Response to Community Comments from Prof. Hai Guo

We thank you for the constructive comments and suggestions, which are very positive to improve scientific contents of the manuscript. We have revised the manuscript appropriately and addressed your comments point-by-point for consideration as below. The remarks from yours are shown in black, our responses (in blue) and the corresponding edits in the manuscript (in red) are shown below. All the page and line numbers mentioned following are refer to the revised manuscript without change tracked.

General Comments

This study employs Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) observations to characterize the vertical distributions of aerosols, NO_2, HCHO, and CHOCHO under different air current conditions (NSBDs, SBDs, and TDs) in a rural coastal area of Hainan Island, China. The results show that NSBDs are associated with higher pollutant levels and broader vertical distribution ranges. During SBDs, sea breezes limited pollutant dispersion, while their cooling effect suppressed O_3 formation. Under TDs, typhoons scavenge pollutants but facilitate mid-to-high altitude BVOC transport and enhance the vertical dispersion of surface pollutants. These findings provide valuable insights into coastal atmospheric processes and pollutant behaviors. The manuscript is generally well-structured and detailed. However, several issues need to be addressed before it can be considered for publication.

R: We sincerely thank you for the positive and constructive comments on our manuscript. The feedback is greatly appreciated and has been carefully considered in the revision. All concerns have been addressed to improve the clarity, rigor, and overall quality of the paper. We believe that the revised version has been significantly improved.

Specific Comments

1. Line 30: References should be consistently ordered, either alphabetically by author or chronologically.

R: Thank you for your comment. References have been arranged alphabetically by author's last name throughout the manuscript.

2. Line 85: Please clarify the time resolution of the MAX-DOAS observations.

R: Thank you for your comment. We have clarified that the temporal resolution of the MAX-DOAS measurements and please refer to Line 102-104.

"Data acquisition, with a temporal resolution of 30 seconds for individual spectrum, is conducted daily from 06:00 to 19:00 local time (LT), with dark current signals automatically extracted from nightly background measurements. A full scan sequence of different elevation angles takes approximately 5 minutes to complete."

3. Line 130: The sentences beginning with "Accurate identification of … of SB and LB" are redundant and should be revised.

R: Thank you for your comment. We have revised the sentences to remove redundancy. Please refer to Line 144-147.

4. Lines 140–150: I suggest moving Figure S4 from the Supplementary Material to the main text and citing it appropriately.

R: Thank you for your comment. Figure S4 has been supplemented into the main text as Figure 2 in Section 2.2. The manuscript has been revised accordingly, and all relevant citations have been updated.

5. Line 165: Please provide the formula used to calculate relative humidity. In addition, the ERA5 data may be too coarse to capture local weather conditions around the in-situ site. For example, uncertainties in planetary boundary layer height are significant. Verification against nearby weather station data is necessary to ensure the robustness of the meteorological analysis.

R: Thank you for your comment. We have presented the equations for RH conversion and relevant descriptions. Please refer to Line 185-192.

"Notably, ERA5 lacks the surface RH data required; therefore, we computed actual and saturated water vapor pressures using the 2m dew temperature (Td in K) and 2m temperature (T in K) from ERA5-Land, and derived RH from their ratio (Zhu et al., 2025):

$$\mathrm{RH} = \frac{e_a(T_d)}{e_s(T)} \times 100\% \quad (1)$$

where $e_a(T_d)$ is the actual vapor pressure at dew point temperature, and $e_s(T)$ is the saturation vapor pressure at the current temperature. These can be determined by the following formula:

$$e_a(T_d) = 0.6108 \times \exp\left(\frac{17.27\times(T_d-273.15)}{T_d-35.86}\right) \quad (2)$$

$$e_s(T) = 0.6108 \times \exp\left(\frac{17.27(T-273.15)}{T-35.86}\right) \quad (3)"$$

Furthermore, we have conducted a comparative analysis of temperature and relative humidity (RH) between ERA5 and the nearest meteorological station to our study site—Danzhou station (19.31°N, 109.35°E, 170 m a.s.l.) (Fig. R1). However, it should be noted that although Danzhou station is the closest meteorological site available, it still far away from the measurement site (~33 km). Such distance may also contribute to the discrepancies in temperature and RH. Overall, the comparison shows relatively high agreement of temperature and RH between these two data sources.

