Consolidated Point-by-Point Response to Reviewers' Comments

Manuscript ID: egusphere-2025-4751

Title: Spatiotemporal patterns of temperature inversions and impacts on surface $PM_{2.5}$ across China

Note: "This document provides a consolidated record of all author responses throughout the peer-review process, including the initial major revision and the subsequent final clarifications."

Contents

Part I: Responses to the First Round of Review (Major Revision)

Response to Reviewer 1 (Finalized)

Review result of "Spatiotemporal patterns of temperature inversions and impacts on surface $PM_{2.5}$ across China" (egusphere-2025-4751)

Response to Reviewer #1:

reviewer's comments are given in blue,

our responses are given in deep red.

Some of the content in the manuscript have been revised and updated.

Major Comments

1.The authors classify Surface-Based Inversions (SBIs) as those with a base height (Hb) < 100 m and Elevated Inversions (EIs) as 100 m ≤ Hb ≤ 2000 m. While this follows some previous studies, the specific rationale for the 100 m threshold is not sufficiently justified. Given that this threshold directly influences the reported frequencies and subsequent correlation analyses with PM2.5， its appropriateness across all of China's diverse terrains (e.g., plateau stations, urban areas) should be demonstrated. The authors should provide a stronger justification, supported by literature or a sensitivity analysis, showing how the results might be affected by a different, physically-based threshold (e.g., related to the nocturnal boundary layer height).

Response: We thank you for this constructive comment regarding the robustness of the SBI classification threshold.

We verify the robustness of the 100 m threshold as suggested. We initially selected the 100 m threshold based on established methodologies in previous studies (Kahl 1990; Guo et al. 2020; Huang et al. 2021), which allows for direct cross-study comparisons.

To address your concern about terrain diversity, we re-calculated the frequencies of TI, SBI, and EI using stricter (50 m) and looser (150 m) thresholds. As shown in the newly added Figures S18–S20 (also pasted below for your reference), while the absolute magnitude of frequencies shifts slightly as expected, the spatial distribution patterns and seasonal variations remain strikingly consistent across all thresholds. This confirms that the choice of 100 m does not introduce bias into the core conclusions of the paper. We have added a brief statement in Section 2.2 citing the literature and referring to these new supplementary figures to justify the robustness of our method.

Revised: (For additional validation at different thickness thresholds, please refer to supplementary Figures S18-S20.)

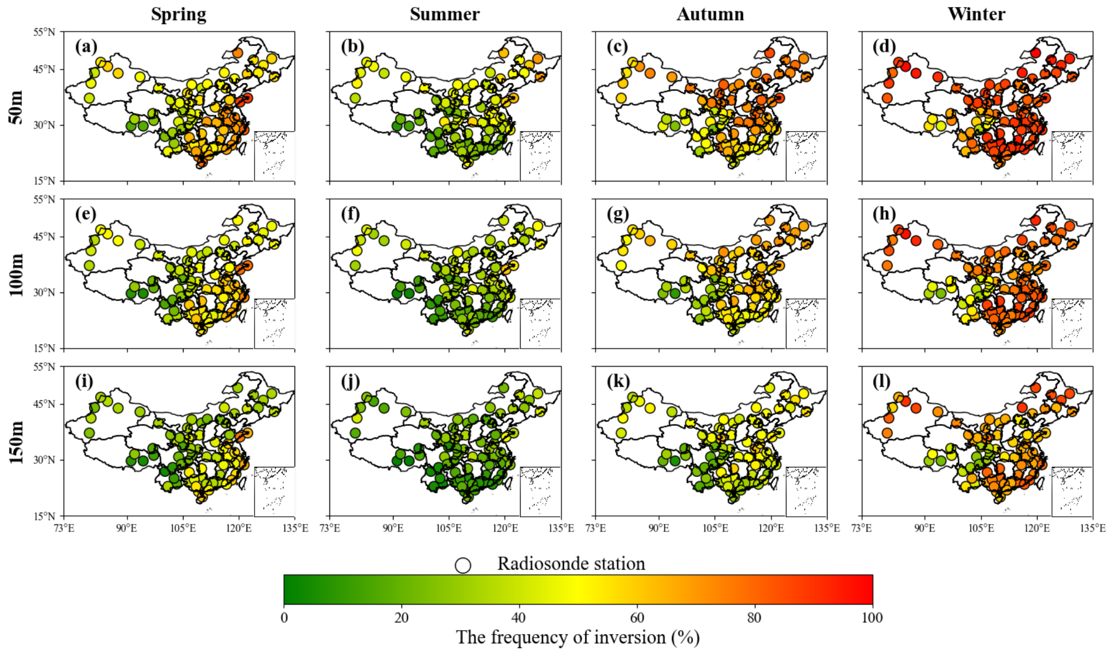


Fig. S18 Distribution of TI frequency across different thickness thresholds

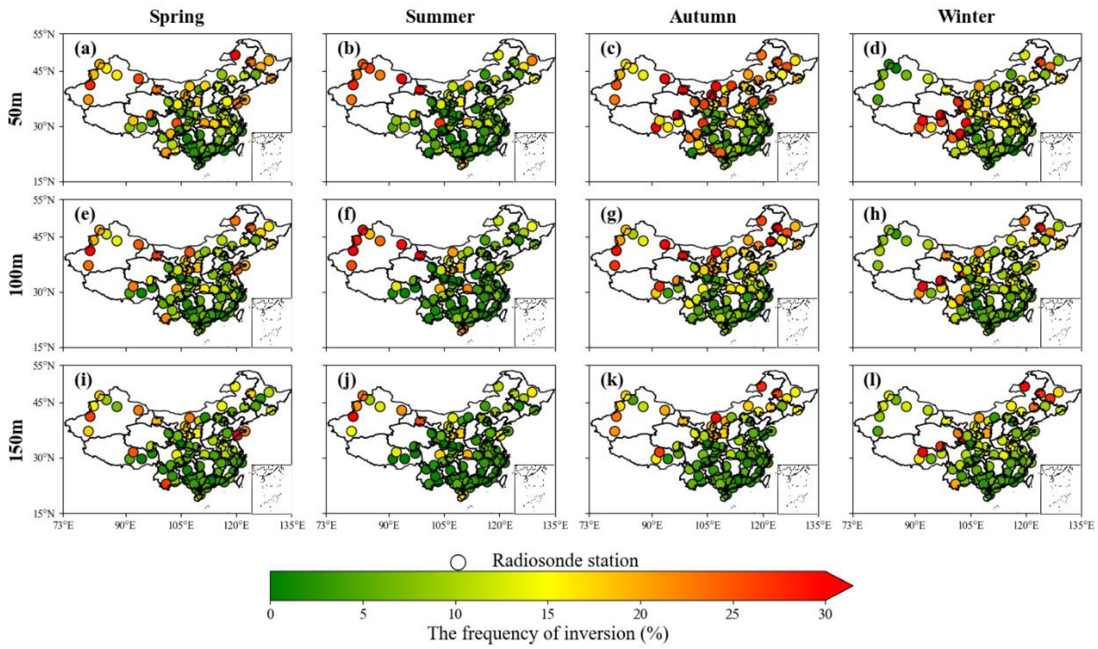


Fig. S19 Distribution of SBI frequency across different thickness thresholds

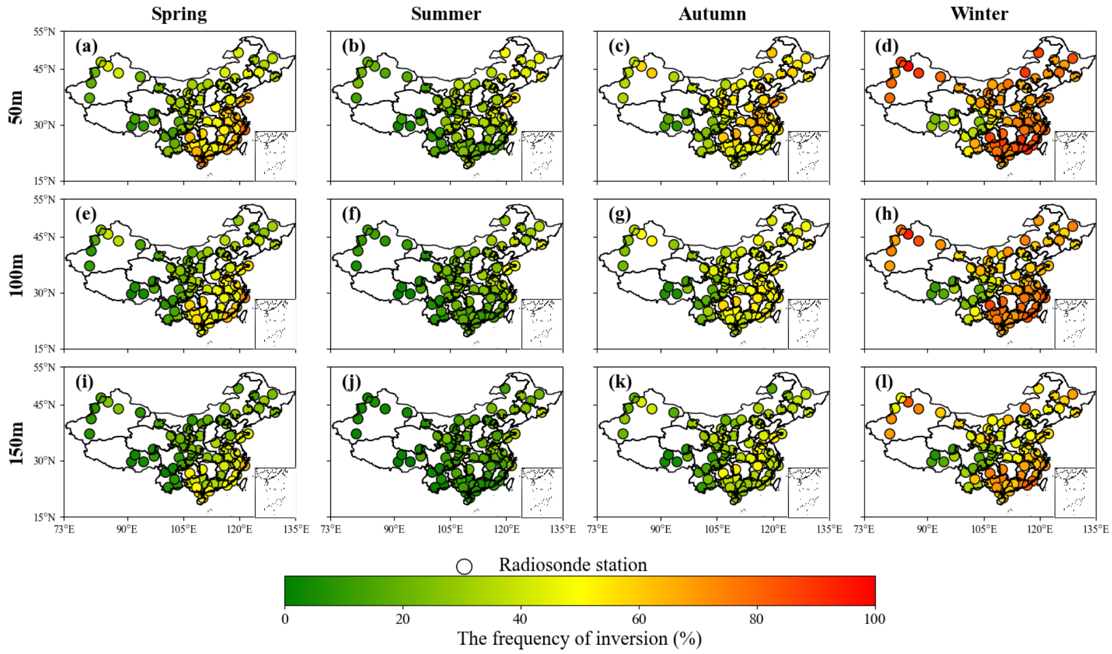


Fig. S20 Distribution of EI frequency across different thickness thresholds

2.The study effectively establishes a statistical association between TI parameters and PM concentrations. However, the assertion of a direct causal impact requires more support. The analysis does not fully disentangle the influence of emissions and synoptic-scale meteorology, which co-vary with inversion conditions. For instance, are the observed PM increases during SBIs primarily due to the inversion trapping locally emitted pollutants, or are the same large-scale stagnant conditions that cause the inversion also responsible for accumulating pollutants via regional transport? The authors should strengthen their causal interpretation by, for example, discussing the diurnal emission cycles or incorporating analysis of wind patterns and back-trajectories during specific inversion events to better attribute the pollution buildup.

Response: Thank you very much for your suggestion. To establish a stronger causal link, we have added a detailed meteorological analysis for the Beijing case study (Fig. 1), incorporating surface wind speed alongside TI strength and $PM_{2.5}$ concentrations. The causal impact of TI is clearly demonstrated through the comparison of two distinct periods: Local Trapping Period (A->B): During this stage, wind speeds remained consistently below the 2 m s^{-1} threshold (indicated by the dashed line), effectively shutting down regional transport. The progressive accumulation of $PM_{2.5}$ to peak levels synchronized with the intensification of TI strength. This confirms that under stagnant synoptic conditions, the TI-induced "lid effect" is an important factor for trapping local emissions. Dispersion Period (C->D): In contrast, when wind speeds increased significantly (> 4 m s^{-1}), the enhanced horizontal ventilation and mechanical erosion of the inversion layer led to a rapid decline in $PM_{2.5}$. This "control experiment" provided by nature confirms that while low wind speeds set the stage, the presence of a strong TI is the key mechanism responsible for the actual buildup of severe pollution.

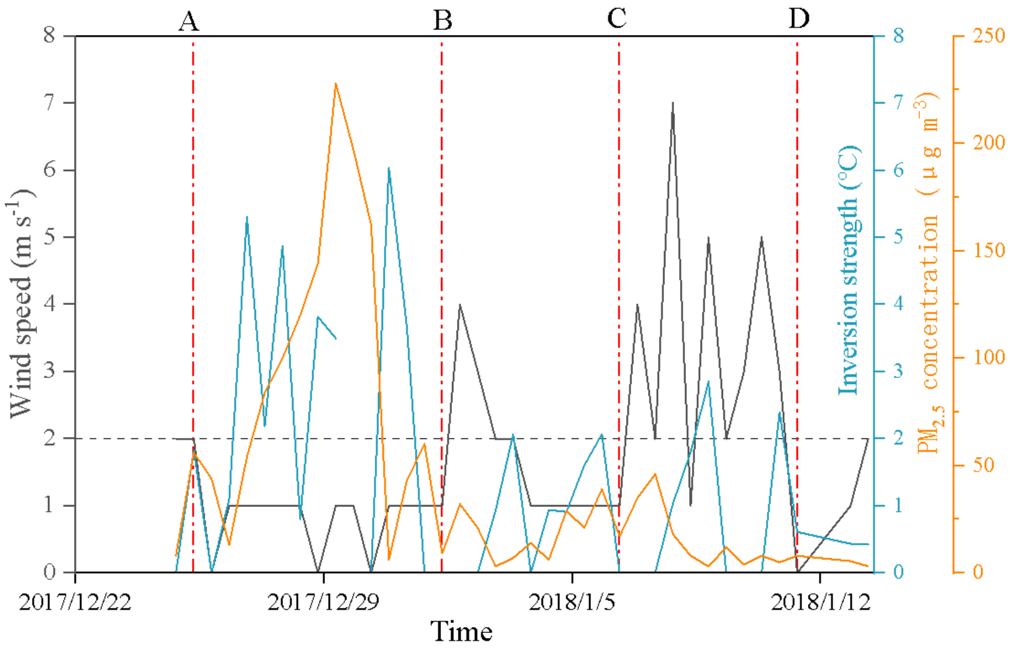


Fig. 1 Temporal evolution of surface wind speed, TI strength, and $PM_{2.5}$ concentration during a typical pollution episode in Beijing. The horizontal dashed line indicates the 2 m s^{-1} wind speed threshold. Periods A–>B and C–>D highlight the pollution accumulation under stagnant conditions and the subsequent dispersion driven by increased wind speed, respectively.

3.The division of China into seven regions is a key aspect of the analysis, but the criteria for this specific partitioning are not clearly defined. The description in Section 2.1 mentions "integrated meteorological characteristics and major urban agglomerations," but this is vague. A more explicit justification is needed. For example, why is the Sichuan Basin grouped within the larger Southwest region rather than being treated separately, given its unique meteorology? The authors should provide a clear rationale or reference an established regional framework, perhaps including a map that overlays key topographic or climatic boundaries with the regional divisions.

Response: We thank you for this critical comment regarding our regional classification.

