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A Year-Long Measurement and Source Contributions of Volatile Organic Compounds in Nanning, South China

Ying Wu [1], Zhaoyu Mo [1], Qinqin Wu [2], Yongji Fan [1], Xuemei Chen [1], Hongjiao Li [1], Hua Lin [1], Xishou Huang [1], Hualei Tang [3], Donglan Liao [3], Huilin Liu [1,*] and Ziwei Mo [4,*]

[1] Guangxi Academy of Environmental Sciences, Nanning 530022, China
[2] School of Ecological Environment Protection, Guangxi Eco-Engineering Vocational & Technical College, Liuzhou 545004, China
[3] Bureau of Ecology and Environment, Nanning 530022, China
[4] School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai 519082, China
* Correspondence: gxhkydqzx@163.com (H.L.); mozw7@mail.sysu.edu.cn (Z.M.); Tel./Fax: +86-0771-2799461 (H.L.)

Abstract: Severe ozone (O_3) pollution has been recorded in China in recent years. The key precursor, volatile organic compounds (VOCs), is still not well understood in Nanning, which is a less developed city compared to other megacities in China. In this study, a year-long measurement of VOCs was conducted from 1 October 2020 to 30 September 2021, to characterize the ambient variations and apportion the source contributions of VOCs. The daily-averaged concentration of VOCs was measured to be 26.4 ppb, ranging from 3.2 ppb to 136.2 ppb across the whole year. Alkanes and oxygenated VOCs (OVOCs) were major species, contributing 46.9% and 25.2% of total VOC concentrations, respectively. Propane, ethane, and ethanol were the most abundant in Nanning, which differed from the other significant species, such as toluene (3.7 ppb) in Guangzhou, ethylene (3.8 ppb) in Nanjing, and isopentane (5.5 ppb), in Chengdu. The positive matrix factorization (PMF) model resolved six source factors, including vehicular emission (contributing 33% of total VOCs), NG and LPG combustion (19%), fuel burning (17%), solvent use (16%), industry emission (10%), and biogenic emission (5%). This indicated that Nanning was less affected by industrial emission compared with other megacities of China, with industry contributing 12–50%. Ethylene, m/p-xylene, butane, propylene, and isoprene were key species determined by ozone formation potential (OFP) analysis, which should be priority-controlled. The variations in estimated OFP and observed O_3 concentrations were significantly different, suggesting that VOC reactivity-based strategies as well as meteorological and NO_x effects should be considered collectively in controlling O_3 pollution. This study presents a year-long dataset of VOC measurements in Nanning, which gives valuable implications for VOC control in terms of key sources and reactive species and is also beneficial to the formulation of effective ozone control strategies in other less developed regions of China.

Keywords: VOCs; ambient concentration; source apportionment; PMF; South China

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1. Introduction

The tropospheric ozone (O_3) is formed through the reactions of volatile organic compounds (VOCs) and nitrogen oxides in the presence of sunlight, which could pose a great threat to human health and the ecosystem. The high concentrations of surface ozone observed on local and regional scales has given rise to wide public attention in different areas around the world [1]. As the hotspot of VOCs and NO_x emissions, China has been facing severe ozone pollution during recent years [2]. The national monitoring network shows that the ozone is increasing in most of the cities [3]. Numerous studies have made enormous efforts to distinguish the effect of meteorology, emission, and chemical reaction on ozone variations using multiple techniques, including numerical simulations [4], monitoring data analysis [5], and intensive field measurements [6]. Under the influence of similar regional

meteorological conditions, the temporal and spatial variations in ozone concentrations are still significant due to the local and inhomogeneous emissions of VOCs and NO_x. In urban areas, the main sources of NO_x are vehicles and industrial fossil combustion, while the sources of VOCs are more complicated and difficult to accurately determine. Therefore, understanding the VOCs' characteristics and quantifying their sources are of the utmost important for local government and policy-makers, in order to formulate effective O_3 control strategies.

VOC measurements have been reported in different areas around the world, such as the highly urbanized city Los Angeles [7], the petrochemical city Houston [8], the oil- and natural-gas-abundant city Colorado [9] in the US; the metropolitan cities Paris in France [10] and Seoul, South Korea [11]; the high-latitude city Greenland in Denmark [12]; and the port megacity Istanbul in Turkey [13]. Yang et al. [14] provides a global review of VOC source apportionment based on highly time-resolved monitoring data from 2015 to 2021. It is found that vehicle emissions and fuel evaporation are the primary contributors to ambient VOCs, while contributions of solvent use, the petrochemical industry, combustion emissions, and industrial emissions vary depending on the energy structure and industrial distributions in each specific city.

