R1:

This study measures the long-term trends of atmospheric heavy metals (HMs) at various station types in the Czech Republic and applies the dispersion normalization method to demonstrate that, in some cases, meteorological variability can mask the true level of emissions. The study was conducted on a robust temporal (12-year) and spatial series, with statistically significant data for measured heavy metal concentrations and correlation analyses between stations confirming the representativeness of the groups by environmental type.

Except for Ni at the industrial site, the results demonstrate statistically significant ($p < 0.001$) decreasing trends at all station types and for all monitored heavy metals, confirming that dispersion normalization is a robust method capable of providing clearer results on the effectiveness of legislative emission control measures.

The article presents good data quality obtained using an appropriate methodology, therefore requiring minor revisions, as suggested below:

1. Improve the clarity of the text in the introduction from lines 36-44.

Original text:

This study investigates the evolution in HM concentrations with immission limits in the Czech Republic from 2010 to 2021 (the period after a substantial lowering of HM concentration is ambient air) across various environments, focusing on the effects of current regulations. These limits are not being exceeded long-term in most of the territory of the Czech Republic.

Central Europe is among the regions with the highest concentrations and deposition of HM in Europe (Travnikov et al., 2020). However, air quality is significantly improving in this region (Aas et al., 2024), so we focused on these three sub-objectives in our study:

The application of dispersion normalization was used for the first time to remove the influence of meteorological changes in describing HM concentrations and trends at air quality stations.

The three main objectives were to investigate:

New text:

This study examines trends in HM concentrations in relation to immission limits in the Czech Republic over the period 2010–2021, following a substantial decline in ambient HM concentrations. The analysis covers multiple types of environments and focuses on the effects of current regulatory measures. Long-term exceedance of immission limits is currently not observed across most of the Czech Republic.

Central Europe remains one of the regions with the highest concentrations and deposition rates of HMs in Europe (Travnikov et al., 2020). At the same time, air quality in this region has been steadily improving (Aas et al., 2024). To better understand these developments, this study addresses three main objectives. Dispersion normalisation is applied here for the first time in the context of HM assessment to reduce the influence of meteorological variability on observed concentrations and trends at air quality monitoring stations.

The main objectives of the study are:

2. Check and correct some errors in station abbreviations. For example, the OPR station in the text is listed as Industrial, while in Table S2 it is BS (background/suburban); in Table S2, the Industrial station is listed as Ostrava-Přívoz, which is designated POP; in all other Tables S2-S10, check the abbreviation OPO

Thank you for the warning. There was an error in the station descriptions: the Ostrava-Poruba station has the abbreviation OPO and the Ostrava-Přívoz station has the abbreviation OPR.

3. It is recommended to improve the clarity of Figure S3 (in the Supplementary Information), for example by dividing it into multiple figures by station type or, at least, increasing the font size for easier reading

Thank you for this suggestion. Figure S3 has been split into two pictures (S3 and S4), which has significantly improved its readability.

R2:

In this manuscript, long-term datasets on heavy metals at different monitoring sites in the Czech Republic are investigated. Dispersion normalized dataset obtained by the application of ventilation coefficients to correct for variations in meteorological conditions was studied and compared with the original dataset. In support of grouping of individual sites and data interpretation, non-parametric statistical tests were applied to describe trends in heavy metal concentrations and correlations between the elements and different sites. While the selected dataset and methodology are appropriate, the manuscript should be improved for clarity before publication.

GENERAL COMMENTS

Although I didn't find many major language issues that would significantly hinder scientific understanding, the manuscript would strongly benefit from thorough language editing (especially the results section).

The manuscript also requires some stylistic edits:

- Introduce abbreviations at their first mentioning. Afterwards, use them throughout the manuscript and do not explain again (except in captions). For instance, abbreviations for different locations are introduced in L123-125 – do not explain them again in L170-180;

Thank you for your feedback. We have carefully reviewed the manuscript and made corrections related to the use of abbreviations. We believe that the requested corrections have been successfully incorporated.

