

Article

Spatiotemporal Variability of Near-Surface Temperature Inversion over Ulaanbaatar City, Mongolia

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Abstract

Near-surface temperature inversions are prevalent during the cold months in Ulaanbaatar city, Mongolia, and significantly degrade urban air quality by trapping hazardous pollutants within a shallow atmospheric boundary layer. This study investigates spatiotemporal variability, physical mechanisms, and long-term evolution of near-surface temperature inversions over Ulaanbaatar by integrating 25 years (2000–2024) of ground-based meteorological and radiosonde observations, with high-resolution Weather Research and Forecasting (WRF) model simulations for 2012–2023. Our results demonstrate the four-dimensional data assimilation (FDDA) grid nudging effectively captures localized topographic influences in the WRF simulations, showing a strong agreement with radiosonde observations ($R^2 = 0.783$, $p < 0.000$). Near-surface temperature inversions are strongly controlled by the Siberian High, with the highest frequency occurring from December to February, when up to 67% of morning observations exhibit inversion conditions. A pronounced diurnal cycle was identified, with inversion intensity peaking at 5.6–6.8 °C during the early morning hours (02:00–08:00 LST) before reaching a minimum around 14:00 LST. Spatially, the strongest inversions occur along the low-lying Tuul River valley, where the planetary boundary layer is compressed to below 350 m and wind speeds decrease to less than 2.4 m·s^{−1}, creating persistent atmospheric stagnation. Despite these favorable conditions for inversion formation, long-term observations indicate that regional warming (+2.0 °C) and the urban heat island effects have reduced inversion frequency by 31%, inversion thickness by 170 m, and inversion intensity by 0.9 °C over the past 25 years. These findings demonstrate the strong coupling between regional complex terrain, and boundary layer thermodynamics, highlighting the need to incorporate urban ventilation corridors and topography-informed planning into climate adaptation and winter air-quality management strategies.



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Keywords: cold season; temperature inversion; air quality; WRF model; atmospheric stagnation; planetary boundary layer height

1. Introduction

Winter temperature inversions have a significant impact on air quality as they increase in temperature with altitude instead of the normal decrease, subsequently trapping local air pollution in the lower parts of the troposphere due to their stable stratification [1,2]. It can be particularly dangerous both from a health and environmental stand point, downwind from industrial facilities where large quantities of particulate matter and other noxious elements are emitted frequently resulting in increased concentrations [3,4]. The trapping effect of temperature inversions on pollutants is known to aggravate air pollution episodes in crowded urban canyons with nocturnal persistence as a fallout of radiative cooling [5]. The unsteady interaction between the local and the larger scale meteorology can create multilayered thermal inversions which further interfere with the atmospheric mixing and subsequent dispersal of pollutants. Elevated breakup stages over Ulaanbaatar, a city well exposed to severe winter air pollution episodes, described [1,6] inversions are further intensified due to the geographical feature of the valley's topography accentuating any cold air and atmospheric pollutants confinement. These inversions are common and have a daily and annual cycle such that it occurs more often in winter or at any one time of the day [1,7,8].

Previous research in various urban environments, such as Salt Lake City and Krasnoyarsk, has consistently linked the persistence and occurrence of temperature inversions to elevated concentrations of particulate matter, $PM_{2.5}$ and PM_{10} , underscoring their critical role in modulating urban air quality [9–11]. Studies have also shown that urban heat island circulation can be weakened under inversion conditions, further impeding pollutant dispersion under periods of calm winds and stable weather [12,13]. Furthermore, observations in other cold-climate cities, such as Ulaanbaatar, have confirmed that strong ground-based temperature inversions are a primary control factor in urban heat island intensity, limiting boundary-layer height and impacting pollutant dispersion [1,6,14,15]. Additionally, in complex terrains such as valleys, these inversions, often referred to as cold-air pools, are primarily formed by surface radiation cooling and nocturnal downslope winds, persisting for extended periods during winter months [16]. These persistent, stable conditions, frequently supported by large-scale meteorological systems like the semi-permanent Siberian High, are critical contributors to sustained air pollution events by inhibiting daytime vertical mixing [17,18]. This leads to a crucial accumulation of harmful substances, as evidenced by studies indicating a sharp rise in pollutant concentrations during such unfavorable meteorological conditions [11,19,20]. Moreover, some types of inversions, such as surface-based temperature inversions, which are common nocturnal features of the atmospheric boundary layer, profoundly influence PM_{10} concentrations [21]. This is particularly true in regions characterized by slow-moving anticyclones, where prolonged subsidence can lead to persistent temperature inversions lasting days to weeks, significantly hindering the daytime dispersion of accumulated nocturnal pollution [17].

In Europe and Central Asian territory, located in the northern mid-latitudes, atmospheric temperature inversions usually occur during the cold season, October to March [22–24]. These conditions are even more significant in highly urbanized sites, such as Ulaanbaatar, one of the most polluted cities worldwide, where the number of temperature inversions increases directly with pollutant concentrations, especially during severe pollution days [1,6]. It causes lower mixing layer heights, which concentrate the emissions into a shallow

boundary layer, so the urban air quality may worsen. One of the unique geographical locations of Ulaanbaatar, located in a basin and surrounded by a mountain, exacerbates those inversion layers, particularly during the city's long, cold winter, resulting in high PM_{2.5} [18,25,26]. Therefore, knowledge of the spatiotemporal variations in the near-surface temperature inversion is crucial to the implementation of air quality management measures for Ulaanbaatar city [1,27,28].

Several studies of the spatial distribution of surface temperature inversions covering continental and global regions have been conducted using radiosonde measurements and reanalysis data. Several studies have used radiosonde measurements and reanalysis data to illustrate the distribution of the near-surface temperature inversions across continental and global scales. For instance, Zheng et al. [29] supposed that global surface-based temperature inversions became more frequent but shallower over time, remaining significantly more prominent over land and the Northern Hemisphere than over oceans and the Southern Hemisphere. This conclusion was based on an evaluation of SBI frequency, strength, and depth using 50 m interpolated radiosonde data from 493 global stations across 1989–2019. Furthermore, Palarz et al. [30] investigated that surface-based temperature inversions over European territory are strongly affected both by surface energy budgets and atmospheric circulation, leading to a very frequent but shallow summer nocturnal temperature inversion, a well-developed glacier-driven layer, and long-term winter decline of both depth and strength over the mainland by tracking frequency, depth and strength of temperature inversion using an objective profiling algorithm by Kahl [31] on ERA-Interim reanalysis data from 1981 to 2015. However, prior investigations in Ulaanbaatar have shown that the level and strength of the strong, deep near-surface temperature inversions are usually determined at discrete times by using radiosonde data [1,8,18]. For instance, Sumiya et al. [1] and Wang et al. [18] used statistical techniques, meteorological observations, LIDAR, and radiosonde measurements to explain the development and dissipation periods of the temperature inversion layer positioned on top of urban surfaces. Notwithstanding these fundamental studies, most previous investigations on air pollution in Ulaanbaatar have tended to overlook seasonal changes in the urban atmospheric boundary layer structure so far, and only a few studies have utilized lidar and radiosonde measurements for air particulate pollutants [14,18]. For local scale, the spatial distribution of near-surface temperature inversion was carried out using the WRF model in different places [6,32–34]. Except for the experimental study by Ganbat and Baik [6] using the Weather Research and Forecasting (WRF) model coupled with the Seoul National University Urban Canopy Model, while recent studies in Ulaanbaatar have characterized these features through parameters such as inversion frequency, depth, and vertical strength, existing data often lack the high-resolution spatial coverage necessary to resolve localized topographic influences on inversion intensity.

Despite previous studies on temperature inversions over Ulaanbaatar, most have focused on observational analyses, individual inversion events, or numerical simulations without integrating long-term observations and high-resolution modeling. A comprehensive assessment of the spatiotemporal variability, physical mechanisms, and long-term evolution of near-surface temperature inversions under changing climatic and urban conditions remains lacking. This study addresses these gaps by integrating 25 years (2000–2024) of ground-based observations, radiosonde measurements, and high-resolution WRF simulations to characterize inversion dynamics, evaluate their driving mechanisms, and quantify long-term changes across Ulaanbaatar's complex terrain.

2. Materials and Methods

2.1. Study Area

Mongolia is located 1600 to 3000 km far from the oceans, deep within the Eurasian continent. The country sits at a high elevation (averaging 1580 m) and is surrounded by high mountains of 2000 to 4000 m on the prevailing wind sides, resulting in an arid, cool, and continental harsh climate. Due to its geographical location, climatic conditions, economic sector structure, and population lifestyle, Mongolia is among the most vulnerable countries to climate change. Wedged between Russia and China, Mongolia is located in the center of the Eurasian continent ($41^{\circ}35' \text{ N}$ to $52^{\circ}09' \text{ N}$ and $87^{\circ}44' \text{ E}$ to $119^{\circ}56' \text{ E}$) with a total land area of approximately 1.564 million square kilometers [35,36] (Figure 1a). Ulaanbaatar is the coldest capital city in the world, and winter temperatures can be lower than -20° C , due to powerful near-surface temperature inversion driven by the Siberian high-pressure system [1,8]. This extreme cold, combined with its high altitude of $\sim 1350 \text{ m}$ and being situated in a large valley sloping down east to west, surrounded by mountains ranging from 1663 to 2268 m in altitude, results in the favorable environment for strong and persistent temperature inversions [1,37] (Figure 1b).