With VOC monitoring instruments developing rapidly and the urgent demand for VOC emission control to mitigate ozone pollution in China, ambient VOC measurements and source apportionments have been conducted in various cities during the last two decades. In the 2000s, VOC measurements were mainly carried out in the cities of Beijing in the North China Plain (NCP), Shanghai in the Yangtze River Delta (YRD), and Guangzhou in the Pearl River Delta (PRD) regions [15–18]. However, as the VOCs are identified as the critical pollutants in ozone pollution control, plenty of studies have been carried out to understand the VOC characteristics in different cities in the past decade, including Lanzhou [19] (Jia et al., 2016), Tianjin [20] (Liu et al., 2016a), Wuhan [21] (Lyu et al., 2016), Jinan [22] (Liu et al., 2016b), Changsha [23] (Liu et al., 2017), and Chengdu [24] (Xiong et al., 2021). However, most of these studies analyzed the VOC sources based on measurements in a period of several weeks or months, which only partly reflects the VOC variability in the specific region.

Nanning, located in Guangxi Province, South China, is a less developed city compared with other megacities of China. It has also been suffering from increasing ozone pollution in recent years, but VOC measurements are seldom reported. In this study, a year-long measurement of ambient VOCs from 1 October 2019 to 30 September 2020 was conducted in an urban site of Nanning. A total of 106 species were analyzed by an online gas chromatography–mass spectroscopy/flame ionization detector (GC-MS/FID) system to characterize the hourly time-series variations in and apportion the sources of VOCs by the receptor model. Ozone formation potential (OFP) was also discussed to understand the VOC reactivity. In the city of Nanning, whose industrial distribution and energy structure are different from those of metropolises in China, one-year-long VOC measurements are firstly reported. The findings of this study could enrich the ambient VOC measurement and source apportionment studies in China, which is beneficial to the formation of effective strategies for ozone pollution control.

2. Methods

2.1. Field Measurements

The field sampling was conducted at the air quality monitoring station in the urban areas of Nanning, located in South China (Figure 1). Ambient samples were automatically collected on the roof of a six-story building (about 25 m high), which is a typical urban site surrounded by residential buildings and traffic roads but away from direct industrial emissions. The online VOC monitoring instrument operated from 1 October 2020 to 30 September 2021. The ozone was also measured by the ozone analyzer (Model 49i, Thermo Scientific, Waltham, MA, USA) operated by a local environmental agency for supplementary analysis.

Figure 1. The location of the sampling site (the image was retrieved from Google Maps).

2.2. VOC Analysis

The automatically collected samples were analyzed at a one-hour resolution by a commercial online gas chromatography–mass spectroscopy/flame ionization detector (GC-MS/FID) system (EXPEC-2000-MS, Puyu, HangZhou, China). The air sample was dehydrated and concentrated by a cryogenic pretreatment apparatus (−45 °C) and was rapidly desorbed by direct thermal high-temperature desorption (200 °C), and was quickly sent to a capillary column for separation. Flame ionization detector (FID) was used for low-carbon (C2-C5) VOC detection while high-carbon (C6-C12), oxygenated, and halogenated hydrocarbon VOCs, etc., were detected by mass spectrometry (MSD) to obtain accurate qualitative and quantitative determination of each single component. A total of 107 species were identified and determined, including 29 alkanes, 11 alkenes, 1 alkyne, 17 aromatics, 35 halocarbons, 13 OVOCs, and 1 other species (carbon disulfide), as listed in Table S1 of Supplementary Materials. Daily measurements of the gas standard (2 ppb) were conducted to check the system stability. The GC-MS/FID analysis was repeated seven times to calculate the detection limits by injecting a 100 mL sample volume with a five-fold dilution of the 1 ppb gas standard.

2.3. Source Apportionment by PMF

The source contributions of VOCs were quantified by the US EPA PMF 5.0 model. The general principle and functions of the model have been introduced before [25,26]. From a time-series dataset of ambient VOC concentrations x_{ij} (i is the number of sample, j is the number of chemical species), the source profiles f, the number of source factors p, the amount of mass g contributed by each factor to each individual sample, and the residual of each sample/species can be resolved (Equation (1)):

$$x_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \quad (1)$$

The PMF solution minimizes the object function Q based upon the uncertainties (Equation (2)):

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\frac{x_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}}{u_{ij}} \right]^2 \quad (2)$$

The uncertainty u_{ij} of each individual data element was calculated based on Equations (3) and (4):

$$Uncertainty = \frac{5}{6} MDL \quad (concentration \leq MDL), \quad (3)$$

$$Uncertainty = \sqrt{(EF \times concentration)^2 + (MDL)^2} \quad (concentration > MDL), \quad (4)$$

where EF represents the error fraction, which is the precision (%) of each species and MDL is the method detection limit. The hourly VOC data were compiled as input of the PMF model. The species with an S/N ratio larger than 2 were used in the PMF model, ensuring the modeling results were stable and reliable. Six factors were chosen according to the physical interpretations of the factor profiles by examining from four to ten factors. Each test performed 20 base runs to ensure the stability of the PMF solution. The test with minimum of the object function Q was used. The ratio of Q (true) to Q (robust) was 1.1. less than the suggested value 1.5, and F_{peak} = 0.5 was selected for the lowest dQ (robust) by varying the F_{peak} values from −5 to 5. The observed concentrations of total VOCs were resolved by the PMF with determination of coefficient $r^2 > 0.95$. The detailed procedures of determining the number of resolved factors followed the previous studies [26,27].

