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On the Temporal Variability of Air Pollutants' Emissions – Case Study of Residential PM_{10} Emission in Silesian Metropolis

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INTRODUCTION

The temporal (seasonal) variability of air pollutants' emissions and its analysis are important parts of air pollutants' emission inventories. Climatic conditions which directly affect heat demand in a residential sector (Isaac & van Vuuren, 2009), and occurrence of the 'heating period' (Rogula-Kozłowska et al., 2013) make that the emission intensities are not distributed through the year equally. As it was suggested by Hławiczka (2008), the volume of pollutant released into the air during the 'heating period' can exceed 70% of total annual emission.

The temporal (e.g. monthly) disaggregation is usually carried out using a normalized temporal distribution called also as a temporal profile of emission (Guevara et al., 2018). Similarly to the spatial surrogates (Zasina & Zawadzki, 2017b, 2018), the temporal profile is also a surrogate assuming that the geographical coordinates and time can contribute to the single reference system.

Lenhart et al. (1997) gave a good example of statistical variables that can be used as surrogates for the temporal profile of emission from households. They are: fuel use, degree days, production, and user behavior. A number of researchers use approximately the same or very similar set of statistical variables. This fact is associated with their availability in official statistics, or possibilities of collecting of the appropriate data.

Annual emissions are usually disaggregated (broken down) into monthly, weekly, and then – diurnal emission time series, according to the formula given below (Sturm & Winiwarter, 2004):

$$E_h = (E_a \cdot f_a \cdot f_w \cdot f_d) \cdot \tau, \tag{1}$$

where:

E_h – emission hourly,
E_a – annual emission of air pollutant,
f_a – emission's share for annual cycle,
f_w – emission's share for the weekly cycle,
f_d – emission's share for the diurnal cycle,

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τ – temporal rate, for hourly emission τ = 1/8760 (1 year ≈ 8760 hours).

Essentially, the temporal profile can be described by the particular time series θ_t with the time resolution corresponding with current needs, e.g., t = 52 for weekly time series, and t = 12 for monthly time series. The series usually summarizes to unity (100%). The θ can be derived from the physical parameter such as temperature of the air or concentration of the particular air pollutant. The parameter θ can be also considered as a value associated with the vegetation indexes, such as the Normalized Difference Vegetation Index (NDVI).

Based on the study considering cadmium emissions (Degórska et al. 2017) it can be concluded that considerable source of the concentrations' monthly variability indicate seasonal changes of emissions. These changes are the result of the seasonal variability of a number of meteorological parameters such as the ambient air temperature.

There are many methods dedicated to evaluate the temporal profiles, such as:

- meteorological measurements (Sturm & Winiwarter, 2004; Bieser et al., 2011),
- air quality measurements (Trapp, 2010; Xue et al., 2016),
- satellite imagery (Efstathiou et al., 2011),
- expert judgement (Hławiczka, 2008),

and

- air quality and geospatial modelling (Zheng et al., 2009; Zasina & Zawadzki, 2017a; Pham et al., 2008; Reis et al., 2009; Degórska et al., 2017).

The profiles for temporal emission disaggregation can also be assessed using various statistical variables (Denier van der Gon et al., 2011; Efstathiou et al., 2011), or combination of them such as temperature and heating demand (Markakis et al., 2010). When discussing various temporal surrogates is worth to stress that many databases (Crippa et al., 2019; Janssens-Maenhout et al., 2017) are based on modelling results (e.g. model GENEMIS, Friedrich & Reis, 2004).

The objective of the study was to compare available time profiles for PM_{10} emission from individually heated dwellings located in the Upper Silesian Metropolitan Area (Zuzańska-Żyśko, 2014) situated in the southern part of Poland (shown in Fig. 1).

