Formation drivers and photochemical effects of $ClNO_2$ in a coastal city of Southeast China

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Abstract. Nitryl chloride ($ClNO_2$) is an important precursor of chlorine (Cl) radical, significantly affecting ozone (O_3) formation and photochemical oxidation. However, the key drivers of $ClNO_2$ production are not fully understood. In this study, the field observations of $ClNO_2$ and related parameters were conducted in a coastal city of Southeast China during the autumn of 2022, combining with machine learning and model simulations to elucidate its key influencing factors and atmospheric impacts. Elevated concentrations of $ClNO_2$ (> 500 ppt) were notably observed during nighttime in late autumn, accompanied by increased levels of dinitrogen pentoxide (N_2O_5) and nitrate (NO_3^-). Nighttime concentrations of $ClNO_2$ peaked at 3.4 ppb, while its daytime levels remained significant, reaching up to 100 ppt and sustaining at approximately 40 ppt at noon. Machine learning and field observations identified nighttime N_2O_5 heterogeneous uptake as the predominant pathway for $ClNO_2$ production, whereas NO_3^- photolysis contributed to its daytime generation. Additionally, ambient temperature (T) and relative humidity (RH) emerged as primary meteorological factors affecting $ClNO_2$ formation, mainly through their effects on thermal equilibrium and N_2O_5 hydrolysis processes, respectively. Ultraviolet (UV) radiation was found to play a dual role in $ClNO_2$ concentrations around noon. Box model simulations showed that under high $ClNO_2$ conditions, the rates of alkane oxidation by Cl radical in the early morning exceeded those by OH radical. Consequently, VOC oxidation by Cl radical contributed ~ 19% to RO_x production rates, thereby significantly impacting O_3 formation and atmospheric oxidation capacity. This research enriched the understanding of $ClNO_2$ generation and loss pathways, providing valuable insights for the regulation of photochemical pollution in coastal regions.

1 Introduction

Chlorine (Cl) radical, as an important atmospheric oxidant, can react with volatile organic compounds (VOCs) to affect RO_x (including OH, HO_2, and RO_2) radicals and ozone (O_3) formation (Yi et al., 2023), thereby perturbing atmospheric chemical components and air quality (Peng et al., 2021; Li et al., 2020). The reaction rates between Cl radical and some alkanes are several orders of magnitude faster than those involving OH radical (Atkinson et al., 2006). Furthermore, the related studies indicated that the production rates of Cl radical in the early morning could significantly exceed the production rates of OH radical formed via O_3 photolysis (Phillips et al., 2012; Tham et al., 2016), thereby enhancing the atmospheric oxidation capacity.

Nitryl chloride ($ClNO_2$) is one of the major Cl radical precursors in the tropospheric atmosphere (Thornton et al., 2010; Xue et al., 2015; Liu et al., 2017). It is mainly generated by the heterogeneous uptake of dinitrogen pentoxide (N_2O_5) on chloride-containing aerosols (Finlayson-Pitts et al., 1989; Thornton et al., 2010), among which N_2O_5 is produced through the equilibrium reaction with nitrogen dioxide (NO_2) and nitrate (NO_3) radical. Since Osthoff et al. (2008) firstly detected over 1 ppb of $ClNO_2$ in the urban outflows of America (Osthoff et al., 2008), significant production of $ClNO_2$ has been widely observed in the polluted coastal and inland areas with abundant anthropogenic emissions and chloride sources, with concentrations ranging from tens of ppt to several ppb (Riedel et al., 2012; Mielke et al., 2013; Mielke et al., 2011; Phillips et al., 2012; Bannan et al., 2015; Wang et al., 2016; Xia et al., 2020; Xia et al., 2021; Yun et al., 2018a; Wang et al., 2022; Li et al., 2023). For the diurnal profile of $ClNO_2$, its concentrations generally peaked and accumulated at midnight, then rapidly decreased to low levels due to strong photolysis after sunrise (Ma et al., 2023; Mielke et al., 2011; Xia et al., 2020). However, elevated daytime concentrations of $ClNO_2$ have been observed in field studies, mainly attributed to reduced photolysis rates under heavy cloud or fog cover, as well as contributions from horizontal and vertical transport (Tham et al., 2016; Xia et al., 2021; Jeong et al., 2019; Mielke et al., 2013; Bannan et al., 2015). Notably, the recent laboratory research demonstrated that nitrate (NO_3^-) photolysis can generate $ClNO_2$ alongside Cl_2 (Dalton et al., 2023), yet this mechanism has not been confirmed under real atmospheric conditions.

At present, the observation studies of $ClNO_2$ focused on investigating its influencing factors, such as the N_2O_5 uptake coefficient and the production yield of $ClNO_2$ (Thornton et al., 2003; Tham et al., 2018). The field and laboratory studies have indicated that $ClNO_2$ production was mainly affected by ambient temperature (T), relative humidity (RH), and particle components (e g., chloride (Cl^-), NO_3^-, and liquid water content) (Bertram and Thornton, 2009; Wang et al., 2023; Wang et al., 2020). In addition to

influencing factors, the photochemical effects of $ClNO_2$ photolysis have been extensively evaluated (Xue et al., 2015; Xia et al., 2021; Tham et al., 2016). Cl radical released by $ClNO_2$ photolysis will oxidize VOCs to promote the formation RO_2 radical and O_3, greatly compensating for the underestimation of RO_2 radical and O_3 generation in model simulations (Peng et al., 2021; Ma et al., 2023). The field measurements of $ClNO_2$ have been conducted in different atmospheric environments, while the key drivers of $ClNO_2$ chemistry were still not well recognized. Moreover, it is pertinent to explore whether there are additional and unrecognized sources of $ClNO_2$ beyond its heterogeneous generation from N_2O_5.

In this study, the comprehensive measurements of $ClNO_2$ and related parameters were conducted in a coastal city of Southeast China during the autumn of 2022. Field observations, combined with a machine learning model, were used to reveal the key driving factors of $ClNO_2$ formation. Furthermore, we further investigated the potential mechanisms driving daytime $ClNO_2$ generation. Additionally, we also assessed the photochemical impacts of $ClNO_2$ based on a box model. Overall, this study underscored the important role of NO_3^- in the $ClNO_2$ chemistry.

2 Materials and methods

2.1 Field Measurements

The intensive field measurements of $ClNO_2$, related precursors, and meteorological parameters from October 9th to December 5th, 2022 were performed at an urban site (Institute of Urban Environment, Chinese Academy of Sciences) in a coastal city (Xiamen) of Southeast China (Fig. S1). Here, $ClNO_2$, N_2O_5, gaseous pollutants (volatile organic compounds (VOCs), NO_x, SO_2, CO, and O_3), aerosol mass concentrations, ionic components, size distribution, and meteorological factors were simultaneously detected. Meanwhile, an iodide-adduct time-of-flight chemical ionization mass spectrometer (I^--ToF-CIMS) was used to measure $ClNO_2$ and N_2O_5. The principles and settings of I^--ToF-CIMS were similar with previous studies (Ma et al., 2023; Yan et al., 2023). Detailed descriptions of this observation site and instruments have been provided in previous work (Chen et al., 2024; Hu et al., 2022), Text S1, and Table S1. For the calibrations of $ClNO_2$ and N_2O_5, $ClNO_2$ was produced by passing Cl_2 (6 ppm in N_2) through a moist mixture of sodium nitrite ($NaNO_2$) and sodium chloride (NaCl) (Thaler et al., 2011; Wang et al., 2022), and N_2O_5 was synthesized by the reactions of O_3 and excessive NO_2 (Tham et al., 2016; Wang et al., 2016). The dependences of $ClNO_2$ and N_2O_5 sensitivities on relative humidity are presented in Fig. S2. The uncertainties of the $ClNO_2$ and N_2O_5 measurements were estimated to be ~20 %. The details of $ClNO_2$ and N_2O_5 calibrations and uncertainty analysis are displayed in Text S2.

2.2 Machine Learning model

Here, the extreme gradient boosting (XGBoost) model coupling with the Shapely additive explanations (SHAP) model (the XGBoost-SHAP model) was used to identify the key influencing factors of $ClNO_2$ formation. Meanwhile, the XGBoost model was applied to establish the predictive model of $ClNO_2$ based on the observed data of gaseous precursors and meteorological factors; the SHAP model was employed to evaluate the importance of each feature affecting the simulated concentrations of $ClNO_2$. The SHAP model is an interpretability tool designed to analyze the contributions of individual features to model predictions. It employs an additive explanatory framework that considers all features as contributors, drawing inspiration from cooperative game theory. For each predicted instance, SHAP assigns a Shapley value, representing the cumulative contribution of each feature. Positive SHAP values indicate that a feature increases the model's predicted outcome, signifying a positive contribution. Conversely, negative SHAP values suggest that the feature reduces the predicted value, reflecting a negative contribution. The absolute value of the SHAP score reflects the magnitude of the contribution, regardless of direction, offering insight into the overall importance of the feature. The true value, on the other hand, reveals the direction of the contribution (positive or negative), facilitating a clearer understanding of the relationship between the feature and the prediction. Besides, the partial dependence plot (PDP) analysis offers a visual representation of the marginal effect that the factors have on the model's predicted outcome. It is based on the principle of stabilizing the values of non-target features, and systematically altered the target feature's values according to the model's algorithmic framework to derive the predicted values.