Following your suggestion, we have clarified the rationale in the revised manuscript. We clarified that our partitioning follows the standard geographical and climatic divisions widely adopted in recent atmospheric research in China. For instance, Fan et al. (2020) and Sun et al. (2024), both of which adopted the same seven-region framework for national-scale air pollution analysis. This ensures that our results remain statistically comparable with the broader community standards. The references are included at the end of this document.

Rationale for the Southwest: We explicitly acknowledge your valid point regarding the unique meteorology of the Sichuan Basin. While we retained the standard "Southwest" grouping to maintain consistency with the cited frameworks, we have ensured that our analysis treats the distinct mechanisms of the basin separately from the plateau areas. For instance, in Section 4.1.1, we specifically differentiate between the inversion mechanisms in the Sichuan Basin (dominated by lower-tropospheric inversions) and the Plateau (dominated by high winds and turbulence).

Revised text: We have updated the sentence in Section 2.1 to explicitly state the criteria: " To capture this diversity, we partition the domain (excluding Hong Kong, Macau, and Taiwan owing to data limitations) into seven regions based on standard administrative divisions, integrated meteorological characteristics and major urban agglomerations (Fig. 1)."

4.The authors mention that temperature inversions primarily affect $PM_{2.5}$ pollution in winter and are one of the causes of severe pollution events. However, this viewpoint is mainly based on nationwide averages and lacks a detailed analysis of specific case studies. To enhance the persuasiveness of the conclusions, it is recommended that the authors include case studies of several major city clusters, such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta. These city clusters face different climatic and geographic conditions, and analyzing specific cases would provide a more comprehensive understanding of the actual impact of temperature inversions on PM2.5 pollution, especially during severe pollution events.

Response: We appreciate this constructive suggestion. You are correct that nationwide averages might obscure the specific dynamics of pollution events in different regions.

Following your recommendation, we selected three representative cities—Beijing (representing Beijing-Tianjin-Hebei, BTH), Nanjing (representing Yangtze River Delta, YRD), and Yangjiang (representing Pearl River Delta, PRD)—and analyzed the temporal evolution of TI strength and $PM_{2.5}$ concentrations during specific heavy pollution episodes (added as Fig.S22 in the revised manuscript).

The case study analysis reveals distinct regional characteristics: In Beijing (Fig. S22a) and Nanjing (Fig. S22b), we observed a clear accumulation process. TI intensification serves as the trigger, followed by a progressive rise in $PM_{2.5}$. The pollution often persists due to high emission loads even when TI fluctuates, demonstrating the "lid effect." In Yangjiang (Fig. S22c), the $PM_{2.5}$ concentrations show a tighter, near-synchronous correlation with TI strength. This suggests that in the PRD region, where background pollution is lower, air quality is highly sensitive to immediate changes in vertical stability.

These case studies provide robust evidence supporting our conclusion that temperature inversions are a primary driver of pollution accumulation, while also highlighting the role of emission loads in modulating the lag time of this relationship.

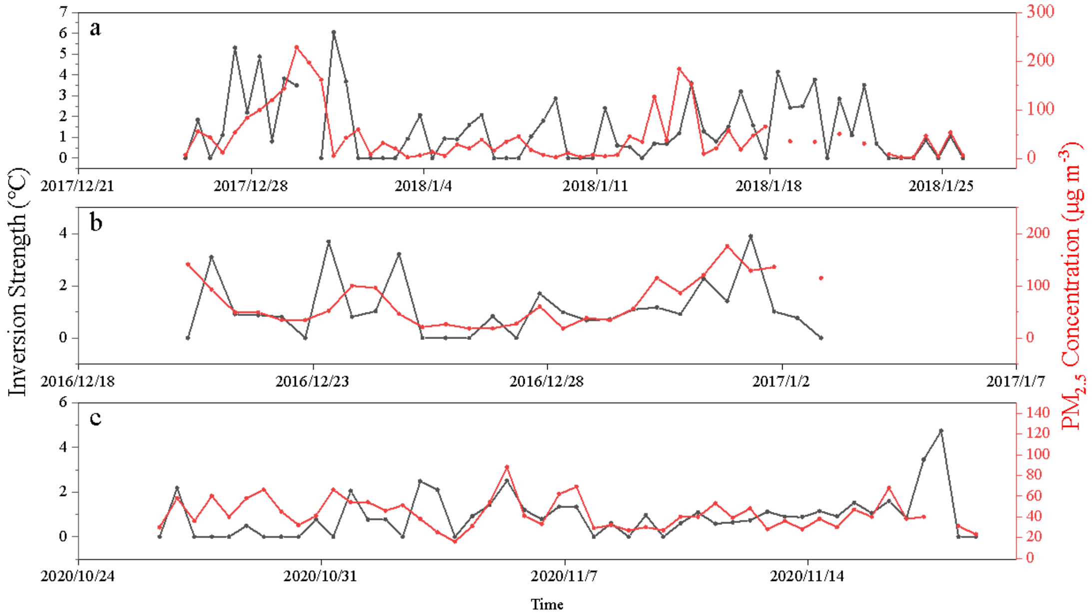


Fig. S22 Temporal variations of temperature inversion (TI) strength and surface $PM_{2.5}$ concentrations during severe pollution episodes in representative cities. (a) Beijing (BTH region), (b) Nanjing (YRD region), and (c) Yangjiang (PRD region). The black line represents TI strength (ΔT, left axis), and the red line represents $PM_{2.5}$ concentration (right axis).

5.One of the most intriguing findings is the negative correlation between EI strength and PM in southern China. The proposed explanation—a "transport-suppression mechanism" where EIs cap the boundary layer and isolate it from northerly pollutant inflow—is plausible but remains speculative. This hypothesis should be supported with more direct evidence. The authors could analyze wind direction and speed data during these EI events to show a reduction in northerly flow, or cite studies that have documented such a synoptic setup in southern China.

Response: We thank you for this insightful comment. You correctly pointed out the need to clarify the distinct pollution mechanisms in South China, particularly why inversions there seem to correlate with better air quality.

To investigate this, we combined Potential Source Contribution Function (PSCF) analysis with a detailed examination of wind fields during inversion (EI) versus non-inversion periods. The results reveal a mechanism driven by "Ventilation vs. Stagnation":

EI Periods (Fig. S24b): Our data shows that EIs in South China are synchronized with northerly winds. While the PSCF results (Fig. S23) identify Central China as a potential upstream source, the strong momentum of these northerly winds acts as a "sweeper," transporting pollutants rapidly into the South China Sea. This strong horizontal advection dominates over the vertical stability of the inversion, leading to lower PM levels.

Non-EI Periods (Fig. S24a): In contrast, non-inversion periods are dominated by weak southerly winds. We found that the Nanling Mountains play a critical role here, not by blocking incoming pollution, but by blocking the northward dispersion of local emissions. This creates a semi-enclosed stagnation zone over the Pearl River Delta, facilitating local accumulation despite the absence of an inversion lid.

To maintain the conciseness of the main text while addressing your concern, we have added a pointer to the Supplementary Material regarding 'this phenomenon'. Detailed mechanistic evidence, including PSCF maps and wind field analysis, is now provided in Text S3 of the supplement.

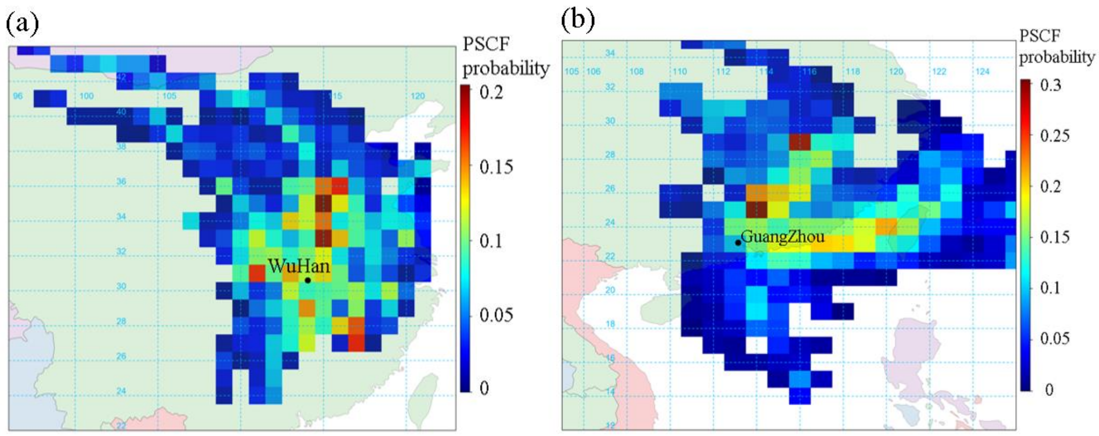


Figure. S23 Spatial distribution of the Potential Source Contribution Function (PSCF) values for PM2.5 during the study period. The analysis is based on 48-h backward trajectories at an altitude of 500 m. (a) Wuhan (representative of Central China), showing dominant potential sources from the North China Plain. (b) Guangzhou (representative of South China), indicating potential transport pathways primarily from Central China and the eastern coast.

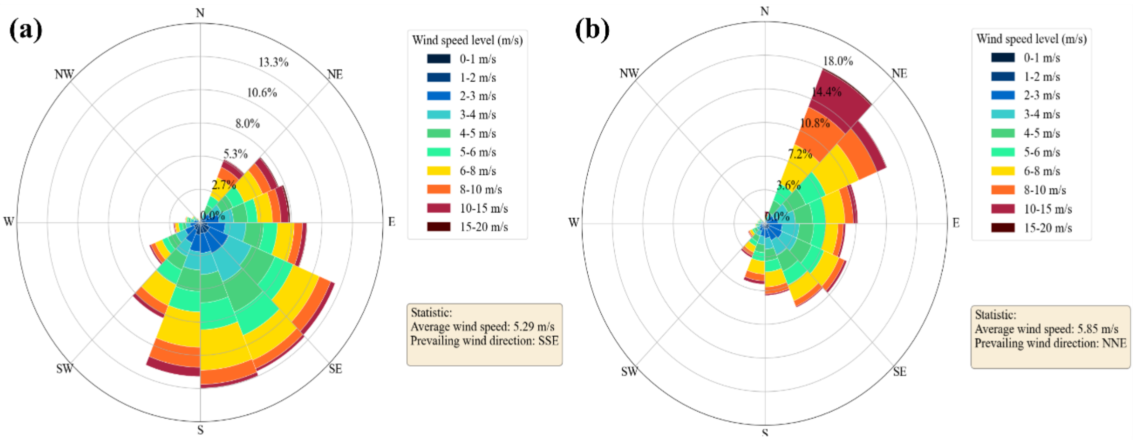
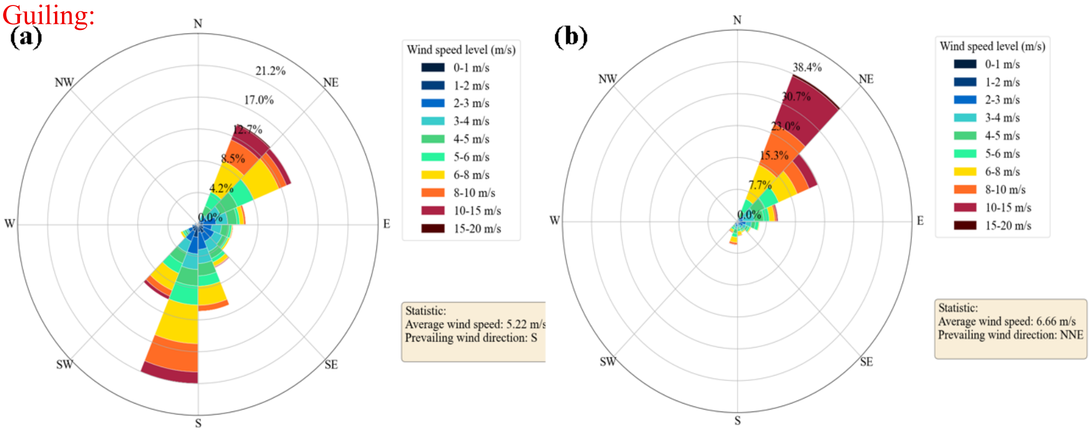


Figure S24. Roses of the mean boundary-layer wind (0–1000 m) in SC. (a) Patterns during non-inversion periods. (b) Patterns during the presence of EIs. Note that EIs are typically associated with stronger northerly winds (ventilation), while non-inversion periods are dominated by weaker southerly winds.

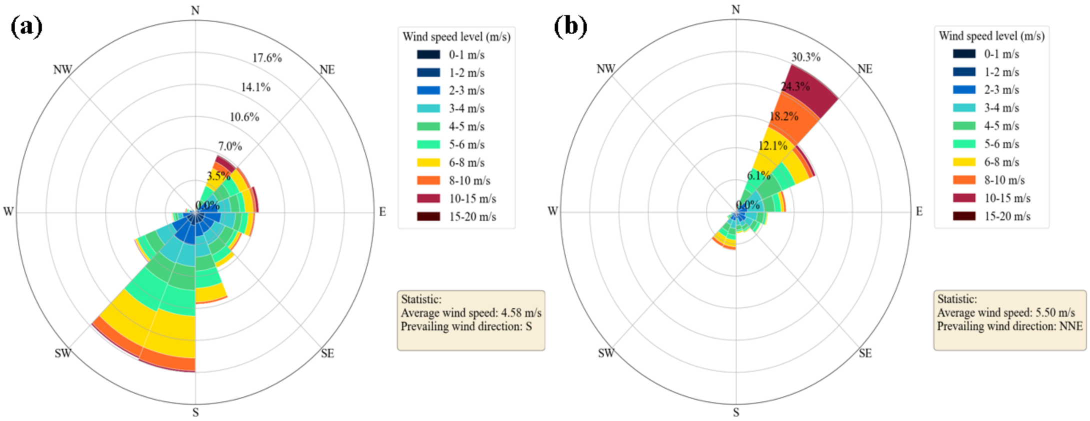
Below are the wind rose diagrams for selected cities in South China during EI and non-EI periods (for the response letter only).

(a) Patterns during non-inversion periods. (b) Patterns during the presence of EIs.

