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Article

Trends in CO, CO₂, CH₄, BC, and NO_x during the first 2020 COVID-19 lockdown: source insights from the WMO/GAW station of Lamezia Terme (Calabria, Southern Italy)

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Abstract: In 2020, the Covid-19 outbreak led many countries across the globe to introduce lockdowns (LDs) that effectively caused most anthropic activities to either stop completely or be significantly reduced. In Europe, Italy played a pioneeristic role via the early introduction of a strict nationwide LD on March 9th. This study is aimed at evaluating, using both chemical and meteorological data, the environmental response to that occurrence as observed by the Lamezia Terme (LMT) GAW/WMO station in Calabria, Southern Italy. The first 2020 lockdown has therefore been used as a “proving ground” to assess CO, CO₂, CH₄, BC, and NO_x concentrations in a rather unique context by exploiting the location of LMT in the context of the Mediterranean Basin. In fact, its location on the Tyrrhenian coast of Calabria and local wind circulation both lead to daily cycles where western-seaside winds depleted in anthropogenic pollutants can be easily differentiated from northeastern-continental winds, enriched in anthropogenic outputs. In addition to that, the first Italian LD occurred during the seasonal transition from Winter to Spring and, consequently, Summer, thus providing new insights on emission outputs correlated with seasons. Findings have clearly indicated BC and, in particular, CO as strongly correlated with average daily temperatures, and possibly domestic heating. CO₂'s reduction during the lockdown and consequent increase in the post-lockdown period, combined with wind data, has allowed to constrain local source of emissions located northeast from LMT. NO_x reductions during specific circumstances are consistent with hypotheses from previous research which linked them to rush hour traffic and other forms of transportation emissions. CH₄'s stable patterns are consistent with livestock, landfills, and other sources assumed to be nearly constant during LD periods.

Keywords: Covid-19; 2020 lockdown; Lamezia Terme; Mediterranean Basin; GAW; carbon monoxide; carbon dioxide; methane; black carbon; nitrogen oxides

1. Introduction

On March 9th, 2020, the Italian Government issued a DPCM (*Decreto del Presidente del Consiglio dei Ministri*, Decree of the President of the Council of Ministers) introducing the first full scale lockdown (LD) in the world, outside China, due to the Covid-19 outbreak [1]. The first LD was extremely strict and effectively prohibited non-essential activities, thus causing most of them to come to a complete stop or be vastly reduced. The LD persisted until May 18th, when a second DPCM lifted most restrictions [2]. In the following year and a half, other minor LDs were introduced, though none

of them were as strict as the first, thus making that LD a unique circumstance for the evaluation of atmospheric concentrations of select parameters. In fact, following similar LDs throughout the globe, researchers quickly performed studies on the unprecedented environmental conditions brought by LD measures [3–10].

The environmental response to reduced anthropic activities was not constant among the main parameters, greenhouse gases (GHGs), aerosols, and other key compounds observed globally across international networks such as the WMO/GAW (World Meteorological Organization – Global Atmosphere Watch). For example, despite generally lower anthropogenic emissions [11] and improved air quality [12,13], methane experienced a global surge in 2020 [14,15]. Stevenson et al. (2022) [16] reported a 3.8 to 5.8 ppb increase in the 2020 annual growth rate of methane linked to the large reduction in anthropogenic NO_x (nitrogen oxides) releases to the atmosphere, which was partially counterbalanced by fewer CO (carbon monoxide) and non-methane volatile organic compounds (NMVOC) emissions; the net increase, accounting for NO_x, CO, and NMVOC counterbalance effects, has been reported as 2.9 (1.7 to 4.0) ppb. NO_x compounds are known to be key regulating factors of methane [17,18], accounting for an approximate 1000 ppb total reduction in atmospheric concentration levels [19]. It is also worth noting that LDs have led to an increase in methane emissions related to the energy sector [20]. In the first year of the Covid-19 pandemic, a 5.3–5.5 ppb increase in the annual methane growth rate up to the value of 15.0 ppb yr⁻¹ has been observed [21]. Locally, the first multi-year evaluation of LMT methane cycles and trends shown in D'Amico et al. (2024a) [22] highlighted a 2020 surge which was in accordance with the global trend observed by NOAA (National Oceanic and Atmospheric Administration) [21]. Conversely, several studies reported a decline in other compounds such as CO, as a direct consequence of LD restrictions and reduced anthropogenic emissions [12–24].

Research studies in Italy primarily focused on the impact of LD restrictions on atmospheric particle concentrations [25,26], urban air quality [27–29], specific GHGs in a variety of environments [30–32], multiparameter evaluations [33,34]. Globally, a review by Addas and Maghrabi (2021) [35] reported that most studies published within one year from the first LDs focused, in order, on NO₂, PM_{2.5}, PM₁₀, SO₂, and CO as key indicators of changes in air quality due to LD restrictions. In the context of Europe, as early as 2020 several studies reported increase in air quality throughout the continent [36–38]. Following research provided information on reduced emissions on a continental scale, in particular with respect to nitrogen compounds [39–41].

With respect to the Lamezia Terme (LMT) observation site in Calabria, Southern Italy, a previous study assessed the effect of LD restrictions on nanoparticle concentrations via a comparison with data gathered at Lecce (Apulia, Southern Italy) [42]. However, no other research has ventured deeper into a multiparameter evaluation of the first LD period at LMT, accounting for multiple gases and aerosols. This study is therefore a first attempt at analyzing CO, CO₂, CH₄, BC, and NO_x trends as well as key meteorological data observed at LMT during that period and provide new insights with respect to source apportionment in an area characterized by multiple anthropogenic and natural emission outputs [22–43].

Each of the analyzed parameters is an indicator of certain sources. Carbon monoxide (CO) is a common byproduct of combustion processes and its atmospheric trends have been frequently linked to the application of sustainable policies and new technologies to combustion engines [44]; carbon dioxide (CO₂) is a primary output of fossil fuel burning and has been known for decades to be a primary driver of climate change [45–50]; methane (CH₄) is also a byproduct of the fuel combustion, for instance, of regular vehicles [51] and airplane engines [22–52], though natural outputs such as wetlands [54] and specific anthropogenic emissions such as livestock [55] are responsible for a considerable fraction of the annual global output; eBC (equivalent black carbon) is an excellent indicator of combustion processes [56], known to pose both health [57] and climate [58–61] hazards; nitrogen oxides (NO_x) also serve as indicators of anthropogenic activities, with various studies highlighting their reduction during LDs [62,63]. Fossil and biomass burning, as well as the use of fertilizers in agriculture, are among the main anthropogenic sources of atmospheric NO_x [64,65].

Overall, the analysis of these parameters, combined with the peculiar configuration of the observation site and local wind circulation, are expected to provide new insights on the first 2020 LD in Southern Italy, which in turn can be used to gather new information on local source apportionment and, by extension, the development of new sustainable policies at a local scale.

This research is organized as follows: section 2 will describe and characterize the observation site of LMT; section 3 will show the results of performed analyses; sections 4 and 5 will be focused on discussion and the conclusions of this study.

2. The LMT Station, Instruments, and Datasets

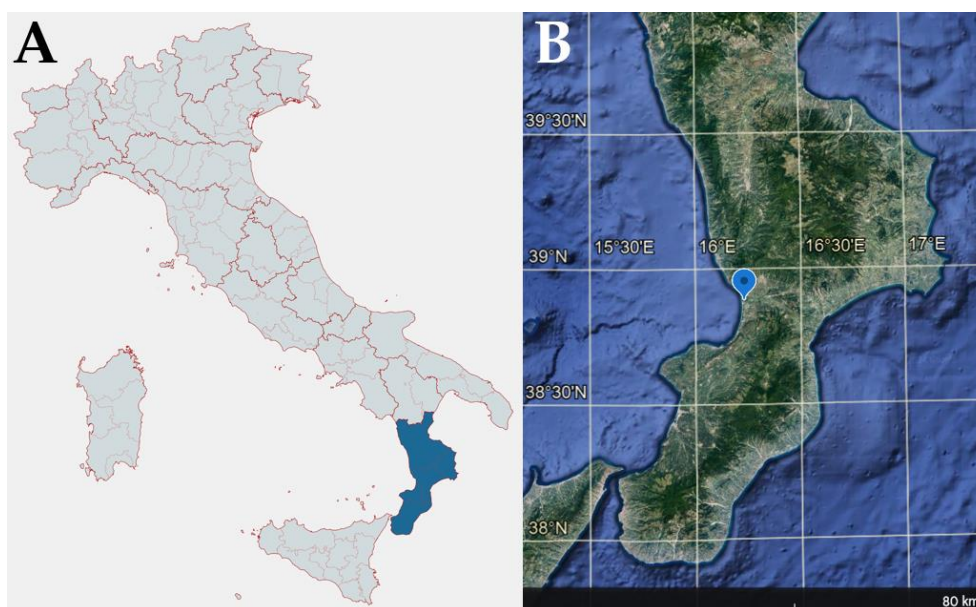
2.1. Characterization of the LMT Site

The regional coastal observation site of Lamezia Terme (WMO/GAW code: LMT) is located 600 meters from the Tyrrhenian coast of the southern Italian region of Calabria, in the Sant'Eufemia plain. The station, active since 2015, is operated by the National Research Council of Italy – Institute of Atmospheric Sciences and Climate (CNR-ISAC) and continuously gathers data on a number of chemical and meteorological parameters.

The observation site is characterized by a peculiar local wind circulation, which results into two main corridors: a western-seaside direction yielding generally low concentrations in pollutants and other parameters, and a northeastern-continental corridor, which generally yields much higher concentrations [22–43]. Figure 1 shows the location of LMT in Italy, and also highlights several key emission sources in the area.

Several studies in the past have analyzed wind circulation, demonstrating that it is locally dominated by a breeze regime [66,67]. Specifically, Federico et al. (2010a) [66] demonstrated how local circulation is dominated by breezes, which also play a relevant role in local climate regulation. The same study reported seasonal changes in wind speeds, in addition to minor changes in terms of wind orientation, though the main W-WSW/NE-ESE corridor remains responsible for most of the circulation throughout the year. It is worth reporting however that when the 850 hPa layer is analyzed, a dominant NW direction is observed, which matches large scale circulation in the sector. In another study, Federico et al. (2010b) [67] used two years of wind data to demonstrate that large-scale forcing is responsible for daytime circulation in the winter season, as well as in November, and nighttime flows are attributable to nocturnal breezes. Moreso, during summer as spring, as well as part of fall, daytime breeze circulation has been demonstrated to be the result of large-scale and local flows.

Local wind circulation also has a direct influence on air traffic, as demonstrated by the 10/28 (100-280 °N) runway orientation at the nearby Lamezia Terme International Airport (IATA: SUF; ICAO: LICA) located 3km north from the observation site.