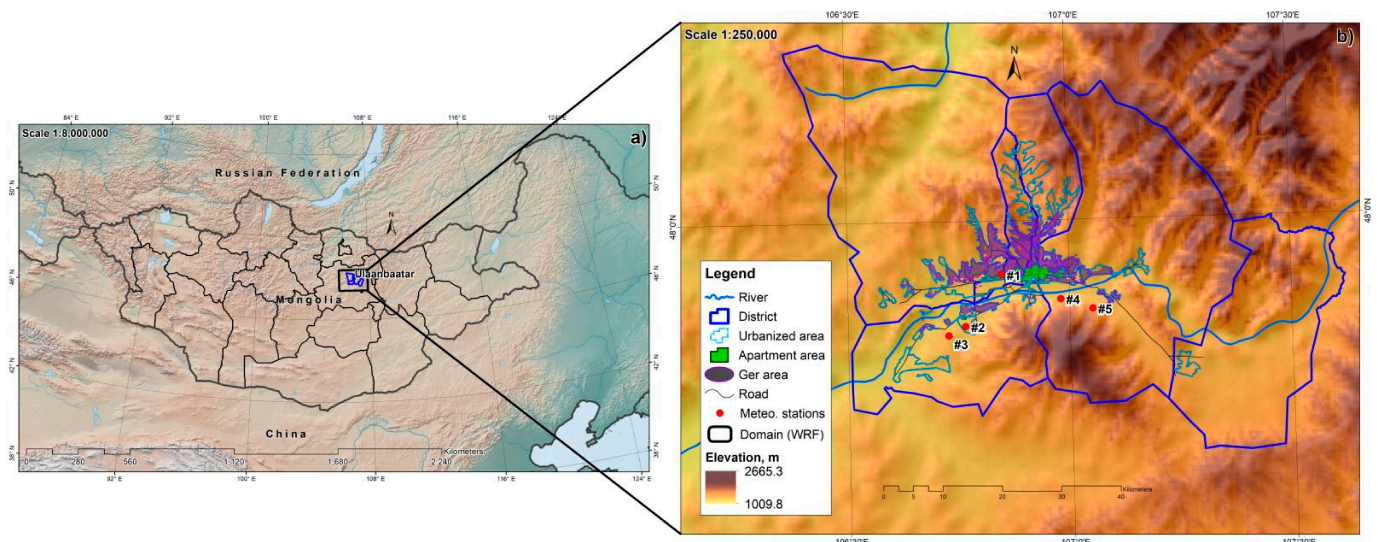


Figure 1. (a) Location of the study area and (b) meteorological observation stations in Ulaanbaatar city, Mongolia.

Rapid urbanization and population density growth have transformed Ulaanbaatar's environment, with the built-up area exceeding suitable capacity by 16.4% due to intense development, including significant expansion in ger areas [38]. Ger areas consist of residential parcels containing one or more traditional portable dwellings, known as gers (also referred to as yurts), typically enclosed by wooden fences approximately 2 m high. These rapid, human-induced changes in land use and socio-economic activity over the past three decades have directly contributed to the city's severe air pollution and altered microclimate. Moreover, Ulaanbaatar experiences a harsh continental climate characterized by a cold season lasting roughly 65% of the year, with winters extending up to 150 days. This climate necessitates a residential heating season of up to 233 days in the city center, driven by high consumption of raw and refined coal, which acts as the primary source of urban air pollution [1,39]. Therefore, the city of Ulaanbaatar was selected as the case study area.

2.2. Data and Methods

2.2.1. Temporal Variability in Near-Surface Temperature Inversion Characteristics

Using data provided by the National Agency of Meteorology and Environmental Monitoring of Mongolia (NAMEM), this study analyzes the vertical temperature profiles, depth, strength, and frequency of near-surface temperature inversions in Ulaanbaatar, based on ground-based meteorological station networks and radiosonde soundings from 2000 to 2024 (Table 1 and Figure 1b). Near-surface temperature inversions were estimated by measuring the vertical temperature profile by detecting increases in air temperature with height above the surface. Inversion frequency was calculated as the percentage of radiosonde profiles exhibiting near-surface temperature inversions for each month and season throughout the study period. Inversion thickness was identified as the vertical distance between the inversion base and the altitude where temperatures no longer increased with height. Inversion intensity is the strength of the layer, calculated by the temperature difference between the top and base by the change in altitude [40,41]. This analysis elucidates the diurnal and seasonal variability, and its trends of these inversion characteristics, as well as their contribution to air pollution potential [1–3,7,26].

Table 1. Location of the weather stations in Ulaanbaatar city.

#	Station Name	Type of Sites	Location Within the City	North Latitude	East Longitude	Elevation (m)	Data Used
1	Ulaanbaatar	Radiosonde, Weather station	City center	47°55′07″	106°50′53″	1306	Trends and climatology of temperature inversion characteristics; Calibration of WRF model results
2	Buyant-Ukhaa	Weather station	Southwestern—foothill and river valley	47°50′29″	106°45′53″	1286	Diurnal variations in intensity of near-surface temperature inversion at western side of Ulaanbaatar city
3	Morin-Uul	Weather station	Southwestern—mountain summit	47°49′40″	106°43′36″	1511	
4	Zalaat	Weather station	Southeastern—foothill and river valley	47°52′49″	106°58′49″	1350	Diurnal variations in intensity of near-surface temperature inversion at eastern side of Ulaanbaatar city
5	Khurel-Togoot	Weather station	Southeastern—mountain summit	47°51′54″	107°03′08″	1615	

Source: National Agency for Meteorology and Environmental Monitoring of Mongolia.

Seasonal variations in near-surface temperature inversion characteristics via hydrostatic and state equations were found from radiosonde flights at 00:00 UTC and 12:00 UTC from Ulaanbaatar station while the diurnal distribution of temperature inversion parameters was determined using temperature differences between weather stations at the foothill and summit of the mountains southwest (Buyant-Ukhaa and Morin-Uul) and southeast (Zalaat and Khureltogoot) of the city (Table 1 and Figure 1b). This analysis aimed to determine how topographic features drive atmospheric stagnation and ventilation conditions, creating an unfavorable natural factor for regional air quality [1,15,26]. While the trend analysis spanned 2000 to 2024, seasonal and diurnal variabilities in temperature inversion characteristics were estimated using high-resolution data from 2012 to 2024, following a radiosonde system upgrade at the Ulaanbaatar station [40]. The temperature difference between the foothill and mountain summit stations was used as a proxy for the temporal evolution of near-surface temperature inversion intensity. Although this approach provides continuous observations of diurnal variability, it does not directly represent the vertical temperature profile above a single location because the measurements are obtained from different sites with contrasting elevations, surface characteristics, and local meteorological conditions. Consequently, the estimated inversion intensity may also reflect the influence

of local microclimates, slope flows, and surface energy balance differences in addition to the actual vertical temperature inversion.

SigmaPlot 14.0 and OriginLab 8.5.1 software were used to generate the figures and diagrams. Spatial distribution mapping was performed using ArcGIS 10.8. Additionally, Python 3.12.0 was used to visualize WRF model outputs and compile observational data into structured tables.

2.2.2. Spatial Distributions of Temperature Inversion Using WRF Model

In order to study the effects of topography and atmospheric circulation on spatiotemporal distribution of temperature inversion intensity in the cold season around Ulaanbaatar, the WRF model was initialized and forced at the lateral boundaries using hourly ERA5 reanalysis data with a horizontal resolution of $0.125^{\circ} \times 0.125^{\circ}$ for the period 2012–2023 [42]. ERA5, obtained from the Climate Data Store, provides high-resolution atmospheric fields, including validated planetary boundary layer heights (PBLH) estimated using the bulk Richardson number method. This study utilizes monthly data for the period, leveraging ERA5’s demonstrated reliability in PBLH and wind speeds compared to other datasets [26].

Using daily radiosonde data from the Ulaanbaatar station from 2000 to 2024, the intensity and thickness of the surface-based temperature inversion were calculated and analyzed using the hydrostatic equation and the equation of state to detect the top of the inversion layer. The study provides critical information for future research on the spatial and temporal variations in surface-based temperature inversions, with the goal of evaluating local atmospheric stagnation within the study area using the WRF model. This analysis aimed to determine the impact of topographic and atmospheric conditions on air quality in the region. The selection and configuration of the physics schemes applied to the WRF model simulation are presented in Table 2.

Table 2. Description of WRF model configurations.

Name	Selection
Model and version	WRF v4.5 [43]
Dynamic core	Advanced Research WRF (ARW)
Horizontal grid spacing	1 × 1 km (160 × 120 grids)
Vertical levels	100 (up to 50 hPa), Hybrid Vertical Coordinate
Initial and lateral boundary conditions	Fifth generation ECMWF reanalysis data (ERA5) [42]
Computational platform	Cray XE6m supercomputer
Simulation length	1 October–31 March (from 2012 to 2023)
Time step	6 s
	Physical schemes
Cloud microphysics	Kessler scheme: [44]
Cumulus parametrization	-
Shortwave radiation	Goddard shortwave scheme [45,46]
Longwave radiation	Rapid Radiative Transfer Model scheme [47]
PBL physics	Mellor–Yamada–Janjic scheme [48,49]
	Analysis
Nudging	Grid Nudging or Analysis Nudging (WRF-FDDA) [43,50]

Source: National Agency for Meteorology and Environment of Mongolia.

WRF downscaling from a $0.125^{\circ} \times 0.125^{\circ}$ latitude/longitude grid to a 1×1 km ($0.008^{\circ} \times 0.008^{\circ}$) resolution was performed for the domain presented in Figure 2. Although direct dynamical downscaling from ERA5 (0.125°) to a 1 km computational grid exceeds the grid ratio commonly recommended for nested WRF simulations, the relatively small computational domain and the application of FDDA grid nudging were adopted to maintain consistency with the large-scale atmospheric forcing while resolving local terrain effects over Ulaanbaatar. The adopted configuration was evaluated against inde-

pendent radiosonde observations and reproduced the observed inversion characteristics with good agreement ($R^2 = 0.783$). Nevertheless, direct downscaling may introduce interpolation artifacts and lateral boundary inconsistencies that could affect some fine-scale atmospheric structures. Future studies incorporating intermediate nested domains (e.g., 9 km–3 km–1 km) would provide a useful assessment of the sensitivity of inversion simulations to the nesting strategy.

