

Subtropical high-driven ozone pollution episodes in coastal cities in southeastern China

Lanbo Zhao^{a,b}, Lian Xue^{a,c,*}, Chengchun Shi^{d,e}, Chuanyou Ying^{a,f}, Erling Ni^{d,e}, Haoran Zhang^{a,b}, Xueyu Zhou^{a,b}, Tianshuai Li^{a,b}, Xin Huang^{a,b,**}, Aijun Ding^{a,b}

^a State Key Laboratory of Severe Weather Meteorological Science and Technology, Nanjing University, Nanjing, 210023, China

^b Joint International Research Laboratory of Atmospheric and Earth System Sciences, School of Atmospheric Sciences, Nanjing University, Nanjing, 210023, China

^c Nanjing-Helsinki Institute in Atmospheric and Earth System Sciences, Nanjing University, Suzhou, 215163, China

^d Fujian Academy of Environmental Sciences, Fuzhou, 350013, China

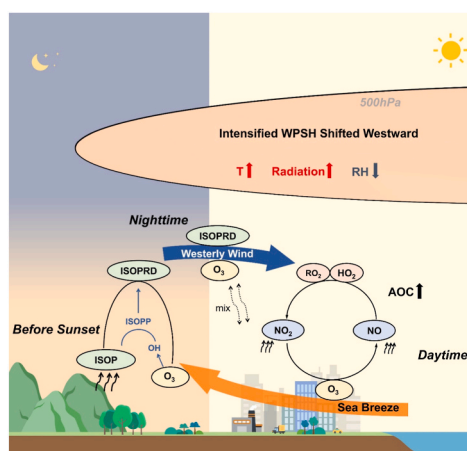
^e Fujian Key Laboratory of Environmental Engineering, Fuzhou, 350013, China

^f Fuzhou Research Academy of Environmental Sciences, Fuzhou, 350013, China

HIGHLIGHTS

- Strong westward-extended WPSH usually promotes severe ozone pollution in Fujian.
- Cloud-free and hot conditions linked with WPSH facilitate local ozone formation.
- Sea-breeze brings ozone to BVOCs-rich forest regions and forms reactive intermediates.
- Elevated atmospheric oxidizing capacity and ozone contribute to lasting pollution.

GRAPHICAL ABSTRACT



ABSTRACT

Ozone pollution is increasingly recognized as a major air pollutant in China, with summertime concentrations showing rising trends across many regions, including southeastern coastal cities. Previous studies have shown that weather conditions associated with strong Western Pacific Subtropical High (WPSH) can facilitate tropospheric ozone formation in eastern China, which can potentially lead to severe regional ozone pollution. In this study, we investigated the role of WPSH in modulating ozone pollution in Fujian Province, which shows that strong and westward-extended WPSH in summer usually coincides with ozone-polluted episodes across Fujian. To understand the underlying dynamic and chemical processes, we analyzed severely polluted ozone pollution period around the Meizhou Bay Rim Region (MBRR, including major coastal cities of Fujian) in July 2022. Reanalysis and air quality simulations revealed that the enhanced downward solar radiation, reduced cloud cover, and high temperatures under the westward-extended WPSH accelerated daytime photochemical ozone formation. In addition, biogenic volatile

* Corresponding author. State Key Laboratory of Severe Weather Meteorological Science and Technology, Nanjing University, Nanjing, 210023, China.

** Corresponding author. State Key Laboratory of Severe Weather Meteorological Science and Technology, Nanjing University, Nanjing, 210023, China.

E-mail addresses: lian.xue@nju.edu.cn (L. Xue), xinhuang@nju.edu.cn (X. Huang).

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organic compounds (BVOCs) such as isoprene emitted from forests in western Fujian interacted with sea-breeze-driven transport of ozone-rich air masses in the afternoon, producing high concentrations of reactive intermediates. These intermediates were recirculated back by westerly to urban areas at night, sustaining elevated atmospheric oxidizing capacity and ozone levels on the following day and leading to prolonged ozone pollution. The combined effects of regional meteorological conditions and enhanced oxidizing capacity induced by local circulations led to an 85% increase in ozone concentrations. Our findings underscore the importance of considering synoptic dynamics and topography-chemistry interactions for more accurate forecasting and effective management of regional ozone pollution, especially in coastal cities.

1. Introduction

Tropospheric ozone (O_3) is an important air pollutant and a short-lived climate forcer, exerting considerable impacts on human health, ecosystems, atmospheric chemistry, and global climate (Ainsworth et al., 2012; Avnery et al., 2011; Krupa and Kickert, 1989; Monks et al., 2015). First recognized in Los Angeles in the mid-20th century (Haagen-Smit, 1952; Rani et al., 2011), elevated ozone concentration has emerged as a pervasive environmental issue globally, particularly in highly industrialized regions including the United States, Europe, and East Asia (Lu et al., 2018; Monks et al., 2015). As a strong oxidant, ozone actively participates in atmospheric chemical processes and has crucial impacts on both the concentrations and lifetime of gases and particles in the atmosphere (Atkinson and Arey, 2003; Lelieveld et al., 2016; Monks et al., 2015). Nevertheless, tropospheric ozone also poses harmful effects on human health, including the cardiovascular, circulatory, and respiratory systems (Kim et al., 2020; Lippmann, 1989; Selin et al., 2009; Zhang et al., 2019). Ozone is not directly emitted by sources, but forms through photochemical reactions involving nitrogen oxides (NO_x , i.e., $NO + NO_2$) and volatile organic compounds (VOCs) in the presence of solar radiation (Jacob, 1999; Seinfeld and Pandis, 2016; Wang et al., 2017). The process of ozone formation begins with the photolysis of nitrogen dioxide (NO_2), which produces an excited oxygen atom (O) that quickly combines with oxygen (O_2) to form ozone. If there are no other reactive species, ozone reacts with nitrogen monoxide (NO) to regenerate NO_2 , forming a cycle with no net ozone production. This null cycle will be broken when hydroxyl radicals (OH) react with VOCs, producing peroxy radicals (RO_2 and HO_2) that convert NO to NO_2 without consuming ozone, allowing continued NO_2 photolysis and net ozone formation (Atkinson, 2000; Haagen-Smit, 1952; Seinfeld and Pandis, 2016; Wang et al., 2017). Because this process is highly nonlinear, surface ozone formation in the real atmosphere often depends on both the concentrations of NO_x and VOCs and their relative proportions (Seinfeld and Pandis, 2016). NO_x emissions are overwhelmingly tied to anthropogenic combustion sources, whereas VOCs stem from a mix of anthropogenic activities and biogenic emissions. As a result, in urban areas where NO_x concentrations are typically high, ozone formation is generally VOC-limited (Wang et al., 2022a; Xu et al., 2021).

In addition to precursor emissions, meteorological conditions play a pivotal role in modulating surface ozone by affecting photochemical reaction rates, the transport of precursors and products, dispersion, and deposition processes (Elminir, 2005; Hidy, 2000; Stull, 2012; Wang et al., 2017). For example, high temperatures and strong solar radiation are favorable for ozone formation through faster photochemical reactions and NO_2 photolysis (Seinfeld and Pandis, 2016). High wind speeds and deep planetary boundary layer (PBL) enhance pollutant dispersion and vertical mixing, thus reducing surface ozone, while stagnant weather conditions with a shallow PBL can trap air pollutants near the surface, leading to serious ozone pollution episodes (Hidy, 2000; Hu et al., 2014; Stull, 2012). Some VOC emissions, such as isoprene and monoterpenes, are strongly temperature-dependent, further complicating the interactions of ozone formation and meteorological conditions (Li et al., 2024a; Wang et al., 2022a).