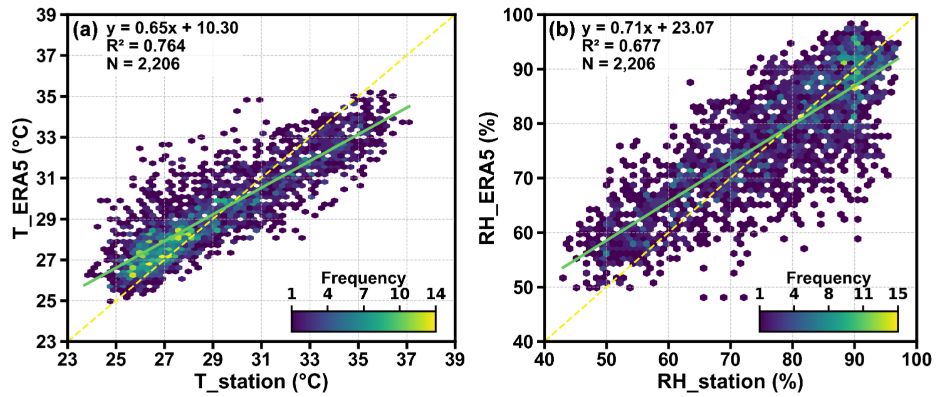

Figure R1. Correlation between Temperature (T_ERA5 and T_station) and Humidity (RH_ERA5 and RH_station) from ERA5_land and Danzhou Meteorological Station (19.31°N, 109.35°E) during summer 2024. The color of each hexagonal bin represents the frequency of data points within that grid cell. The yellow dashed line indicates the 1:1 line, and the green line shows the regression line between the two datasets.

As shown in Fig. R2, the Danzhou station and ERA5_Land exhibit broadly consistent variations in WS and wind direction WD throughout the study period. The ERA5_Land WS is derived from the 10 m u- and v-wind components and represents grid-averaged conditions, whereas the Danzhou station is influenced by strong local surface roughness caused by nearby buildings and vegetation, resulting in lower observed WS. Despite these differences in magnitude, both datasets display similar prevailing wind directions on non-typhoon days, a shift toward southwesterly winds during typhoon periods, and comparable diurnal patterns in WS, as shown in Fig. R2(b), (c) and (d).

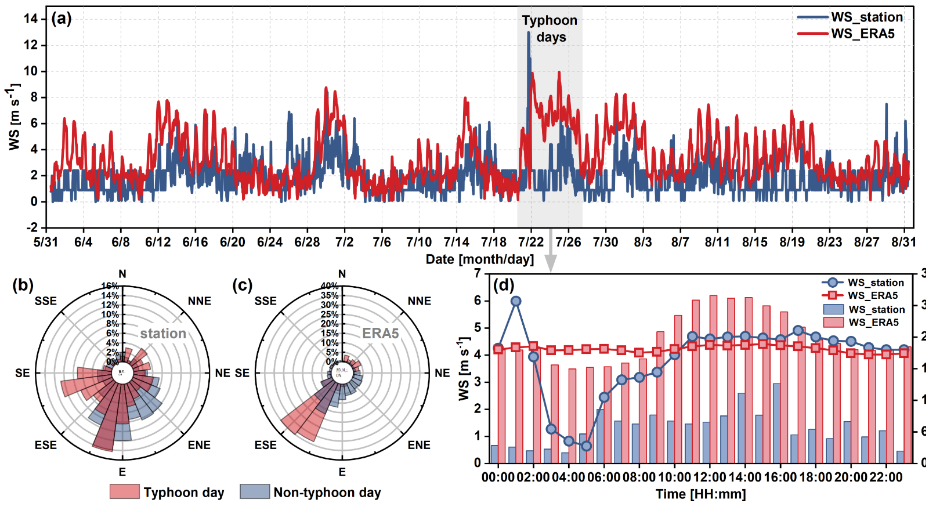

Figure R2. Comparison of WS and WD between the Danzhou station and ERA5_Land. (a) Hourly variations in WS for the Danzhou station and ERA5_Land over the entire observation period; WD patterns at the (b) Danzhou station and (c) ERA5_Land during typhoon and non-typhoon days; (d) Diurnal variations of mean WS and WD for the Danzhou station and ERA5_Land on typhoon days. The gray shaded area indicates the range of the typhoon's duration. Wind direction is plotted in polar coordinates with percentage frequency indicated by concentric circles.

