COMPARATIVE ANALYSIS OF NITROGEN DIOXIDE (NO2) LEVELS IN MUNICH USING SENTINEL-5P ATMOSPHERIC PRODUCTS AND GROUND-BASED MEASUREMENTS

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ABSTRACT

In this paper, we compare trends in air quality measured by official stations on the ground with remote-sensing-based measurements in Munich, Germany. With Earth Observation data from Sentinel-5P and Sentinel-2, this study investigates the discrepancies that may arise in trends and pollutant levels of NO_2. We find that the defined fixed measuring stations in Munich cover the worst pollution levels in the city. However, we do also find inconsistencies in the information provided by ground measurements regarding pollutant concentrations in contrast to high spatial coverage remote sensing data.

***Index Terms*—** Air Pollution, Remote Sensing, Health, Measuring Sustainable Development

1. INTRODUCTION

Air pollution is recognized by the World Health Organization (WHO) as the major environmental threat to human health [1], accounting for 4.2 million premature deaths worldwide [2] and half a million in the European Union (EU) in 2020 [3]. Poor air quality results in increased mortality from cardiovascular and respiratory diseases which are the primary causes of global mortality [1]. In Europe, despite the reduction in emissions over the past decades, concentrations still exceed the maximum levels defined by the EU and WHO for NO_2 in many locations [1, 3].

Nitrogen dioxide (NO_2) is one of the main pollutants of concern. It is not only dangerous to human health but also contributes to the greenhouse effect and to the formation of smog and acid rain [4]. The major sources of NO_2 pollution are combustion processes. Thus, it is a strong indicator of emissions from vehicle traffic [4] and it remains one of the major challenges for urban areas.

The Air Quality Directive of the European Commission (EC) [5] sets limit concentration values of different pollutants, including NO_2 to reduce their adverse effects on human health. Analogously, the WHO offers limit values for the same pollutants. These limit values are expressed as the maximum average concentration over a defined time period. For the yearly average, the limit values set by the EC (40 $\mu g/mm^3$) and the WHO (10 $\mu g/mm^3$) differ significantly. The WHO limit sets tighter boundaries for NO2 pollution than the EU limit. This could imply that the EU threshold balances economical objectives with health concerns while the WHO focuses primarily on health effects [1].

A good understanding of the pollution levels and trends is essential to take effective action to reduce air pollution and its impacts on health and the environment [1]. Available and reliable data is the main prerequisite for establishing a good understanding for decision- and policy-making. In the last decades the use of remote sensing instruments has been established as a valid tool for estimating ambient pollutant concentrations [6, 7]. Pollutant levels derived from remote sensing offer information with higher spatial coverage and at a global scale [6]. These technological advances have drastically improved our understanding of pollution levels and trends [1]. The current analysis of concentrations in the EU is based on EU-regulated ground-based measurements at fixed sampling points [3]. As a consequence, policymakers rely solely on data from the ground stations which the member states report themselves [5]. However, measurements at a fixed location do not necessarily represent concentrations across a wide area. Recent studies [8, 9] demonstrate how the monitoring of air pollution can suffer manipulations or become unreliable due to lack of data. This underlines the importance of having global coverage of ambient pollution and an independent source of measurements. Using satellite-based remote sensing data offers the possibility to use an independent source of air pollution measurements to validate the information gathered from ground stations and increase the spatial coverage. The objective of this study is to build a comparative analysis of the NO_2 levels based on the Sentinel-5P NO_2 column product and ground station measurements. Using Munich as the study area the representativeness of the official information on air quality will be evaluated.

2. DATA

The Copernicus Sentinel-5 Precursor mission for atmosphere monitoring provides global daily coverage of data products.

The TROPOMI instrument on board the satellite provides the spatial distribution of the pollutants at a resolution of 7kmx7km [10]. For this study, we will use the NO_2 total atmospheric column product.

The Sentinel-2 mission is an Earth Observation mission of the Copernicus programme to acquire global multispectral imagery at 10 m resolution. Processing of Top of the Atmosphere Sentinel-2 data products (Level 1) allows the retrieval of Aerosol Optical Depth (AOD) [11]. AOD is widely used for air pollution monitoring since it is the most comprehensive variable to assess aerosol burden in the atmosphere [12]. Taking advantage of its high resolution, it will be used as a proxy for air pollution in the city, to analyse the spatial distribution of air pollution with high granularity. In this study, we used the MAJA algorithm [13] to process Sentinel-2 data since it captures spatial differences better than other processors [14].

Regarding the ground-based measurements used for our analysis, there are five ground stations providing the hourly concentration of pollutants in Munich. All five sites provide data for the concentration of NO_2, which is measured in $\mu g/mm^3$, the same as the directive limit values.