$ClNO_2$ concentrations served as the dependent variable, with trace gases (SO_2, CO, NO_2, NO, O_3, and N_2O_5), $PM_{2.5}$ and its inorganic compositions (NO_3^-, SO_4^{2-}, NH_4^+, and Cl^-), and meteorological parameters (T, RH, UV, WS, WD, and BLH) acting as independent variables. The simulated $ClNO_2$ concentrations by the XGBoost model were highly similar with the observed values (R^2=0.91), indicating the good performance of the XGBoost model (Fig. S3). Detailed introductions and settings of the XGBoost-SHAP model are provided in Text S3.

2.3 The box model

The observation-based model (OBM) was utilized to assess the impacts of $ClNO_2$ on photochemically atmospheric oxidation. As delineated in earlier studies (Xue et al., 2015; Tham et al., 2016; Xia et al., 2021; Peng et al., 2021; Peng et al., 2022), the Master Chemical Mechanism (MCM, version 3.3.1) was adopted, and established chlorine chemistry mechanisms have been integrated. The Tropospheric Ultraviolet and Visible Radiation (TUV) model was used to calculate $ClNO_2$ photolysis rates ($J$$ClNO_2$) under clear-sky

conditions. The simulated $J\mathrm{ClNO_2}$ values were then scaled based on field-measured $J\mathrm{NO_2}$ values. A thorough exposition of the box model configuration can be found in our previous publications (Liu et al., 2022b; Liu et al., 2022a) and Text S4. Observation data, including $\mathrm{ClNO_2}$, VOCs, HCHO, HONO, CO, $\mathrm{O_3}$, NO, $\mathrm{NO_2}$, $\mathrm{SO_2}$, along with meteorological factors as constraint were input into the box model at an hourly resolution (Table S2). Due to the levels of $\mathrm{ClNO_2}$ in the box model determined by observed levels of $\mathrm{ClNO_2}$, the parametrization for $\mathrm{N_2O_5}$ uptake and $\mathrm{ClNO_2}$ yield was not utilized in the box model. Two scenarios were examined: one representing observation-average conditions from October 9th to December 5th, the other reflecting a high $\mathrm{ClNO_2}$ case observed on November 28th.

This study focused on elucidating the influence of $\mathrm{ClNO_2}$ on the formation of $\mathrm{RO_x}$ radical and $\mathrm{O_3}$. The $\mathrm{O_3}$ production rate minus the $\mathrm{O_3}$ loss rate was used to calculate the net $\mathrm{O_3}$ production rate (Eq. S1-3). The AOC is calculated by the sum of the rates of $\mathrm{CH_4}$, CO, and VOCs oxidized by atmospheric oxidants ($\mathrm{O_3}$, OH, Cl, and $\mathrm{NO_3}$ radical) (Eq. S4) (Xue et al., 2015; Yi et al., 2023). Both scenarios were evaluated with and without including $\mathrm{ClNO_2}$ inputs to assess its impacts on these processes.

3 Results and discussion

3.1 Overview of observations

Fig. 1 displays the time series of $\mathrm{ClNO_2}$, $\mathrm{N_2O_5}$, and related parameters including $\mathrm{O_3}$, $\mathrm{NO_x}$, $\mathrm{PM_{2.5}}$, $\mathrm{Cl^-}$, $\mathrm{NO_3^-}$, and meteorological parameters during the autumn observation period. Our observation shows a decline in T and UV values from October to November, with average RH values increasing from ~ 60% in October to ~ 70% in November (excluding rainy days). During the entire measurement period, $\mathrm{ClNO_2}$ concentrations exhibited significant variability, with elevated levels (> 500 ppt) frequently observed in late autumn, particularly after November 10th. The elevation of $\mathrm{ClNO_2}$ concentrations coincided with increased levels of $\mathrm{N_2O_5}$ and $\mathrm{NO_3^-}$ during late autumn. The concentrations of $\mathrm{ClNO_2}$ at our study site reached several ppb, compared with previous field measurements conducted at urban, suburban, rural, background, and mountain sites (Table S3), indicating its widespread presence in diverse atmospheric environments. The highest concentrations of $\mathrm{ClNO_2}$ were detected during the night of November 27th, with a maximum hourly average of 3.4 ppb. Peak concentrations of $\mathrm{N_2O_5}$ and $\mathrm{NO_3^-}$ were also observed on that night (Fig. 1). On the evening of November 27th, $\mathrm{N_2O_5}$ concentrations rapidly decreased after 7 p.m., while $\mathrm{ClNO_2}$ and $\mathrm{NO_3^-}$ concentrations significantly increased, reflecting fast $\mathrm{N_2O_5}$ heterogeneous hydrolysis and effective formation of $\mathrm{ClNO_2}$. Notably, on the following day (November 28th) (Fig. 2a), $\mathrm{ClNO_2}$ concentrations sustained above 100 ppt around noon, partially related with weaken UV values (~ 14 $\mathrm{W \cdot m^{-2}}$) under heavy fog and cloud

cover, with the RH values of ~ 70% at that time. Similar research in California has shown $ClNO_2$ concentrations exceeding 100 ppt after sunrise 4 hours due to reduced photolysis (Mielke et al., 2013).

The average diurnal changes of $ClNO_2$ and related parameters during the entire measurement campaign are depicted in Fig. 2b. As expected, $ClNO_2$ exhibited a distinct diurnal variation, peaking and accumulating after sunset and decreasing in the early morning. However, $ClNO_2$ concentrations remained ~ 40 ppt around noon, different with some studies that $ClNO_2$ concentrations decreased to near the detection limit around midday (Wang et al., 2022; Niu et al., 2022). Similar observation in North China declared $ClNO_2$ concentrations above 60 ppt in the afternoon (Liu et al., 2017). Previous studies have indicated that abundant $ClNO_2$ may be transported from upper atmosphere or air mass, contributing to the elevated $ClNO_2$ concentrations in the early morning (Tham et al., 2016; Xia et al., 2021; Jeong et al., 2019). However, the explanations for the concentrations of $ClNO_2$ around noon remained elusive.

To evaluate the contribution of the heterogeneous N_2O_5 uptake to daytime $ClNO_2$ levels, we calculated $ClNO_2$ production using Eq. (S7), considering the loss of $ClNO_2$ through photolysis. This method has been employed in a previous study (Text S4-S5) (Tham et al., 2016). We used a $\gamma(N_2O_5)$ value of 0.06 and a $\phi(ClNO_2)$ value of 1.0 in our calculations, which represent upper-end estimates based on previous field studies (Mcduffie et al., 2018a; Mcduffie et al., 2018b; Tham et al., 2016). However, as shown in Fig. 3, the calculated $\phi(ClNO_2)$ with $\gamma(N_2O_5) = 0.06$ fails to reproduce the observed levels of daytime $ClNO_2$. A larger $\gamma(N_2O_5)$ of 0.11 would be necessary, but such high uptake coefficients and yields are not supported by the current literature. Therefore, we believe that the observed daytime $ClNO_2$ levels, particularly around noon, cannot be adequately explained by heterogeneous N_2O_5 uptake alone, suggesting the presence of additional sources contributing to the formation of daytime $ClNO_2$.

3.2 Key drivers of $ClNO_2$ formation

The XGBoost-SHAP model was employed to investigate the major drivers of $ClNO_2$ production during the whole observation period. The average absolute SHAP value of each feature was ranked to determine the key drivers of $ClNO_2$ formation, with larger SHAP values suggesting greater contributions (Fig. 4a). Additionally, features with positive SHAP values (depicted as red points) indicate that higher values of those features positively affect $ClNO_2$ concentrations, and vice versa (Fig. 4b). Overall, N_2O_5, NO_3^-, T, RH, and UV were the most important features affecting $ClNO_2$ concentrations. Notably, these factors exhibited varied behaviors between daytime and nighttime periods.

