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Comparison of ammonia air concentration before and during the spread of COVID-19 in Lombardy (Italy) using ground-based and satellite data

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**HIGHLIGHTS**

- We used ground and satellite data to estimate NH$_3$ concentrations in Lombardy.
- We analyzed the period before, during and after the COVID-19 lockdown.
- We divided both datasets in three zones: city, countryside and mountain.
- NH$_3$ concentrations increased by 31% in countryside areas in 2020.
- No difference was found between pre- and post-lockdown NH$_3$ from satellite data.

**GRAPHICAL ABSTRACT**

**ABSTRACT**

Several anthropogenic activities have undergone major changes following the spread of the COVID-19 pandemic, which in turn has had consequences on the environment. The effect on air pollution has been studied in detail in the literature, although some pollutants, such as ammonia (NH$_3$), have received comparatively less attention to date. Focusing on the case of Lombardy in Northern Italy, this study aimed to evaluate changes in NH$_3$ atmospheric concentration on a temporal scale (the years from 2013 to 2019 compared to 2020) and on a spatial scale (countryside, city, and mountain areas). For this purpose, ground-based (from public air quality control units scattered throughout the region) and satellite observations (from IASI sensors on board MetOp-A and MetOp-B) were collected and analyzed. For ground-based measurements, a marked spatial variability is observed between the different areas while, as regards the comparison between periods, statistically significant differences were observed only for the countryside areas (+31% in 2020 compared to previous years). The satellite data show similar patterns but do not present statistically significant differences neither between different areas, nor between the two periods. In general, there have been no reduction effects of atmospheric NH$_3$ as a consequence of COVID-19. This calls into question the role of the agricultural sector, which is known to be the largest responsible for NH$_3$ emissions. Even if the direct comparison between the two datasets shows little correlation, their contextual consideration allows making more robust considerations regarding air pollutants.

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1. Introduction

Ammonia (NH₃) is an air pollutant of increasing environmental concern, whose emissions are primarily anthropogenic, released mainly from the agricultural sector by field application of synthetic fertilizers and manure management (Van Damme et al., 2015). NH₃ causes a series of cascading negative effects that damage both ecosystem biodiversity due to acidification and nitrogen enrichment (EMEP Centre on Emission Inventories and Projections, 2020; Erismann et al., 2007; European Commission, 2005) and human health (Van Damme et al., 2014), being a precursor of secondary fine particulate matter (PM₂.₅) (Lovarelli et al., 2020; Perone, 2021). The damages to public health and ecosystems have been evaluated in 10–25 €/kg NH₃ (Executive Body of the Convention on Long-Range Transboundary Air Pollution, 2019). For these reasons, in recent decades, international integrated policies have been increasingly interested in quantifying, monitoring, and limiting NH₃ emissions. Despite the reduction obtained in absolute terms since 1990, in 2018, agriculture accounted for 93% of NH₃ emissions in relative terms in the European Union, still showing the criticality of this sector (EEA, 2019). The reduction of NH₃ emissions is a complex process. First of all, measuring this compound is not easy, which also makes accurate monitoring difficult. The most widely used methodologies to date are measurements through ground-based instruments and satellite-based remote-sensing (Nair and Yu, 2020). However, each of these two techniques has advantages and problems. The ground-based measurements currently allow understanding the evolution of the atmospheric concentrations over time at ground level, but they are affected by local spatial and meteorological variability. Indeed, NH₃ volatilization from main primary sources (fertilizers and manure) is influenced by weather parameters such as wind speed, rainfall, and temperature, among others (Brentrup et al., 2000). Given the high variability related to NH₃ emissions, a geographically dense network of control units can be a useful method to fulfill monitoring requirements. However, due to the stickiness of NH₃ to observational instruments, the control units that collect NH₃ data are normally fewer per unit area than those used to measure other air pollutants (Van Damme et al., 2015). Satellite remote sensing, on the other hand, is based on the distinction of the NH₃ spectrum in the gas-phase by means of infrared spectrometers and allows to obtain a broad spatial coverage (both superficial and vertical) of NH₃ atmospheric concentrations, but the measurements available to date suffer from temporal discontinuity because deployed instrumentation is not onboard geostationary satellites (Nair and Yu, 2020). Furthermore, the reliability of the measurements at night or in the presence of clouds decreases. Ultimately, since the two methods compensate, at least partially, the respective limitations, considerations on atmospheric NH₃ pollution made by integrating both types of measurement can be more solid and comprehensive.

During the worldwide spread of Coronavirus Disease (2019) (COVID-19) in 2020, attention on air quality and the need to understand changes in the presence of pollutants in the atmosphere increased considerably. In literature, several studies have focused on the relationships among the COVID-19 outbreak, government actions to contain the spread of the SARS-CoV-2 virus and for their responsibility for respiratory and cardiovascular diseases (Li et al., 2018; Srivastava, 2021). However, NH₃ influence on secondary aerosol is significant as it is a recognized precursor (Perone, 2021). Moreover, Zheng et al. (2020) and Manigrasso et al. (2020) discussed the possibility that SARS-CoV-2 spread is favored by a mild alkaline pH of airborne particles, and thus related to ammonia-polluted environments such as the Po Valley. To support this hypothesis, in the world 28 hotspots were identified with an NH₃ column concentration above 0.5 mg/m², which were linked to either biomass burning and fires or (and especially) agricultural areas, in particular with agricultural valleys surrounded by mountains, such as the case of Po valley in Northern Italy. Perone (2021) also identified cities in Northern Italy as those with the highest mortality risk in the country.

