Evidence for a Change to Aerosol Fractions: In a Gobi Town

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## -- Attaching core tidyverse packages ------------------------ tidyverse 2.0.0 --
## v dplyr     1.1.4     v readr     2.1.5
## v forcats   1.0.0     v stringr   1.5.1
## v ggplot2   3.5.1     v tibble    3.2.1
## v lubridate 1.9.3     v tidyr     1.3.1
## v purrr     1.0.2
## -- Conflicts ------------------------------------------ tidyverse_conflicts() --
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Munkhtsetseg. E, Shimizu. A, Matsuki. A, Batdorj. D, Matsui. H, Bayanjargal. D

To whom correspondence should be addressed:

Plain text summary Driven by industrial progress in the mining sector, household coal combustion has increased significantly in Mongolia since the 2000s. Demographic evidence has revealed an ongoing reduction in rural-nomadic lifestyle and a rise in urban population, which may gradually extend household winter heating as a major source of fine particulate matter (PM2.5). In conjunction with a stagnant atmosphere and observations that winter fine pollutants (PM2.5 and PM10) are persistently trapped within the boundary layer and can be exacerbated by stagnant weather or emission sources, these results have led to hypotheses that fine aerosols may be subject to suspension in the near-surface atmosphere, potentially available for emission via dust storms in the spring. Here, through the analysis of long-term datasets, we demonstrate distinct spatio-temporal patterns in variations of PM10 and PM2.5 relative to recent drivers of emission sources in Mongolia, and that the concentration of PM2.5 in a Gobi town has increased in association with winter heating. Furthermore, the ratio of fine to coarse aerosols indicates that the fine fraction in the spring has increased despite decreased wind speeds. Our results strongly suggest that the aerosol fraction has undergone changes at the local-level, and is subject to both natural and anthropogenic constraints.

Abstract (150 words: 200, cut 50 words)

Here, through the analysis of long-term datasets, we demonstrate distinct spatio-temporal patterns in variations of PM10 and PM2.5 relative to recent drivers of emission sources in Mongolia, and that the concentration of PM2.5 in a Gobi town has increased in association with winter heating. Furthermore, the ratio of fine to coarse aerosols indicates that the fine fraction in the spring has increased despite decreased wind speeds. Our results strongly suggest that the aerosol fraction has undergone changes at the local-level, and is subject to both natural and anthropogenic constraints.

Introduction /Why you should care/

Gobi Desert is known for its high dust storm frequency and substantial dust emissions, precise quantification of its contribution to the global dust budget is somewhat simplified. It is well defined that Mongolian dust has a brown color, seasonal characteristics, mainly consisted coarse fractions. Mongolian dust has an attention of the its mass fraction in global dust, yet unlikely elaborated in the climate models due to its majority of coarse fraction for its a small contribution to the climate system through its radiative feedback.But, such recognized characterization might get no longer valid due to recent change in the driving of the emissions of air particulate matters. POINT 1: AEROSOL EFFECTS ON radiation POINT 2: COLD DESERTS, POINT 3: AIR QUALITY AND HEALTH

Aerosols from cold arid areas, particularly the Gobi Desert in Asia, constitute the second most substantial global source of atmospheric aerosols (Fitzgerald et al., 2015). These dust particles considerably impact Earth's radiative equilibrium by directly scattering solar radiation and serving as nuclei for cloud droplet and ice crystal formation, while also influencing climate through its interactions with solar radiation (Huang et al. 2014), clouds (Kawai et al. 2021), and terrestrial and oceanic biogeochemistry (Jickells et al. 2005; Mahowald et al. 2017). This dust is carried towards the North Pacific by prevailing westerly winds (Husar et al. 2001; Uno et al. 2009), significantly affects local and regional air quality (Sugimoto et al. 2003; Jugder et al. 2011) and human health (Higashi et al. 2014).

There has been a [tremendous improvement] in the understanding of atmospheric aerosols and their climate effect over the last decades, with some important observational and modelling breakthroughs. Long-term measurements of aerosols (e.g., Nishikawa et al. 2010, Andrews et al. 2011), observational campaigns (e.g., Shinoda, Park, chinse), and lidar (Holben et al. 1998, Remer et al. 2008), and bioaerosol (dd), health (ff) have remarkably increased knowledge about the composition and characteristics of atmospheric aerosols. dust brown color, seasonal characteristics, with coarse fractions. Gobi Desert dust typically has a shorter atmospheric residence time (1.5 days) tends to remain at lower altitudes, (Tanaka, 2012) During dust storms, PM2.5 and PM10 concentrations can surge to 343 and 1.642 gm^3, respectively (Filonchyk et al., 2021). Regarding aerosol fractions, PM2.5 and PM10 concentrations in the Gobi Desert area were found to be 36.2 ś 23.7 and 97.3 ś 84.5 gm^3, respectively (Filonchyk et al., 2021). Clean continental aerosol type is predominant (73.9 percent), followed by mixed aerosols (20.4 percent), with minor contributions from clean marine, urban/industrial, biomass burning, and desert dust aerosol types. During dust storms, PM2.5 and PM10 concentrations can surge to 343 and 1.642 gm^3, respectively (Filonchyk et al., 2021) Gobi Desert is known for its high dust storm frequency and substantial dust emissions, precise quantification of its contribution to the global dust budget is challenging. Nevertheless, the land surface parameters governing Asian dust emissions exhibit substantial seasonal and inter-annual variations and complex interactions, leading to significant uncertainties in simulating them for Asian dust (Kawai Sola 2021).

Advanced the knowledge of global dust, has reached to recognize the sources,. Classification dust brown color, seasonal characteristics, with coarse fractions. Much studies, The Gobi Desert is a primary source of global atmospheric aerosols, with dust emissions heavily influenced by wind strength and surface dust availability (Liang et al., 2021). Gobi Desert dust typically has a shorter atmospheric lifetime (1.5 days) compared to Taklimakan Desert dust (2.1 days) (Tanaka, 2012), indicating differences in transport patterns and atmospheric persistence (Tanaka, 2012). Gobi dust tends to remain at lower altitudes, while Taklimakan dust can be transported to higher elevations, potentially contributing to the Asian tropopause aerosol layer (Tanaka, 2012). Gobi Desert is known for its high dust storm frequency and substantial dust emissions, precise quantification of its contribution to the global dust budget is somewhat simplified. It is well defined that Mongolian dust has a brown color, seasonal characteristics, mainly consisted coarse fractions.

This knowledge further efficient to climate system when elaborating dust-aerosol effects. But, a large uncertainties in the global dust model has existed so for climate models which clearly limits our understanding the climate system and shape the facing global issues of global warming. This is first mainly, caused by the lack of parameterization and the complex nature of its aerosol composition. [AND] surface ... [AND] anthropogenic, livestock These findings highlight the significant contribution of the Gobi Desert to global dust aerosols and the complex nature of its aerosol composition.