In our study, N_2O_5 was identified as the most important influencing factor, consistent with its role in

$ClNO_2$ formation through heterogeneous uptake processes (Thornton et al., 2010; Finlayson-Pitts et al., 1989). After sunset, $ClNO_2$ concentrations markedly increased due to active nighttime N_2O_5 chemistry, while this heterogeneous uptake process was hindered after sunrise as N_2O_5 concentrations decreased significantly (Fig. 1) (Niu et al., 2022; Wang et al., 2020; Tan et al., 2022). Indeed, the concentrations of $ClNO_2$ were evidently increased when N_2O_5 concentrations exceeded ~13 ppt, predominantly during the nighttime (Fig. 5a). Conversely, in Northern Europe, the $ClNO_2$ concentrations were mainly controlled by O_3 and NO_2, rather than by the heterogeneous uptake of N_2O_5 (Sommariva et al., 2018). In Heshan of South China, chloride and $PM_{2.5}$ were the major factors affecting $ClNO_2$ formation (Wang et al., 2022). Differently, the relative importance of NO_3^- derived from the XGBoost-SHAP result indicated that elevated $ClNO_2$ concentrations were associated with high concentrations of NO_3^- besides N_2O_5. According to Fig. 5b, high NO_3^- concentrations (> 3.7 $\mu g \cdot m^{-3}$) are accompanied by the elevation of $ClNO_2$, especially its concentrations reaching 6.2 $\mu g \cdot m^{-3}$. Previous studies suggested that increased concentrations of NO_3^- decreased $\gamma(N_2O_5)$, which would limit the production of $ClNO_2$ (Wahner et al., 1998; Mentel et al., 1999; Bertram and Thornton, 2009). As depicted in Fig. S4, the dependence of $\gamma(N_2O_5)$ on NO_3^- concentrations follows the nitrate suppression effect. Therefore, the importance of nighttime NO_3^- for $ClNO_2$ levels is that they are co-products from the processes of N_2O_5 heterogeneous uptake. As shown in Fig. 1, compared to low NO_3^- conditions, $ClNO_2$ production was enhanced in high NO_3^- conditions. Especially in late autumn, increased aerosol abundances and N_2O_5 levels increased N_2O_5 uptake further promoting $ClNO_2$ and NO_3^- production. Considering the limited contribution of N_2O_5 hydrolysis to daytime NO_3^- levels (Yan et al., 2023; Zang et al., 2022; Chen et al., 2020), the impact of high NO_3^- concentrations on daytime $ClNO_2$ concentrations warrants further analysis.

The simulated concentrations of $ClNO_2$, based on the XGBoost-SHAP model, were significantly elevated when NO_3^- concentrations were higher than 3.7 $\mu g \cdot m^{-3}$ (Fig. 5b). Consequently, the average daily concentrations of NO_3^- were classified as high (> 3.7 $\mu g \cdot m^{-3}$) and low (< 3.7 $\mu g \cdot m^{-3}$) to further elucidate the impacts of NO_3^- on the formation of $ClNO_2$. Fig. 6 presents the diurnal variations in the relative importance of factors based on the SHAP values under high and low NO_3^- concentrations. Unexpectedly, daytime NO_3^- was the dominant influencing factors for daytime $ClNO_2$ (Fig. 6a). High concentrations of daytime NO_3^- positively affected the daytime concentrations of $ClNO_2$, independent of N_2O_5 uptake processes. As depicted in Fig. 6a, daytime N_2O_5 did not promote the elevation of daytime $ClNO_2$. Negative SHAP values for N_2O_5 during the daytime indicate that the contribution of N_2O_5 chemistry to daytime $ClNO_2$ levels was limited. Therefore, it is very likely that high concentrations of daytime NO_3^- participated in daytime $ClNO_2$

production. A recent study suggested that nitrate photolysis produced $ClNO_2$ in addition to Cl_2 (Dalton et al., 2023), while it has been not verified by field observations. Fig. 7 shows that daytime $ClNO_2$ concentrations correlated well (R=0.62) with the product of a proxy of NO_3^- photolysis ($NO_3^-\times JNO_2\times S_a$) on aerosol surfaces ($S_a$), implying that the photolysis of NO_3^- contributed to the daytime concentrations of $ClNO_2$ at our study site. Furthermore, high concentrations of NO_3^- and Cl^-, along with large values of S_a (Fig. 7a, b, c) in the daytime accelerated NO_3^- photolysis, promoting the formation of $ClNO_2$. Overall, N_2O_5 uptake processes were the major pathways dominating nighttime $ClNO_2$ formation, while NO_3^- photolysis contributed to daytime $ClNO_2$ production during our observation period.

In term of meteorological factors, UV, T, and RH were the major influencing factors. The photolysis was the most important sink of $ClNO_2$ in the daytime, leading to a rapid reduction in $ClNO_2$ concentrations, particularly in the early morning (Fig. 5e and Fig. 6). However, it is crucial to understand the dual role of photolysis intensity in determining daytime $ClNO_2$ levels. Photolysis can contribute to the generation of $ClNO_2$ by promoting NO_3^- photolysis, while also causing the rapid decomposition of $ClNO_2$. As reported in California (Mielke et al., 2013), reduced photolysis rates even increased daytime $ClNO_2$ levels by decreasing $ClNO_2$ loss through photolysis. The impact of ambient temperature on $ClNO_2$ was probably reflected in its thermal equilibrium with N_2O_5. Elevated daytime ambient temperature suppressed the formation of N_2O_5, resulting in low N_2O_5 concentrations, which further limited the contribution of heterogeneous N_2O_5 uptake to daytime $ClNO_2$ generation (Fig. 5c and Fig. 6). During the whole observation period from October to November, the drop in ambient temperature facilitated $ClNO_2$ production by decreasing the thermal decomposition process. Increased RH values provided favorable conditions for the nighttime N_2O_5 hydrolysis reactions, thereby affecting $ClNO_2$ production (Fig. 5d and Fig. 6), while high RH (> 80%) also weakened the generation of $ClNO_2$. Notably, Cl^- was not the most important factors of $ClNO_2$ formation at our study site (Fig. 4), likely attributed to the abundant chlorine source in coastal regions (Peng et al., 2022).

3.3 Impact of $ClNO_2$ photolysis on RO_x budget

The photochemical effects of $ClNO_2$ were evaluated under the observation-average condition and the high $ClNO_2$ case based on the box model. The largest Cl production rates (P(Cl)) contributed from $ClNO_2$ photolysis were 0.05 $ppb\cdot h^{-1}$ for the observation-average condition, which was lower than 0.19 $ppb\cdot h^{-1}$ for the high $ClNO_2$ case. The difference led to variable levels of atmospheric oxidation capacity induced by Cl radical. Cl radical released via the photolysis of $ClNO_2$ initiated the oxidation of VOCs. Among VOC groups (including alkanes, alkenes, alkynes, aromatics and OVOCs), Cl radical primarily oxidized alkanes

(~ 65.0%), followed by OVOCs (~ 12.7%) for both the observation-average condition and the high $ClNO_2$ case (Fig. 8a, b). The contributions of Cl radical and other atmospheric oxidants (including OH radical and O_3) to daytime VOC oxidation were also compared (Fig. 8c, d and Table 1). In our study, the oxidation of alkanes by Cl radical for the observation-average condition were about 11.7%, which increased by 44.8% for the high $ClNO_2$ case, were higher than those in London (Bannan et al., 2015), Weybourne (Bannan et al., 2017), Boston (Rutherford et al., 1995), and LA (Fraser et al., 1997), lower than that in Hong Kong (Xue et al., 2015). It should be noticed that the rates of Cl radical reacting with alkanes even exceeded those of OH radical in the early morning for the high $ClNO_2$ case. The largest rates of alkanes oxidized by Cl radical were approximately twice as high as those of OH radical at 10 a.m. (Fig. 8e, f), highlighting that the photochemical effects of Cl radical released via $ClNO_2$ photolysis were particularly important for VOC oxidation during the morning hours at our study site.