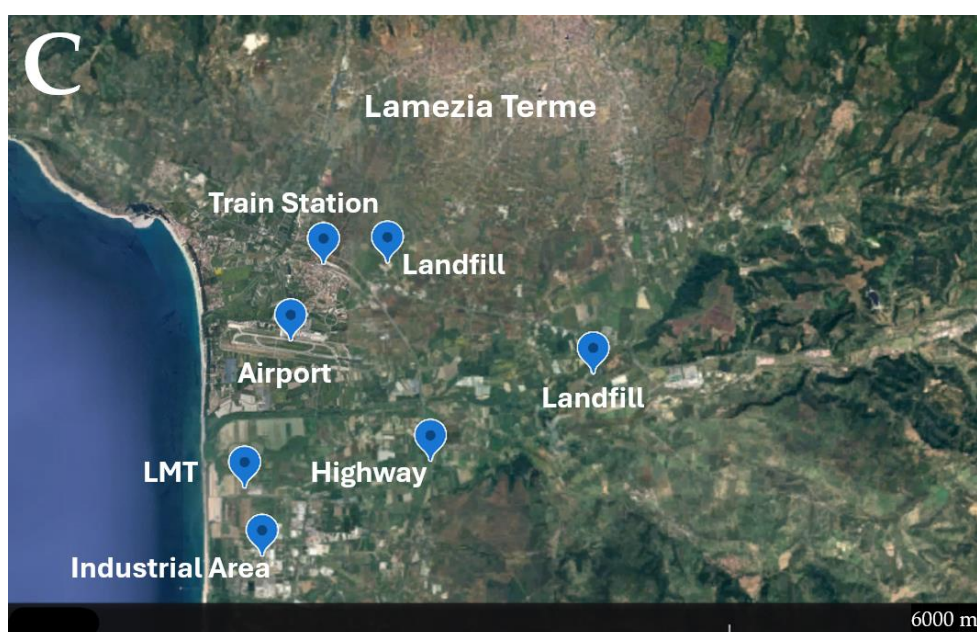


Figure 1. A: MapChart of Italy highlighting the region of Calabria. B: Location of LMT in Calabria itself. C: details of the Lamezia Terme area with a highlight on notable emission sources in the area. The “Highway” mark refers to a point where the distance between the A2 highway and LMT is approximately 4.3 km. Farms are spread over the area. “Lamezia Terme” points to the most densely populated areas of the municipality.

Further research on breeze and its influence on local circulation was performed in the following years via a characterization of wind profiles at several altitude thresholds (10 to 300 meters), using a Zephir lidar 300 [68]. Additional research has been aimed specifically at PBL (Planetary Boundary Layer) structure via the combination of multiple instruments and techniques [69,70].

As mentioned before, there are several local sources of emission in the area. Previous studies have reported the airport, A2 highway (part of the European route E45), local livestock farming, landfills, and urban traffic among these sources [22–43]. These local outputs are deemed responsible for the observed peaks in CO, CO₂, CH₄, eBC, and NO_x. With respect to NO_x, previous research indicated rush hour traffic and other forms of transportation [43], while landfills and livestock farming have been indicated as key CH₄ emission hotspots [22–43]. Data gathered at the observatory has been used to assess possible anthropic influences via an evaluation of weekday/weekend patterns, which are assumed to be subject to anthropic cycles [71,72]. Due to its location in the Mediterranean Basin, LMT is also subject to summertime open fire emissions [73], which result into notable CO and eBC peaks, as well as Saharan dust events [74].

2.2. Instruments and Datasets

Measurements of CO, CO₂, CH₄, eBC, and NO_x have been performed using three distinct instruments. Data on carbon monoxide (ppb), carbon dioxide (ppm), and methane (ppb) mole fractions have been gathered by a CRDS (Cavity Ring-Down Spectrometry) analyzer, the Picarro G2401 (Santa Clara, California, USA). CRDS analyzers such as the G2401 measure, with high degrees of precision, the mole fractions of trace gases via the ring-down principle, specifically via the light scattering and absorption effects that occur at certain wavelengths [75]. At the WMO/GAW observation site of Lamezia Terme, Picarro G2401 operate via a four-point configuration type which is handled by a Vici-Valco rotative valve (model: EMTMA-CE) that switches, at regular intervals, between the following points: one is used for ambient air gathering; three points are connected to standard cylinders (CO: WMO X2014; CO₂: WMO X2019; CH₄: WMO X2004) provided by NOAA’s GML (Global Monitoring Laboratory). These reference cylinders cover CO concentrations in the 40–500 nmol/mol range, CO₂ mole fractions in the 250–520 μmol/mol range, and CH₄ concentrations in the 300–2600 nmol/mol range. Every 14 days, the same cylinders are measured by G2401 analyzers

three times each, and each measurement is performed for 30 continuous minutes. In order to contain the effect of water vapor on the accuracy of all measurements, a Nafion dryer (model: MD-070-144S-4) is used to dry ambient air prior to CRDS analysis. G2401 analyzers at LMT perform a measurement every 5 seconds (precision: 1 ppb).

eBC measurements have been performed by a MAAP (Multi-Angle Absorption Photometer), specifically the model Thermo Scientific 5012 (Franklin, Massachusetts, USA). The MAAP relies on short-wave absorption properties of eBC and other aerosol particles to perform its measurements. The MAAP measures equivalent black carbon (eBC) and the short-wave radiation aerosol absorption coefficient (sa) at 637nm on a per-minute basis [76,77]. For the sampling of aerosol, a pump maintaining a flow rate set to a constant value (200L/min) gathers ambient air at 4m above local ground level. The gathered stream of aerosols is isokinetically split into several instruments, such as a nephelometer and the above mentioned. With respect to the MAAP, it illuminates a particle-loaded filter and measures, at the same time, the radiation passing through said filter, as well as backscattered light from three different angles [78]. The flow is set at 16.7L/min. It was constantly verified, via a mass closure, that eBC was lower than 50% of the overall PM_{2.5} mass concentration.

NO_x (NO + NO₂) measurements have been performed by another Thermo Scientific instrument, specifically the 42i (Franklin, Massachusetts, USA). The instrument relies on a chemiluminescence (CL) reaction by which atmospheric NO gathered by the 42i reacts with O₃ (ozone) released by the instrument itself, and the reaction results into the release NO₂ (in an excited state) and O₂ [79]. The excited NO₂ returns to a more stable condition by emitting ultraviolet radiation at a specific wavelength, which is measured by the instrument to estimate NO mole fractions in the atmosphere. In order to measure NO₂ concentrations, some of the analyzed ambient air passes through a catalytic converter capable of reducing atmospheric NO₂ in NO. Via a pure subtraction between total NO_x mole fractions and NO, NO₂ concentrations are therefore calculated. Measurements are subject to monthly checks against zero and span checks via external zero air generators (Thermo 1160), plus GPT/gas dilution systems (Thermo 160i). More details on NO_x measurements and calibrations at LMT are available in Cristofanelli et al. (2017) [43].

Key meteorological data (wind speed and direction, temperature) have been gathered by a Vaisala WXT520 (Vantaa, Finland). Wind data are gathered by the instrument via ultrasonic transducers placed on a horizontal plane and the measurement of the time span it takes for the ultrasound pulses to travel between transducers. Temperature is measured by a RC oscillator and two reference capacitors, with a continuous measurement of the capacitance of the sensors themselves. Specifically, a microprocessor performs compensations for temperature dependencies on humidity and pressure sensors. Wind speed is recorded in meters per second (m/s) with a precision of 0.3 m/s, wind direction in degrees (°) with a precision of 3°, and temperature in Celsius degrees (°C) with a precision of 0.3 °C. Meteorological data are gathered on a per-minute basis, but for the purpose of this research, hourly and daily aggregates have been used. Additional information on instruments and their configurations are available in previous research works on LMT findings [43–74]. Figure 2 shows the main features of local wind circulation between February and July 2020.

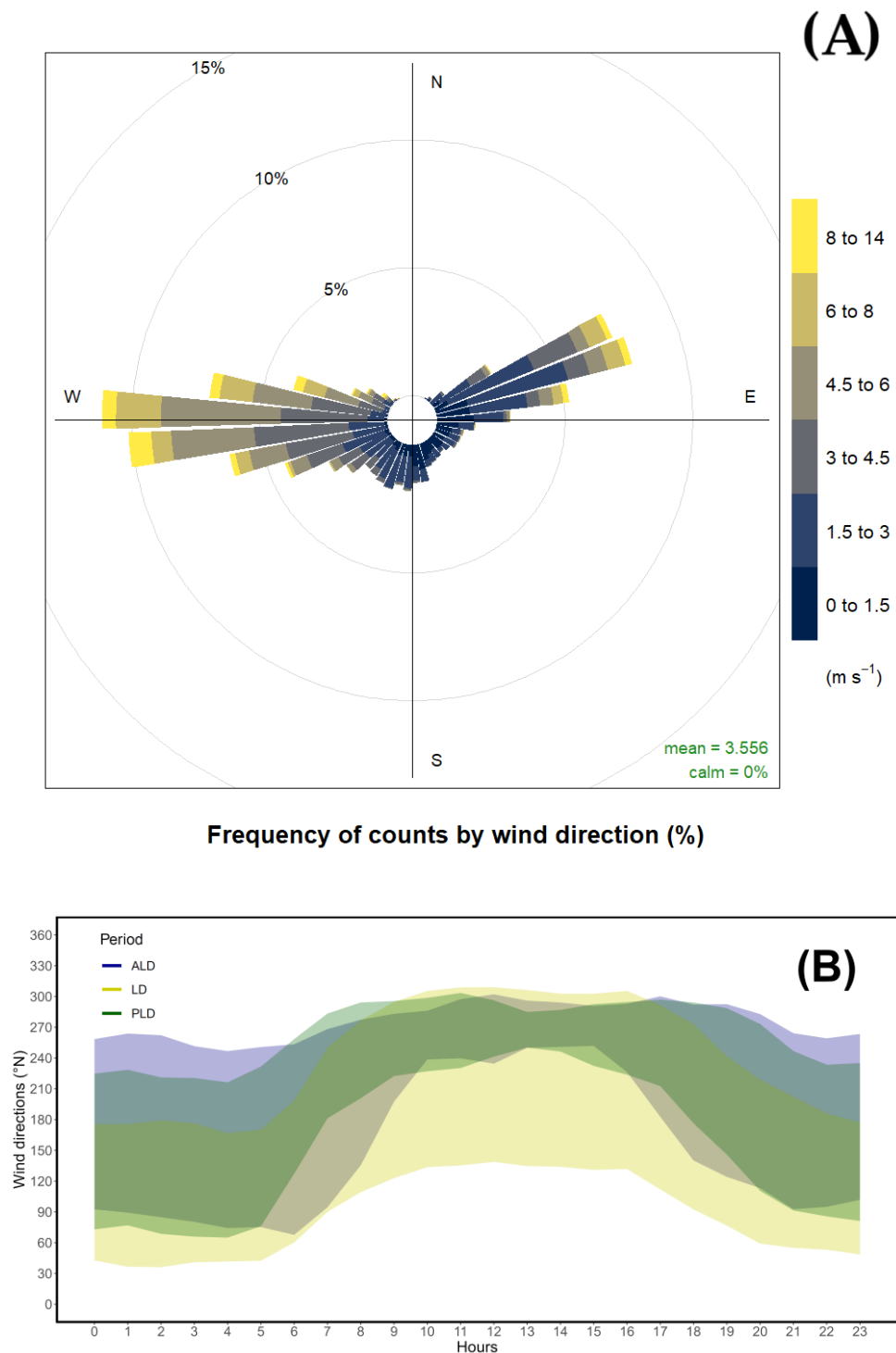


Figure 2. A: Total hourly wind speeds and directions observed between February 1st and July 31st 2020 at LMT, plotted in a wind rose highlighting the main W (seaside) and NE (continental) corridors described in section 2.1. Each bar covers an angle of 8 degrees (1/45 of 360°). B: Average hourly wind directions during the ALD (ante-lockdown), LD (lockdown), and PLD (post-lockdown) periods, with shaded areas covering the average $\pm\sigma$ (standard deviation) range.

