

Article

Not peer-reviewed version

Background Variability of NO₂ in a Remote North Atlantic Island and Its Association with Atmospheric Transport Regimes

[Maria Gabriela Meirelles](#) * and [Helena Cristina Vasconcelos](#)

Posted Date: 2 April 2026

doi: 10.20944/preprints202604.0129.v1

Keywords: reactive nitrogen; nitrogen dioxide (NO₂); atmospheric transport regimes; background atmosphere; marine boundary layer; air-mass transport



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Background Variability of NO₂ in a Remote North Atlantic Island and Its Association with Atmospheric Transport Regimes

Maria Gabriela Meirelles ^{1,2,*} and Helena Cristina Vasconcelos ^{1,3}

¹ Faculty of Science and Technology, University of the Azores, 9500-321 Ponta Delgada, Portugal

² Research Institute of Marine Sciences, University of the Azores (OKEANOS), 9901-862 Horta, Portugal

³ Laboratory of Instrumentation, Biomedical Engineering and Radiation Physics (LIBPhys, UNL), Department of Physics, NOVA School of Science and Technology, 2829-516 Caparica, Portugal

* Correspondence: maria.gf.meirelles@uac.pt

Abstract

Atmospheric nitrogen dioxide (NO₂) is an important component of reactive nitrogen and plays a key role in the atmospheric nitrogen cycle outside major emission regions. However, its variability under remote background conditions remains poorly characterized, as most observational studies focus on urban or continental environments. This study investigates the background variability of in situ NO₂ measurements at a remote North Atlantic island (Azores) over the period 2015–2024 and examines its association with large-scale atmospheric transport regimes. Monthly NO₂ concentrations were classified into background Atlantic conditions and months influenced by continental air masses using an objective PM₁₀ percentile-based criterion. Differences between regimes were assessed using non-parametric statistics. Although NO₂ concentrations were systematically higher during months associated with continental transport, the differences did not reach statistical significance. Wind speed analysis for the overlapping period 2018–2024 showed consistently higher values during continental transport months, supporting enhanced large-scale advection during these periods. Overall, the results indicate that background NO₂ levels in this remote insular environment exhibit modest but coherent modulation associated with atmospheric transport regimes. These findings contribute to improving the interpretation of reactive nitrogen variability in remote marine settings and highlight the value of island observatories for studying the atmospheric nitrogen cycle.

Keywords: reactive nitrogen; nitrogen dioxide (NO₂); atmospheric transport regimes; background atmosphere; marine boundary layer; air-mass transport

1. Introduction

Reactive nitrogen (Nr) plays a central role in atmospheric chemistry and in the broader biogeochemical nitrogen cycle. Since the industrial revolution, anthropogenic activities have substantially altered the global nitrogen cycle through fossil fuel combustion, agriculture, and industrial processes, increasing the abundance and reactivity of nitrogen compounds in the atmosphere [1,2]. Among these species, nitrogen dioxide (NO₂) is of particular importance as a key component of nitrogen oxides (NO_x = NO + NO₂), influencing ozone formation, oxidative capacity, secondary aerosol production, and nitrogen deposition [3–5].

While numerous studies have characterized NO₂ in urban and industrialized regions, comparatively less attention has been given to its variability under remote, background conditions. Most long-term analyses of NO₂ focus on source-dominated environments where local emissions strongly control observed concentrations [6,7]. In contrast, remote marine and insular environments offer a unique opportunity to investigate the behavior of reactive nitrogen decoupled from strong

local sources and dominated instead by large-scale atmospheric transport and background chemistry [8–10].

Transport processes exert a fundamental influence on the distribution of reactive nitrogen in the troposphere. Advection of continental air masses, vertical mixing, and synoptic-scale circulation patterns can modulate NO₂ concentrations even in regions far removed from primary emission sources [11–13]. In marine boundary layer environments, background NO₂ levels typically remain low but can exhibit episodic enhancements associated with long-range transport from continental regions [14,15]. These transport-driven variations provide insight into hemispheric-scale redistribution of reactive nitrogen and its role in regional nitrogen budgets.

The North Atlantic region represents a particularly valuable natural laboratory for studying background atmospheric composition. Air masses arriving in this region are influenced by a combination of mid-latitude westerlies, subtropical circulation, and occasional incursions of continental or dust-laden air [16,17]. Remote island stations in the North Atlantic have historically contributed to advancing understanding of background atmospheric composition, including greenhouse gases and trace species [18,19]. However, sustained observational analyses focusing specifically on background NO₂ variability in such environments remain limited.

Previous work has highlighted the importance of long-term observations in detecting variability and transport signatures in reactive nitrogen species [2,20]. Non-parametric statistical approaches and percentile-based classification methods are increasingly used to distinguish between background and transport-influenced regimes in atmospheric time series without imposing strong distributional assumptions [21]. Such approaches are particularly appropriate for low-concentration environments where variability is modest and episodic.

In this study, we investigate the background variability of in situ NO₂ concentrations measured at a remote North Atlantic island (Azores) over the period 2015–2024. Using an objective percentile-based criterion applied to PM₁₀ as a transport indicator, monthly conditions are classified into background Atlantic and continental-influenced regimes. Differences between regimes are evaluated using non-parametric statistics, and wind speed data are used to support the physical interpretation of transport intensity over the overlapping period 2018–2024. By focusing on a remote insular environment, this work aims to contribute observational evidence to the understanding of how atmospheric transport regimes modulate background reactive nitrogen levels in marine settings.