The aim of this study is to analyze NH₃ air concentration in Lombardy, the region most affected by the pandemic (Altuwajiry et al., 2021; Bonati et al., 2021; Perone, 2021), by using both data from control units at ground level and satellite observations to evaluate the temporal and spatial scale of NH₃ concentration before and during lockdown (i.e., the strict national lockdown occurred in Spring, 2020), highlighting relationships, similarities or differences between these two measurement solutions.

2. Methods

2.1. Data collection of ground-based observations

Ground-based observations were retrieved from the database of the Regional Environmental Protection Agency of Lombardy (ARPA Lombardia, 2020). Data from all the control units collecting NH₃ measurements in the Lombardy Region were considered; overall data from 12 control units were available. These latter measure NH₃ indirectly through special analyzers using the chemiluminescence technique, by which NH₃ is first oxidized to nitrogen oxide (NO) and its concentration in the air sample is measured alongside NO and NO₂ (nitrogen dioxide). In particular, hourly data on air NH₃ concentration (expressed as μg/m³) collected by the control units in question were sourced.

Furthermore, from the same ARPA Lombardia control units and for the same period, the daily weather parameters of temperature (T; °C), relative humidity (RH; %), rainfall (R; mm) and wind speed (W; m/s) were downloaded to consider their effects on NH₃ air concentration. The main characteristics of the control units used to retrieve these data are shown in Table 1.

All control units were distinguished in “city”, “country” (short for countryside) or “mountain” stations, to investigate the effect of COVID-19 on NH₃ air concentration in the city, the most densely populated and characterized by traffic jams and industrial activities, in the countryside, where agricultural and livestock activities are most concentrated, and in mountain areas. This grouping was based on the zoning of Lombardy for air quality monitoring according to the Italian legislative decree 155/10 under the directive 50/08/CE on ambient air quality and cleaner air for Europe (ARPA Lombardia, 2020). According to the previous regulations, the stations located in urban agglomerations or highly urbanized plains have been considered as “city” stations, those located in the plain area as...
“country” and finally those located in the pre-Alps, Apennines and mountains as “mountain”. The same grouping of stations was also adopted by Lonati and Cernuschi (2020). The zone shapefile was obtained from the Lombardy region geo-portal website (http://www.geoportale.regione.lombardia.it/) with the zone classification carried out at the municipality level. Fig. 1 shows the regional zoning for Lombardy and the geographical position of each control unit. To further investigate the land cover in each zone, the Corine Land Cover (CLC) classification (Feranec, 2016) from 2018 was reclassified to a binary layer with the classes agriculture/other. Agricultural land cover was 87% in the country class, 55% in the city class and 14% in the mountain class.

The temporal coverage of the collected data goes from the beginning of 2013 to the end of October 2020. This period was selected because the same data were available also from the satellite dataset. Some data were lacking or were characterized by excessive uncertainty; therefore, the dataset was cleaned before data processing. NH$_3$ concentrations not included in ±3 standard deviations were excluded from the dataset. Data were averaged as daily measures in order to be merged with the weather data for further analyses. All data were grouped in 2 periods to allow comparisons between normal living conditions and the period of the pandemic: the first included data from 2013 to 2019, while the second those of 2020.

Statistical analyses were conducted using SAS version 9.4 (SAS Institute, Cary, NC, USA) statistical software. Descriptive and multivariate statistics were carried out on each meteorological variable and on NH$_3$ concentration. A general Linear Model procedure (GLM Proc) was carried out to identify a model predicting the air concentration of NH$_3$ based on the unit zoning, local weather, monitoring period, and their interactions. In particular, in the model the following class parameters were included: (i) the period, with the 2 levels of 2013–2019 and 2020, and (ii) the zone, with the 3 levels of city, country, and mountain; the weather variables of temperature, rainfall and wind speed and the months of the year were included as well, together with their interactions for (i) year, zone and month, and (ii) temperature, rainfall and wind speed.