2.4. Ozone Formation Potential

To evaluate the VOC reactivity in terms of producing O_3 during the measurement period, OFP was calculated by Equation (5) [28]:

$$OFP_i = \sum_{j=0}^{n} C_{ji} \times MIR_j \quad (5)$$

where $C_{j,i}$ is the mass contribution of species j from source i (μg m^{-3}) and MIR_j is the maximum incremental reactivity (MIR) value of species j.

3. Results and Discussion

3.1. VOC Concentrations

During the period between 1 October 2020 and 30 September 2021, a total of 107 species were identified and determined, including 29 alkanes, 11 alkenes, 1 alkyne, 17 aromatics, 35 halocarbons, 13 OVOCs, and 1 other species (carbon disulfide). Figure 2 shows the daily-averaged concentrations of total VOCs. It can be found that the VOC concentration varied significantly across the entire year, ranging from 3.15 ppb to 136.18 ppb, with an average of 26.37 ppb. The high concentrations (up to 100 ppb) of total VOCs mainly occurred in winter (January 2021 to February 2021). In November 2020 and March 2021, we can also observe high VOC concentrations up to 60 ppb to 80 ppb. As shown in Figure 3, the alkanes, alkenes, alkyne, aromatics, and halogenated hydrocarbons were highest in winter. The high concentration is probably due to the meteorological conditions (i.e., low wind speed, stratification, and slow boundary layer growth) that is favorable for pollutant accumulation in winter. The unregulated high VOC emissions could be another reason for such remarkable lifted-up concentrations. It is worth noting that the OVOCs were found to be highest in spring, which could be attributed to the secondary production of OVOCs. Secondary production of OVOCs was also strong in summer, but the dilution effect could lower the concentrations.

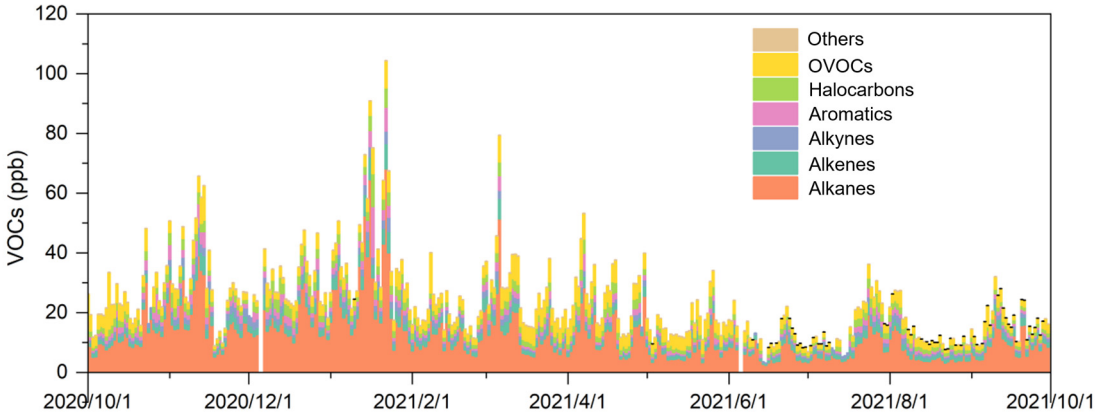

Figure 2. VOC daily-averaged concentrations of VOCs between 1 October 2020 and 30 September 2021.

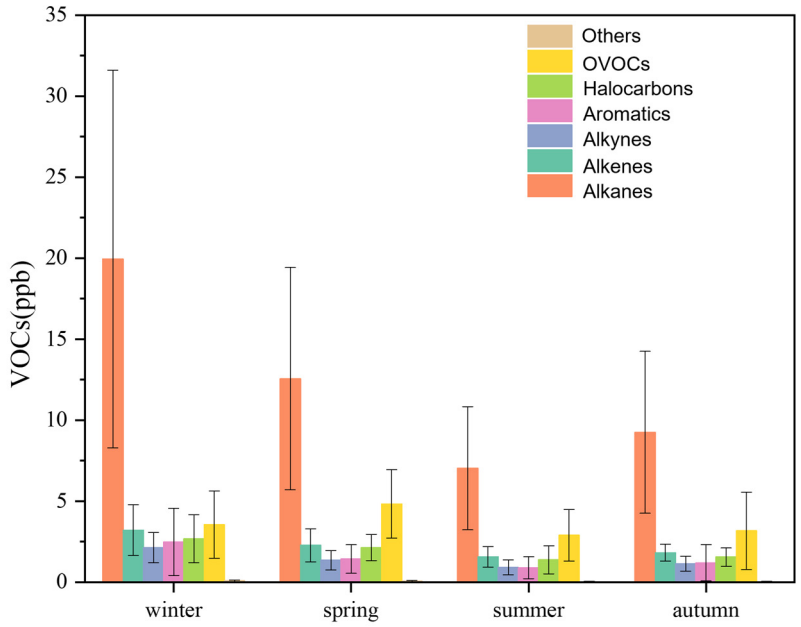

Figure 3. The seasonal variations in the VOC concentrations.