The availability of Sentinel-5P data is limited to the overpass times of the satellite. Additionally, images with over 20% of cloud coverage were filtered out, since clouds disrupt the atmospheric products. To be able to compare the data accurately the hourly ground-based measurements are reduced to match the used satellite data. The analysis is then based solely on the data that is both available from ground-based and satellite-based sources. This significantly reduces the temporal coverage of the data.

3. METHODS AND RESULTS

The time-series data of NO_2 from the ground-based measurements is compared to the data from Sentinel-5P in Figure 1. For the ground station measurements, the average between the concentrations of all five stations was calculated. For Sentinel-5P, the data was averaged over the whole Munich area. The result of the correlation analysis shows a moderate correlation between the Sentinel-5P measurements of NO_2 and ground-based measurements, with a coefficient of determination is $R^2 = 0.33$. This means that 33 % of the variance of the Sentinel-5P measurements of NO_2 can be explained by the ground-based measurements.

To get more insight into the differences between both sources of data, reflected in the linear regression analysis, the development of NO_2 levels in the whole Munich area was analysed over time. Figure 2 shows the annual averages of NO_2 concentrations in $\mu g/mm^3$ from 2018 to 2021. The concentration values of all the ground stations were aggregated. As can be observed, the level of NO_2 measured at the ground stations in the last years has constantly decreased with respect to the previous year. This is consistent with the political measures implemented starting in 2019 to reduce vehicle traffic in the city and thus contain the levels of NO_2 within the limits established by the European Commission [15]. Money and resources have been invested into these measures as a consequence of the NO_2 limit concentrations being surpassed significantly in 2017 and 2018 [15], especially in the 'Landshuter Alle' and 'Stachus' locations.

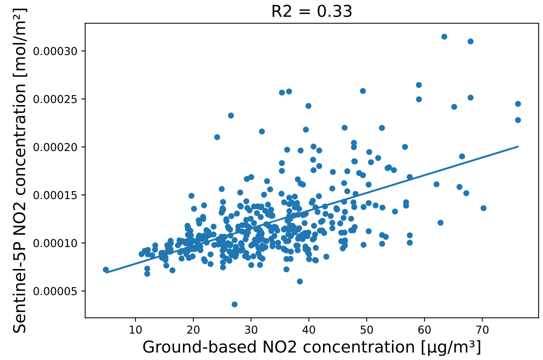

Fig. 1. Linear Regression of TROPOMI over ground-based NO_2 concentrations.

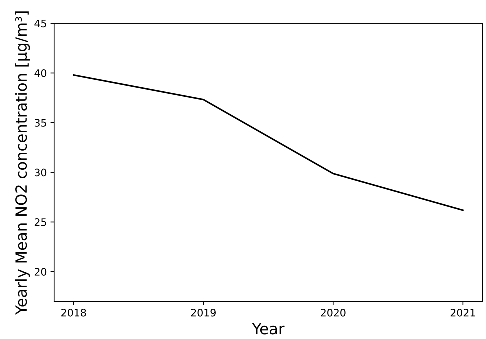

Fig. 2. Yearly averages of ground-based measurements of NO_2 over the Munich area.

For comparison, the TROPOMI NO_2 column concentrations were used to display the annual averages of the NO_2 levels, as shown in figure 3. In contrast to the ground stations, remote sensing data is not limited to a few fixed sampling points. Therefore, in this case, the yearly average over the whole Munich area was computed, where the values in all geographic cells were equally weighted. The plotted yearly averages are displayed in the unit mol/m^2, as provided by the measuring instrument. The NO_2 levels do not seem to decrease with such a clear trend. The development of the pollutant rather seems to decrease in 2020, but increase slightly again in 2021.

Ground sensors differ from remote sensors in the way they are able to capture the pollutant concentration. While the ground sensor measures the volumetric concentration on the

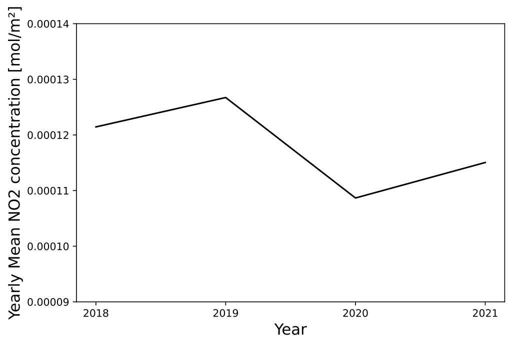

Fig. 3. Yearly averages of satellite-based (Sentinel-5P) measurements of NO_2 over the Munich area.

ground in $\mu g/m^3$, the remote sensing instrument measures the whole atmospheric column from the sensor to the ground and thus provides projected information in the unit mol/m^2. Thus, the cardinal values of the data cannot be compared directly. Nevertheless, we can analyze and evaluate the trend in the development of NO_2 concentration over the study area.