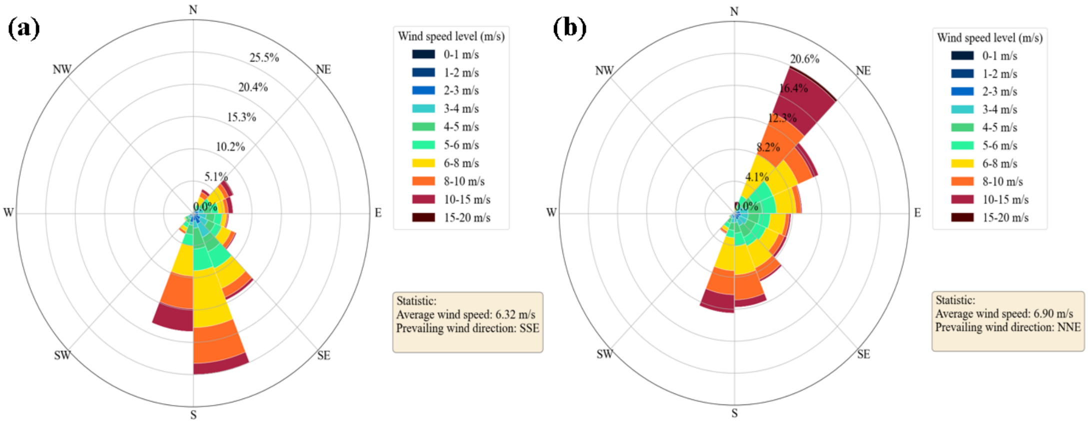
Guiling:



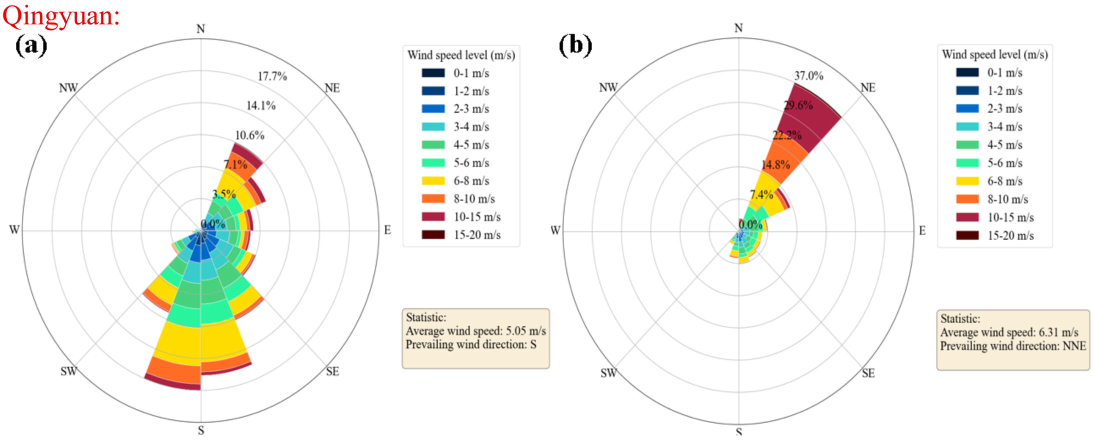
Heyuan:



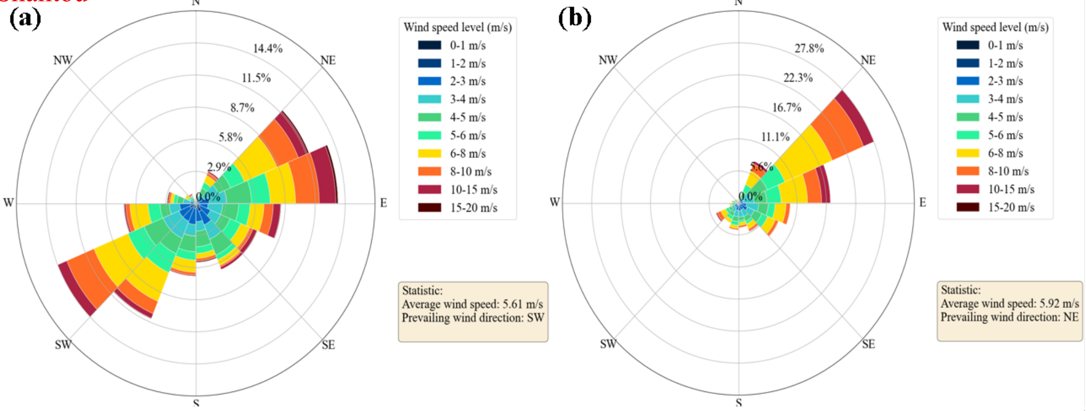
Nanning



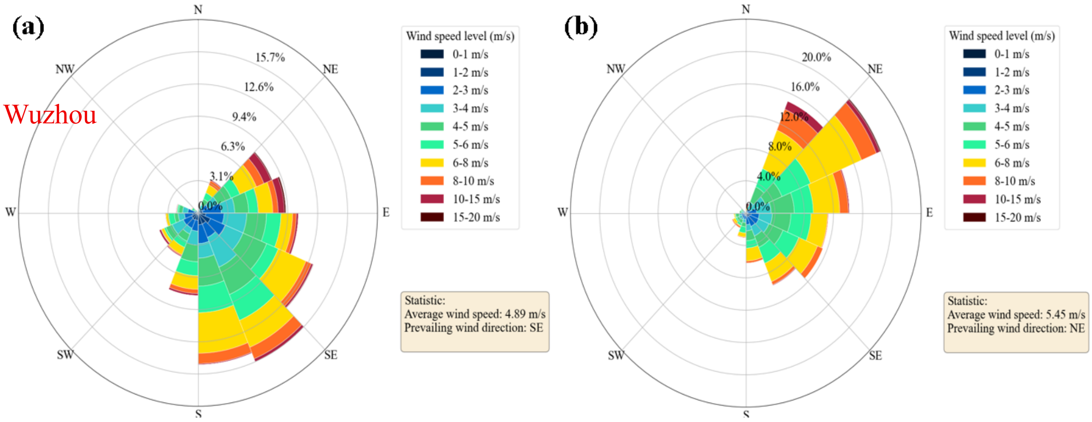
Qingyuan:



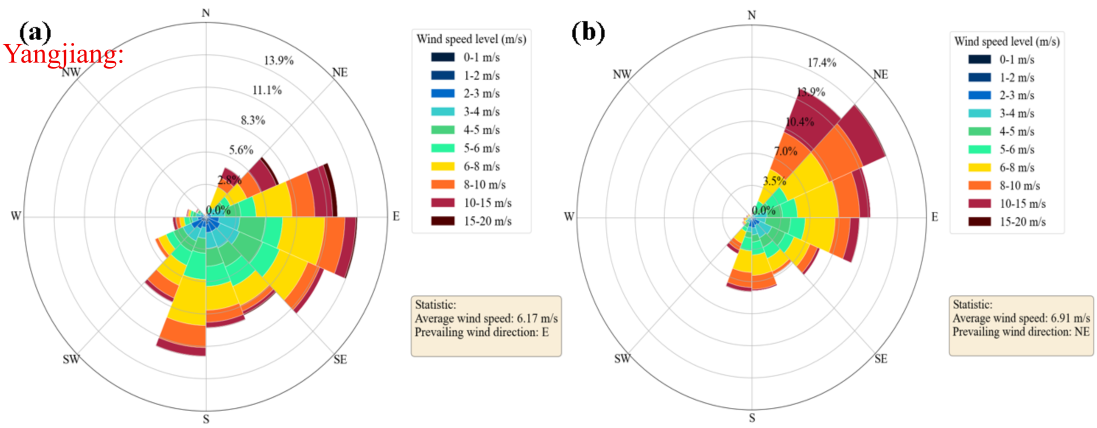
Shantou



Wuzhou



Yangjiang:



Specific Comments

1. **Line 99-107** Does this section lack a description of Central China?

   Response: Thank you very much for the suggestion. As recommended, we have added a description of Central China's geographic and climatic context in the section to better frame the study area.

   The newly added section is as follows:

   "Central China (CC), located in the heart of the country, experiences a transitional monsoon climate between the northern subtropical and warm temperate zones, characterized by a terrain dominated by plains and hills. Pollutants tend to accumulate in basins such as the Jianghan–Dongting Basin due to the region's enclosed topography and stable atmospheric conditions, where they further combine with polluted air masses transported from the north, resulting in regional and complex air pollution."

2. **Line 211** I believe you are describing three figures rather than two. "(Fig S2, 4a)" changed to "(Fig S2, S3, and 4a)".

   Response: We appreciate your careful reading. This was indeed an error in the figure citation. We have revised the sentence to correctly reference all three relevant figures: "(Fig S5, S6, and 4a)". (The supplementary materials have been updated, and the figure numbers have been modified accordingly.)

3. Figure 2: The color scheme for the different regions in the bar plot is difficult to distinguish. Please use a more distinct and colorblind-friendly palette.

   Response: Thank you for your suggestion regarding the color scheme in Figure 2. We agree that the original palette may not be sufficiently distinct or color-blind-friendly.

   We have improved the visual clarity of Figure 2 through the following revisions: The color contrast between regional curves has been enhanced, and uniform markers have been replaced with distinct symbols to facilitate inter-regional comparison. The originally ambiguous color representing the "Southwest" region has been adjusted to ensure clear differentiation. The vertical resolution of the histogram has been refined from 200 m to 100 m bins, allowing more explicit discrimination between the base-height distributions of surface-based inversions (SBIs) and elevated inversions (EIs).

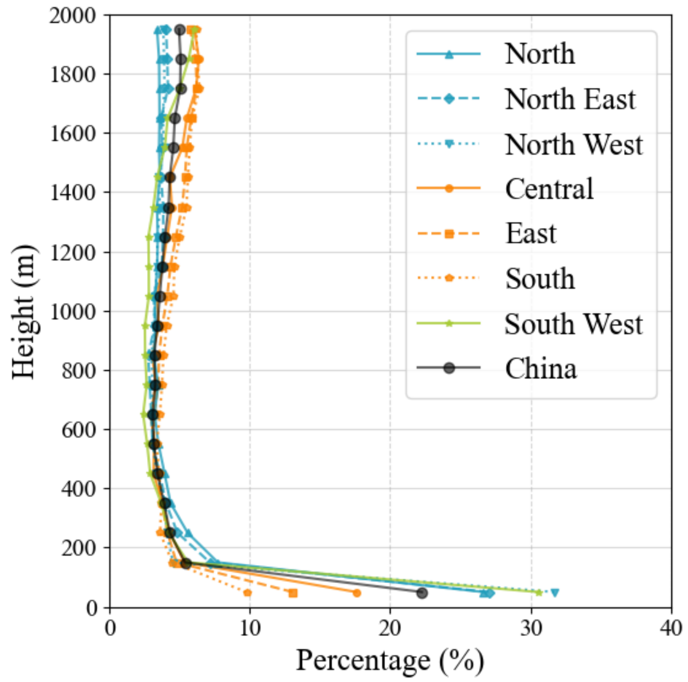


Fig.2 Vertical distribution of inversion base height: fraction of total inversions per height bin.

4. **Figure 8:** The presentation of the results in this figure is very dense. Consider breaking it down into two separate figures (e.g., one for 08:00 BJT and one for 20:00 BJT) for improved clarity.

Response: Thank you for your constructive suggestion regarding the clarity of Figure 8. We apologize for the insufficient clarity in its original description and will revise the explanation accordingly.

In the manuscript, Figure 8 presents the seasonal average of $PM_{2.5}$ differences between inversion and non-inversion conditions, combining data from both 08:00 and 20:00 BJT. To address your concern and improve readability, we have already included time-resolved analyses in the Supplementary Material.

Both supplementary figures include significance markers from two-sample t-tests, allowing direct comparison of diurnal inversion impacts. We have revised the relevant sentence in Section 4.2.2 to clarify this point: "We quantify inversion impacts by contrasting the daily mean $PM_{2.5}$ concentrations under inversion and non-inversion conditions, with statistical significance assessed using two-sample t-tests (Fig. 8). The time-resolved analyses for 08:00 and 20:00 BJT are shown in Figs. S12 and S13."

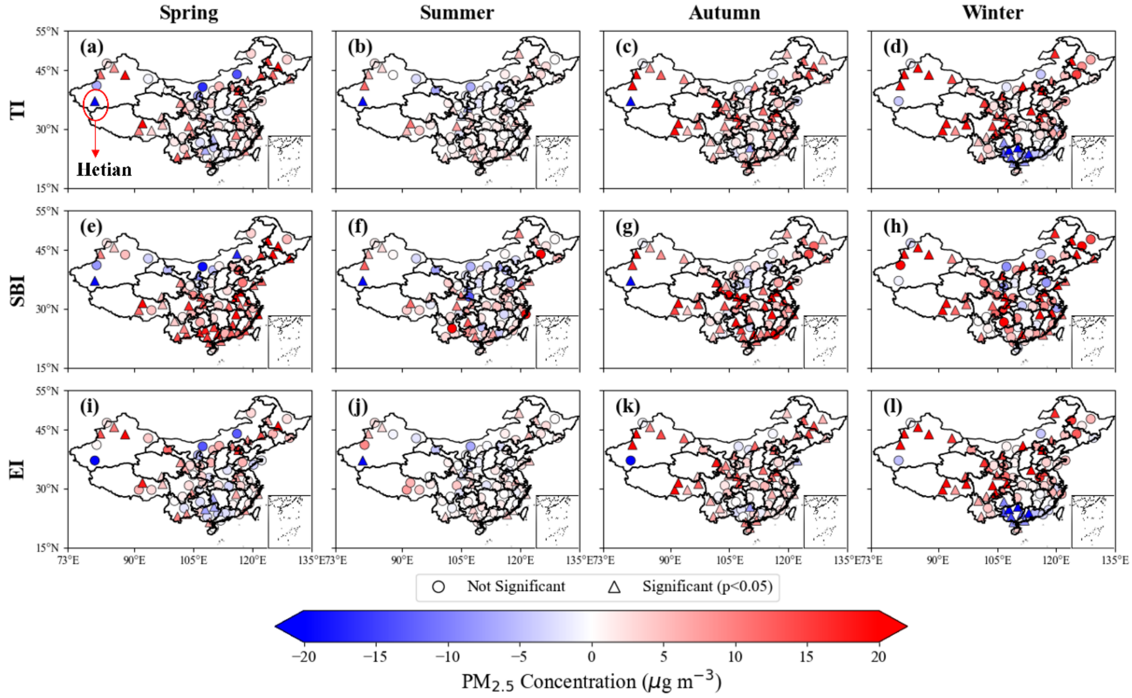


Fig S12. Distribution of $PM_{2.5}$ concentration differences with and without temperature inversion at BJT 08:00.