The following section describes the study area, datasets, and methodological approach used in this work.

2. Materials and Methods

2.1. Study Area

The study was conducted on Faial Island, located in the Azores archipelago in the central North Atlantic Ocean. Owing to its remote oceanic location between Europe and North America, the region is predominantly influenced by marine boundary layer conditions and mid-latitude westerlies (Figure 1).

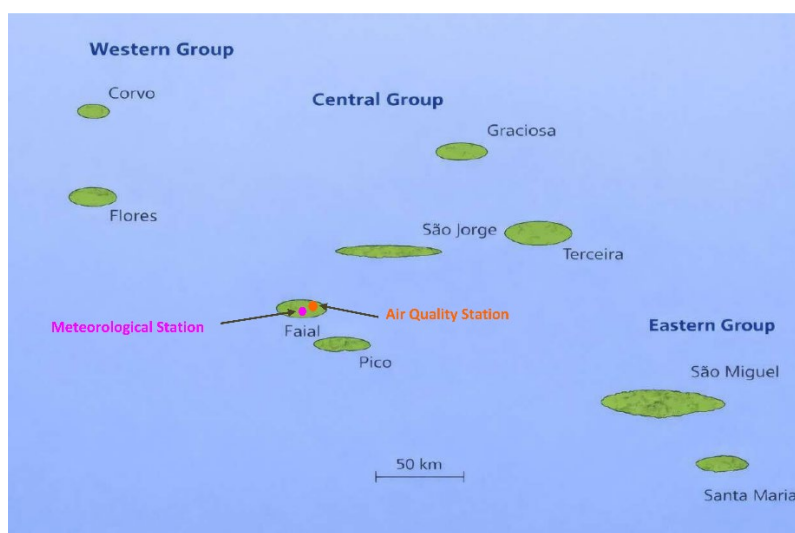


Figure 1. Geographic location of the Azores archipelago in the North Atlantic Ocean, indicating the Western, Central, and Eastern island groups. The positions of the meteorological station and the air quality monitoring station on Faial Island are shown.

The island environment is characterized by the absence of major industrial emission sources, making it suitable for investigating background atmospheric composition and transport-driven variability of atmospheric pollutants.

Air quality observations were obtained from the Espalhafatos monitoring station, located in the parish of Ribeirinha (municipality of Horta) at approximately 38.60° N, 28.63° W, at an elevation of about 120 m above sea level (Figure 2).



Figure 2. Location of the Espalhafatos air quality monitoring station on Faial (Azores), used for continuous measurements of NO₂ and PM₁₀ under rural background conditions. The station is part of the regional air quality monitoring network and contributes data to the national air quality information system QualAr.

The station is part of the regional air quality monitoring network of the Azores, and its measurements are integrated into the Portuguese national air quality information system QualAr, operated by the Portuguese Environment Agency. According to the classification criteria established under Directive 2008/50/EC [22], the site is categorized as a rural background monitoring station, meaning that pollutant concentrations measured at this location are minimally influenced by nearby emission sources and are representative of regional atmospheric conditions. Continuous measurements include nitrogen dioxide (NO₂), sulfur dioxide (SO₂), ozone (O₃), and particulate matter (PM₁₀ and PM_{2.5}). In the present study, NO₂ and PM₁₀ observations were used to characterize

background atmospheric conditions and to identify periods influenced by enhanced atmospheric transport.

Meteorological conditions were characterized using observations from the Alto do Cabouco meteorological station, located on Faial Island at approximately 38.59° N, 28.69° W, at an elevation of about 330 m above sea level (Figure 3).



Figure 3. Alto do Cabouco meteorological station located on Faial (Azores). The station belongs to the regional hydrometeorological monitoring network and provides observations of wind speed and wind direction, which were used to characterize atmospheric transport conditions influencing the variability of NO₂ in the study area.

The station belongs to the regional hydrometeorological monitoring network of the Azores and records standard meteorological variables including wind speed, wind direction, air temperature, relative humidity, atmospheric pressure, and precipitation. In this study, wind speed and wind direction were used to support the interpretation of atmospheric transport conditions influencing the observed variability of NO₂ concentrations.

Due to its position in the mid-latitude North Atlantic, the Azores region is frequently influenced by synoptic-scale atmospheric circulation patterns, including westerly flow and episodic continental air-mass transport, which can modulate background trace gas variability. Remote oceanic islands such as the Azores provide valuable observational platforms for studying background atmospheric composition, as they are largely decoupled from strong local emission sources while remaining sensitive to long-range transport processes.

2.2. NO₂ and PM₁₀ Observations

Hourly NO₂ and PM₁₀ data were obtained from the QualAr air quality monitoring network (Agência Portuguesa do Ambiente) for the period January 2015 to December 2024. All analyses were performed using monthly aggregates derived from hourly observations.