2.2. Data collection of remote sensing observations

Remote sensing data were retrieved from the online freely available database of the IASI sensor (https://iasi.aeris-data.fr/nh3/), which is the Infrared Atmospheric Sounding Interferometer onboard the ESA’s (European Space Agency) MetOp satellites. In particular, data observed by the MetOp-A and MetOp-B satellites were obtained for the period 2013–2020, as MetOp-B became operational in early 2013, and thus data from two satellites were available to obtain a higher number of observations. While a third satellite, MetOp-C has also been operational since 2019, IASI data from this platform were not used to avoid introducing a bias in the later period of the dataset. For both satellites, daily level 2 products were downloaded, which report total column NH$_3$ in

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**Table 1** List of the control units used. Their location is provided as well as the grouping in different zones.

| Province | Station Name     | Analyzer model | Longitude (E°) | Latitude (N°) | Altitude (m) | Zoned as   |
|----------|------------------|----------------|----------------|---------------|--------------|------------|
| Cremona  | Corte de Cortesi | API 201E       | 10.0062        | 45.2785       | 57           | Country    |
| Cremona  | Fatebenefratelli | TEI 17i        | 10.0438        | 45.1425       | 43           | City       |
| Cremona  | Gerre Borghi     | TEI 17i        | 10.0692        | 45.1095       | 36           | City       |
| Lecco    | Colico           | TEI 17i        | 9.3847         | 46.1381       | 229          | Mountain   |
| Lecco    | Moggio           | TEI 17i        | 9.4975         | 45.9128       | 1194         | Mountain   |
| Lodi     | Bertinico        | API 201E       | 9.6663         | 45.2335       | 65           | Country    |
| Mantua   | Schivenoglia     | TEI 17i        | 11.0761        | 45.0169       | 12           | Country    |
| Milan    | Pascali          | API 201E       | 9.2355         | 45.4790       | 122          | City       |
| Pavia    | Folperti         | TEI 17i        | 9.1646         | 45.1947       | 77           | City       |
| Pavia    | Sannazzaro       | ENVEA AC32e    | 8.9042         | 45.1028       | 87           | Country    |

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![Fig. 1. Zoning of the Lombardy region (Northern Italy) in city (violet colored), country (green colored), and mountain (blue colored) zones. Colored dots represent the position of every ground-based control unit. Bottom-left: original zoning; bottom-right: the zoning resampled to IASI pixels. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image-url)
molecules/cm² and their relative uncertainty (in percentage) for discrete points observed by the satellite with an approximate footprint of 12 km (at nadir). Only daytime observations were used, as these are considered more accurate owing to the larger thermal contrast compared to nighttime observations (Van Damme et al., 2014). As cloud cover and thermal contrast in the atmospheric column greatly reduce the number of available measurements, daily observations lying partially or entirely within the Lombardy region were spatially re-gridded to a 0.5° × 0.5° grid (for a total of 26 grid points) and temporally averaged to obtain monthly means. This grid size is similar to the choice adopted by Van Damme et al. (2014) and allowed us to obtain on average 100 measurements per grid cell per month, thus producing more statistically robust NH₃ monthly estimations. The averaging was weighted based on the uncertainty of each measurement, following the procedure described by Van Damme et al. (2014), i.e. (equation (1)).

\[
\sigma = \frac{\sum w_i x_i}{\sum w_i}, \quad (1)
\]

where \(x_i\) is a IASI measurement contained in the 0.5° × 0.5° cell, \(w_i\) is the weighting factor, equal to \(1/\sigma^2\) and \(\sigma\) is the error of the total column retrieval on a pixel basis.

The uncertainty of each monthly average was then expressed as

\[
\sigma = \sqrt{\frac{1}{\sum w_i^2}} \quad (2)
\]

Moreover, it was established to discard monthly means for which the uncertainty was higher than 75% and measurements were fewer than 10 (30% of a month), as per recommendations by Van Damme et al. (2014).

Similar to the methodology adopted for the ground-based control units, satellite-based measurements were also divided into two periods, i.e., 2013–2019 and 2020, and classified as “city”, “country” or “mountain” based on the areas defined by ARPA Lombardia. In this case, the analysis was limited to the months from January to June owing to the unavailability of IASI data from June 2020 onwards at the time of writing. The zone shapefile was transformed to a raster and resampled to the same 0.5° × 0.5° grid used for IASI observations; each IASI pixel was then classified by assigning to it the zone with the largest count within the pixel (see Fig. 1). In addition, the CLC 2018 was resampled to the IASI grid and the percentage of agricultural land use was counted for each pixel. In the country zone, agricultural land use ranged between 50% and 83% except for one pixel (21%). In the mountain zone, it ranged between 4% and 21% while in the city zone it was 13%.

Statistical analyses were also conducted using SAS version 9.4 (SAS Institute, Cary, NC, USA) statistical software, with a General Linear Model procedure (GLM Proc) similar to the ground-based dataset; also in this case, a model predicting NH₃ air concentration based on the units zoning, local weather, monitoring period and their interactions was carried out for satellite data. The statistical model used for satellite data was the same as for ground-based data, to allow the best comparability of results; therefore, the parameters included in the model were class parameters for the period (levels of 2013–2019 and 2020) and for the zone (3 levels of city, country, and mountain) and the weather variables of temperature, rainfall and wind speed, the months of the year and the interactions among year, zone and month, as well as temperature, rainfall and wind speed.

To complement satellite observations with meteorological data in a similar way as done for ground NH₃ measurements, daily temperature, rainfall and wind speed from the reanalysis model ERA5 (European center for meteorology and weather forecast reanalysis, (Hersbach et al., 2020)) at 0.25° × 0.25° resolution were obtained. The values were then regridded to the same 0.5° × 0.5° grid of IASI observations and averaged to monthly values to conduct the GLM procedure. The steps of the adopted methodology are summarized for both ground-based and remote sensing observations in Fig. 2.