Previous studies have revealed that synoptic-scale systems such as the Western Pacific Subtropical High (WPSH) are closely associated with ozone episodes in eastern China (Chang et al., 2019; He et al., 2012; Jiang et al., 2021; Lo and Hung, 2015; Shu et al., 2016; Zhao and Wang,

2017). While it is widely recognized that WPSH can modulate regional weather conditions and circulations related to ozone pollution, such as temperature, humidity, solar radiation, regional transport, etc. (Guan et al., 2019; Li et al., 2015; Ma et al., 2023), its specific impacts on ozone levels are usually region-dependent and vary from case to case. For example, Jiang et al. (2021) found that a stronger WPSH suppresses ozone formation in southern China due to enhanced humidity and less cloud, while Chang et al. (2019) and Li et al. (2024) concluded that an intensified WPSH leads to higher ozone levels due to stagnant meteorological conditions and enhanced photochemical activity. This suggests that WPSH-related ozone pollution is a complex process, shaped not only by the position and intensity of the WPSH but also by regional features such as emissions and topography. On the other hand, with the recognition of the importance of natural emissions, more attention have been drawn to ozone pollution in less urbanized regions, such as coastal cities of China (Chen et al., 2024; Liu et al., 2022; Wang et al., 2025; Zhang et al., 2022), where the mechanisms driving regional air pollution may differ from those in highly industrialized urban clusters such as Yangtze River Delta (YRD), the Pearl River Delta (PRD), and the Beijing–Tianjin–Hebei (BTH) region (Ding et al., 2013; Fang et al., 2020; Shu et al., 2019; Wang et al., 2021, 2022b; Zhan et al., 2021). Fujian is a province on the southeast coast of China, with most large cities located along the eastern coast and dense forest coverage in the west. Severe ozone pollution episodes have been reported to occur frequently in Fujian during recent summers, highlighting the urgent need to understand the complex interactions between large-scale systems such as the WPSH, regional circulations, and atmospheric chemistry (Ge et al., 2022; Hu et al., 2024). In this study, we selected the Meizhou Bay Rim Region (MBRR) for study. The Meizhou Bay Rim Region consists of three major coastal cities, Fuzhou, Putian, and Quanzhou, around Meizhou Bay, with a population of more than 20 million. The location of MBRR is shown in Fig. S1. This region represents one of the most industrialized and urbanized zones of southeastern China. In 2022, the combined gross domestic product (GDP) of Fuzhou, Quanzhou, and Putian reached 2.75 trillion CNY, accounting for approximately 52% of Fujian Province's total economic output. With the industrial development, the ozone pollution deteriorated in this region in recent years (Hu et al., 2025). We first investigated the general relationship between WPSH and the summertime ozone pollution in the Meizhou Bay Rim Region. Based on the overall understanding, we focused on a typical ozone pollution event over the MBRR associated with the WPSH in July 2022. We then conducted a comprehensive analysis of both dynamic and chemical processes during the episodes, incorporating ground-based observations, reanalysis datasets, and regional meteorology-chemistry coupled model simulations.

The rest of this paper is structured as follows. The data and methods used in this study are introduced in Section 2. Then, Section 3.1 presents the general relationship between the WPSH and summer ozone concentrations over the MBRR, as well as an overview of the case selected for further analysis. Section 3.2 describes how WPSH-related regional weather conditions varied during the pollution episodes and their relations to ozone formation and concentration. Section 3.3 discusses the detailed local circulation and chemical processes contributing to the formation and maintenance of high ozone levels in this case. Conclusions are summarized in Section 4.

2. Data and methods

2.1. Observational and reanalysis datasets

Hourly surface ozone, NO, and NO₂ concentrations of the recent decade were collected from the China National Environmental Monitoring Center (CNEMC, <http://www.cnemc.cn>), which has been used in air quality research in numerous previous studies (Jiang et al., 2021; Wang et al., 2022b; Zhou et al., 2025). A total of 39 sites in 9 cities is located in Fujian Province. We selected 17 sites located in MBRR for air pollution research, and most of the sites are in the urban region. The overall geography of the cities and the distribution of the stations are shown in Fig. 1, Fig. S2, and Table S1. O₃ was measured by the Thermo Scientific Model 49i analyzer, which operates as a dual-cell ultraviolet photometer. NO and NO₂ were measured by the Thermo Scientific Model 42i chemiluminescence NO-NO₂-NO_x analyzer. We adopted the metric MDA8 (Maximum Daily 8-h Average) O₃ to evaluate surface ozone pollution levels (Liu et al., 2023; Lu et al., 2018). It is calculated as the highest value among all 8-h running mean ozone concentrations within a day.

Meteorological data near the surface, including air temperature, wind speed, and wind direction, were obtained from site observations measured by the Lufft WS500 Smart Weather Sensor. To investigate the influence of large-scale weather systems including the subtropical high, the geopotential height and horizontal wind field (u- and v-components) data from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) were used, which provided hourly estimates of atmospheric variables with a spatial resolution of $0.25^\circ \times 0.25^\circ$ (approximately 31 km) on multiple vertical levels

(Hersbach et al., 2018).

2.2. Model simulation

To reveal the influence of the subtropical high system on regional ozone pollution over the coastal city in southeastern China and its underlying mechanisms, we employed the Weather Research and Forecasting model with Chemistry (WRF-Chem) version 4.1.1 (Grell et al., 2005). The model configuration consisted of two nested domains with horizontal resolutions of 15 km and 3 km, covering southeastern China (D01) and the Fujian-Taiwan region (D02), respectively (Fig. 1a). The vertical structure included 45 layers extending from the surface to 50 hPa. To achieve a refined vertical resolution near the surface while maintaining computational efficiency, a vertical grid stretching factor of 1.1 (dzstretch_s = 1.1) in the model setting was applied, ensuring more than 10 height levels located below 1000 m in the urban region of the D02. Simulations were conducted from July 1st to 30th, 2022, with the first 4 days designated as spin-up time. The initial and boundary meteorological conditions were derived from ERA5 data. Observational surface and upper-air data were assimilated to improve the simulation of meteorological fields. The simulation results well captured the temporal variation of ozone concentration in Fujian Province compared with observational data (Fig. S3), proving its reliability for detailed analysis of meteorological and chemical processes.

To more accurately represent the effects of small-scale physical processes, including radiation, boundary layer dynamics, and microphysics, various physics parameterization schemes were employed (see Table S2). As for atmospheric chemistry modeling, the Carbon Bond Mechanism Z (CBMZ) (Zaveri and Peters, 1999) was used. This