2.2.1. Data Completeness Criterion

To ensure representativeness of monthly statistics, a completeness threshold was applied. For each month *m*, data completeness was defined as shown in Equation (1):

$$C_m = (N_{v,m} / N_{t,m}) \times 100 \text{ [1]}$$

where *N_{v,m}* is the number of valid hourly observations in month *m* and *N_{t,m}* the total expected number of hourly observations in that month. Only months satisfying Equation (2):

$$C_m \geq 80\% \text{ [2]}$$

were retained in subsequent analyses.

The data coverage and completeness of the NO₂ observations for the period 2015–2024 are summarized in Table 1.

Table 1. Data coverage and completeness of NO₂ observations at the Faial (Espalhafatos) station (2015–2024).

Year	Valid hours	Total hours	Data completeness (%)
------	-------------	-------------	-----------------------

2015	8571	8760	97.84
2016	7504	8784	85.43
2017	8721	8760	99.55
2018	8736	8760	99.73
2019	8732	8760	99.68
2020	8755	8784	99.67
2021	8748	8760	99.86
2022	8729	8760	99.65
2023	8735	8760	99.71
2024	8689	8784	98.89

Note: Hourly NO₂ measurements were obtained from the QualAr air quality monitoring network (Agência Portuguesa do Ambiente). Data completeness is expressed as the percentage of valid hourly observations relative to the total expected hours per year (8784 in leap years). Monthly averages used in subsequent analyses were calculated only for months with ≥80% data availability.

2.2.2. Monthly Aggregation

Monthly mean NO₂ concentrations were computed as presented in Equation (3):

$$\overline{NO_{2m}} = \frac{1}{n_m} \sum_{i=1}^{n_m} NO_{2,i} \quad [3]$$

where n_m denotes the number of valid hourly observations in month m and $NO_{2,i}$ the corresponding hourly concentration.

Monthly mean PM₁₀ concentrations were calculated analogously.

2.2.3. Transport Regime Classification

Transport regimes were defined using a percentile-based classification applied to monthly mean PM₁₀ concentrations. The 90th percentile of the monthly PM₁₀ distribution over the study period was computed as shown in Equation (4):

$$P_{90} = \text{Percentile}_{90}(\overline{PM_{10m}}) \quad [4]$$

where distribution of monthly mean is PM_{10m}.

Months were classified as:

Continental regime if $\overline{PM_{10m}} \geq P_{90}$,
Background regime if $\overline{PM_{10m}} < P_{90}$

This objective threshold was used to distinguish months influenced by enhanced continental transport from prevailing background Atlantic conditions.

2.3. Wind Data

Hourly wind speed and direction data were obtained from the regional hydrometeorological network for the period 2018–2024. Wind speed values provided in km h^{−1} were converted to International System units according to Equation (5):

$$u_i = \frac{u_{kmh,i}}{3.6} \quad [5]$$

Monthly mean wind speed was computed as indicated in Equation (6):

$$\bar{u}_m = \frac{1}{n_m} \sum_{i=1}^{n_m} u_i \quad [6]$$

Wind data were used solely to support the physical interpretation of transport regimes over the overlapping period 2018–2024.

2.4. Statistical Analysis

Differences between transport regimes were evaluated using the Mann–Whitney U test, a non-parametric method appropriate for independent samples without assuming normality.

Two samples were defined as:

$$X = \{\overline{NO_2}(m)\}_{\text{background}}$$

$$Y = \{\overline{NO_2}(m)\}_{\text{continental}}$$

where $\overline{NO_2}(m)$ represents the monthly mean NO₂ concentration in month m , and the subscripts denote the transport regime classification.

The Mann–Whitney U statistic is given by Equation (7):

$$U = n_X n_Y + \frac{n_X(n_X+1)}{2} - R_X \quad [7]$$

where n_X and n_Y denote the sample sizes of the background and continental groups, respectively, and R_X is the sum of ranks assigned to the observations in sample X .

A two-sided test was applied with a significance level of $\alpha = 0.05$.

The magnitude of the regime difference was quantified using the difference in medians, Equation (8):

$$\Delta = \tilde{Y} - \tilde{X} \quad [8]$$

where $\tilde{Y}$ and $\tilde{X}$ denote the sample medians of the background and continental regimes, respectively.

An analogous procedure was applied to monthly mean wind speed for the overlapping period 2018–2024.

3. Results

This section presents the main observational results obtained from the analysis of the NO₂ time series and associated meteorological conditions at the Faial monitoring station. First, the temporal variability of background NO₂ concentrations over the period 2015–2024 is described. Subsequently, differences between background Atlantic conditions and months influenced by continental transport are examined. Finally, wind speed characteristics are analysed for the overlapping period 2018–2024 to support the physical interpretation of the identified transport regimes.

3.1. Temporal Variability of NO₂ (2015–2024)

Monthly mean NO₂ concentrations measured at the Faial (Espalhafatos) station are shown in Figure 4.