Data have been aggregated on an hourly and daily basis, depending on each analysis. Table 1 shows the degrees of data coverage per category/instrument. Datasets focus entirely on the period between February 1st and July 31st, which is longer than the first Italian LD (March 9th – May 18th). The longer time span is used to assess and evaluate late responses of the environment to the LD in June

and July, as well as the conditions that preceded the LD itself (February and early March). Overall, the analyzed period includes 4368 hours in 182 days.

Unless the integration of multiple parameters is required (e.g., CO and eBC), each analysis will focus on instrument-specific data. This choice was meant to optimize total data availability, as choosing data with all four instruments fully operating at the same time would have resulted in unnecessary data loss. Due to the 100% coverage rate of wind and temperature data, meteorological parameters can be easily implemented with other data without any loss in terms of coverage. Multiple instruments were affected by extended power shortages between March 1st and Mar. 5th, with Mar. 3rd having no operational instruments except for the Vaisala WXT520.

Table 1. Coverage of all instruments with respect to the observation period (Feb. 1st – July 31st), vided by aggregation type (hourly and daily). The “Type” refers to performed data aggregations, which were either hourly or daily. “Count” refers to the total number of hours and days elapsed during the study period (February-July 2020). Columns referring to various employed instruments indicate the coverage rate (%) of their respective datasets compared to maximum count per type.

Type	Count	G2401 (%)	T5012 (%)	T42i (%)	WXT520 (%)
Hours	4368	97.32	96.15	97.57	100
Days	182	97.8	97.8	97.8	100

All datasets have been processed in R 4.4.0 via ggplot2, ggpubr, openair, tidyverse and dplyr packages, as well as their respective libraries. When required, pre(*ante*)-lockdown, lockdown, and post-lockdown periods have been grouped in the categories ALD, LD, and PLD, respectively. ALD includes all hours/days between February 1st and March 8th; LD includes March 9th through May 18th; PLD includes May 19th through July 31st.

3. Results

3.1. Daily Temperatures and Correlations with Observed Parameters

The observation period (FEB-JUL 2020, 182 days) involved a seasonal transition from winter to spring, then summer. Some of the observed parameters in this research are believed to be dependent on domestic heating and other activities correlated with temperatures. Figure 3 shows averaged daily temperatures throughout the entire observation period.

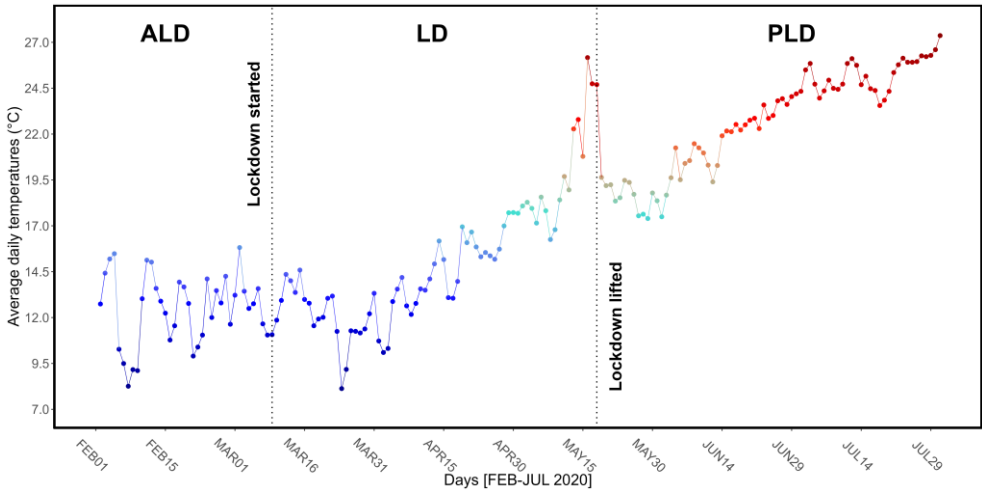
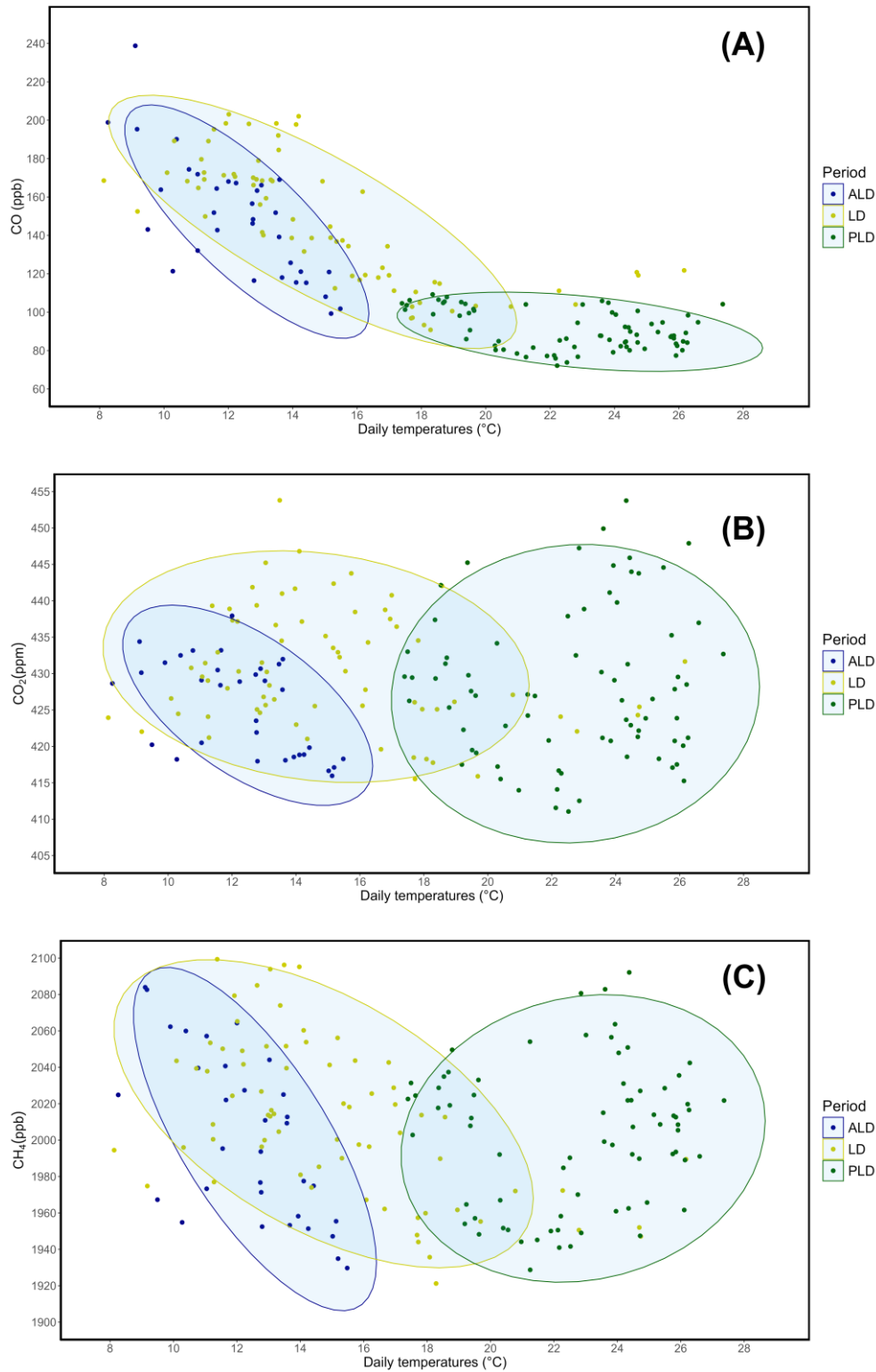


Figure 3. Daily averaged temperatures (°C) throughout the entire FEB-JUL 2020 study period. The vertical dotted lines mark the beginning and the end of the first Italian nationwide LD, respectively. These periods are also marked by the horizontal ALD, LD, and PLD labels. The color pattern is set to mark the difference between typical Mediterranean winter temperatures (dark blue) and temperatures closer to summertime averages (red).

Consequently, the correlation between daily temperatures and each parameter (CO, CO₂, CH₄, eBC, NO_x) has been tested. ALD, LD, and PLD categories (described in section 2.2) have been used to differentiate averaged data by their period of occurrence, *i.e.* if they were observed before (ALD), during (LD), or after (PLD) the first nationwide LD. Hours falling in the same period have been grouped in data ellipses [80] with a 90% multivariate t-distribution confidence level; the results are shown in Figure 4.



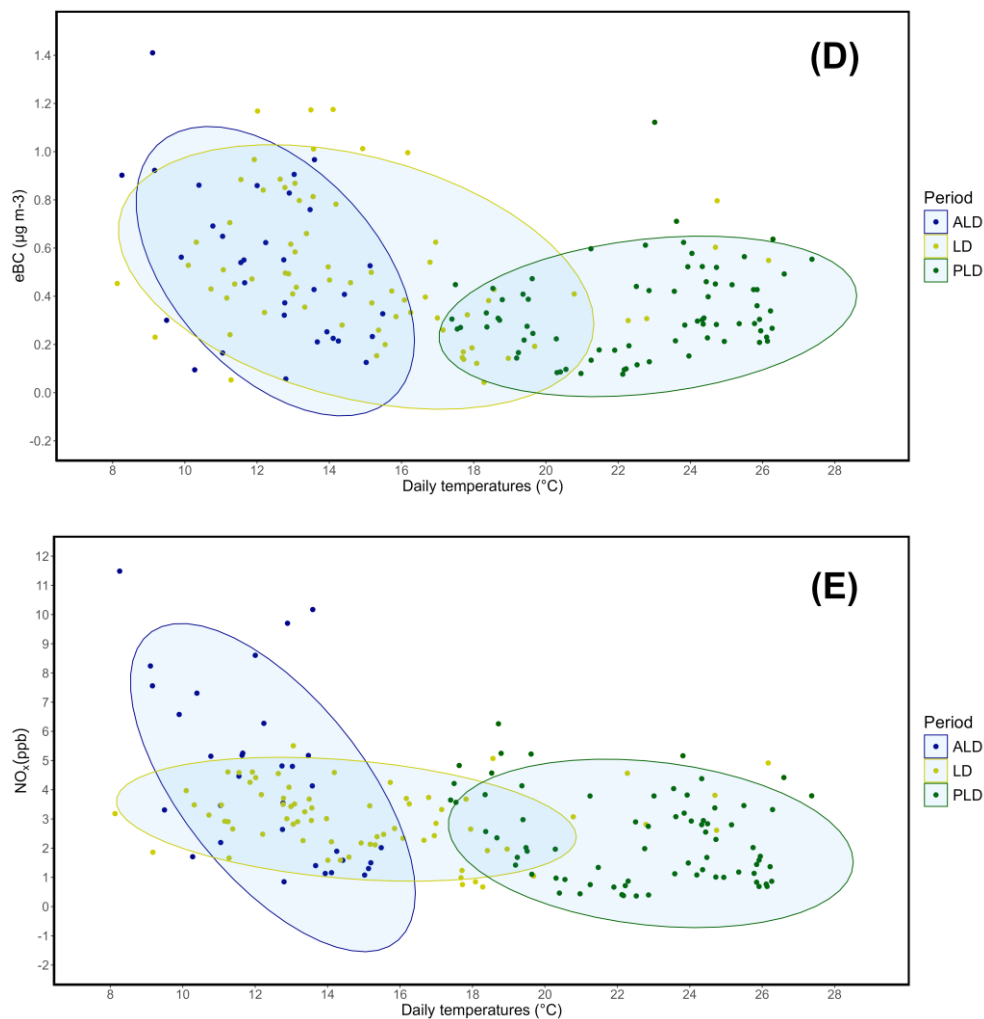


Figure 4. Correlations between daily temperatures and each parameter, differentiated by period of observation (ALD, LD, PLD). Data ellipses refer to a 90% confidence interval. A: CO; B: CO₂; C: CH₄; D: eBC; E: NO_x.