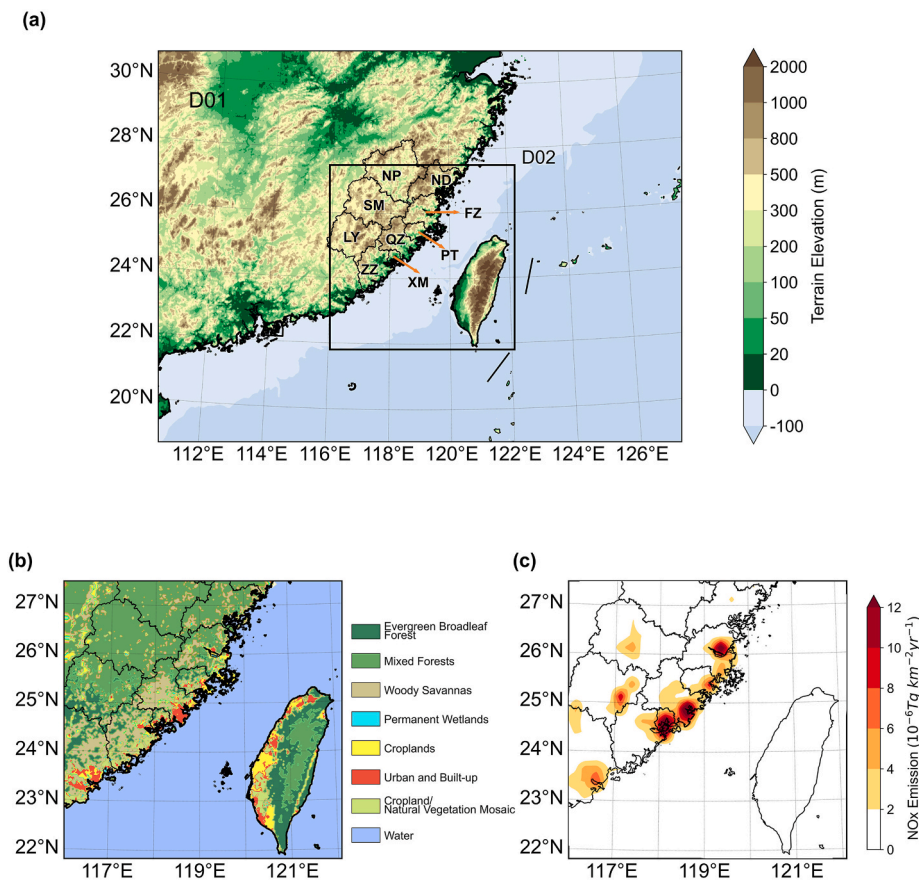


Fig. 1. (a) Terrains over study region with the domain configuration in WRF-Chem. Major cities in Fujian Province are labeled with their initials (FZ: Fuzhou, XM: Xiamen, ZZ: Zhangzhou, QZ: Quanzhou, SM: Sanming, PT: Putian, NP: Nanping, LY: Longyan, ND: Ningde). (b) Land use type information in domain 2 of WRF-Chem simulations. (c) Daily averaged NO_x emission rate from the Multi-resolution Emission Inventory for China (MEIC).

mechanism categorizes organic compounds by their molecular bond structures, simulating 67 chemical species and 164 reactions through a lumped-structure approach. Anthropogenic emissions were obtained from the 2019 Multi-resolution Emission Inventory for China (MEIC) (Li et al., 2017). The distribution of NO_x emission rate over D02 is depicted in Fig. 1c, which shows dense anthropogenic activities in urban regions, especially along the coast. Biogenic emissions were calculated online using the Model of Emissions of Gas and Aerosols from Nature (MEGAN) (Guenther et al., 2006).

2.3. WPSH index

Previous research has widely used different WPSH indices to illustrate the intensity and location of the WPSH (Guan et al., 2019; Huang et al., 2016; Liu et al., 2019b). In this study, we used the westward ridge point index (WPSH-W) and the ridge line index (WPSH-R) to represent the location of the WPSH. Specifically, WPSH-W shows the western extent of the WPSH. It is defined as the westernmost longitude of the contour line of 5880 geopotential meters (gpm) at the 500 hPa pressure level, within the region north of 10°N and between 90°E and 180°E. WPSH-R, defined as the latitudinal average of the ridge line (where $u = 0$ and $\partial u / \partial y > 0$) within the 5880 gpm isoline at the 500 hPa level, was used to note the meridional (north–south) position of the WPSH. In addition to the WPSH location, we also used WPSH-I to measure the intensity of the WPSH. WPSH-I is calculated as the integrated geopotential height anomaly above 5880 gpm at 500 hPa within the region spanning 110°E to 180°E longitude and north of 10°N latitude. It's considered to be positively correlated with the intensity of the high-pressure system (Li et al., 2024b).

3. Results

3.1. Observed ozone pollution deterioration under westward-extended subtropical high

To understand the overall relationship between WPSH and ozone in Fujian, we first analyzed the seasonal and monthly averages of WPSH and ozone concentrations over the past decade, as shown in Fig. 2 and Fig. 3. Strong interannual variability in MDA8 ozone was observed in several major cities, particularly in coastal cities around Meizhou Bay (Fig. 2a–c). As an example, from 2021 to 2022, the July–August (JA) mean ozone concentration increased about 57.5% from 37.71 ppbv to 59.41 ppbv in Fuzhou, with the number of ozone pollution days (defined as the day when MDA8 ozone concentration exceeds 160 $\mu\text{g}/\text{m}^3$) in July and August concurrently increased from 0 day to 7 days. Similar increases in ozone levels were also obvious in Putian and Quanzhou. The deterioration of ozone pollution in coastal cities in 2022 was combined with the variation in the location of the WPSH. Compared with its 10-year average, the WPSH in 2022 expanded markedly westward, reaching as far as 95°E and covering most of southern China. In contrast, the averaged WPSH in 2021 retreated toward the ocean, with its western edge about 5° east of the climatological position. Fig. 3 shows scatter plots of the monthly-mean WPSH index of July and August in the past decade versus ozone concentration in coastal cities of Fujian from 2015 to 2024. Significant correlations were found between MDA8 ozone and both WPSH-W and WPSH-I, suggesting that the western edge and the intensity of the high-pressure system play important roles in modulating regional ozone concentration in Fujian. Specifically, the negative correlation ($r = -0.53$, $p < 0.05$) between WPSH-W and ozone concentration suggests that a westward extension of WPSH tends to enhance ozone pollution. By contrast, the positive correlation ($r = 0.53$, $p < 0.05$) between WPSH-I and ozone concentration indicates that a stronger high-pressure system tends to trigger severe ozone pollution. WPSH-R shows no strong correlation with MDA8 ozone, suggesting that the meridional displacement of the WPSH is less essential for ozone

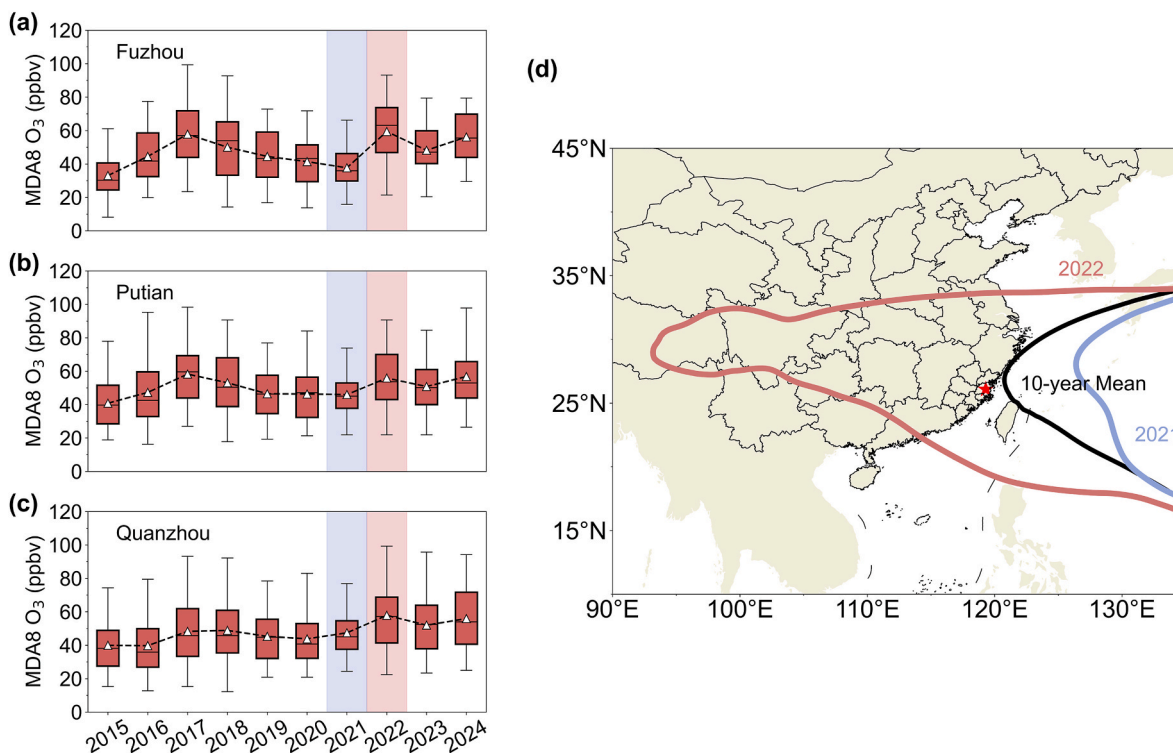


Fig. 2. (a)–(c) July–August (JA) mean MDA8 ozone concentration in 2015–2024 from site observations in (a) Fuzhou, (b) Putian, and (c) Quanzhou. (d) Climatological (black), 2021 (blue), and 2022 (red) WPSH, shown as the contour lines of 5880 gpm at 500 hPa. The red star marker in (d) denotes Fuzhou City.