The Sentinel-5P analysis shows that NO_2 yearly trends do not match the narrative suggested by ground-based measurements. One important shortcoming of Sentinel-5P data is the inability to analyse spatial variation in depth due to the limited spatial resolution. That is why Sentinel-2 data is used as a source for high-resolution Earth Observation data to evaluate pollution levels and their spatial variability.

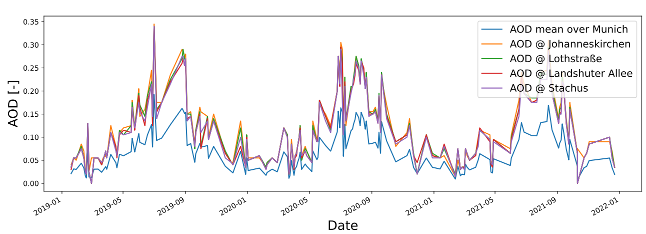

Fig. 4. Sentinel-2-retrieved AOD values at the pixels equivalent to the measuring stations compared to mean AOD over the whole Munich area

In Figure 4, the blue line shows the mean value of AOD over the whole area of Munich. The other lines represent AOD values at the pixels corresponding to each individual measuring station. The average AOD line follows the same pattern as the individual measuring station's lines, although on a clearly lower level. This indicates that the measuring stations are recording aerosol pollution in high-intensity regions and thus when averaging over the whole city other regions with lower levels of the mentioned pollutant reduce the mean values. This suggests that the location of the measuring stations is well chosen to report high pollution exposure in Munich.

4. DISCUSSION

The results show that ground-based measurement and remote sensing data do not tell the same story about the state of NO_2 pollution over the city of Munich. Where ground-based measurements suggest decreasing NO_2 levels in the last years, Sentinel-5P suggests an increase in the pollutant concentration in 2021.

The reason for the increase in NO_2 not captured by the ground measurement sites could come from arising sources of NO_2 in areas of the city not covered by the measuring sites. For instance, it could be traffic being redirected to outer parts of the city, by the master plan for air pollution control in Munich [15], which has the goal to reduce NO_2 concentrations in the city centre. Possibly these pollution emissions are then redirected to other parts of the city, which no longer agree with the locations of the measuring sites.

On the other hand, the results of the analysis of the high-resolution AOD data demonstrated that, at least for aerosol pollution, the measuring stations are placed in pollution hotspot areas reporting the worst pollution exposure in the city. In urban areas, the main source of aerosols is anthropogenic and especially from traffic. NO_2 is also mainly produced as the consequence of fossil fuel combustion. Thus, it can be suspected that this discovery holds as well for NO_2, even though unfortunately the spatial resolution of Sentinel-5P data is too low to actually evaluate this hypothesis. This discovery suggests that the diverging trends could rather be a consequence of the difference in the measurement techniques. The total atmospheric column measured in the space-borne source might and possibly does contain a higher concentration of nitrogen dioxide compared to the ground-level concentration in 2021.

The performed analysis and the used data also suffer from limitations that might influence the outcome and lead to the observed trend differences. First, as explained above a reduced number of data points is used, restricted by the availability of the satellite data and the cloud coverage of the available images. Robustness checks were performed with different levels of cloud coverage, comparing all available ground-based measurements to the reduced set of measurements according to remote sensing availability. The experiments indicated no major bias being included in the data due to the reduced temporal coverage and that the dataset used for these analyses represents the time series pollutant levels fairly. Nevertheless, one needs to be aware of this topic when analysing and interpreting remote sensing data for air quality monitoring.

5. CONCLUSION

In this study, we compare ground-based measurements of air pollutant concentrations to remote sensing data of air pollutant levels.

We find some important discrepancies in the trends derived from ground-based measurements and remote sensing data. The yearly trends of NO_2 from ground-based measurements suggest decreasing pollutant levels, while Sentinel-5P data rather shows an increase in the same pollutant. At the very least, these unexpected temporal patterns deserve further investigation. This is because they might be indicative of undesired policy behaviour. Limitations to the remote sensing data have to also be taken into account. These discrepancies can come from a lack of data on the ground basis, however, the cause may also lie in the satellite data, as it suffers from important constraints.

On the other hand, the results of the analyses with Aerosol Optical Depth show that the measuring stations are indeed positioned at locations of high pollution occurrence. This discovery is important for the validation of the representativeness of the pollutant concentrations from ground-based measurements and most probably holds also for nitrogen dioxide due to the similar origin to NO_2 and aerosol pollution in urban areas.

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