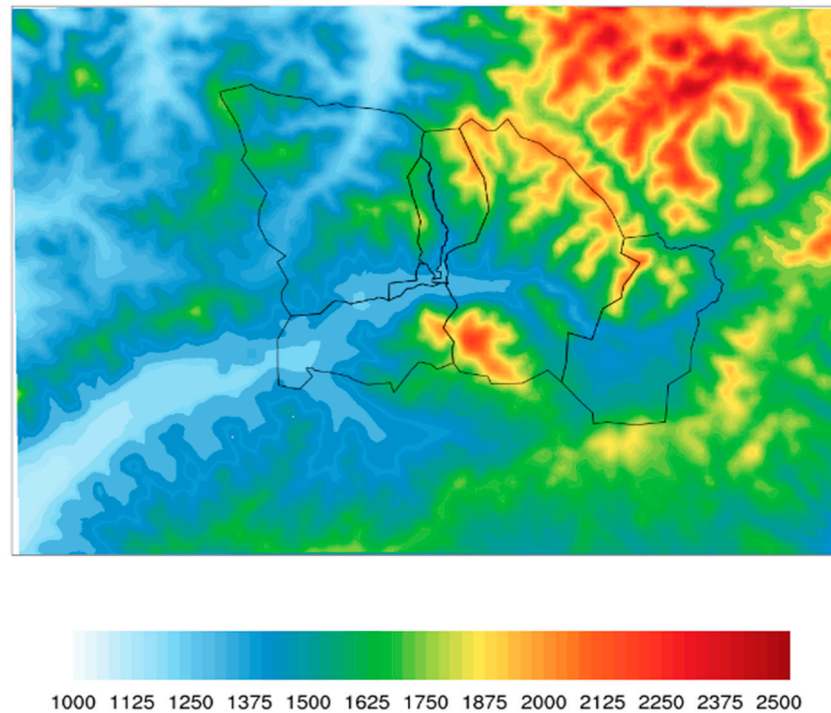


Figure 2. Domain and topography (m) of the WRF model simulation.

The persistent near-surface temperature inversion that develops during the cold season is a distinctive physical process in the lower troposphere over Ulaanbaatar. It suppresses vertical mixing, stabilizes atmospheric stratification, and promotes the accumulation of air pollutants near the surface [1]. These inversion conditions are further strengthened by the influence of the semi-permanent Asian anticyclone (or Siberian high), which dominates over Mongolia during winter and favors clear skies, weak winds, and strong nocturnal radiative cooling [6,8]. As a result, the atmospheric boundary layer becomes highly stable and shallow, substantially reducing the vertical dispersion of pollutants.

To investigate these processes, near-surface temperature inversions were analyzed using the radiosonde observations and high-resolution simulations with the WRF model. The simulations were performed over Ulaanbaatar with a horizontal grid resolution of 1 km (Table 2 and Figure 2) for the cold seasons spanning October 2012 to March 2023. Hourly ERA5 reanalysis data were refined using the FDDA method to address spatial and temporal variability, as well as noise in the model calculations [43,50,51]. Four-dimensional data assimilation (FDDA) grid nudging was applied to constrain the large-scale atmospheric fields toward ERA5 reanalysis while allowing the WRF model to develop mesoscale and local-scale processes within the computational domain. The primary objective of using FDDA was to improve the temporal consistency of the simulations and reduce the accumulation of large-scale forecast errors during the six-month integration periods. Although grid nudging generally improves agreement with observations, it may also partially damp small-scale thermally driven circulations and localized boundary-layer features. Therefore, the selected nudging configuration represents a compromise between maintaining realistic

large-scale meteorological conditions and preserving the high-resolution representation of terrain-induced atmospheric processes.

To quantify inversion intensity, three-dimensional WRF output fields were analyzed throughout the model domain. By calculating the temperature $T_c(x, y, z)$ at each z -level via Equation (1), the inversion intensity was determined by comparing the maximum temperature within the vertical profile against the surface temperature [50].

$$T_c(x, y, z) = \left((T(x, y, z) + 300) \times \exp \left(\log \left(\frac{PB(x, y, z) + P(x, y, z)}{100000} \right) \times \frac{R_d}{C_p} \right) \right) - 273.15, \quad (1)$$

where $PB(x, y, z)$ represents the base-state pressure (Pa), $P(x, y, z)$ denotes the perturbation pressure (Pa), and $T(x, y, z)$ signifies the perturbation potential temperature ($\theta - T_0$) (K). The term $\kappa = \frac{R_d}{C_p} = \frac{2}{7} = 0.286$ is the Poisson constant, and $\theta(x, y, z) = T(x, y, z) + 300$ is the full potential temperature, where $T(x, y, z)$ represents the deviation from a base state of 300 Kelvin.

Hourly and monthly mean inversion intensity maps over Ulaanbaatar were generated from FDDA-enhanced simulations for the 2012–2023 cold seasons and validated against radiosonde observations. For this period, climatological cold season mean maps of air temperature, wind speed, temperature inversion intensity, and PBLH then produced to examine their spatial and temporal variability.

3. Results and Discussion

3.1. Temporal Variations in Temperature Inversion Characteristics and Meteorological Parameters During the Cold Season

To date, observational records after the establishment of the meteorological network in Mongolia (1940s), the country warmed by 2.3 °C over the past 80+ years, which was nearly twice the global average, according to the Fourth National Communication of Mongolia under the United Nations Framework Convention on Climate Change [52]. The residential- and developed-area of Ulaanbaatar spreads across 42,598 hectares area, hosting over 45% of Mongolia's total population, making it the primary source zone for air and environmental pollution, caused by its high degree of centralization [1,38]. Mongolia has the lowest population density in the world of less than two people per square kilometer. However, urbanization in Mongolia was accelerated rapidly in the second half of the last century, switching the demographic balance in favor of the urban sector, where average population density in the urban sector today in Mongolia is approximately 250–270 people per square kilometer [35,37]. Extensive utilization of the relatively confined space along with forced dynamic changes affecting built environment by its resident holders, inevitably affects the quality of local air, soils, and waters, as well as physical processes in the planetary boundary layer [53].

As shown in Figure 3, the characteristics of near-surface temperature inversion over Ulaanbaatar have changed markedly during the past 25 years. The average inversion thickness decreased by approximately 170 m ($R^2 = 0.325$, $p < 0.01$), while inversion intensity and frequency declined by 0.9 °C ($R^2 = 0.151$, $p < 0.05$) and 31% ($R^2 = 0.60$, $p < 0.000$), respectively (Figure 3a–c). These long-term changes coincide with significant atmospheric warming [54], likely driven by the combined effects of regional climate change and the urban heat island effect [12,13,15,29,55]. The observed long-term decline in inversion frequency, thickness, and intensity is likely associated with the combined influence of regional climate warming and increasing urbanization in Ulaanbaatar. However, because the present analysis is based on observations from a single urban meteorological station, the respective contributions of regional climate change and the urban heat island effect cannot be quantitatively separated. Therefore, the observed trends should be interpreted as

reflecting the combined influence of these processes rather than the isolated effect of either mechanism.

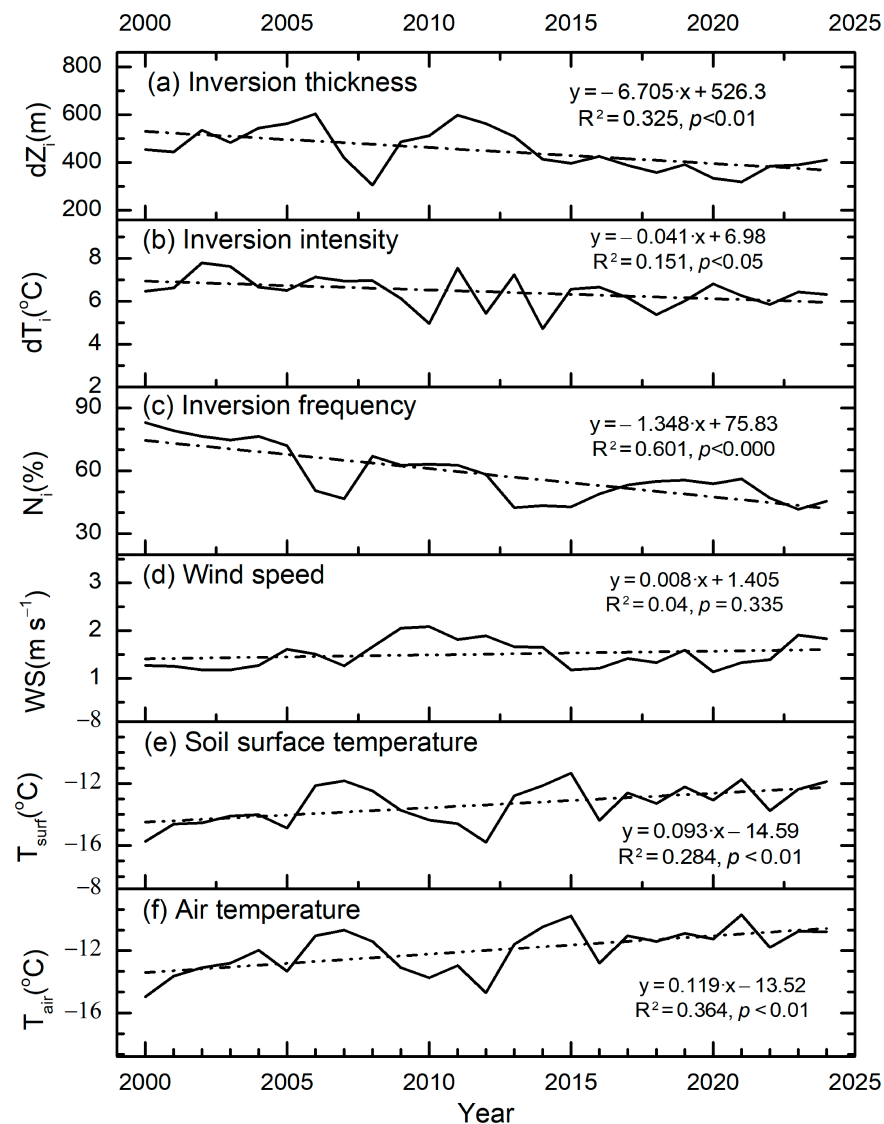


Figure 3. Temporal variations in near-surface temperature inversion characteristics ((a) thickness, (b) intensity, and (c) frequency) and meteorological variables ((d) wind speed, (e) soil surface temperature, and (f) air temperature) in the cold season.