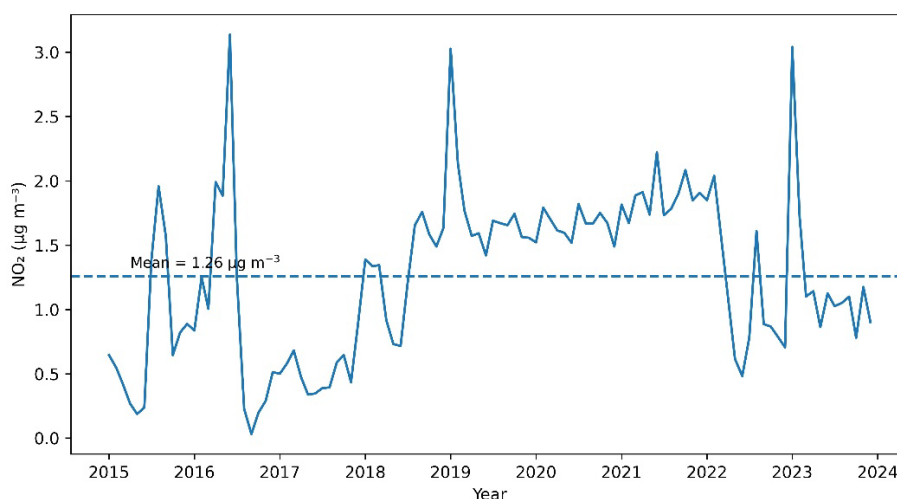


Figure 4. Monthly mean NO₂ concentrations measured at the Espalhafatos air quality monitoring station (Faial Island, Azores) during the period 2015–2024. The dashed horizontal line represents the overall mean NO₂ concentration for the study period.

Over the study period, NO₂ concentrations remained generally low, consistent with background conditions in a remote North Atlantic environment. The overall mean NO₂ concentration was 1.26 µg m⁻³.

Interannual variability was modest, with no abrupt regime shifts or sustained step changes. Short-term enhancements are visible in several months throughout the record.

3.2. NO₂ under Background and Continental Transport Regimes

Months classified as influenced by continental air masses (defined as months with PM₁₀ ≥ P90) are indicated by shaded areas in Figure 5. These periods do not dominate the time series but appear intermittently across multiple years, suggesting episodic large-scale transport influences superimposed on relatively stable background conditions.

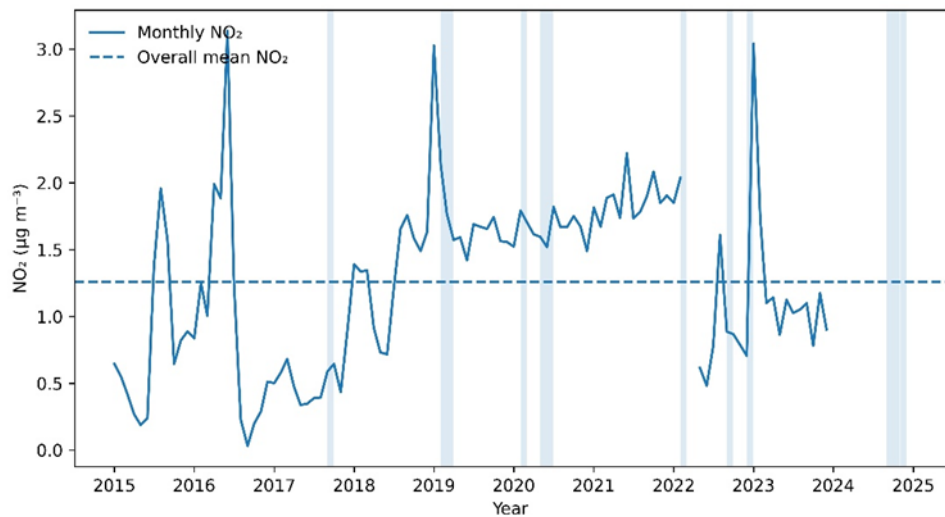


Figure 5. Monthly mean NO₂ concentrations at the Espalhafatos monitoring station (Faial, Azores) for the period 2015–2024. The dashed line indicates the overall mean NO₂ level, and shaded areas represent months influenced by continental air-mass transport (PM₁₀ ≥ P90). Only months with ≥80% NO₂ data availability were included.

To further examine the effect of transport regimes on NO₂ variability, monthly mean NO₂ concentrations were grouped according to background Atlantic conditions and months influenced by continental air masses. The distributions of NO₂ concentrations for both regimes are shown in Figure 6.

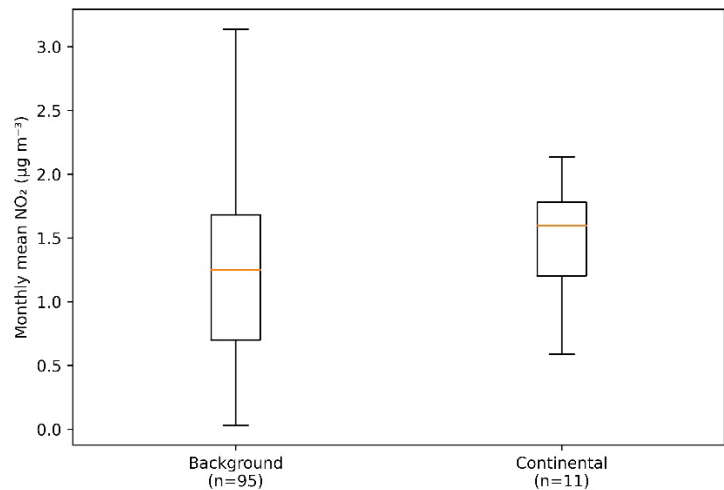


Figure 6. Distribution of monthly mean NO₂ concentrations under background Atlantic conditions and months influenced by continental air-mass transport (PM₁₀ ≥ P90). Boxes represent the interquartile range, the central line indicates the median, and whiskers extend to the minimum and maximum values.