Second, the significant contribution of the Gobi Desert to global dust aerosols is not fully recognized; and their is the rapid growing changes controlled by the natural forces and anthropogenic drivings. Mongolian dust has an attention of the its mass fraction in global dust, yet unlikely elaborated in the climate models due to its majority of coarse fraction for its a small contribution to the climate system through its radiative feedback. ... Rapid change ; few research; needs to enroll such changes and multidisciplinary

But, such recognized characterization might get no longer valid due to recent change in the driving of the emissions of air particulate matters. A large high concentrations of PM2.5 in the capital city of Mongolia has been observed as a result of the heavy consumptions of coal as a winter heating has rapidly spread as a mining industry taken off since 2000. Demographic evidence has revealed an ongoing reduction in rural-nomadic lifestyle and a rise in urban population, which may gradually extend household winter heating as a major source of fine particulate matter (PM2.5). Winter weather stagnant conditions governed by the Siberian magnifies the concentrations of the particulate matter emissions by trapping the polluted air below the boundary layer, so that results in a very large high concentrations of PM2.5, locally. Even within a short span, UB has recognized as one of the highly polluted capital cities in the world.; resulted a human health issues.

Therefore, It is important to examine the emerging changes and shifting patterns of air particulate matters in Mongolia. More importantly, it is essential to reveal the significant changes in the the altered fraction particularly, in the dust seasons considering its high potential of intriguing in the free atmosphere to transported in the long-distance, so carrying capacity of the role to shift the global climate system, and its side impacts on downwind regions.

- Study goal - We hypothesize ... - Our study will benefit not only to the global dust research but also climate, and further to the country itself for urban planning, and coal combustion.

Research Qs

Therefore, we aimed to demonstrate the distinct temporal and spatial variations of PM2.5 and PM10 across urban and rural Mongolia using extensive data from 2008 to 2020.

On spring, the dust storm from the Gobi Desert contribute significantly to increased aerosols in the atmosphere and ambient air pollution, leading to sporadic peaks in PM10 concentrations reaching as high as 64-234 gm^3 per day or exceeding 6000 gm^3 per hour (Jugder). concentrations of particulate matter is ephederemal, yet vary depending on whether the pollution cause is natural or industrial, local or transported, seasonal or non-seasonal, makes complex and challenging.

1. Do concentrations of particulate matters differ in between urban and rural sites, and even within Gobi sites? 2. Do distinct temporal variations has existed among the sites? 3. Do PM2.5 particulates has contributed to the PM10 annual variations?

- If yes, how much, and when and where?
- What is the sd, mean, and median
  - box plot
  - violin
  - scatter points, epidemic, sporadic
- Daily variations to examine it related to the heating
  - 2 peaks: smaller and bigger
  - compare the t-duration exceeds 50 mug/m3/hour

4. Does it has distinct patterns among the sites regarding to the drivings

- How PMs varies with the wind speed and visibility

- Do they differently explained with variables and changes in drivings (with PCA analysis)

5. Is there any significant changes in time-series of PMs at 4 seasons
6. Is there any significant changes in ratio in the spring in respect to winter pollutions?

Results

The spatio-temporal variations of the PMs at the study sites

To evaluate the spatial variations in particulate matter (PM) concentrations, we displayed hourly observed values of PM10 and PM2.5 for all study sites (figure_3). The mean p-values indicate that PM concentrations differ significantly at a 99% confidence level across all sites (figure_3), with the exception of a 95% confidence level between DZ and UB for PM10 (figure_3a), highlighting substantial concentration disparities among sites. While quantitative differences in PM concentration values exist across all sites, two key patterns emerge when examining median deviations from mean values and irregular observation fluctuations. For instance, PM10 demonstrates more erratic behavior than PM2.5 at each location, particularly evident at ZU and SS sites. Furthermore, the mean values calculated from hourly measurements surpass the median concentrations for both PM10 and PM2.5 across all sites, with notable prominence at UB and DZ locations. Consequently, significant spatial differences in PM concentrations exist among all sites, regardless of urban or rural classification. However, the sites can be categorized into two groups based on their characteristics: UB (urban) and DZ (rural town, Gobi); and SS (rural, Gobi) and ZU (rural, Gobi). These findings for DZ appear to support our hypothesis of emerging new emission patterns related to increased coal consumption during winter months.

To investigate whether emerging PM patterns are associated with household winter heating activities, we demonstrated annual variations in PM10 and PM2.5 concentrations at the sites. Significant annual variations in PM10 and PM2.5 levels were observed at UB and DZ sites, with maximum concentrations exceeding 100 g/m^3 during colder months (January, November, December) and lower levels consistently below 50 g/m^3 during warmer months (May-September).

These annual maximums coincided with the diurnal variations in PM10 and PM2.5 concentrations at sites DZ and UB, where PM concentrations reached their highest values during nighttime and early morning hours (approximately 8 PM to 4 AM UTC), with median values surpassing 50 g/m^3. Conversely, both pollutants exhibited reduced concentrations during daytime hours (8AM to 4PM UTC), likely due to increased atmospheric dispersion. UB site exhibited similar daily fluctuations with extended periods (approximately 8 PM to 5 AM UTC) of elevated concentrations. Additionally, winter PM10 concentrations at both sites were primarily composed of PM2.5 (figure_5; mean values for PM10 with the color bar). The increase in PM10 and PM2.5 aligns with the heating active hours, suggesting that household coal consumption contributes to elevated PM levels at both DZ and UB sites. In contrast, ZU and SS sites displayed significantly lower annual PM10 and PM2.5 levels, with sudden frequent spikes in spring followed by occasional instances in autumn. These annual variations were more pronounced in PM10 compared to PM2.5, highlighting the impact of Gobi dust and sand storms. Similar occurrences were also noted at the DZ site, suggesting its exposure to both winter heating emissions and natural spring dust, reflecting its Gobi-region characteristics. The annual variability in PMs with higher concentrations during nighttime and colder months, indicating the influence of localized emission sources and reduced boundary layer mixing at UB and DZ sites. Additionally, the upward extended ranges without the bottom bottle of the violin plot, demonstrating greater variability during colder months. It implies instability in concentrations potentially reaching high levels above 400 g/m^3 when Arctic oscillation/Siberian high intensifies with heating, and dropping below 50 g/m^3 when it weakens or heating demand decreases. These findings confirm the (DZ) emerging PM pattern is caused by household activities and influenced by meteorological conditions. Overall, meteorological factors appear to play a crucial role in governing PM levels.