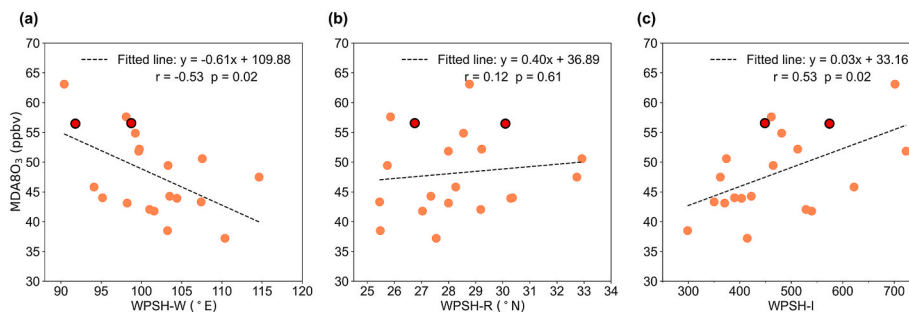


Fig. 3. Scatter plots of three monthly mean WPSH indices: WPSH-W (a), WPSH-R (b) and WPSH-I (c) in July and August versus MDA8 O₃ in the MBRR in the past decade (2015–2024). The black dashed line in each subplot denotes the linear regression. The points circled in black denote the values for 2022.

variability in Fujian. The moderate linear relationships ($r = \pm 0.53$) suggest that the WPSH exerts a notable but non-exhaustive influence on ozone levels, and the ozone concentrations are also modulated by other factors. The precursor concentrations and the ratio of NO_x to VOCs influence chemical reactions related to ozone formation (Wang et al., 2017), and the spatiotemporal changes of precursor emissions further contribute to ozone variability. Regional transport from regions adjacent to Fujian and inland cities in Fujian can also exert a significant influence on ozone pollution, as a previous study suggests that ozone transport from non-Fujian regions can impact 29–38% of ozone pollution days in coastal cities (Ge et al., 2022). Additionally, the vertical dilution governed by PBL thermal turbulence and mechanical turbulence also played a crucial role in ozone distribution (Garratt, 1994; Hu et al., 2013; Schumann, 1989). Because these turbulent eddies are inherently non-linear and on much smaller spatial and temporal scales than synoptic-scale forcing, their contributions to ozone variability are difficult to be fully captured by WPSH indices.

As discussed previously, anomalously strong WPSH in the summer of 2022 coincided with intense ozone pollution around MBRR. Therefore, we focused on a severe ozone pollution episode in July 2022. Daily variation of mean MDA8 ozone concentration in MBRR and the mean value of six coastal cities from July 6th to 20th in 2022 is exhibited in Fig. 4. A severe ozone pollution episode occurred from July 10th to July 17th, during which the MDA8 ozone concentration of MBRR from observation remained consistently high, exceeding 8-h WHO Global Air Quality Guidelines (AQG) level ($100 \mu\text{g}/\text{m}^3$) throughout the period. Notably, from July 15th to 16th, the MDA8 ozone concentration in MBRR exceeded China's light-polluted ozone concentration standard ($160 \mu\text{g}/\text{m}^3$ or 81.6 ppbv), posing a substantial threat to the environment and public health.

To better reveal the role of WPSH in this ozone episode, we divided

the study period into three stages based on the ozone concentration levels. Stage I (the pre-stage, July 6–9) is characterized by moderate ozone levels and a gradual increase in ozone concentration. Stage II (the pollution episode stage, July 10–17) refers to the period with the most severe ozone pollution, characterized by the highest concentrations observed during the entire study period. During the pollution stage, the MDA8 ozone concentration remained high in MBRR, with 6 days exceeding 70 ppbv and even 2 days exceeding 80 ppbv. Stage III (the post-stage, July 18–19) is considered the end of the pollution episode, with ozone concentration dropping sharply from July 17 to July 18 and remaining below 50 ppbv until the next pollution episode occurred.

The associated position and intensity of WPSH during the three stages are shown in Fig. 5 and Table 1. Before the pollution episode, the edge of the WPSH reached the East Asian continent, while its high-pressure center remained over the East China Sea. Later, the WPSH extended rapidly westward into inland areas, with its center covering southeastern coastal regions, including Fujian. After July 18, the WPSH retreated eastward and southward toward the ocean (Fig. 5c), accompanied by a reduction in ozone pollution in Fujian. The WPSH-W, which reflects the average western ridge point of the subtropical high, shifted from 113.88°E in Stage I to 98.53°E in Stage II, and then moved to 109.10°E in Stage III, clearly capturing the westward-eastward progression of the system across the three stages. On the other hand, the normalized WPSH intensity index, calculated as daily WPSH-I divided by its mean value in July 2022, also showed the strongest high pressure during the pollution stage. This suggests a positive influence of the high-pressure system's intensity on ozone pollution levels, consistent with our previous monthly statistical analysis.

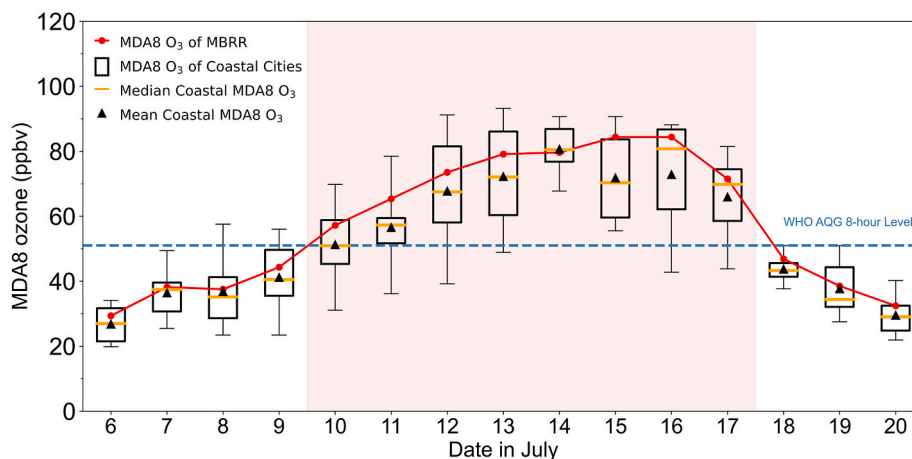


Fig. 4. Daily variation of MDA8 ozone concentrations (ppbv) of coastal cities in Fujian Province from July 6th to July 20th, 2022. The red shading denotes Stage II (ozone pollution episode). The blue dashed line indicates the WHO air quality guideline (AQG) level for 8-h ozone concentration ($100 \mu\text{g}/\text{m}^3$).

