

Article

Air Quality at Ponta Delgada City (Azores) Is Unaffected so Far by Growing Cruise Ship Transit in Recent Years

Filipe Bernardo ^{1,2,3,4,*} , Patrícia Garcia ^{1,3,4}  and Armindo Rodrigues ^{1,2} ¹ Faculty of Sciences and Technology, University of the Azores, 9501-801 Ponta Delgada, Portugal² IVAR, Institute of Volcanology and Risks Assessment, University of the Azores, 9501-801 Ponta Delgada, Portugal³ Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências, Universidade de Lisboa (cE3c-FC-ULisboa), 1749-016 Lisboa, Portugal⁴ Centre for Ecology, Evolution and Environmental Changes, Azorean Biodiversity Group (cE3c-GBA), University of the Azores, 9501-801 Ponta Delgada, Portugal

* Correspondence: address: filipe.mt.bernardo@uac.pt

Abstract: The ease of travel allowed by contemporary means of long-range transportation has brought increasingly higher numbers of visitors to remote and relatively undisturbed insular territories. In a framework of environmental conservation of the natural patrimony, sustainably accommodating touristic flooding and the associated polluting footprint poses a demanding challenge. Over the past decade, Ponta Delgada, the largest city of the mid-Atlantic Azores archipelago, has become a hotspot for transatlantic cruise ship (CS) lines in spring and autumn. CSs are substantial contributors to the emissions of greenhouse gases (GHG), as well as hazardous sulphur (SO_x) and nitrogen (NO_x) oxides. It is hereby retrospectively investigated whether the background levels of air pollutants were raised following the CS influx at Ponta Delgada, which conventionally displays great air quality. The daily CS traffic at the local harbor was associated with the daily concentrations of air pollutants (SO₂, O₃, NO₂, NO_x, PM₁₀ and PM_{2.5}), monitored by the local urban background monitoring station (~1.3 km northwards). Exceedances above daily legislated limits from 2013 until 2020 only occurred sporadically for PM₁₀ and PM_{2.5}, often during episodes of natural dust storms. No major correlation was found between CS parameters with the recorded values of pollutants, although a noticeable signal of NO_x increase of southern origin is observed during spring days with CS presence. Daily data suggest CS influx has not strongly influenced background air quality. A near-source, real-time monitoring network should be implemented in the city to provide the necessary spatial and temporal resolution for tracking short-term fluctuations in air pollutants during CS arrivals and departures.

Keywords: air pollutants; air quality monitoring; diesel; cruise ships; island tourism

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1. Introduction

Socio-economic development is exceptionally challenging in insular regions, given their isolation, confinement, territorial fragmentation, complex orography, restricted land availability and limited supply of natural resources [1–3]. Travel accessibility, allowed by contemporary means of long-range transportation, has allowed for increasingly higher numbers of visitors to reach remote islands around the world, long sought after as adventurous destinations [4]. Capitalizing on island touristic appeal has created the opportunity to grow their weak economies, compensating for the exceeding costs of development inherent to insularity and dependence on subsidization from central governments [5,6]. However, sustainably accommodating the demands of touristic flooding in a framework of environmental conservation of the natural patrimony of insular territories is a primary concern. The propensity for tourism massification is a vector of dramatic landscape changes and aggravates the contaminating footprint from anthropogenic pollution [6,7].

Coastal and marine tourism provided by the cruise industry remains one of the fastest-growing economic sectors, reaching almost 30 million passengers worldwide in 2019 [8]. Considering their massive size, luxuries, and population aboard, akin to floating hotels, long-distance travels and reliance on combustion engines, cruise ships (CS) have become principal pollution sources in marine ecosystems and substantial contributors to the emissions of greenhouse gases (GHG) such as CO₂ and CH₄, as well as sulphur (SO_x) and nitrogen (NO_x) oxides [9,10]. It was recently estimated that CS NO_x emissions in Europe are equivalent to 15% of the yearly volume emitted by Europe's whole passenger car fleet. Moreover, CSs belonging to the world's largest luxury cruise operator were responsible for 10× more SO_x in ports from European coasts than 260 million European cars [11]. CS engines can use up to 10× as much fuel as a standard cargo bulk carrier [12]. Even the most efficient CS currently operating emit up to twice as much CO₂ per passenger per kilometre (CO₂/pax-km) than common passenger jet planes [13]. The increasing environmental and health impacts of cruise tourism warrant closer monitoring and regulation [14].

There is a vast and ever-growing body of evidence sustaining the global concern about the adverse effects and burden of disease associated with air pollution. Tropospheric, outdoors air pollution, especially particulate matter, is a leading cause of premature death globally and is linked to a higher risk of congenital anomalies [15,16]. Thurston et al. (2017) provide an overview of diseases, conditions and biomarkers affected by pollutants such as gaseous and particulate emissions from traffic activity. Multiple organs are deeply affected, contributing to respiratory diseases, lung cancer, pneumonia and decreased lung function, cardiovascular diseases, arrhythmia and congestive heart failure, neurodegenerative diseases, metabolic diseases such as diabetes, high blood pressure, deep vein thrombosis, decreased birthweight or premature birth, cutaneous conditions/skin ageing and decreased sperm quality. The disease burden from short-term exposure is not to be neglected either, particularly the exacerbations in patients suffering from chronic respiratory diseases such as asthma, COPD and cystic fibrosis [17].

In view of the magnitude of CS emissions for coastal air pollution, the main goal of this article is to retrospectively investigate whether the onset of CS influx had a significant effect on urban background levels of regularly monitored air pollutants. The setting is Ponta Delgada city, remotely located in the mid-Atlantic Azores archipelago, whose population habitually enjoys clean air favoured by the relatively smaller scale human activities and the oceanic surrounding, allowing for a greater regeneration capacity of the atmosphere. Nevertheless, a precedent of concern with preserving air quality is motivated by the increase in emissions of atmospheric pollutants resulting from the intensification of agricultural and touristic activities in the region [18]. Data since 1990 for the Azores show that fossil fuel combustion, mainly for transportation and electricity, has contributed to a 73% increase in CO₂ and 45% in CH₄ emissions [19]. Legal standards for preserving ambient air quality and protecting the atmosphere in the Azores follow the conjugation of European Commission directives and their adaptation to the national legal framework, namely EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe. This framework requires that specific goals are met to preserve air quality and take corrective action when air quality is worsening, hence the pertinence of continuously monitoring the impact of new or increasing emission sources in the region [20,21].