The oxidation of VOCs by Cl radical further affects the generation of RO_x (OH + HO_2 + RO_2) radicals. The RO_x radical production rates for the high $ClNO_2$ case were evidently lower than that under the observation-average condition, primarily due to reduced photolysis rates on that day. However, the total RO_x radical production rates averagely increased by 23.8% with $ClNO_2$ photolysis for the high $ClNO_2$ case, higher than a 4.9% increase for the observation-average condition (Fig. S5). For the observation-average condition, O_3 (32.7%), HONO (31.7%), and OVOCs (21.6%) photolysis were the most significant contributors to RO_x radical production in the early morning (7-10 a.m.), with VOC oxidation by Cl radical contributing only 3.7% (Fig. 9a). However, for the high $ClNO_2$ case, VOC oxidation induced by Cl radical in the early morning accounted for 19.1% of RO_x radical production, which was higher than O_3 (7.4%) and HCHO (4.1%) photolysis, close to OVOCs (19.0%) photolysis (Fig. 9b). The contributions of $ClNO_2$ photolysis to the RO_x radical production rates in our study were larger than previous results observed in autumn of Heshan (Wang et al., 2022) and North China (Xia et al., 2021), similar with that in summer of Wangdu (Tham et al., 2016). Thus, the concentrations of OH, HO_2, and RO_2 radicals in the box model with $ClNO_2$ inputs averagely increased by 17.9%, 34.6%, and 54.3% for the high $ClNO_2$ case, higher than the increases of 3.7%, 7.1%, and 10.3% contributed from the observation-average conditions, respectively (Fig. S6). The uplift in the concentrations of RO_x radicals also accelerated the generation of O_3. The increase in the net O_3 production rates ($P(O_3)$) for the observation-average condition averagely reached 0.13 $ppb \cdot h^{-1}$ (15.8 %) in the daytime (Fig. 10a), while larger elevations in the net $P(O_3)$ were observed for the high $ClNO_2$ case (Fig. 10b), with a maximum of 0.64 $ppb \cdot h^{-1}$ (120 %) at 10 a.m. As a result, increased RO_x radical and O_3 greatly enhanced the atmospheric oxidation capacity (Fig. 10c, d), especially for the high

$ClNO_2$ case (up to 65%).

Table 2 summarizes the impacts of $ClNO_2$ photolysis on RO_x radical and O_3 production in our study and previous observations around the world (Xia et al., 2021; Wang et al., 2022; Tham et al., 2016; Wang et al., 2016; Xue et al., 2015; Bannan et al., 2017; Jeong et al., 2019), indicating that the photochemical impacts of $ClNO_2$ were variable in different atmospheric environments. At our study site, the effects of $ClNO_2$ photolysis on RO_x radical production were important, especially in the early morning. The enhanced RO_x radical production induced by $ClNO_2$ photolysis accelerated the chemical generation of O_3. Primary RO_x radical production rates (including O_3, HONO, HCHO, OVOCs, and $ClNO_2$) were considered as one of the most important parameters to O_3 formation (Lu et al., 2023). Therefore, the considerable contribution of $ClNO_2$ photolysis to primary RO_x radical production in the early morning may bring new challenges for O_3 alleviation.

Conclusions

In conclusion, we present two months of field measurements in the coastal area of Southern China during the autumn, coupled with machine learning and model simulations, providing new insights into $ClNO_2$ chemistry. Our observation shows the increase in the concentrations of $ClNO_2$ were accompanied by elevated concentrations of N_2O_5 and NO_3^-, low values of T and UV, and high values of RH. The nighttime heterogeneous uptake of N_2O_5 was identified as the major source of $ClNO_2$, while NO_3^- photolysis promoted the elevation of daytime $ClNO_2$ concentrations. Cl radical released by $ClNO_2$ photolysis after sunrise had important photochemical effects in the early morning. The photolysis of high $ClNO_2$ concentrations resulted in net O_3 production rates and atmospheric oxidation capacity levels increasing by 120% and 65%, respectively. Our results enhanced the understanding of $ClNO_2$ chemistry in coastal regions, calling for more observations and laboratory research to fully reveal its exact role in different atmospheric environments.

Data availability. Data are available upon request to Jinsheng Chen (jschen@iue.ac.cn).

Author contributions. JC provided funding support for field measurements, designed this study, and revised this manuscript. GC designed this study, analyzed the data, and wrote this manuscript. HW helped perform the calibrations and revised this manuscript. XF revised this manuscript. XF, HW, YT, ZL, XJ, LX, BH contributed to discussions of this manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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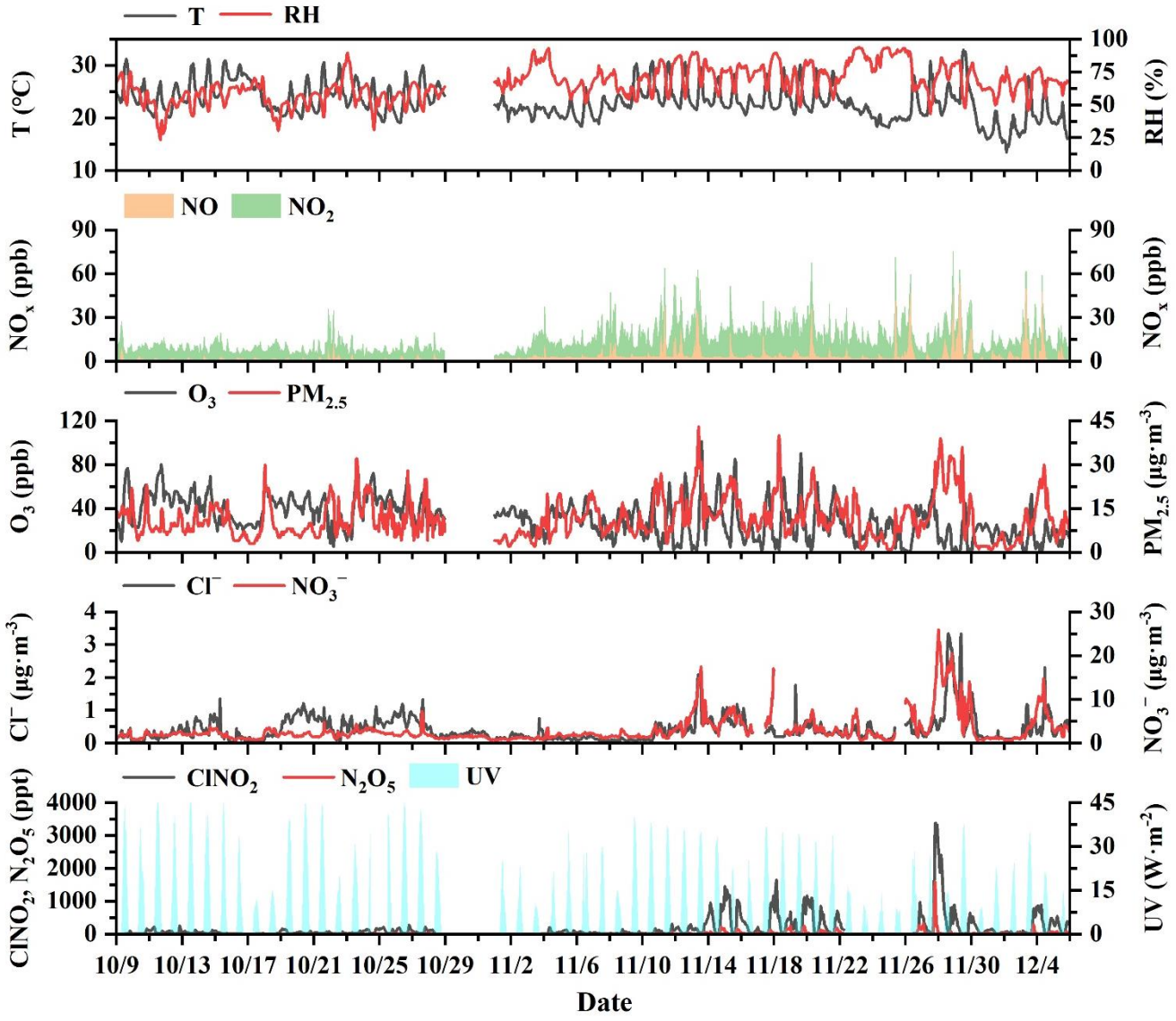


Figure 1. The time series of $ClNO_2$, related precursors, and meteorological parameters during the autumn observation period.