Although ground-based observations can better capture near-surface meteorological conditions, their strong short-term fluctuations—particularly in wind fields—introduce substantial noise and complicate the identification of sea–land breeze circulations.

More importantly, the Danzhou station is located far from the measurement site, making its data unrepresentative to some extent. In contrast, ERA5_Land provides smoother and more continuous spatiotemporal fields that coherently depict the evolution of large- and mesoscale wind structures. As a result, ERA5_Land has been widely applied in sea–land breeze research worldwide and is generally regarded as reliable and internally consistent for such analyses (Azorin-Molina et al., 2011; Hallgren et al., 2023; Xia et al., 2022; Zhao et al., 2022).

In summary, despite certain uncertainties, ERA5_Land offers physically consistent estimates of all required variables and supplies complete, continuous, and quality-controlled time series—advantages that ground-based observations cannot fully match. The comparison with station measurements further confirms good agreement between these two datasets. These features make ERA5_Land particularly suitable for investigating sea–land breeze circulations in this study.

6. Line 175: Please provide the actual values instead of vague expressions such as “values recorded in Chinese megacity centers.”

R: Thank you for your comment. We have provided average NO_2 concentration data for major Chinese megacity clusters, specifically reporting values of 7.62 ± 1.39 ppbv for the Beijing–Tianjin–Hebei and surrounding regions, and 7.45 ± 0.87 ppbv for the Yangtze River Delta. To ensure comparability between our observations and those from previous studies, we consulted additional literature containing concurrent records from the same monitoring period and re-compare the NO_2 levels in this study and those in the megacity clusters. The results indicate that the NO_2 concentration in this study was approximately one-third to one-fifth of that observed in the megacity clusters. Please refer to Line 205-208.

"The average NO_2 surface VMRs (1.61 ± 0.53 ppbv) was about 3 to 5 times lower than the values recorded in major Chinese megacity centers, such as the Beijing–Tianjin–Hebei region (7.62 ± 1.39 ppbv) and the Yangtze River Delta (7.45 ± 0.87 ppbv) (Lou et al., 2025; Ministry of Ecology and Environment of the People's Republic of China, 2024a, b, c), reflecting minimal local traffic and industrial emissions."

7. Figure S5: This figure is not cited in the text.

R: Thank you for your comment. We have to clarify that Figure S5 is intended to illustrate the average atmospheric conditions in the study region during the observational period. It is cited in Text S2, and used to determine the parameters required to accurately calculate the semidiurnal pressure waves and is not directly related to the main content of the paper.

8. Line 225: The statement of “Notably, most of the SBDs occur consecutively.” can be explained by meso-scale circulations, which usually occur under stable atmospheric

conditions dominated by persistent high pressure.

R: Thank you for your comment. We have rephrased the sentence as following and please also refer to Line 267-268.

"Notably, most of the SBDs occur consecutively. This can be explained by the mesoscale circulation, which usually occur under stable atmospheric conditions dominated by persistent high pressure."

9. Line 245: The claim that "southwesterly winds persist under the typhoon's peripheral airflow" needs clarification. Since both the typhoon's location and the sampling site (in this and other studies) change over time, is the peripheral airflow always associated with southwesterly winds?

R: Thank you for your comment. Indeed, the typhoon's peripheral circulation does not always produce southwesterly winds at the study site; the WD depends on the typhoon's relative position and movement. For example, during the selected seven TDs, Figure R3 shows that when Typhoon "Prapiroon" approached Hainan on July 21, the peripheral circulation produced easterly to northerly winds. On July 22, as the typhoon moved northwestward and made landfall, the winds shifted to southwesterly. After its departure, southwesterlies dominated for several days due to the residual circulation. It illustrates that the peripheral airflow can vary substantially over time, and the resulting wind direction at a given site is determined by the typhoon's location, trajectory, and rotation rather than being inherently southwesterly.