OR and DN are not explained when first mentioned in L180, instead they are explained later on in L245, which is not needed;

An explanation of the OR and DN methods has been added to the revised manuscript in the introduction:

3. Examine the influence of meteorological variables on measured immission concentrations in relation to evaluating the effects of emission regulations. The study evaluates whether normalisation techniques constitute an appropriate methodological tool for isolating emission signals from meteorological influence. Specifically, the study focuses on dispersion normalisation using the ventilation index. The differences between the original (HMOR) and dispersion normalised (HMDN) HM concentration datasets are evaluated. The goal of this objective is to explore the potential masking of changes in emission signals due to meteorological effects.

- abbreviations of individual monitoring sites are only explained in SI and not in the main manuscript (maybe include them in Fig. 2?)

Thank you for these notes. A simplified version of Table S1 has been added to the main manuscript.

- Figure and table captions should be self-explainable, which needs to be improved. Bear in mind that one should understand figures/tables without reading the manuscript. For instance, it is not clear from the caption what circles in Figure 4 mean. Moreover, avoid using abbreviations in figure and table captions (or explain them for clarity).

Thank you for your feedback; the figure captions have been revised accordingly. See examples:

Table 1: Overview of total emissions in 1990 and 2021 in the Czech Republic. The structure of emissions changed in response to technological developments and regulatory measures. Source: CEIP (2026).

Figure 1: Structure of selected HM emission sources according to economic sectors in 1990 and 2021. Only the first three sectors are visualised; the other sources are in the 'rest' category. Source: CEIP (2026).

Figure 2: Spatial distribution of selected stations measuring HM in the period of 2010–2021 in the Czech Republic, Europe. Colours represent particular station types. Background Rural Mountain stations (BRM) are coloured light blue, Background Rural Lowland stations (BRL) in green, Background Urban stations (BU) in red, Background Suburban stations (BS) in orange, Industrial stations (I) in yellow and Traffic station (T) in black. The map data were processed in ArcGis software; ASL denotes metres above sea level (ESRI, 2018).

Figure 3: HM concentration overview at all station types, 2010–2021. Colours represent particular station types. Background Rural Lowland stations (BRL) in green, Background Rural Mountain stations (BRM) in light blue, Background Suburban stations (BS) in orange, Background Urban stations (BU) in red, Industrial stations (I) in yellow, and Traffic stations (T) in black.

Figure 4: Spatial relationships among monitoring stations based on individual HMDN correlations ($R_s > 0.7$). Coloured lines connect pairs of stations with strong correlations. Ellipses (circles) indicate spatial clusters of mutually correlated stations. Dot colours represent particular station type. Background Rural Mountain stations (BRM) are coloured light blue, Background Rural Lowland stations (BRL) in green, Background

Urban stations (BU) in red, Background Suburban stations (BS) in orange, Industrial stations (I) in yellow and Traffic stations (T) in black.

Table 2: Results of long-term trend analyses of HM concentrations for the grouped stations according to station type – EOI classification and altitude. Background Rural Lowland stations (BRL), Background Rural Mountain stations (BRM), Background Suburban stations (BS), Background Urban stations (BU), Industrial stations (I) and Traffic stations (T). The overall trend is shown as a percentage increase/decrease per year, and the 95% confidence intervals in the slope are listed in [%/year]. Significance level: $p < 0.001$ = ∗ ∗ ∗.

- Proof edit literature citations throughout the text (e.g. L98, L193).

Thank you for the notification. The citations have been corrected.

I suggest to introduce OR and DN abbreviations early in the manuscript (in the methods section). I further suggest using these abbreviations also to distinguish between the two datasets (e.g. L235 HMDN and HMOR datasets).