The emission patterns of interrelations among meteorological variables at the study sites

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To identify the key factors influencing PM emissions, we examined the relationships between wind speed (WS), visibility (VIS), and particulate matter (PM10 and PM2.5) concentrations across the study sites (figure_6). In UB during winter, elevated PM levels typically coincide with low wind speeds and reduced visibility (indicated by darker blue points). Notably, at DZ and ZU locations, high PM10 concentrations were observed during both low and high wind speed conditions in winter. All Gobi sites exhibit the greatest variation in PM concentrations during spring, with extreme outliers primarily associated with increased WS and reduced visibility below 10000 km. Similar findings were also revealed through Principal Component Analysis (PCA). The initial two principal components (Dim 1 and Dim 2) account for 66.52% of the total variance. Dim 1 shows a strong association with PM10 and PM2.5, while visibility demonstrates an inverse correlation, suggesting that reduced visibility corresponds to higher pollution levels. Wind speed and direction align positively with Dim 2 (22.16%), reflecting their impact on emissions. When comparing PM10 aligns with PM2.5, the 1:1 ratio increases approximately 1.3 times for UB, 2 times for DZ, XXX for ZU, and XXX for SS as PM10 concentrations increase. This increase in Gobi sites further escalated up to 2-5 times in ZU, and XXX times in SS sites, indicating insufficient PM2.5 particulates in those locations, particularly at the ZU site. It is worth noting that instances where PM2.5 values exceed PM10 reflect equipment accuracy, correction errors, and higher sensitivity rates (ability to record emissions such as smoking near the sensor area). However, this discrepancy diminishes as PM concentrations increase, validating that higher observational records of PM2.5 compared to PM10 do not invalidate our results. Furthermore, clustering of monitoring sites based on PM concentrations and geographic features (Figure 7b) reveals distinct patterns. UB (urban, capital city) is characterized by high PM concentrations (positive Dim 1 scores), while SS (rural, Gobi, town (site located in the prevailing wind above the town)) shows low PM levels, clustering tightly along the negative Dim 1 axis. DZ (rural, Gobi, town center) displays considerable variability, with clusters extending into higher Dim 1 and Dim 2 ranges, reflecting the complex interplay of emission sources and meteorological factors. ZU (rural, Gobi, village) overlaps with SS but exhibits greater spread, indicating moderate pollution levels influenced by seasonal and localized factors. These findings highlight the complex interplay of spatial, meteorological, and local factors influencing air particulate matter concentrations across the studied locations and emphasizing the need for considering not only regional influences but also site-specific characteristics.

fig caption: the Principal Component Analysis (PCA) bi-plot (Figure 7a) highlights the relationships among key variables, including PM10, PM2.5, wind speed (WS), wind direction (WD), visibility, ratio of PM2.5 to PM10 (r), and numbers of aerosols by optical particle counter (OPC). The first two principal components (Dim 1 and Dim 2) explain 66.52% of the total variance, with Dim 1 (44.36%) strongly associated with PM10 and PM2.5. Wind speed and wind direction are positively aligned with Dim 2 (22.16%), reflecting their influence on pollutant dispersion.

The recent trends in concentrations of PMS and fine-coarse fractional changes at the sites

add table, add trend figure: r, add relationship figure: r in spring and pm2.5 in winter

Figure 8 illustrates the trend analysis of PM10 and PM2.5 concentrations across study sites from 2009 to 2020. The time series demonstrates seasonal patterns and trends, with p-values of trend changes, seasonally: winter (Q1), spring (Q2), and summer-autumn (Q3). At UB, significant negative trends both in PM10 and PM2.5 concentrations are observed for winter and spring (Q1 and Q2, $p < 0.001$). At DZ, a significant positive trend in PM10 and PM2.5 concentrations is observed for winter (Q1, $p < 0.001$), indicating increasing particulate matter levels during this season. At ZU, a significant negative trend is observed in both PM10 and PM2.5 for winter (Q1, $p < 0.001$), suggesting a consistent reduction in particulate matter during winter months (may reduced transboundary traffic associated with covid periods, resulted in declined PM10 concentrations; or data gaps). At SS, a negative trend is observed in PM2.5 for spring (Q2, $p < 0.001$), reflecting a seasonal decline potentially linked to reduced wind speed during spring. The significant decreasing trends in PM concentrations in UB during colder months likely indicate improvements in emission control measures and a transition to more efficient heating practices. In contrast, a significant increasing trend is observed at DZ, particularly during winter (Q1), suggesting rising emissions potentially associated with urbanized household practices and other local activities in Mongolia's regional towns.

ratio in spring when dust

Dust particles are emitted from the surface to the atmosphere when wind speed on the surface (i.e., friction velocity) u* exceeds a threshold value u*t, which is determined from soil particle size* *and land surface conditions (Shao 2008). In the case of Asian dust, u*t is controlled by a number of land surface parameters such as snow cover, soil moisture, soil crust, soil freezing, and vegetation (Kurosaki et al. 2011), reflecting the location of its source regions (mainly the Gobi and Taklimakan Deserts) at middle latitudes and high altitudes.

Conclusions

Arctic oscillation, the atmospheric system most influenced by global warming, triggers Arctic-Asian Dust with its potential phase changes (). Understanding how Arctic oscillation may interact with variability of concentrations in particulate matter (PM) in colder regions will contribute to the comprehension of these climate-teleconnection systems and their anthropogenic feedback mechanisms. Assessments of how aerosol fractions in the Gobi dust source region are affected by anthropogenic factors will provide better predictions of dust-aerosols and facilitate the reduction of household emissions under future climate scenarios. This information becomes increasingly significant if the negative phase of arctic oscillation intensifies and subsequent cold intensity and frequency increase with global climate change, as some models predict (....). In addition to changes in aerosol fraction, a warming climate will be driven by it as a key factor influencing the Earth's radiative energy balance.

In general, aerosols increase the outgoing solar radiation at the top of the atmosphere (TOA) through reflection, thus producing a planetary cooling effect. However, aerosols can also produce a warming effect due to increased reflected radiation from the surface, which enhances the aerosols' absorption. Recent shifts in surface types and their corresponding fine particulates, driven by both human activities and natural processes, raise a pivotal and yet unresolved question: How do these alterations impact the radiation budget of the Earth?

This research provides crucial insights into the complex interplay between Arctic oscillation, aerosol fractions, and climate change in Mongolia's Gobi Desert region. By analyzing long-term datasets of PM10 and PM2.5 concentrations, we have uncovered distinct spatio-temporal patterns and trends in aerosol fractions, revealing the significant impact of both natural processes and human activities on air quality and climate dynamics.

Our findings demonstrate that the fine-to-coarse aerosol ratio has increased in the Gobi region, particularly during spring, suggesting a shift in aerosol composition towards finer particles. This change is likely driven by anthropogenic activities, especially winter heating, which contributes to the accumulation of fine pollutants in the atmosphere. The persistence of these pollutants through spring, combined with natural dust emissions, indicates a fundamental alteration in the aerosol profile of Mongolian Gobi dust.

These changes in aerosol composition have significant implications for regional and global climate systems. While aerosols have traditionally been associated with planetary cooling through increased reflection of solar radiation, our research highlights the growing importance of fine aerosol fractions in contributing to warming effects. This shift challenges existing assumptions about aerosol-climate interactions and underscores the need for more nuanced climate models that account for these complex dynamics.

The study also emphasizes the critical role of human activities in shaping regional air quality and climate patterns. The observed increase in PM2.5 concentrations in Gobi towns, particularly associated with winter heating, illustrates the tangible impact of anthropogenic emissions on local environments. This finding underscores the importance of targeted interventions to reduce household emissions, especially during winter months, as a means of mitigating both local air quality issues and broader climate impacts.

Our research opens up several avenues for future investigation, including the study of winter pollutant behavior during spring thawing, the transformation of black carbon during deposition and transportation, and the broader environmental implications of changing aerosol fractions. Additionally, the potential consequences of continued coal use and population growth on PM2.5 levels and global climate systems warrant further examination.

