High NO\textsubscript{2} Levels in Madrid, Spain

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Results from a modeling study to investigate nitrogen dioxide pollution in Madrid, Spain.
Air pollution is a major environmental concern with severe health effects. According to the World Health Organization (WHO), poor outdoor air quality is associated with 4.2 million premature deaths annually. Exposure to air pollution is particularly important in urban areas, where both emissions and population concentration hot-spots are common. Even in regions where significant abatement efforts have been made in recent years, such as Europe, air pollution causes serious impacts (around 0.5 million attributable deaths). Many urban areas, including the largest cities in Spain, are struggling to meet air quality standards, especially those related to nitrogen dioxide ($\text{NO}_2$). This pollutant is known to cause a series of health effects, including lung and cardiovascular diseases. In addition to direct health effects, nitrogen oxides (NOx) are precursors of particulate matter (PM) and other photochemical pollutants such as tropospheric ozone ($\text{O}_3$), a potent oxidant with significant environmental and health effects.

NOx emissions are related to combustion processes in a variety of anthropogenic activities. However, road traffic is a major source in urban areas. According to the Madrid regional inventory, road traffic (SNAP 07 group) accounted for 62–71% of NOx emissions in 2010–2017 (see Figure 1). The contribution of residential, commercial, and institutional (RCI) combustion (SNAP 02) is around 15–20%, while other mobile sources (SNAP 08) are responsible for 8–12% of total NOx emissions. The contribution from industry and power generation is rather small, around 5%. As shown in Figure 1, total NOx emissions were reduced by 11,700 t yr$^{-1}$ (19%) in the 2010–2017 period. This downward trend is mainly related to abatements in the road transport sector (5,800 t yr$^{-1}$). Nonetheless, traffic remains the main contributor to NOx emissions and the primary target of air quality plans in the region.

Despite such reductions, NO$_2$ air quality standards (Directive 2008/50/EC) are often exceeded in the region, especially in Madrid City. In 2017, 15 (8 traffic and 7 background) out of the 24 air quality monitoring stations in the city exceeded the annual limit value (40 $\mu$g m$^{-3}$ as an annual mean). As for the hourly limit value (200 $\mu$g m$^{-3}$), it was exceeded more than 18 times in 7 monitoring stations (5 traffic and 2 background). Most of these exceedances were recorded in downtown Madrid (see Figure 2a). The analysis of hourly NO$_2$ records shows that both traffic and urban background monitoring stations record higher concentrations in fall and winter, especially in December (Figure 2b). High NO$_2$ episodes in Madrid are typically related to high pressure synoptic conditions, characterized by low wind and thermal inversion that favor air stagnation and, consequently, the build up of pollutant concentrations at surface level.

In this study, we apply a mesoscale Eulerian air quality model to provide a comprehensive picture of the NO$_2$ concentration dynamics in Madrid during the most unfavorable
conditions (December) for a better understanding of (a) regional concentration gradients; (b) source apportionment; and (c) outcome of potential abatement measures, both permanent and short action plans.

**Study Methodology**
The state-of-the-science modeling system used in this study consists of three main components, applied in four nested domains with a maximum resolution of 1 km²:

- Weather Research and Forecasting, v 3.8 meteorological model (WRF)
- Sparse Matrix Operator Kernel Emissions, v 3.6.5 emission processing system (SMOKE)
- Community Multiscale Air Quality Modeling, v 5.0.2 chemical-transport model (CMAQ)

This modeling system is able to simulate air pollution levels as the combination of emission, dispersion, deposition, and chemical reactions in the urban atmosphere. The source apportionment analysis carried out is based on a zero-out methodology. First, a baseline scenario (2015 is used as a representative year), considering all emission sources, is modeled to depict current air quality conditions. Then, emissions from the main sectors are removed in SMOKE and the CMAQ model is re-run using exactly the same meteorological conditions. The contribution of each sector is computed as the difference between each perturbed simulation (where emissions from that particular sector have been zeroed-out) and the baseline scenario. Similarly, the effect of potential abatement measures are derived from the comparison of the CMAQ simulations of the emission scenario and the baseline (without measures). The results are shown as control minus baseline, e.g. negative values imply air quality improvements.