From the time-series of daily-averaged VOC concentrations, it is obvious that alkanes were the dominant species contributing almost half of the total VOCs while other species accounted for the other half. Figure 4 shows the average pattern of the VOC compositions. Alkanes have the highest contributions, representing 46.94% of the total VOCs. The most abundant alkane is propane, with an average concentration of 3.8 ppb. It is followed by OVOCs (25.2%), with the most significant contribution from ethanol (2.84 ppb). Alkenes (8.57%), halocarbons (7.8%), aromatics (6.1%), and alkyne (6.1%) have similar contributions that are in the range of 5%-10%. Ethene (1.45 ppb), dichloromethane (0.6 ppb), benzene (0.38 ppb), and ethyne (1.4 ppb) are the representative species. Other species such as carbon disulfide only contribute 0.2%.

The diurnal patterns of the VOC concentrations are further elaborated in Figure 5. We can see that during the high-VOC-concentration period (November 2022 and January 2021), the high values of VOC concentrations were mainly observed at night-time and in the early morning, while concentrations were relatively low in the afternoon. This phenomenon was widely found in other cities, which resulted from the constant emissions and low boundary layer during the night-time and the chemical reactions and boundary layer growth in the daytime.

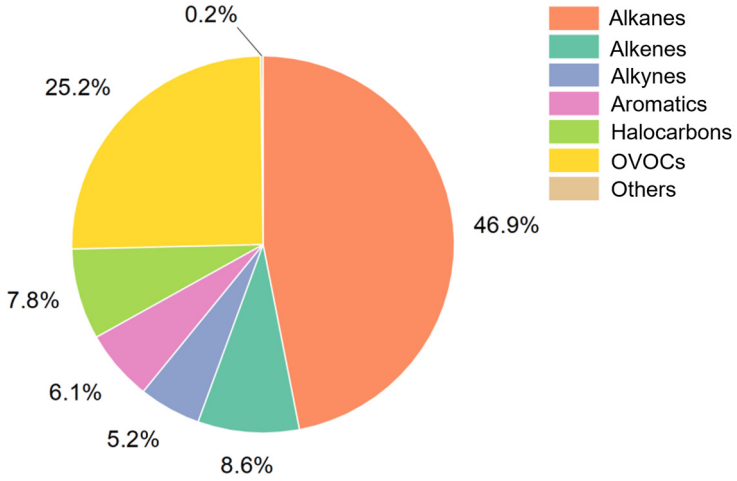

Figure 4. VOC functional group pattern.

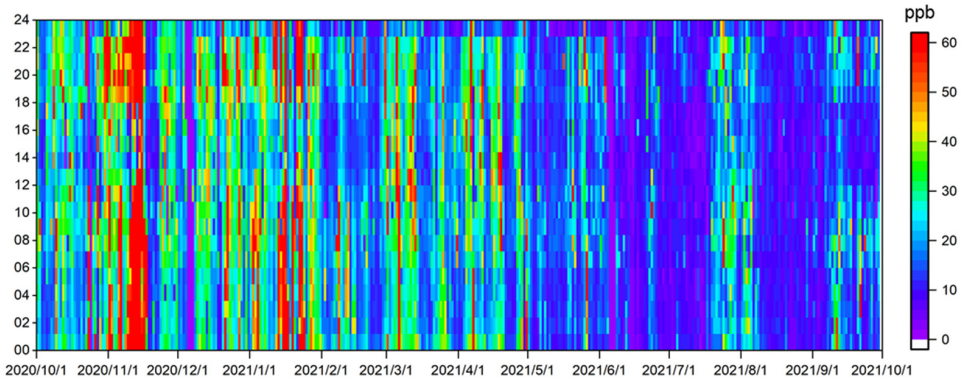

Figure 5. The diurnal patterns of the VOC concentrations.