The boxplots indicate that NO₂ concentrations tend to be higher during months classified as continental transport regimes compared to background conditions. The median NO₂ concentration

during continental months was $1.60\text{ }\mu\text{g m}^{-3}$, whereas the median value during background conditions was $1.25\text{ }\mu\text{g m}^{-3}$, corresponding to a median difference of $0.35\text{ }\mu\text{g m}^{-3}$.

To assess whether this difference was statistically significant, a Mann–Whitney U test was applied. The test indicated that the difference between the two regimes was not statistically significant ($U = 384$, $p = 0.153$). Despite the lack of statistical significance at the conventional 0.05 level, the consistent shift toward higher values during continental transport months suggests a systematic modulation of background NO_2 concentrations associated with changes in air-mass origin.

Overall, the distributions indicate that continental transport episodes are associated with modest increases in NO_2 concentrations relative to prevailing background conditions, although the magnitude of these differences remains small in the context of the low baseline concentrations observed at this remote site.

To further support the interpretation that these variations are associated with changes in air-mass transport, wind speed characteristics were analysed for the overlapping period 2018–2024.

3.3. Wind Speed Characteristics during Transport Regimes (2018–2024)

Wind speed data were available for the overlapping period 2018–2024 and were used to support the physical interpretation of the transport regimes identified in the NO_2 analysis. Monthly mean wind speeds were classified according to the same regime definition applied to NO_2 (background vs. continental transport regimes).

The distributions of monthly mean wind speed under background and continental transport regimes are presented in Figure 7. Wind speeds were generally higher during months classified as continental transport regimes compared to background Atlantic conditions. The median wind speed during continental months was 4.27 m s^{-1} , whereas the median value under background conditions was 3.64 m s^{-1} , corresponding to a median difference of 0.63 m s^{-1} .

A Mann–Whitney U test indicated that this difference was not statistically significant ($U = 194$, $p = 0.247$). However, the consistent shift toward higher wind speeds during continental months supports enhanced large-scale advection during these periods.

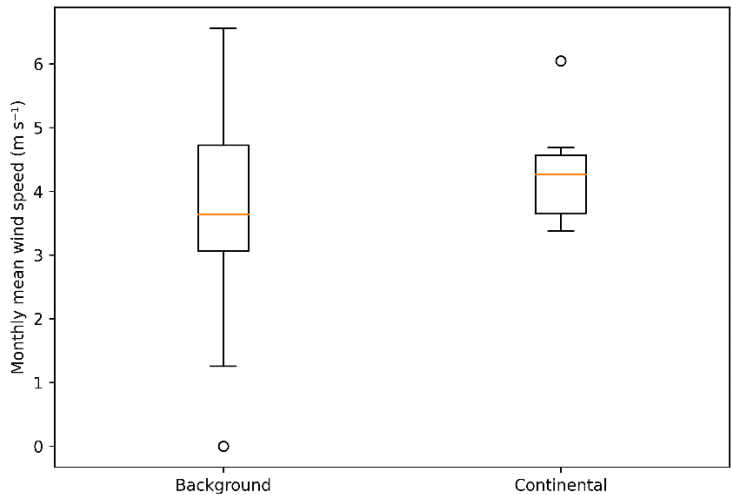


Figure 7. Distribution of monthly mean wind speed under background Atlantic conditions and months influenced by continental transport ($\text{PM}_{10} \geq \text{P90}$) for the period 2018–2024.

Taken together, the NO_2 and wind analyses suggest that background reactive nitrogen levels at this remote site are influenced by changes in air-mass origin and transport intensity, rather than by local emission variability.

4. Discussion

The results presented in this study provide observational insight into the variability of background NO₂ concentrations in a remote North Atlantic environment and their association with atmospheric transport regimes. In contrast to coastal environments, where nitrogen pollution is often dominated by local anthropogenic sources and regional emission trends [23], and where NO₂ variability reflects a combination of local and regional influences [24], the present study focuses on a remote insular setting where background conditions prevail, and transport-related processes become more evident. The consistently low NO₂ concentrations observed at the Faial monitoring station reflect the dominance of marine boundary layer conditions, while modest increases during continental transport months indicate the influence of long-range advection processes.

Despite the overall stability of the time series, NO₂ concentrations tended to be higher during months classified as influenced by continental air-mass transport. Although this difference did not reach statistical significance, the direction and consistency of the signal across the dataset suggest that transport-related processes exert a measurable influence on NO₂ variability. Previous studies have shown that long-range transport can significantly influence NO₂ concentrations, even in regions dominated by local emissions [25], reinforcing the importance of transport processes in shaping atmospheric NO₂ variability. Such behavior is consistent with the episodic nature of long-range transport, where enhancements are intermittent and may not produce strong statistical separation when aggregated at monthly time scales.