Table 2 reports R² values computed for linear and quadratic regressions of the same data shown in Figure 4.

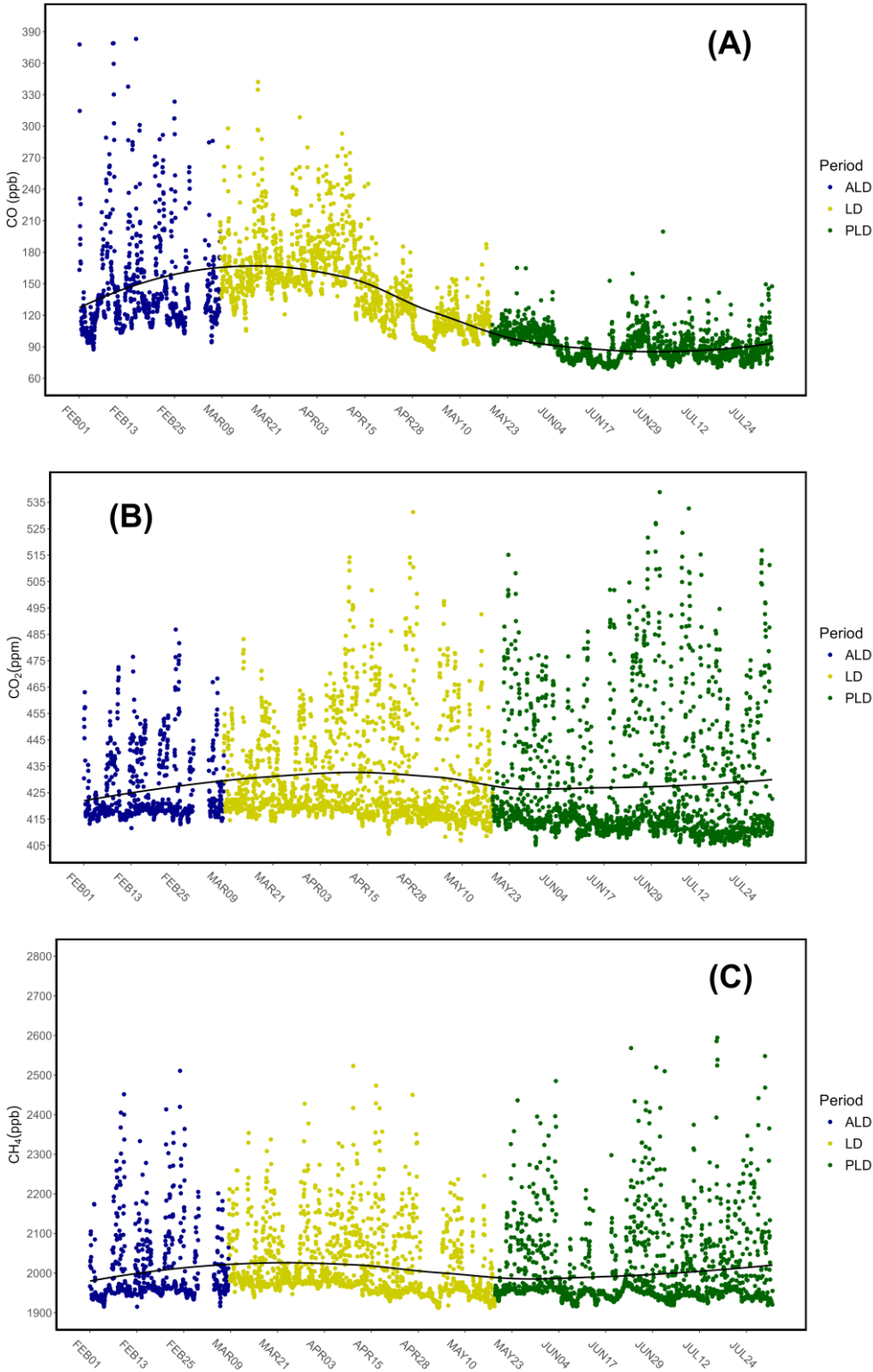
Table 2. Linear and quadratic R² values for CO (Figure 4A), CO₂ (Figure 4B), CH₄ (Figure 4C), eBC (Figure 4D), and NO_x (Figure 4E) daily averages, all compared with average daily temperatures.

Regression lines and curves are not shown in these plots to optimize visualization.

Parameter	Linear	Quadratic
CO	0.69	0.75
CO ₂	0.001	0.006
CH ₄	0.004	0.098
eBC	0.11	0.17
NO _x	0.17	0.21

3.2. Hourly Averaged Trends

After the evaluation of daily averages and their correlation with temperatures, hourly trends have been tested and differentiated by period of observation (ALD, LD, PLD). The results are shown in Figure 5.



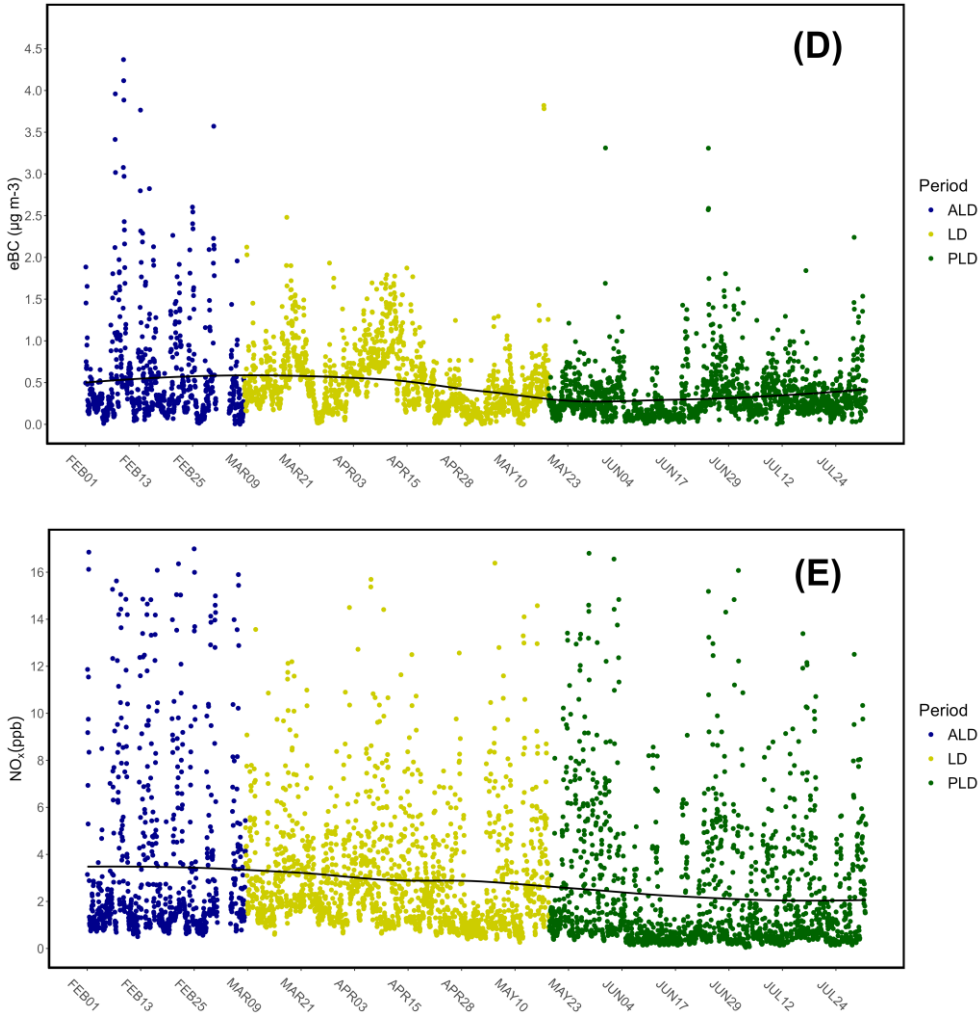
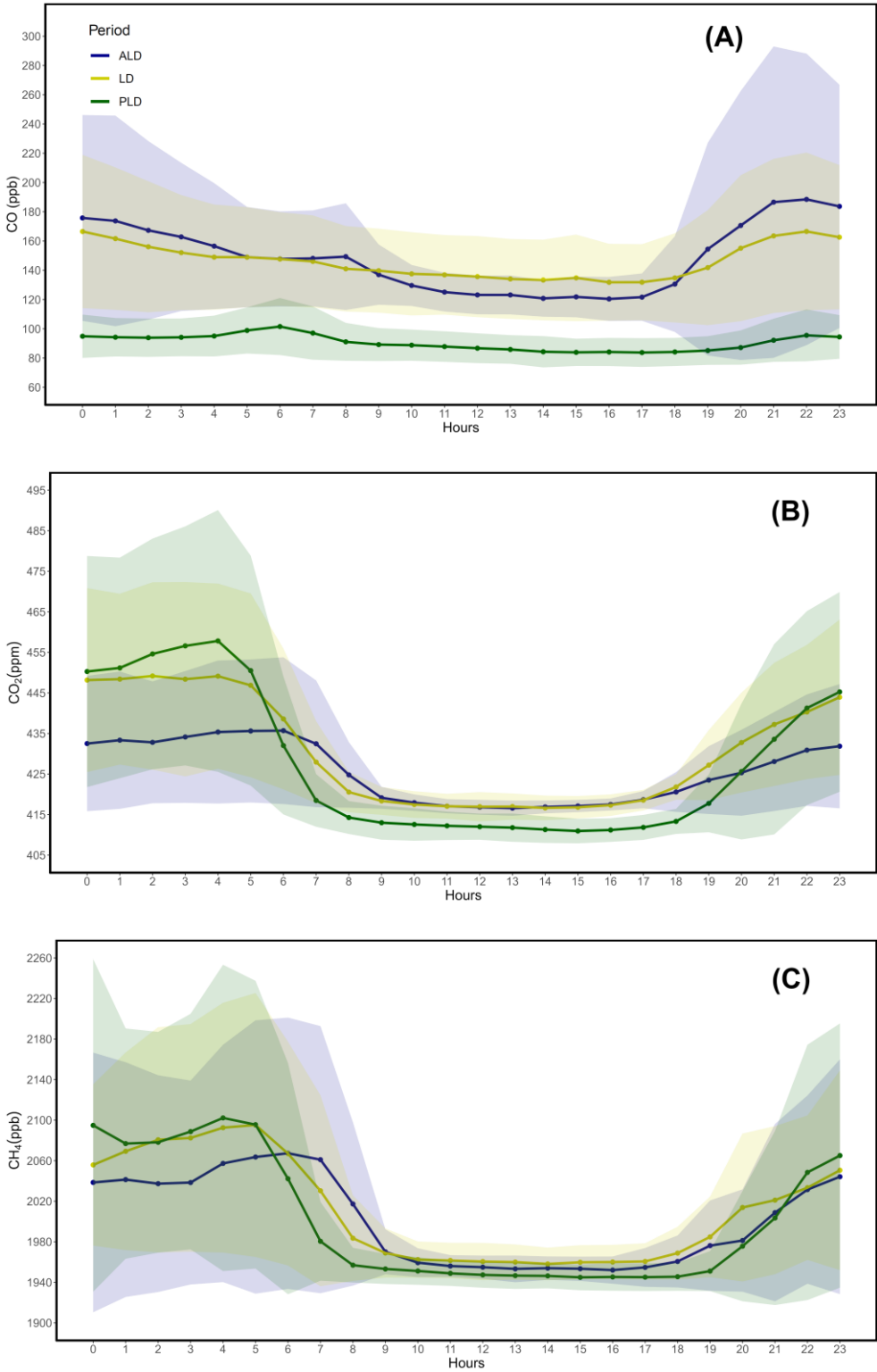


Figure 5. Hourly trends observed between February and July 2020, differentiated by period (ALD, LD, PLD). The smoothed black line has been computed using the “loess” method to estimate trends through time. A: CO; B: CO₂; C: CH₄; D: eBC; E: NO_x.