In conclusion, this study contributes significantly to our understanding of the complex relationships between aerosols, atmospheric systems, and climate dynamics in the Gobi Desert region. By bridging critical knowledge gaps and providing evidence of changing aerosol compositions and their impacts, our findings offer valuable insights for refining climate models, informing policy decisions, and developing strategies to mitigate the effects of climate change. As we continue to grapple with the challenges of a changing climate, research such as this will be instrumental in guiding our efforts to create a more sustainable and resilient future.

The present study will contribute significantly to the understanding of air particulate matter patterns in Mongolia and providing comprehensive data insights for policymakers and public health sectors. Our findings is useful not only for addressing national health impacts but also beneficial for understanding air particulate matter as ambient air pollution, and tackling atmospheric aerosol effects in the climate system, and revealing their transboundary effects to the downwind regions in South-east Asia.

2. Summarize the main findings Novel conclusions: that change/advance our understanding of the field
3. Interpret the results within a broader context

In this study, Spatio-temporal distinct patterns in variations of PM_{10} and $PM_{2.5}$ relative to the recent drivings of emission sources in Mongolia we investigated the temporal variations of PM2.5 and PM10 concentrations at the 4 sites of rural and urban those located along the the wind corridor.

Air particulate matter concentrations in urban-town sites of UB and DZ is episodically dictated by dust events in spring or late autumn, yet seasonally governed by anthropogenic emissions in winter. Air particulate matter concentrations in rural sites of SS and ZU is episodically dictated by dust events in spring or late autumn. Air quality in urban sites is episodically dictated by dust events in spring or late autumn, yet seasonally governed by anthropogenic emissions in winter. [Air quality is governed by natural dust emission, and anthropogenic emissions]

Three distinct variations has been detected. 1. A new pattern is emerged It is evident of the new emission patterns in Mongolia. With recent growing interest in urban life style, and combustion of coal/oyutolgoi for heating winter conditions results a highly increase in not only capital city but also towns

In a result, spring coarse dust, plus winter fine pollutants Related to the winter emission patterns, fine particulates fraction in the spring is increased. r ratio shows . . . emission source; dust might carry anthropogenic fine particulates as well. [spring coarse dust is immediately transported and deposited in the source area, whereas winter fine pollutants is permanently stayed in the source area due to stagnant atmosphere govern over entire country., perhaps floating in the near surface, deposits in the surface] We found spring fine to coarse fraction has increased in a Gobi town, suggesting winter fine pollutants is permanently stayed in the source area due to stagnant atmosphere might related to AO, is emitted in the spring with the dust. This indicates the Mongolian Gobi dust aerosol fractions has changed with a more fine pollutants, so has an aerosol radiation effects.

- Alarms, the Mongolian dust in the spring, optical properties will be shifted; this gives . . . Gobi dust and sand storms has become tuiren, from the shoroon shuurga. which clearly requires the attention. Main conclusion 1: A distinct pattern is emerged as a . . . Main conclusion 2: Trends in atmospheric fine particulate concentrations since 2008 were driven and modified by anthropogenic emissions in DZ Main conclusion 3: Trends in fine to coarse fraction is increased in the spring in DZ Main conclusion 4: WS is decreased; with the wind speed up to. . . Main conclusion 5: Such changes is local. Main conclusion 6: Our study highlighted the attribute of Gobi dust as a cold desert, with the anthropogenic impact.

4. Point limitations/alternate interpretations

5. Describe implications for other systems

6. List practical applications National level; meteorological impact is large. . . . However, reduced. . . On the other hand, it is . . . with the towns. This points that air quality will be poor whether it is changed fuel, .. unless to change heating system. Therefore, it is not the reason to move the capital city. Only solution is to change the heating system, do not burn any type of the coal.

7. Suggest areas for future research

- Winter pollutants state in the land surface go under chemical reaction as soil thawing process in the spring or invoke the airborne infection?
- black carbon, has a death records. In winter, it has detrimental effects on local; in spring, it will bring the effect on the downwind regions. More dangerously, how much it changed its initial form during the depositions and transportation period. More, research has focused on the direct emission of black carbon to the atmosphere. However, it is not clear the changed form of black carbon on its properties, and chemical compositions so on.
- Other environmental problems?
- If continued use of coal, with the population increase result the more and more pm2.5, and affect Climate system.

The findings not only contribute to our understanding of the climate impacts of aerosol and surface albedo, but also emphasize the importance of integrating these factors into climate models and strategies aimed at mitigating climate change.

Study materials and Methods

A description of study sites

Mongolia's diverse geography and climatic conditions provide a unique backdrop for understanding particulate matter pollution and its impacts. This study focuses on four distinct locations across the country, selected to represent varying urban and desert environments with different elevations and climatic conditions.

Ulaanbaatar (47.92řN, 106.92řE): The capital city, situated at an elevation of 1350 m, characterized by high urban activity and associated air pollution.

Dalanzadgad (43.57řN, 104.42řE): A Gobi Desert town at an elevation of 1470 m, representing arid and sparsely populated areas.

Sainshand (44.87řN, 110.12řE): Located at an elevation of 947 m, featuring semi-arid conditions.

Zamyn Uud (43.72řN, 111.90řE): A border town at 967 m elevation, characterized by cross-border trade activities.

Table 1 summarizes the geographical coordinates, elevations, and relevant site characteristics, while Figure 1 provides a spatial representation of the locations. These sites capture a wide spectrum of environmental conditions, facilitating a comprehensive assessment of particulate matter pollution.

Data

Data Collection

Particulate matter with aerodynamic diameters less than 2.5 (PM2.5) and 10 micrometers (PM10) were measured at these sites using an instrument that measures light scattering by air-borne particulates. Meteorological parameters, including wind speed, wind direction and visibility were determined by automatic instruments and are detailed in previous articles (Jugder et al., 2011, 2012; Nishikawa, Sugimoto). The instruments for measuring particulate matters were placed 2 m above the ground level (AGL) at Dalanzadgad, Sainshand and Zamyn-Uud (Table 2.1). Wind sensors and visibility (meteorological optical range-MOR) sensors with a maximum measurement range of 20 km were installed at a height of 3 m AGL at the three Gobi sites. At the Ulaanbaatar site, the wind sensor height and a visibility sensor was placed at 15 m AGL. Datasets were obtained from measurements at Dalanzadgad, Sainshand, and Zamyn-Uud from January 2009 to May 2018, and at Ulaanbaatar from the end of April 2008 to May 2020.

To improve the data quality, we removed spikes exceeding above 7 gm^3 considering the reported extreme values (XXXXX Jugder, XXXX Tsatsral), unrealistic PM2.5 values exceed PM10 (pm2.5 > pm10 *1.1) and detected signals that invariate with an extended period caused by electricity shortage and equipment malfunctions for all sites. Further, we handled data each stations separately to remove suspective data, carefully. For example, In Sainshand station, ... was ... Prior to data quality improvement, there were missing data with percentages ranged from 10.3% to 23.6%, attributed to equipment malfunctions or adverse weather conditions. Ulaanbaatar demonstrated the highest data completeness for both PM2.5 (88.6%) and PM10 (89.7%), whereas Dalanzadgad recorded the lowest (PM2.5: 76.4%; PM10: 81.5%)(Table 1). After data quality improvement, missing data percentages has increased by XXXXXX. [Due to electricity shortage and equipment malfunctions contributed to the bad data, and missing data....]

