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Barcelona intense urban activity greatly limited the role of the atmosphere in driving NO₂ concentration in 2018

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Abstract

The World Health Organization defines an annual average threshold of 40 μg m⁻³ as the safe limit for human health. This threshold was clearly surpassed in 2018 in a large part of the Barcelona area during weekdays. In view of these data, it is of great interest to ascertain whether the impact of large-scale meteorological situations enables NO₂ concentrations to be reduced to weekend levels and whether daily NO₂ variability can be modulated by atmospheric variables. Results indicated that the main atmospheric patterns of the cold months in 2018 were unable to reduce NO₂ concentration levels during weekdays to render them comparable with those of the weekend. Only one pattern, referring to higher wind speeds, was relatively similar to average weekend NO₂ levels, although values did not descend to these levels. In addition, our study showed that changes in atmospheric conditions had almost no effect upon neighbourhoods presenting more consistently abundant daily NO₂ emissions. Daily variability in NO₂ therefore appears to be independent from large-scale meteorological changes.

1. Introduction

Air pollutant emissions currently constitute a serious health problem, but also economic and social ones, as they have been increasing in recent years due to the continuous growth of urban environments (Kahn 2007). An estimated 4.2 million premature deaths globally are linked to ambient air pollution (WHO 2018); this mortality mainly refers to heart disease (Clancy et al 2002, Mills et al 2009, Brook 2008), stroke (Hong et al 2002, Wollenius et al 2012), chronic obstructive pulmonary disease (Andersen et al 2011), lung cancer (Loonis et al 2013, Raaschou-Nielsen et al 2013), and acute respiratory infections in children (Romieu et al 2002, Darrow et al 2014). Indeed, air pollution in urban environments is determined by a combination of different factors such as volume of emissions (Altshuler et al 1995), the physical characteristics or limitations of the urban environment (Fenger 1999) and atmospheric conditions (Demuzere et al 2011, Pearce et al 2011). Specifically, in the metropolitan area of Barcelona (Spain), nitrogen dioxide (NO₂) from traffic is the most prominent pollutant. A total of 80% of the annual volume of NO₂ emissions are from land transport, while the remaining 20% results from industry or domestic use (AMB 2020).

In recent decades, the study of the relationship between atmospheric variables and air pollution has garnered much interest. For example, many studies have investigated the effects of temperature, relative humidity, wind speed and direction or precipitation, among others, upon concentrations of O₃ (Filleul et al 2006, Carro-Calvo et al 2017), PM (Tian et al 2014, Zhang et al 2018) and NO₂ (Arain et al 2009, Šerevičiene et al 2014). Many of these studies, however, were based on individual analysis, evaluating the interaction between one single atmospheric variable and a given pollutant. Study of the effects of air masses (or rather, synoptic climate conditions) upon air pollution has become more commonplace in recent years, thus promoting research that associates atmospheric patterns, often called weather types, with variability in the aforementioned air pollutants (Davis and Gay 1993, Russo et al 2014). This type of study sometimes focuses on the impact of an atmospheric pattern, such as the impact of blocks and subtropical ridges on winter PM₁₀ (Garrido-Perez et al 2018) values, or on O₃ (Ordóñez et al 2017) in Europe. With regard to the variable scrutinised herein (NO₂), several studies have
explored the influence of atmospheric patterns on the concentration of this pollutant (Shahgedanova et al 1998, Pope et al 2014, Pope et al 2015), revealing that anticyclonic situations favour the accumulation of NO2, while cyclonic situations or those exhibiting a clear advective component favour the dispersal thereof. Cold months were also shown to present a higher concentration of NO2 due to the increase in thermal inversion events (Wallace and Kanaroglou 2009), a very common phenomenon during situations of atmospheric stability in winter.

Nonetheless, no study has attempted to establish the degree to which atmospheric patterns influence NO2 concentration, on weekdays and on weekends, separately, on a grid with very high spatial resolution. Keeping in mind that weekends present a significant reduction in NO2 concentration due to the big drop in urban traffic, the principal aim of the present research involves answering the following questions:

1. Are some weekday atmospheric situations capable of producing NO2 concentrations similar to weekend values?
   It is well known that weekends have a much lower concentration of NO2 emissions than weekdays. However, we intend to assess whether atmospheric situations favourable to the dispersion of NO2 particles (such as advective or cyclonic situations) occurring during weekdays are able to match the concentrations on weekends.

2. Is the daily variability in NO2 concentration conditioned by atmospheric circulation or by the internal dynamics of the city?

   Apart from the previous question, we are also interested in determining whether the increases and decreases in NO2 values are partially influenced by atmospheric variability, or whether, on the contrary, meteorological variations do not have significant implications for the daily variability of NO2.