3.3. Daily ALD, LD, and PLD Cycles

Following the evaluation of CH₄ daily cycles seen in D’Amico et al. (2024a) [22] and their correlation with local wind circulation patterns, similar plots have been created to test the response of each observed parameter to daily cycles between February and July 2020. The x axis of these plots is identical to that of Figure 2B. The results of these analyses, differentiated by category (ALD, LD, PLD) are shown in Figure 6.



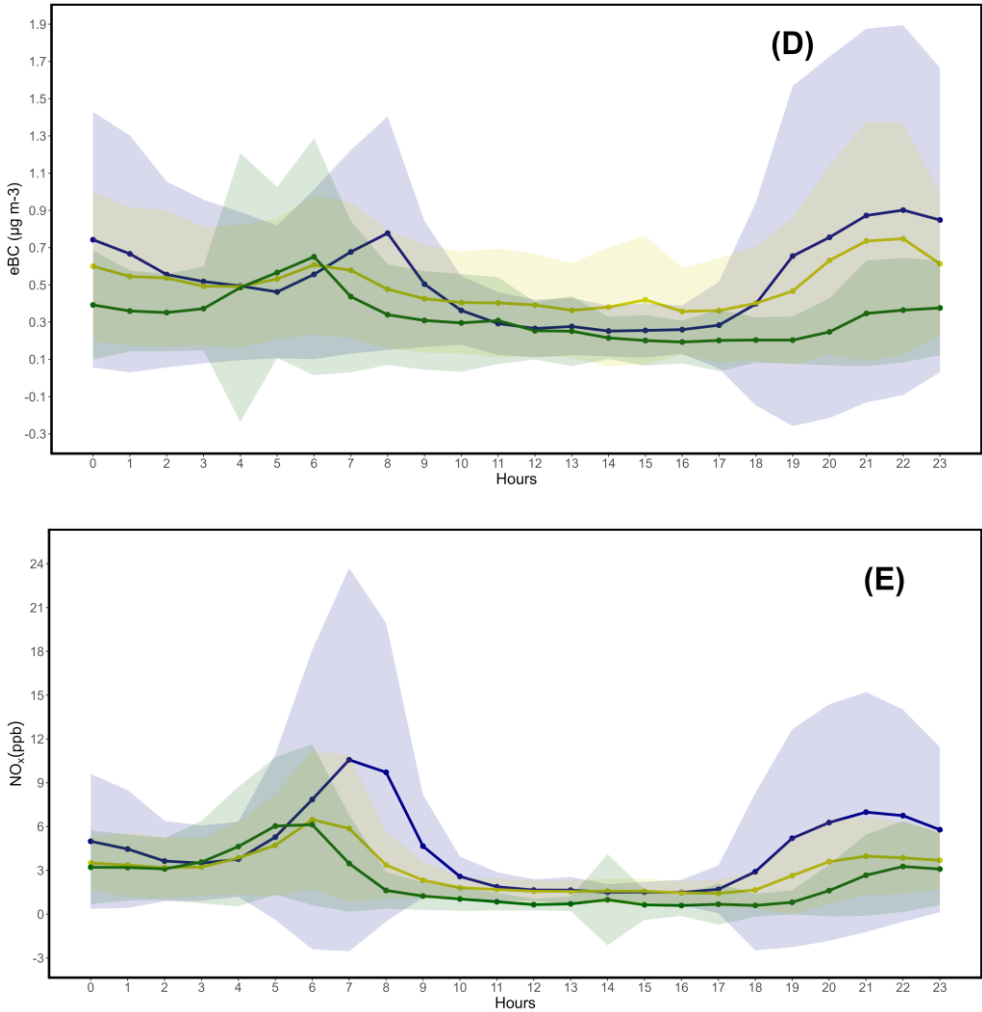


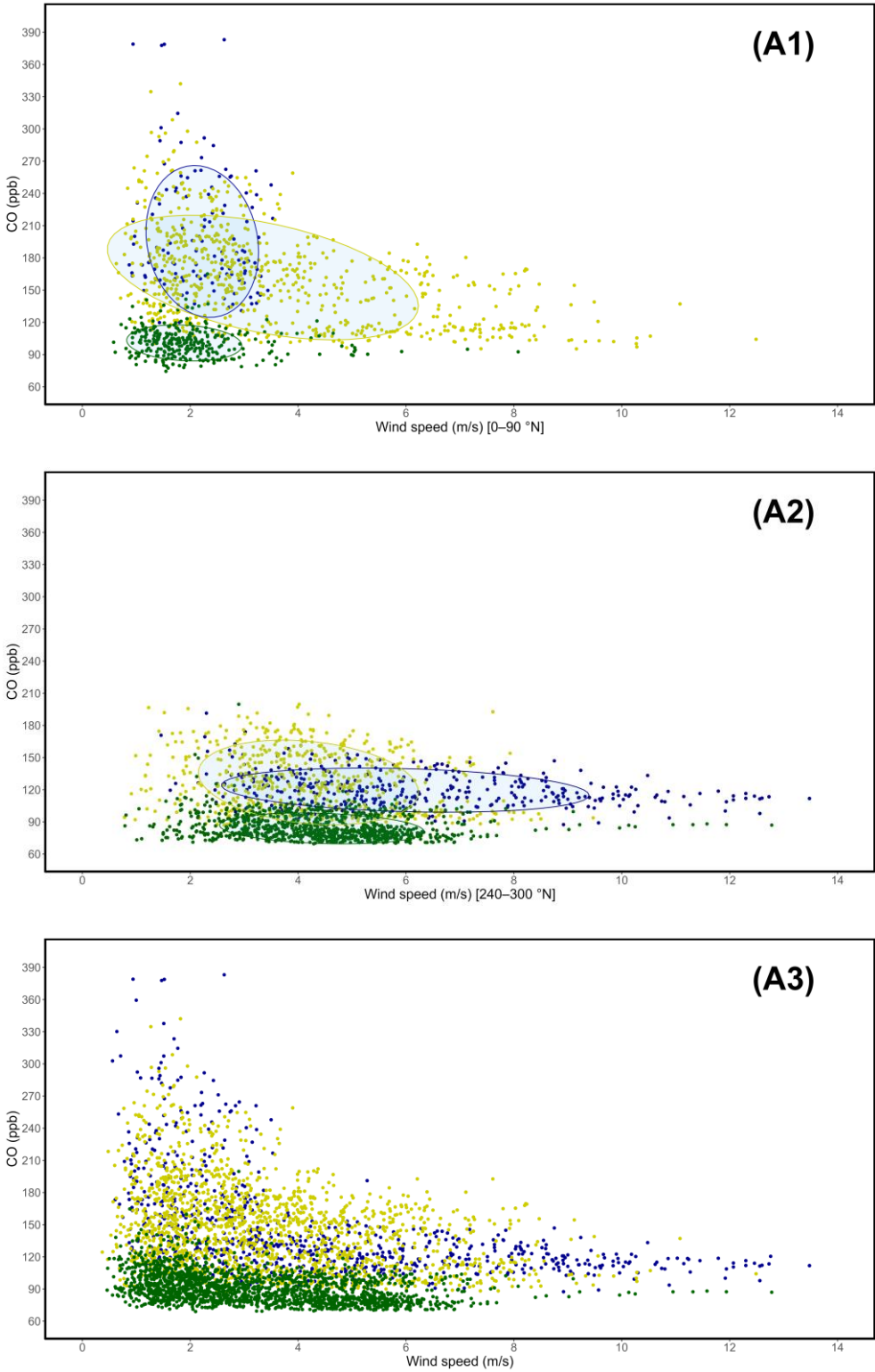
Figure 6. Averaged daily cycles of all observed parameters, differentiated by ALD, LD, and PLD periods. Shaded areas show $\pm\sigma$ (standard deviation) ranges. To ease visualization, the legend is shown in Figure 6A alone. A: CO; B: CO₂; C: CH₄; D: eBC; E: NO_x.