Consistent with this interpretation, the mean cold-season air temperature at the Ulaanbaatar station increased by $2.0\text{ }^{\circ}\text{C}$ ($0.12\text{ }^{\circ}\text{C year}^{-1}$, $R^2 = 0.364$, $p < 0.01$) between 2000 and 2024, while land surface temperature increased by $2.3\text{ }^{\circ}\text{C}$ ($0.09\text{ }^{\circ}\text{C year}^{-1}$, $R^2 = 0.284$, $p < 0.01$) (Figure 3e,f). In contrast, near-surface wind speed increased by only 0.2 m s^{-1} during the same period (Figure 3d), indicating that changes in wind conditions were relatively minor compared with the observed warming.

To better understand the physical mechanisms controlling inversion development, Figure 4 examines the relationships between inversion intensity, air temperature, and wind speed during the cold season. A significant inverse relationship was observed between air temperature and inversion intensity ($R^2 = 0.55$, $p < 0.001$), indicating that stronger inversions develop under colder surface conditions (Figure 4b). During winter, enhanced nocturnal radiative cooling lowers the surface temperature, strengthening the temperature gradient within the lower atmosphere and promoting the formation and deepening of

near-surface inversions [56,57]. Consequently, inversion intensity typically reaches its maximum when surface temperatures are lowest, usually around midnight [8].

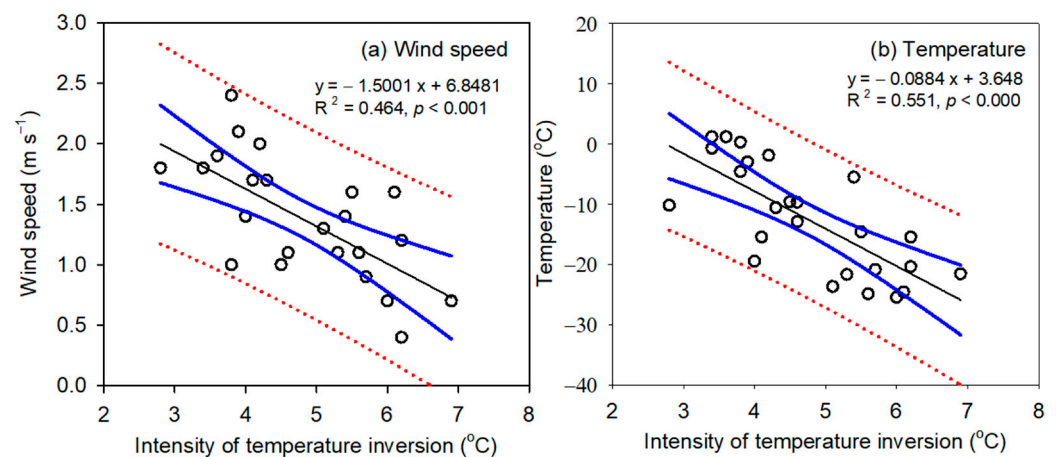


Figure 4. Relationship between the cold-season average intensity of near-surface temperature inversion and (a) wind speed and (b) surface temperature from 2000 to 2024. The 95% prediction and confidence bands are shown as red dotted and blue solid lines, respectively.

Wind speed also plays an important role in regulating inversion strength. As shown in Figure 4a, strong inversions are associated with weak wind conditions, whereas increasing wind speeds enhance turbulent mixing and weaken or erode the inversion layer [57,58]. These results demonstrate that the long-term reduction in inversion intensity is primarily associated with increasing air and surface temperatures, while short-term variability is largely controlled by nocturnal radiative cooling and local wind conditions.

Although the observed reductions in inversion thickness, intensity, and frequency are consistent with regional warming trends, these changes cannot be attributed solely to climate change. Urban expansion and the intensification of the urban heat island effect may also contribute by increasing nocturnal air and surface temperatures, thereby weakening the temperature gradients required for strong inversion development [59]. In addition, land-use and land-cover changes can alter surface energy balances and boundary-layer processes, while changes in anthropogenic emissions may influence atmospheric stability through aerosol–radiation interactions [60,61]. Therefore, the long-term evolution of temperature inversions over Ulaanbaatar is likely driven by the combined effects of regional climate warming, urbanization, land surface modification, and local atmospheric conditions, rather than by a single controlling factor.

3.2. Seasonal Variations in Temperature Inversion Characteristics During the Cold Season

3.2.1. Intensity of Near-Surface Temperature Inversion

Understanding the characteristics and intensity of near-surface temperature inversions, in which air temperature increases with height within the lower atmosphere, is critical for assessing air quality, atmospheric stability, agricultural productivity, and public safety [19]. These inversions are a common feature of middle and high-latitude climates, where they strongly influence the surface energy balance and boundary layer development [8,23,62]. In Ulaanbaatar, near-surface temperature inversions predominantly occur during the cold season from October to March [8] as a result of strong nocturnal radiative cooling and the persistent influence of the Siberian High. Therefore, the seasonal characteristics of inversion intensity and frequency during the cold season are summarized in Table 3.

Table 3. Intensity of near-surface temperature inversion in cold season.

Parameter	October	November	December	January	February	March	Cold Season
(a) Intensity of temperature inversion (°C)							
Morning at 00:00 (UTC+08)	4.1	5.3	7.6	8.8	6.9	4.8	6.2
Evening at 12:00 (UTC+08)	1.1	2.7	5.2	4.7	3.0	0.7	2.9
(b) Frequency of intensity range of temperature inversion (%)							
Intensity range (°C)							
<2.0	35.5	23.5	15.4	12.7	21.4	27.5	22.7
2.0–4.0	28.5	25.3	18.0	17.0	21.6	25.0	22.6
4.0–6.0	18.6	17.6	17.1	16.5	17.9	26.2	19.0
6.0–8.0	10.6	13.4	16.4	18.1	16.4	14.6	14.9
8.0–10.0	5.5	11.4	14.3	14.7	11.8	4.6	10.4
10.0–12.0	1.1	5.6	9.1	11.2	6.2	0.8	5.7
12.0–14.0	0.2	2.1	4.7	5.4	2.6	1.0	2.7
14.0–16.0	0.0	0.9	2.5	3.1	1.6	0.2	1.4
16.0–18.0	0.0	0.2	1.6	0.7	0.2	0.0	0.5
18.0–20.0	0.0	0.1	0.6	0.5	0.1	0.0	0.2
20.0–22.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
>22.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0

Estimating the near-surface temperature inversion intensity around Ulaanbaatar city during the cold season demonstrates that the annual average from morning radiosonde measurements is 6.2 °C. The maximum intensity occurs in January at 8.8 °C, while the minimum is in October at 4.1 °C, with other months fluctuating between 4.8 °C and 7.6 °C. According to evening radiosonde measurements, the average inversion intensity is 2.9 °C, which is more than twice as weak as the morning inversion. It is clear that the morning inversion, formed by radiative cooling of the underlying surface throughout the night, is stronger than the evening inversion, which weakens during the day and begins to intensify after sunset. The temperature inversion intensity reaches its peak in December at 5.2 °C, whereas the lowest value is in March at 0.7 °C. In the remaining months, the evening inversion intensity fluctuates between 1.1 °C and 4.7 °C. Examining the variation in inversion intensity during the cold season shows that the monthly average increases starting from October, reaches its peak in January, then decreases to its lowest value in March (Table 3a). These results were similar to the findings of the studies by Sumiya [8], Palarz et al. [30], Stryhal et al. [7] and Ruman et al. [23]. Particularly, the inversion intensities in the morning and evening were weakened by 0.5 °C and 1.5 °C, respectively, compared to those estimated for the 1957–2004 period by Sumiya [8].

As shown in Table 3, an inversion with an intensity not exceeding 4.0 °C was observed in more than 45% of all occurrences around Ulaanbaatar city from 2012 to 2024 while it was 45.3% during 1957 to 2004 as the investigation results by Sumiya [8]. Half of these were weak inversions with an intensity below 2.0 °C. Such weak inversions have the highest frequency of occurrence in October, accounting for 35.5% of total cases, while the lowest frequency was in January at 12.7%. Inversions with an intensity of 2.0–4.0 °C also exhibited their maximum and minimum frequencies in these same months, reaching 28.5% and 17.0%, respectively. An inversion intensity of 4.0–6.0 °C was measured in 19% of all observed temperature inversion occurrences, with the highest frequency being 26.2% in March, while fluctuating between 16.5% and 18.6% in the remaining months of the cold season. Nearly 15% of all temperature inversions observed around Ulaanbaatar city have an intensity of 6.0–8.0 °C. Such moderate-intensity inversions have the highest frequency in January at over 18%, and the lowest in October at 10.6%. A temperature inversion with an intensity of 8.0–10.0 °C was recorded in 10.4% of all occurrences, with the maximum frequencies reaching 14.3% in December and 14.7% in January, respectively. Conversely, the minimum frequencies for such strong inversions were 4.6% in March and 5.5% in October of all

observed inversion occurrences. Strong inversions with an intensity of $10.0\text{ }^{\circ}\text{C}$ or higher account for 10.4% of the total temperature inversions formed around Ulaanbaatar city. For instance, the cold-season average frequency of inversions with an intensity of $10.0\text{--}12.0\text{ }^{\circ}\text{C}$ was 5.7%, peaking at 11.2% in January. Additionally, the cold-season average frequency for intensities of $12.0\text{--}14.0\text{ }^{\circ}\text{C}$ reached nearly 3.0%, with January occurrences rising to 5.4%. Inversions with an intensity of $14.0\text{--}16.0\text{ }^{\circ}\text{C}$ were rarely observed in October and March, whereas their frequencies in December and January were 2.5% and 3.1%, respectively. Extremely strong inversions within the $16.0\text{--}18.0\text{ }^{\circ}\text{C}$ range accounted for 1.6% and 0.7% of total occurrences in December and January, respectively, and were virtually absent during the rest of the cold season. Similarly, the frequency of inversions with an intensity of $18.0\text{--}20.0\text{ }^{\circ}\text{C}$ was 0.6% in December and 0.5% in January. In very rare cases, extreme inversions exceeding $20.0\text{ }^{\circ}\text{C}$ occurred solely in December, accounting for approximately 0.3% of the total. Although the frequency of these exceptionally strong inversions was low, their concentration in December is likely driven by the maximum nighttime duration occurring during the winter solstice (Table 3b) [41].

