0.230). The Fluorene/(Fluorene + Pyrene) ratio (0 and 0.87) does not indicate whether petrol or diesel is the source (Ravindra et al., 2008). Therefore, neither petrogenic nor pyrogenic sources can be ruled out and the aged Antarctic air might make the diagnostic ratios rather inconclusive (Kim et al., 2009), instead of pointing towards one specific kind of source.

The gas-particle partitioning of compounds is highly relevant to their transport capacities (Lohmann and Lammel, 2004), and compounds were measured both in particulate phase and gas phase. However, most compounds occur predominantly in one phase (Fig. S4), making direct analysis of partitioning within compounds impossible, as no compound was consistently detected in both phases without null values (Fig. S4). However, there is a significant correlation between the sum of particle-phase and gas-phase PAH within the same samples (r=0.730, p = 3.11 x 10^{-6}), which suggests a common origin rather than local remobilization, reemission or PAH loss following (Cabrerizo et al., 2014; Na et al., 2020). As filters were collected once per week, partitioning that occurred during atmospheric transport and within the filter itself cannot be distinguished.

A key factor driving PAH accumulation in polar regions is the cold trap: chemicals transported through the air condense in the low temperatures, become enriched in the environment, and remain effectively trapped (Mackay and Wania, 1995). In this remote region, the initial deposition of PAHs is likely dominated by long-range atmospheric transport, facilitated by subsidence over the station (Fig. S1). Crucially, air mass trajectory analysis reveals a strong seasonal difference: during summer, circulation is more localized, with shorter transport distances and lower marine influence compared to winter (Figs. 1, 2, 3, S2). This trajectory-based seasonal confinement directly limits long-range transport of PAHs to PES during summer. We therefore propose that the measured summer PAH levels primarily reflect the remobilization of previously deposited PAHs from snow and ice back into the atmosphere. This process effectively constitutes the “local” source at PES during summer, even if the compounds were initially delivered from distant regions. This remobilization is temporally variable and involves complex chemical and physical transformations during snow-air exchange. The remobilization of PAH from snow in summer is supported by the in some cases significant dependence of atmospheric concentrations on temperatures at the station (Fig. S6) following (Cabrerizo et al., 2014; Na et al., 2020), as opposed to a relationship with temperature along the trajectory (Fig. S5.4). Additionally, the station temperature – PAH relationship is opposite for particles and gas, although surprisingly, an interesting pattern emerges: PAH gas concentrations tend to decrease with increasing temperature at the station, while particle concentrations increase, which is unusual and occasionally significant for some compounds (Fig. S6). This possibly reflects different temperature-dependent mechanisms of degradation in gas phase and resuspension of previously deposited particles. In colder temperatures, there should be a shift towards higher particle concentrations (Cabrerizo et al., 2014), while gas concentrations are expected to be less temperature-dependent and reflect long-range transport, (Giannarelli et al., 2019; Na et al., 2020). This is not the case here, where gas and particles have a common origin and both show some local and opposite temperature dependence, further inviting research on snow-air exchange for different compounds and phases in remote polar environments and in sub-zero conditions.

Initial PAH deposition in winter is likely enhanced by longer atmospheric lifetimes due to lower temperatures and less sunlight exposure. Some long-range transport still occurs in summer, as suggested by the mostly non-significant increase in gas and decrease in particle concentrations with average trajectory distance (Fig. S5.2) and concentration spikes associated with volcanic eruptions (Van Overmeiren et al., 2024). The absence of effects from air mass clusters and marine contribution aligns with previous research on atmospheric PAH concentrations

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by Cabrerizo et al., (2014) and suggests a lack of immediate marine PAH sources. Notably, this differs from PAH concentrations in snow samples, further suggesting a rather complex interplay of snow-atmosphere exchange. Analysis of Antarctic snow and firn samples collected at different altitudes, distances from the sea, and depths showed that PAH concentrations were influenced by marine aerosol transport and compound volatility, with higher concentrations near the coast and lower concentrations at higher elevations (Giannarelli et al., 2019).

5 Conclusion and outlook

PAH are toxic but chemically reactive compounds with short atmospheric lifetimes. At PES, they occur predominantly in the gas phase and phenanthrene is the most abundant compound with concentrations ranging from 10-30 pg/m³ and total PAH concentrations of 25-100 pg/m³. They are susceptible to trapping in snow.

Atmospheric circulation patterns around Princess Elisabeth station show a strong seasonal contrast: Summer is dominated by Antarctic continental air from comparatively shorter distances and less marine contribution, while all other seasons allow air masses from more distant source regions to reach East Antarctica. During summer, air masses typically descend from higher altitudes and follow curved, zonal pathways consistent with the synoptic conditions, rather than direct transport from the ocean. These distinct seasonal patterns make PES a valuable site for investigation of trace pollutants.

Variability in PAH concentrations could not be explained by associated parameters to the backward trajectories such as marine contribution, distance, temperature and their combinations and interactions. However, a slight temperature dependence at the station suggests that remobilization from snow is the main source of atmospheric PAHs at PES during summer. This implies that winter deposition likely supplies a PAH reservoir that is subsequently released during the summer period. Additional sampling across all seasons would be valuable to investigate seasonal differences in PAH concentrations and transport, especially as the winter atmosphere is influenced by more spatially extensive source regions. Atmospheric PAH concentrations in East Antarctic summer do not follow a simple source-to-sink trajectory but instead reflect seasonally distinct long-range transport processes and short-term snow-air exchange occurring locally at the station. More focused, time-resolved measurements at key source interfaces such as snow, ocean, coast, and anthropogenic sources, are needed to better constrain PAH sources and transport in Antarctica, for example by deploying multiple filters with staggered sampling intervals. This could be combined with detailed chemistry-transport modelling of the sources, emissions and atmospheric transformation processes of primary and secondary aerosols and precursor gases.

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Supplement

To view supplementary material for this article, please visit the Supplementary file on Egusphere.

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Competing interests

The authors declare that they have no competing interests.

Author contributions

PvdB: conceptualization, analyses, writing and editing. AM: conceptualization, editing. KDC: trajectory analysis. PVO: data collection, PAH analysis. CW: conceptualization, editing. AD: trajectory analysis, editing.

Declaration

ChatGPT was used to assist with data analysis scripts and to support sentence structure improvements in this manuscript.

Data availability

Atmospheric trajectories are available in the ZENODO repository under https://doi.org/10.5281/zenodo.20509863. PAH data are available in (Van Overmeiren et al., 2024) under https://pubs.acs.org/doi/suppl/10.1021/acs.est.3c06425/suppl_file/es3c06425_si_001.pdf

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