In this setting, naturally characterized by lower levels of disturbance, it is reasonable to conjecture that CS influx, as a relevant incoming source of fuel emissions, may have a more nefarious impact over this cleaner atmospheric background, as opposed to a major continental city, whose baseline levels of air pollution are inherently higher. With this purpose, the daily CS traffic at the local harbor was associated with the daily average concentrations of air pollutants monitored by the air quality monitoring station. The data analysis, ranging from 2013 to 2020, not only looks for exceedances to local legislated limits for the protection of the environment and human health, but also for the degree of variation in the concentrations of air pollutants during CS seasons.

2. Methods

2.1. Setting

Ponta Delgada is the main city of São Miguel Island, the largest and most populated of the Azores archipelago, a group of peaks of volcanic origin rising from the Mid-Atlantic Ridge. The city is located on the southwest coast (Figure 1), in between two of its central volcanoes with caldera (Sete Cidades and Fogo), within Picos fissural volcanic system. The island is under a typical temperate oceanic seasonal climate, generally characterized by mild temperatures, high air humidity and a distinct wet season (October–March) [20,22]. Given the altitudinal slope of the island, Ponta Delgada's coastal location is relatively warmer and drier than sites at higher elevations, especially during summertime. The city is also inserted in a geomorphological unit lacking relevant water streams [23]. Daily records of meteorological data registered by the Ponta Delgada air quality monitoring station, in the years between 2013 and 2020, show annual mean temperatures of around 17 to 18 °C, annual mean air humidity around 74 to 79%, and total annual accumulated precipitation between 400 and 800 mm. The average wind speed in the windier season (October–May) is 2.39 m/s as opposed to 1.70 m/s during summer months, while predominant wind directions were from southwest (225°) to northwest (315°) in 46% of daily records and southeast (135°) to southwest (225°) in 38% of daily records. In Figure 1, it is shown that Ponta Delgada city directly faces the ocean in orientation from SE to SW. São Gonçalo (SG) air quality monitoring station (of the urban background type) is located about 1.3 km north of the ship harbor, at an elevation of only 55 m (Figure 1). Consequently, the monitoring station is not only placed on a straightforward pathway from the seafront through the historical centre, without relevant orographic or manmade barriers to obstruct the wind and dispersal of pollutants (most buildings are not higher than 3 floors), but also it is in alignment with the frequently predominant southwestern winds. Hence, on most days of the year, the atmospheric transport of airborne pollutants is not opposed by wind against the SG monitoring station.

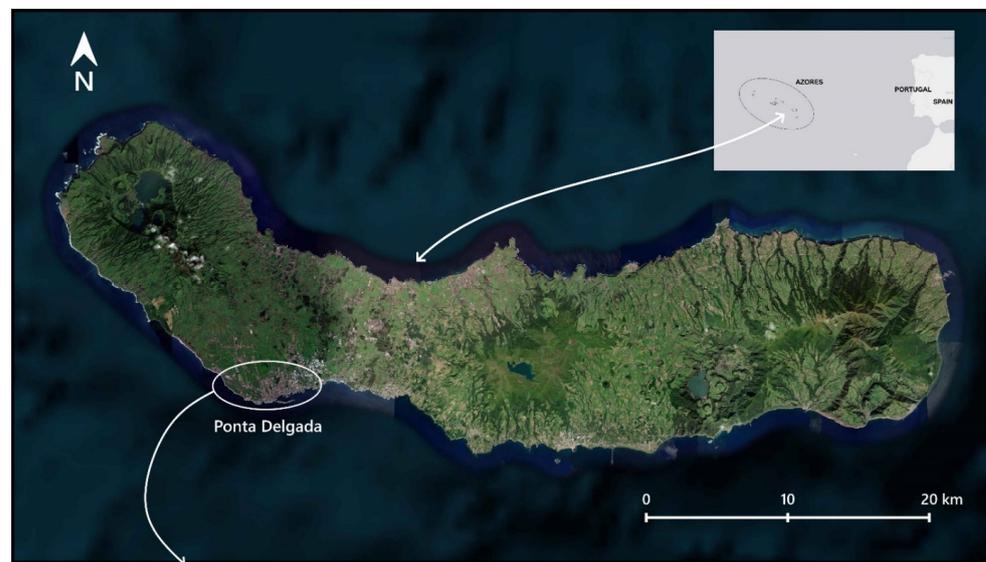


Figure 1. Cont.



Figure 1. Locations of the São Gonçalo air quality monitoring station and the cruise ship terminal at the harbor of the city of Ponta Delgada, São Miguel Island, Azores. Map created with ArcGIS® world imagery online basemap by Esri (attributions provided below the image).

The city centre extends to a radius of about 2 km north of the bay (Figure 1), holding a resident population of 17,304 inhabitants between the three civil parishes within this innermost radius (according to the 2021 census) [24]. Despite being a small city with a stable population number (by mainland standards), the influx of visitors has steadily increased year after year, noticeable by greater crowding at the city centre during peak seasons. This is the consequence of better travel accessibility and the heavy touristic promotion of the Azores to traditional and new markets. Whether by air or by the ocean, Ponta Delgada is the main gateway for visitors to the island and to the rest of the archipelago. The city has become a hotspot for transatlantic CS lines in spring and autumn, especially since the last renovation of the seafront and construction of the cruise terminal in 2008. Since 2015, air transport liberalization has allowed operation by low-cost airlines. The generated transit of aircraft, watercraft and associated road traffic is unprecedented and presents a sustainability challenge for the region. Consequently, transportation is bound to intensify as the major polluting activity in the city, since industrial facilities or other strikingly focal sources of air pollution are located further away.

2.2. Datasets

The two datasets explored for the aim of this study were obtained by the authors in early 2022. Both datasets range from 1 January 2013 to 31 December 2020. The daily movement of cruise ships at Ponta Delgada city harbour was provided by Portos dos Açores, S.A. (PA), the entity responsible for the management of the Azorean harbors and marinas. This dataset includes the date of docking, CS name and flag, ship length, as well as the total number of passengers and crew in route. The authors also further obtained publicly available data of the CS gross tonnage (GT), type of fuel powering the main engines, combined power (kW) of the main engines and the year of first service deployment, neatly compiled by nedcruise.info [25]. In cases of retrofitted ships, the most updated data was considered. The grouping of ships by GT follows an informal classification defined by Marine Insight [26].