Table 1 shows the top 10 species of VOCs during the measurement period. Propane was the highest with an average concentration of 3.8 ± 3.6 ppb, followed by ethane (3.2 ± 2.0 ppb), ethanol (2.8 ± 7.1 ppb), n-butane (2.1 ± 1.8 ppb), acetone (1.7 ± 1.4 ppb), ethylene (1.5 ± 0.9 ppb), acetylene (1.4 ± 0.8 ppb), isobutane (1.1 ± 1.0 ppb), isopentane (0.9 ± 0.6 ppb), and isopropyl alcohol (0.7 ± 0.9 ppb). Together with the key aromatic species, i.e., benzene, toluene, and m/p-xylene, we compared the VOC concentrations measured in Nanning with other cities in China (Table 1). The significant species were propane, ethane, ethanol, and n-butane in Nanning. They were all in the range of concentrations measured in other cities. However, there were apparent differences in the dominant species between different cities. The most abundant species were found to be acetylene (5.4 ± 2.9 ppb) and ethylene (4.6 ± 3.0 ppb) in Beijing [15], propane (4.8 ± 2.1 ppb) and toluene (4.7 ± 4.2 ppb) in Shanghai [16], ethane (3.9 ± 1.3 ppb) and toluene (3.7 ± 2.9 ppb) in Guangzhou [29], ethylene (3.8 ± 2.4 ppb) and ethane (3.6 ± 3.3 ppb) in Nanjing [30], ethane (5.2 ppb) and ethylene (2.7 ppb) in Wuhan [21], ethane (3.0 ± 1.8 ppb) and ethylene (2.7 ± 2.6 ppb) in Ningbo [27], and ethane (8.6 ppb) and isopentane (5.5 ppb) in Chengdu [31]. It is shown that the alkane species were dominant in Nanning while aromatics were important in Guangzhou and Shanghai, which are highly industrialized cities, and alkenes were significant in Beijing and Wuhan, which are highly affected by fuel combustion. Ningbo is also high in alkenes, which are contributed by petrochemical production [27]. These features indicated that the VOCs were greatly influenced by the source structures in a specific city. The tracers from industrial and solvent use such as toluene and m/p-xylene were much lower in Nanning because of less industrial activities. Therefore, a city-oriented VOC abatement strategy is needed to better address the air pollution problem.

Table 1. The key species measured in Nanning and other cities in China (unit: ppbv).

Species	Nanning	Beijing	Shanghai	Guangzhou	Nanjing	Wuhan	Ningbo	Chengdu
Propane	3.8 (3.6)	3.6 (2.2)	4.8 (2.1)	3.0 (1.8)	2.0 (1.7)	1.9	2.6 (2.1)	3.7
Ethane	3.2 (2.0)	3.8 (1.7)	--	3.9 (1.3)	3.6 (3.3)	5.2	3.0 (1.8)	8.6
Ethanol	2.8 (7.1)	--	--	--	--	--	--	--
n-Butane	2.1 (1.8)	2.8 (1.7)	2.0 (1.2)	1.9 (1.3)	1.3 (1.1)	1.3	1.5 (1.3)	2.0
Acetone	1.7 (1.4)	--	--	--	--	--	--	4.7
Ethylene	1.5 (0.9)	4.6 (3.0)	--	2.9 (3.3)	3.8 (2.4)	3.3	2.7 (2.6)	4.0
Acetylene	1.4 (0.8)	5.4 (2.9)	--	3.4 (2.3)	3.0 (2.0)	1.9	2.1 (1.7)	4.5
Isobutane	1.1 (1.0)	2.3 (1.4)	1.4 (0.9)	--	1.2 (0.9)	1.1	2.0 (2.1)	1.6
Isopentane	0.9 (0.6)	4.1 (2.5)	2.3 (1.4)	1.9 (2.2)	1.1 (1.0)	1	1.3 (1.7)	5.5
Isopropyl Alcohol	0.7 (0.9)	--	--	--	--	--	--	--
Benzene	0.4 (0.3)	1.8 (0.9)	1.8 (1.2)	--	2.3 (2.2)	1.7	0.7 (0.7)	1.4
Toluene	0.4 (0.3)	3.3 (1.7)	4.7 (4.2)	3.7 (2.9)	1.2 (1.5)	2	1.7 (2.4)	2.3
m/p-Xylene	0.3 (0.3)	2.0 (1.3)	1.4 (1.1)	1.6 (1.4)	0.6 (0.3)	0.4	0.6 (0.9)	1.0
Reference	This study	Song et al. [15]	Cai et al. [16]	He et al. [29]	Shao et al. [30]	Lyu et al. [21]	Mo et al. [27]	Tan et al. [31]

Note: the values in the parentheses indicate the standard deviation. Double dash indicates the data are not available.

3.2. Source Apportionment by PMF

According to the PMF modelling, six factors were resolved, with the source profiles and distribution of each species among sources (the relative contribution of resolved factors to each species) shown in Figure S1. Factor 1 was dominated by isopropyl alcohol and 1,4-dioxane, contributing over 90% and 70% among the five factors. Because isopropyl alcohol and 1,4-dioxane are important chemical raw materials and products, Factor 1 was identified as "industrial emission". Factor 2 was abundant in ethane, ethylene, propylene, acetylene, and benzene, which are characteristic species of combustion [32]. Therefore, this factor was labelled as "fuel burning". Factor 3 was mainly contributed by isoprene, which is a well-known tracer of biogenic emissions [33]. It was accordingly considered as "biogenic emissions". Factor 4 was characterized by a high contribution of propane, isobutane, n-butane, isopentane, n-pentane, 2,3-dimethylbutane, propylene, and 1-butene. These low-carbon alkanes and alkenes are widely identified as the tracers of vehicular emissions [34]. Factor 5 has a high abundance of ethane, propane, n-butane, and isobutane, which were measured in natural gas (NG) and liquefied petroleum gas (LPG) emission profiles, and hence labelled as "NG and LPG" [35]. Factor 6 was treated as solvent use because the profile was composed of abundant acetone and 2-butanone, which are widely used in solvent-related sources such as shoemaking [36].