Since radiosondes are launched only twice a day from the Ulaanbaatar station, it was impossible to determine the detailed diurnal variations in the temperature inversion intensity; therefore, these variations were determined from temperature measurements from automatic weather stations at the foothills and summits of the southwestern and southeastern mountains of Ulaanbaatar City (Figure 5).

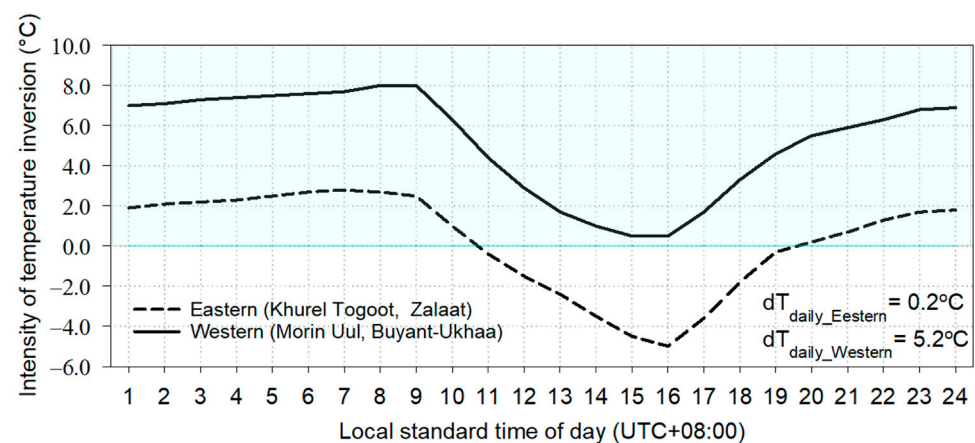


Figure 5. Diurnal variations in the intensity of the near-surface temperature inversion. The cyan-shaded area corresponds to atmospheric stagnation or temperature inversion conditions, while the remaining area represents unstable atmospheric conditions or ventilation periods.

The elevation differences in the meteorological stations located to the southwest and southeast mountains of Ulaanbaatar city were 225 m and 265 m, respectively. As illustrated in Figure 5, the maximum cold-season temperature inversion intensities are observed between 06:00 and 08:00 LST at eastern sites, and between 08:00 and 09:00 at western sites. This aligns with previous findings stating that the maximum intensity of near-surface temperature inversions is observed just before sunrise [63]. While the maximum cold-season inversion intensity at the Khureltogoot–Zalaat location reached $2.7\text{--}2.8\text{ }^{\circ}\text{C}$, an inversion nearly three times stronger with an intensity of up to $8.0\text{ }^{\circ}\text{C}$ developed at the Buyant-Ukhaa–Morin-Uul location. Furthermore, the minimum cold-season inversion intensity decreases to $0.5\text{ }^{\circ}\text{C}$ between 15:00 and 16:00 LST at the southwestern mountain, whereas the inversion completely dissipates between 11:00 and 19:00 LST at the southeastern place. Due to the declining solar elevation angle, the inversion intensity begins to rise after 17:00 at Buyant-Ukhaa–Morin-Uul, while it starts to reform around 20:00 LST at Khureltogoot–

Zalaat. These findings were similar to some results of investigation by Sumiya [8] and Sumiya et al. [1].

The daily average inversion intensity during the cold season was 5.3 °C at the Buyant-Ukhaa–Morin-Uul location (Figure 5), which was 0.8 °C higher than the inversion intensity (4.5 °C) recorded for this season at the Ulaanbaatar radiosonde station. This indicated that in winter, surface temperatures are, on average, lower than at the Ulaanbaatar station. Consequently, a stronger inversion developed across Buyant-Ukhaa and its surrounding areas, which are situated at a lower elevation in the Tuul River valley [6,8]. This is demonstrated in Section 3.3. In contrast, the daily average inversion intensity that forms during the cold season around Zalaat–Khureltogoot located at a relatively high elevation southeast of the city reached a mere 0.2 °C. Notably, in this part of the city, the temperature inversion dissipated during the daytime (sunny hours) due to the influence of the east-to-west airflow along the Tuul river basin [39].

3.2.2. Thickness of Near-Surface Temperature Inversion

The thickness of the temperature inversion depends on numerous factors, including the specific characteristics of the area such as the relative height of the surrounding mountains, the station's elevation above sea level, geographical terrain, relief as well as atmospheric circulation, solar radiation absorption, and radiative cooling of the underlying surface. According to measurements from the Ulaanbaatar radiosonde station located in the Tuul River valley, the average thickness of the near-surface temperature inversion during the cold season was 510 m at 00:00 (UTC+08:00) in the morning and 403 m at 12:00 (UTC+08:00) in the evening (Table 4).

Table 4. Thickness of near-surface temperature inversion in cold season.

Parameter	October	November	December	January	February	March	Cold Season
(a) Thickness of temperature inversion (m)							
Morning at 00:00 (UTC+08)	421	500	522	609	545	460	510
Evening at 12:00 (UTC+08)	310	384	519	539	425	239	403
(b) Frequency of thickness range of temperature inversion (%)							
Thickness range (m)							
<200	20.4	12.7	9.5	9.5	12.3	15.8	13.4
200–400	33.1	24.9	20.1	20.0	23.6	26.2	24.6
400–600	20.6	22.8	23.4	24.6	27.2	30.5	24.9
600–800	12.6	16.0	15.8	17.4	17.8	15.6	15.9
800–1000	8.4	9.4	12.0	12.8	8.7	7.0	9.7
1000–1200	3.0	7.5	8.5	7.3	4.6	2.7	5.6
1200–1400	0.8	3.0	5.6	3.5	2.3	1.0	2.7
1400–1600	0.2	1.9	1.9	2.5	1.7	0.5	1.5
1600–1800	0.9	1.1	1.3	1.1	1.0	0.7	1.0
1800–2000	0.0	0.2	0.7	0.6	0.8	0.2	0.4
2000–2200	0.0	0.3	0.4	0.3	0.0	0.0	0.2
2200–2400	0.0	0.2	0.2	0.3	0.0	0.0	0.1
2400–2600	0.0	0.0	0.2	0.1	0.0	0.0	0.0
2600–2800	0.0	0.0	0.1	0.0	0.0	0.0	0.0
2800–3000	0.0	0.0	0.1	0.0	0.0	0.0	0.0
>3000	0.0	0.0	0.1	0.0	0.0	0.0	0.0

According to data from the 08:00 LST radiosonde observations, the long-term mean inversion thickness reached a maximum of 609 m in January and a minimum of 421 m in October, with values ranging from 460 m to 545 m in the remaining months. In contrast, the 20:00 LST observations showed a maximum inversion thickness of 539 m in January and a minimum value of 239 m in March, while values in other months ranged from 310 m to 519 m. Overall, the mean inversion thickness derived from the morning soundings was

approximately 1.3 times greater than that observed in the evening. The difference was most pronounced during the transition months of October and March, when morning inversion thickness exceeded evening values by factors of 1.4 and 1.9, respectively. As the duration of nighttime cooling increased toward mid-winter, the difference between morning and evening inversion thickness diminished, decreasing to only 3 m in December and 70 m in January.

Orography plays a major role in the development and persistence of near-surface temperature inversions. In mountainous regions, inversion thickness is generally constrained by the elevation of the surrounding topography, although its magnitude also depends on the orientation of valleys and mountain ranges relative to the prevailing airflow [64,65]. Furthermore, there are cases where the average inversion thickness can be greater even when the relative height of the surrounding mountains is low. While this indicates that the orographic influence on inversion formation and intensification is practically absent in that specific area, it also demonstrates that the inversion primarily develops due to radiative cooling from the near surface into depressions and, in some cases, due to warm air advection aloft [16,17,66,67].

3.2.3. Frequency of Near-Surface Temperature Inversion

Temperature inversions can form through several mechanisms; however, near-surface inversions are primarily produced by the nocturnal radiative cooling of the underlying surface. Consequently, their occurrence is most frequent during the cold season and nighttime, when the radiative heat loss from the Earth's surface is the greatest [6,7]. Near-surface inversions may also develop under persistent high-pressure systems through large-scale subsidence, commonly referred to as subsidence inversions. While atmospheric circulation governs the occurrence and movement of these inversion events, radiative cooling largely determines their intensity and thickness. As a result, inversion frequency is strongly influenced by the spatial and temporal evolution of anticyclonic systems rather than exhibiting a distinct annual cycle [1,6,8,40]. Figure 6 shows the frequency of morning and evening inversions at the Ulaanbaatar radiosonde station.

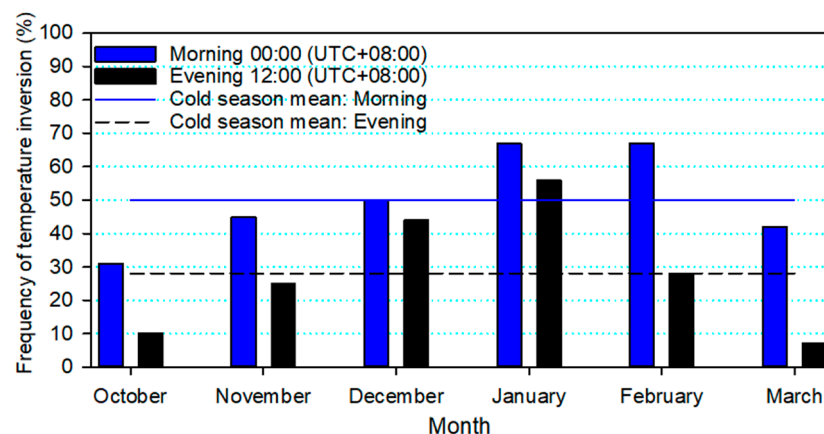


Figure 6. Monthly frequency of the near-surface temperature inversion.