The compilation of the average daily concentrations of air pollutants and weather parameters by the air quality monitoring station were provided by *Direção Regional do Ambiente e Alterações Climáticas do Governo dos Açores*, the regional governmental branch dealing with the environment and climate change. The station has certified automatic analyzers continually monitoring the concentrations ($\mu\text{g}/\text{m}^3$) of SO_2 by UV fluorescence, O_3 by UV absorption, NO_x by chemiluminescence and $\text{PM}_{10} + \text{PM}_{2.5}$ by beta radiation method. The analyzers can calculate mean values every 15 min, which are then validated before official hourly and daily mean concentrations are calculated. Only the daily means for each pollutant were provided to the authors. Meteorological parameters monitored include wind velocity (m/s) and direction ($^\circ$), temperature ($^\circ\text{C}$), solar radiation intensity (W/m^2), precipitation (mm H_2O) and relative air humidity (%). All are provided as daily means except for precipitation which is defined as total daily precipitation [20]. Wind direction was converted in an ordinal variable by assuming a maximum value of 4 if the wind is originating from SE (135°) to SW (225°) (from the south towards the monitoring station to the north), and a minimum value of 1 if the wind is originating from NW (315°) to NE (45°) towards the south.

2.3. Data Analysis

The total number of daily and yearly exceedances to legislated limits were counted from 2013 to 2020, except in the case of NO_x for which a daily limit is not established. The number of daily exceedances on the subset of days with CS docking was also accounted for. The percentage of daily records for each year is provided for each monitored pollutant. Missing daily records are most often attributable to anomalous analytical errors or downtime for equipment maintenance. The differences in mean values of the pollutant concentrations between periods with and without CS docking were checked by Welch's *t*-test with Cohen's *d* effect size. Mean values are reported followed by the standard error of the mean (mean \pm SEM). Correlations between variables were tested by Spearman's rank correlation coefficient (ρ). The levels of statistical significance were set at $p \leq 0.05$ (*), $p \leq 0.01$ (**) and $p \leq 0.001$ (***). A linear regression model was tested for the relationship between CS features. A principal component analysis was carried out to overview the pattern of correlations between pollutant concentrations, weather parameters and CS features. Factors were assumed to be correlated, thus a method for oblique rotation was used, direct oblimin with Kaiser normalization and a Delta of 0. The variable loadings on each principal component were obtained for the obliquely rotated factor solution. Statistical analysis was performed with JASP v0.16.3 [27], IBM SPSS Statistics v.28.0.1.0 [28] and the latest MS Office Excel [29].

3. Results and Discussion

3.1. Cruise Ships

In the 2922 days between 1 January 2013 and 31 December 2020, 414 days (14%) had CS visits at Ponta Delgada city harbour, 58 of which (2%) had more than 1 CS docking simultaneously. In this period, 490 visits were made by 135 different CSs, 95 of them with at least one returning visit (Figure 2), mostly distributed between two main docking seasons: spring season, usually peaking in April with 20–25 CSs; autumn season, usually peaking in October with 5 to 10 CSs (Figure 3). A growing trend is observed over the years, reaching its highest peak in the year 2018 with 76 CS dockings carrying 117,798 visitors (passengers and crew). This increasing tendency was interrupted by a sharp decline in 2020 due to the restrictions imposed by the COVID-19 pandemic. In total, over the span of these 8 years, close to 1 million CS visitors passed by Ponta Delgada harbor, representing an unprecedented mark highlighting the contemporary touristic demand at the remote Azores archipelago.

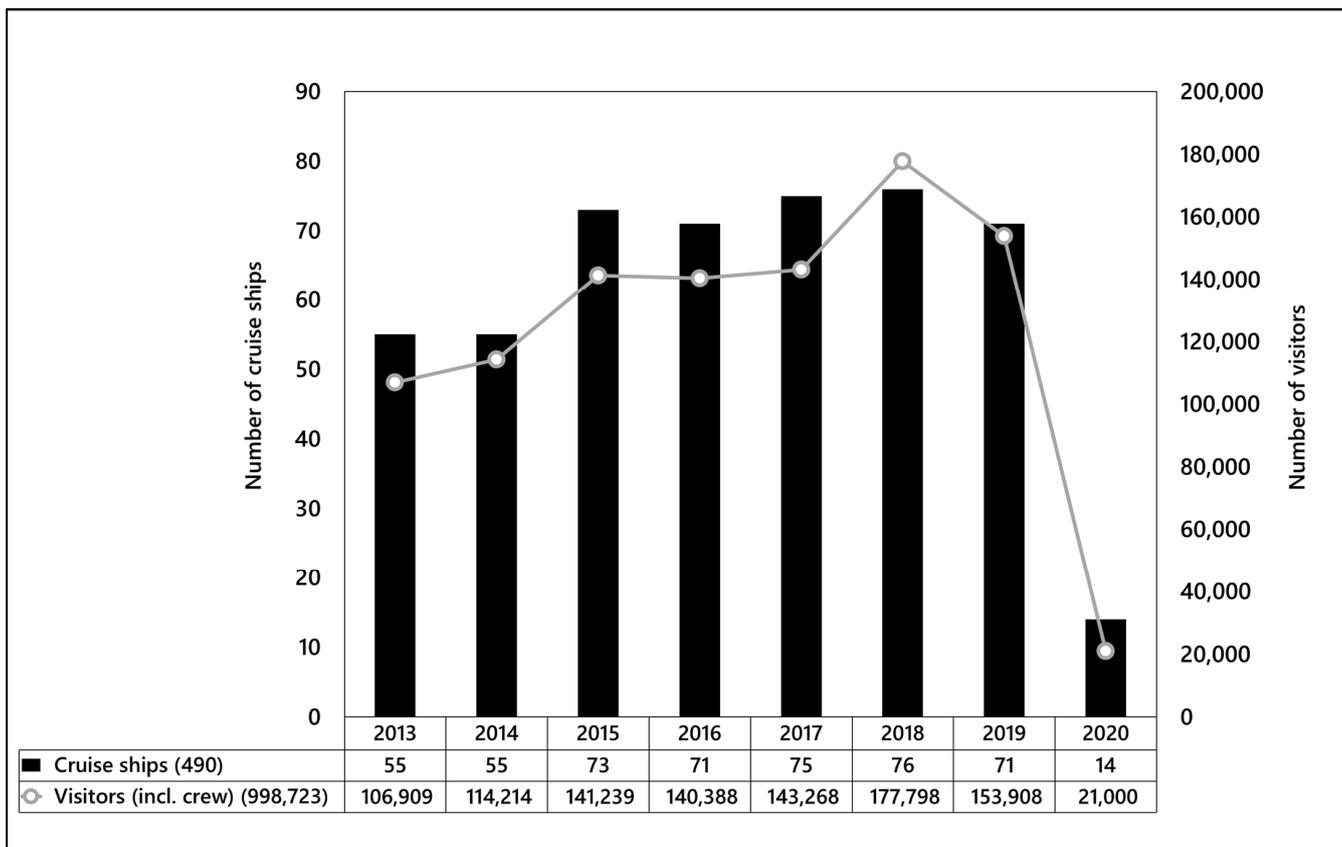


Figure 2. Yearly number of cruise ships and visitors (passengers + crew) which docked at Ponta Delgada city harbor in the period between January 2013 to December 2020.