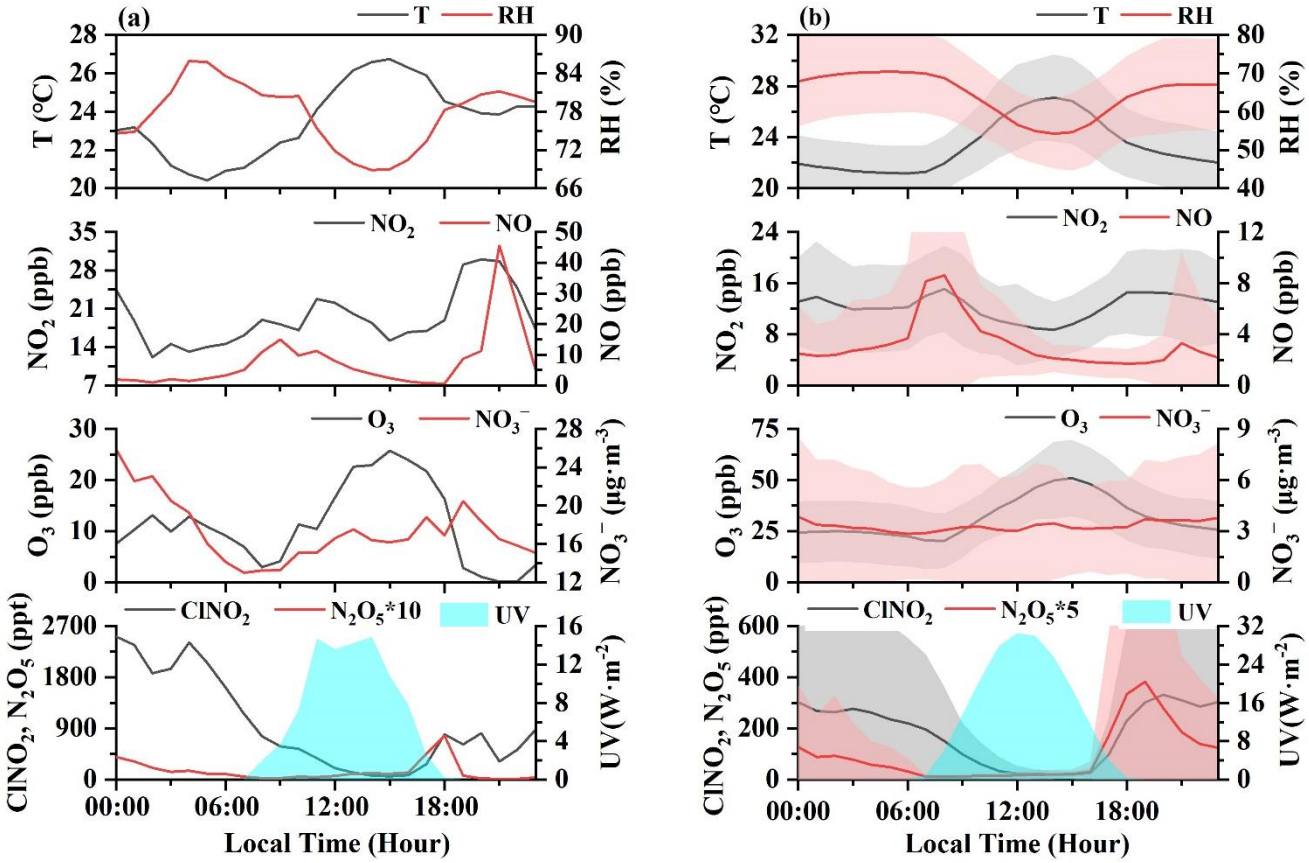


Figure 2. Diurnal variations of $ClNO_2$ and other related parameters for the highest concentrations of $ClNO_2$ (case) on November 28th (a) and the observation-average condition (from 9 October to 5 December) (b).

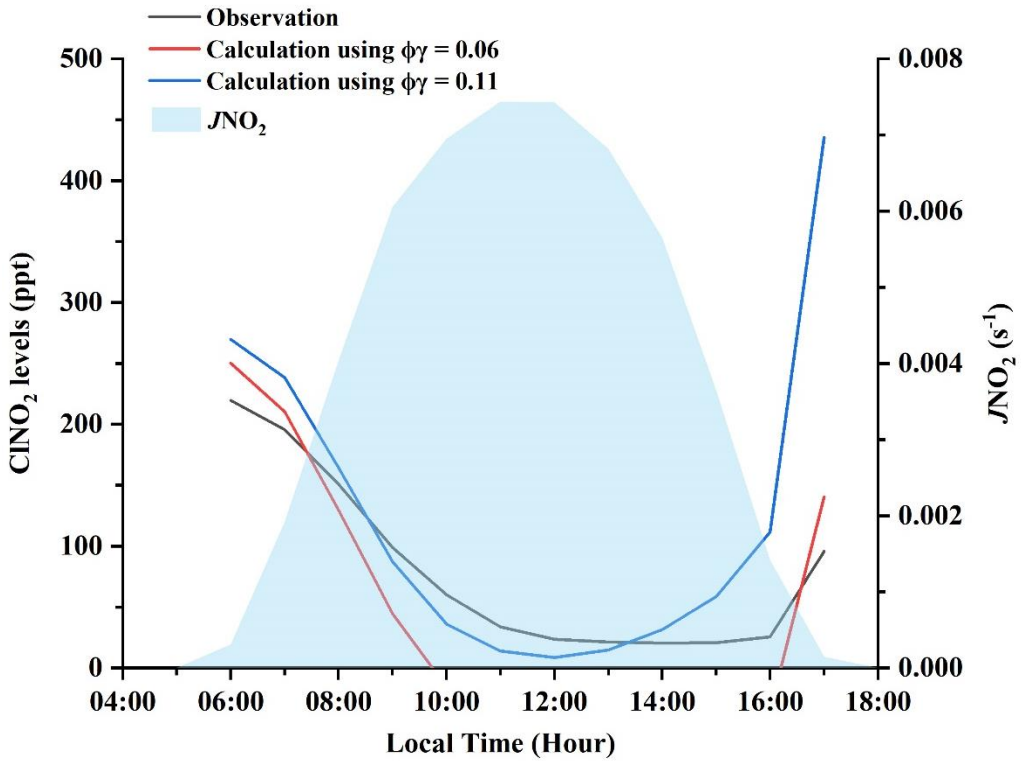


Figure 3. Comparisons of daytime $ClNO_2$ levels between observation, and calculation using Eq. (4) with a $\phi(ClNO_2)$ of 1.0 and a $\gamma(N_2O_5)$ of 0.06 ($\phi\gamma = 0.06$), or a $\phi(ClNO_2)$ of 1.0 and a $\gamma(N_2O_5)$ of 0.11 ($\phi\gamma = 0.11$).

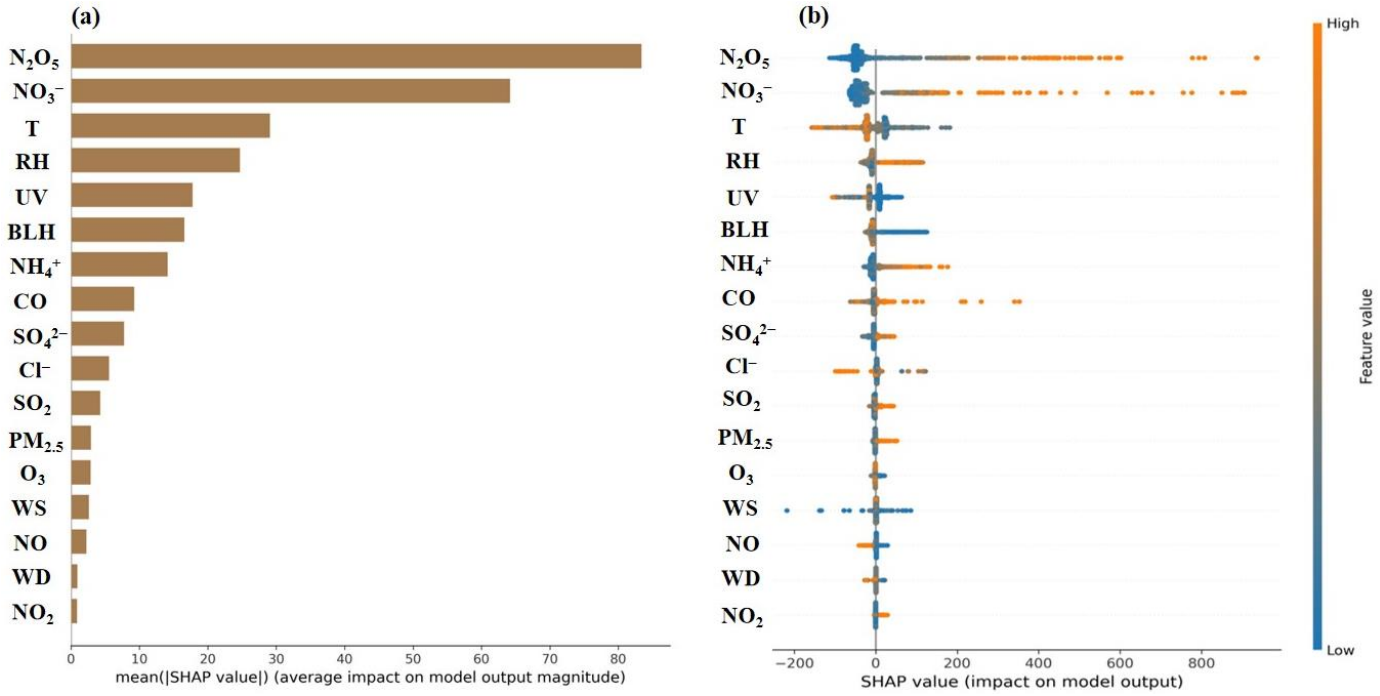


Figure 4. Relative importance of each feature to $ClNO_2$ using XGBoost-SHAP during the autumn observation period. The mean absolute SHAP value (a), summary plot of SHAP values of each feature (b).