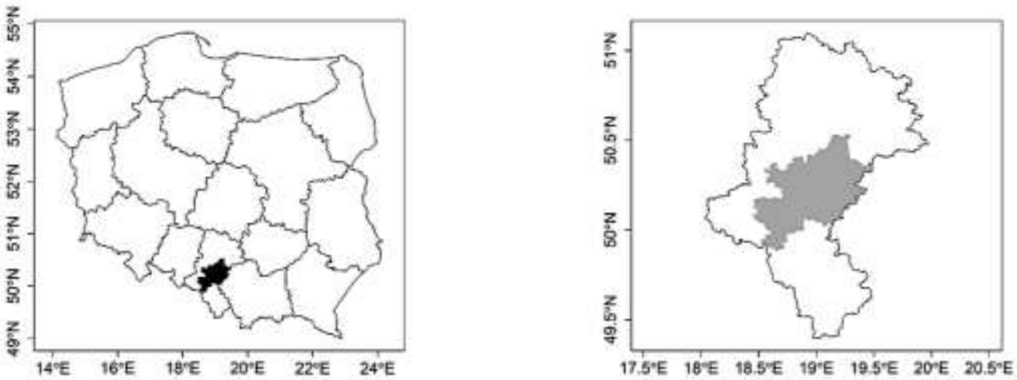

Fig. 1 The location of the study area (left figure, black spot), and in Silesian Voivodeship (right figure, grey area)

According to the data obtained from the project 'Heat Roadmap Europe' (Europa-Universität Flensburg et al., 2018), the area is characterized by the considerable heat demand from residential sector, and the district heating system plays an important role in fulfilling of the heat demand.

MATERIALS AND METHODS

The area of the study consists of 41 communities (Polish local administrative unit) aggregated into 21 counties (from 380 ones in whole Poland). It has an approximate area of 6,000 km^2, a 100 km of length (from north to south), a 60 km of width (from east to west). The population density in the area varies approximately from 200 to 4,000 people per square kilometer (Statistics Poland, 2018).

According to the information given by Szajnowska-Wysocka & Zuzańska-Żyśko (2013), the majority of the area consists of the central metropolitan complex (core), and the external metropolitan zone. Based on the cities' hierarchy elaborated using the Centrality Index (CI), the area covers all types of urban development, namely, from A to E (Szajnowska-Wysocka & Zuzańska-Żyśko, 2013). This fact confirms an existence of highly complicated urban development in the considered area. The complexity of the study area is presented in Fig. 2.