We acknowledge that the original statement "southwesterly winds persist under the typhoon's peripheral airflow" may have been misleading. To avoid confusion, we have revised this sentence for greater precision. Please refer to Line 283-285.

"The prevailing southwesterly winds are caused by the typhoon's peripheral airflow over the area of measurement, whereas NSBDs feature daytime southwest winds shifting to southerly at night."

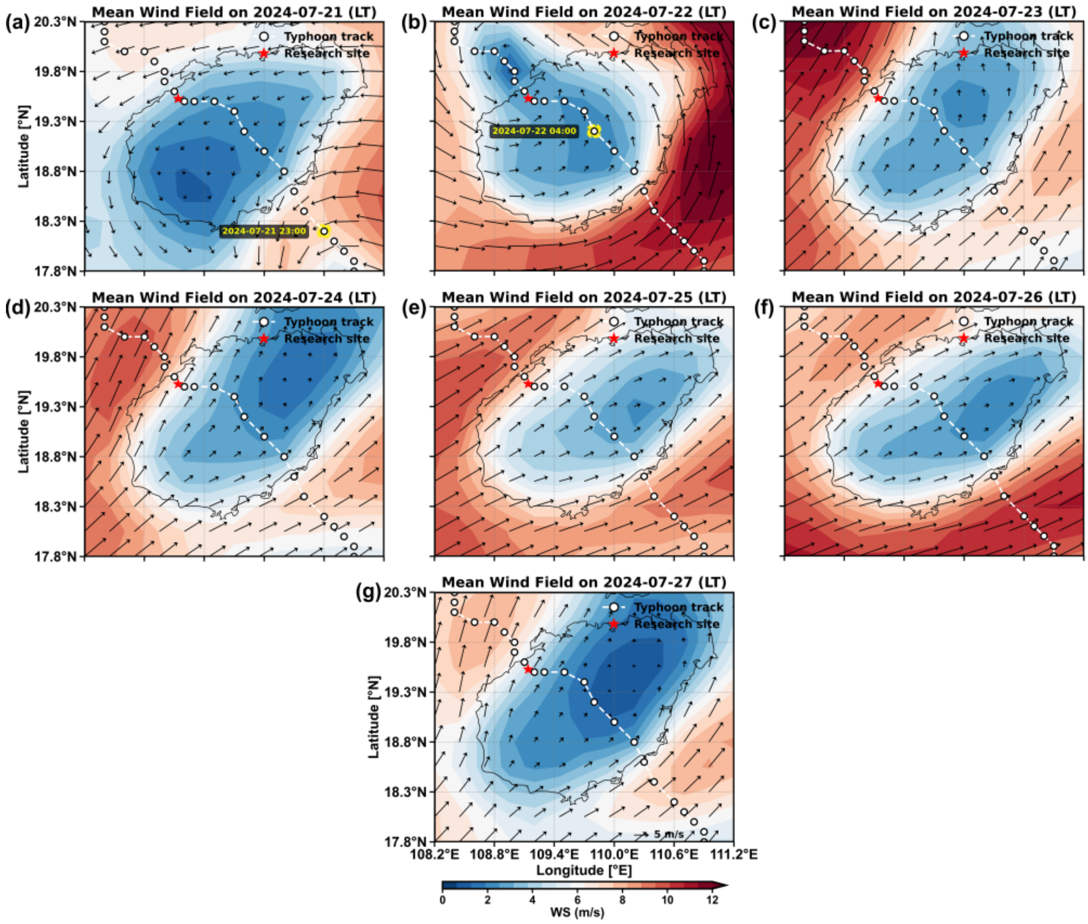

Figure R3. Daily mean wind field characteristics of Hainan Island on seven consecutive typhoon days: (a) 2024-07-21, (b) 2024-07-22, (c) 2024-07-23, (d) 2024-07-24, (e) 2024-07-25, (f) 2024-07-26, and (g) 2024-07-27. Typhoon "Prapiroon" is indicated by a yellow spiral logo, and LT stands for local time.