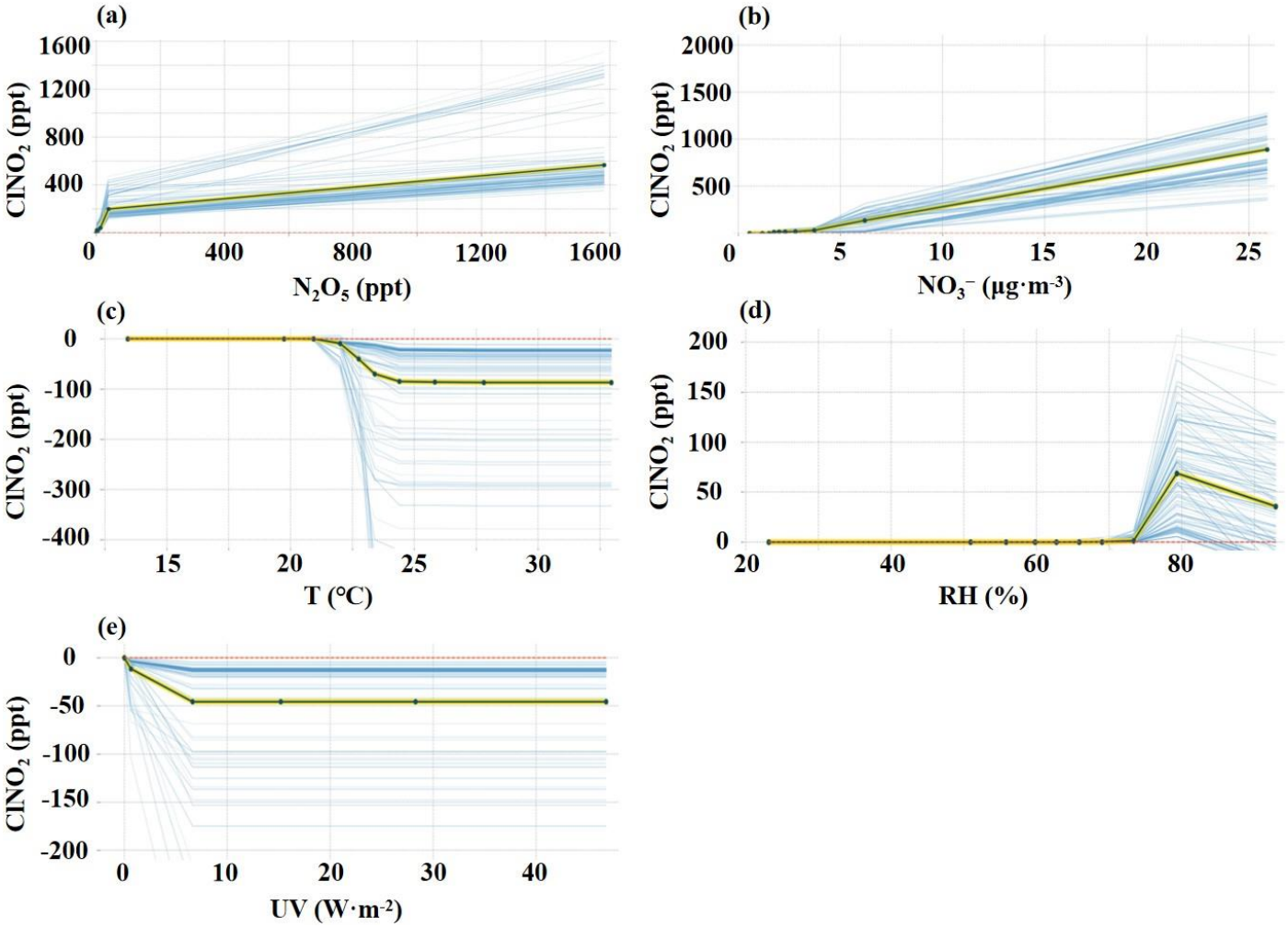
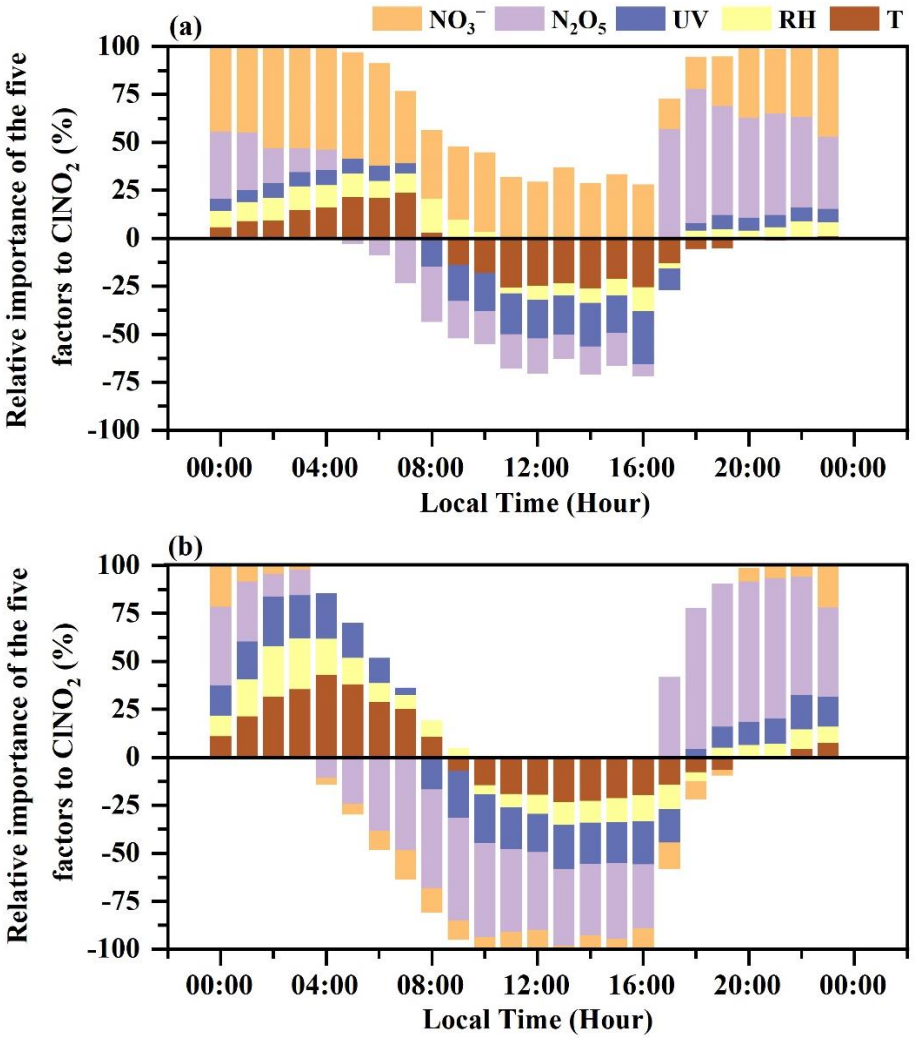


Figure 5. Isolation plots of PDP for N_2O_5 (a), NO_3^- (b), T (c), RH (d), and UV (e). The average variations of simulated $ClNO_2$ with factors' changes spline are indicated by the yellow and black curve, and blue curves presents all situations during the whole observation period.



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578 Figure 6. The diurnal variations of the relative importance of factors to $ClNO_2$ based on the SHAP values

579 under the high (> 3.7 μg·m^{-3}) (a) and low (< 3.7 μg·m^{-3}) (b) $ClNO_2$ concentrations.