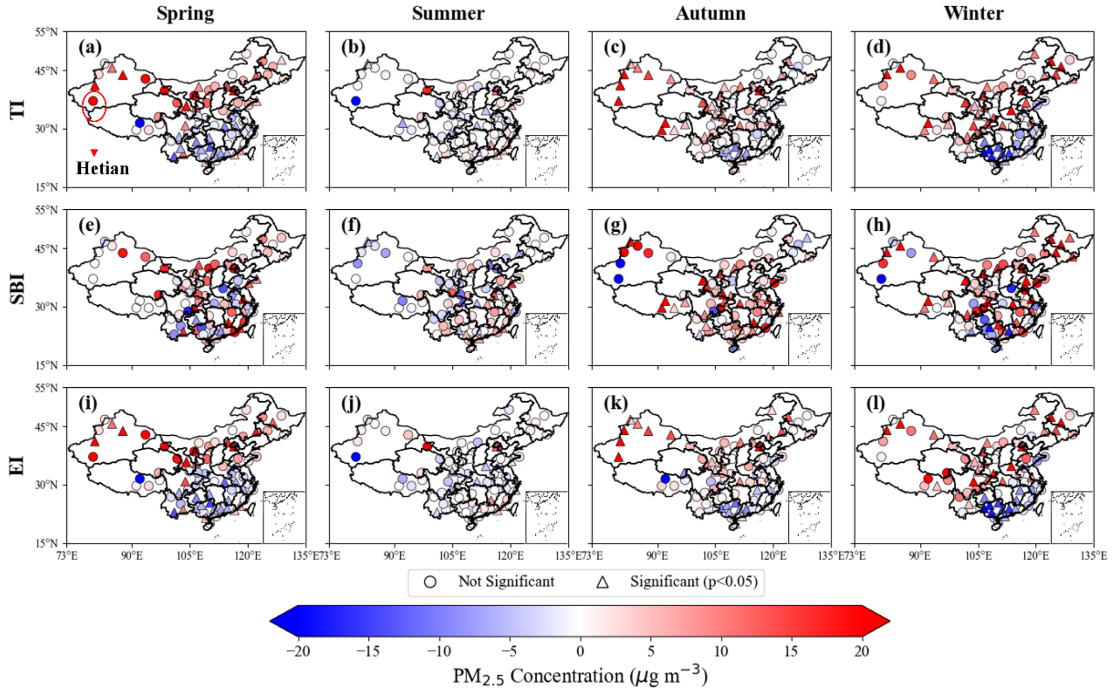


Fig S13. Distribution of $PM_{2.5}$ concentration differences with and without temperature inversion at BJT 20:00.

5. **Line 295-297:** The location of **'Hetian'** in southern Xinjiang, as discussed in the text, should be marked on **Figure 8** to improve readability.

   Response: We thank the reviewer for this constructive suggestion. As recommended, we have marked the location of the Hetian station in southern Xinjiang on Figure. 8a in the revised manuscript.

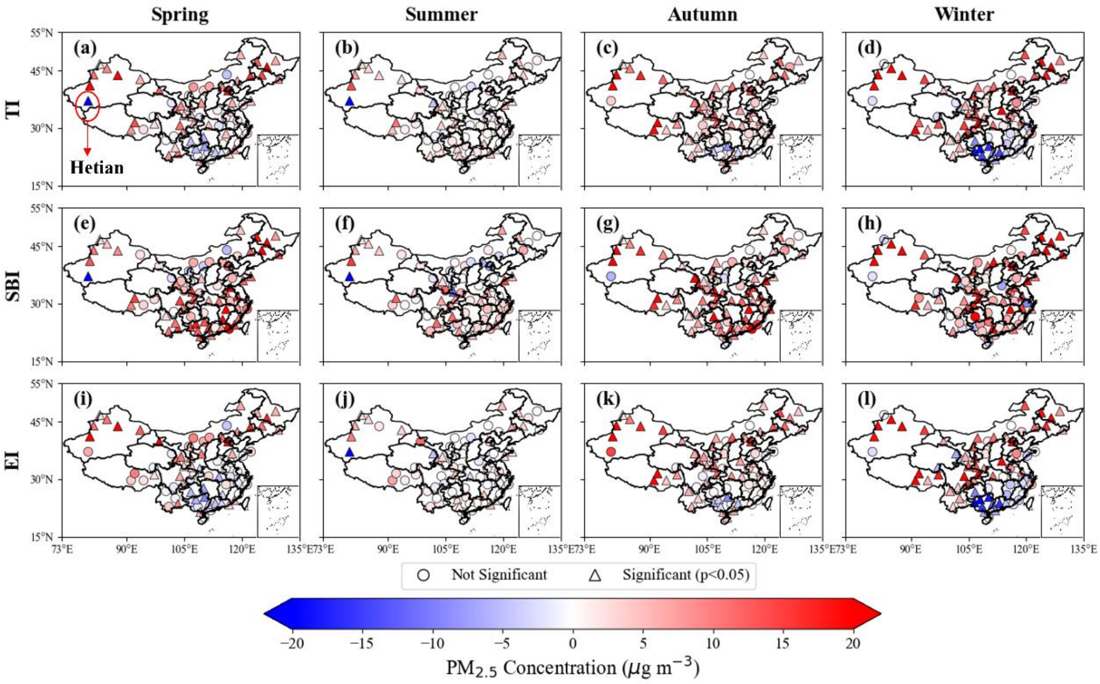


Fig.8 Distribution of $PM_{2.5}$ concentration differences with and without temperature inversion. The larger circle indicates significance at the 95% level (t-test)

6. **Line 334** Extra parentheses in citation "(Liu et al., 2022))" → Remove extra parenthesis

   Response: Thank you for catching this typographical error. The extra parenthesis has been removed, and the citation now correctly reads "(Liu et al., 2022)" in the revised manuscript.

7. **Line 354-356:** The statement "a deep but weak inversion can be eroded by mechanical turbulence more readily than a shallow but intense one" is a key physical insight. This point could be emphasized earlier in the manuscript to better frame why strength is a more dominant factor than thickness.

   Response: Thank you very much for the suggestion. Following your suggestion, we have relocated and expanded this statement to an earlier section of the discussion (Section 4.2.2) to better frame the physical rationale behind why inversion strength is a more dominant predictor than thickness.

Revised: By contrast, inversion thickness shows a much weaker and less uniform association with $PM_{2.5}$ (Fig. S14). SBI thickness is generally positively correlated with $PM_{2.5}$ (except in NEC). For EI, significant thickness–$PM_{2.5}$ relationships appear only in NEC and NWC (R^2 = 0.86 and 0.92, respectively); elsewhere, EI thickness exerts negligible influence. Together, these results establish inversion strength—not thickness—as the dominant predictor of $PM_{2.5}$ accumulation (Fig. 9 vs. Fig. S14)., Thickness primarily defines the volume of the trapping layer: a deep but weak inversion can be eroded by mechanical turbulence more readily than a shallow but intense one. This mechanism ensures that a stronger temperature gradient yields greater static stability and more effective suppression of turbulent mixing (Liu et al., 2022).

8. Language and Abbreviations: The manuscript is generally well-written. A minor check for consistent use of abbreviations is recommended (e.g., "TI" is used throughout, but the full term is sometimes repeated unnecessarily).

Response: Thank you for your careful reading and helpful suggestion regarding abbreviation consistency. We have now systematically reviewed the entire manuscript to ensure that "temperature inversion (TI)" is defined at its first occurrence and subsequently referred to consistently as "TI." All other abbreviations have been checked for uniformity.

Reference:

Fan, Hao, Chuanfeng Zhao, and Yikun Yang. 2020. "A Comprehensive Analysis of the Spatio-Temporal Variation of Urban Air Pollution in China during 2014–2018." *Atmospheric Environment* 220: 117066. https://doi.org/10.1016/j.atmosenv.2019.117066.

Guo, Jianping, Xinyan Chen, Tianning Su, et al. 2020. "The Climatology of Lower Tropospheric Temperature Inversions in China from Radiosonde Measurements: Roles of Black Carbon, Local Meteorology, and Large-Scale Subsidence." *Journal of Climate* 33 (21): 9327–50. https://doi.org/10.1175/JCLI-D-19-0278.1.

Huang, Qianqian, Yiqi Chu, and Qianhui Li. 2021. "Climatology of Low-Level Temperature Inversions over China Based on High-Resolution Radiosonde Measurements." *Theoretical and Applied Climatology* 144 (1–2): 415–29. https://doi.org/10.1007/s00704-021-03536-w.

Kahl, Jonathan D. 1990. "Characteristics of the Low-level Temperature Inversion along the Alaskan Arctic Coast." *International Journal of Climatology* 10 (5): 537–48. https://doi.org/10.1002/joc.3370100509.

Sun, Zhixu, Jiani Tan, Fangting Wang, et al. 2024. "Regional Background Ozone Estimation for China through Data Fusion of Observation and Simulation." *Science of The Total Environment* 912

(February): 169411. https://doi.org/10.1016/j.scitotenv.2023.169411.

Response to Reviewer 2 (Initial Response)

Review result of "Spatiotemporal patterns of temperature inversions and impacts on surface $PM_{2.5}$ across China" (egusphere-2025-4751)

Response to Reviewer #2:
reviewer's comments are given in blue,
our responses are given in deep red.

Some of the content in the manuscript have been revised and updated.

We would like to thank the editor and reviewers for carefully reading the manuscript and providing detailed and constructive comments, which have helped a lot in improving the manuscript. We quote each comment below, followed by our response.

1. Is ~16 m significant?
   Response: We fully agree with your assessment. You are correct that a thickness difference of ~16 m is marginal. We have removed the specific mention of the "~16 m" thickness difference from the Abstract. The revised sentence now focuses on the robust contrasts in frequency and intensity, which are the primary distinguishing features between regions.

   Revised abstract text: "Distinct regional patterns emerge: SBIs dominate in northern China and are significantly stronger 1.3 °C higher than EIs, whereas EIs prevail in eastern China."

2. Line 26, we don't really say that $PM_{2.5}$ is a driver.
   Response: Thank you very much for your suggestion. We agree that the term "driver" could be misinterpreted. Our intention was to emphasize the central role of $PM_{2.5}$ in causing air pollution-related problems. To be more precise, we have changed "a major driver" to "a key indicator and a primary pollutant" in the revised manuscript.

   Revised text: "Fine particulate matter ($PM_{2.5}$, aerodynamic diameter ≤ 2.5 μm) is a dominant component of atmospheric aerosols and a key indicator and a primary pollutant of air pollution in China"

3. Line 39, specific weather systems could also trigger TIs.
   Response: Thank you very much for your suggestion. We agree that specific synoptic-scale weather systems are crucial triggers for temperature inversions. Following your advice, we have revised the manuscript to include the role of anticyclones (high-pressure systems) and frontal systems as key weather systems that foster TI formation. The corresponding text in Line ?? has been modified accordingly.

   Revised text: "TIs arise through multiple mechanisms, including nocturnal radiative cooling, warm-air advection, topographic confinement, as well as under specific synoptic conditions such as stationary high-pressure systems (subsidence warming) and frontal zones."

4. Line 42, a reference is needed for the mentioned wind speed.
   Response: Thank you very much for your suggestion. A relevant reference (Czarnecka et al., 2019) has now been added to support the statement regarding wind.

5. Line 43, warm advections do not necessarily be synoptic-scales.
   Response: Thank you very much for your suggestion. We agree that warm advection can occur across various scales. Our intention was to refer specifically to synoptic-scale warm advection as a driver for elevated inversions. We have also revised the text accordingly, please refer the revised manuscript.

   Revised text: "In contrast, elevated inversions (EIs) are often associated with synoptic-scale phenomena. Key driving mechanisms include synoptic-scale warm advection, subsidence within high-pressure systems, and frontal overrunning."

6. Line 48, does this "ventilation" mean vertical dispersion?
   Response: We thank the reviewer for raising this important point for clarification. In the context of atmospheric pollution, "ventilation" typically refers to the combined effect of both vertical dispersion and horizontal advection (wind-driven transport) that together act to remove and dilute pollutants from a source region. To be more precise and to avoid potential ambiguity, we have revised the sentence to explicitly include both vertical and horizontal processes. We have replaced "pollutant ventilation" with "atmospheric pollutant dispersion and transport".

   Revised text: "The resulting suppression of atmospheric pollutant dispersion and transport operates through three interconnected mechanisms."

7. Please provide the locations of all used air quality monitoring stations in Fig. 1. Please also provide terrain features to show if the 10 km threshold result in any large differences in terrain features.
   Response: Thank you for these valuable suggestions regarding spatial representation, which have significantly improved our manuscript.

   Updated main map: As suggested, we have revised Fig. 1 to include the locations of all used air quality monitoring stations and have overlaid terrain features. This demonstrates that the 10 km pairing threshold generally does not span large terrain gradients.
   Station matching rationale: The 10 km threshold was strategically chosen to balance spatial representativeness and sample size. It was identified via a saturation analysis (see new Supplementary Fig. S1) as the point where increasing the distance yields diminishing returns in viable station pairs, thus ensuring robust national-scale coverage without compromising the physical relevance of the $PM_{2.5}$ data to the sounding profile.
   Full network context: To provide full transparency and contextualize our site selection, we have

added a new supplementary map (Supplementary Fig. S2) showing the complete, unfiltered national network of all radiosonde and air quality stations. This map visually affirms that our 10 km filtering resulted in a representative subset of stations with extensive geographical coverage.