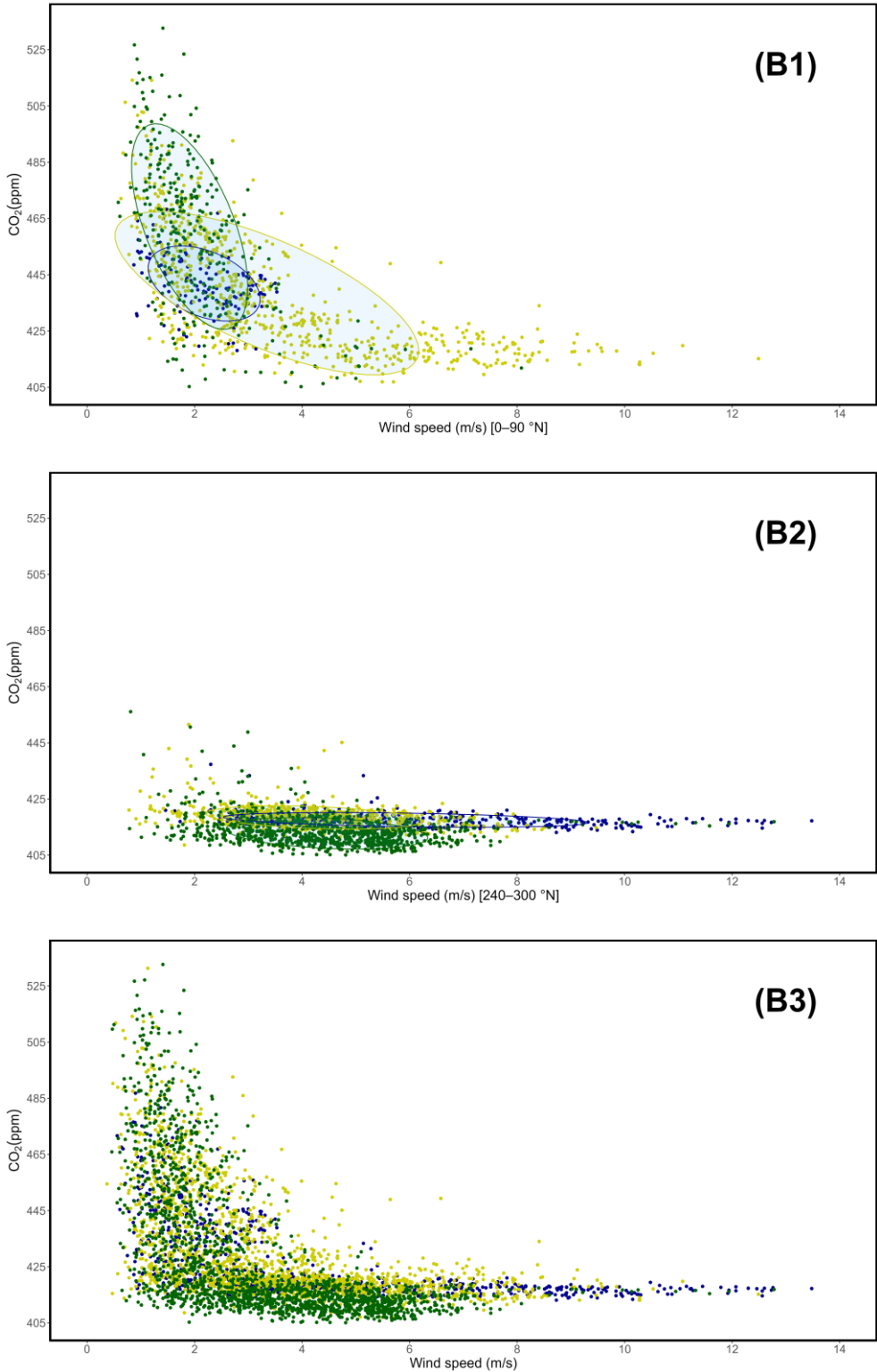
3.4. Integration of Wind Data

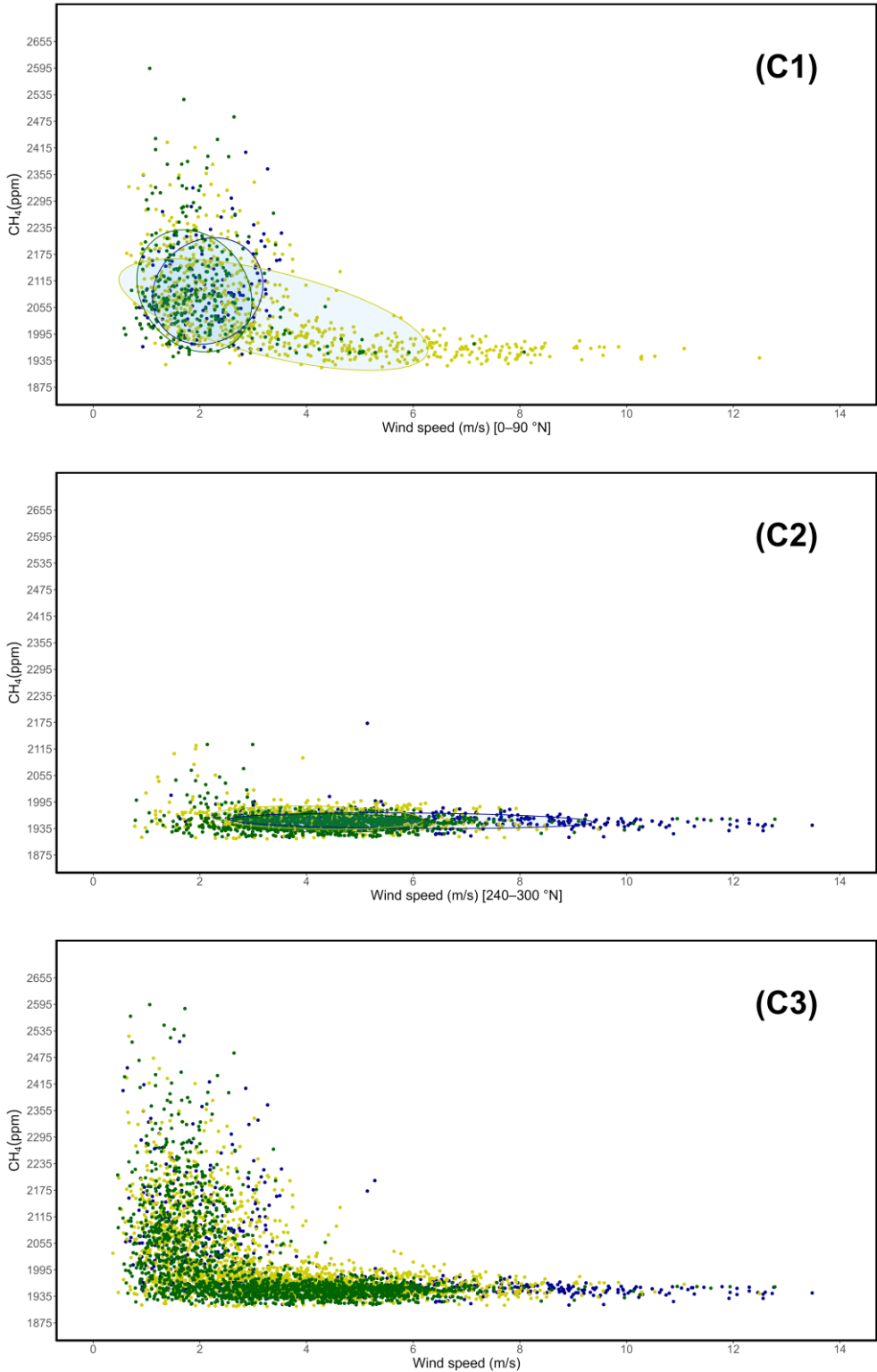
Following the correlations observed in D’Amico et al. (2024a) [22] with respect to wind corridors and speeds, this research performed a similar analysis aimed specifically at ALD, LD, and PLD periods in 2020. The results are shown in Figure 7, while Table 3 reports the number of hourly data falling in each wind sector category. Data ellipses in this case have a lower confidence level of 70% compared to Figure 4, set to ease visualization. Figure 7A3,B3,C3,D3,E3 consider all wind directions, including those outside the 0-90 °N and 240-300 °N ranges set for the NE and W sectors, respectively. Ellipses are excluded from these plots to ease visualization and highlight the “hyperbola branch pattern” (HBP) observed in D’Amico et al. (2024a) [22].

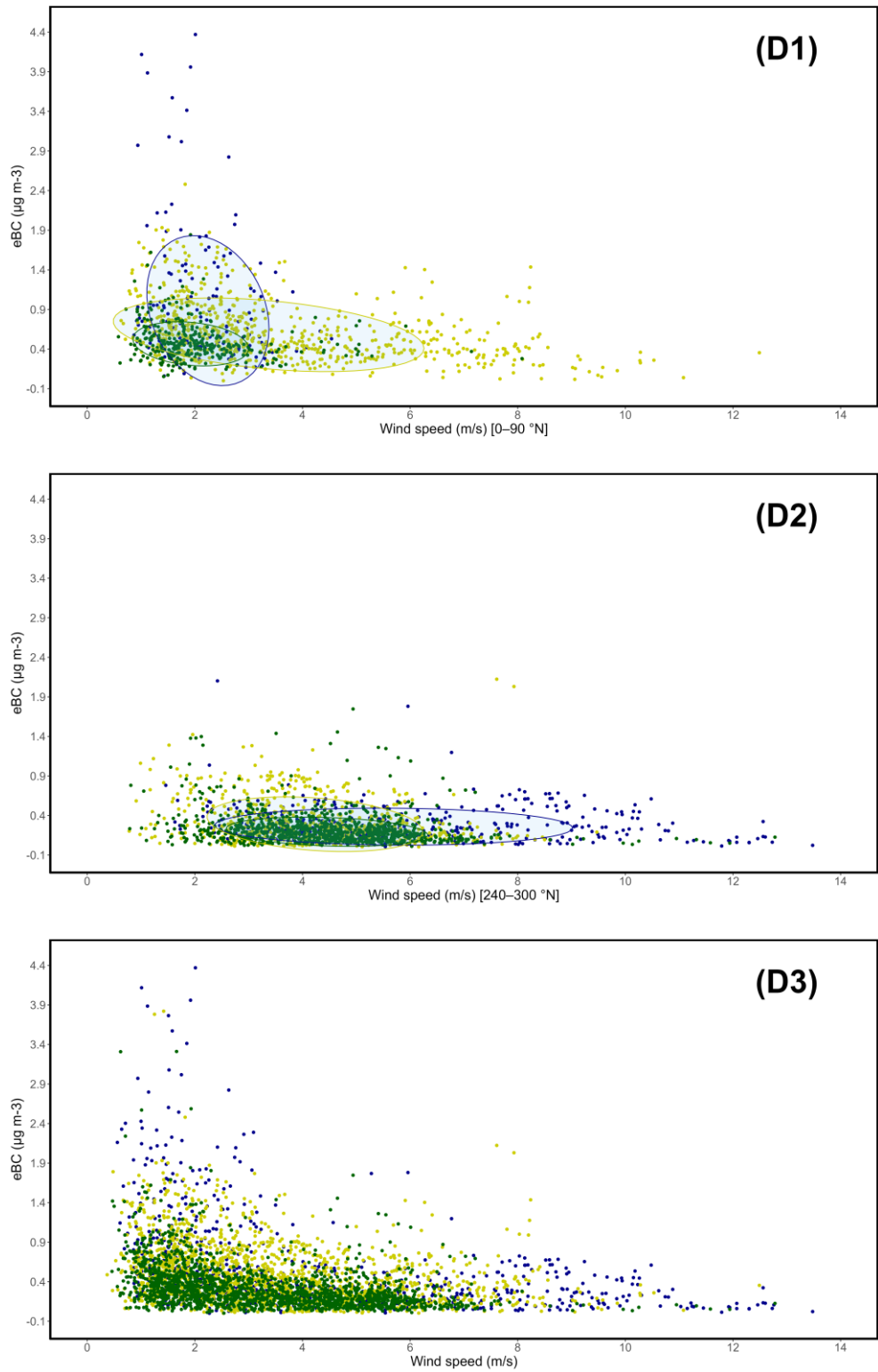
Table 3. Number of hours falling into the western-seaside (240-300 °N) and northeastern-continental (0-90 °N) filters by wind direction, as well as their ratios. Vaisala WXT520 data, due to their coverage rate of 100% (see Table 1), are used as reference.

Corridor	WXT520	G2401	T5012	T42i
West	2002	1937	1927	1934
Northeast	1167	1143	1123	1155
Ratio	1.71	1.69	1.71	1.67