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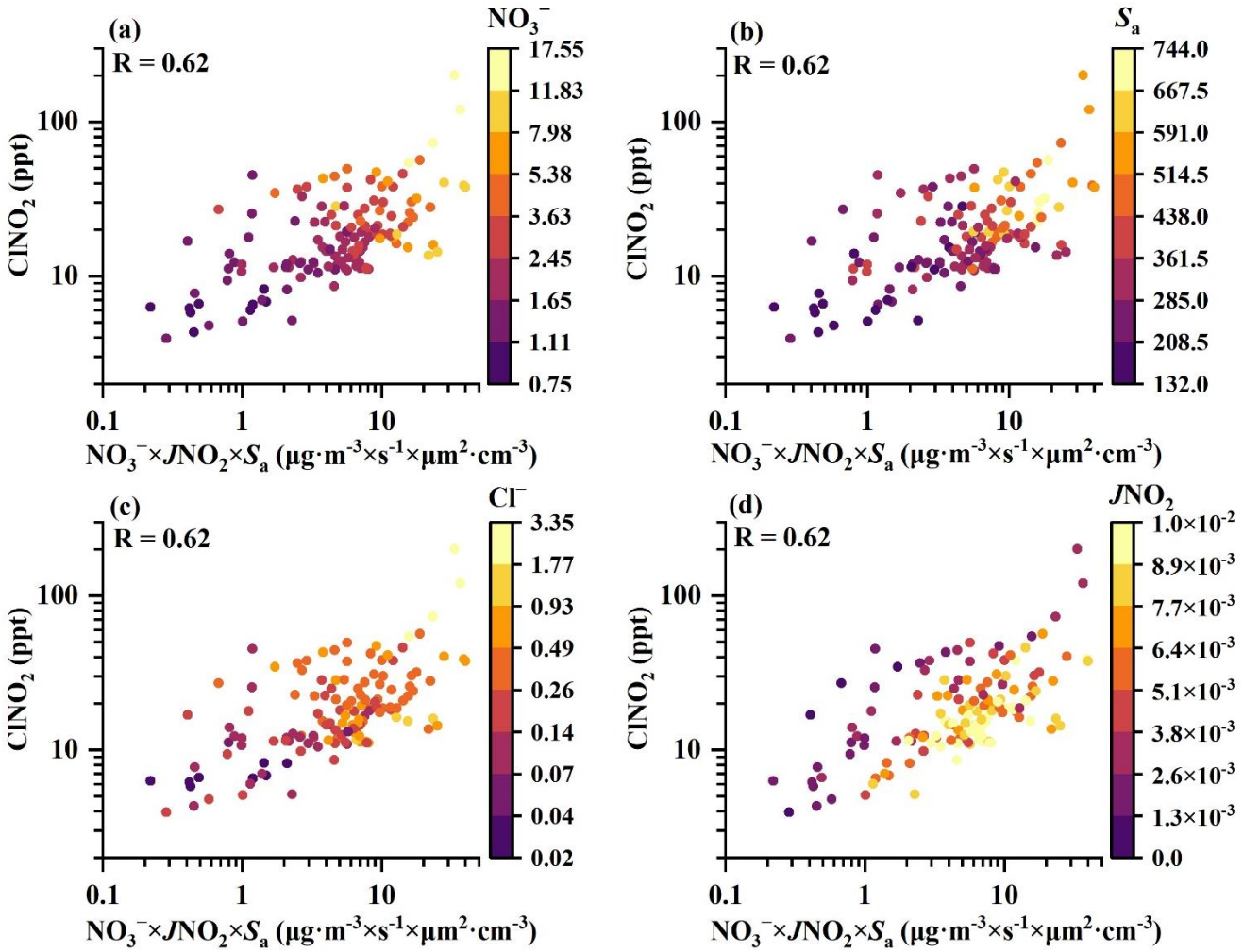

Figure 7. The relationship of daytime $ClNO_2$ concentrations (12:00-15:00 Local Time) and a proxy of nitrate (NO_3^-) photolysis ($NO_3^-\times JNO_2\times S_a$). The color of the dots respects the NO_3^- (a), S_a (b), Cl^- (c), JNO_2 (d), respectively.

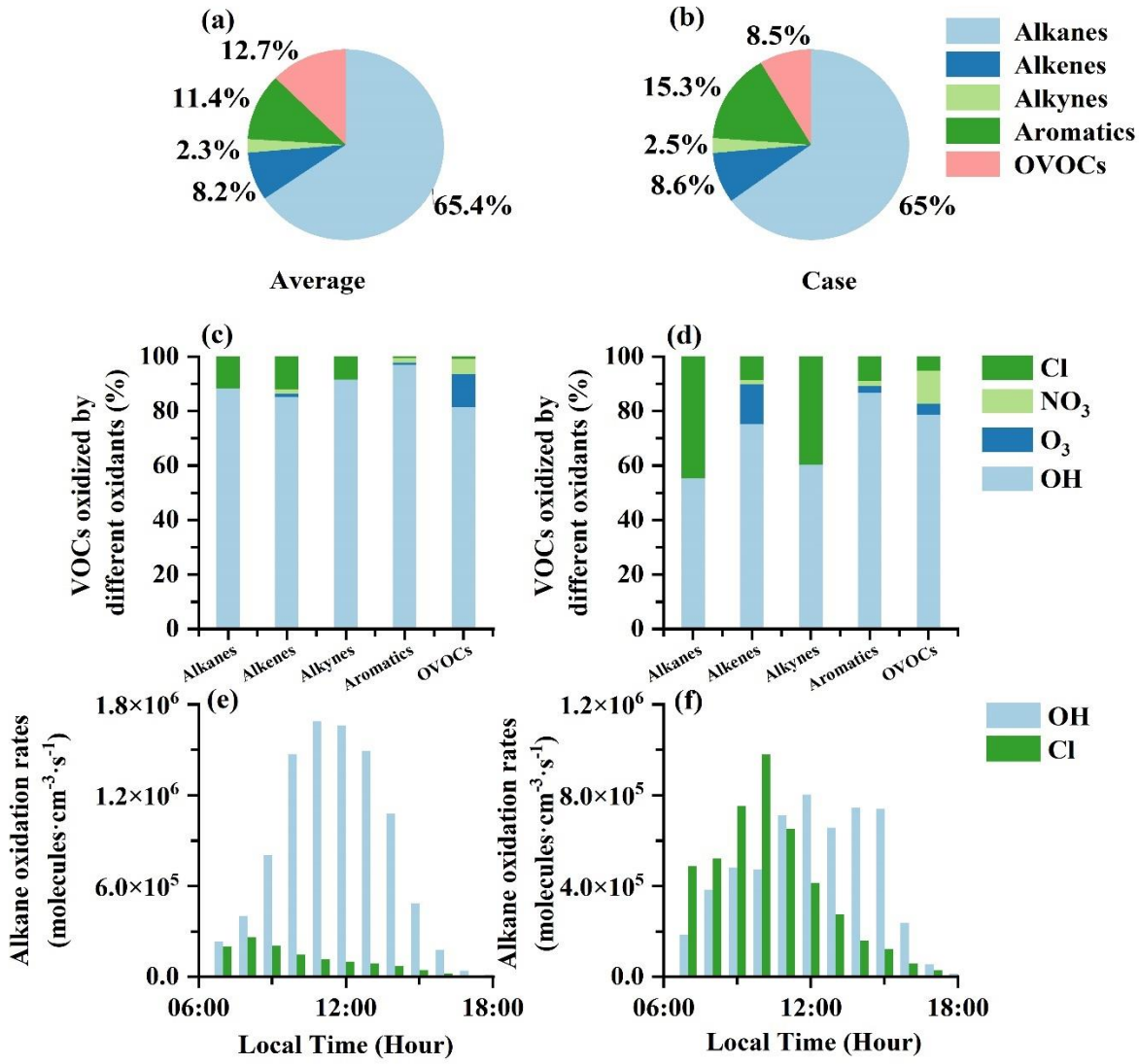

Figure 8. The impacts of Cl radials released by $ClNO_2$ photolysis and other atmospheric oxidants (including OH, NO_3, and O_3) on VOC oxidation under the observation-average condition and high $ClNO_2$ case, respectively. The contributions of different VOC groups oxidized by Cl radical during the observation-average (a). The contributions of different VOC groups oxidized by Cl radical during the case (b). The contributions of different atmospheric oxidants (including OH, Cl, NO_3, and O_3) to VOC groups during the observation-average (c). The contributions of different atmospheric oxidants (including OH, Cl, NO_3, and O_3) to VOC groups during the case (d). Comparisons of alkane oxidation rates (molecules·cm^{-3}·s^{-1}) by OH and Cl radical during the observation-average (e). Comparisons of alkane oxidation rates by OH and Cl radical (molecules·cm^{-3}·s^{-1}) during the case (f).