The data used in the study are based on hourly means derived from 1 and 10 min averages. For trend analysis, we added the data derived after data filling with the procedure, detailed in the next section.

Data filling Missing data handling with the statistical packages At last, we filled the missing data with 3-hour maxgaps with imputeTS package for univariate time series, and larger gaps using mtsdi R package (well-used for time-series data), and improved the missing data percents by... from ... to ... Additionally, meteorological parameters such as wind speed, direction, and visibility are integrated into the analysis to elucidate their impact on PM levels.

The MTSDI method (Junger, Santos, and Ponce de Leon (2003), Junger and Leon (2012)) uses the EM algorithm with the Autoregressive Integrated Moving Average (ARIMA) method, also known as Box–Jenkins model (Box et al. (2015), Meyler, Kenny, and Quinn (1998)). The data provided by ARIMA (p, d, q) depend on the number of autoregressive terms (p), the number of differences (d), and the number of terms in the moving average (q) (Meyler, Kenny, and Quinn (1998)). Default configuration was used. The mtdsi method is widely used to impute missing data like in cosmic data Fernandes, Lucio, and Fernandez (2017). Similar multiple imputation methods have been applied for multivariate solar data Zhang et al. (2020), highly univariate seasonal data even with the large amount of missing data Chaudhry et al. (2019), missin data imputation and modeling for leaching processes He et al. (2017). Recently, Motesaddi Zarandi et al. (2022b) used the mtdsi method to imputing missing data air pollution in Tehran (We used the complete data of temperature (řC), relative humidity (RH) (%), wind speed (m/s), barometric pressure (BP) (mbar), PM10, PM2.5, NO2, CO, and CVD variables to impute SO2 and O3 with the mtdsi R package.).

Spatial Representation Figure 1 illustrates the geographical distribution of study sites and the locations of meteorological stations. The visual contrast between urban (e.g., Ulaanbaatar) and desert (e.g., Dalanzadgad) environments underscores the spatial variability in air quality measurements across Mongolia.