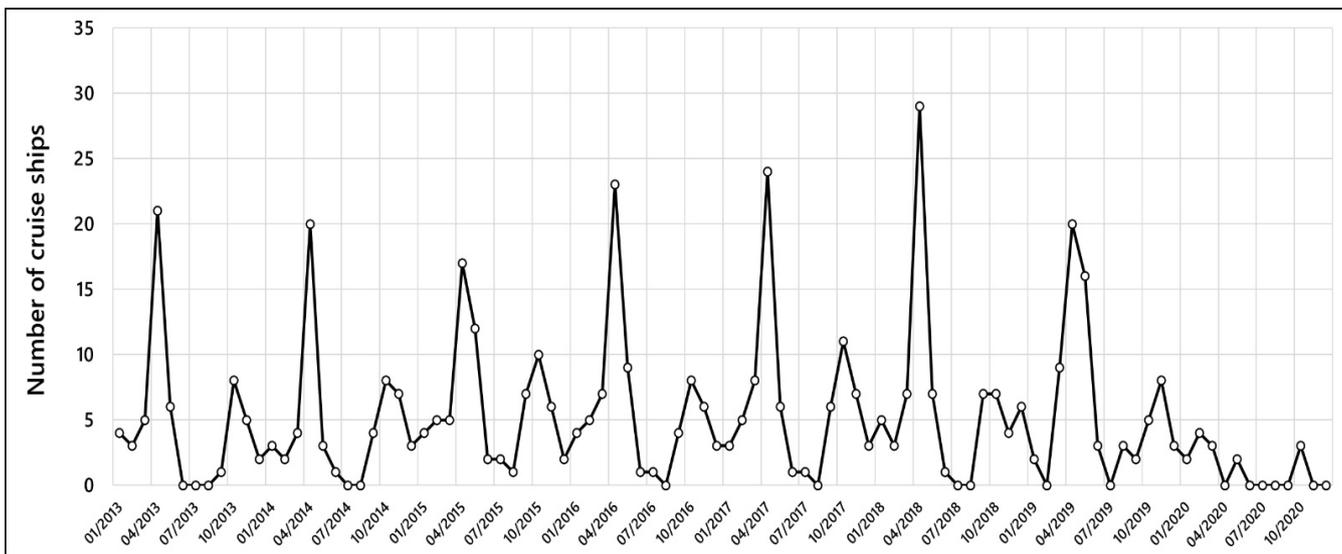


Figure 3. Seasonal pattern of cruise ship docking at Ponta Delgada city harbor displayed by the monthly number of ships in the period between January 2013 and December 2020.

The vast majority (119) of the 135 visiting CSs have both main and propulsion diesel engines, with an additional 9 propelled by wind sails but possessing also auxiliary propulsion diesel engines, leaving only a minority of 4 CSs powered by gas turbines. Therefore, exhaust emissions from diesel hydrocarbon combustion are expected to be the main concern regarding potential air pollution associated with the influx of CSs, potentially including

each of the pollutants monitored by SG station (PM₁₀ and PM_{2.5}, SO₂, NO_x and O₃) [30]. A primary factor determining a ship’s diesel consumption is the combined power of the main engines (EP), which is dependent on the volume (GT) of the ship they must support. A model of linear regression was found to best fit the relationship between GT and EP, validating the use of the latter as a proxy variable for diesel consumption ($F(1, 397) = 3099.955$, $p < 0.001$, $EP = 0.546GT + 2911.879$; $R^2 = 0.886$). Except for 2015 and 2017, over half of the CS dockings at Ponta Delgada harbor are classified mid-sized or greater in terms of GT (>50,000) (Figure 4). Docking by mega cruise ships (>135,000 GT) has also risen over the years, reaching its highest percentage of 13.2% in the peak year of 2018.

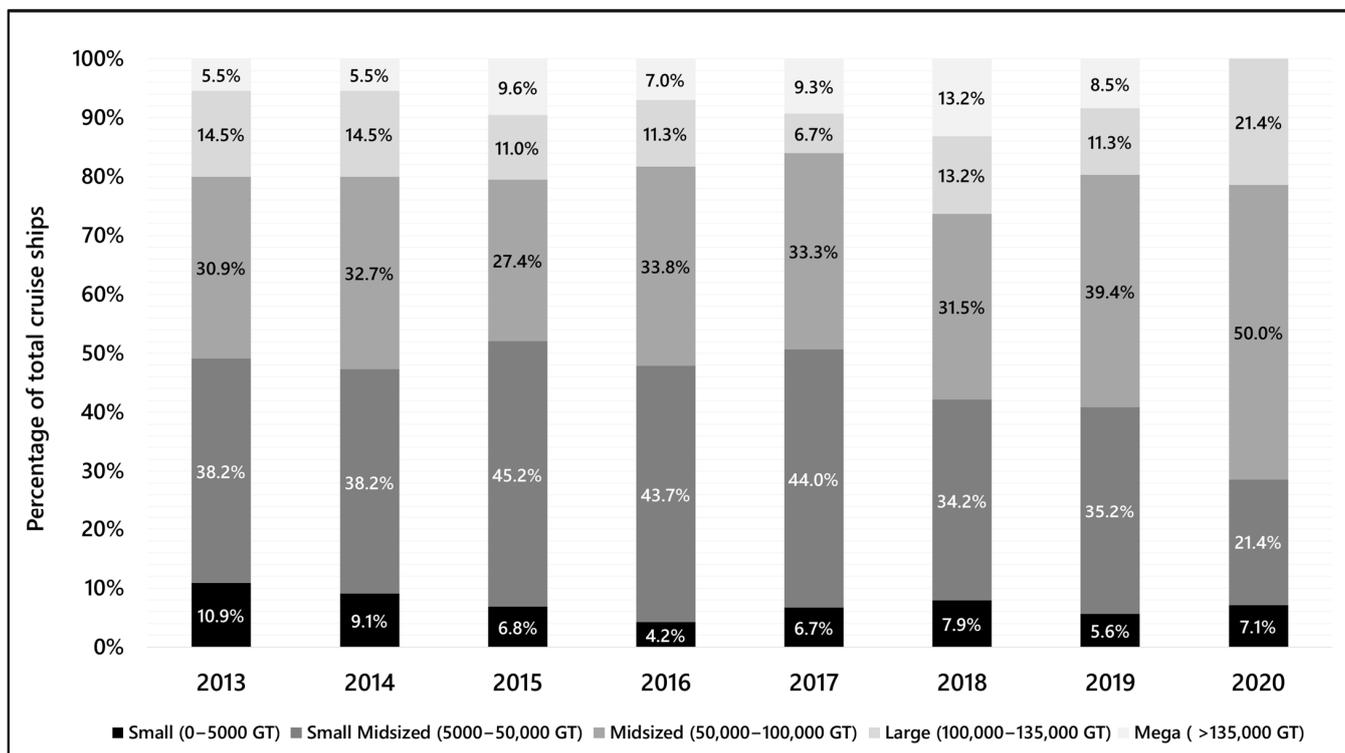


Figure 4. Annual proportions of cruise ships, classified by gross tonnage (GT), which docked at Ponta Delgada in the period between January 2013 and December 2020.