3. Results

3.1. Ground-based measurement

For what concerns NH₃ air concentrations, Fig. 3 reports the average concentration (µg/m³) for the control units according to the classification in the zones of city, country, and mountain, with the mean and standard error for each month of the two periods 2013–2019 and 2020.

In both periods, the highest NH₃ concentrations can be observed for countryside stations. These stations are located in areas near agricultural,
production sites, whose seasonal practices affect mostly NH$_3$ emissions. Statistically significant differences can be found among the three zones, with country zones showing much higher concentrations than stations located in city and mountain zones. In particular, the mean yearly value for country zones was 22.5 and 29.5 μg/m$^3$ for 2013–2019 and 2020, respectively. The highest concentrations were recorded in August and September for 2013–2019 (27.5 and 28.1 μg/m$^3$, respectively) and in February and September for 2020 (44.7 and 36.8 μg/m$^3$, respectively). The lowest average value of NH$_3$ concentration in the country zone (21.5 μg/m$^3$, June 2020) was higher than the highest of city and mountain zones (13.0 and 6.6 μg/m$^3$, October and April 2020, respectively).

In all cases, mountain stations show the lowest concentrations, with 2020 higher than 2013–2019 in all months except for June, July, September, and October. The yearly average is equal to 4.2 and 4.4 μg/m$^3$ in 2013–2019 and 2020, respectively. The city zone has intermediate values, with a yearly average equal to 8.6 and 8.8 μg/m$^3$ for 2013–2019 and 2020, respectively. Although for half the months the considered, the city zone NH$_3$ concentration was higher in 2020 than in the previous period (i.e., February, March, April, May, and October), the annual average is still slightly higher in 2020. Interestingly, the months in which NH$_3$ in the city was higher than in the previous periods were the same months in which the strictest lockdown was in progress (i.e., spring 2020). A similar observation can be done with respect to the mountain zone.

Both country and city zones showed higher NH$_3$ concentration in 2020 than in the previous period in February, March, April, and May. Such higher concentration, especially the peak observed in February, can be attributed to manure management and manure field spreading. In particular, because field application of manure can be carried out depending on the constraints fixed by crops cultivation (sowing periods), by laws (European nitrates directive 91/676/EEC and the regional action programs for the protection of water pollution, Nitrates Directive (Eu), 2016), as well as by weather conditions (field spreading can be carried out when field conditions permit it, such as when no rainfall occurs), quite strict temporal windows can be identified during the year. Therefore, slurry application, and the related NH$_3$ air concentration were higher at the beginning of 2020 than in previous years probably because the unfavorable weather conditions of the previous autumn (i.e., in October 2019 high rainfall was observed at country zone stations with average rainfall of 115 mm, equal to 15% of the year) did not favor slurry spreading. Hence, a massive field application of slurry occurred at the beginning of 2020, which led to the consequent observation of high NH$_3$ concentrations. Moreover, during the months of lockdown, transport and industrial activities mostly stopped, and consequently also the related emissions decreased. The reduction of other air pollutants, such as sulfuric acid and nitric acid, with which NH$_3$ combines to form secondary PM (Ge et al., 2020), may have contributed to binding less NH$_3$ and a higher chance to find it in its free form. The main zone differences mentioned above are reported in Fig. 4. Here, NH$_3$ air concentrations are reported split into 2 periods and 3 zones. In 2020, NH$_3$ concentration recorded at country stations were 69% of the total and were 31% higher than in 2013–2019. No significant differences between NH$_3$ values in 2013–2019 and 2020 can be observed for the city zone (+2%). In the mountain zone, instead, NH$_3$ concentration participates for 10% of the total, with +6% in 2020 compared to 2013–2019. The three zones of city, country, and mountain show statistically significant differences.

### 3.1.1. Meteorological observations in relation to NH$_3$ air concentration

Fig. 5 reports the average meteorological data of the analyzed provinces, with control units grouped by zone in the two selected periods for temperature (Fig. 5-top), rainfall (Fig. 5-middle), and wind speed (Fig. 5-bottom). Considering that Po Valley is located in Northern Italy and that it is mostly characterized by a temperate climate, without a dry season and with a hot summer (Beck et al., 2018), the meteorological data show a pattern consistent with these characteristics. In particular, regarding temperature a cold winter and a warm summer can be identified; rainfall is concentrated in spring and autumn and wind speed is low on average throughout the year.