<table>
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<th>Sector</th>
<th>Annual mean NO₂ (%)</th>
<th>December NO₂ (%)</th>
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<tbody>
<tr>
<td>RCI (SNAP 02)</td>
<td>Total 5.9</td>
<td>Local sources 8.2</td>
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<tr>
<td></td>
<td>Total 6.6</td>
<td>Local sources 10.2</td>
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<tr>
<td>Industry (SNAP 03-04)</td>
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<td>0.4</td>
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<td></td>
<td>Total 0.3</td>
<td>Local sources 0.5</td>
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<td>Road traffic (SNAP 07)</td>
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<td>74.4</td>
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<td></td>
<td>Total 46.4</td>
<td>Local sources 71.9</td>
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<tr>
<td>Other mobile sources (SNAP 08)</td>
<td>2.7</td>
<td>3.7</td>
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<tr>
<td></td>
<td>Total 2.8</td>
<td>Local sources 4.3</td>
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<tr>
<td></td>
<td>Total 8.3</td>
<td>Local sources 12.9</td>
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<tr>
<td>Local</td>
<td>71.7</td>
<td>100</td>
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<tr>
<td></td>
<td>Total 64.4</td>
<td>Local sources 100</td>
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<td></td>
<td>Total 35.6</td>
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</table>

*Figure 2.* (a) Observed NO₂ annual mean (2017) in the air quality monitoring stations across the Madrid Greater Region; and (b) Box and whisker plot of monthly means (2010–2017) by monitoring station type.
Study Results
The simulation of the baseline scenario (see Figure 3a) suggests that the highest NO₂ concentration values are related to the main roads, especially within the city. The model yielded a citywide average December mean concentration of 53 μg m⁻³, approximately double the corresponding annual mean (26 μg m⁻³). The monthly mean reaches values above 100 μg m⁻³ in the city center. The source apportionment analysis confirms that road traffic is the main contributor to NO₂ levels in the whole region, both outside (Figure 3b) and inside (Figure 3d) the city. Table 1 shows a summary of the contributions of the main sectors as an average for the grid cells within Madrid City.

Figure 3. (a) December NO₂ mean for the baseline scenario; (b) Contribution of road traffic (SNAP 07) and (c) RCI (SNAP 02) to NO₂ December average concentration in the Greater Madrid Region; and (d, e respectively) Same for Madrid City.
Figure 4. (a) Variation on 1-hr maximum NO₂ ambient concentration (stage 3): absolute and (b) relative to the baseline scenario. Traffic restrictions associated to the NO₂ protocol are applied inside the M-30 ring road, highlighted in blue.

Road traffic is responsible for 53.3% of NO₂ annual mean levels. This contribution represents 74.4% of local sources (those inside the Madrid City). The relative relevance of traffic is slightly smaller in winter (46.4%), when the contribution from heating systems is maximum. The contribution of power generation and industry is negligible throughout the year. Although the external contribution is significant (up to 35.6% in December), it should be noted that it is also originated from road traffic emissions in contiguous municipalities (Figure 3b). This clearly indicates that air quality plans intended to meet NO₂ standard should be primary targeted at reducing traffic emissions in the entire metropolitan area. Of note, the contribution of this sector to ambient NO₂ concentration is higher than that for NOx emissions. This points to the fact that abating traffic emissions is particularly effective to reduce NO₂ levels.

In addition to necessary permanent measures aimed at meeting the annual limit value, the Madrid City Council has enforced a short-term action plan for high NO₂ episodes. The so-called NO₂ protocol considers several stages depending on observed concentration levels that involve speed limit reductions, parking restrictions, and access restriction to the city center inside the innermost ring road, M-30; see Figure 4). A detailed simulation of the most restrictive scenario (stage 3) suggests that NO emissions may be reduced by 23.6% within M-30 by preventing 50% of non-resident passenger cars from circulating in that area.21

The effect of such drastic measures has been evaluated for a strong NO₂ episode that took place in December 2016 (Figure 4). Under typical unfavorable conditions in winter, NO₂ peak values can be reduced by 23 μg m⁻³ (around 14%) in Madrid City. However, the effect of the abatement measures outside the intervention area was practically negligible, or may even produce slight concentration increase due to traffic diversion.

Conclusion
This modeling study investigated NO₂ pollution features in Madrid by means of the WRF–SMOKE–CMAQ modeling system (using 2015 as baseline). We found that the average concentration in Greater Madrid in December reached 53 μg m⁻³, with values over 100 μg m⁻³ in Madrid. City
This concentration broadly doubles that of the annual mean value. Very high NO₂ episodes are associated with strong high pressure conditions with weak pressure gradients at surface that favor the formation of thermal inversions that bring about shallow mixing heights and reduced ventilation. Road traffic (SNAP 07) was found to be the main contributor to ambient NO₂ concentrations, with a contribution of 74.4% to the annual mean value. Consequently, the options to meet European standards have to address this sector. We found that permanent measures that can reduce traffic emissions in the entire Madrid metropolitan area are the most effective strategy. However, the simulations demonstrate that the application of short-term measures under very unfavorable conditions have a very limited potential. This highlights the need to implement bold permanent traffic-related measures to meet NO₂ air quality standards.

References
1. Monitoring Health for Sustainable Development Goals (SDGs); World Health Organization (WHO), 2016.
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