3.2. Compliance with Air Quality Monitoring Data

Table 1 summarizes SG monitoring data by pollutant according to exceedances over legislated limits applicable to the Autonomous Region of the Azores from 2013 until 2020. During the periods with daily records of each year, SO₂, O₃, and NO₂ daily values have never exceeded daily limits. Their subsequent yearly average values (as well as NO_x) also remained far below yearly limits. It is noteworthy that the lowest daily maximum values and the lowest yearly averages for O₃, NO_x and NO₂ were observed in 2020, suggesting that the interruption of the normal patterns of urban activity, during the COVID-19 pandemic restrictions, somewhat contributed to reducing the emission of these pollutants.

Table 1. Daily and yearly exceedances of the legislated limits ($\mu\text{g}/\text{m}^3$) for each of the monitored air pollutants from 2013 until 2020.

	Year	Daily Records	Daily Maximum	Daily Limit	Daily Exceedances	Exceedances on CS Days	Yearly Average	Yearly Limit	Yearly Exceedances
SO ₂	2013	78.9%	3.3	>125	0	0	0.8	>20	0
	2014	99.2%	2.4		0	0	0.8		0
	2015	98.6%	24		0	0	0.9		0
	2016	97.8%	3.7		0	0	0.9		0
	2017	92.6%	9.1		0	0	1		0
	2018	98.6%	3.2		0	0	0.9		0
	2019	100.0%	3.8		0	0	1		0
	2020	86.3%	3.3		0	0	0.9		0
O ₃	2013	91.5%	104.6	>120	0	0	67.1	>120	0
	2014	99.2%	101.6		0	0	61.1		0
	2015	98.1%	108.1		0	0	64.2		0
	2016	99.7%	99.5		0	0	62.5		0
	2017	95.1%	106.8		0	0	63.6		0
	2018	99.7%	105		0	0	63		0
	2019	100.0%	110.9		0	0	61.3		0
	2020	99.7%	81.8		0	0	50		0
NO _x	2013	79.7%	31.7	Not applicable			7.3	>30	0
	2014	98.4%	24.7				6.5		0
	2015	96.2%	31.1				7.1		0
	2016	96.2%	35.5				6.8		0
	2017	96.2%	26.5				7		0
	2018	57.5%	43.1				8		0
	2019	97.3%	41.7				7.3		0
	2020	100.0%	24				5.1		0
NO ₂	2013	79.7%	25.2	>200	0	0	5.6	>40	0
	2014	98.4%	19.3		0	0	4.8		0
	2015	96.2%	21		0	0	5.5		0
	2016	96.2%	25.2		0	0	4.8		0
	2017	96.2%	19.6		0	0	4.9		0
	2018	57.5%	28.1		0	0	5.8		0
	2019	97.3%	24.4		0	0	5.7		0
	2020	100.0%	18.4		0	0	3.9		0
PM ₁₀	2013	97.3%	55	>50	1	0	11.8	>40	0
	2014	99.2%	103.7		4	0	11.6		0
	2015	96.4%	51.6		2	1	5.5		0
	2016	92.9%	125.1		1	0	10.7		0
	2017	97.0%	55.8		1	0	11.3		0
	2018	94.5%	61.6		2	0	12.7		0
	2019	98.1%	50.7		1	1	13.9		0
	2020	98.9%	88.4		3	0	13.9		0

Table 1. Cont.

	Year	Daily Records	Daily Maximum	Daily Limit	Daily Exceedances	Exceedances on CS Days	Yearly Average	Yearly Limit	Yearly Exceedances
PM _{2.5}	2013	78.90%	37.1	>20	1	0	5.9	>7	0
	2014	94.50%	60.7		6	0	5.8		0
	2015	83.30%	32.6		4	1	5.4		0
	2016	85.50%	73.4		4	0	5.2		0
	2017	93.70%	25.7		2	0	5		0
	2018	77.80%	33.3		4	1	6.6		0
	2019	69.60%	29.5		5	1	7.3		1
	2020	85.50%	55.2		6	0	7		0

Regarding particulate matter, a total of 15 out of 2813 daily exceedances (>50 µg/m³) were recorded for PM₁₀, only 2 were coincident with CS docking in Ponta Delgada, whereas 32 out of 2411 daily exceedances (>20 µg/m³) were recorded for PM_{2.5}, only 3 of which were on days with CS docking (Figure 5). A small exceedance of the yearly average occurred for PM_{2.5} in 2019, although possibly skewed by the incomplete dataset with over 30% of missing daily PM_{2.5} records in that year. Unlike O₃, NO_x and NO₂, PM daily maximum and yearly average concentrations were not particularly decreased in 2020, further corroborating that the sporadic exceedances of PM levels at Ponta Delgada are more influenced by natural long-range transport of Saharan dusts over the Atlantic than by emissions from local sources [20,31]. Overall, background air quality over these 8 years remained well within legislated safety limits for the environment and human health.

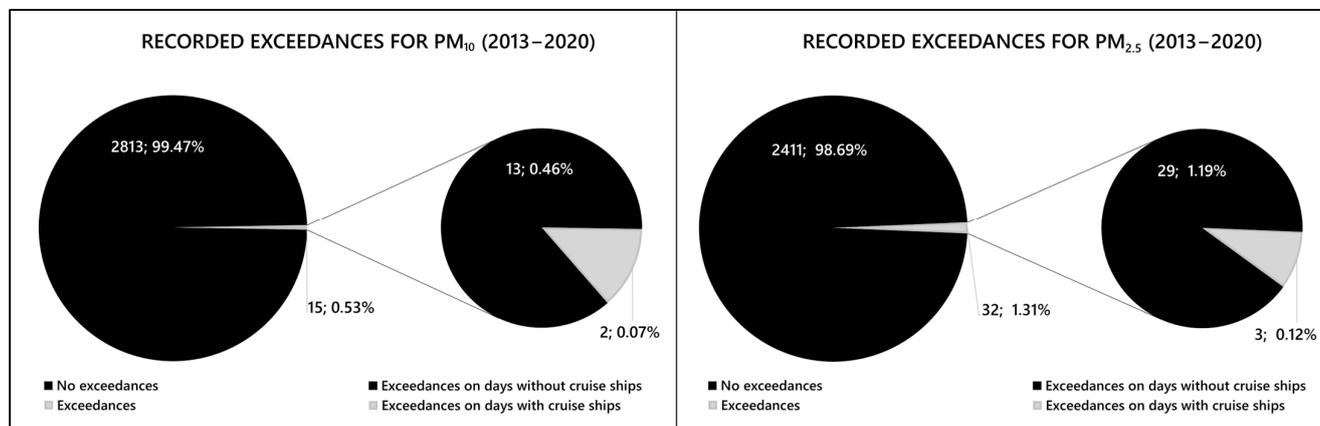


Figure 5. Daily exceedances of PM₁₀ and PM_{2.5} recorded in the period between January 2013 and December 2020.