In general, it can be observed that both city and country station units

![Fig. 3. Mean and standard error of NH$_3$ concentration, expressed in μg/m$^3$, per zone, month and period.](image)

![Fig. 4. Mean and standard error of NH$_3$ concentration, expressed in μg/m$^3$, per zone and period.](image)
Fig. 5. Mean meteorological data (temperature -top, rainfall – middle, and wind speed -bottom) per zone (city, country, and mountain), month (Jan–Oct) and period (2013–2019, 2020).
recorded similar average yearly values for temperature, with 2020 showing slightly higher values (15.7 and 16.2 °C in 2013–2019 and 2020 in the city zone and 15.7 and 15.8 °C in the country zone, respectively). In the mountain zone they were lower (10.2 and 10.9 °C in 2013–2019 and 2020, respectively). The average rainfall was lower in 2020 compared to the previous period in the city (2.5 and 1.9 mm/d in 2013–2019 and 2020, respectively) and country (1.8 and 1.6 mm/d) zones, while in the mountain zone rainfall was higher (4.4 and 4.9 mm/d). As regards wind speed, all values were low: 1.3 and 1.1 m/s as average of 2013–2019 and 2020 in the city zone, country averaging 1.6 and 1.7 m/s and mountain averaging 1.5 m/s in both periods. Pearson correlations were calculated (data not shown) and significant differences were found among all the meteorological parameters considering the different zones and months. Although the linear relationship is not very strong, temperature is significantly negatively correlated with rainfall and wind speed. In contrast, rainfall and wind speed are positively correlated with each other. The changes in NH₃ air concentration and meteorological parameters during the period of observation are reported in Table 2.

The relative difference between the periods 2020 and 2013–2019 is carried out by using the data reported in Figs. 3 and 5. From these data, it emerges that NH₃ concentration in air was higher in 2020 than in the previous period from February to May for all zones and this occurred, in most cases, together with higher temperatures. Except for these four months and October, in city zones NH₃ was lower in 2020 than over the previous years, which occurred with changes in the meteorological parameters that, however, do not allow to identify clear links between NH₃ and weather patterns, and especially with rainfall/wind speed.

To clarify the relationships among these variables, a GLM procedure was performed to obtain a predictive model for NH₃ concentration in air. The model was generated on the classes of year (2 levels: 2013–2019 and 2020) and zone (3 levels: city, country, and mountain) and was found statistically significant, although with a very low coefficient of determination (R² = 0.19). All variables were also significant with “year” and “zone” very significant (p < 0.0001) and month, weather parameters and their interactions significant (p < 0.05). Among the meteorological parameters, rainfall was the variable with the lowest significance for the prediction of NH₃. The calculated Least Squares Means (LS Means) were all significant (p < 0.0001). However, the statistical significance of LS Means for the effect year*zone showed no difference between the 2 periods for the city and the mountain zones as reported in Table 3.

This result shows that, in the two studied periods, both city zones and mountain zones have comparable results. Since NH₃ is mostly released in countryside areas and normally deposited within a short radius from the emissive source, it can be expected that lower concentrations reach cities and mountain zones and that these latter do not show significant

### Table 2

| Month | Zone     | NH₃  | T    | R    | W    |
|-------|----------|------|------|------|------|
|       | City     | -15.4% | -3.3% | -34.0% | -24.6% |
|       | Country  | 39.6% | 15.5% | 1.0%  | -4.3% |
|       | Mountain | 6.5%  | 682.6% | -87.7% | -32.3% |
| June  | City     | -19.7% | -2.3% | 1.1%  | -22.1% |
|       | Country  | -0.6% | -6.6% | 28.1% | 15.2% |
|       | Mountain | -9.8% | -6.1% | 47.0% | 11.3% |
| July  | City     | -17.5% | 2.2%  | 9.7%  | -32.9% |
|       | Country  | 51.4% | -2.2% | 94.8% | 4.7% |
|       | Mountain | -1.9% | 0.8%  | -49.2% | 8.6% |
| August| City     | -5.2% | 7.1%  | -34.6% | -27.6% |
|       | Country  | 14.7% | 2.5%  | 133.9% | 13.1% |
|       | Mountain | 11.9% | 6.8%  | 39.0% | 18.8% |
| September| City     | -22.3% | 6.3%  | -40.7% | -25.6% |
|        | Country  | 31.0% | 4.5%  | -52.7% | 11.6% |
|        | Mountain | -33.7% | 5.5%  | 28.7% | 2.3% |
| October| City     | -24.2% | 7.3%  | 15.3%  | -10.0% |
|        | Country  | -17.6% | -10.3% | -1.4% | 20.6% |
|        | Mountain | -49.7% | -16.8% | 104.1% | 13.5% |
differences in the analyzed periods. Since agricultural activities are more subject than others to annual variability and seasonality, the fact that NH$_3$ in countryside areas is significantly different between 2013 and 2019 and 2020 prompted us to investigate the effects of seasonality on NH$_3$ every year. Thus, the model was relaunched evaluating the effect of each year on NH$_3$, focusing only on the country zone. This model was found significant with the coefficient of determination $R^2 = 0.29$ and all weather parameters significant ($p < 0.05$). Significant differences for NH$_3$ concentration emerged in some years, while no differences were found between (i) 2013 and 2016, (ii) 2014 and 2015, and (iii) 2017, 2018 and 2020. The results of this second analysis suggest that meteorological variability can play a role on NH$_3$ air concentration in country zones.