The use of a percentile-based PM₁₀ threshold provides an objective and reproducible method to identify transport-influenced conditions. While PM₁₀ is not a direct tracer of NO₂, it is widely associated with continental and dust-laden air masses, making it a suitable proxy for distinguishing between background and transport regimes in the absence of trajectory analysis. This approach is supported by previous studies conducted in the Azores, where PM₁₀ variability has been shown to be strongly influenced by atmospheric transport processes [26]. The consistency of the NO₂ response across these independently defined regimes supports the robustness of the classification approach.

The analysis of wind speed further strengthens the physical interpretation of the results. Months classified as continental transport regimes were systematically associated with higher wind speeds, indicating enhanced atmospheric advection. Although the differences in wind speed were not statistically significant, the agreement between increased wind intensity and elevated NO₂ concentrations provides converging evidence for the role of large-scale transport. This coherence between independent variables is particularly relevant in low-variability environments, where individual signals may be weak but physically consistent.

It is important to emphasize that the absence of statistical significance does not preclude the existence of a physically meaningful relationship. In remote marine environments, background concentrations are low and variability is limited, reducing the statistical power of classical hypothesis tests. In such cases, consistent directional changes observed across multiple variables (NO₂ and wind speed) can provide meaningful evidence of underlying atmospheric processes.

The Azores region, located between major continental emission regions, is particularly sensitive to long-range transport processes. Air masses reaching the archipelago can carry trace amounts of reactive nitrogen from distant sources, leading to subtle but detectable variations in background NO₂ levels. This interpretation is consistent with previous studies conducted in the Azores, which have linked multiscale variability in atmospheric trace gases to large-scale atmospheric forcing [27] and have shown that surface pollutant concentrations, including NO₂, can be modulated by synoptic-scale circulation patterns such as the North Atlantic Oscillation [28]. In addition, similar variability has been reported for other atmospheric indicators measured in remote island environments, including ambient gamma radiation, where fluctuations have been associated with meteorological conditions and large-scale transport processes [29]. The results presented here are therefore consistent with the conceptual understanding of the North Atlantic as a transition zone between continental influence and marine background conditions. These findings are also consistent with previous observational studies conducted in remote marine environments, where NO_x variability

has been linked to large-scale atmospheric transport processes [30], reinforcing the broader applicability of the patterns observed in this study.

Some limitations should be acknowledged. The classification of transport regimes is based on PM_{10} as a proxy variable and does not explicitly resolve air-mass origin. Wind data were only available for the period 2018–2024, limiting the temporal overlap with the full NO_2 record. In addition, the use of monthly averages, while necessary to ensure data completeness and statistical robustness, may smooth short-term variability associated with individual transport events.

Future work could incorporate air-mass trajectory analysis, chemical transport modelling, or higher temporal resolution data to better resolve the mechanisms underlying the observed variability. Such approaches would allow a more direct attribution of NO_2 variations to specific source regions and transport pathways.

Overall, the results provide consistent, though not statistically significant, evidence that background NO_2 variability at this remote North Atlantic site is influenced by atmospheric transport regimes. These findings contribute to improving the interpretation of reactive nitrogen behavior in marine boundary layer environments and highlight the importance of long-term observational datasets for detecting subtle but physically meaningful atmospheric signals.

5. Conclusions

This study examined the variability of background NO_2 concentrations at a remote North Atlantic site (Faial, Azores) over the period 2015–2024. The results indicate that NO_2 levels remained consistently low, reflecting the dominance of background marine conditions in this region.

A comparison between background and continental transport regimes revealed a consistent increase in NO_2 concentrations during months influenced by continental air masses. Although these differences were not statistically significant, the observed patterns were coherent and physically consistent with transport-related variability.

The combined analysis of NO_2 and wind speed suggests that atmospheric transport plays a role in modulating background reactive nitrogen levels at this site. These findings highlight the importance of long-term observations in remote marine environments for identifying subtle atmospheric signals that may not be detectable through statistical tests alone.

Overall, this study contributes to improving the understanding of reactive nitrogen variability in the North Atlantic and reinforces the value of insular monitoring stations for studying background atmospheric composition.

Author Contributions: “Conceptualization, M.G.M.; methodology, M.G.M. and H.C.V.; software, M.G.M.; validation, M.G.M. and H.C.V.; formal analysis, M.G.M.; investigation, M.G.M.; resources, H.C.V.; data curation, M.G.M. and H.C.V.; writing—original draft preparation, M.G.M.; writing—review and editing, M.G.M. and H.C.V.; visualization, H.C.V.; supervision, M.G.M.; project administration, M.G.M. All authors have read and agreed to the published version of the manuscript.”

Funding: This research received no external funding. The article processing charge (APC) was waived by the publisher.

Data Availability Statement: The air quality data used in this study (NO_2 and PM_{10}) are publicly available from the Agência Portuguesa do Ambiente (APA) through the QualAr platform. The datasets were obtained from the Faial background monitoring station (Espalhafatos, Azores) and can be accessed at: https://qualar.apambiente.pt/qualar/dados_horarios.php. Meteorological data (wind speed) were obtained from the Alto do Cabouco station of the Azores Hydrometeorological Network, available at <https://redehidro.ambiente.azores.gov.pt/>. This data is available upon request from the corresponding regional authorities.