The contributions of the six identified sources are shown in Figure 6. Vehicular emissions contributed the most, taking up 33% of the total VOCs. It was followed by NG and LPG (19%), fuel burning (17%), solvent use (16%), industry emissions (10%), and biogenic emissions (5%). As a typical urban site with road traffic and residential buildings around, the major sources of the measurement point were vehicular emissions and NG and LPG, which are expectable. Fuel burning may include industrial and residential fossil fuel burning as well as biomass burning. However, this study could not distinguish between fossil fuel and biomass burning. The solvent use mainly comes from the use of adhesives for residential purposes and from the shoemaking industry rather than furniture and surface coatings, which are characterized by a high abundance of aromatics. This explained well that the VOC sources are highly dependent on the industry distribution and structure in each specific city. Industry contributed 10% of the total VOCs in Nanning, which was much lower than other highly industrialized cities in China. The biogenic emissions contributed 5% of the total VOCs, which might be due to the urban greening and vegetation areas around.

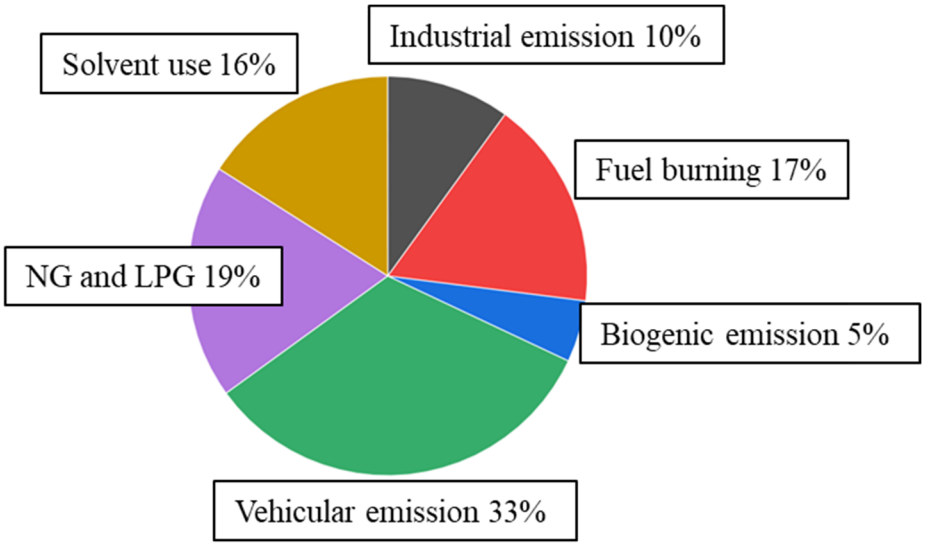

Figure 6. Source contributions of ambient VOCs in Nanning resolved by PMF.

The seasonal variation in the source contributions resolved by the PMF is shown in Figure 7. The vehicular emissions (contributing 44% of total VOC emissions) dominated in summer, probably due to increasing outdoor activities and transportation. The biogenic emissions were much higher in summer and autumn, contributing 7% compared with less than 1% in winter. This is mainly because of the high solar radiation, inducing larger vegetation emission strength. The NG and LPG contributed much more in spring and winter. This is probably because of increasing residential and industrial use of natural gas and LPG during these periods. It was suggested that these variations were highly associated with the human activities in different seasons in Nanning.

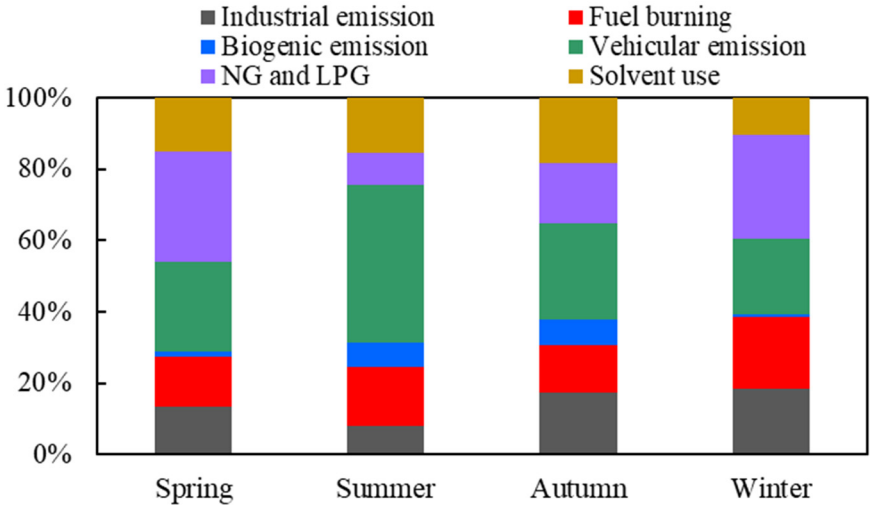

Figure 7. Seasonal variation in the source contributions of ambient VOCs resolved by PMF.