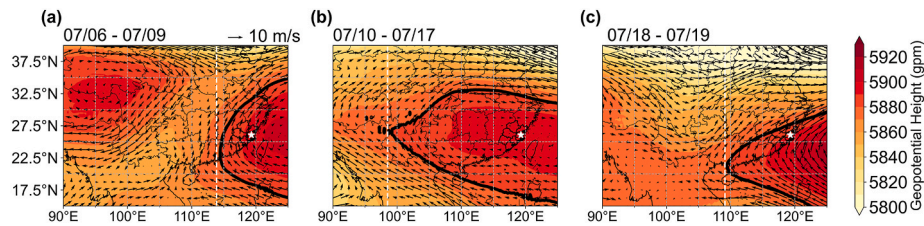


Fig. 5. Geopotential heights (shading, gpm) and winds (vector, m/s) at 500 hPa at 08:00 LST averaged over each of the three stages: (a) Stage I, (b) Stage II, and (c) Stage III. The black contour represents the 5880 gpm isoline, indicating the location of the WPSH. The white dashed vertical line marks the western edge of WPSH. The white star denotes the location of Fuzhou.

Table 1
The mean WPSH indices for the three stages.

	WPSH-W (°E)	Normalized WPSH-I
Stage I	113.88	0.54
Stage II	98.53	1.04
Stage III	109.10	0.93

3.2. WPSH-associated meteorology favorable for biogenic emission and photochemistry

To quantitatively understand the dynamic and chemical processes during the episode, we used WRF-Chem simulation results. As shown in

Fig. 6a and b, both ozone concentration and its chemical production over the three coastal cities of MBRR were much stronger during Stage II compared with those before and after this stage. Daytime chemical formation of ozone (08:00–14:00 LST) was very strong in Stage II, with the diagnosed ozone formation rate 25.8% and 28.1% higher than those during Stage I and Stage III, respectively. Active photochemistry greatly contributed to ozone levels, leading to an average regional increase of about 36.8 ppbv (98.6%) and 31.3 ppbv (73.1%) relative to Stage I and Stage II, respectively.

Previous studies have shown that the WPSH features strong descending motions, which suppress cloud formation and enhance surface solar radiation, resulting in persistent clear-sky conditions and high temperatures (Liu et al., 2019a). As discussed in section 3.1, the WPSH

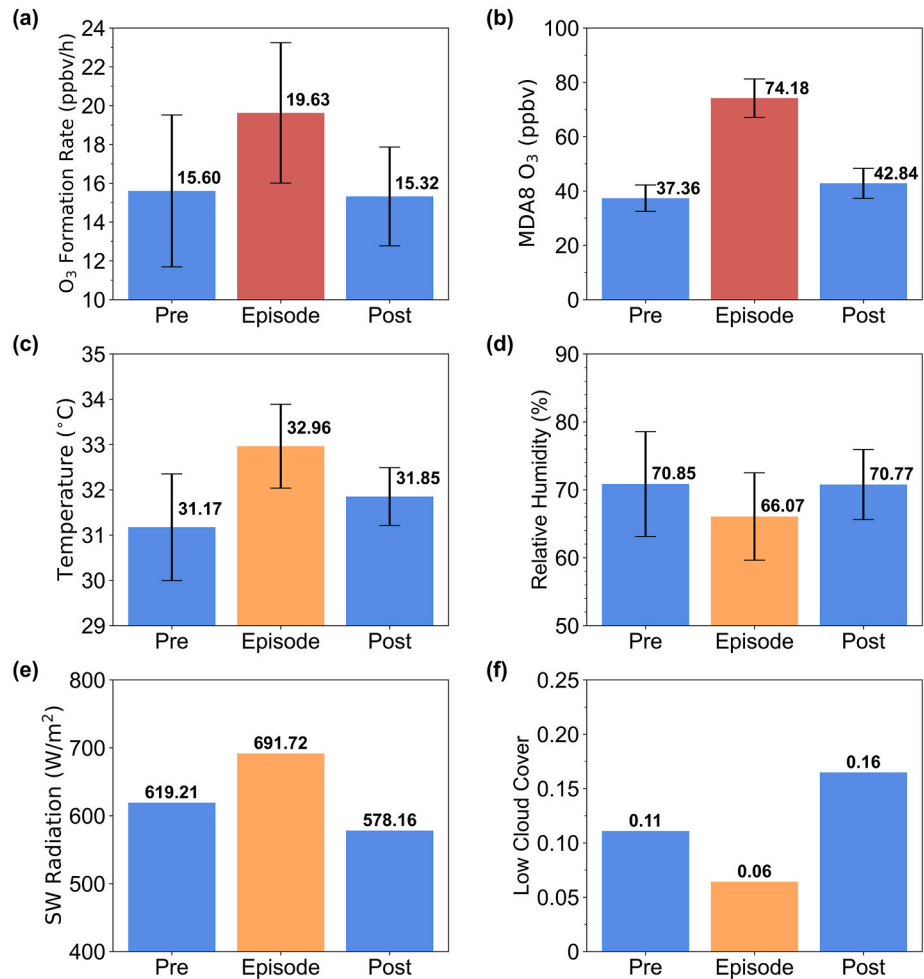


Fig. 6. The mean value of (a) model-diagnosed ozone chemical production rate, (b) MDA8 ozone concentration, (c) 2 m temperature, (d) relative humidity, (e) surface short-wave solar radiation downwards, and (f) low cloud cover over MBRR during the three stages. The solid bars represent the MBRR regional mean values, and the error bars denote the spatial standard deviation among the monitoring stations over MBRR.

was extremely westward extended and enhanced during the pollution episode. Therefore, low cloud cover was much lower at that time, leading to stronger downward shortwave radiation, higher air temperature, and lower relative humidity (Fig. 6c–f). On the one hand, elevated temperatures and enhanced solar radiation provided favorable conditions for photochemical ozone formation, while on the other hand, reduced humidity suppressed ozone loss. Meanwhile, during this week-long pollution episode, the position and intensity of the WPSH remained nearly unchanged. The persistent and stable circulation pattern sustained the occurrence of pollution, leading to a regional ozone pollution event in the coastal cities.

In addition to intensified photochemical reaction, the typical hot and cloud-free weather under the control of WPSH could also boost BVOCs emissions from vegetation, and many species of BVOCs (such as isoprene) usually serve as precursors of tropospheric ozone (Li et al., 2024a; Ma et al., 2019; Wang et al., 2022a). For example, as shown in Fig. 7, isoprene concentrations increased noticeably at Stage II, resulting from higher emission rates of it estimated by MEGAN (Fig. S4). Observation of daytime isoprene concentration at three typical sites confirmed that the elevated temperatures and enhanced solar radiation significantly stimulated biogenic emissions during the pollution episode (Fig. S5). The highest isoprene emissions and concentrations are found mainly in central and northwestern Fujian Province and neighboring regions, where the land surface is dominated by forests (Fig. 1b). Given the high chemical reactivity of isoprene, these maxima generally coincide with its source regions. On the other hand, since most cities are located in coastal regions, NO_x emitted by intensive anthropogenic activities is predominantly concentrated in these coastal urban areas (Fig. 7d–f), which are often in a VOC-limited or transitional ozone

formation regime (Chen et al., 2024). Therefore, mixing of the air masses originated from different sources by proper atmospheric circulation tends to facilitate ozone formation, potentially contributing to large-scale regional ozone pollution events along the southeastern China, as seen in Fig. 7b.

3.3. Enhanced ozone formation and transport under extremely westward-extended WPSH

Coastal regions are often affected by local land–sea breeze systems in addition to the large-scale prevailing circulation (Chen et al., 2016; Zhong and Takle, 1993). During the daytime, the land surface heats up faster than the adjacent ocean, creating a localized low-pressure area over land and driving a near-surface sea breeze from the ocean toward the land (Ding et al., 2004). When WPSH dominates the region, persistent strong radiation and high temperatures over land amplify the thermal contrast between land and sea (Li et al., 2015), thus an intensified sea breeze and frequent occurrence of the sea breeze events would be expected. Adopting the method of the sea breeze event identification proposed by Shen et al. (2019) (see Text S1), we found that the sea breeze frequently occurred during the pollution episode, with a frequency of 62.5% compared with 25.0% and 55.6% at the pre-stage and post-stage, and the primary duration period of sea breeze was from 14:00 to 17:00 in Fuzhou (Fig. S6). From the wind observations at three sites in Fuzhou, sea breeze featuring as southeasterly winds has been clearly noted in the afternoon, and with the strongest intensity during the pollution episode (Fig. S7). The diurnal variation of winds coincided with the daily radiation cycle under stagnant weather conditions associated with a high-pressure system.