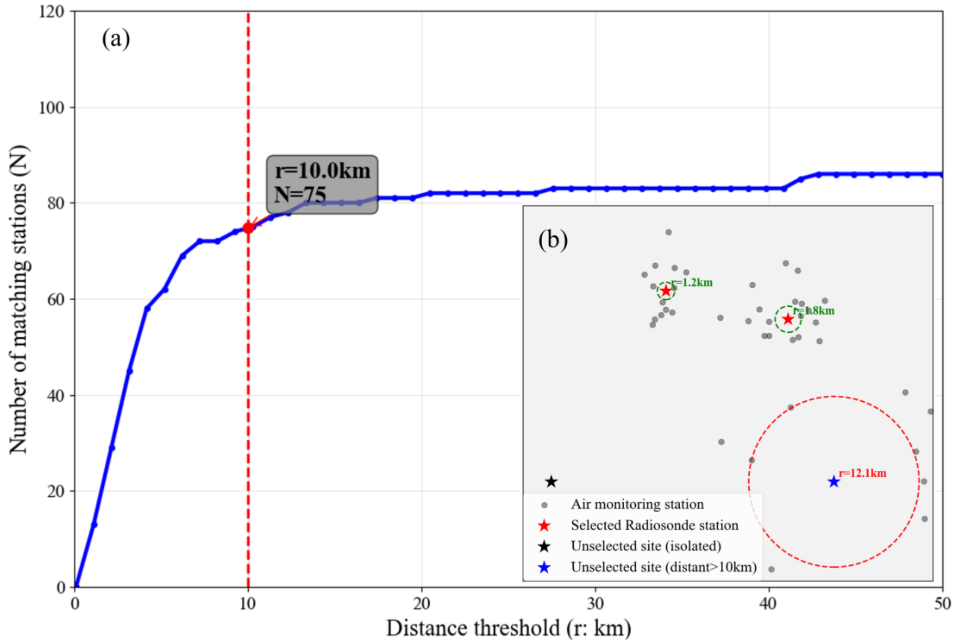


Fig S1. Site filtering method. (a) Relationship between distance and the number of matching stations. (b) Example diagram of site matching process. 'r' represents the distance from the nearest air quality monitoring station to the sounding station.

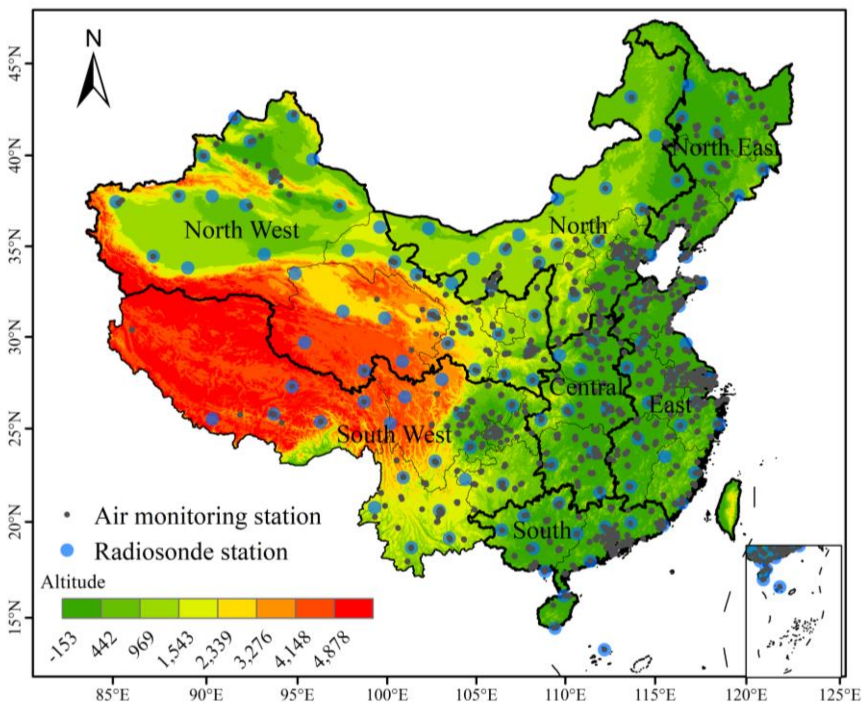


Fig.S2 Distribution of all radiosonde stations and air monitoring stations in China as of 2021. The inset map in the lower right shows the South China Sea Islands.

8. Line 115, please provide the valid bottom height for radiosonde observations.

Response: We confirm that the valid bottom height of the radiosonde observations used in this study is 0 m (Surface Level).According to the operational observation standards of the L-band sounding system in China, the initial surface meteorological data (including temperature, pressure, and humidity measured by the co-located surface weather station) must be input into the sounding system as the initiating record before the balloon release.

Therefore, our vertical profiles consist of: The Surface Layer (H = 0 m): Based on in-situ surface station observations. The Upper Air Layers: Followed continuously by the radar-tracked measurements. This data integration ensures that there is no blind zone at the surface, allowing for the precise identification of Surface-Based Inversions (SBIs) starting strictly from the ground.

Revised: "The GTS1 digital radiosonde provides vertical profiles of temperature, pressure, humidity, wind speed, and direction from the surface (0 m AGL) to ~30 km, with 5–8 m nominal vertical resolution (sampling frequency 1.2 s). By integrating in-situ observations from the co-located surface weather station as the initial record, the valid bottom height for all profiles is strictly maintained at 0 m."

To visually demonstrate this data structure and the validity of the bottom height, we have provided two new items in the Supplementary Material:

Table. S1 A comprehensive list of the 75 radiosonde stations, including their specific station IDs, geolocation (latitude/longitude), and elevation.

Station_Name	Station_ID	Latitude	Longitude	Altitude (m)	Region
Aksu	51628	41.12	80.38	1108	North West
Ankang	57245	32.7166	109.0333	291	North West
Anqing	58424	30.623	116.9672	63	East
Baise	59211	23.9027	106.6063	176	South
Beihai	59644	21.4475	109.1836	14	South
Beijing	54511	39.8061	116.4694	32	North
…	…	…	…	…	…

Note: Please refer to the Supplementary Material for the complete list of 75 stations.

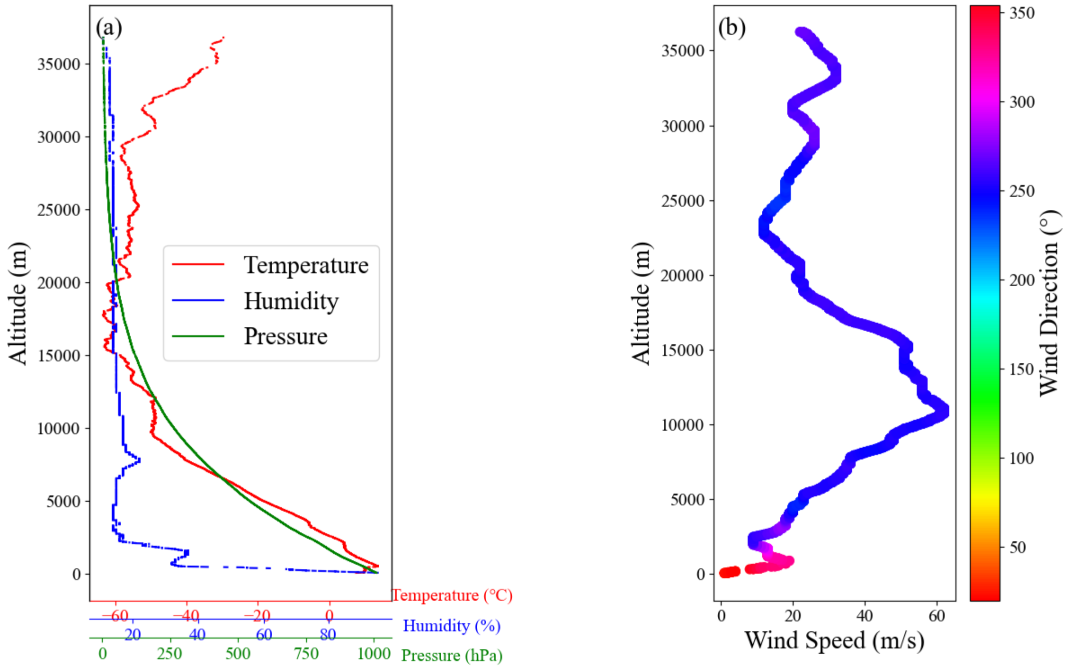


Figure.S3 A representative vertical profile (Temperature, Pressure, Humidity, Wind Speed/Direction) from the Beijing station (Nov 7, 2017, 08:00 BJT).

9. Maybe lapse rate is a better parameter for TI strength.

   Response: We thank the reviewer for this comment. It is substantively the same as Question 22, and therefore, a unified response is provided under Question 22. Please refer to that section for our detailed reply and the corresponding revisions made to the manuscript.

10. Line 162, it should be "a daily mean $PM_{2.5}$ concentration exceeding 75 ug m^{-3}can be identified as a pollution event". However, the authors could use this threshold to identify pollution events, do not necessarily follow the official standards.

    Response: We sincerely thank you for this constructive comment. You are absolutely correct that the GB3095-2012 standard strictly defines a pollution event based on the daily mean PM2.5 concentration, rather than hourly value.

    As you kindly noted, our study aims to capture the specific meteorological conditions (temperature inversions) at the exact moments of the radiosonde launches (08:00 and 20:00 BJT). Using a 24-hour average would smooth out these critical sub-daily variations. Therefore, we followed your suggestion to clarify that while we reference the official threshold value 75 μg m^{-3}, we are applying it to hourly data for the purpose of this specific analysis.

    We have revised the text in Section 3 (Method) to explicitly state this distinction and ensure accuracy: " According to China's National Ambient Air Quality Standards (GB3095-2012), the standard for a pollution event is based on a daily mean $PM_{2.5}$ concentration exceeding 75 μg m^{-3}. In this study, to align with the instantaneous radiosonde observations at 08:00 and 20:00 BJT, we applied this concentration threshold 75 μg m^{-3} to the hourly $PM_{2.5}$ data to identify pollution events corresponding to the sounding times."

11. Line 171, if a TI event's depth is more than 200 m, will it be counted twice?
Response: We thank you for this thoughtful question, which allows us to clarify our methodology. Your concern regarding potential double-counting would be valid if we were binning by the depth or vertical extent of the inversion. However, in this analysis, we are binning strictly by the base height of the inversion layer.

Each inversion event is assigned to one, and only one, 200-m height bin based on where its base is located. Therefore, regardless of how thick an inversion layer is (i.e., whether its depth is 100 m or 500 m), it is counted only once in the bin corresponding to its base height. This approach ensures that no double-counting occurs.

12. Figure 2, it seems this 200 m threshold could not tell more details about the proportion of SBI. Please provide such information in line 172.
Response: We thank the reviewer for this important suggestion. We agree that the original 200-m binning obscured the specific contribution of SBIs (base height < 100 m).

In direct response, we have revised the analysis as follows: We have regenerated Figure 2 using a 100-m vertical resolution. This change directly and clearly isolates the SBI contribution in the 0-100 m bin. This refined 100-m resolution allows for a clear separation between SBI and the EI. The revised text now explicitly states: "The TI proportion peaks sharply in the lowest 0–100 m bin, which comprises exclusively SBIs and accounts for 22.2% of all inversion events." The fine-scale distribution of SBI base heights (10-m bins) and the full vertical extent of EIs up to 2000 m are provided in Figs. S4, respectively.

Revised:
The base height of TI sets the effective lid for vertical pollutant dispersion. To resolve its vertical structure within the boundary layer, we quantified the vertical distribution of inversion events. This is defined as the percentage of the total number of inversion events falling within each 100-m height bin from the surface to 2 km (Fig. 2). A distinct non-linear profile emerges: The TI proportion peaks sharply in the lowest 0–100 m bin, which comprises exclusively SBIs and accounts for 22.2% of all inversion events. This peak is followed by a rapid decline to a minimum of 3.1% at 600–700 m, and then a gradual recovery to 5.1% at 1800–1900 m—i.e., a "rapid decline, then slow recovery" with height.
Marked regional contrasts accompany this vertical pattern. In the near-surface layer (0–100 m, i.e., the SBI), the Northwest exhibits the highest TI proportion 31.6%, followed by Southwest 30.5%. In comparison, Central, East, and South China show lower near-surface SBI proportions, with South China the lowest 9.8%. The pattern reverses aloft: for elevated inversions in the 1000–2000 m layer, South China records the highest proportion 56.0%, whereas northern regions are much less affected. Taken together, intense near-surface trapping by SBIs preferentially occurs over inland northern and southwestern China, while EIs are more common and reach higher altitudes in the southeastern coastal belt. A potential driver of this dipole is the

diurnal temperature range (DTR): larger DTRs over inland regions enhance nocturnal radiative cooling, favoring strong SBIs; weaker DTRs in maritime-influenced southeastern areas favor synoptic processes that produce EIs."

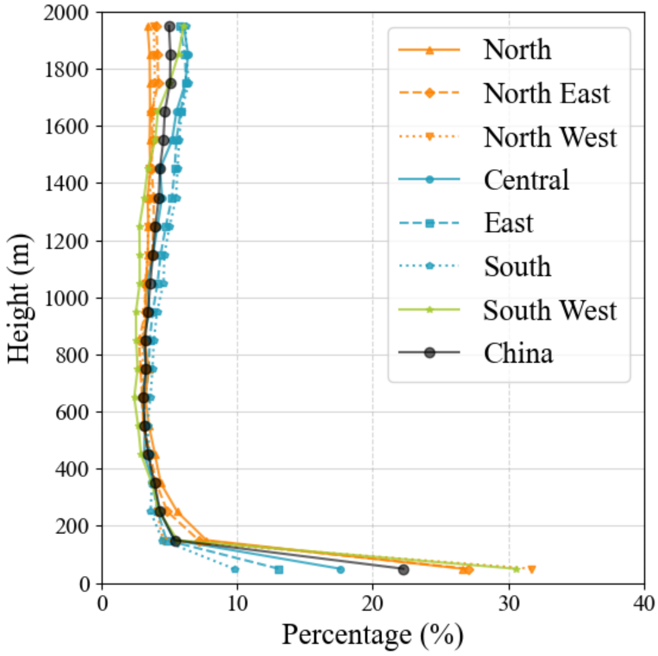


Fig.2 Vertical distribution of inversion base height: fraction of total inversions per height bin.