Acknowledgments: The authors acknowledge the Agência Portuguesa do Ambiente (APA) for providing access to air quality data through the QualAr platform, as well as the regional authorities responsible for the Azores Hydrometeorological Network for the provision of meteorological data from the Alto do Cabouco station. The

authors also thank all institutions involved in the maintenance and operation of these monitoring networks, whose efforts ensure the availability of high-quality environmental data for scientific research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NO ₂	Nitrogen dioxide
PM ₁₀	Particulate Matter with an aerodynamic diameter less than or equal to 10 micrometers
Nr	Reactive nitrogen
NO _x	Nitrogen oxides
NO	Nitric oxide
SO ₂	Sulfur dioxide
O ₃	Ozone

References

1. Galloway, J.N.; Townsend, A.R.; Erisman, J.W.; Bekunda, M.; Cai, Z.; Freney, J.R.; Martinelli, L.A.; Seitzinger, S.P.; Sutton, M.A. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* **2008**, *320*, 889–892. <https://doi.org/10.1126/science.1136674>
2. Fowler, D.; Coyle, M.; Skiba, U.; Sutton, M.A.; Cape, J.N.; Reis, S.; Sheppard, L.J.; Jenkins, A.; Grizzetti, B.; Galloway, J.N.; Vitousek, P.; Leach, A.; Bouwman, A.F.; Butterbach-Bahl, K.; Dentener, F.; Stevenson, D.; Amann, M.; Voss, M. The global nitrogen cycle in the twenty-first century. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **2013**, *368*, 20130164. <https://doi.org/10.1098/rstb.2013.0164>
3. Seinfeld, J.H.; Pandis, S.N. *Atmospheric Chemistry and Physics*, 3rd ed.; Wiley: 2016.
4. Cooper, O.R.; Parrish, D.D.; Ziemke, J.; Balashov, N.V.; Cupeiro, M.; Galbally, I.E.; Gilge, S.; Horowitz, L.; Jensen, N.R.; Lamarque, J.-F.; et al. Global distribution and trends of tropospheric ozone: An observation-based review. *Elem. Sci. Anth.* **2014**, *2*, 000029. <https://doi.org/10.12952/journal.elementa.000029>
5. Monks, P.S.; Granier, C.; Fuzzi, S.; Stohl, A.; Williams, M.L.; Akimoto, H.; Amann, M.; Baklanov, A.; Baltensperger, U.; Bey, I.; Blake, N.; Blake, R.S.; Carslaw, K.; Cooper, O.R.; Dentener, F.; Fowler, D.; Fragkou, E.; Frost, G.J.; Generoso, S.; Ginoux, P.; Grewe, V.; Guenther, A.; Hansson, H.C.; Henne, S.; Hjorth, J.; Hofzumahaus, A.; Huntrieser, H.; Isaksen, I.S.A.; Jenkin, M.E.; Kaiser, J.; Kanakidou, M.; Klimont, Z.; Kulmala, M.; Laj, P.; Lawrence, M.G.; Lee, J.D.; Liousse, C.; Maione, M.; McFiggans, G.; Metzger, A.; Mieville, A.; Moussiopoulos, N.; Orlando, J.J.; O'Dowd, C.D.; Palmer, P.I.; Parrish, D.D.; Petzold, A.; Platt, U.; Pöschl, U.; Prévôt, A.S.H.; Reeves, C.E.; Reimann, S.; Rudich, Y.; Sellegri, K.; Steinbrecher, R.; Simpson, D.; ten Brink, H.; Theloke, J.; van der Werf, G.R.; Vautard, R.; Vestreng, V.; Vlachokostas, C.; von Glasow, R. Atmospheric composition change—global and regional air quality. *Atmos. Environ.* **2009**, *43*, 5268–5350. <https://doi.org/10.1016/j.atmosenv.2009.08.021>
6. Duncan, B.N.; Lamsal, L.N.; Thompson, A.M.; Yoshida, Y.; Lu, Z.; Streets, D.G.; Hurwitz, M.M.; Pickering, K.E. A space-based, high-resolution view of notable changes in urban NO_x pollution around the world (2005–2014). *J. Geophys. Res. Atmos.* **2016**, *121*, 976–996.
7. Tørseth, K.; Aas, W.; Breivik, K.; Fjaeraa, A.M.; Fiebig, M.; Hjellbrekke, A.G.; Lund Myhre, C.; Solberg, S.; Yttri, K.E. Introduction to the European Monitoring and Evaluation Programme (EMEP). *Atmos. Chem. Phys.* **2012**, *12*, 5447–5481.
8. Parrish, D.D.; Lamarque, J.-F.; Naik, V.; Horowitz, L.; Shindell, D.T.; Staehelin, J.; Derwent, R.; Cooper, O.R.; Tanimoto, H.; Volz-Thomas, A. Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes. *Atmos. Chem. Phys.* **2014**, *14*, 4723–4738.
9. Logan, J.A. Nitrogen oxides in the troposphere: Global and regional budgets. *J. Geophys. Res.* **1983**, *88*, 10785–10807. <https://doi.org/10.1029/JC088iC15p10785>
10. Lamarque, J.-F.; et al. Historical and future trends in global tropospheric ozone and nitrogen oxides. *Atmos. Chem. Phys.* **2010**, *10*, 7017–7037.