2. Data and methods

2.1. Very high resolution NO2 dataset

The 2018 NO2 concentration data were provided by the Lobelia Earth & Royal Netherlands Meteorological Institute (KNMI) and made available to the public at https://bit.ly/3m4NkX0, under the Open Database Licence (https://lobelia.earth/odbl). The original data was furnished at hourly resolution but was aggregated at daily scale for the present research. The spatial resolution is ~20 m. It should be noted that this dataset was only generated for the year 2018 for research purposes. The application of the coefficient of variation (CV) to the daily NO2 data was based on the following equation (1)

\[ CV = \frac{\sigma}{\bar{x}} \cdot 100 \]  

Where \( \sigma \) is the standard deviation of the daily series of NO2 and \( \bar{x} \) is the mean of the daily series.

2.2. Atmospheric data

The atmospheric variables used for the synoptic classification and for the statistical modelling of NO2 were extracted from ERA-5 (Hersbach et al 2020) and ERA-5 Land Reanalysis. Specifically, ERA-5 provided mean sea level surface pressure (mslp), temperature at 850 hPa (t850), geopotential height at 500 hPa (z500) and the zonal (u10) and meridional (v10) components of wind speed at 10 m, all at a spatial resolution of 0.25°. Furthermore, precipitation was extracted from ERA-5 Land at a resolution of approximately 9 km. All variables, regardless of the dataset of origin, were averaged at daily level -except precipitation, which was aggregated to the daily total-and in the geographical region 10°W-12°E, 35°N-50°N, thus placing Barcelona in the centre of the region.

2.3. Classification of atmospheric patterns

To compute the synoptic classification, we employed mslp, t850 and z500 for the months of January, February, March, April, October, November and December.

   To classify the main synoptic patterns, we followed an approach based on Principal Components Analysis (PCA), a methodology commonly used for this purpose (Manley et al 1976, Lemus-Canovas et al 2019a and 2019b). We applied a PCA to a T-mode (temporal) matrix of mslp, t850 and z500, where the variables (columns) were the 212 days that constituted the aforementioned cold months; the observations (rows) were the grid points of the ERA-5 variables. Once the PCA is applied to the standardized data matrix, new variables are obtained; these are known as the principal components (PC), which are linear combinations of the original variables. Once the PCs are obtained, the ones explaining a greater part of the variance of the original data must be retained. For this purpose, we employed the well-known Scree Test (Cattell 1966), which is based on the
amount of variance explained by each PC. Once the more explanatory PCs had been retained, these components were rotated by means of a varimax rotation, the purpose of which is to readjust the linear combination of each PC in order to obtain the maximum variance explained by each PC (Richman 1986). From the rotated PCs, we obtained the loadings, i.e. the correlation matrix, which indicates the degree of correlation between each day and each PC. In this sense, the assignment of each day to each of the PCs is based on the value of maximum positive correlation and minimum negative correlation. For example, day 1 is assigned to the highest absolute correlation, but subsequently retains the correlation sign. For this reason, the PC1 can be split into two groups, one for days presenting a maximum positive correlation, and another for days with a minimum negative correlation. This means that, if 4 PCs are retained, up to 8 atmospheric patterns can be obtained. We used the R package synoptReg (Lemus-Canovas et al 2019c) to develop the synoptic classification.

We assessed the statistical significance of the difference between the NO$_2$ concentration on weekdays conditioned by each synoptic pattern and weekend NO$_2$ concentration, based on a two-sample t-test (Wilks 2019) at the 0.01 significance level. Note that there is practically no skew in the daily frequency distribution between the synoptic patterns of weekdays and weekends (see figure S1 (available online at stacks.iop.org/ERC/3/105006/mmedia)).

2.4. Statistical modelling of NO$_2$

The Multiple Linear Regression (MLR) model relates the daily variability of NO$_2$ and the atmospheric variables of ERA-5 at the neighbourhood scale (equation (2)):

$$\text{NO}_2(i, t_w, t_e) = a + b \cdot z500 + c \cdot t850 + d \cdot mslp + e \cdot u10 + f \cdot v10 + \varepsilon$$

(2)

Where $\text{NO}_2(i, t_w, t_e)$ is the predicted NO$_2$ value in each neighbourhood ($i$) and for weekdays ($t_w$) and weekends ($t_e$), separately; $a$ is the model intercept; $b, c, d, e$ and $f$ are the $z500$, $t850$, mslp, u10 and v10 coefficients and $\varepsilon$ is the random error.