Supplementary material: To provide even deeper insight and address the spirit of the reviewer's comment, we have also conducted a more granular analysis. We include new supplementary figures:

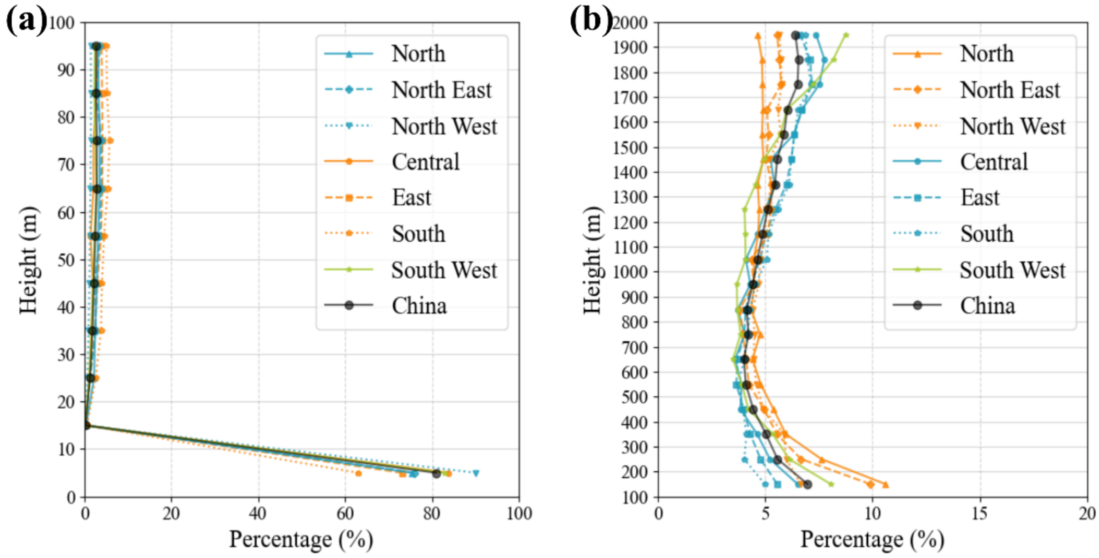


Fig S4. (a) The fine-scale distribution of SBI base heights at 10-m intervals (0-100 m); (b) The full vertical distribution of EI base heights at 100-m intervals (100-2000 m).

13. Line 180, “plausible”?

Response: We thank you for this refinement regarding our word choice. Following your suggestion, we have replaced "plausible" with "potential" to more accurately describe the role of the Diurnal Temperature Range (DTR) as a driving factor. The revised sentence in Section 4.1 now reads:

"A potential driver of this dipole is the diurnal temperature range (DTR): larger DTRs over inland northern and southwestern regions enhance nocturnal radiative cooling."

14. Figure 3, the consistent color bar conceals lots of useful information especially for SBI.

Response: We appreciate this insightful observation regarding the visualization of SBI frequencies. You are correct that the consistent color bar, while covering the full range of TI frequencies, tends to compress the dynamic range of Surface-Based Inversions (SBIs), thereby obscuring some finer spatial details. Our primary intention in Figure 3 was to enable a direct magnitude comparison between SBIs and EIs. Using a unified color scale allows readers to visually grasp the relative dominance of different inversion types across regions (e.g., immediately seeing that EIs are significantly more frequent than SBIs in eastern China). Adopting different scales might mislead readers regarding these relative magnitudes. However, to address your valid concern and reveal the hidden spatial details of SBIs, we have generated a supplementary figure (Fig. S15) with an independent color scale optimized specifically for the SBI range. We have also added a note in the caption of Figure 3 to direct interested readers to this supplementary figure for a more detailed view.

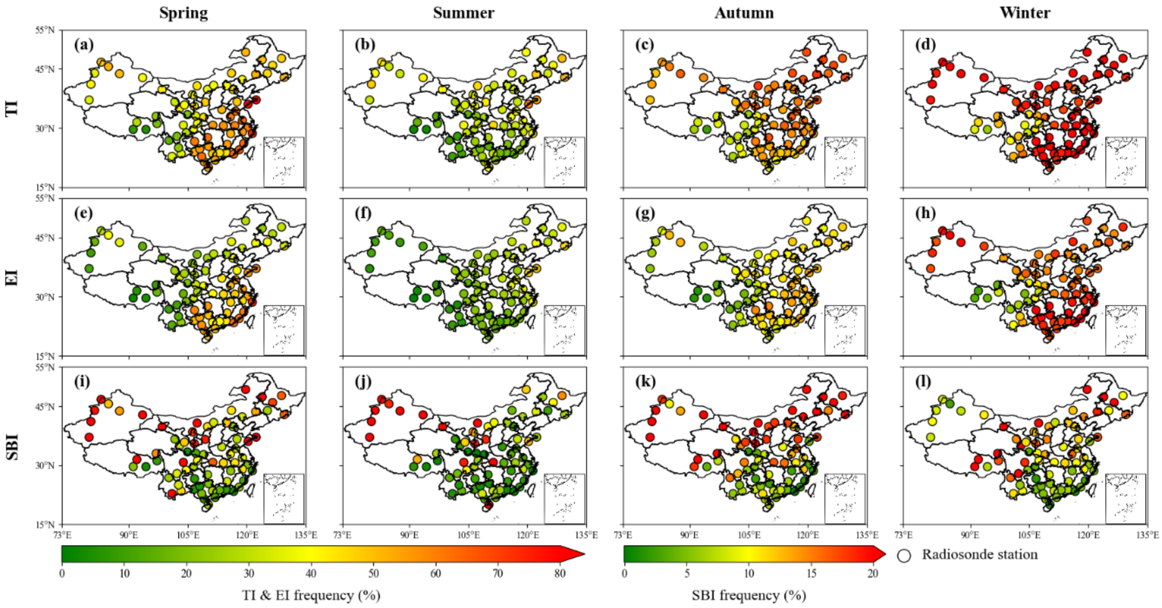


Fig. S15. Spatial and seasonal distribution of occurrence frequency for different types of TI.

15. Line 191, grammar issue.

Response: We thank you for your careful reading. You are correct that the original sentence lacked grammatical parallelism and logical precision, particularly in the clause "whereas the Southwest is lowest." Following your advice, we have revised the sentence to ensure the subject and verb agree logically and to maintain parallel structure with the preceding clause. The revised

text in Section 4.1.1 now reads:
"Regionally, Northeast China records the highest frequency (59.5%), whereas the Southwest exhibits the lowest (31.3%; Table 1)."

16. Line 192, please make the first factor clearer.
Response: Thank you for this constructive suggestion. We have revised the text to explicitly describe the altitude discrepancy that leads to the lower observed inversion frequency in the Southwest. Specifically, we clarified that while our study focuses on inversions within the 0–2,000 m range (boundary layer), the dominant inversion structures in the Sichuan Basin are lower-tropospheric inversions (LTIs) that typically occur at higher altitudes of 2,200–3,400 m (Feng et al., 2020). Consequently, these high-altitude inversions are not captured in our statistics. The revised sentence reads:
"The suppressed occurrence in the Southwest likely reflects two factors: (i) in the Sichuan Basin, the dominant signal is lower-tropospheric inversions (LTIs) which typically occur at altitudes of 2,200–3,400 m (Feng et al., 2020)—well above the 0–2,000 m height range examined in this study—resulting in their exclusion from our frequency statistics;"

17. Line 201-202 & 208, shouldn't these sentences be placed in the previous paragraph?
Response: We thank you for identifying this structural inconsistency. You are absolutely correct. The sentences discussing the "east-high, west-low" gradient and the bias caused by the fixed launch time (BJT 08:00 vs. local solar time) pertain to the spatial distribution of inversions. However, they were misplaced in the second paragraph, which focuses on seasonal variability.

Following your suggestion, we have moved the sentences describing the 'east-high, west-low' gradient to the end of the first paragraph of Section 4.1.1. Additionally, to further enhance the logical flow, we have repositioned the sentence 'National averages by type indicate SBIs ~13% and EIs ~43% annually...' to immediately precede the statement 'Elevated inversions (EIs) dominate total events nationally.

This adjustment ensures that all discussions regarding spatial patterns and their underlying causes (including the time zone effect) are consolidated in the first paragraph, while the second paragraph remains dedicated to seasonal and diurnal variations.

18. Line 202, when the term "peak" is used, please do not mention so many months. Please rephrase this sentence.
Response: Thank you for this precise correction. You are absolutely right. Using "peaks" for multiple months dilutes the term. We have rephrased the sentence as follows to more accurately describe the pattern without misusing "peak":

Revised text: "SBI occurrence shows relatively high frequencies (>24%) in February, March, September, and October, whereas EI frequency exhibits a sharp, single peak in January (75.2%)."

19. Line 211, “are more likely to occur”.

Response: Thank you very much for your suggestion. We have revised the phrasing to 'are more likely to occur' as you suggested.

20. Line 214-219, the authors tried to explain the seasonal features of TI, but more detailed and in-depth analysis are needed (better with some evidences from meteorological data).

Response: We thank you for this insightful suggestion. You are correct that relying solely on solar forcing is insufficient to explain the seasonal variability. Following your advice, we conducted a detailed statistical analysis of the mean wind speed and relative humidity within the boundary layer (0–1000 m) using the radiosonde profiles. This vertical range was selected as a representative proxy for the lower troposphere, encompassing the primary domain of pollutant dispersion and inversion development while ensuring statistical consistency across seasons (regardless of the fluctuating boundary layer height). The results, presented in the new Fig. S7 (Supplementary material).

The analysis shows that winter is significantly drier than summer across all regions (Fig. S7b). For instance, in Northeast China, the mean relative humidity is ~49% in winter compared to ~71% in summer. This dry atmosphere significantly enhances nocturnal radiative cooling efficiency. Contrary to the assumption that inversions require calm winds, our data shows that boundary-layer wind speeds are actually higher in winter than in summer (Fig. S7a), likely due to the winter monsoon. This analysis suggests that the high frequency of winter inversions is not due to stagnation, but rather because the strong thermodynamic forcing (extreme dryness + long nights) is powerful enough to override the mechanical turbulence caused by higher winter winds.

We have revised Section 4.1.1 to include this mechanism and added Fig. S7 to the Supplementary Material to support these findings.

Revised: “In winter, short days and long nights promote the development of deeper and more persistent inversions through enhanced radiative cooling. With sunrise as late as around 07:20 BJT, the weak early-morning insolation preceding the 08:00 sounding is insufficient to dissipate the TI layer significantly. Furthermore, the wintertime atmosphere is significantly drier (Fig. S7), which minimizes downward longwave radiation and thereby maximizes the efficiency of nocturnal surface cooling. The subsequent ~10 hours of low-angle daylight provide insufficient thermal energy to significantly disturb the stable surface layer before 20:00. Consequently, the 08:00–20:00 frequency difference contracts to 14.8% in winter”

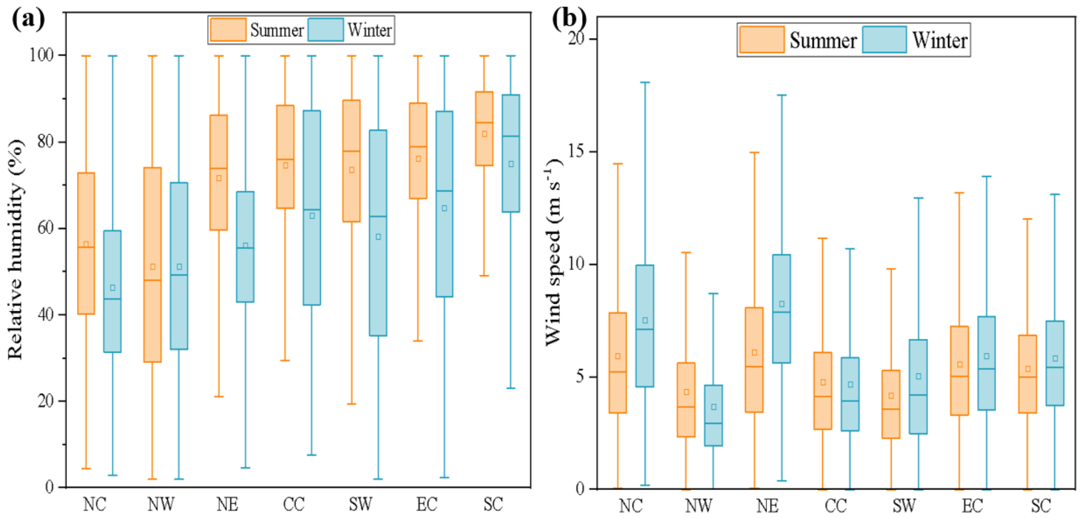


Fig. S7 Seasonal comparison of meteorological conditions within the boundary layer (0–1000 m).

21. Line 232, this sentence is hard to understand.

    Response: We thank you for pointing out this unclear phrasing. You are absolutely correct that the original sentence suffered from both grammatical inaccuracy (subject-verb disagreement) and ambiguity regarding what "TIs" specifically referred to. As you inferred, our intended meaning was that inversion strength (specifically, the temperature difference ΔT) is the most critical parameter regulating vertical diffusion.

    Following your comment, we have revised the sentence to be precise and grammatically correct: "Among the key TI parameters, strength exerts first-order control on pollutant dispersion."

22. Section 4.1.2, the TI strength defined in this paper is strongly related to the thickness of the TI. Thus, if a TI is very tick but with smaller temperature lapse rate, the strength could still be very strong. Please also see question 9.

    Response: We appreciate this valuable suggestion regarding the characterization of inversion intensity. In our study, we adopted inversion strength (ΔT = Tt − Tb) as the primary metric for TI intensity, which is widely used in similar investigations (e.g. Li et al, 2016; Huang et al, 2021; Liu et al., 2022) and facilitates direct comparison with existing literature on inversion–pollution relationships. Our analysis demonstrates that ΔT exhibits a clear and robust association with surface $PM_{2.5}$ concentrations across most regions, supporting its utility as a predictor of pollution accumulation. While we have not incorporated lapse rate into the main analysis, we recognize its potential relevance. To address your point, we have prepared a supplementary figure illustrating the spatial distribution of lapse rate derived from our inversion data. The Fig. S16 shows that lapse rate generally follows patterns similar to ΔT.

    You are correct that the lapse rate ($\Delta T/\Delta H$) provides a normalized measure of thermal stability per unit thickness, theoretically indicating the local thermodynamic stability gradient. Following your suggestion, we calculated the lapse rate and examined its correlation with surface $PM_{2.5}$ concentrations to compare its predictive power against TI strength (ΔT). The results led to the following observations: Statistical Evidence: As shown in the revised analysis

(Figure. S17 and Table. S4), the empirical data indicates that ΔT exhibits the strongest correlation with $PM_{2.5}$, followed by inversion thickness, while the lapse rate actually shows the weakest correlation.