11. Stohl, A. Characteristics of atmospheric transport into the Arctic troposphere. *J. Geophys. Res.* **2006**, *111*, D11306. <https://doi.org/10.1029/2005JD006888>
12. Huntrieser, H.; et al. Lightning-produced NO_x in the tropical troposphere. *Atmos. Chem. Phys.* **2011**, *11*, 109–125.
13. Lelieveld, J.; Dentener, F.J. What controls tropospheric ozone? *J. Geophys. Res.* **2000**, *105*, 3531–3551.
14. Carpenter, L.J.; et al. Reactive nitrogen in the marine boundary layer. *Phil. Trans. R. Soc. A* **2012**, *370*, 1195–1215.
15. Lee, J.D.; Moller, S.J.; Read, K.A.; Lewis, A.C.; Mendes, L.; Carpenter, L.J. Year-round measurements of nitrogen oxides and ozone in the tropical North Atlantic marine boundary layer. *J. Geophys. Res. Atmos.* **2009**, *114*, D21302. <https://doi.org/10.1029/2009JD011878>
16. Hurrell, J.W. Decadal trends in the North Atlantic Oscillation. *Science* **1995**, *269*, 676–679. <https://doi.org/10.1126/science.269.5224.676>
17. Trigo, R.M.; Osborn, T.J.; Corte-Real, J.M. The North Atlantic Oscillation influence on Europe: Climate impacts and associated physical mechanisms. *Clim. Res.* **2002**, *20*, 9–17. <https://doi.org/10.3354/cr020009>
18. Keeling, C.D.; et al. Atmospheric CO₂ variations at Mauna Loa. *Tellus* **1976**, *28*, 538–551. <https://doi.org/10.3402/tellusa.v28i6.11322>
19. Carpenter, L.J.; Fleming, Z.L.; Read, K.A.; et al. Seasonal characteristics of tropical marine boundary layer air measured at the Cape Verde Atmospheric Observatory. *J. Atmos. Chem.* **2010**, *67*, 87–140. <https://doi.org/10.1007/s10874-011-9206-1>
20. Vestreng, V.; et al. Evolution of NO_x emissions in Europe. *Atmos. Chem. Phys.* **2009**, *9*, 1503–1520.
21. Wilcoxon, F. Individual comparisons by ranking methods. *Biometrics Bulletin* **1945**, *1*, 80–83.
22. European Parliament and Council. Directive 2008/50/EC on ambient air quality and cleaner air for Europe. *Off. J. Eur. Union* **2008**, *L152*, 1–44.
23. Howarth, R.W. Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae* **2008**, *8*, 14–20. <https://doi.org/10.1016/j.hal.2008.08.015>
24. Tian, X.-P.; Wang, D.; Wang, Y.-Q.; Gao, Z.-Q.; Tian, C.-G.; Bi, X.-L.; Ning, J.-C. Long-term variations and trends of tropospheric and ground-level NO₂ over typical coastal areas. *Ecol. Indic.* **2024**, *164*, 112163. <https://doi.org/10.1016/j.ecolind.2024.112163>
25. Graham, A.M.; Pope, R.J.; Chipperfield, M.P.; Dhomse, S.S.; Pimlott, M.; Feng, W.; Singh, V.; Chen, Y.; Wild, O.; Sokhi, R.; Beig, G. Quantifying effects of long-range transport of NO₂ over Delhi using back trajectories and satellite data. *Atmos. Chem. Phys.* **2024**, *24*, 789–806. <https://doi.org/10.5194/acp-24-789-2024>
26. Meirelles, M.G.; Vasconcelos, H.C. Physical–statistical characterization of PM₁₀ and PM_{2.5} concentrations and atmospheric transport events in the Azores during 2024. *Earth* **2025**, *6*, 54. <https://doi.org/10.3390/earth6020054>
27. Meirelles, M.G.; Vasconcelos, H.C. Multiscale variability of atmospheric CO₂ at the Azores: Detecting seasonal and decadal oscillations. *Atmosphere* **2025**, *16*, 1308. <https://doi.org/10.3390/atmos16111308>
28. Vasconcelos, H.C.; Ferreira, A.C.; Meirelles, M.G. Synoptic-scale modulation of surface O₃, NO₂, and SO₂ by the North Atlantic Oscillation in São Miguel Island, Azores (2017–2021). *Pollutants* **2025**, *5*, 27. <https://doi.org/10.3390/pollutants5030027>
29. Meirelles, M.G.; Vasconcelos, H.C. Ambient gamma radiation as an atmospheric indicator in a remote oceanic island environment: Long-term variability and meteorological controls. *Atmosphere* **2026**, *17*, 264. <https://doi.org/10.3390/atmos17030264>
30. Lee, J.D.; Moller, S.J.; Read, K.A.; Lewis, A.C.; Mendes, L.; Carpenter, L.J. Year-round measurements of nitrogen oxides and ozone in the tropical North Atlantic marine boundary layer. *J. Geophys. Res. Atmos.* **2009**, *114*, D21302. <https://doi.org/10.1029/2009JD011878>

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.