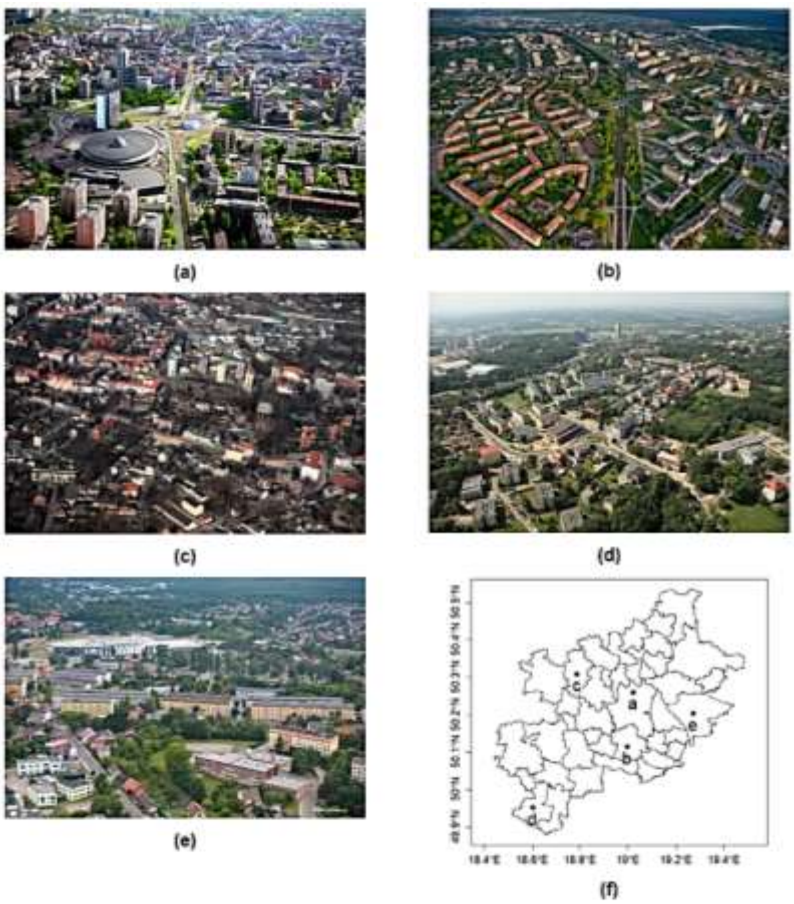

Fig. 2 The photographs showing a variety of urban development in the analyzed area: (a) Katowice (https://portalkomunalny.pl/), (b) Tychy (https://umtychy.pl/), (c) Zabrze (https://d-art.pl), (d) Jastrzębie Zdrój (https://www.tujastrzebie.pl/), (e) Jaworzno (photo by A. Gontarz, https://dziennikzachodni.pl/), (f) locations of selected urbanized structures in analyzed area

Apart from complexity of the cities' structures, the analyzed area is partially supplied with the heat from the district heating network. The problem is also related to spatial split between households of the heat from the district heating infrastructure (Zasina & Zawadzki 2016, 2017b, 2018; Zasina 2019). The problem can be effectively solved by performing an emission inventory with very high spatial resolution (building by building), however it frequently exceeds the financial possibilities and dedicated time framework.

Brizio et al. (2007) indicate that the emission inventory carried out for urbanized area require only a careful and detailed data collection effort. However, to tackle the problem in the considered area (of a considerable complexity) would be exceptionally time- and money-consuming. On the other hand, Holnicki & Nahorski (2015) emphasize that the air quality modelling in urban areas is burden with substantial share of uncertainty. Ignoring this fact can lead to incorrect policy decisions, and further, negative consequences for environment and human health.

IETU's study

Monthly variability of heavy metals' air emissions was the subject of studies carried out in the Institute for Ecology of Industrial Areas (IETU) (Hławiczka, 2008). Elaborated normalized fractions of temporal variability θ_t were applied for the study of IPIŚ PAN et al. (2011) and are given below in Table 1.

Table 1 Monthly coefficients for temporal allocation of air emission from households based on Hławiczka (2008)

Month:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	∑
θ_t:	0.140	0.153	0.115	0.094	0.056	0.033	0.025	0.028	0.033	0.066	0.112	0.145	1.000

TNO's study

TNO adopted temporal profiles from the LOTOS-EUROS model (Denier van der Gon et al., 2011; Schaap et al., 2008) to elaborate European CO_2 emission inventory (Denier van der Gon et al., 2017). Monthly coefficients (original and normalized) are given below in Table 2.

Table 2 Monthly coefficients for temporal allocation of air emission from households basing on Denier van der Gon et al. (2011)

Month:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	∑
θ_t:	1.7	1.5	1.3	1	0.7	0.4	0.2	0.4	0.7	1.05	1.4	1.65	12
$\hat{\theta}_t$:	0.142	0.125	0.108	0.083	0.058	0.033	0.017	0.033	0.058	0.088	0.117	0.138	1.000

θ_t – original data, $\hat{\theta}_t$ – normalized data

Monthly distribution using the Heating Degree Days

Heating Degree Days (HDD) is a parameter obtained from the ambient air temperature (Dopke, 2011, 2016; EUROSTAT, 2017). It is used to reflect temporal distribution of heating demand during particular period (annually, monthly, weekly, etc.). The formula for obtaining HDD elaborated by EUROSTAT (2017) is given below:

$$\mathrm{HDD}_m = \begin{cases} \sum_{i=1}^{n} \left(18^{\circ}\mathrm{C} - \overline{T}\right), & \overline{T} \leq 15^{\circ}\mathrm{C} \\ 0, & \text{otherwise} \end{cases}, \tag{2}$$

where:
HDD_m – number of HDD (monthly, m) [K·d ⇔ ºC·d],
n – number of days in month m,
$\overline{T}$ – 'average' ambient air temperature calculated for particular month using formula:
$\overline{T} = (T_{min} + T_{max})/2$ [ºC].
Results of calculations are given in the Table 3 below.