### 3.2. Satellite measurements

The NH$_3$ total column observations from IASI data reported in Fig. 6 show slightly different patterns compared to ground measurements, although it is a shared feature that country zones show the highest values in all months during 2013–2019 and in 2020. The highest total column NH$_3$ was recorded for grid points classified as “country” in June, both over 2013–2019 ($5.89 \times 10^{-4}$ mol/cm$^2$) and in 2020 ($5.31 \times 10^{-4}$ mol/cm$^2$); over 2013–2019, May was the second highest month with respect to NH$_3$ values ($4.59 \times 10^{-4}$ mol/cm$^2$), while in 2020 it was March, when the lockdown started ($5.22 \times 10^{-4}$ mol/cm$^2$). In March 2020, mountain grid points also show very high values ($5.11 \times 10^{-4}$ mol/cm$^2$), possibly because of the actual inclusion of agricultural areas within grid points classified as mountain at the IASI scale (maximum agricultural cover was 21% in mountain grid points from CLC, 2018). As a further hint of this, compared to ground observations, city zones show generally lower total column NH$_3$ than mountain zones, with the lowest values overall recorded for city zones in January 2020 ($1.34 \times 10^{-4}$ mol/cm$^2$). For country zones, all months except June show an increase in total column NH$_3$ compared to the average of 2013–2019. For the other zones, the pattern is more variable: city grid points show a higher NH$_3$ total column in February, March, April, and June 2020 while for mountain stations the months with a higher NH$_3$ total column are January, March (with an increase of 108% compared to the same month over 2013–2019), April and June.

As shown in Fig. 7, averaging all monthly observations between January and June, mountain and country zones show an increase in NH$_3$ total column in 2020 compared to 2013–2019, with similar values (18% for mountain zones and 15% for country zones).

As for ground observations, the NH$_3$ total column for city zones is unvaried between the two periods ($-0.73\%$). In contrast with ground observations, however, the share of NH$_3$ for the different zones is more uniform: in 2020, country zones accounted for 42% of the total column, mountain zones for 27% and city zones for 31%. This might be caused by the coarse spatial grid of IASI measurements and mix between different land use classes at the IASI scale.

#### 3.2.1. Meteorological observations in relation to NH$_3$ air concentration

As for ground observations, monthly meteorological data and NH$_3$ total column divided in the two periods were compared. Table 4 reports such results.

In most months, temperature was higher in 2020 than in 2013–2019, particularly in the mountain zones where it was always higher except for March, with an increase of 449.99% in February 2020 compared to 2013–2019. In contrast, precipitation was lower in most months, except for mountain zones in March and all zones in June, while wind speed showed a more varied pattern with a decrease in January 2020 and an increase in May 2020 in all zones.
A GLM procedure was carried out to identify a prediction model for NH$_3$ total column, in a similar way as done for ground-based measurements. The model was found significant with a coefficient of determination of 0.55. The main difference with the GLM for ground-based observations is related to the fact that none of the meteorological parameters was found statistically significant, and only the zone parameter and month*zone effect were significant in the prediction of NH$_3$. In addition, no statistical difference emerged from the evaluation of LS Means for year*zone, as reported in Table 5.

The result of the GLM procedure with satellite NH$_3$ observations and meteorological parameters shows no statistical difference with respect to the NH$_3$ concentration in the air between the two periods. This is in contrast with the ground-based measurements, which showed a significant difference for NH$_3$ concentrations in country stations, between 2013 and 2019 and 2020. The reason for this result may be due to the

**Table 4**
Percentage change between 2020 and 2013–2019 for NH$_3$ total column, temperature (T), rainfall (R) and wind speed (W) from IASI and ERA-5 observations. When the resulting changes are positive (year 2020 > years 2013–2019) cells have a green background.

| Month | Zone   | NH$_3$ | T     | R     | W     |
|-------|--------|--------|-------|-------|-------|
| January | City   | -41.30% | 12.53% | -81.74% | -15.22% |
|        | Country | 57.09%  | 8.67%  | -66.28% | -5.94%  |
|        | Mountain| 17.62%  | 50.67% | -69.93% | -2.42%  |
| February | City   | 1.53%   | 50.45% | -87.94% | -1.07%  |
|         | Country | 10.67%  | 48.31% | -90.94% | 48.47%  |
|         | Mountain| -9.82%  | 449.90%| -66.97% | 32.27%  |
| March   | City    | 7.72%   | -5.11% | -4.30%  | 4.73%   |
|         | Country | 36.02%  | -4.51% | -22.97% | 46.01%  |
|         | Mountain| 108.41% | -5.71% | 14.73%  | -9.26%  |
| April   | City    | 15.62%  | 3.15%  | -57.28% | -47.02% |
|         | Country | 18.64%  | -0.05% | -52.21% | -24.42% |
|         | Mountain| 13.32%  | 9.78%  | -57.93% | 28.69%  |
| May     | City    | -1.68%  | 9.32%  | -10.92% | 24.81%  |
|         | Country | 9.80%   | 9.55%  | -36.25% | 46.39%  |
|         | Mountain| -2.54%  | 16.17% | -12.84% | 26.45%  |
| June    | City    | 1.84%   | -7.49% | 49.63%  | -11.88% |
|         | Country | -9.85%  | -5.65% | 47.79%  | 41.90%  |
|         | Mountain| -16.59% | 9.58%  | 44.44%  | 32.56%  |