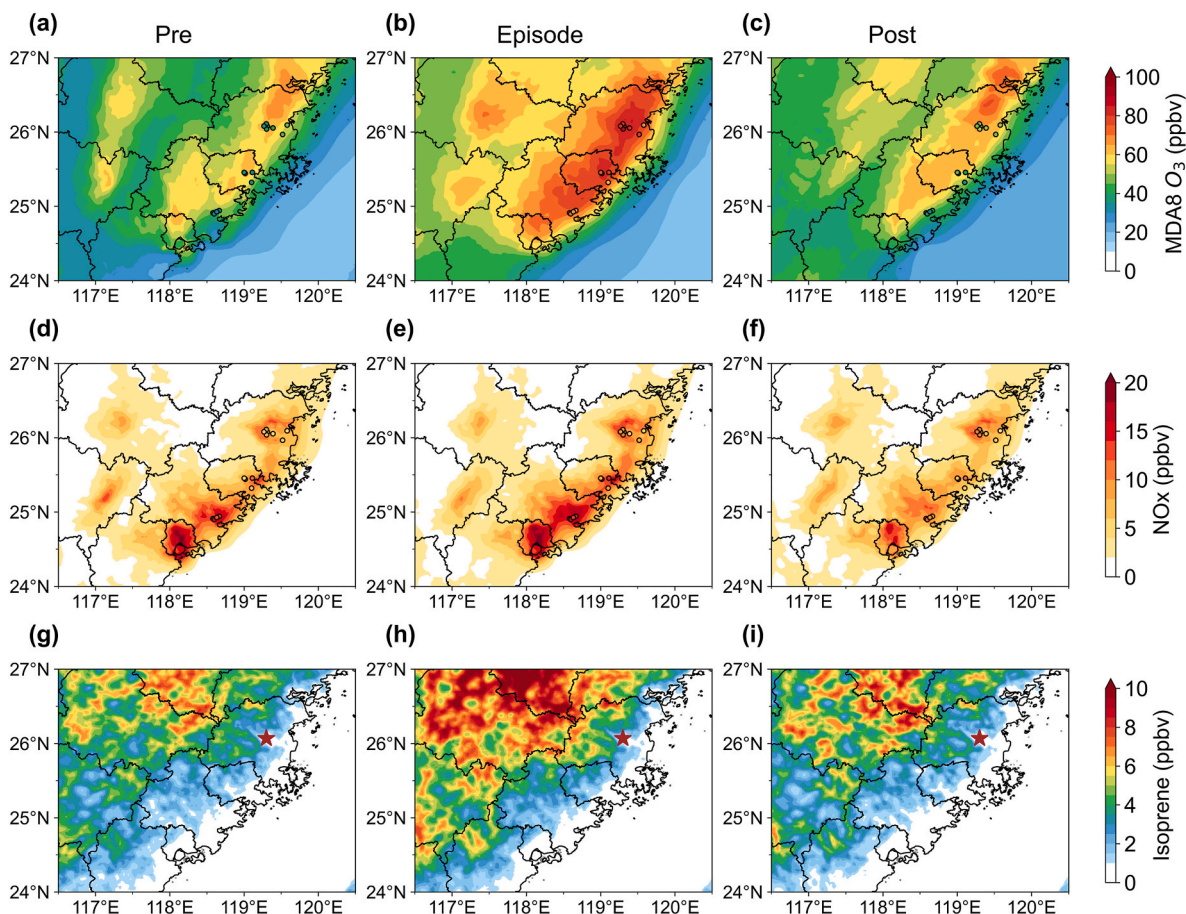


Fig. 7. Observed (colored markers) and simulated (contour shades) near-surface MDA8 O₃ (a–c) and NO_x (d–f) in three stages. Simulated near-surface isoprene concentrations in three stages (g–i). The brown star marker denotes Fuzhou City.

As the ozone concentration reached its maximum after midday, the sea breeze transported ozone-rich air masses from the east coastal urban region to the west forest region during the pollution episode. Through diagnosing the ozone tendency due to horizontal and vertical advection from the WRF-Chem simulations, we quantified the contribution of the transport process to ozone concentration. Fig. 8a–c shows the transported ozone near the surface in the afternoon, in which the dipole pattern (positive–negative) indicates that ozone from the coastal area was transported by the sea breeze to the western mountainous region. Such a process was most significant during the pollution episode due to the high frequency of sea breeze events, and both the transported ozone and the eastward spread were highest during the pollution episode. It should be noted that the land–sea breeze is usually a shallow circulation system, with stronger sea breezes during the day than land breezes at night (Park and Chae, 2018; Zhong and Takle, 1993). In our case, nighttime circulation was mainly dominated by large-scale systems, especially at levels above the near-surface layer. The wind field at 1000 m from 03:00–06:00 was characterized by westerly during Stage II and southwesterly during Stage I and Stage III (Fig. 8d–f). Westward-extended WPSH during Stage II clearly induced a more stagnant condition with weaker winds, but ozone at higher concentrations remaining in the residual layer from the western Fuzhou was transported eastward during the night.

More frequent and strengthened daytime sea breeze during the pollution episode transports more air pollutants from urban areas to inland regions, while nighttime westerlies send the air masses back to the coastal regions. The dynamics lead to the mixing of pollutants from different sources and reduce their original spatial separation. How would it contribute to the persistent ozone pollution event over MBRR from the perspective of chemical reactions? With the CBMZ gas-phase reaction mechanism in WRF-Chem, we are able to disentangle these complex processes. We found that isoprene oxidation intermediates (ISOPRD) played a crucial role in ozone formation during the episode. Isoprene can react with oxidants, like OH radical and ozone, to form intermediate products ISOPRD. During the daytime, the subsequent

transformation of ISOPRD includes reaction with the OH radical and the photolysis of ISOPRD. The main products are peroxy radicals (RO_2 , including C_2O_3 , HO_2 , etc.) and VOCs, with RO_2 playing a key role in modulating the oxidizing capacity of the atmosphere.

We selected a specific cross-section transect along the sea breeze direction for analysis, spanning different land-use types, including mountains, urban areas, and the ocean (shown in Fig. 8 and Fig. S8). As discussed earlier, the ozone transported from the coastal region to the inland mountains by the sea breeze would have the chance to react with the isoprene emitted in the forest area in western Fuzhou (Fig. S9). Particularly, the OH radical generated from ozone photolysis could react with isoprene to form ISOPRD. Subsequently, one typical RO_2 , C_2O_3 , formed through reactions related to ISOPRD. Fig. 9 shows the cross sections of ISOPRD and C_2O_3 at early morning (06:00 and 08:00 LST, respectively) during the three stages. It is evident that the concentrations of both products were much higher during the episode stage than before and after, indicating a favorable chemical environment for subsequent reactions. ISOPRD was mainly concentrated on the western side of Fuzhou from near surface up to about 1000 m, with a notable peak of about 1 ppbv located within the residual layer (500–1200 m) over the urban region at dawn. This could be attributed to the nighttime westerly transporting ISOPRD eastward to the city region above the nocturnal stable boundary layer. Primarily as a photolysis production of ISOPRD, C_2O_3 rapidly formed after sunrise. The highest C_2O_3 concentrations (approximately 5 pptv) were centered around 119.2°E at heights between 500 m and 1200 m, corresponding to the large ISOPRD values shown in Fig. 9b. Other RO_2 , like ISOPo_2 , XO_2 , and HO_2 , also showed significant increases during Stage II compared to Stage I and Stage III (Fig. S10).