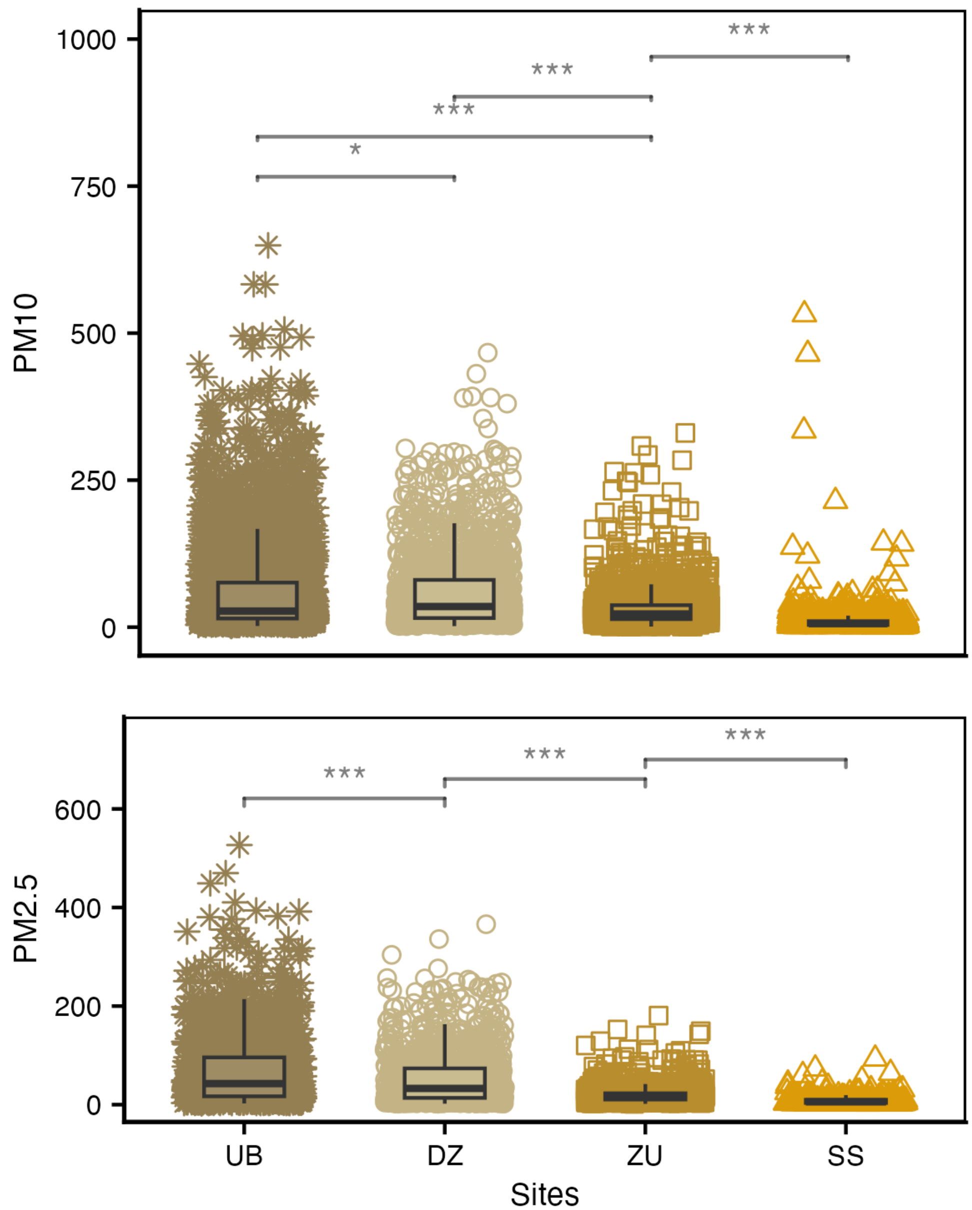


Figure 1: Distinct concentrations of coarse and fine particulates among sites

1. Compare the concentrations of PMs at UB is the 2. Significance level difference 3. Conclude

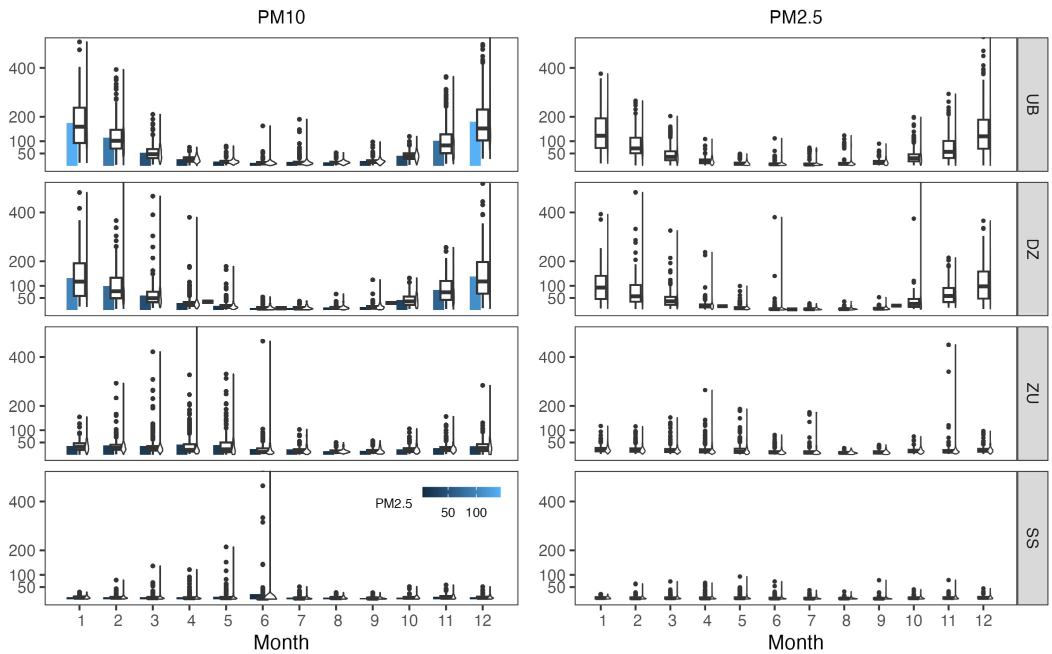


Figure 2: Annual variations of PM_{10} and $PM_{2.5}$

1. Clear annual variations at UB and DZ from pm2.5 pollutions 2. at ZU, and SS has a seasonally peaks episodic spring and late autumn from PM10

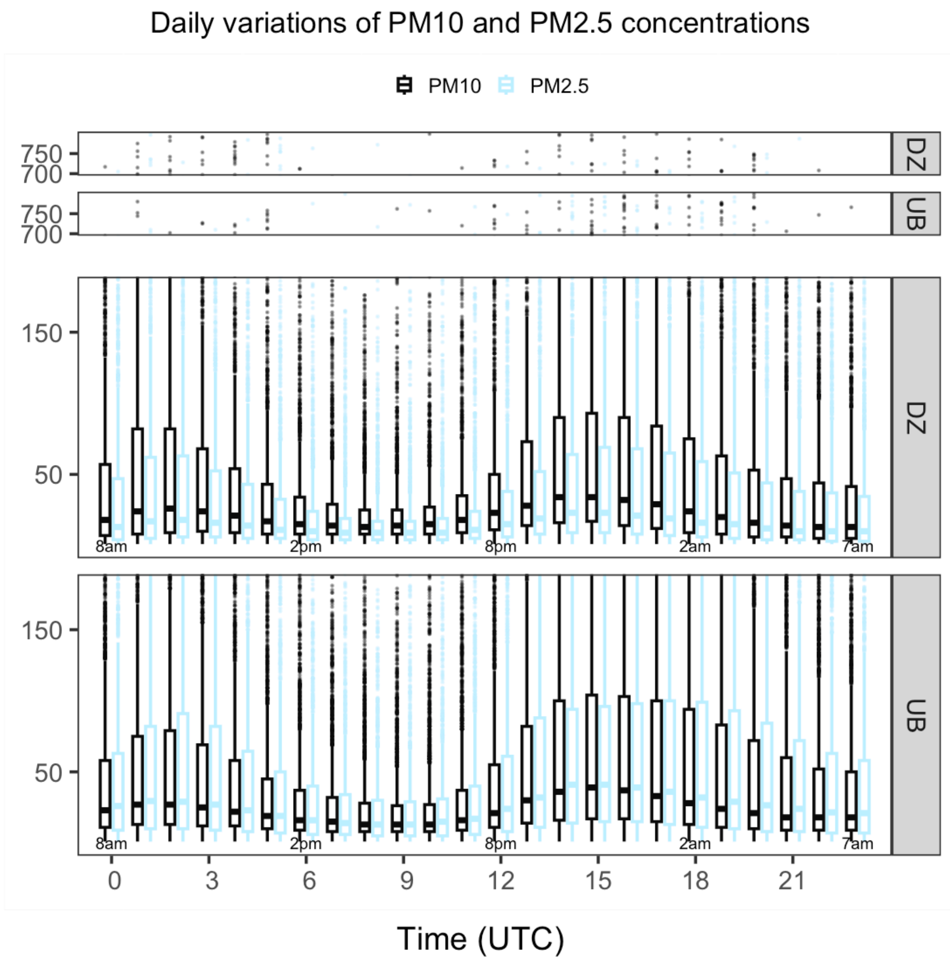


Figure 3: Daily variations of PM_{10} and $PM_{2.5}$ at UB and DZ sites

Meteorological influence on PM_{10} and $PM_{2.5}$ variations

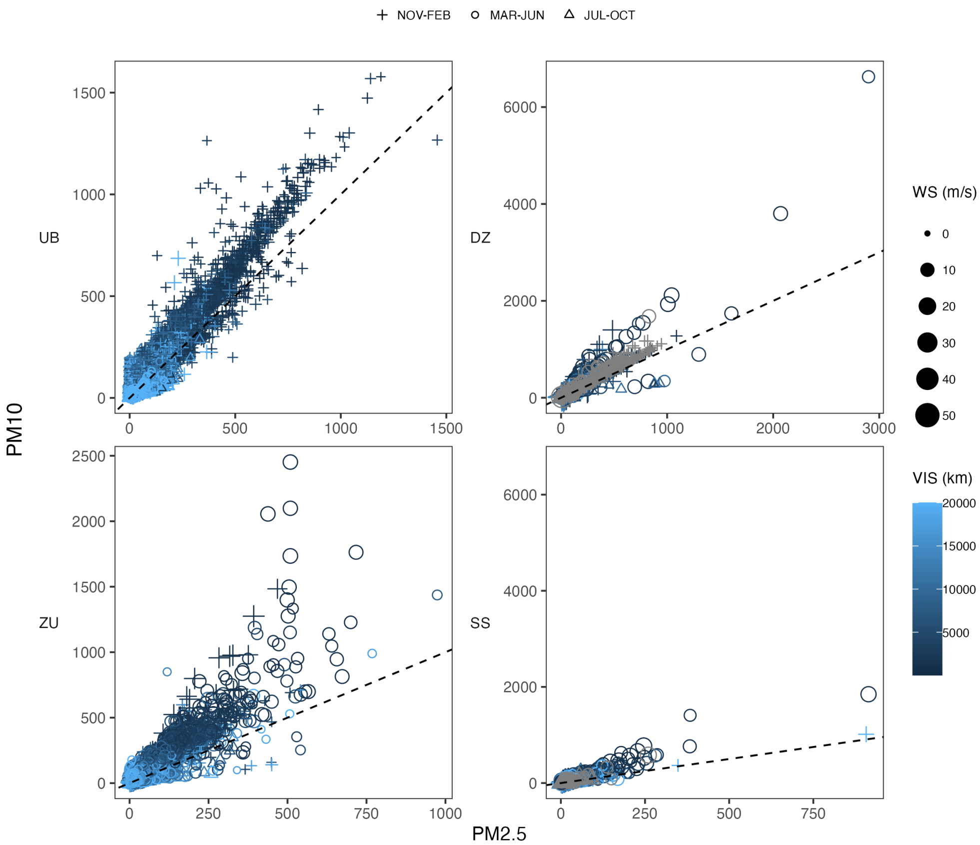


Figure 4: Relationships between meteorological major factors and variations of PM_{10} and $PM_{2.5}$