10. Line 260: Please add vertical wind components to the correlation figures to better support the conclusions.

R: Thank you for your comment. We have updated Fig. 5 with supplements of mean vertical velocity profiles for NSBDs, SBDs, and TDs, respectively. Please refer to the updated Fig. 5 (Fig. 6 in the revised manuscript and shown as Fig. R4 following) and related descriptions in Line 303-308. In addition, information on vertical velocity has been incorporated into Table S4 in the Supplementary Materials.

"As shown in Fig. 6(g) to (i), the differences in BLH further modulate vertical motion under the three ACPs. The positive values of vertical velocity (ω) indicate downward airflow movement. Upward motion prevails below 2 km on NSBDs and TDs, associated with enhanced convection and typhoon-induced ascent, respectively. In contrast, SBDs feature weak morning uplift that transitions to subsidence as the sea breeze intensifies, with the strongest downward motion ($\omega \approx 0.05$ m s^{-1}) near 1.5 km, suggesting that the SB further restricts pollutant dispersion in FK."

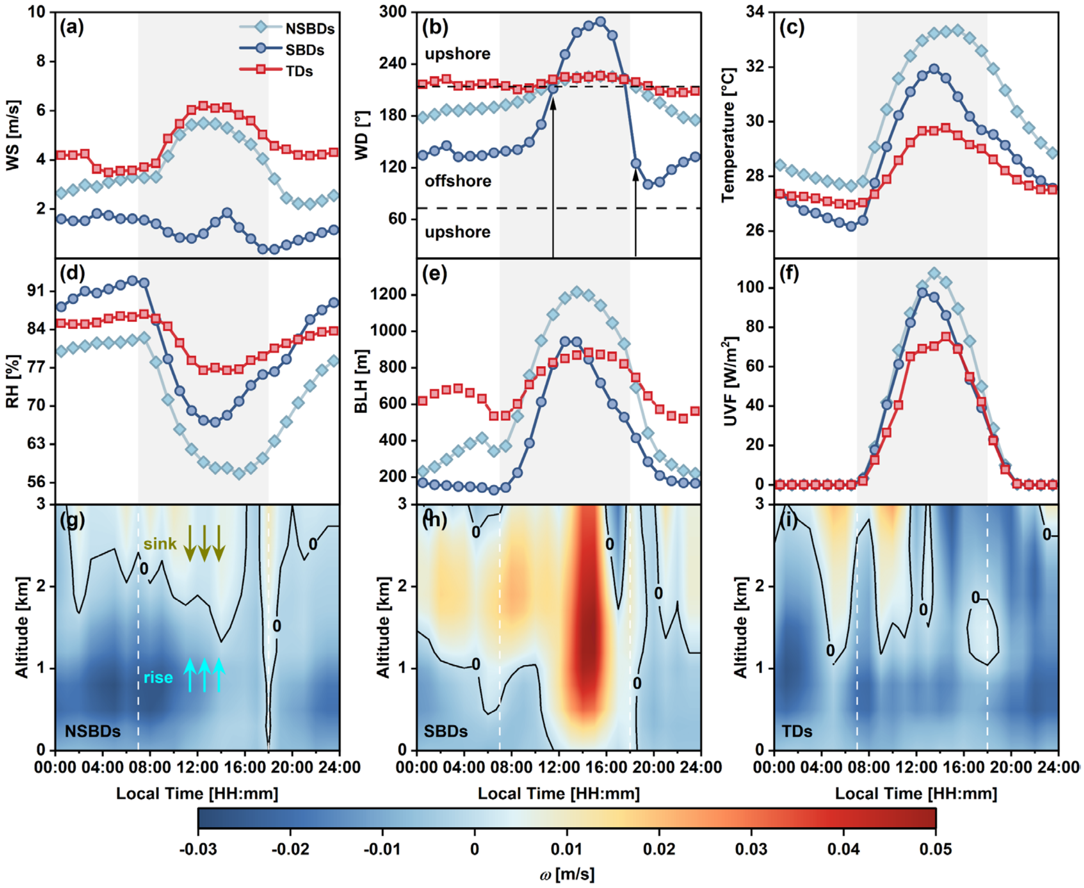

Figure R4. Diurnal variations of meteorological factors under different air currents. Mean diurnal variations of (a) WS, (b) WD, (c) temperature, (d) RH, (e) BLH, (f) UV radiation flux (UVF) and (g, h and i) vertical velocity (ω) under three air current patterns (ACPs): NSBDs, SBDs, and TDs. The gray shaded area represents the observation period of MAX-DOAS. The two black dotted lines define the range of WD for onshore and offshore winds. Critical transition points for SB initiation and cessation are marked with arrows in (b). The blue and brown arrows represent rising and sinking air currents, respectively.