With the development of the daytime convective boundary layer, RO_2 would gradually mix downward, leading to an enhanced atmospheric oxidizing capacity. This highly oxygenated environment could facilitate the chemical conversion of NO to NO_2 . As a result, converted NO_2 underwent photolysis and formed ozone afterward, contributing to the ozone pollution belt in Fig. S9 in the week-long pollution episode.

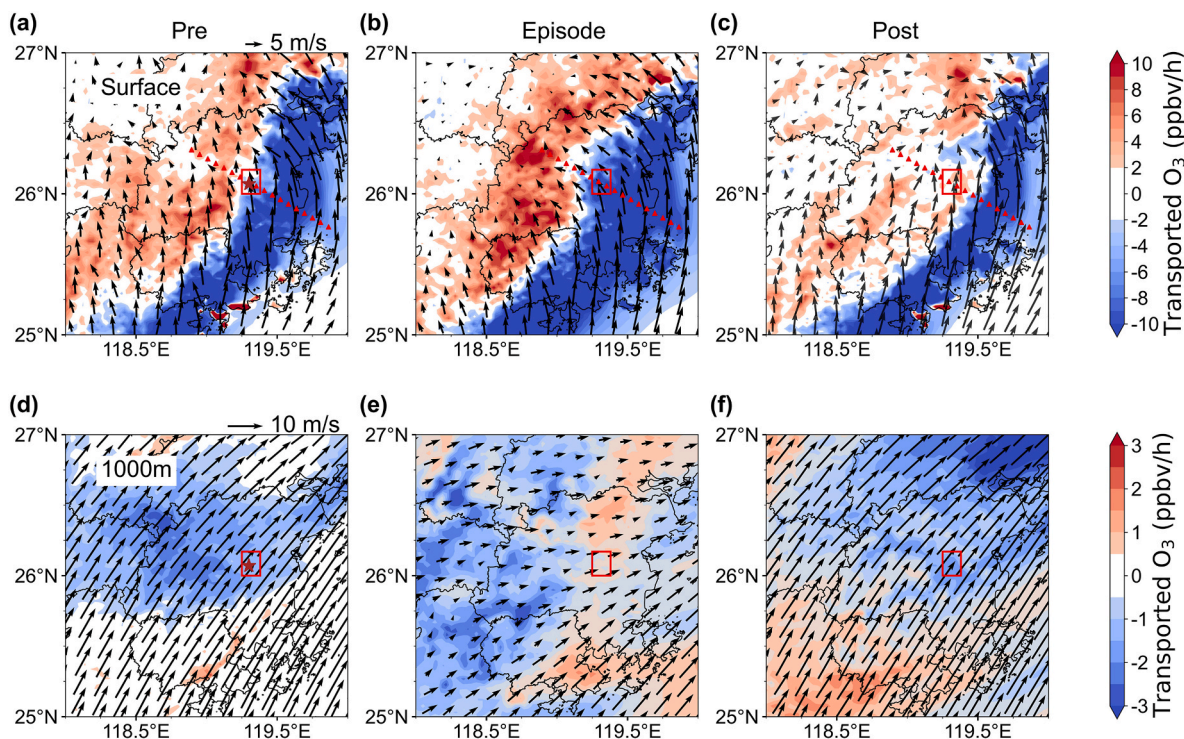


Fig. 8. Simulated transported ozone (color shading) and wind field (vector) (a–c) near the surface in the afternoon (14:00–17:00 LST) and (d–f) at 1000 m in the early morning (03:00–06:00 LST) during 3 stages. The red rectangle denotes the urban region in Fuzhou. The red triangle markers denote the selected cross-section transect.

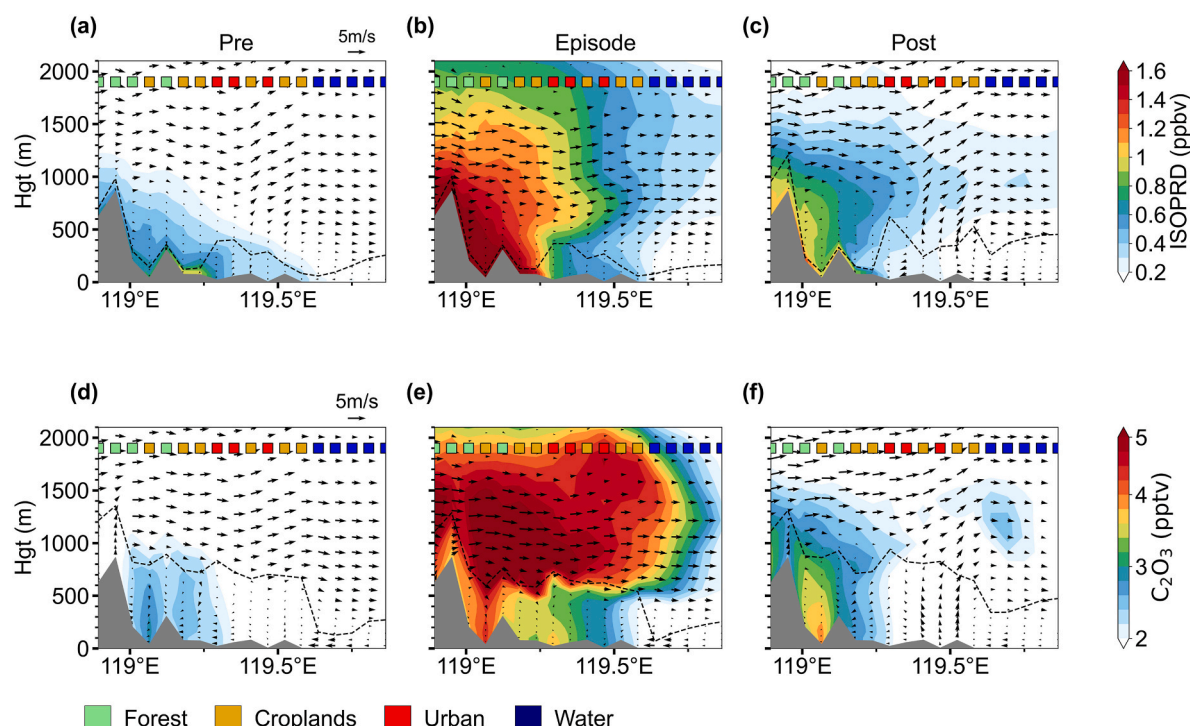


Fig. 9. Simulated concentrations of ISOPRD and winds at 06:00 LST (a–c) and C_2O_3 and winds at 08:00 LST (d–f) along the transect during 3 stages. Square markers at the top represent different land-use types. The black dashed lines indicate the top of the boundary layer.

Table 2

Simulated concentrations of typical species of RO_2 and gases at 08:00 LST involved in the ozone formation process.

	Stage I	Stage II	Stage III
C_2O_3 (pptv)	1.93 ± 0.45	3.37 ± 0.44	1.69 ± 0.49
XO_2 (pptv)	7.39 ± 1.26	10.69 ± 1.21	7.11 ± 1.49
HO_2 (pptv)	20.54 ± 3.52	30.22 ± 3.04	18.27 ± 4.14
HCHO (ppbv)	4.65 ± 0.70	7.52 ± 0.86	5.12 ± 0.92
NO_2 (ppbv)	4.35 ± 0.66	5.98 ± 1.14	5.59 ± 0.54

Table 2 quantitatively summarizes the daytime near-surface concentration of key RO_2 and gases at 08:00 during the three stages in Fuzhou. Notable peaks of all these species during Stage II were observed, including formaldehyde (HCHO), a key intermediate product of VOCs oxidation. HCHO contributed to ozone formation through photolysis, which generated HO_2 radicals that participated in the NO-to- NO_2 conversion cycle. Thus, HCHO played a dual role as an indicator and an active participant in photochemical ozone production. Increases in precursors were also found in the other two major cities in MBRR (Putian and Quanzhou), as listed in Tables S3 and S4, suggesting they shared a similar mechanism in this WPSH-induced regional ozone pollution episode.