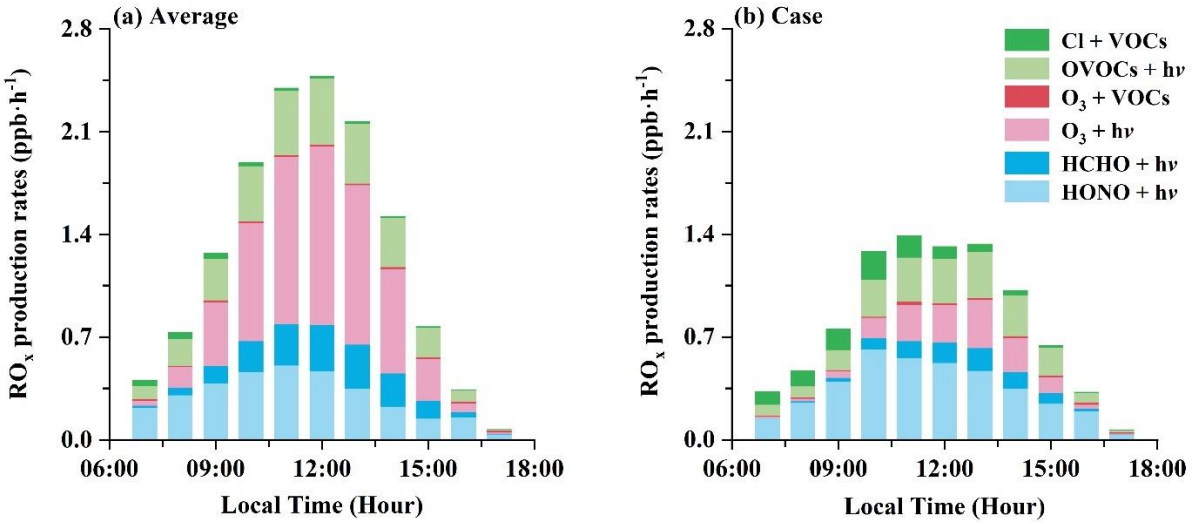

Figure 9. The contributions of different production pathways to RO_x production rates under the observation-average condition (a) and high $ClNO_2$ case (b), respectively.

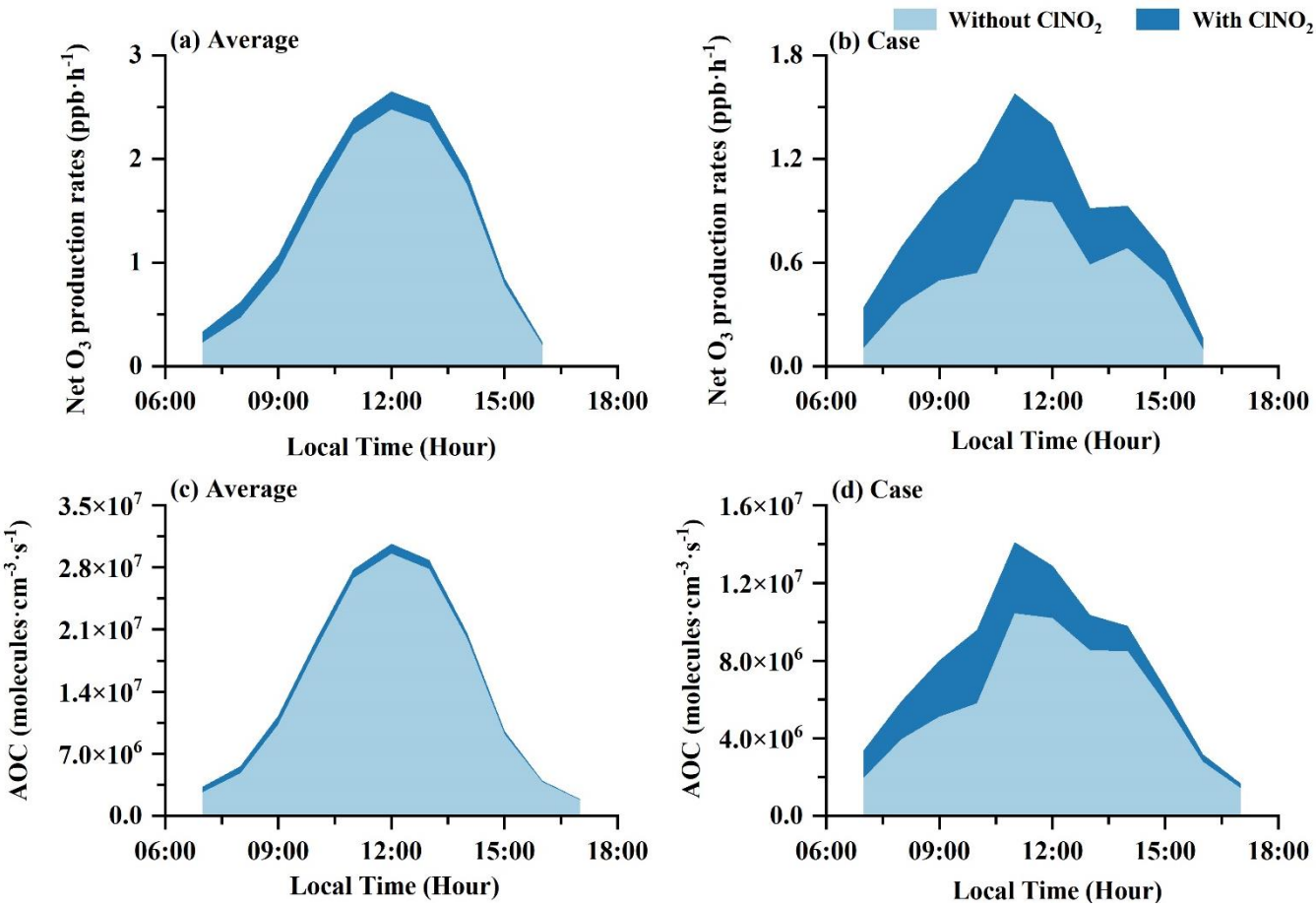

Figure 10. The impacts of Cl radials released by $ClNO_2$ photolysis on net O_3 production rates and the AOC levels under the observation-average condition (a, c) and high $ClNO_2$ case (b, d), respectively.

Table 1. Relative importance of Cl, OH, and O_3 to the daytime oxidation of VOC groups (including alkanes, alkenes, alkynes, aromatics, and OVOCs) around the world (Xue et al., 2015; Bannan et al., 2015; Bannan et al., 2017; Rutherford et al., 1995; Fraser et al., 1997).

	Xiamen (average)	Xiamen (case)	Hong Kong (max)	London (average)	Weybourne (average)	Boston	LA
Alkane Cl%	11.7	44.8	53.0	3.5	1.0	8.5	9.9
Alkane OH%	88.3	55.2	47.0	96.5	99.0	91.5	90.1
Alkane O_3%	-	-	-	-	-	-	-
Alkene Cl%	12.2	8.7	14.0	0.6	0.4	0.3	0.3
Alkene OH%	85.0	75.2	81.0	77.9	78.3	33	31.3
Alkene O_3%	1.2	14.7	5.0	21.5	21.4	66.7	68.4
Alkyne Cl%	8.5	40.0	-	7.0	2.6	8.7	8.7
Alkyne OH%	91.5	60.0	-	91.8	96.7	89.7	89.7
Alkyne O_3%	-	-	-	1.2	0.7	1.6	1.6
Aromatics Cl%	0.7	9.1	11.0	-	-	-	-
Aromatics OH%	97.0	86.6	89.0	-	-	-	-
Aromatics O_3%	0.7	2.6	-	-	-	-	-
OVOCs Cl%	0.9	5.2	6.0	-	-	-	-
OVOCs OH%	81.4	78.7	85.0	-	-	-	-
OVOCs O_3%	12.0	3.9	-	-	-	-	-

Table 2. The impacts of $ClNO_2$ photolysis on RO_x (OH, HO_2, and RO_2) levels, $P(RO_x)$, and $P(O_3)$ around the world (Xia et al., 2021; Wang et al., 2022; Tham et al., 2016; Wang et al., 2016; Xue et al., 2015; Bannan et al., 2017; Jeong et al., 2019).

Study Area	Season	OH	HO_2	RO_2	$P(RO_x)$	$P(O_3)$
Xiamen (average)	Autumn	3.7%	7.1%	10.3%	4.9%	6.7%
Xiamen (case)	Autumn	17.9%	34.6%	54.3%	23.8%	41.7%
Wangdu/Beijing/Mt. Tai	Winter	15.0%–22.0%	24.0%–31.0%	36.0%–52.0%	1.3%–3.8%	1.3%–6.2%
Heshan	Autumn	1.5%–2.6%	1.9%–4.6%	3.0%–6.8%	< 2.2%	1.0%–4.9%
Wangdu	Summer	-	-	-	10%–30%	3.0%–13.0%
Mt. Tai Mo Shan, Hong Kong	Winter	40.0%–77.0%	53.0%–106.0%	-	-	11.0%–41.0%
Hok Tsui, Hong Kong	Summer	6.6%	12.2%	45.1%	-	10.3%
Weybourne	Spring	5.0%	7.0%	9.0%	-	-
Seoul	Spring	-	-	-	-	1.0%–2.0%