11. Section 3.3: It is unclear why O_3 concentrations are clustered instead of directly analyzing their evolution under NSBDs, SBDs, and TDs. Please clarify.

R: Thank you for your comment. It is indeed that the O_3 concentration analysis can be discussed either via their evolution under different ACPs or via clustered diurnal pattern. We know that NSBDs, SBDs and TDs are each associated with markedly different atmospheric conditions, including WS, RH, solar radiation, and vertical motion, which are also influencing O_3 diurnal pattern via both physical and chemical mechanisms. Besides, even within a same ACP, some of the meteorological parameters varied significantly. This variability makes it challenging to disentangle the relative contributions of individual factors, such as the effect of wind-driven transport versus photochemical production, or the roles of temperature, humidity, and vertical mixing in shaping the observed O_3 diurnal variations.

Figure R4 illustrates the diurnal O_3 profiles under NSBDs, SBDs, and TDs. The results show that although the absolute O_3 concentrations are substantially lower on SBDs compared to NSBDs, the net increments of their diurnal variations are quite similar. This feature cannot be fully explained by weather-type classification alone, underscoring the added value of clustering analysis.

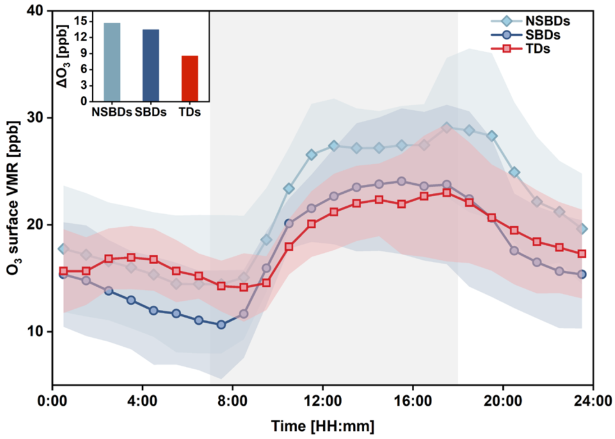

Figure R5. Diurnal variations of O_3 surface VMR under different air currents. The net O_3 increment (ΔO_3) under each airflow pattern is displayed in the bar chart in the upper left corner.

Clustering analysis takes a "bottom–up," data-driven approach, without imposing any a priori meteorological assumptions. Instead, it identifies inherent groups of similar O_3 behaviors directly. Then the influencing factors helping the enhancement of daily O_3 can be recognized from perspective on both ACPs and physical/chemical mechanisms. In general, integrating both approaches, i.e. O_3 diurnal patter classified with ACPs or clustered by itself, enable a more refined association between meteorological conditions and O_3 response, deepening our understanding of the drivers of O_3 pollution.

12. Lines 315–320: Is it reasonable to use the minimum early-morning O_3 concentration as background O_3? Have the effects of NO_x titration been excluded?

R: Thank you for your comment. We fully agree that the early-morning O_3 concentration can indeed be influenced by NO_x titration, and we acknowledge that defining it as background level is not so cautious. In this study, the minimum early-morning concentration was served as a baseline to calculate the daytime increment, which represents a net change. This metric of net change effectively allows for a clearer isolation and revelation of the net impact of the day's meteorological processes (i.e., sea breeze and non-sea breeze conditions) on local photochemical production efficiency. To avoid the misleading, we have corrected the sentence and please refer to Line 356-357.

"The differences between the midday peak and the morning minimum represents net O_3 increment (ΔO_3)."

13. The dataset includes only seven typhoon days, which may be insufficient to represent general typhoon-related airflows. This appears more like a case study.