For improved clarity, the text in the Methods section (4.2) has been revised. The new version is as follows:

The final dataset covers 12 years of data measured under different meteorological conditions. Therefore, correct evaluation requires data normalisation and the exclusion of meteorological conditions. The reduction of [LCW1.1]meteorological influence was calculated according to a recently developed method intended for dispersion normalisation of Positive Matrix Factorization analysis. This approach is widely used by the research community (e.g., Alfeus et al., 2024; Chen et al., 2022; Hopke, 2021; Mbengue et al., 2023; Wu et al., 2023; Yang et al., 2022). Dispersion normalisation concentration is calculated according to Equation (2):

$$C_{DN} = C_{OR} \times \frac{VC_i}{\overline{VC}}, \qquad (2)$$

Where C_{DN} denotes dispersion normalised concentrations, C_{OR} is measured (original) concentration, VC_i is the value of the ventilation coefficient and $\overline{VC}$ is the averaged ventilation coefficient under the whole studied period.

VC in this study is used from Numerical Weather Prediction model Aladin operation by CHMI. The calculation of VC for Czech conditions is based on methodology listed in Ferguson (2001) with the thickness and average wind speed in the MLH being used (Škáchová, 2020; Škáchová and Keder, 2025).

Figs. 5-8: in the discussion the authors refer to these figures and emphasize specific years for which data normalization was especially important. However, it is hard to read the discussion and search for details in the figures at the same time. Therefore, I suggest the authors specifically mark the cases they refer to in these figures.

Thank you for this suggestion. We believe that adding further annotations to Figs. 5–8 would compromise their legibility. The current versions are, in our view, sufficiently clear and representative of the discussed trends.

Was VC calculated on a yearly basis?

The mean value ($\overline{VC}$) was calculated over the entire study period. This is described in section 4.2 (VC_i is the value of the ventilation coefficient and $\overline{VC}$ is the averaged ventilation coefficient under the whole studied period).

SPECIFIC REMARKS

Is it possible that dispersion normalization skewed original data in the case of strongly episodic/non-continuous emissions? For example, refer to L263-264: AsOR–AsDN range: 7–47% probably reflected not only episodic emission events but also changes in meteorological influences... While industrial emissions are presumably episodic, the correction averages meteorological conditions over long time periods, including time frames without significant emissions. Can you comment on that?

We thank the reviewer for this important comment. We agree that dispersion normalization may influence the interpretation of data in the case of strongly episodic or non-continuous emissions. The method is designed to remove the effect of meteorological variability by averaging over a wide range of meteorological conditions, which can, in principle, smooth short-term peaks associated with episodic emission events.

However, dispersion normalization does not remove emission signals themselves; rather, it adjusts their representation under comparable meteorological conditions. In the case of episodic industrial sources, the method may reduce the apparent magnitude of extreme events, since these are not always consistently linked with specific meteorological patterns and may be underrepresented in the resampled meteorological space.

Therefore, we interpret differences between original (OR) and dispersion-normalized (DN) concentrations (e.g., AsOR–AsDN range: 7–47%) as reflecting a combination of meteorological influences and, to some extent, the irregular occurrence of emission events. This is particularly relevant for pollutants with strong episodic sources, where the DN approach may partially smooth short-term variability.

To address this limitation, we have clarified in the manuscript that dispersion normalization is primarily intended to assess long-term trends and reduce meteorological noise, rather than to capture the full magnitude of short-term emission episodes.

L23: Once released into the atmosphere, HMs can be absorbed onto aerosol particles... HMs are typically released as particles and do not attach to particles after their release. Moreover, absorbed onto -> adsorbed on. Please clarify.

The text has been corrected, and the following sentence has been added.

In the atmosphere, heavy metals are usually released in particulate form or become associated with aerosol particles after release, which may be inhaled and contribute to adverse health effects.

L61: especially for traffic sites, very important source of Pb is also road dust resuspension, still containing large amounts of Pb due to historical use of leaded gasoline

The text has been updated to include the following sentence:

Another important source of Pb is the resuspension of road dust, especially applicable to locations affected by road traffic.

L175: ...As concentrations were elevated at BU and T station types. Isn't BS (0.79 ng/m3) also higher than BRM/BRL (0.35 and 0.54 ng/m3)? Please clarify.

Thank you for the notification. It was probably a mistake in the sentence; the BS was unfortunately omitted by mistake. The new sentence is as follows:

As concentrations were elevated at BS, BU and T station types.