**Table 5**
Statistical significance of LS Means resulting from the GLM procedure for the effect year*zone and NH$_3$ as dependent variable.

| i/j   | 2013–2019 country | 2013–2019 mountain | 2020 city | 2020 country | 2020 mountain |
|-------|--------------------|--------------------|-----------|--------------|---------------|
| 2013–2019 | n.s.               | n.s.               | n.s.      | n.s.         | n.s.          |
| city   |                    |                    |           |              |               |
| 2013–2019 | n.s.               | n.s.               | n.s.      | n.s.         | n.s.          |
| country|                    |                    |           |              |               |
| 2013–2019 | n.s.               | n.s.               | n.s.      | n.s.         | n.s.          |
| mountain|                    |                    |           |              |               |
| 2020 city|                    |                    | n.s.      | n.s.         | n.s.          |
| 2020 country|                    |                    | n.s.      | n.s.         | n.s.          |
| 2020 mountain|                    |                    |           |              |               |
susceptibility of control units to a series of site-specific aspects that, instead, cannot be measured in the satellite coarse grid, and the fact that satellites measure total column NH$_3$, which might be the result of emissions originating in a different grid point than the footprint observed by the satellite at the time of data acquisition.

4. Discussion

This study was carried out with a focus on comparing the period (i.e., from year 2013–2019) before the lockdown determined by the emergency of COVID-19 and the subsequent period during the pandemic (i.e., year 2020, with the strict lockdown lasting from March–June 2020), adopting two measurement systems. Remote sensing datasets show no significant difference in NH$_3$ air concentration between the period before the spread of COVID-19 and the one during the pandemic. From the ground based analysis, NH$_3$ was observed higher than other years in city and mountain, and significantly in country zones. As NH$_3$ is strongly dependent on agricultural and livestock activities, its concentration was found subject to seasonality, weather conditions and to agricultural management. This aspect has been underlined also in the study of Lonati and Cermaschi (2020) and Deserti et al. (2020). The same result was observed also by Gualtieri et al. (2020) who state that, in 2020, NH$_3$ concentration increased in Italy compared to 2019. They also report that more than 90% of NH$_3$ is of agricultural origin in Milan, while this contribution decreases to 71% in Rome and 62% in Bologna, suggesting once more the relevance of livestock activities in Northern Italy. Therefore, the role of agriculture and livestock appears to be the largest influence on NH$_3$ air concentrations. Given the relationship of weather and seasonality with agricultural field activities, and the characteristics of NH$_3$ emissions (Brentrup et al., 2000; Sutton et al., 2013), it can be expected that NH$_3$ concentration is higher in summer (high temperatures) than in winter (when regulations prohibit field spreading due to nitrate leaching), and that peaks are observed in periods before crop cultivation (generally from February to June and from August to October in the analyzed area, where double cropping is widespread) when base-dressing fertilizers are applied on the field (Guido et al., 2020; Pedersen et al., 2020). All these aspects are confirmed also by the present study. Independently from the period considered, the highest NH$_3$ concentration can be observed in February–March and July–October, compared to the other months.

Moreover, different values in NH$_3$ concentration are strictly linked to manure storage (Zilio et al., 2020) and to field application, since this operation can be carried out when no rainfall occurs and in agreement with the European nitrates directive 91/676/EEC and the regional action programs for the protection of water pollution caused by nitrates from agricultural sources. These aspects have been widely investigated in literature, such as by Skjøth et al. (2011), Ramanantenasoa et al. (2018), and Ge et al. (2020).

4.1. Limitations of ground-based and satellite observations

In this study, measurements from both ground control units and satellite sensors were used to investigate air concentrations of NH$_3$. The two techniques showed similar patterns, such as the higher yearly average concentrations in country zones in 2020 compared to 2013–2019 but also some differences for individual months and in the relative contribution of the different zones to total NH$_3$ concentrations, which are related to the limitations inherent in measurement techniques.

For the entire Lombardy region (surface area about 23000 km$^2$), the availability of NH$_3$ measured data for the analyzed period was limited to 10 control units for the assessment using ground stations. However, NH$_3$ concentration may vary considerably within few kilometers (Lonati and Cermaschi, 2020). This confirms the scarcity of NH$_3$ control units compared to other air pollutants; in fact, in the same area available stations amount to 90 units for PM$_{10}$ and 38 units for PM$_{2.5}$ (ARPA Lombardia, 2020). Moreover, for the same control units, air concentrations of different pollutants, such as NH$_3$ and PM, are not always available, making comparisons more difficult.

As concerns satellite images, the number of measurements, after filtering for observations with high uncertainty, did not allow us to create a grid finer than 0.5 x 0.5', which would have introduced a large number of data gaps. The coarse grid however complicates the assessment of local variability; the comparison between data gathered from each ground based control unit and satellite observations is problematic because of 1) the different spatial resolution; in fact, ground stations classified as “city” might be included in country zones in IASI pixels, with a much larger contribution of NH$_3$ air concentration from agricultural areas; 2) the different unit of measure and assessment method, as one is a ground level observation, the other is a column observation. An attempt to correlate monthly data from ground and satellite observations showed an r$^2$ of 0.21–0.29; this is in line with Van Damme et al. (2015), who report Pearson’s correlations of 0.28 comparing monthly data from IASI and ground observations from a global network, ranging from 0.81 (Russian Fyodorovskoye site, with very high NH$_3$ concentrations owing to fire events) to negative correlations at several sites in Finland, probably caused by the low concentrations at these sites in association with low temperatures and thus the low thermal contrast of IASI.