We attribute this result to the fact that ΔT represents the total "energy barrier" (or heat deficit) that must be overcome by surface heating to erode the inversion. A thin inversion layer might have a very high lapse rate (very stable locally), but due to its small volume and low total heat deficit, it can be easily destroyed by morning turbulence, failing to trap pollutants effectively over long periods. In contrast, a thicker inversion with a large cumulative ΔT (even with a moderate lapse rate) imposes a massive energetic constraint on vertical mixing, serving as a persistent "lid" for pollution accumulation.

Revised text: "Additionally, we discussed the scenario where the lapse rate ($\Delta T/\Delta H$) was used as a proxy for inversion strength, as elaborated in supplementary Fig. S16, S17 and Table. S4."

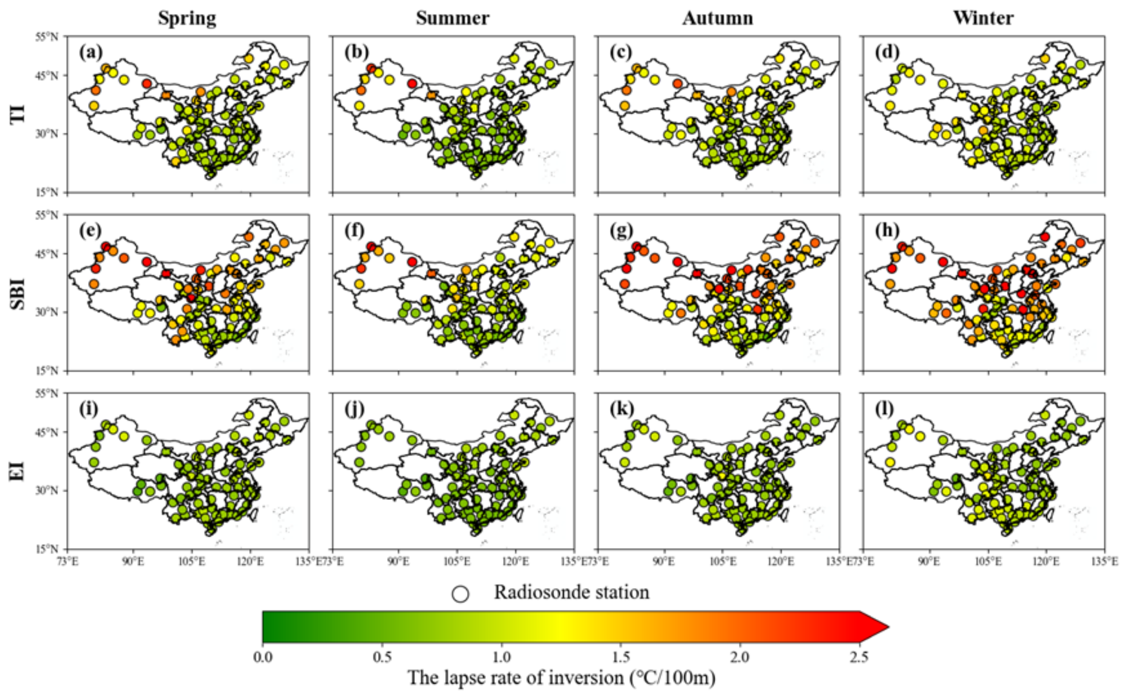


Fig. S16. Spatial and seasonal distribution of lapse rate for different types of TI.

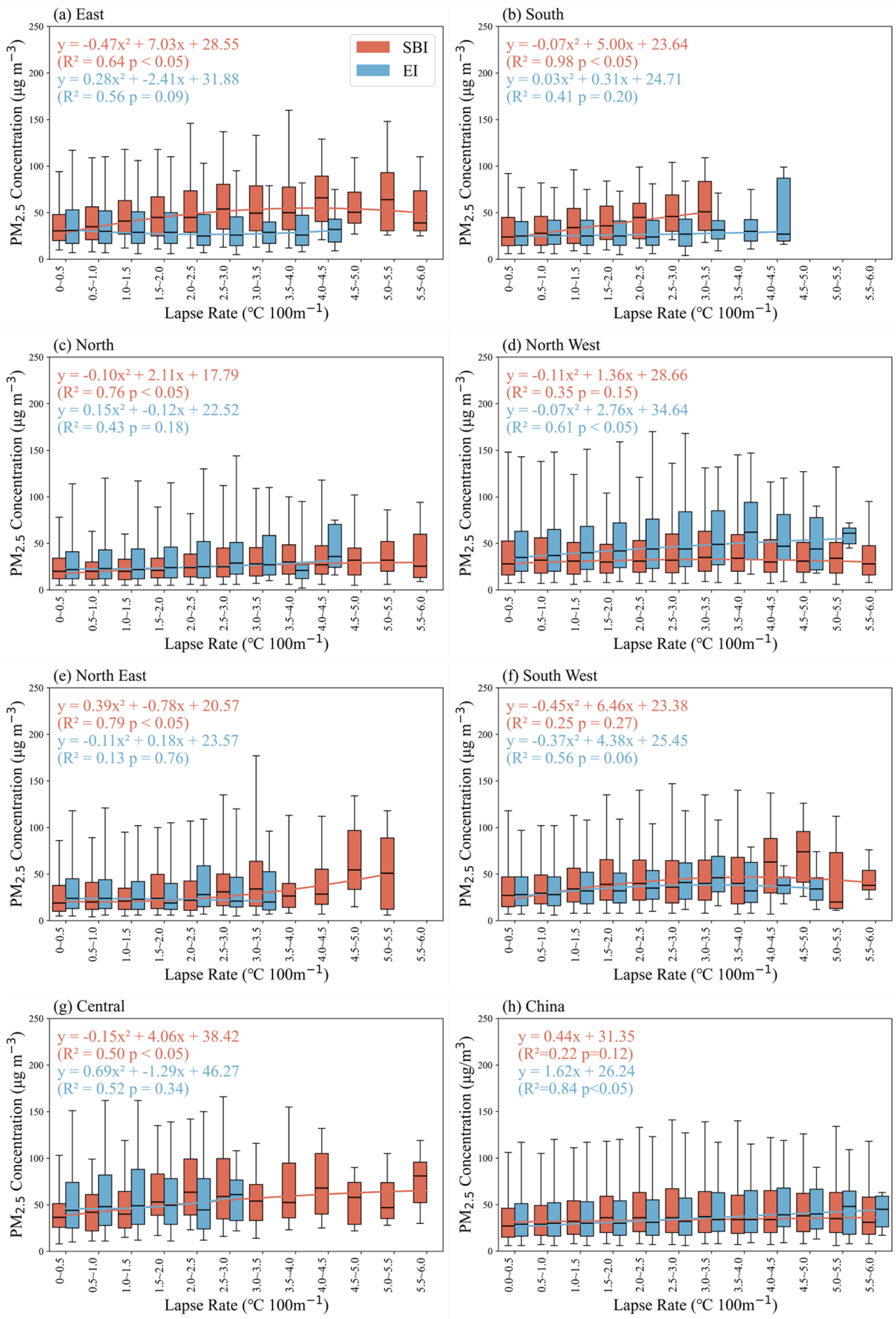


Figure. S17 Fitting relationship between lapse rate and $PM_{2.5}$ concentration across seven regions of China from 2016 to 2021. The ends of the boxes, the ends of the bars, and the short line across each box represent the 25th and 75th percentiles, the 5th and 95th percentiles, and the median, respectively. Each strength interval contains a sample size ≥ 10.

Table. S4 Correlation coefficients between inversion parameters and $PM_{2.5}$ concentrations. '\' indicates insignificance

Region/R^2	Inversion Strength		Inversion Thickness		Lapse Rate	
	SBI	EI	SBI	EI	SBI	EI
East	0.98	0.82	0.63	0.42	0.64	\
South	0.97	0,92	0.66	0.66	0.98	\
North	0.90	0.78	0.53	\	0.76	\
North West	0.47	0.78	0.84	0.92	\	0.61
North East	0.83	\	0.76	0.86	0.79	\
South West	0.94	0.66	0.74	\	\	\
Central	\	\	0.58	\	0.50	\
China	0.72	0.66	0.66	0.28	\	0.84

23. It seems the SBI and EI have very close thickness. However, for EIs, especially for those occurred over higher altitudes, generally have thicker depth, even reach kilometers. For now, because we don't have a full access to the data, we don't know if such thick TI exists.

Response: We thank you for this insightful comment. You are correct that synoptic subsidence inversions in the free troposphere can be very thick (kilometer-scale). However, we would like to clarify our specific selection criteria and how they explain the observed thickness: Selection Criteria ($H_{base} \leq$ 2000 m): To focus strictly on inversions relevant to surface air quality, we only selected inversion events where the inversion base height was less than or equal to 2000 m. Inversions initiating above this level were excluded as they are typically decoupled from the surface boundary layer.

It is important to clarify that we did not impose a ceiling on the inversion top. If an inversion started at 1500 m and extended to 3000 m, our algorithm would correctly identify its thickness as 1500 m. The fact that our derived average thickness for EIs is relatively small (comparable to SBIs) reflects the physical nature of these low-base EIs. They are predominantly nocturnal residual layers, shallow frontal zones, or top-down capping layers, which are inherently thinner than the deep, pure subsidence inversions found in the middle/upper troposphere.

The "thin" EI results are a true representation of the specific subset of inversions (low-tropospheric start) that impact surface pollution, rather than a result of data truncation.

24. Please rephrase line 259.

Response: We thank you for pointing out the awkward phrasing in this sentence. Following your suggestion, we have rewritten this part to improve readability. The revised text in Section 4.1.3 now reads:

"Spatially, TIs are notably thicker in the eastern and southern regions compared to the northern and western inland areas. Specifically, the average thickness in East, South, and Central China is 223 m, whereas it is 209 m in Northeast, North, and Northwest China."

25. The calculation of the thickness of TI when both SBI and EI exist was not clear.

Response: We thank you for pointing out this ambiguity in our methodology. You are correct that the handling of multi-layer inversions needs explicit definition to avoid confusion.

We have clarified in Section 2.2 that we adopt a "layer-based" statistical approach. Specifically, when both an SBI and an EI (or multiple EIs) appear in the same profile, they are identified and recorded as separate inversion events. The statistics for TI thickness presented in this study represent the average thickness of all individual inversion layers identified, not the cumulative thickness per profile.
Revised Text in Section 2.2: " The temperature profile was scanned upward from the surface, and the first continuous layer satisfying $\Delta H \geq 100$ m and $\Delta T \geq 0.5$°C was identified as the inversion for that sounding. To specifically target thermodynamic processes influencing surface air quality, this study considers only inversion layers with a base height $H_b \leq 2000$ m."

26. There is an issue about the statistical analysis of the relationships between TIs and $PM_{2.5}$. For now, there are only two profiles of temperature per day for most of the stations, and the observing time are 08:00 and 20:00 BJT, which are usually accompanied by relatively low planetary boundary layer height. Such bias is more significant over western regions, since 08:00 BJT there means 06:00 or even 05:00 LST. Such low PBLH is usually the result of the lack of solar heating and is thought to be the major reason for trapping air pollutants during early morning and evening. Therefore, the identification of PBLH and the analysis of TIs and $PM_{2.5}$ under different PBLH is very important here.
Response: Thank you for your suggestion. You are absolutely correct that the co-variation of low PBLH and strong inversions makes causal attribution challenging.
To exclude the potential confounding influence of low Planetary Boundary Layer Heights (PBLH), we utilized PBLH data from the Beijing station (July 2017 to January 2018). Beijing was selected as a representative site due to the high frequency of both temperature inversions and pollution episodes. We filtered the dataset to include only observations with a PBLH below 500 m and examined the relationship between $PM_{2.5}$ concentrations and TI strength under these low-boundary-layer conditions. As shown in Fig 1, the results demonstrate that a significant positive correlation persists between them. This confirms that the thermodynamic stability provided by the inversion layer exerts a direct suppression effect on diffusion, independent of the geometric depth of the boundary layer.

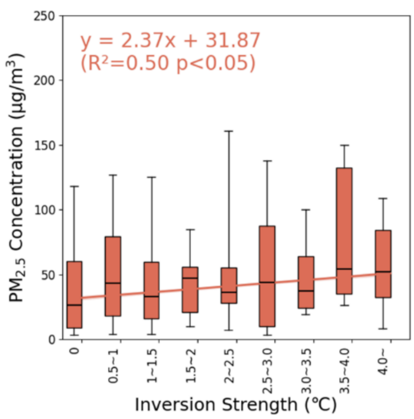


Fig 1. Fitting relationship between TI strength and $PM_{2.5}$ concentrations (PBLH < 500 m).

27. Line 360, does the “intensity” here means strength? Please make these terms consistent.
Response: We sincerely thank the reviewer for pointing out this inconsistency in our terminology. The reviewer is absolutely correct. "Intensity" was used interchangeably with the previously defined parameter "strength" (ΔT), which caused unnecessary confusion. We have now standardized our terminology throughout the entire manuscript by using "strength" exclusively to refer to the parameter ΔT. The specific sentence has been corrected to "Nationally, $PM_{2.5}$ increases near-linearly with strength for both SBI and EI." We have carefully reviewed the text to ensure consistency.

28. Line 363-364, the path of incorporating real-time diagnostic information into nowadays operational models (mostly numerical models) is unclear. It is better to say, improve vertical resolutions and the forecasting skills of temperature inversions in numerical models could benefit the forecast of air pollution events.
Response: We thank the reviewer for this insightful comment and for proposing a more precise and actionable recommendation. We agree that the original phrasing was vague. We have fully adopted the reviewer's suggested direction to enhance the clarity and scientific rigor of our conclusion.
The revised text now reads:
"These findings offer concrete avenues for improving air pollution forecasting. (i) Improving the vertical resolution and the predictive skill of temperature inversions in numerical models could enhance the forecast of air pollution events, particularly in winter."

Part II: Responses to the Second Round of Review (Major Revision/Final Stage)

Response to Reviewer 2 (Final Response)

Review result of "Spatiotemporal patterns of temperature inversions and impacts on surface $PM_{2.5}$ across China" (egusphere-2025-4751)

Response to Reviewer #2:

reviewer's comments are given in blue,

our responses are given in deep red.