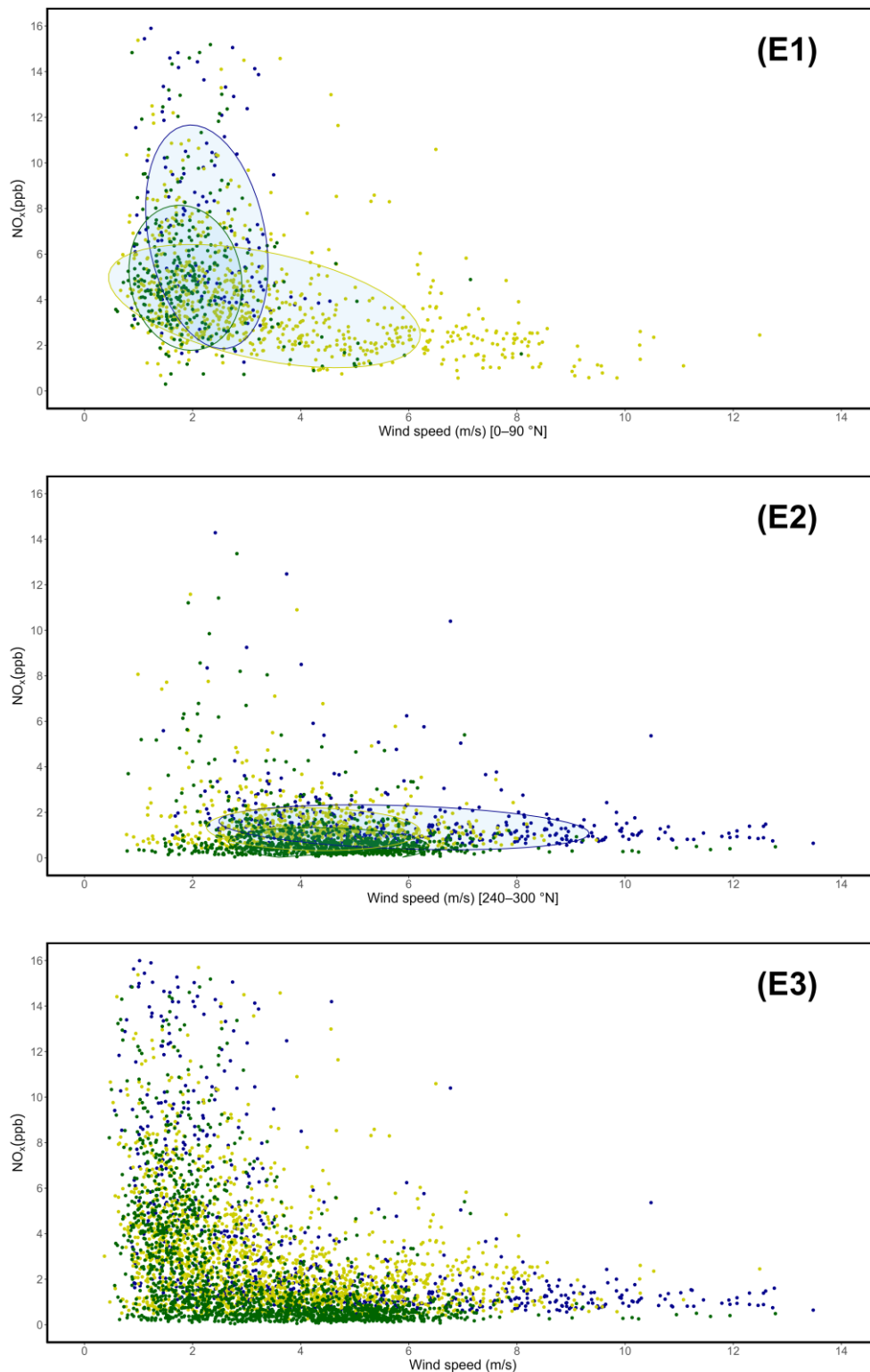
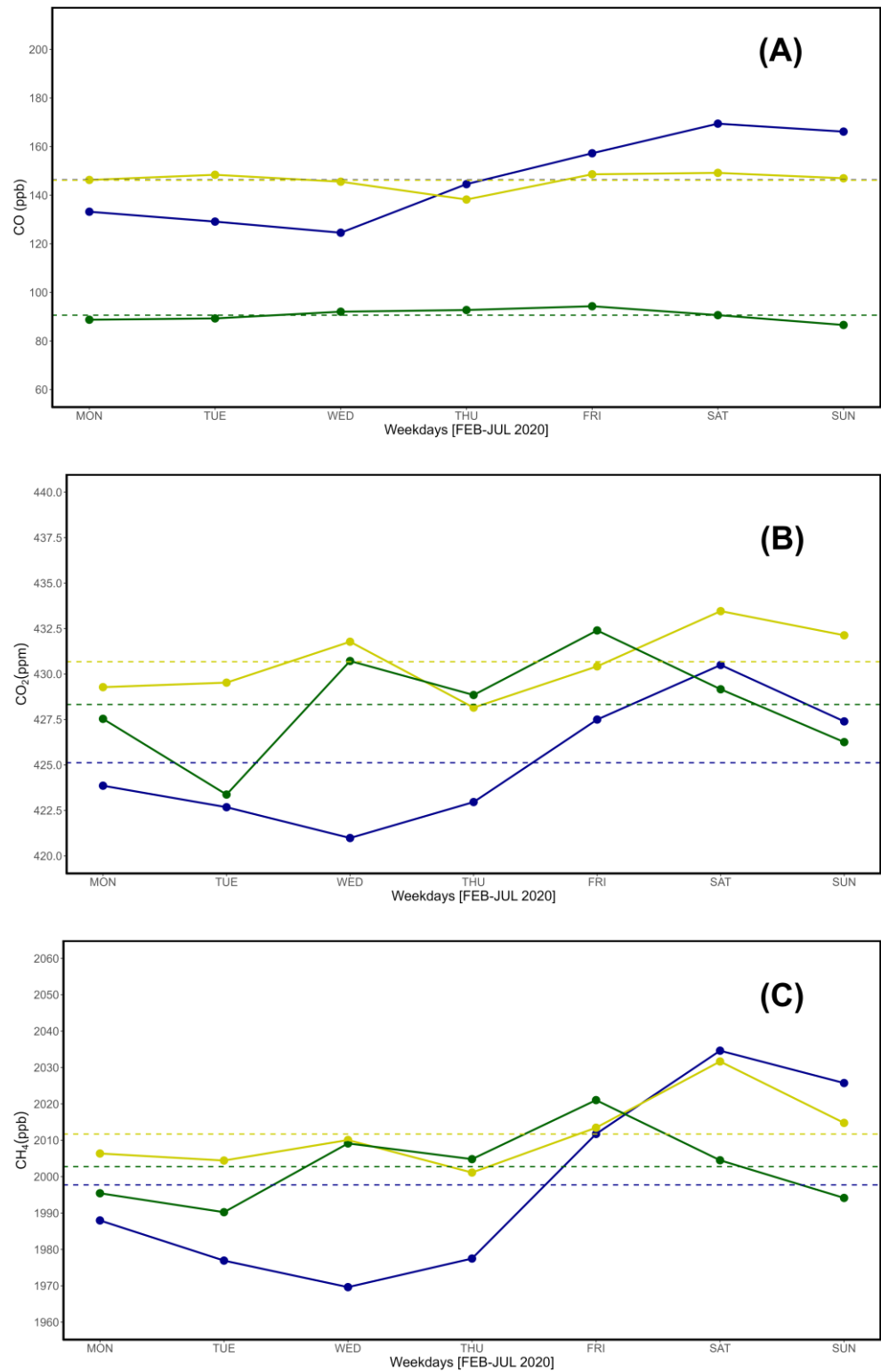


Figure 7. Correlation between hourly averaged data and wind speeds, differentiated by sector (#1 plots for the NE-continental corridor, #2 plots for the W-seaside corridor, and #3 plots for all wind directions, including those falling outside the two main corridors). The color scheme differentiates periods of observation (ALD, LD, PLD) following the same pattern used in other graphs. A: CO; B: CO₂; C: CH₄; D: eBC; E: NO_x.

3.5. Assessment of Weekly Cycles

Following the methods seen in D'Amico et al. (2024a, 2024b) [22–72], weekly cycles have been assessed by period of observation (ALD, LD, PLD). This type of evaluation has been computed to

highlight the impact of LD restrictions on anthropogenic emissions characterized by a weekly cycle. The results are shown in Figure 8.



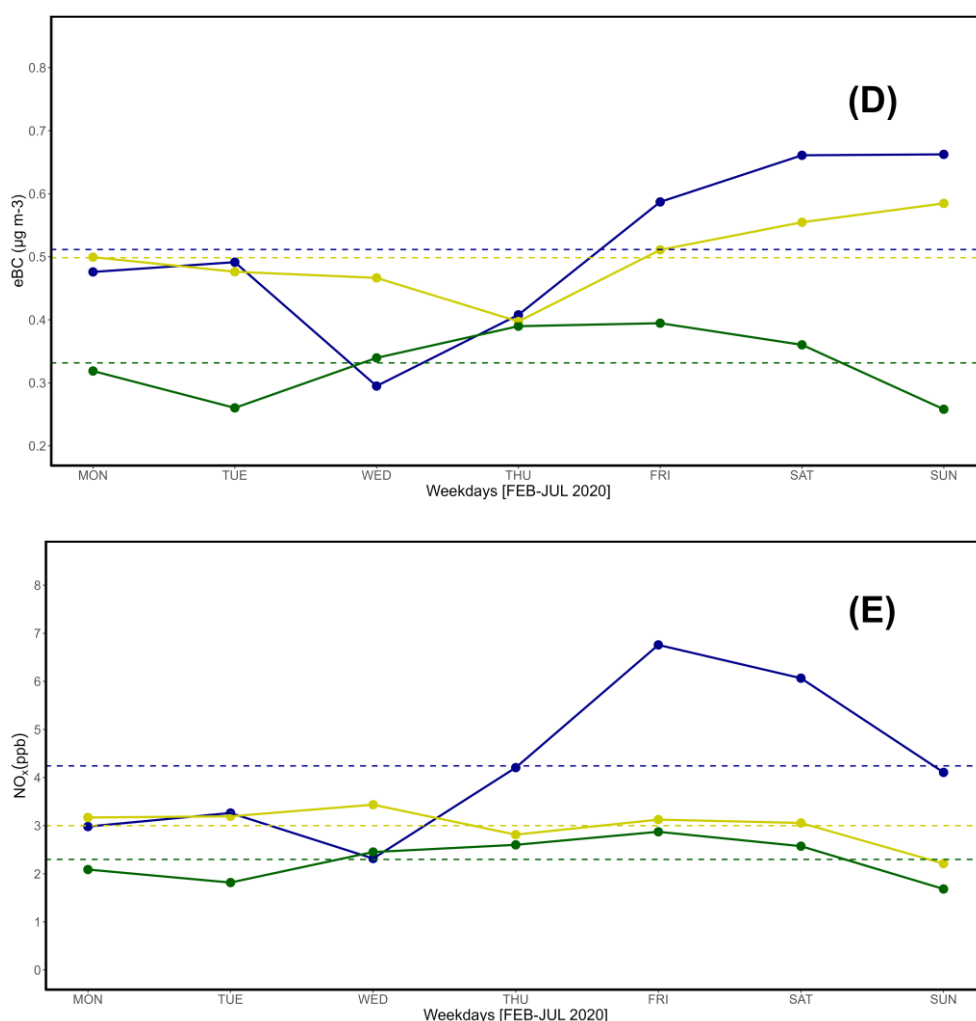


Figure 8. Weekly trends observed at LMT between February and July 2020. The dotted horizontal lines show average values per category. A: CO; B: CO₂; C: CH₄; D: eBC; E: NO_x.

4. Discussion

In this study, Italy's pioneeristic role in introducing a nationwide lockdown (LD) [1] during the Covid-19 pandemic in early 2020 and Lamezia Terme's (LMT) coastal location (Figure 1) and local wind circulation (Figure 2) have both been exploited to assess CO, CO₂, CH₄, eBC and NO_x parameters between February and July 2020, a time span exceeding the first nationwide LD (March 9th – July 31st) in order to account for pre- and post-LD trends and late environmental responses to LD restrictions. The first Italian LD, which was more strict than similar measures meant to contain Covid-19 in late 2020 and in 2021, therefore provided a unique circumstance to analyze key parameters with reduced anthropic activities. Among the observed parameters, CH₄ alone has so far been subject to a detailed multi-year study accounting for most of LMT's observation history [22], while the others are as of today not characterized on an observation site level.

Generally speaking, the Mediterranean Basin is considered as a hotspot for air quality assessments [81] as well as a context where multiple air mass transport mechanisms combine [82–84]. The first LD occurred during a seasonal transition between Mediterranean winter and spring, then summer, and resulted into most anthropic activities either being completely interrupted or significantly reduced. The most documented reduction in anthropic activity in the LMT area is that of the nearby international airport (Figure 1), where only one daily flight to/from Rome-Fiumicino (IATA: FCO; ICAO: LIRF) operated during the LD to ensure the most basic connections to air travel networks [85]. The LD has also affected other activities, such as the education sector, in a country where schools are normally open from Monday to Saturday and urban rush hours in the Lamezia Terme municipality area are linked to that form of commuting. The A2 highway (Figure 1) has also

experienced a sharp reduction in vehicular traffic, though the toll free policy applied to it does not allow a detailed estimate on traffic reduction.