Table 3 Monthly coefficients for temporal allocation of air emission from households basing on EUROSTAT (2017)

Month:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	∑
θ_t:	519.43	475.23	397.43	290.49	161.88	56.64	12.37	4.07	92.9	315.48	369.84	416.93	3112.69
$\hat{\theta}_t$:	0.167	0.153	0.128	0.093	0.052	0.018	0.004	0.001	0.03	0.101	0.119	0.134	1.000

θ_t – original data, $\hat{\theta}_t$ – normalized data

RESULTS AND DISCUSSION

The obtained results are shown in Fig. 3. Calculations based on studies carried out by Hławiczka (2008), TNO Denier van der Gon et al. (2011), and authors' estimation using the heating degree days (HDD) are presented in form of sets of the monthly coefficients.

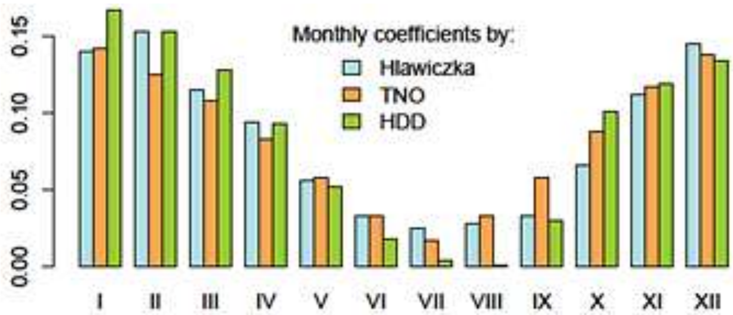

Fig. 3 Normalized monthly coefficients for allocation of residential emission

All sets of the monthly coefficients have strong similarities, such as clear drop of values during the warm period, from May to September. Monthly coefficients estimated for the summer period, from June to September are significantly lower when using HDD compared to other methods. This fact is due to taking into consideration only ambient air temperature without considering the demand for hot water which occurs in individually heated households.
The spatiotemporal distributions of the PM_{10} emission using HDD and approaches given in (Zasina, 2019; Zasina & Zawadzki, 2018, 2017b) are shown in Fig. 4. They were carried out using geostatistical methodology (Zawadzki, 2011) and split into monthly data using HDD. It can be noticed that the center of analyzed area is especially densely populated so it inflates emission values (is an emission hot-spot) and should be corrected.