3.3. Cruise Ship Presence and Air Pollutants

Table 2 presents an overview of the pattern of correlations between pollutant concentrations, weather parameters and CS combined engine power for the full 8-year datasets (Barlett’s $\chi^2(78) = 12113.998, p \leq 0.001; KMO = 0.580$). Three principal components (PC) were extracted with eigenvalues higher than 1.5, cumulatively accounting for 50% of variance. The presence of CSs has no effect in contributing to positive loadings of SO₂, PM₁₀ and PM_{2.5}. Meanwhile, O₃, NO_x and NO₂ load most positively when CS engine power also loads positively, suggesting that the second PC might be expressing a faint association of CS docking with the variations of O₃ and NO_x at the city centre. On the other hand, PM₁₀ and PM_{2.5} load most positively when the wind velocity is highest and originates from the south quadrant (SE-SW), matching the southern origin of the Saharan dusts and conveying

the wind's assistance in carrying these particles towards the monitoring station. SO₂ is indifferent to either CS presence or weather variables.

Table 2. Results of the principal component analysis. Eigenvalues, variance, and cumulative variance are shown for the three principal components, along with the variable loadings (sorted by decreasing size) for either component on the obliquely rotated factor solution. Loadings above 0.5 or below −0.5 are marked with (*).

	PC1	PC2	PC3
Eigenvalue	2.73	2.15	1.63
Variance (%)	21.02	16.56	12.56
Cumulative Variance (%)	21.02	37.58	50.14
Variables	Loadings		
NO ₂	−0.952 *	0.253	0.091
NO _x	−0.945 *	0.209	0.103
Wind Velocity	0.608 *	0.320	0.304
SO ₂	−0.199	−0.070	−0.008
Precipitation	0.064	−0.003	0.006
Air Temperature	0.055	−0.895 *	0.036
O ₃	0.358	0.744 *	−0.034
Solar Radiation	0.210	−0.523 *	−0.399
Combined Engine Power	−0.053	0.205	−0.121
PM ₁₀	0.198	0.110	0.892 *
PM _{2.5}	0.185	0.073	0.891 *
Wind Direction	−0.147	−0.174	0.329
Relative Humidity	−0.037	−0.051	0.328

Gauging fluctuations in atmospheric levels of pollutants on days with CS docking, even within compliance with legislated limits, requires the cognizance that: (i) over 81% of the total CS visits between 2013 and 2020 are concentrated in either the spring season (54%) or the autumn season (27%) (Figure 3); (ii) pollutant levels naturally fluctuate throughout the year with seasonality. This fluctuation is verified cyclically in the full datasets from 2013 to 2020, even if excluding data points from days with CS docking. Except for PM_{2.5}, whose levels remain statistically even throughout the year, the other pollutants show a seasonal pattern, with higher daily mean concentrations of O₃ and PM₁₀ in the spring season (March to May), while SO₂, NO₂ and NO_x are more elevated in the autumn season (September to November) (Kruskal–Wallis H + Dunn's post-hoc test not shown for the sake of conciseness).

Hence, given the patently seasonal pattern of CS visits at Ponta Delgada, a direct contrast between days with and without CS docking is more legitimate if considering only data points within the same season, thus minimizing the bias of natural variability if comparing days from different seasons. In harmony with the PCA overview, CS engine power shows a modest positive correlation with mean daily concentrations of O₃, NO_x and NO₂ in the spring season, a correlation which is weakened in the autumn season (Table 3). Within the spring season, daily mean concentrations of all pollutants were increased on days with CS docking, although only NO₂ and NO_x showed a significant difference (with a small effect size) (Table 4). The same tendency is observed in the autumn season except for PM₁₀ and PM_{2.5}, but no significant differences were found.

Table 3. Spearman correlation coefficients and corresponding significance *p* values associating daily air pollutant concentrations with the combined engine power of all CSs which docked on the same day. Significant correlations are flagged at $p \leq 0.05$ (*), $p \leq 0.01$ (**) and $p \leq 0.001$ (***). Total period: data from January to December of each year. CS spring season: data from March to May of each year; CS autumn season: data from September to November of each year.

Correlation		Spearman's ρ	SO ₂	NO ₂	NO _x	O ₃	PM ₁₀	PM _{2.5}
Combined Engine power	Total Period	Coefficients	0.010	0.085 ***	0.084 ***	0.144 ***	0.001	−0.001
		<i>p</i> value	0.595	<0.001	<0.001	<0.001	0.939	0.953
	CS Spring Season	Coefficients	0.040	0.116 **	0.129 **	0.133 **	0.006	0.012
		<i>p</i> value	0.341	0.004	0.001	<0.001	0.883	0.774
	CS Autumn Season	Coefficients	0.023	0.083 *	0.093 *	0.075 *	−0.022	−0.023
		<i>p</i> value	0.537	0.035	0.018	0.045	0.556	0.567

Table 4. Mean atmospheric pollutant concentrations ($\mu\text{g}/\text{m}^3$) of days with cruise ships versus days without cruise ships in the spring and autumn docking seasons from 2013 until 2020. Significant mean differences within each line are flagged at $p \leq 0.01$ (**) (independent samples Welch's *t*-test + Cohen's *d* effect size). Spring season: data from March to May of each year; CS autumn season: data from September to November of each year.