According to Figure 6, the frequency of temperature inversions during the cold season determined by measurements from the Ulaanbaatar radiosonde station increases starting from October. The maximum values were observed in January and February for morning measurements and in January and December for evening measurements. During the cold season, the morning inversion frequency ranges between 31% and 67%, meaning inversions are observed in the morning for an average of 9 to 21 days per month. Meanwhile, the evening inversion frequency ranges between 7% and 56%, meaning inversions are observed

in the evening for an average of 2 to 17 days per month. The frequency of evening inversions during the cold season is 22% lower than the frequency established by morning measurements. For morning measurements, the largest increase occurs during the transition from December to January, rising by 17%, while the largest decrease occurs during the transition from February to March, dropping by 25%. For evening measurements, the frequency increases the most during the transition from November to December by 19%, and decreases the most during the transition from January to February by 28%. Researchers who have studied the cold season, particularly winter, inversion frequencies attribute them to surface radiative cooling [6,7]. A clear manifestation of this is reflected in the difference between morning and evening observed inversions. The minimum difference between morning and evening inversion frequencies occurs in December at 6%. This indicates that the inversion formed in the morning does not dissipate during the day, or even if it does, it quickly reforms [68]. However, variations occur in the inversion frequency depending on how warm or cold that specific year is. On the other hand, the maximum value of this difference reaches 35–39% in February and March. This demonstrates that the inversion is predominantly established through nocturnal radiative cooling [2]. Within a year, the difference between morning and evening inversion frequencies tends to stabilize relatively as the station's altitude above sea level decreases [8,40].

3.3. Spatiotemporal Variability of Near-Surface Temperature Using the FDDA Approach in the WRF Model

Studying cold-season processes within the atmospheric boundary layer over Ulaanbaatar using radiosonde observations or single-point measurements alone provides limited spatial and temporal coverage, making it difficult to characterize the city's heterogeneous meteorological conditions. Consequently, evaluating boundary-layer characteristics solely from observations at a single radiosonde station is insufficient. Therefore, one objective of this study was to investigate the spatiotemporal variability of cold-season boundary layer meteorology, particularly the intensity of the near-surface temperature inversion using the WRF model.

To evaluate model performance, WRF simulations were first performed for two representative cold seasons: 2012–2013 (a relatively cold winter) and 2017–2018 (a relatively warm winter). Initial comparisons with radiosonde-derived inversion intensity showed only moderate agreement ($R^2 = 0.49$, $p < 0.01$ for 2012–2013 and $R^2 = 0.40$, $p < 0.05$ for 2017–2018), with the model underestimating inversion intensity by approximately a factor of two. To improve the simulation accuracy, FDDA using the grid nudging method was applied to the model configuration [43,50,51]. This modification significantly enhanced the correlation, yielding values much closer to the observations ($R^2 = 0.79$, $p < 0.001$ for 2012–2013 and $R^2 = 0.76$, $p < 0.001$ for 2017–2018). This FDDA-enhance configuration was subsequently adopted for all simulations to generate the final spatiotemporal distributions of near-surface temperature inversion intensity.

Figure 7 shows the correlation between the surface temperature inversion intensity calculated using the WRF model's grid nudging approach for October 2021 to March 2023, and the values calculated from radiosonde measurements from the Ulaanbaatar station during this period.

The validation evidence demonstrated that the configured WRF run reproduces radiosonde-observed temperature inversion intensity over the Ulaanbaatar domain with strong linear agreement ($R^2 = 0.783$), high statistical significance ($p < 0.000$), and a small, physically reasonable offset (≈ -0.377 °C) (Figure 7).

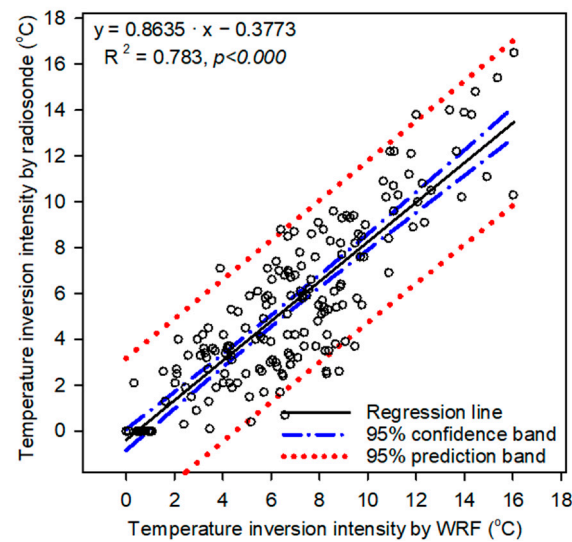


Figure 7. Correlation between the modeled and observed temperature inversion intensity.

Figure 8 shows the spatial distribution of the average cold-season surface air temperature, wind speed, PBLH, and calculated surface temperature inversion intensity from October to March between 2012 and 2023, simulated using the WRF grid nudging approach.

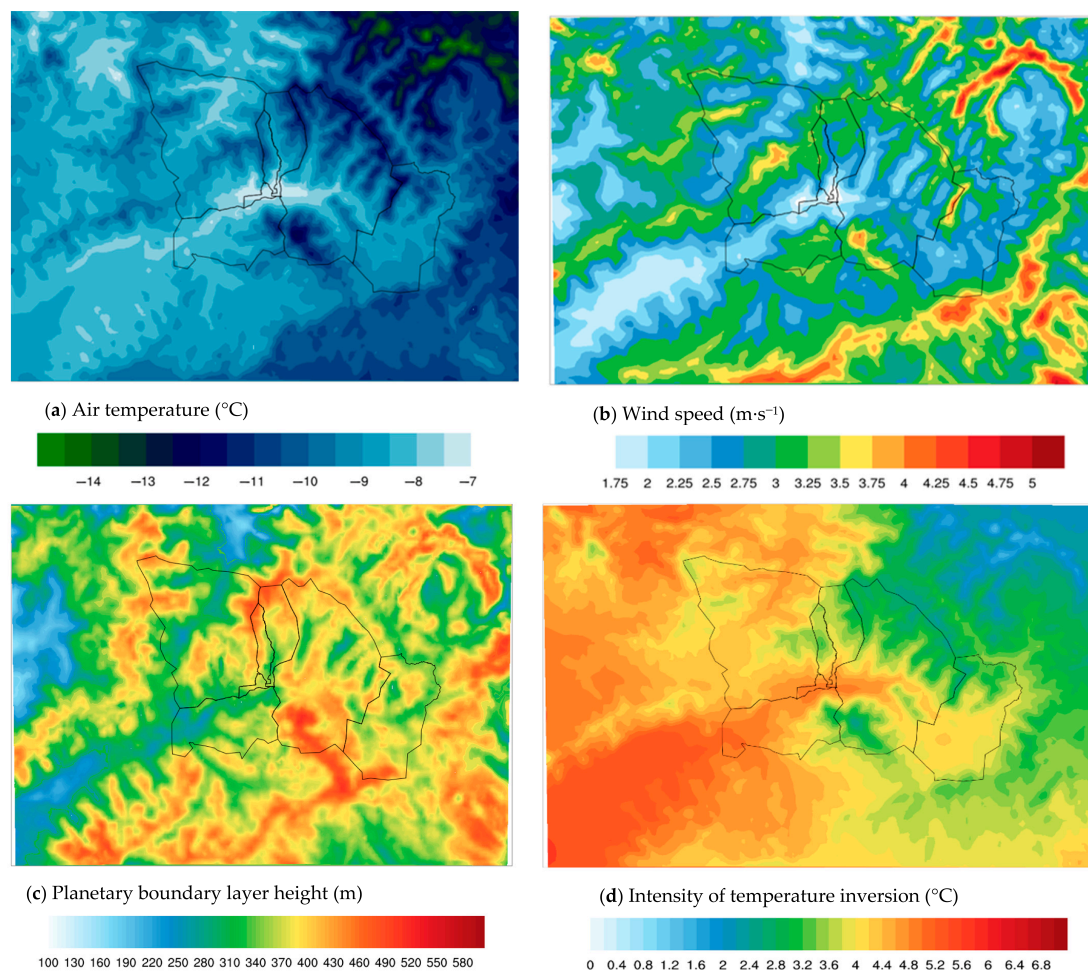


Figure 8. Cold season average maps for (a) surface air temperature, (b) wind speed, (c) planetary boundary layer height, and (d) temperature inversion intensity for a period from 2012 to 2023 using WRF grid nudging approach.