Comparisons of the source contributions resolved by PMF in different cities of China are tabulated in Table 2. As the sources identified among the studies were different, we categorized the sources into six common groups, i.e., vehicle, oil evaporation (including gasoline, diesel, NG and LPG evaporation), fuel burning (including biomass and fossil fuel burning), solvent use, industry, biogenic, and others for comparisons. It is shown that the VOC concentrations in all the cities except Ningbo [27] and Shanghai [16] were dominated by vehicle sources, contributing 52% in 22–58% of the total VOCs. Ningbo was dominated by industry (50%) because a large-scale petrochemical complex is located there, while Shanghai was dominated by solvent use (32%). Oil evaporation, fuel burning,

solvent use, and industry were important but show significant variations in different cities. Their contributions are in the ranges of 9–27%, 15–24%, 5–32%, 10–50%, respectively, which depend on the energy and industrial structures in the specific cities. It should be noted that biogenic emissions take up 5% in Nanning, compared with 5% in Nanjing [30] and 12% in Chengdu [31]. This suggested that the VOCs emitted from vegetation should also be considered in O_3 control strategies.

Table 2. Comparison of the source contribution of ambient VOCs in different cities of China (%).

	Vehicle	Oil Evaporation	Fuel Burning	Solvent Use	Industry	Biogenic	Others	Reference
Nanning	33	19	17	16	10	5	--	This study
Beijing	52	16	--	5	20	2	--	Song et al. [15]
Shanghai	25	15	16	32	12	--	--	Cai et al. [16]
Guangzhou	58	--	24	18	--	--	--	He et al. [29]
Nanjing	34	9	--	30	22	5	--	Shao et al. [30]
Wuhan	28	20	22	17	14	--	--	Lyu et al. [21]
Ningbo	16	27	--	7	50	--	--	Mo et al. [27]
Chengdu	22	--	15	21	13	12	17	Tan et al. [31]

3.3. Ozone Formation Potential

To evaluate the chemical reactivity of VOCs measured in Nanning, the OFPs were calculated. The daily-averaged OFPs during the measurement period displayed significant variations with an average value of 126.2 $\mu g/m^3$, and were mainly dependent on the VOC concentrations (Figure 8a). The alkenes (30%) contributed the most to the OFP, followed by aromatics (27%), alkanes (20%), and OVOCs (19%). Alkynes and halocarbons contributed less than 3% of the total OFP (Figure 8b) because of their low chemical reactivity. The top 10 species with high OFP are shown in Figure 8c. The species with the highest OFP is ethylene, followed by m/p-xylene, butane, propylene, isoprene, toluene, isopentane, o-xylene, 1,3-butane, and propane. While m/p-xylene, isoprene, and toluene were not in the top 10 species with the highest concentration, they could contribute significantly to the OFP due to their high reactivity to ozone formation. In addition, the estimated OFPs are compared with the observed O_3 concentrations in Figure 8a. We can see that the estimated OFPs cannot fully reflect the O_3 variations, which could be affected by meteorological conditions, solar radiation, as well as NO_x concentrations. In particular, high O_3 concentrations were observed on 1 August 2021 but the estimated OFP was not high. The observed O_3 concentrations were fluctuating below 20 $\mu g/m^3$ between 1 October 2020 and 1 February 2021, but the estimated OFPs were found to be high in November 2020 and January 2021. It is suggested that the ozone variations are not only governed by the VOC contributions, but are also complicated by the reactions with NOx and meteorological conditions. To reduce O_3 pollution, we need to consider VOC-reactivity-based strategies as well as to examine meteorological and NO_x effects. However, the estimated OFPs could provide important implications for formulating an effective VOC abatement strategy.