4. Conclusions

The WPSH is a crucial high-pressure system often associated with high temperatures and clear weather in regions covered by its center, providing an environment favorable for ozone formation. Using observational and reanalysis data, we found that both seasonal and monthly ozone concentrations in southeastern China were closely correlated with the summer intensity and zonal displacement (particularly the westward extension) of the WPSH. Specifically, variations in the western boundary and spatial coverage of the WPSH had the strongest influence on ozone levels over the Meizhou Bay Rim Region (MBRR), a coastal urban cluster consisting of Fuzhou, Putian, and Quanzhou. The ozone responses were

spatially consistent across the three cities, indicating a coherent regional-scale impact of WPSH variability. While other factors, including localized precursor emissions, regional transport, and boundary layer dynamics, influence ozone levels, the synoptic system WPSH can exert a significant impact on regional ozone pollution through its variations in zonal displacement and intensity.

To disentangle the dynamic and chemical processes in WPSH-associated ozone pollution, we focused on a week-long regional ozone pollution episode in July 2022, when the WPSH extended unusually far westward. Reanalysis data and WRF-Chem simulations showed that the clear and hot weather conditions under the deep high-pressure system led to stronger downward solar radiation and reduced low cloud cover, accelerating the photochemical ozone formation. Nevertheless, biogenic VOCs emitted by forests in western Fujian also played a crucial role in the chemical processes, aided by the background circulations and local sea breeze. In afternoons during the pollution episode, sea breezes transported ozone-rich air masses from the coastal cities westward, where they reacted with BVOCs such as isoprene, producing high-concentration oxidant products like ISOPRD. At night, nocturnal westerlies transported ISOPRD back to the city regions, contributing to the increase in RO_2 on the following day through photolysis and reaction with OH. More RO_2 in the air could then facilitate ozone formation in the urban areas by increasing the atmospheric oxidizing capacity (AOC), leading to persistent regional ozone pollution. The influence of the westward-extended intensified WPSH enhanced the photochemical ozone formation by 25%–28% in MBRR, resulting in nearly a 90% increase in ozone concentrations. The dynamic and chemical processes of this pollution event, triggered by sea breeze under the control of strong inland-extended WPSH, are summarized in the schematic diagram shown in Fig. 10. Observational data from 2023 to 2024 further reveal multiple ozone pollution episodes where the westward expansion and enhancement of the WPSH acted as a key forcing to regional ozone elevation (Fig. S11–13).

Ozone pollution has emerged as an increasing threat to public health, with summertime concentrations exhibiting a rising trend across many regions, including southeastern coastal cities in China. In this study, we

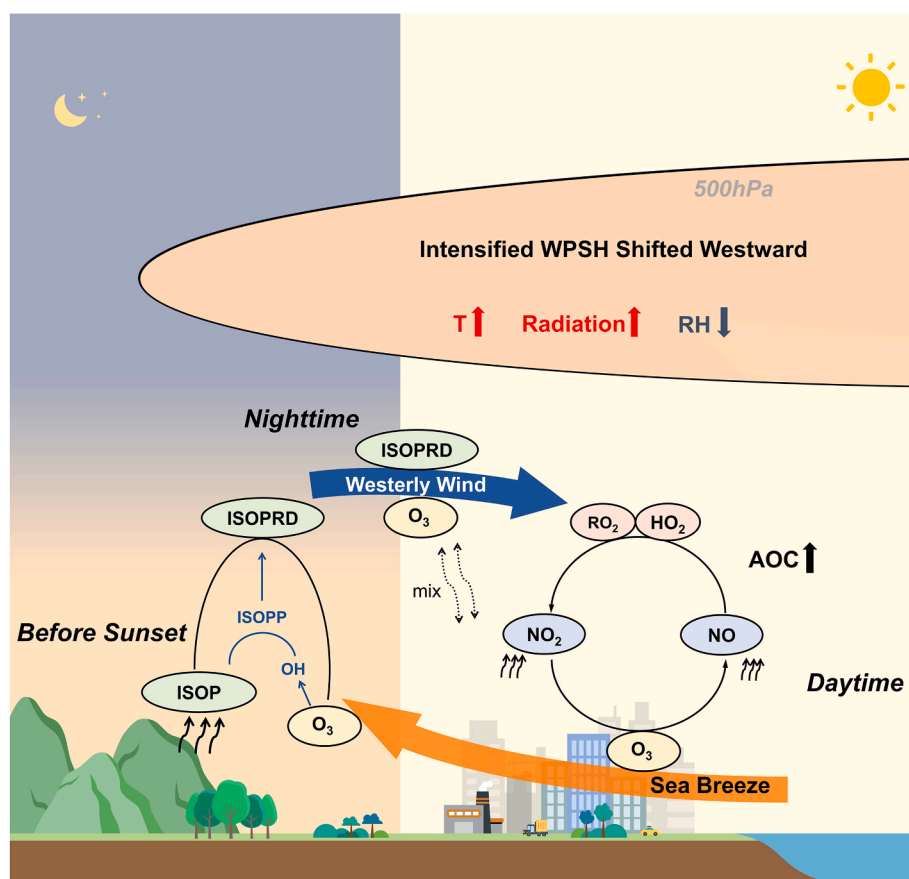


Fig. 10. Schematic diagram illustrating the mechanism of ozone enhancement induced by local-scale circulation and anthropogenic-biogenic emission interaction under extremely inland-extended WPSH.

highlight how large-scale atmospheric systems can modulate regional ozone pollution through weather conditions and local-scale circulation, incorporating different emission sources from both anthropogenic activities and natural biogenic processes. In the context of global and regional climate change, the interactions among topography, synoptic weather systems, and atmospheric chemistry should receive greater attention in pollution forecasting and management.

Data availability statement

The data related to the WRF-Chem modeling are available at https://github.com/Zhao-nju/Fujian_ozone_research. Topographic data were obtained from the ETOPO Global Relief Model at <https://www.ncei.noaa.gov/products/etopo-global-relief-model>. The shapefile data of China are available at <https://www.heywhale.com/mw/dataset/62da07fe3915ed2e06b1c135/file>. ERA5 reanalysis data (geopotential, u/v-component wind, solar radiation, cloud cover, etc.) are available at <https://cds.climate.copernicus.eu/datasets>. In situ meteorological observations from sites in Fujian Province were provided by the Fujian Provincial Department of Environmental Protection and can be made available on request. WPSH index data can be obtained from https://cmdp.ncc-cma.net/Monitoring/cn_stp_wpshp.php. Observed ground-level O₃, NO, and NO₂ observation data can be obtained from the China National Environmental Monitoring Center at <http://www.cnemc.cn>.

Other data and codes can be made available on request.

CRedit authorship contribution statement

Lanbo Zhao: Data curation, Formal analysis, Investigation,

Methodology, Visualization, Writing – original draft, Writing – review & editing. **Lian Xue:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Chengchun Shi:** Investigation, Methodology. **Chuanyou Ying:** Investigation, Methodology. **Erling Ni:** Investigation, Methodology. **Haoran Zhang:** Investigation, Methodology. **Xueyu Zhou:** Investigation, Methodology. **Tianshuai Li:** Investigation, Methodology. **Xin Huang:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing. **Aijun Ding:** Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.atmosenv.2026.121907>.

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