Only the cell closest to the geographical location of Barcelona was extracted from the atmospheric variables entered in the model, as the reanalysis data does not have enough spatial resolution to provide a time series per neighbourhood. For this experiment we employed the 365 days of the year, thus extending the sample of days at the weekend. Since weekends possess a much smaller data population (104 days) than weekdays (261), a random sample of 104 days was extracted from the latter, to make it equal to that of weekends, and the model was then
adjusted. This process was repeated 1000 times. This way we can determine the neighbourhoods where both synoptic patterns significantly contribute to the daily variability of NO2.

The model was validated by means of a leave-one-out cross validation, in which the model fit was performed with n-1 days, and the day extracted was used for validation. Pearson’s correlation was used to estimate the accuracy of the time variability modelled on weekends and weekdays, at a statistical significance level of 0.01 (p-value). We also tested the assumption of normality using the Kolmogrov-Smirnov test, first for the daily NO2 series for each neighbourhood (figure S2), and then for the series of atmospheric variables (table S1). The results show that all the series fulfil the normality requirement at a 99% confidence level (p-value < 0.01).

3. Results

3.1. Sensitivity of NO2 to changes in air mass
It is a well-known fact that NO2 emissions show a clear decrease in urban areas during weekends (Khoder 2009) and holidays (Hua et al 2021) due to the decline in urban traffic, and the city of Barcelona (Malik and Tauler 2015) is no exception (figure 1). Nonetheless, air masses can also modulate NO2 concentrations, lowering or raising levels. It is therefore of great interest to ascertain whether these air masses are capable of bringing weekday NO2 concentration levels down to weekend values, or even lower, when synoptic conditions are favourable.
In an attempt to address the previous question, we computed the most representative atmospheric patterns or weather types of the days belonging to the January-April and October-December periods, thus avoiding the seasonal bias of NO2 in the summer months (Pope et al 2014) (figure S3).

These selected days are classified into 8 atmospheric patterns reflecting different situations which provide different air masses affecting the northeast of the Iberian Peninsula (figures 2(a)–(a)). In addition, such patterns can cause changes in temperature, wind speed and precipitation, among others, and have a significant impact on NO2 concentrations at local scale.

Thus, figures 2(a)–(a) first shows the most representative atmospheric patterns of the days selected according to mean sea level pressure, the temperature anomaly at 850 hPa, and finally the geopotential height anomaly at 500 hPa. Figures 2(b)–(b) shows average wind speed at an altitude of 10m based on each atmospheric pattern, and similarly, average daily precipitation is provided in figures 2(c)–(c). Finally, figures 2(d)–(d) reveals the difference between the average NO2 of each weather type during weekdays, and the average NO2 at weekends -regardless of weather type-. In the latter case, a positive difference, i.e. above 0, indicates that the average daily NO2 concentration values for a given weather pattern on working days is higher than the NO2 concentration observed at weekends - regardless of which weather pattern pertains to the weekend. On analysing what occurs in the Barcelona area in practically all atmospheric situations, the NO2 on working days was seen to be higher than at weekends, with a statistically significant difference (p-value < 0.01).

This reveals that in the months with the highest concentration of NO2 in 2018, only one type of atmospheric situation was capable of reducing weekday NO2 values to weekend values. Pattern number 6, characterized by west-northwest winds in the northeast of the Iberian Peninsula (figure 3(a)), represents one of the highest wind speeds in the Barcelona area (figure 3(b)), and is the only one that implied that the NO2 values were more similar to those observed at the weekends. However, although no statistically significant difference is observed in
relation to the weekend, the value is still positive. In contrast, other patterns exhibiting a high baric gradient and a moderate wind situation - see patterns 2 and 4 (figures 2(a)–(b)) - involved no significant reduction in NO$_2$ concentration. Moreover, the situation of abundant rainfall in Barcelona, pattern 3, did not imply a reduction in NO$_2$ concentration comparable to weekends, either. However, in situations with moderate precipitation on weekdays, the most forested areas can exhibit NO$_2$ values close to the usual weekend values, as shown in pattern 8 (see figures 3(c)–(d)).

These results reveal that the different atmospheric situations do not tend to reduce NO$_2$ concentrations a fact which indicates that, regardless of the atmospheric situation, NO$_2$ concentration is lower at weekends.

3.2. Impact of atmospheric conditions on NO$_2$ daily variability

The weekend presents a greater daily variability in NO$_2$ as emissions are not as regular as on weekdays. This is reflected in figure 4, which shows a significantly higher coefficient of variation (CV) during the weekend. However, it would be interesting to investigate whether a higher daily variability in a given neighbourhood implies a greater capacity of the atmospheric variables to describe the daily concentration of NO$_2$.