Given the limitations of both measurement approaches, among which the temporal and spatial resolution, improvements should be introduced both in the number and density of ground stations, especially in areas where agriculture is widespread, and in the availability of satellite data with a higher spatial resolution, which might also make validation efforts easier in comparison with ground observations.

4.2. Prospects for improving air quality and opportunities for further study

In the future, a significant reduction in NH$_3$ air concentrations is expected as a consequence of the abatement measures that are being introduced in agricultural and livestock farms (e.g., closed tank storages, manure and slurry treatments, precision application of slurry on field) (Finzi et al., 2019; Zilio et al., 2020), although these measures are currently present only in few contexts. Considerable improvements have already been introduced in the European Union, which brought to a strong reduction of NH$_3$ air concentration, reaching –24% from 1990 to 2017 (Costantini et al., 2020). However, this trend of reduction is proceeding further; in fact, in some countries, regions, and farms additional improvements are being introduced or are under study. For example, Miranda et al. (2021) investigated through the Life Cycle Assessment method, the environmental implications of treating slurry and found positive results for the reduction of gases, among which NH$_3$, with the addition of sulfuric acid to slurry. Slurry acidification was found effective in reducing NH$_3$ and other greenhouse gases (GHGs) also by Fanguereiro et al. (2015). However, supporting farmers in the direction of abating NH$_3$ is fundamental to increase the spread of such ameliorative techniques and solutions. The chief aspects on which to focus include efficient livestock rearing techniques supported by technology, balanced animal feed rations, air scrubbers in barns, adequate manure management with frequent removal from the barn, manure treatments such as anaerobic digestion, solid-liquid separation, slurry acidification, proper manure storage with closed tanks and proper field application with precision application equipment (Guido et al., 2020; Regueiro et al., 2016).

Important from the environmental point of view, avoiding NH$_3$ losses can lead to maintaining nutrients in the manure/slurry and therefore applying more nutrients to the soil when spreading manure or slurry, thus requiring fewer mineral fertilizers and bringing benefits to the environmental sustainability, plus valorizing an already available resource that is free of charge. Finally, while high NH$_3$ concentration in air may represent a local issue, damages to ecosystems from NH$_3$ are not
only local and are widely investigated due to the main effects of acidification and eutrophication on biodiversity loss in coastal and estuarial areas, such as in the study by Vetterli et al. (2016).

Despite the improvements in agricultural practices, this study has shown that NH₃ concentrations in air remained high in areas such as the Po Valley even during the lockdown caused by the spread of COVID-19. To further validate the considerations made regarding NH₃ air concentrations during 2020, future research should consider a wider area (e.g. Italy, Europe), as well as expand the analysis to other air pollutants. To this end, it would also be interesting to integrate ground-based and satellite datasets with physico-chemical dispersion models (e.g. LOTOS-EUROS, Schaep et al., 2008; also employed by Van Damme et al., 2014, 2015) to better understand their origin and interactions, while in this study a purely statistical comparative approach was adopted.

5. Conclusions

This study aimed to evaluate the atmospheric concentrations of NH₃ during the spread of the COVID-19 pandemic in Northern Italy and the related changes in anthropogenic activities. For this purpose, ground-based and satellite measurement data related to 2020 were analyzed and compared with previous years (2013–2019). Ground-based measurements showed statistically significant differences between the two periods in the country areas, where NH₃ was found higher in 2020 (+31% compared to the 2013–2019 average); on the other hand, no significant differences emerged for the city and mountain areas. Satellite data show similar patterns, but no significant differences between the two periods and less spatial variability between city, country, and mountain areas, probably due to the coarse spatial grid of IASI measurements. Contrary to other air pollutants, it can be concluded that no NH₃ reduction effect has occurred as a consequence of the anti-COVID-19 measures, which can be explained by the non-interruption of agricultural activities, the main emission source of this pollutant. The integration between datasets from different measurement sources allows for a better understanding of their origin and interactions, while in this study a purely statistical comparative approach was adopted. The impact of stay-home periods in the country areas, where NH₃ was found higher in 2020 (+31% compared to the 2013–2019 average); on the other hand, no significant differences emerged for the city and mountain areas. Satellite data show similar patterns, but no significant differences between the two periods and less spatial variability between city, country, and mountain areas, probably due to the coarse spatial grid of IASI measurements. Contrary to other air pollutants, it can be concluded that no NH₃ reduction effect has occurred as a consequence of the anti-COVID-19 measures, which can be explained by the non-interruption of agricultural activities, the main emission source of this pollutant. The integration between datasets from different measurement sources allows for a better understanding of their origin and interactions, while in this study a purely statistical comparative approach was adopted.

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