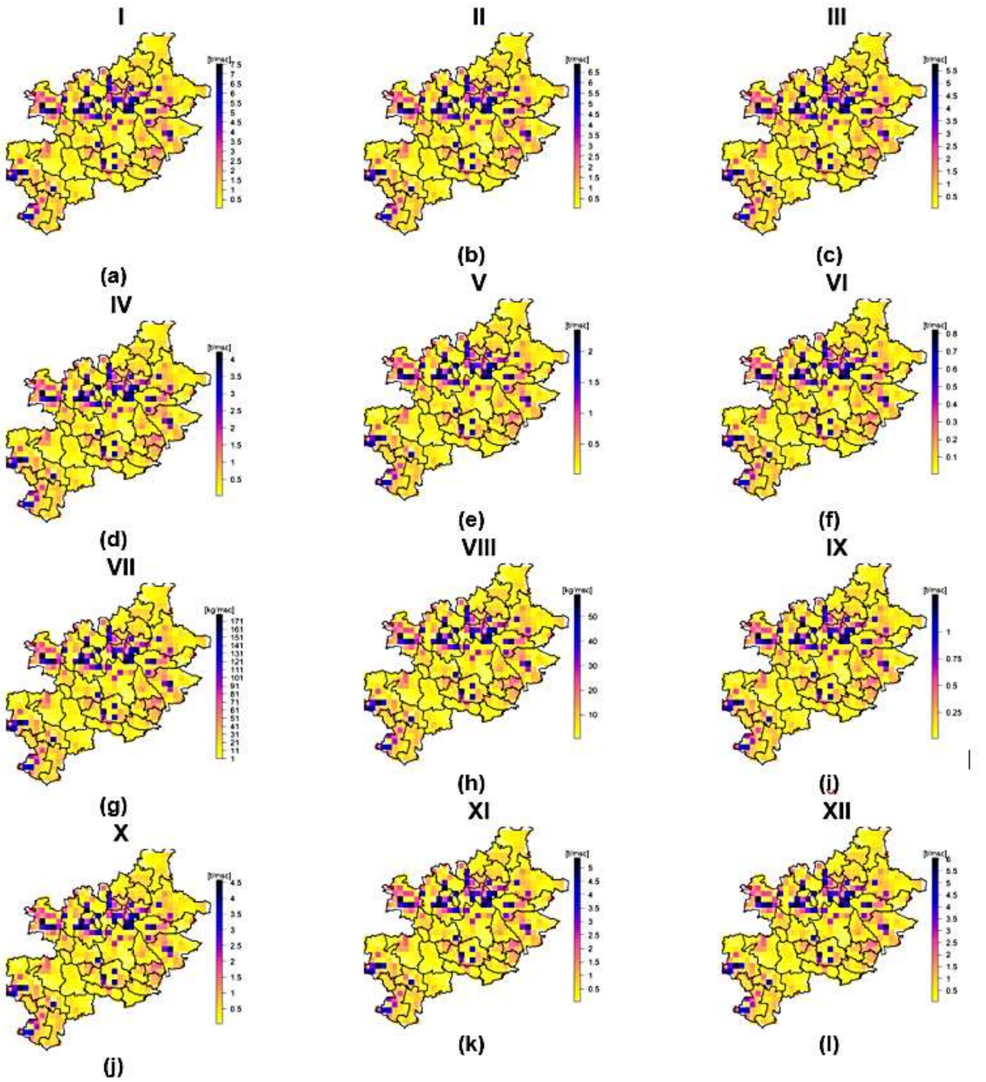

Fig. 4 The spatiotemporal distribution of the PM_{10} emission from households located in the study area [t/month]: (a) JAN, (b) FEB, (c) MAR, (d) APR, (e) MAY, (f) JUN, (g) JUL, (h) AUG, (i) SEP, (j) OCT, (k) NOV, (l) DEC

Limited accuracy of the elaborated spatiotemporal distributions of the PM_{10} emission is also the result of scarcity of available data about population density, urbanized area extent, or distribution of the heating network (Zasina & Zawadzki, 2016, 2017b, 2018; Zasina, 2019; Zawadzki, 2011).

CONCLUSIONS

Comparison of the obtained coefficients for temporal disaggregation of the PM_{10} emission has shown strong similarities among applied approaches: Hławiczka (2008), Denier van der Gon et al. (2011), and the method of spatiotemporal estimation developed by the Authors using HDD. The observed differences between the latter approach and two former ones arise from the fact that the application of HDD parameter should be further improved in terms of demand for hot water in individually heated households.

However, the approach using HDD has turned out to be especially effective way for carrying out spatiotemporal distributions of air emissions. The use of this approach can ameliorate the process of obtaining detailed spatiotemporal input data necessary for the air quality modelling.

When anticipating further progress in emissions inventories, air quality observation and modelling the growing role of remote sensing should be here stressed. In the near future remote sensing imagery is expected to be widely used for these purposes, which will have a great impact on the efficiency improvement.

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Abstract.

The paper summarizes previous studies associated with carrying out of the air pollutant emission inventories. There are presented three approaches for obtaining monthly distribution of PM_{10} air emission: using expert's judgement, modelling of the heating demand, and temporal disaggregation using the heating degree days (HDD). However some differences due to not considering hot water demand, it can be effectively used for obtaining temporal, and spatiotemporal distributions of air pollutants' air emissions necessary for air quality modelling.

Keywords: air pollution, emission inventory, particulate matter, PM_{10}, temporal distributions