Pollutant	Season	Days with no Cruise Ships		Days with Cruise Ships		Effect Size
		n	Mean ± S.E.M	n	Mean ± S.E.M	
SO ₂	Spring	483	0.822 ± 0.027	172	0.823 ± 0.039	−0.002
	Autumn	588	0.938 ± 0.024	120	0.994 ± 0.057	−0.094
NO ₂	Spring	520	3.896 ± 0.105 **	188	4.515 ± 0.212 **	−0.232
	Autumn	539	6.012 ± 0.174	110	6.539 ± 0.348	−0.137
NO _x	Spring	520	5.184 ± 0.125 **	188	6.274 ± 0.335 **	−0.285
	Autumn	539	7.911 ± 0.218	110	8.912 ± 0.481	−0.198
O ₃	Spring	516	73.500 ± 0.754	196	76.042 ± 1.227	−0.148
	Autumn	599	58.921 ± 0.545	123	61.217 ± 1.205	−0.172
PM ₁₀	Spring	513	12.417 ± 0.263	188	12.670 ± 0.496	−0.039
	Autumn	590	11.992 ± 0.290	122	11.688 ± 0.634	0.043
PM _{2.5}	Spring	475	5.962 ± 0.153	171	6.191 ± 0.278	−0.066
	Autumn	503	5.804 ± 0.174	106	5.551 ± 0.374	0.066

A more detailed analysis of the daily mean concentrations by the predominant wind quadrant (Figure 6) further confirms the increase in NO_x/NO₂ in days with CS docking. Both in the spring and autumn seasons, nitrogenous emissions are overall higher for any quadrant except the opposing NW-NE when CS are present. Their mean concentration values are noticeably skewed by wind originating from NE-SE (by as much as 3.4 $\mu\text{g}/\text{m}^3$ in spring) and SE-SW (by as much as 1.94 $\mu\text{g}/\text{m}^3$ in autumn), thus matching a possible influence of the CS terminal as emission source at the south of the monitoring station. SO₂ mean concentrations also show slight skewing to the NE-SE quadrant in days with CS docking for both seasons, though by thinner margins which were otherwise unnoticed. O₃ is likewise generally higher on days with CS docking, however without a clear origin from any specific quadrant. As for PM₁₀ and PM_{2.5}, mean concentrations are generally the same or slightly higher on days without CS docking, with a noticeable skewing in the NE-SE quadrant in the spring season, matching consistently with the southeastern arrival of the Saharan dusts and thus, once again, displaying no relationship with the presence of CSs.

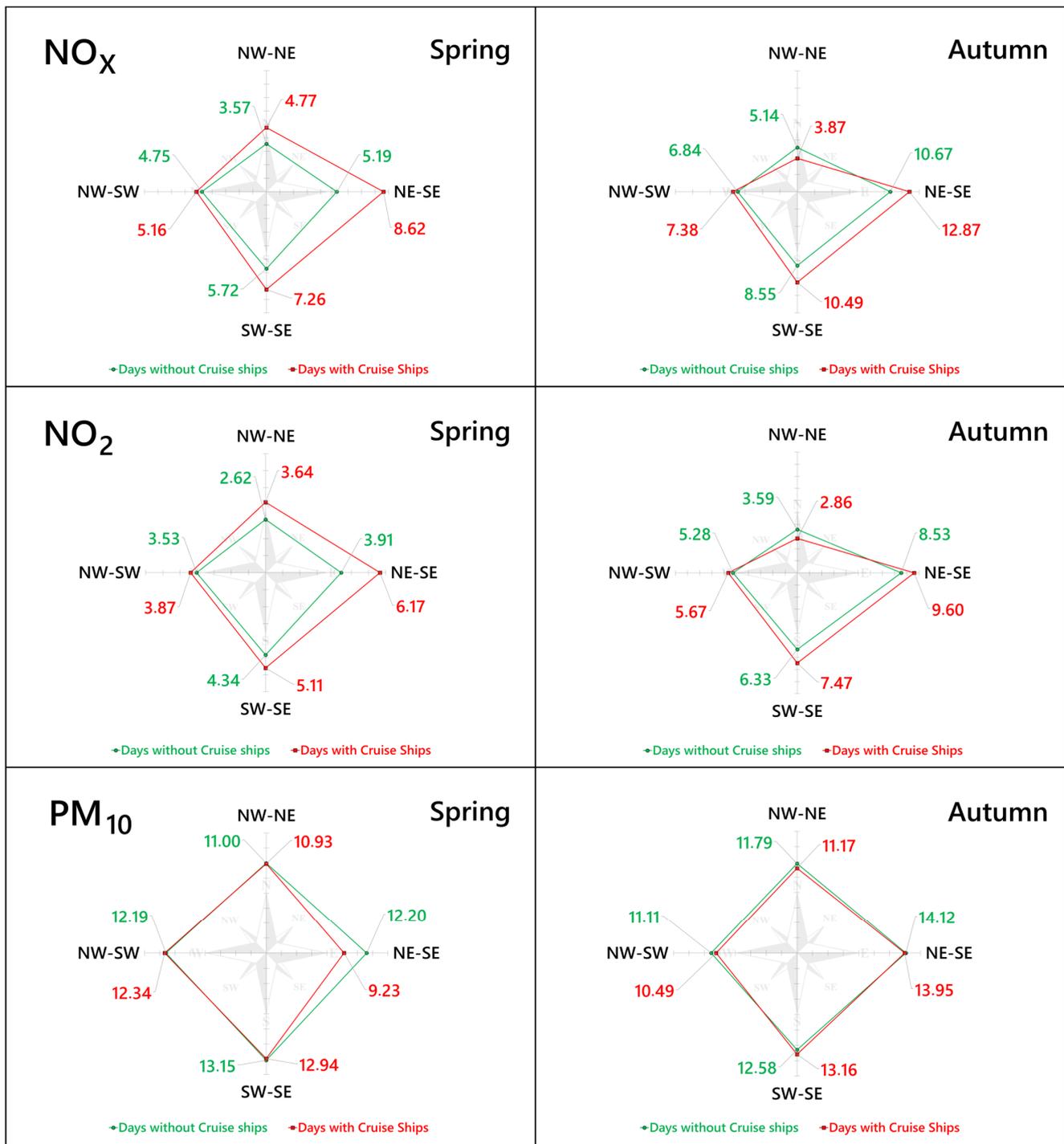


Figure 6. Cont.