Since the primary objective of this section is to investigate the physical processes of the planetary boundary layer in relation to winter urban air pollution, the analysis focuses specifically on the residential areas of Ulaanbaatar. In this regard, we will examine how the geographical features of Ulaanbaatar are characterized by the low-lying, east–west oriented Tuul River valley and its surrounding mountains influence the distribution of these physical parameters within the atmospheric boundary layer (Figures 1b and 2). As shown in Figure 8a, cold-season air temperature generally increases toward the urban center, reflecting the influence of urban heat island effect, consistent with previous studies by Ganbat et al. [69], Ganbat and Baik [70], and Sumiya et al. [1]. Ulaanbaatar’s residential basin suffers from a severe winter temperature inversion that traps freezing, stagnant air at the surface. Consequently, the lowest temperatures in winter concentrate directly where people live on the valley floor, while the surrounding mountain ridges remain relatively warmer due to near-surface temperature inversion [8,39]. Because wind speeds in these residential zones are low, ranging between 1.75 and $2.5\text{ m}\cdot\text{s}^{-1}$, and they reach $3\text{--}5\text{ m}\cdot\text{s}^{-1}$ in the mountainous terrain and $2\text{--}3\text{ m}\cdot\text{s}^{-1}$ in other areas, they create a stagnant atmospheric layer that prevents clean air from entering to flush out the basin (Figure 8b). Acting as a “tight lid”, a shallow atmospheric boundary layer compresses urban pollutants right into the human breathing zone, dropping below 260 m over central neighborhoods. It reaches $400\text{--}500\text{ m}$ in the elevated areas and is around $300\text{--}400\text{ m}$ elsewhere (Figure 8c). Simultaneously, inversion intensity peaks heavily over dense residential areas, forcefully blocking all vertical air movement. A more detailed analysis reveals that the inversion intensity is high ($6\text{--}8\text{ }^{\circ}\text{C}$) in the low-lying southwestern part of Ulaanbaatar, moderate ($4\text{--}6\text{ }^{\circ}\text{C}$) in the city center, and weak ($2\text{--}4\text{ }^{\circ}\text{C}$) in the relatively elevated eastern part, while the lowest intensities ($1.4\text{--}3\text{ }^{\circ}\text{C}$) occur in the high-altitude, mountainous areas (Figure 8d). These results indicate that the combined effects of complex topography, weak wind conditions, a shallow planetary boundary layer, and persistent temperature inversions substantially restrict atmospheric ventilation during winter, allowing emissions from residential heating, particularly in the ger districts, to accumulate within the urban basin [6,8,40].

Figure 9 presents the three-hourly average spatial distribution maps, aimed at investigating the diurnal variation in surface temperature inversion intensity.

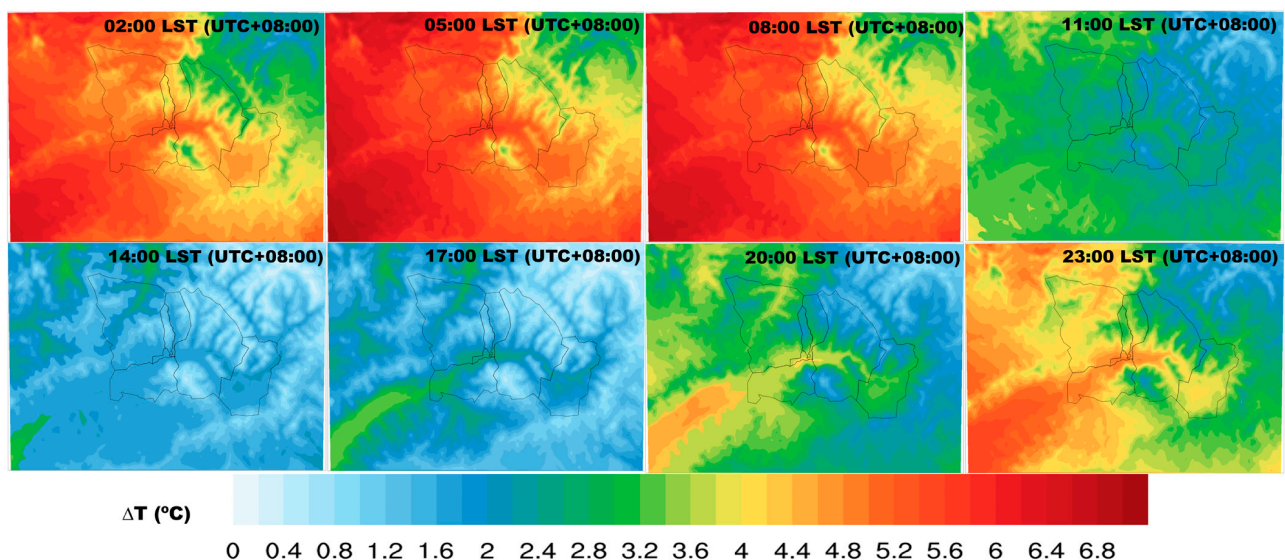


Figure 9. Three-hourly average temperature inversion intensity maps for the cold season of 2012 to 2023, simulated using the WRF grid nudging approach.

Ulaanbaatar experiences a severe daily cycle of temperature inversions. The inversion peaks between 02:00 and 08:00 LST. Intensity levels reach a critical $5.6\text{ }^{\circ}\text{C}$ to $6.8\text{ }^{\circ}\text{C}$. This

peak matches early morning home heating hours. Cold air drains into the valley floor nightly. It creates a powerful, inescapable trapping mechanism. The atmospheric lid never breaks fully during cold season days. Solar heating weakens the inversion by mid-afternoon. Intensities drop to a daily low at 14:00 LST. However, stable air layers constantly remain over neighborhoods. The inversion rapidly intensifies immediately after sunset. Consequently, trapped toxic pollution accumulates continuously over multiple days (Figure 9). These results agree with the findings of studies by Ganbat and Baik [6] and Sumiya et al. [1].

Figure 10 exhibits the monthly average spatial distribution maps during the cold season, to explore seasonal variations in surface temperature inversion intensity.

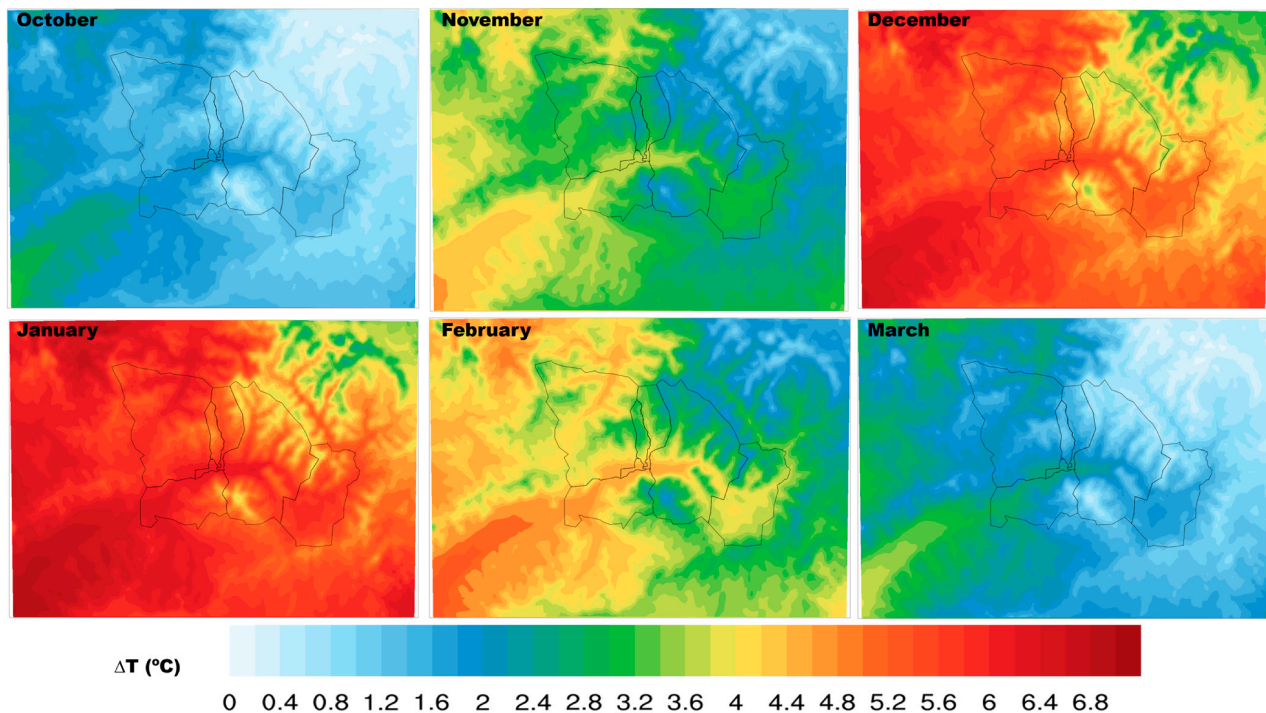


Figure 10. Monthly average temperature inversion intensity maps for the cold season of 2012 to 2023, simulated using the WRF grid nudging approach.

A distinct seasonal cycle is evident, with the inversion intensity peaking during the core winter months of December and January, where mean values widely exceeded 5.6 °C and maximum intensities reached up to 6.8 °C. During this peak period, the strongest inversions are heavily concentrated within the low-lying valley areas, particularly across the western and central residential areas, due mainly to intense radiative cooling and cold air pooling. In the mid-season months of October and March, the inversion drastically weakens, dropping below 2.0 °C across most of the domain. Dynamically, November and February are transition months, with November exhibiting a moderate intensity gradient ranging from 2.4 to 4.4 °C, while February maintains a slightly stronger residual inversion pattern (3.6 to 5.2 °C), especially in the low-lying southern and western topography before the onset of spring thermal breakup [1,6,8,39]. The seasonal distribution of surface temperature inversion intensity exhibits comparable dynamics in other topographically similar regions worldwide [7,9,11,23,71,72].

Figure 11 presents a spatial distribution and vertical cross-sections of key atmospheric and topographic variables within the planetary boundary layer over Ulaanbaatar during cold-season temperature inversions from 2012 to 2023. The figure illustrates a typical topographically confined inversion, highlighting the dominant influence of the surrounding

terrain on atmospheric stability and pollutant dispersion. As shown in Figure 11a, the strongest near-surface temperature inversions are concentrated within the low-lying central basin of Ulaanbaatar. Crosshairs mark the Ulaanbaatar radiosonde station at the intersection of latitude of 47.92° N and longitude of 106.85° E, which acts as the reference point for the subsequent longitudinal and latitudinal cross-section analysis.