L232: The individual HM concentrations trend analyses confirmed that the data series from individual stations are suitable for group calculations and further evaluation. Can you explain why?

The suitability of using data from individual stations for group assessment is based on the high degree of consistency between trends determined at the level of individual stations and the corresponding trends for aggregated groups of stations. In most cases, the same trend directions (mostly decreasing) and comparable levels of statistical significance were found, both for individual stations and for their groups.

The deviations observed at a few stations (e.g. insignificant trends or lower levels of significance) were rather local in nature and did not affect the overall trend of the given group. This suggests that the variability between stations within a category is not so significant as to prevent their joint assessment.

L254: … confirms the effectiveness of legislative measures targeting As emissions. Can you support with concrete examples?

In particular, the observed decrease in As concentrations is consistent with the implementation of the Industrial Emissions Directive (2010/75/EU), which introduced stricter emission limits and Best Available Techniques (BAT) requirements for key industrial sources such as metal production and large combustion plants. These requirements were further specified in BAT reference documents (BREFs), leading to the modernization of emission control technologies (e.g., improved filtration systems and flue gas cleaning).

At the national level, additional reductions are linked to the gradual modernization or closure of outdated industrial facilities and the tightening of emission limits under Czech air protection legislation (e.g., Act No. 201/2012 Coll., on Air Protection).

L265: In those cases, the added value of the DN method is visible. -> where can I see this?

In response to this comment, the text was revised to better describe the added value of the DN method. The updated text is as follows:

This consistent pattern suggests that the observed decrease is at least partly associated with legislative measures targeting As emissions. The highest AsDN concentrations were recorded at I stations (0.83–1.92 ng m^{-3}), as expected, due to industry being the dominant source of As.

Differences between AsOR and AsDN (7–47%) likely reflect not only episodic emission events but also the influence of meteorological conditions. A short-term increase in emission-related concentrations during 2011–2013 is more clearly captured in the dispersion-normalised data, particularly at T and I stations, where it is less apparent in the original time series due to meteorological variability. This effect can be observed in Fig. 5, where the DN data reveal a distinct, temporary deviation from the long-term trend, which is partially masked in the OR data.

L321: add main findings about dispersion conditions here or move to methodology. Please also explain what very good, good, slightly unfavorable, unfavorable refer to.

Thank you for your comment. The dispersion condition categories are defined in the cited literature. We believe the meteorological influence is sufficiently described in the current text; the dispersion conditions at individual stations should serve only as supplementary context.

MINOR COMMENTS

L26: Dot missing at the end of the paragraph

L29> LRTAP -> CLRTAP (as further used in L73)

L40: … we focused on these three sub-objectives in our study: -> rewrite (objectives only follow down below)

L44: delete investigate

L63: from -> for

These comments have been corrected in the reviewed text.

L73: what is CIEP and CHMI? In Table 1 and Figure 1 captions, CEIP is used together with a different year in the brackets. Please clarify what these abbreviations stand for. Moreover, explain NFR in Figure 1 caption.

Explanations for the abbreviations have been added to the text. They represent the following:

CEIP – Centre on Emission Inventories and Projections

CHMI – Czech Hydrometeorological Institute

NFR – Nomenclature for Reporting (a standardised sector-based classification system used by European and international environmental agencies to report national emissions of air pollutants).

L98: introduce new paragraph starting with The character of MLH…

These comments have been corrected in the reviewed text.

Figure 2: explain legend (ASL)

L125: en dash is missing in Industrial station I -> Industrial station – I

L161: explain HMDN

L175: … Ni concentrations at traffic station differed from those recorded at BU and BS locations. Ni at T station differed from BU and BS. -> repeating

L227: BMR -> BRM?

L332: permanent -> constant

L341: local and regionally transported ?pollution?

L395: start new paragraph with The ventilation coefficient…

L400: start new paragraph with The only location of all observed stations…

L426: metallurgical and processes -> needs correction

L439: rewrite Three factors demonstrated specifications of mountain locations…

These comments have been corrected in the reviewed text.