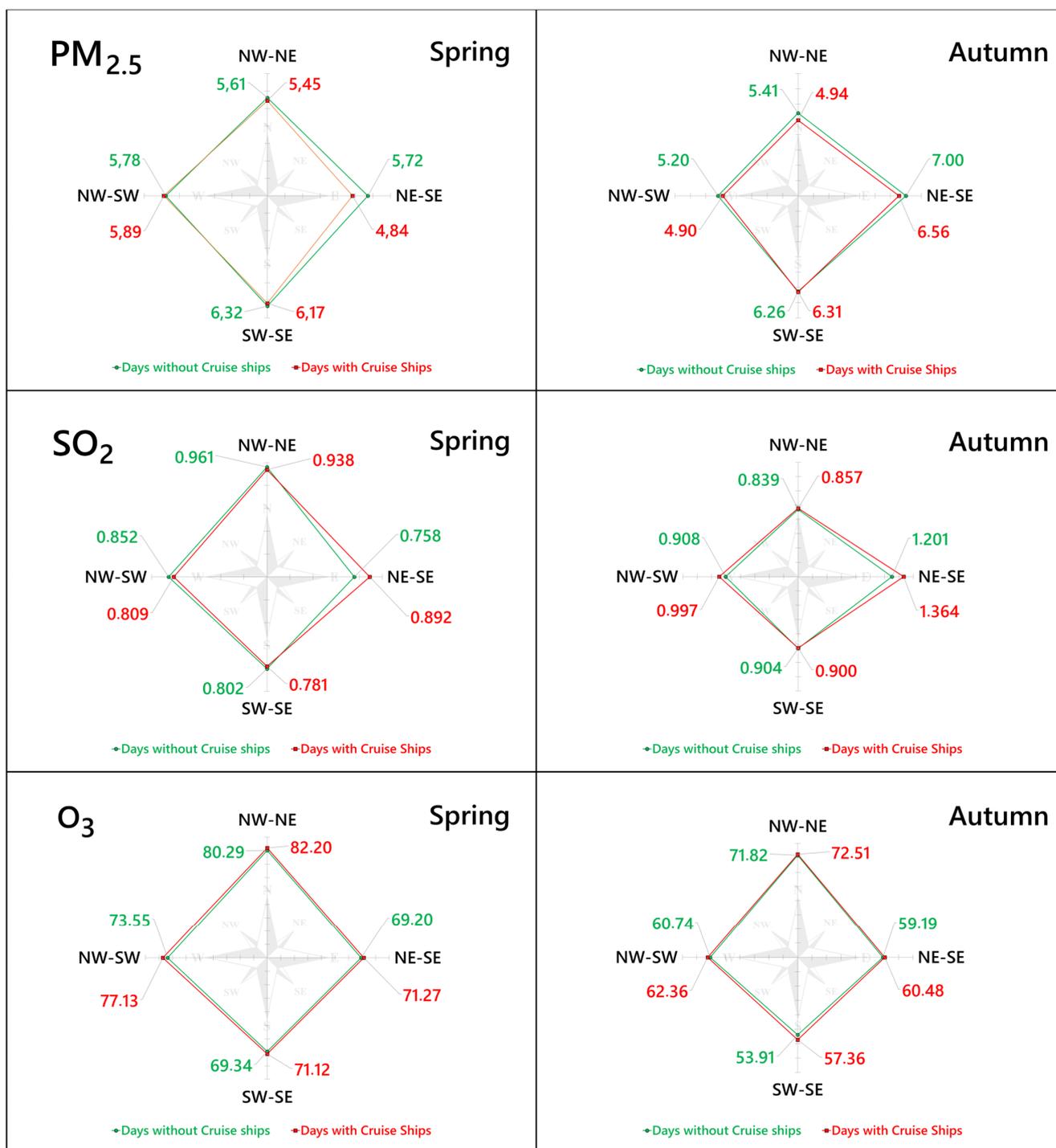


Figure 6. Mean daily concentrations of NO_x, NO₂, PM₁₀, PM_{2.5}, SO₂ and O₃ for the corresponding daily predominant wind quadrant in the spring (March to May) and autumn (September to November) seasons between the years 2013 and 2020.

Though noteworthy in the context of historically clean air quality of the study area, these are rather small increments for SO₂, O₃ and NO_x, far below the respective legislated limits for the protection of the environment and human health. At most, CS traffic, at current levels, had a marginal contribution to the overall regular patterns of background air quality of the city, mostly with nitrogenous emissions. Nevertheless, this early signal is not to be neglected [32], bearing in mind that these are 24-h average concentrations from background monitoring (with significant dissipation over distance) rather than real-

time and near-source monitoring. Further increases in the concentrations of NO_x and tropospheric O_3 might become worrisome due to their nefarious environmental impacts. The former has a long residence time in the environment and contributes to acid rains, vegetation damage, eutrophication phenomena, depletion of the ozone layer, greenhouse effect, formation of tropospheric ozone and particular matter [33,34]. The latter is also a greenhouse gas contributing to global warming, with potentially adverse effects on natural vegetation and crop productivity by reducing plant photosynthetic activity [35–37].

CS influx at Ponta Delgada is bound to continue escalating. As of September 2022, the total number of CS stopovers at the Azores harbours has already surpassed the previous maximum recorded in 2017. It is foreseen that, by the end of 2022, for the first time in history, over 200,000 maritime passengers will have visited the Azores within a single year [38]. Collecting real-time data for short-time pollutant concentrations at a distance gradient funnelling nearer the harbour is fundamental for evaluating with robustness the concrete contribution of CS emissions, notwithstanding the increasingly efficient CS emission control systems (in modern and retrofitted ships) and the adoption of cleaner (e.g., low-S marine diesel) or alternative (LNG) fuels [39,40]. Such a refined monitoring approach would lessen the dissipation of pollutants over distance, while the temporal window could be narrowed to periods of CSs arrival and departure. CS engines are usually not on full throttle outside the deep ocean and remain in low-performance eco mode during the docking period [12]. Just like rush hour road traffic, monitoring data is particularly relevant in shorter, specific periods of the day when the rate of emissions and the degree of exposure of the population are highest. Previous studies have shown that the impact of cruise ship emissions can be relevant for short-time concentration levels [32]. It is also a fitting scenario for applying isotopic analysis, with the use of biomonitors, to disentangle between overlapping emission sources of SO_x or NO_x over time, an approach that has been widely successful even when total elemental concentrations are low [18,41–44].

4. Conclusions

Data at the daily level suggest the growing CS transit at Ponta Delgada has not meaningfully influenced background levels of air pollutants at the city centre in a manner that would deviate from the usual patterns of air quality corresponding to local urban activities. The concentrations of nitrogen oxides are the only ones that display a clear though slight association with the presence of CS, but far from jeopardizing the daily maximum limit. The emissions of combustion by-products from diesel engines into the atmosphere are likely mitigated by the intermittency of CS engine loads (running on low-performance mode during most of the docking period), and the adoption of low-sulphur diesel fuel and emission control systems. Dissipation over the distance to the monitoring station could also further dilute the contribution of CS emissions to the overall urban background levels of air pollution. Touristic inflow is bound to continue in remote destinations worldwide and thus, appropriate air quality monitoring routines are warranted to correspond to the maritime, aerial and road transit. Future assessments should complement urban background monitoring with near-source, real-time monitoring networks providing the necessary spatial and temporal resolution for tracking short-term fluctuations in air pollutants during busier periods of CS arrivals and departures, as well as discriminating their specific influence amongst other urban sources. Eventually, this will be useful for gauging the efficacy of measures to reduce atmospheric emissions, most notably the adoption of alternative fuels.

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