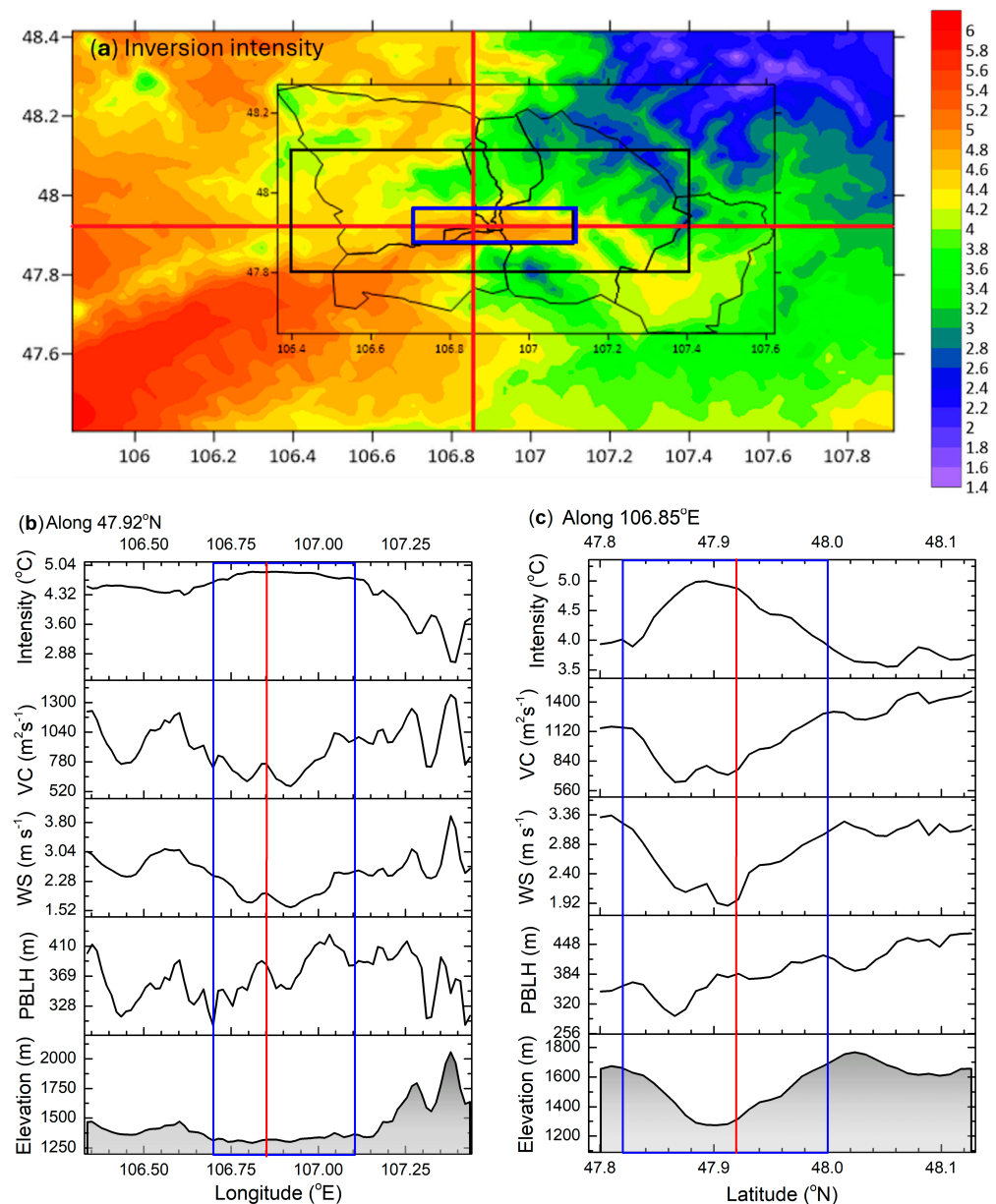


Figure 11. Cross-section of topographic and physical variables within the planetary boundary layer beneath the temperature inversion layer at the Ulaanbaatar radiosonde station. Abbreviations: PBLH, planetary boundary layer height; WS, wind speed; VC, ventilation coefficient; Intensity, temperature inversion intensity; Elevation, topography. (a) The blue rectangle represents the core urban settlement area of Ulaanbaatar. The radiosonde station is located at the intersection of the red latitudinal (b) and longitudinal (c) lines.

The cross-sectional profiles (Figure 11b,c) reveal a strong coupling between topography, thermodynamics, and fluid dynamics. As elevation drops into the valley floor, temperature inversion intensity spikes to its maximum value of approximately 5.0°C . This strong thermal stability acts as a physical lid, severely compressing the PBLH below 350 m and causing wind speeds to drop to a localized minimum of under 2.0 m s^{-1} . Consequently,

the ventilation coefficient (VC), the product of wind speed and PBLH [26], plummets to its lowest levels directly over the urban basin. This simultaneous reduction in vertical mixing and horizontal transport creates an atmospheric stagnation zone. These conditions explain the mechanism behind Ulaanbaatar's severe winter air pollution events, as urban emissions become trapped near the surface with virtually no capacity for dispersion.

One limitation of the present numerical simulations is the application of FDDA grid nudging. By continuously constraining the model toward ERA5 reanalysis, FDDA improves the representation of synoptic-scale circulation and substantially enhances agreement with radiosonde observations. However, this approach may partially suppress fine-scale thermally driven circulations, including downslope drainage flows, localized cold-air pooling, and small-scale turbulence that naturally develop over Ulaanbaatar's complex terrain. Consequently, although the simulations realistically reproduce the overall spatial distribution and climatological characteristics of temperature inversions, some local boundary-layer structures and inversion intensities may be underestimated. Future studies using nested simulations with selective upper-level nudging or spectral nudging could further improve the representation of local atmospheric processes while retaining realistic large-scale forcing.

A limitation of the present study is that the continuous diurnal variation in inversion intensity was estimated using temperature differences between foothill and summit stations rather than direct vertical profiles. Radiosonde observations are available only twice daily (00:00 and 12:00 UTC; 08:00 and 20:00 LST), making continuous validation of the proxy throughout the diurnal cycle impossible. Therefore, the station-based analysis should be interpreted as an indicator of the temporal evolution of inversion conditions rather than an exact measurement of the vertical inversion profile. Future studies combining continuous remote-sensing observations (e.g., lidar, microwave radiometers, or ceilometers) with radiosonde measurements would allow a more comprehensive evaluation of the proxy and improve characterization of diurnal inversion dynamics.

Another limitation is that the long-term trend analysis is based on observations from the Ulaanbaatar meteorological station, without comparison to a nearby rural or background reference station. Consequently, it is not possible to quantitatively distinguish the effects of regional climate warming from those of urbanization and the urban heat island. While previous studies have documented significant urban warming associated with the rapid expansion of Ulaanbaatar, the present dataset does not permit formal attribution of the observed inversion changes to either process individually. Future studies incorporating paired urban–rural observations, satellite-derived land surface temperatures, or numerical experiments with different land-use scenarios would enable a more rigorous assessment of the relative contributions of regional climate change and urbanization.

4. Conclusions

This work presents a comprehensive spatiotemporal analysis of cold-season near-surface temperature inversions over Ulaanbaatar, Mongolia, by integrating long-term radiosonde observations (2000–2024) with high-resolution WRF simulations (2012–2023). Using four-dimensional data assimilation (FDDA) grid nudging within the WRF framework, a realistic representation of the interactions between complex terrain and boundary-layer processes provides reliable spatial characterization of inversion dynamics across the Ulaanbaatar basin.

The results demonstrate that near-surface temperature inversions are primarily controlled by the combined effects of the semi-permanent Siberian High, basin topography, and nocturnal radiative cooling. Inversion occurrence and intensity reached their maximum during December and January, when strong atmospheric stability compressed the planetary

boundary layer to below 350 m and reduced near-surface wind speeds to less than $2.0 \text{ m}\cdot\text{s}^{-1}$. These conditions substantially restricted both vertical and horizontal atmospheric ventilation, creating persistent stagnation over the valley and favoring the accumulation of residential heating emissions within densely populated urban areas.

Long-term observations further revealed significant changes in inversion characteristics during the past 25 years. Concurrent with increases of approximately $2.0 \text{ }^{\circ}\text{C}$ in winter air temperature and $2.3 \text{ }^{\circ}\text{C}$ in land surface temperature, inversion frequency, thickness, and intensity decreased by approximately 31%, 170 m, and $0.9 \text{ }^{\circ}\text{C}$, respectively. The long-term weakening of near-surface temperature inversions coincides with increasing regional temperatures and rapid urban development in Ulaanbaatar. However, the present analysis does not permit quantitative attribution of the observed trends to these individual drivers.

Overall, Ulaanbaatar's winter air pollution intensity and duration are fundamentally tied to a close-coupling of terrain, local thermodynamics and fluid dynamics. Despite a slow decrease in these structural inversion characteristics over time as the backdrop climate changes, the strong stagnation periods mid-winter remain a direct environmental and health concern for the city's population. Consequently, effective air-quality management requires not only reductions in emission sources but also consideration of meteorological controls on pollutant dispersion. Future urban planning and climate adaptation strategies should therefore incorporate boundary-layer dynamics, topography-informed ventilation corridors, and urban design measures that enhance atmospheric ventilation and reduce population exposure to winter air pollution.

Author Contributions: Conceptualization, E.S. and S.D.; methodology, E.S., S.D., M.B.-O. and B.G.; software, S.D., M.B.-O., B.G. and D.D.; validation, E.S., S.D., D.D., D.S. and G.G.; formal analysis, S.D., M.B.-O., B.G., D.D. and E.E.; investigation, E.S., S.D., M.B.-O. and B.G.; resources, E.S., M.B.-O., G.G., D.S. and B.G.; data curation, E.S., M.B.-O., E.E. and B.G.; writing—original draft preparation, E.S., S.D., M.B.-O., E.E. and B.G.; writing—review and editing, E.S., S.D., D.S. and G.G.; visualization, S.D., M.B.-O. and B.G.; supervision, E.S.; project administration, E.S.; funding acquisition, E.S. and S.D. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NAMEM	National Agency for Meteorology and Environment of Mongolia
WRF	Weather Research and Forecasting
PBL	Planetary Boundary Layer

PBLH	Planetary Boundary Layer Height
ERA5	The fifth generation of the European Centre for Medium-Range Weather Forecasts
FDDA	Four-Dimensional Data Assimilation
VC	Ventilation Coefficient

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