The seasonal transition during which the first LD has occurred allowed to test several correlations with parameters usually linked to domestic heating and, consequently, daily temperatures. In fact, although a full-scale census and assessment on the phenomenon does not exist, many households in the rural areas nearby rely on biomass burning (in particular, wood) as domestic heating during the winter season.

Figure 3 confirms the seasonal change, which has resulted in a nearly constant increase in daily temperatures since mid-April, with the exception of a heat wave slightly before the restriction lift, which occurred on May 18th [2]. This allowed a direct comparison between the above-mentioned daily temperatures and daily-aggregated data concerning key parameters, as seen in Figure 4 and Table 2, which allowed to determine two different types of response to rising temperatures. In particular, CO (Figure 4A), eBC (Figure 4D), and NO_x (Figure 4E), as shown by 90% confidence ellipses and R² values reported in Table 2, are characterized by a correlation between daily temperatures and observed concentrations. CO in particular seems the most affected parameter, as winter concentrations are higher due to more emissions from domestic heating as well as lower OH (hydroxyl radical) concentrations, the latter being a notable sink [86]. Conversely, CO₂ (Figure 4B) and CH₄ (Figure 4C) show no correlation, as the range of daily concentrations does not seem to be affected by temperature changes and the R² values reported in Table 2 are low.

Different trends among observed parameters have also been reported in the evaluation of hourly averages throughout the entire observation period (FEB-JUL 2020), as shown in Figure 5. In the case of CO (Figure 5A), hourly data have added extra detail to the correlation with daily temperatures, as peaks fall considerably from mid-April onwards, reflecting an increase in daily temperatures (Figure 3). This is also observed in the case of eBC (Figure 5D), though the pattern is not as prominent as that observed for CO. CO₂ (Figure 5B) and CH₄ (Figure 5C) both lean towards a stabilization of observed hourly trends but show an upward trend in the PLD period. CH₄ in particular yields the notable hourly peaks in the PLD period, a finding that is not in accordance with the general seasonal trend of CH₄ at LMT reported in D'Amico et al. (2024a) [22] but does reflect the peak experienced by this compound in 2020. Previous studies linked CH₄ concentrations and their relative stability to local sources, such as landfills (Figure 1), waste management, and livestock [43], which are all believed to have been constant during the LD. NO_x have experienced a decline (Figure 5E), though peaks in hourly averages are present during the LD.

Following the daily cycle analysis seen in D'Amico et al. (2024a) [22], ALD, LD, and PLD trends have been analyzed for the purpose of this research study, with results shown in Figure 6. At LMT, the daily cycle is heavily influenced by local wind circulation (Figure 2): daytime flows generally come from the sea and yield low values in all parameters, while nighttime flows come from the northeast and are enriched. Unlike the trends seen in D'Amico et al. (2024a), Figure 6 show different responses of daily cycle between ALD, LD, and PLD periods: CO (Figure 6A) mole fractions are very low during the PLD period, but follow similar trends during the ALD and LD periods and nighttime peaks are consistent with previous research which attributed them to stable layer conditions [43]; CO₂ (Figure 6B) and CH₄ (Figure 6C) both show the actual daily cycle expected at LMT due to local wind circulation, with ALD values being generally lower than their LD and PLD counterparts; eBC (Figure 6D) and NO_x (Figure 6E) both show a daily cycle affected by a perturbation in the early morning, which is linked to the transition between NE-continental and W-seaside winds. The observed NO_x pattern in early morning hours is compatible with the findings of a previous study [43], which linked them to rush hour emissions within the shallow coastal PBL. In fact, the ALD peak is significantly greater than LD and PLD concentrations observed at the same hours, highlighting a reduction in anthropic activities (specifically, transportation).

The influence of local wind circulation was further analyzed in Figure 7. Table 3 shows that, once the filters are applied, the W to NE ratio in terms of gathered hourly data is 1.67-1.71. D'Amico et al. (2024a) [22], in analyzing CH₄ data at LMT, already reported a clear differentiation between W and NE mole fractions. The same study also reported a correlation between NE concentrations and wind

speed, with lower speeds being correlated with the highest concentrations observed at the site, attributable to nearby sources. The study found evidence of a “hyperbola branch pattern” (HBP) in wind speeds and mole fractions. This finding from previous research is not only confirmed for CH₄ in the context of the 2020 LD period but is also extended to all other observed parameters (CO, CO₂, eBC and NO_x) and allows to better constrain some of the local sources of pollution. CO (Figure 7A1, 7A2, 7A3) shows a clear seasonal trend, with ALD and PLD mole fractions being well differentiated; the main source of CO is from the NE sector and shows little influence of wind speeds, which may point to remote sources. The highest reported values from the W sector have been observed during the LD at low to moderate wind speeds, which also point to contributions from other locations in the context of the Mediterranean Basin. CO₂ (Figure 7B1, 7B2, 7B3) shows a clear W/NE differentiation, with LD data yielding generally low values regardless of wind speed, though peaks linked to the LD period are reported. CH₄ (Figure 7C1, 7C2, 7C3) shows patterns similar to those of CO₂, which is consistent with other evaluations in this research paper, as well as finding from previous research [43], and may indicate contributions from remote and local sources alike. eBC (Figure 7D1, 7D2, 7D3) shows a seasonal trend, plus a peculiar behavior during the LD period: contributions from nearby and remote locations are prominent in the NE sector alone. NO_x (Figure 7E1, 7E2, 7E3) concentrations show reduced influence from wind speeds, which results into high values even from the W sector, which previous research attributed to offshore ship emissions related to traffic to and from the Gioia Tauro port, located ≈55 km S-SW of LMT, which is a key logistical hub in the central Mediterranean [43].

A final comparison between ALD, LD, and PLD data has been performed on a weekday *latu sensu* (Monday to Sunday) basis, as shown in Figure 8, following the findings from D’Amico et al. (2024a, 2024b) [22–72]. By averaging gathered hourly data per weekday, anthropic influences have been tested under the assumption that no natural phenomenon would lead to a proper weekly cycle, unlike anthropogenic emissions which are subject to such cycles [87–90]. CO (Figure 8A) shows no LD and PLD weekly cycles, while a weekly cycle during the ALD period is present and is consistent with changes in anthropic activities across the week, a pattern that is believed to have been reduced to a bare minimum during the LD. The LD period does not show a proper weekly cycle for CO, which is consistent with constant domestic heating emissions during the lockdown; in addition to that, the PLD period does not show a weekly cycle, which is also consistent with a shift from CO emissions from domestic heating (and comparable sources of emission) to wildfires, which are assumed to be spread equally over the course of a standard week. In the case of CO, fluctuations in daily concentrations differ up to ≈50%. CO₂ (Figure 8B), CH₄ (Figure 8C), eBC (Figure 8D), and NO_x (Figure 8E) all show well defined weekly changes in the ALD period. In the case of CO₂, it is worth noting that the observed fluctuations are in the order of a few ppm around the average of 427.5 ppm and are therefore not comparable to the major fluctuations seen for other parameters. CH₄ shows a clear pattern in the ALD period, which is consistent with a weekly cycle of anthropogenic emissions; LD and PLD CH₄ weekly behaviors tend towards a normalization, which supports the hypothesis of a constant, or nearly constant, output from sources such as landfills and livestock. eBC’s flattening in the PLD period is consistent with a shift from anthropogenic emissions to other outputs such as wildfires (which can be of anthropic origin, but do not have a clear weekly cycle). NO_x has a prominent ALD cycle, with weekly fluctuations reaching a peak of ≈250%, a threshold not observed in any of the other parameters.

In addition to weekly fluctuations, averaged values per weekday (dotted horizontal lines) in Figure 8 also highlight the differences between absolute ALD, LD, and PLD concentrations, which reflect clear seasonal changes in the case of CO and eBC and major shifts in emission sources. Both parameters have much lower PLD averages compared to their LD and ALD counterparts.

An assessment of the environmental response to LDs also needs to consider restrictions and regulations enforced in other countries. As described in section 2.1, in fact, LMT’s location in the central Mediterranean area makes the site subject to the influence of several European and African outputs [74]. The Mediterranean Basin itself is also known to be subject to air masses originating in continental Europe and enriched in various pollutants [84–91]. At LMT, the W sector is assumed not

to have physical obstacles for hundreds of kilometers, as the Italian island of Sardinia is in fact located ≈ 600 km W-NW from LMT. Continental Spain and France are located ≈ 1300 and ≈ 1000 km in those directions, respectively. In the case of the NE corridor however, it is worth noting that both Greece and Albania are in a ≈ 350 km radius from the LMT observation site in the E/NE direction, meaning that at least some of the observed emission outputs could be attributable to such “remote” regions as well as other countries in the Balkans. For instance, Greece had a different LD policy in early 2020 compared to Italy (March 23rd – May 4th in Greece, 42 days [92]) which does not overlap with the definitions of ALD, LD, and PLD used in this paper.

Overall, a cross analysis of the ALD, LD, and PLD periods at LMT has allowed to better constrain, for the first time in its operational history, the seasonal cycles of parameters such as CO and eBC in conditions with extremely low anthropogenic emissions, as well as provide new insights on the sources of CO₂, CH₄, and NO_x emissions in the NE sector. These new findings significantly expand the knowledge on source apportionment at LMT and provide baseline data for future research relying on additional atmospheric tracers.

5. Conclusions

For the first time, the first Italian lockdown (LD) of 2020 has been used to assess the behavior of CO (carbon monoxide), CO₂ (carbon dioxide), CH₄ (methane), eBC (equivalent black carbon), and NO_x (nitrogen oxides, NO + NO₂) at the WMO/GAW regional coastal site of Lamezia Terme in Calabria, Southern Italy. The study exploited the station’s location in the context of the Mediterranean Basin, where local wind circulation patterns allow to discriminate western-seaside corridors yielding generally low concentration values with northeastern-continental corridors, enriched in most pollutants and agents of climate change. The study considered a period longer than the actual first nationwide LD, which was introduced on March 9th and consequently lifted on May 18th. Data gathered between February and July therefore allowed to assess the behavior of observed parameters before (ALD), during (LD), and after (PLD) the first lockdown.

The research has allowed to better constrain the correlation between key parameters and seasonal changes, as the observation period is characterized by a nearly constant increase in daily temperatures. CO and eBC have proven to be the most affected by seasonal changes, thus confirming that local sources of emissions may in fact be related to domestic heating and similar outputs.

Other evaluations considered hourly averages and, particularly, their patterns in daily cycles. The analysis of these cycles, differentiated by ALD, LD, and PLD, allowed to better constrain local and potentially remote emission sources, as well as the influences of wind circulation on observed data. Consequently, the integration of wind data (direction and speed) has also allowed to find notable differences between the W and NE corridors, with the former being depleted in most parameters across the entire observation period. The NE corridor is characterized by the same hyperbola branch pattern (HBP) observed in a previous study, with low wind speeds being correlated with high concentrations and, vice versa, high speeds yielding low values. The finding has allowed to identify local sources in the NE sector as responsible for most of these peaks.

Finally, following the implementation of new methods seen in previous research, all parameters have been evaluated with respect to their weekly cycles, under the assumption that no natural phenomenon (unlike anthropic activities) would lead to a proper weekly cycle and trend. This analysis has proved the ALD period to be affected by such cycles, while the LD and PLD periods were much less affected, further corroborating the hypothesis proposed in other research by which anthropogenic emissions are responsible for a significant fraction of the peaks observed at LMT station.

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