As shown in figure 4, the areas with a higher daily NO$_2$ variability both on weekdays and at the weekend are forest and green areas, as well as the coastline. In order to quantify the impact of the atmospheric variables on the daily variability of NO$_2$ concentration, we applied an empirical multiple linear regression model based on the relationship between the predictand – NO$_2$ – and the predictor variables - mean sea level pressure, temperature at 850 hPa, geopotential height at 500 hPa, zonal component of wind at 10m, meridional component of wind at 10m-, at the neighbourhood scale. This indicates whether the neighbourhoods displaying a higher daily variability of NO$_2$ (figure 5(a)) correspond to those presenting a better goodness-of-fit of the NO$_2$ empirical model (figure 5(b)).

On examining the relationship between the CV of each neighbourhood and the R adjustment of the multiple linear regression model between NO$_2$ and the atmospheric variables (figure 5), during the weekdays the neighbourhoods with the highest traffic density and the biggest volume of emissions (figure S4) and, therefore, the least variability in NO$_2$, are observed to be the ones that least depend upon atmospheric changes (R $\approx$ 0) in relation to NO$_2$ concentration (see the black box indicating weekdays figures 5(a)–(b)). On the other hand, we found that the areas displaying a greater daily variability are those presenting a higher goodness of the model fit, and atmospheric changes therefore had a greater impact with regard to driving NO$_2$. This occurred both on the working days and during the weekend (figure S5), the forest areas and the non-industrial seafront (see the black box indicating weekends figures 5(a)–(b)) constituting the areas in which meteorology exerted a greater impact upon daily NO$_2$ variability. Interestingly, precisely during the weekend we detected no statistical relationship
between the volume of emissions per neighbourhood and the goodness of the model fit (figure S6).

Furthermore, it is noticeable that those neighbourhoods where the daily variability of NO₂ increases on weekends with respect to weekdays (figure 6(b)), are approximately the same as those where the goodness of fit also increases (figure 6(a)). This indicates that meteorological variability has some influence in driving NO₂ changes in these neighbourhoods.

Figure 7 shows that the greater the increase in the coefficient of variation of the weekends with respect to that of the weekdays, the greater the incidence of atmospheric conditions on the daily variability in NO₂ concentration. Nonetheless, despite this slightly stronger influence of atmospheric variables in some specific neighbourhoods, in general terms NO₂ concentration is governed by the internal dynamics of the city.

4. Conclusions

In the present paper we computed the impact of synoptic weather patterns on NO₂ concentration on weekdays versus weekend values in a very high-resolution dataset (~20 m) for the cold months of 2018. Our objective
involved establishing the extent to which atmospheric patterns constitute a driver of urban NO2. On the other hand, we developed a multiple linear regression model linking NO2—separating weekdays from weekends—to different atmospheric variables with the aim of determining the dependence of daily NO2 variability upon atmospheric conditions.

The main results indicated that synoptic situations favourable to NO2 dispersal—adverse conditions with moderate winds or situations of abundant precipitation—were not capable of reducing the NO2 concentration of weekdays to weekend levels. Of the 8 synoptic patterns studied, only one, characterized by a western-northernwestern advection with moderate winds, enabled a significant reduction of NO2 concentration to values more similar to those recorded at weekends, but without actually reaching these. Moreover, statistical modelling of NO2 with atmospheric variables revealed that the neighbourhoods in the city centre, or the area with the most traffic and NO2 emissions during the weekdays, did not respond to atmospheric changes, but rather possessed its own internal dynamics. It was only the neighbourhoods furthest from the city centre that suffered a certain impact from changes in synoptic meteorology. In this sense, the greater the daily variability of the NO2, the greater the impact of the atmosphere with regard to modifying its concentrations. The weekends showed a similar response to the weekdays, and the areas exhibiting greater daily variability of NO2 were the ones most affected by atmospheric circulation. As for the difference between the impact of the atmosphere during the weekends in relation to weekdays, it was shown that this was more noteworthy in the neighbourhoods where the daily variability showed a greater increase than on weekdays. Although this work provides some important results about the impact of atmospheric circulation in NO2 concentration at very high resolution, some limitations were found during this research. The main limitation of our analysis was the temporal coverage of the NO2 data due to it was only provided for the 2018 year for research purposes. A potential consequence of this is the limited characterization of circulation patterns in western Europe; thus, it is possible that some relevant synoptic patterns were omitted due to the short length of the time series. In this way, future research should work with an extended NO2 time series when it becomes available. In addition, extrapolate this work to other cities would reinforce the findings of this work.

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Data availability statement

No new data were created or analysed in this study.

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Figure 7. Scatterplot in which each point symbolises each of the city’s neighbourhoods (73). The y-axis shows the difference between the weekend and weekday R-adjustment (Rdif). The x-axis shows the difference between the daily coefficient of variation of the weekends and the weekdays (%dif). The colour palette refers to the Rdif values.
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