R: Thank you for your comment. We acknowledge that the dataset of seven TDs may appear limited from a purely statistical standpoint compared to the other two ACPs. However, Typhoon "Prapiroon" during observation period provided a valuable, albeit singular, opportunity to capture its direct influence on local air quality at measurement site. We have amended the manuscript to include a clarification regarding the case-study nature of this specific analysis and to avoid overgeneralization. Please refer to Line 260-266.

"During the campaign, a unique opportunity arose to study the impact of Typhoon "Prapiroon", which traversed Hainan from southeast to northwest on July 21–23, 2024. Its intense disturbances to the local meteorology continued for one week after landfall (Fig. 1a and 6). Although the seven typhoon-influenced days (TDs) may be not sufficient sample from a statistical perspective, they represent a coherent case of a recurring meteorological phenomenon—typhoons following a characteristic east-to-west track across the South China Sea. This consistent pathway results in systematic advection of specific air masses into the study region. So we treated these TDs as an independent case against NSBDs and SBDs identified by the ORA (Table S3)."

We also wish to emphasize the strong meteorological rationale for considering these events together. Typhoons originating in the South China Sea and moving past Hainan Island almost invariably follow a consistent east-to-west trajectory. This predictable pathway produces a systematic transport mechanism, consistently advecting distinct air masses from the typhoon's trajectory into our study region. Therefore, while the seven-day sample size is modest, it represents observations of a coherent and recurring meteorological phenomenon rather than seven random and disparate events. This consistency strengthens the relevance of our findings for understanding the air quality impacts of typhoons taking this common track.

14. Please clarify whether the results apply only to Hainan Island or can be generalized to other coastal/island environments. Which findings can be extended to similar regions?

R: Thank you for your comment. We note that a similar comment was raised by another reviewer (Reviewer #1, Comment 6), so we have added a dedicated paragraph in the conclusion section outlining the extent to which our findings can be generalized and also the key limitations of our study. Please refer to Line 535-543.

"This study reveals several summertime physical and chemical processes that are characteristic of Hainan Island, so the quantitative values reported here—such as pollutant concentrations, ORA parameter ranges and FNR/GNR thresholds—are shaped by the island's unique land–sea configuration, monsoon regime, and emission environment and should be treated as site-specific. However, the vertical stratification mechanisms linked to species lifetimes and atmospheric dynamics, the thermodynamic and compositional effects of SB intrusions, the typhoon-related scavenging, redistribution, and uplift, and the diagnostic value of different photochemical indicators under different ACPs are processes that commonly occur across many coastal and island settings. Thus, while specific numerical thresholds may vary, the underlying conceptual processes and the ORA framework offer a transferable basis for interpreting similar coastal phenomena, particularly in regions with comparable climatic and geographic conditions."

Technical Corrections

1. Ensure consistent use of abbreviations: introduce the full term at first mention, followed by the abbreviation, and use the abbreviation thereafter.

R: Thank you for your comment. We have carefully checked and revised the manuscript to ensure that all abbreviations are introduced with their full terms at the first mention, followed by the abbreviation in parentheses. Thereafter, only the abbreviations are used consistently throughout the text.

2. Line 60: Add a comma before "Nevertheless."

R: Thank you for your comment. A comma has been added and please refer to Line 72.

3. Line 135: Use "Fig. 1a and b" instead of "Fig. 1a,b."

R: Thank you for your comment and we have corrected accordingly. Please refer to Line 148.

4. Correct typos, grammatical errors, and syntactic mistakes throughout the manuscript.

R: Thank you for your comment. We have thoroughly checked the manuscript and corrected all typos, grammatical errors, and syntactic mistakes to improve clarity and readability.

5. The English should be polished further, ideally by a native speaker.

R: Thank you for your comment. we have polished the manuscript carefully, corrected grammatical mistakes and expressed more academically and briefly.

Reference:

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Zhu, M., Zhu, D., Huang, M., Gong, D., Li, S., Xia, Y., Lin, H., and Altan, O.: Assessing the Impact of Climate Change on the Landscape Stability in the Mediterranean World Heritage Site Based on Multi-Sourced Remote Sensing Data: A Case Study of the Causses and Cévennes, France, Remote Sens., 17, 203, https://www.mdpi.com/2072-4292/17/2/203, 2025.