The authors have answered most of my questions properly, while there are some issues still exist. Please see below:

1. Line 18, it is hard to understand this revised sentence.

Response: Thank you for pointing this out. We realize that the phrasing "significantly stronger 1.3 °C higher" in the previous revision was grammatically incorrect and confusing.

Revised text (Line 17-18): " Distinct regional patterns emerge: SBIs dominate in northern China, whereas EIs prevail in eastern China. Overall, SBIs are 1.3 °C stronger than EIs."

2. The response for my question no. 3 contains "???"?

Response: Thank you for your careful review. We sincerely apologize for this oversight. The "???" was a placeholder used during our drafting process to mark line numbers that were subject to change, and we regret missing it in the final check. We have confirmed that the revised text regarding specific weather systems is located at Line 39-40 in the current manuscript.

3. Line 47, duplicated '.'.

Response: Thank you for pointing out this detail. We have removed the duplicated period in the revised manuscript.

4. The results shown in Fig. S1 are questionable. When you calculate the distance, did you use degree as the unit rather than km?

Response: Thank you for this comment. We apologize for the confusion and revised to provide the following clarifications:

Calculation Unit (km): We confirm that all distance thresholds and calculations in Fig. S1(a) are strictly in kilometers (km). As mentioned in our previous response, we used the Haversine formula to compute the physical distance between stations based on their coordinates. The distance between the radiosonde station and the air quality monitoring stations was calculated as the great-circle distance using the Haversine formula, assuming a spherical Earth with a mean radius of 6,371 km. This method accounts for the curvature of the Earth, ensuring accurate distance measurements across different latitudes.

Given the latitude and longitude of two points as (ϕ_1, λ_1) and (ϕ_2, λ_2)
ϕ: latitude, in radians.
λ: longitude, in radians.
R: Earth radius, typically taken as 6,371 km.

Step1: Calculate the semi-positive vector value (a)

$$a = sin^2\left(\frac{\Delta\phi}{2}\right) + cos\phi_1 \cdot cos\phi_2 \cdot sin^2(\frac{\Delta\lambda}{2})$$

Step2: Calculate the central angle (c)

$$c = 2 \cdot arctan2(\sqrt{a}, \sqrt{1-a})$$

Step3: Calculate distance (d)

$$d = R \cdot c$$

where R is the Earth's radius, 6371 km.

Nature of Fig. S1(b): The inset panel (b) is a schematic diagram designed to illustrate our station matching algorithm, rather than a map of actual geographical coordinates.

Red star: Represents a successful match where an air quality station falls within the search radius (r) and is the nearest one.

Black star: Represents an isolated radiosonde station (e.g., in plateau areas) with no air quality stations nearby.

Blue star: Represents a case where candidate stations exist but are beyond the maximum distance threshold (r>10 km), and are thus excluded.

The green circle indicates that the nearest site (air monitoring station) has not exceeded the threshold range; red circle indicates that the nearest site has exceeded the threshold range.

Revision: To prevent further misunderstanding, we have: Updated the figure caption to state: "Panel (b) is a schematic illustration of the nearest-neighbor matching method within a defined radius, rather than a map of actual geographical coordinates."

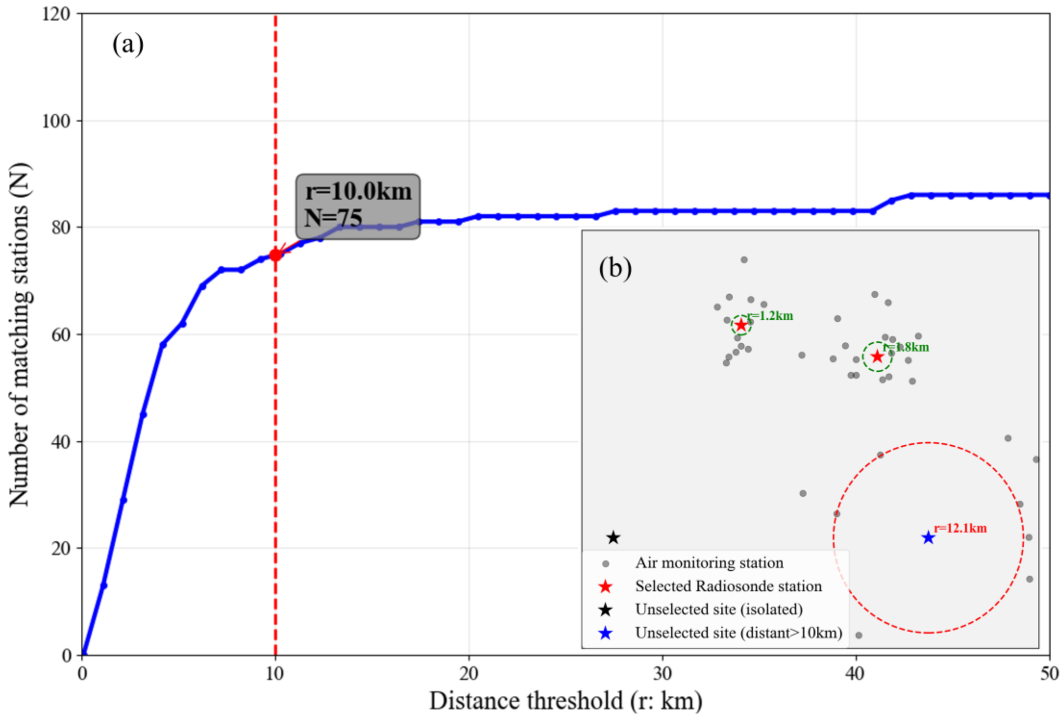


Fig S1. Site filtering method. (a) Relationship between distance and the number of matching stations. (b) Example diagram of site matching process. 'r' represents the distance from the nearest air quality monitoring station to the sounding station. Panel (b) is a schematic illustration of the nearest-neighbor matching method within a defined radius, not a plot of actual station coordinates.

5. The answer to question 26 is not satisfactory. If you select Beijing station as an example, we would be happy to see the original PBLH data first. Then, the correlation of $PM_{2.5}$ and inversion strength when PBLH is below 500 m alone is insufficient to confirm the strong relationship between them.

   Response: We sincerely thank the reviewer for this critical insight regarding the coupling of low PBLH and TIs. To isolate the independent role of TIs and provide the "original PBLH data" as requested, we have conducted a comprehensive analysis based on the hourly ERA5 dataset for Beijing (2019).

   Characteristics of original PBLH data: As shown in Fig.1, we confirm the reviewer's point that the standard sounding times (08:00 and 20:00 BJT), indeed coincide with the diurnal minima of PBLH in Beijing. This confirms that our primary dataset cover or obtained the most stable atmospheric conditions in the morning and evening.

   To address the concern that $PM_{2.5}$ accumulation might be solely attributed to a low PBLH, we integrated the results from Fig.2 and Fig.3. Evidence of independent impact (Fig.2): By categorizing the data into specific PBLH intervals (<200 m, 200–500 m, and >500 m), we "fixed" the geometric volume of the boundary layer. Fig.2 clearly demonstrates that within the same PBLH bin, the $PM_{2.5}$ concentrations during TI episodes are significantly higher than those during non-TI periods. This sufficiently demonstrates that TIs have an additional suppression effect on pollutant dispersion, and that this effect is independent of PBLH. We further examed on the most critical scenarios where PBLH is below 200 m. As shown in Fig.3, a strong linear correlation ($R^2 = 0.71$, $p < 0.01$) exists between TI strength and $PM_{2.5}$ concentrations. This high correlation indicates that when the "air container" is small suppressed and stable, the thermodynamic intensity of the inversion becomes the primary determinant of pollution severity.

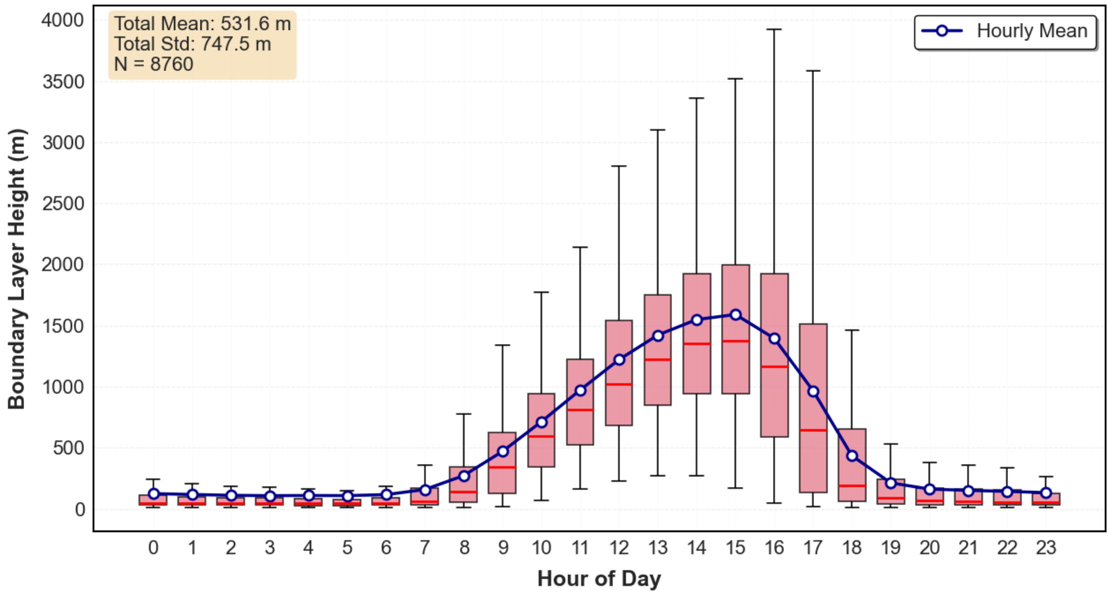


Fig.1 Diurnal variation of hourly mean boundary layer height in Beijing throughout 2019 (Beijing Time).

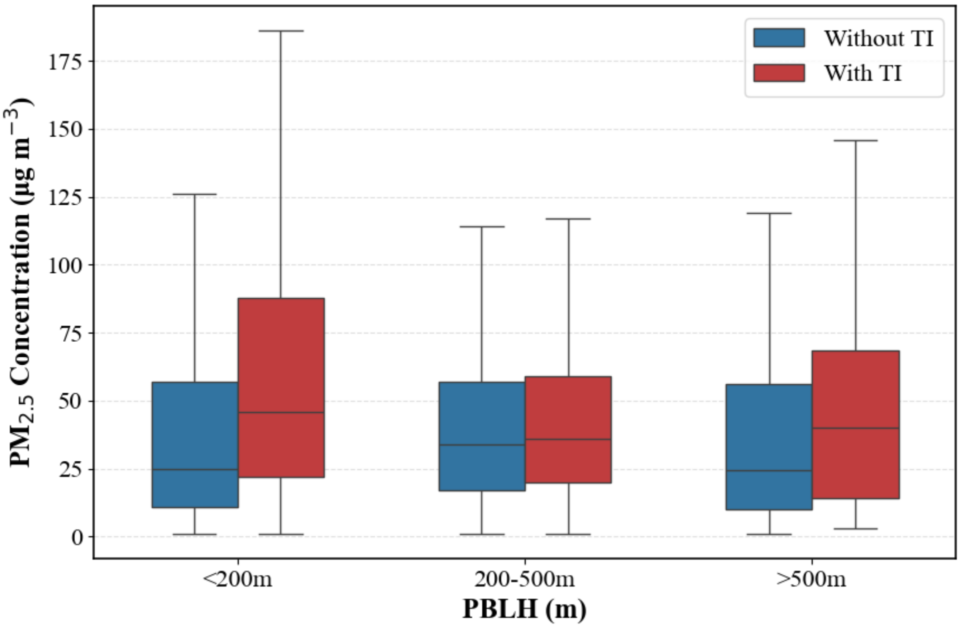


Fig.2 Impact of TI on $PM_{2.5}$ under different PBLH bins.

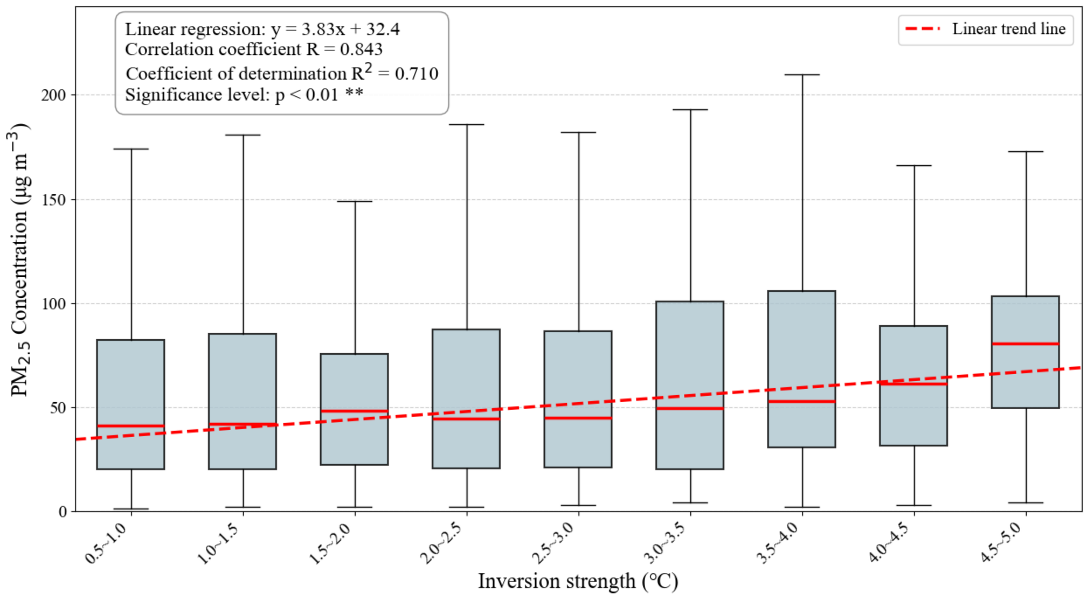


Fig.3 $PM_{2.5}$ concentration distribution across different inversion strength intervals (PBLH < 200 m).

Finally, we would like to thank the editor and all reviewers for their constructive comments, which have significantly improved the quality of this manuscript.