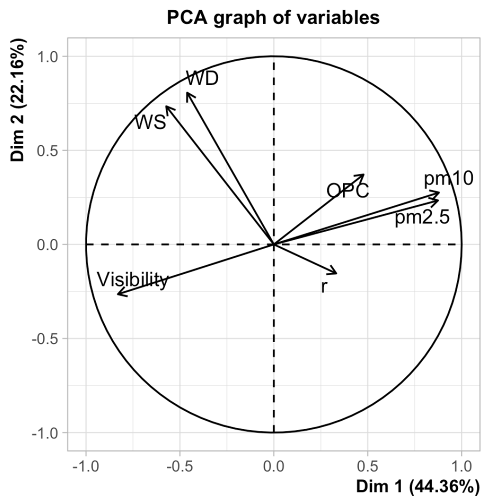


Figure 5: Spatio-temporal distinct feature of variations of PM_{10} and $PM_{2.5}$ with PCA analysis

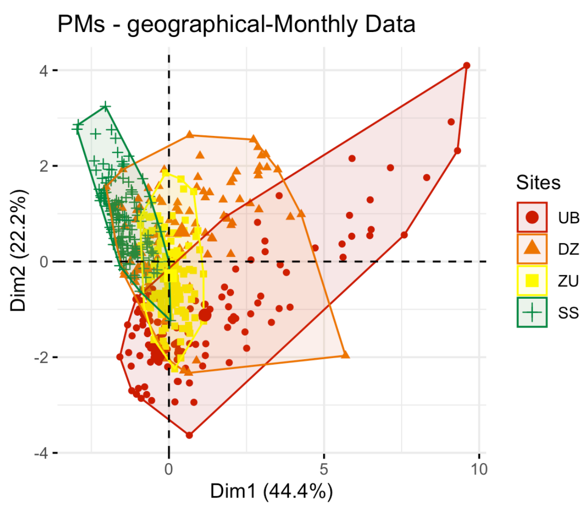
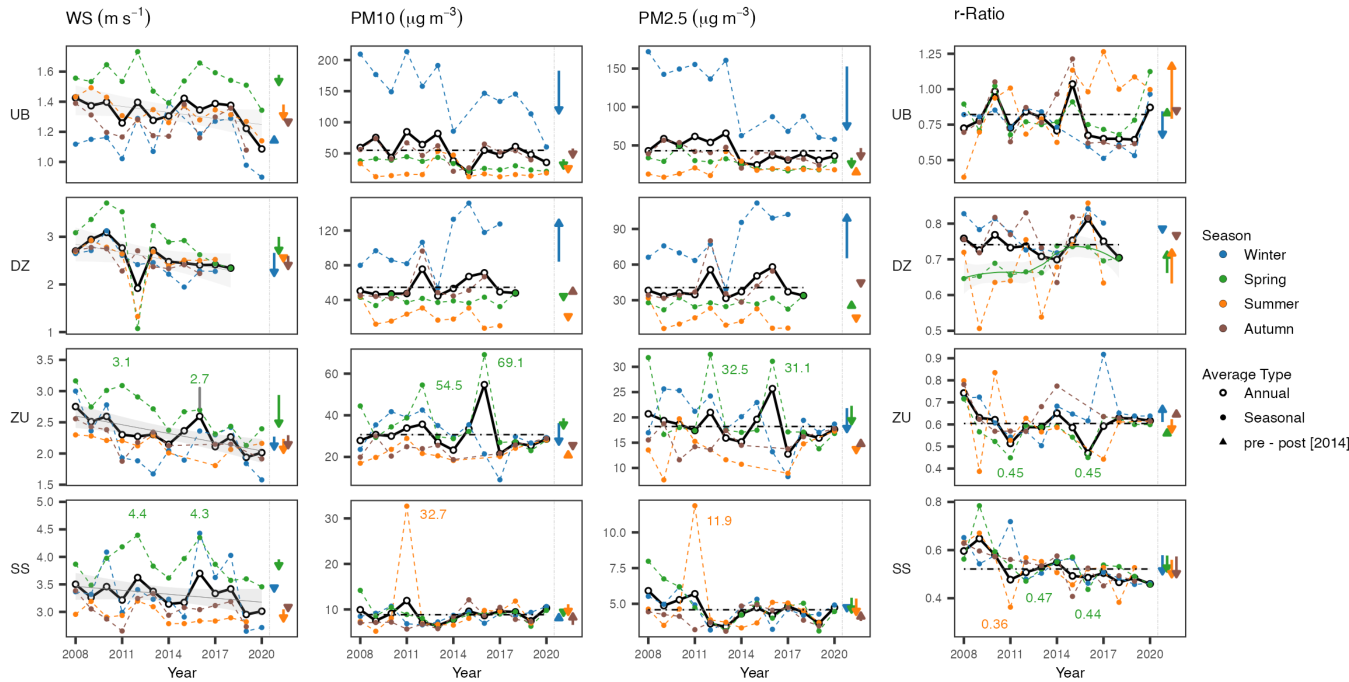
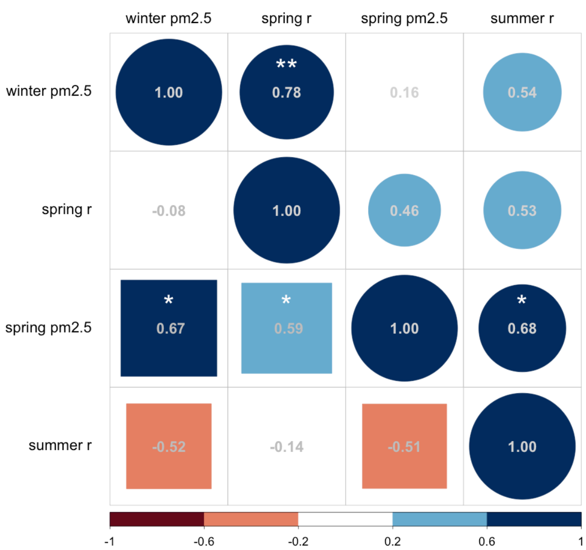


