Meteorological Normalization of NO_2 using Generalized Additive Models (GAMs)

Statement

To normalize NO_2 concentrations on a daily aggregation, we employ metrics that consider wind speed and direction averages. From the numerous metrics available in the literature, we chose one that integrates meteorological factors using vectorized wind components within a Generalized Additive Model (GAM).

There are two critical questions to address:

1) Why is it essential to use the mathematical convention over the meteorological one?

First, in meteorological terms, a northerly wind is defined as 0°, an easterly wind as 90°, a southerly wind as 180°, a westerly wind as 270°, and a northerly wind again as 360° (equivalent to 0°). If we use the meteorological convention for wind direction, where 0° and 360° represent the same direction (north), it complicates the normalization process because it introduces ambiguity in distinguishing between the two (ERA5, 2024). In contrast, the mathematical convention treats angles continuously, making it easier to handle and normalize, as there is no overlap between 0° and 360°." Second, the discontinuity at the transition between 360° and 0° could introduce artifacts into the model, making it difficult for the GAM to fit the data smoothly. This could lead to poor model performance or misleading results, where the effects of wind direction on NO_2 concentrations are not accurately captured (Voiculescu et al., 2020; Zhang et al., 2023).

2) Why is it important to apply a GAM for normalizing NO_2?

NO_2 concentrations are not influenced by wind speed and direction per se, but also vary with other components such as humidity and temperature (Voiculescu et al., 2020). While (generalized) linear models can provide some insights, Generalized Additive Models (GAMs) are particularly well-suited for capturing the complex, non-linear relationships between NO_2 concentrations and these meteorological variables (Grange, 2014; Ma et al., 2020; Ni et al., 2023). This allows for more accurate generation of residuals, which are essential for isolating NO_2 variations that cannot be explained by meteorological factors (Zhang et al., 2023).

Procedure

To ensure a systematic approach, we established the following procedure:

1. Conversion of Degrees to Radians and Vectors

We first convert compass-based wind directions (e.g., NW, E, SW) from Clincarthill Met Station, located 4.3 km from Glasgow's Low Emission Zone (LEZ), into degrees (0-360°). These degree measurements were then converted into radians (θ) and further transformed into vectors for precise modelling (Grange, 2014).

The vector representing the east-west wind direction (u) is calculated as follows:

$$u = -windspd \times \sin\left(\frac{\pi}{180} \times \theta\right)$$

And the vector representing the east-west wind direction (v) is calculated as follows:

$$v = -windspd \times cos\left(\frac{\pi}{180} \times \theta\right)$$

Wind speed data from the station was used in these calculations.

2. Fit all the met factors to GAM

Once the vectorized wind components are computed, we added all the meteorological factors into GAM (Ma et al., 2020).

The specific GAM equation is as follows:

$$E(Y) = \beta_0 + s(temp_{daily}) + s(humid_{daily}) + s(ws_{daily}) + s(u_{daily}) + s(v_{daily}) + \varepsilon$$

where:

- β_0 is the intercept.
- s( ) denotes a smooth function
- $temp_{daily}$ is the daily temperature
- $humid_{daily}$ is the daily relative humidity
- ws_{daily} is the daily averaged windspeed
- u_{daily} is the vectorized daily wind direction indicating east-west[1] i.e. ws*sin(θ)
- v_{daily} is the vectorized daily wind direction indicating north-south i.e. ws*cos(θ)
- Note θ must be in radians (if θ is in degrees, it needs to be converted by multiplying π / 180).

We applied the model to High Street and Hope Street for both August and September of 2022 and 2023. The model generated residuals for each time period.

3. Add Daily Averaged NO_2 to Residuals

The final stage of normalization is to add the mean to the residuals. As the aim of this study was to compare pre-LEZ with post-LEZ, we calculated the mean of

[1] Positive u indicates wind blowing from the west (toward the east), whereas negative u indicates wind blowing from the east (toward the west). Likewise, Positive v indicates wind blowing from the south (toward the north), whereas negative v indicates wind blowing from the north (toward the south).

Aug-Sep 2022 and 2023 respectively and added it to the residuals. This will result in a normalized NO_2 for this study.

Alternative methods

Other methods are also available, where wind speed can be computed based on $\sqrt{(u^2 + v^2)}$. Also, Grange & Carslaw (2019) used a machine learning method (i.e. random forest) to normalize the weather by air quality (NO_x and NO_2) using examples from London Marylebone station.

References

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