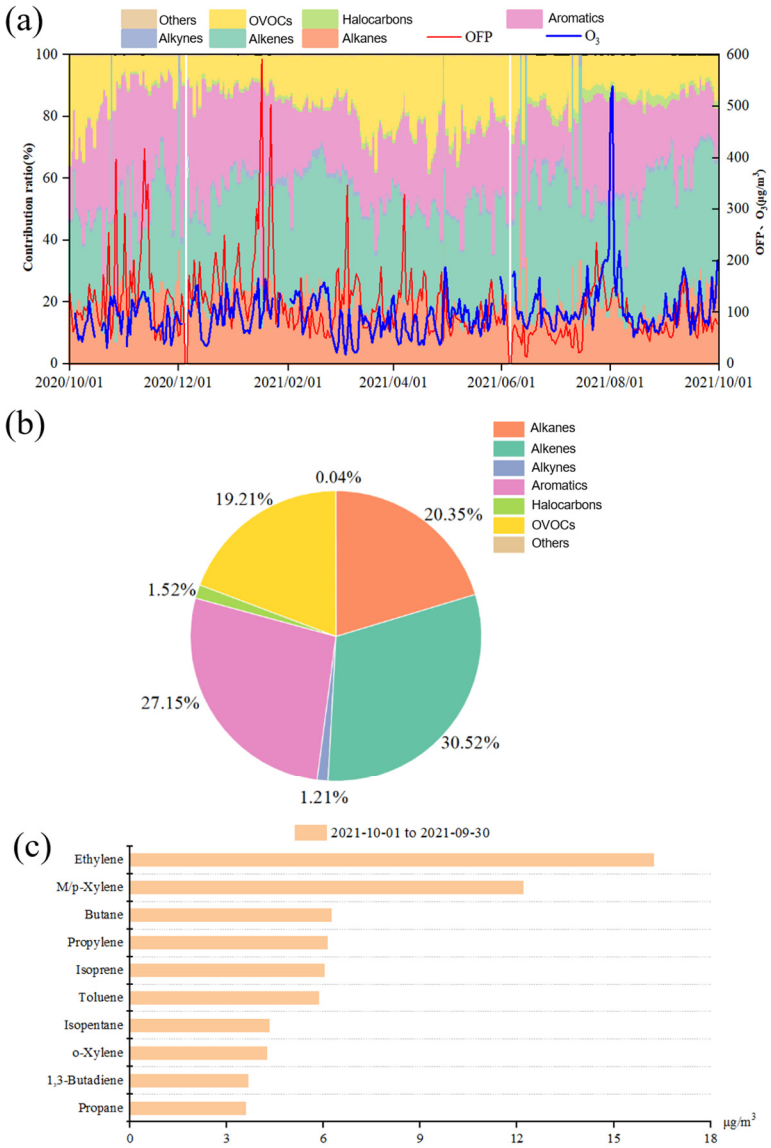

Figure 8. (**a**) The daily-averaged OFP, (**b**) function group contribution, (**c**) and the top 10 species contributing to the OFP.

4. Conclusions

A year-long measurement (from 1 October 2020 to 30 September 2021) of VOCs was conducted at an urban site in Nanning, Guangxi Province in South China. The daily-averaged concentration of total VOCs varied significantly across the entire year, ranging from 3.15 ppb to 136.18 ppb, with an average of 26.37 ppb. High VOC concentrations were mainly observed at night-time and in the early morning, while they were relatively low in the afternoon, which resulted from the constant emissions and low boundary layer during night-time and the chemical reactions and boundary layer growth in the daytime. Alkanes contributed 46.9% of the total VOC concentration, followed by OVOCs (25.2%), alkenes (8.6%), halocarbons (7.8%), aromatics (6.1%), alkyne (6.1%), and other (0.2%). The major species were alkane and OVOC species such as propane (3.8 ppb), ethane (3.2 ppb), and ethanol (2.8 ppb) in Nanning, which is different from the high-concentration species such as toluene (3.7 ppb) in Guangzhou, ethylene (3.8 ppb) in Nanjing, and isopentane (5.5 ppb) in Chengdu.

Source apportionment was conducted by the PMF model and six factors were resolved. Vehicular emissions (33%) contributed the most, followed by natural gas (NG) and liquefied petroleum gas (LPG) (19%), fuel burning (17%), solvent use (16%), industry emissions (10%),

and biogenic emissions (5%). It is suggested that industry contributed much less in Nanning than in other cities of China, in which it ranges from 12% to 50%. This indicated that the VOC sources are highly dependent on the energy and industrial structure in a specific city. Biogenic emissions should also not be neglected in formulating the O_3 control strategies.

The ozone formation potential analysis suggested that ethylene, m/p-xylene, butane, propylene, and isoprene were key species in producing O_3, which are on the priority list for VOC abatement in Nanning. In addition, we found that the estimated OFP cannot fully reflect the observed O_3 variations. It is suggested that we should consider reactivity-based strategies as well as take meteorological and NO_x effects into account for controlling O_3 pollution. This study provides an important dataset of a year-long measurement of VOCs in Nanning, where the VOC characteristics were not well understood. The ambient variations and source apportionment could give valuable scientific implications for designing effective VOC abatement and O_3 control strategies, which are also beneficial to other regions in China.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos15050560/s1, Figure S1. Concentration profiles and composition profiles of the six factors resolved from the PMF model; Table S1. The average concentration and standard deviation of each species.

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