Figure 6: Patterns of meteorology and PMs at the 4 sites

Trends

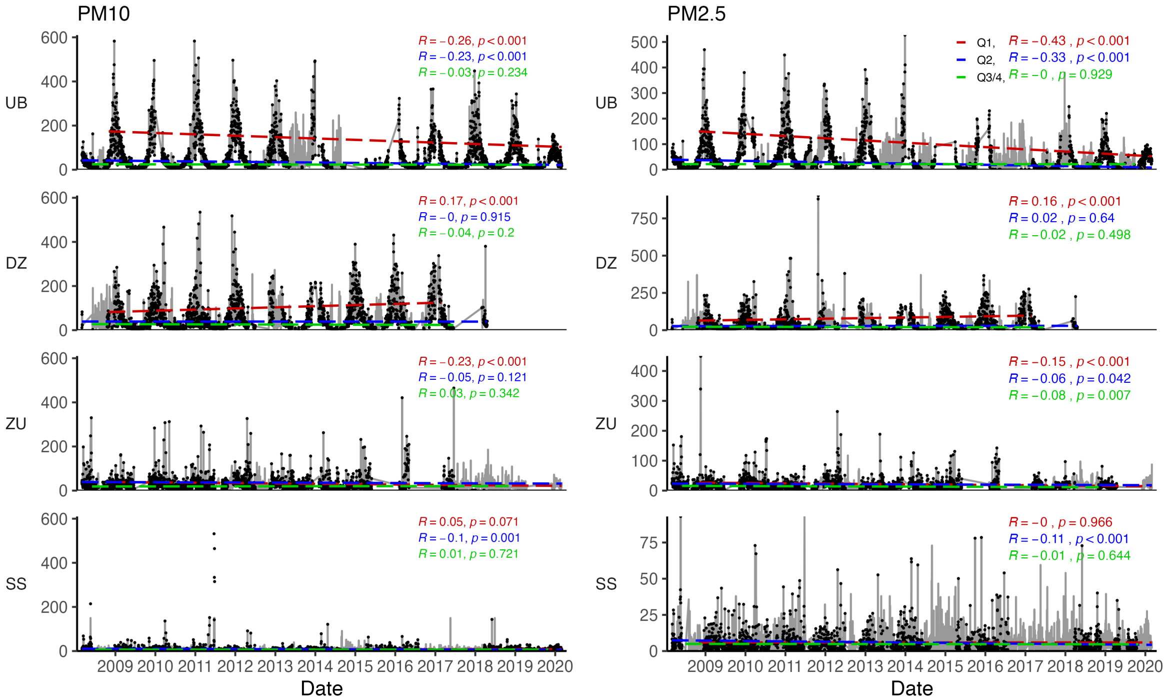


WS (m s^{-1})
PM10 (μg m^{-3})
PM2.5 (μg m^{-3})
r-Ratio
UB
DZ
ZU
SS
Year
Season
Winter
Spring
Summer
Autumn
Average Type
Annual
Seasonal
pre - post [2014]



winter pm2.5
spring r
spring pm2.5
summer r

422




winter pm2.5
spring pm2.5
spring r
summer r
Corr: 0.571**
UB: 0.665*
DZ: 0.156
Corr: 0.151
UB: -0.084
DZ: 0.783**
Corr: 0.546**
UB: 0.586*
DZ: 0.464
Corr: -0.105
UB: -0.519.
DZ: 0.541
Corr: -0.313
UB: -0.512.
DZ: 0.676*
Corr: 0.125
UB: -0.140
DZ: 0.533
winter pm2.5
spring pm2.5
spring r
summer r

423

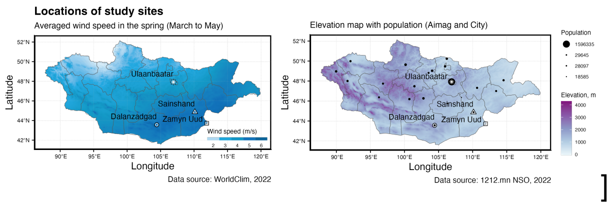


Table 1. Measured data

	Location		Measured and collected data						Missing data	
SITE	COORDINATE	ELEVATION	TOTAL[1]	WS&WD[2]	VIS[3]	OPC[4]	PM2.5[5]	PM10[5]	PM2.5	PM10
Ulaanbaatar	47.92°N, 106.92°E	1350 m	76656	72603	72886	33241	67940	68777	11.4%	10.3%
Dalanzadgad	43.57°N, 104.42°E	1470 m	60336	46332	33812	-	46066	49172	23.6%	18.5%
Sainshand	44.87°N, 110.12°E	947 m	59040	50513	49720	-	47111	47313	20.2%	19.9%
Zamyn Uud	43.72°N, 111.90°E	967 m	67392	62432	63948	-	57317	58512	14.9%	13.2%

[1] Equipment height: 15 meter at urban site (Ulaanbaatar), 2 meter at Gobi sites (Dalanzadgad, Sainshand and Zamyn Uud); [2] Measurement range: 0–60 m/s; 0-365 degrees. Instrument model: Wind speed and direction PGWS-100, Gill, England; [3] Range: 10–20 000 m. Visibility meter PWD10, Vaisala, Finland; [4] Optical Particle Counter; [5] Range: 0.003–100 mg/m3, Flow rate: 20 L/m, Suction rate: 2 L/ m. Measured by Kosa monitor ES-640, TDK Co. LTD, Japan;

Figure 7: **Table 1.** A description of datasets obtained at the sites

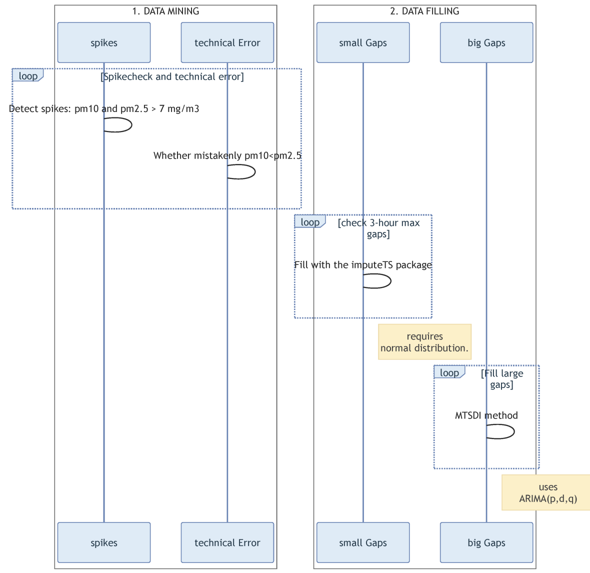


Figure 8: Scheme 1. Data handling procedure

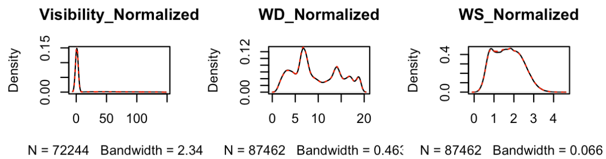


Figure 9: Figure 2. Data gap filling

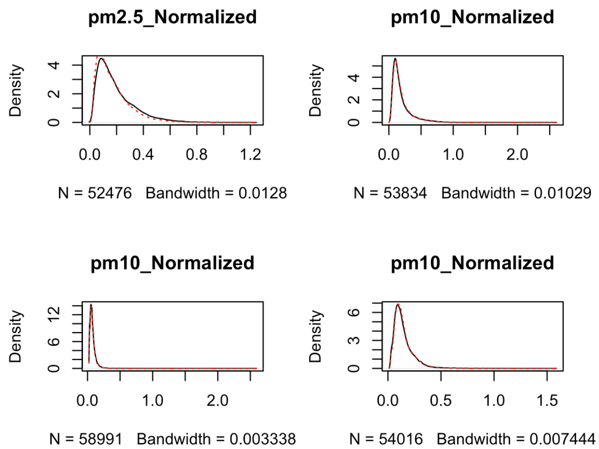


Figure 10: Figure 2b. Data gap filling

(1)

References

1. **Munkhtsetseg E**, **Shinoda M**, **Ishizuka M**, **Mikami M**, **Kimura R**, **Nikolich G**. 2017. Anthropogenic dust emissions due to livestock trampling in a mongolian temperate grassland. Atmospheric Chemistry and Physics **17**:11389–11401. doi:10.5194/acp-17-11389-2017.