

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 tidyverse  1.3.1
## v purrr     1.0.2
## -- Conflicts ----- tidyverse_conflicts() --
## x dplyr::filter() masks stats::filter()
## x dplyr::lag()    masks stats::lag()
## i Use the conflicted package (<http://conflicted.r-lib.org/>) to force all conflicts to beco
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1 Plain text summary Driven by industrial progress in the mining sector, household coal combustion
2 has increased significantly in Mongolia since the 2000s. Demographic evidence has revealed an
3 ongoing reduction in rural-nomadic lifestyle and a rise in urban population, which may gradually
4 extend household winter heating as a major source of fine particulate matter (PM2.5). In
5 conjunction with a stagnant atmosphere and observations that winter fine pollutants (PM2.5 and
6 PM10) are persistently trapped within the boundary layer and can be exacerbated by stagnant
7 weather or emission sources, these results have led to hypotheses that fine aerosols may be
8 subject to suspension in the near-surface atmosphere, potentially available for emission via
9 dust storms in the spring. Here, through the analysis of long-term datasets, we demonstrate
10 distinct spatio-temporal patterns in variations of PM10 and PM2.5 relative to recent drivers of
11 emission sources in Mongolia, and that the concentration of PM2.5 in a Gobi town has increased
12 in association with winter heating. Furthermore, the ratio of fine to coarse aerosols indicates that
13 the fine fraction in the spring has increased despite decreased wind speeds. Our results strongly
14 suggest that the aerosol fraction has undergone changes at the local-level, and is subject to both
15 natural and anthropogenic constraints.

16 **Abstract (150 words: 200, cut 50 words)**

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

24 **Introduction /Why you should care/**

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

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

43 There has been a [tremendous improvement] in the understanding of atmospheric aerosols
44 and their climate effect over the last decades, with some important observational and modelling
45 breakthroughs. Long-term measurements of aerosols (e.g., Nishikawa et al. 2010, Andrews et
46 al. 2011), observational campaigns (e.g., Shinoda, Park, chinse), and lidar (Holben et al. 1998,
47 Remer et al. 2008), and bioaerosol (dd), health (ff) have remarkably increased knowledge
48 about the composition and characteristics of atmospheric aerosols. dust brown color, seasonal
49 characteristics, with coarse fractions. Gobi Desert dust typically has a shorter atmospheric
50 residence time (1.5 days) tends to remain at lower altitudes, (Tanaka, 2012) During dust storms,
51 PM_{2.5} and PM₁₀ concentrations can surge to 343 and 1.642 gm^3 , respectively (Filonchyk et al.,

52 2021). Regarding aerosol fractions, PM2.5 and PM10 concentrations in the Gobi Desert area
53 were found to be 36.2 ± 23.7 and $97.3 \pm 84.5 \text{ gm}^3$, respectively (Filonchyk et al., 2021). Clean
54 continental aerosol type is predominant (73.9 percent), followed by mixed aerosols (20.4 percent),
55 with minor contributions from clean marine, urban/industrial, biomass burning, and desert dust
56 aerosol types. During dust storms, PM2.5 and PM10 concentrations can surge to 343 and 1.642 gm^3 ,
57 respectively (Filonchyk et al., 2021) Gobi Desert is known for its high dust storm frequency
58 and substantial dust emissions, precise quantification of its contribution to the global dust budget
59 is challenging. Nevertheless, the land surface parameters governing Asian dust emissions exhibit
60 substantial seasonal and inter-annual variations and complex interactions, leading to significant
61 uncertainties in simulating them for Asian dust (Kawai Sola 2021).

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

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

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

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

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

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

103 **Research Qs**

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

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

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

114 • If yes, how much, and when and where?

115 • What is the sd, mean, and median

116 – box plot

117 – violin

118 – scatter points, epidemic, sporadic

119 • Daily variations to examine it related to the heating

120 – 2 peaks: smaller and bigger

121 – compare the t-duration exceeds $50 \text{ mug/m}^3/\text{hour}$

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

123 • How PMs varies with the wind speed and visibility

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

125 5. Is there any significant changes in time-series of PMs at 4 seasons

126 6. Is there any significant changes in ratio in the spring in respect to winter pollutions?

127 **Results**

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

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

144 To investigate whether emerging PM patterns are associated with household winter heating
145 activities, we demonstrated annual variations in PM10 and PM2.5 concentrations at the sites.

146 Significant annual variations in PM10 and PM2.5 levels were observed at UB and DZ sites,
147 with maximum concentrations exceeding 100 g/m^3 during colder months (January, November,
148 December) and lower levels consistently below 50 g/m^3 during warmer months (May-September).

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

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

173 add table, add r 1.3, 2 on figure_6, add supplement figures

174 To identify the key factors influencing PM emissions, we examined the relationships between wind
175 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 PM_{2.5}, 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 PM_{2.5}, 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 PM_{2.5} particulates in those locations, particularly at the ZU site. It is worth noting that instances where PM_{2.5} 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 PM_{2.5} 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

205 among key variables, including PM10, PM2.5, wind speed (WS), wind direction (WD), visibility,
206 ratio of PM2.5 to PM10 (r), and numbers of aerosols by optical particle counter (OPC). The first
207 two principal components (Dim 1 and Dim 2) explain 66.52% of the total variance, with Dim 1
208 (44.36%) strongly associated with PM10 and PM2.5. Wind speed and wind direction are positively
209 aligned with Dim 2 (22.16%), reflecting their influence on pollutant dispersion.

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

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

212 Figure 8 illustrates the trend analysis of PM10 and PM2.5 concentrations across study sites from
213 2009 to 2020. The time series demonstrates seasonal patterns and trends, with p-values of trend
214 changes, seasonally: winter (Q1), spring (Q2), and summer-autumn (Q3). At UB, significant
215 negative trends both in PM10 and PM2.5 concentrations are observed for winter and spring (Q1
216 and Q2, $p < 0.001$). At DZ, a significant positive trend in PM10 and PM2.5 concentrations is
217 observed for winter (Q1, $p < 0.001$), indicating increasing particulate matter levels during this
218 season. At ZU, a significant negative trend is observed in both PM10 and PM2.5 for winter
219 (Q1, $p < 0.001$), suggesting a consistent reduction in particulate matter during winter months
220 (may reduced transboundary traffic associated with covid periods, resulted in declined PM10
221 concentrations; or data gaps). At SS, a negative trend is observed in PM2.5 for spring (Q2, p
222 < 0.001), reflecting a seasonal decline potentially linked to reduced wind speed during spring.
223 The significant decreasing trends in PM concentrations in UB during colder months likely indicate
224 improvements in emission control measures and a transition to more efficient heating practices.
225 In contrast, a significant increasing trend is observed at DZ, particularly during winter (Q1),
226 suggesting rising emissions potentially associated with urbanized household practices and other
227 local activities in Mongolia's regional towns.

228 ratio in spring when dust

229 Dust particles are emitted from the surface to the atmosphere when wind speed on the surface
230 (i.e., friction velocity) u^* exceeds a threshold value u_t , which is determined from soil particle size

231 and land surface conditions (Shao 2008). In the case of Asian dust, it is controlled by a number of
232 land surface parameters such as snow cover, soil moisture, soil crust, soil freezing, and vegetation
233 (Kurosaki et al. 2011), reflecting the location of its source regions (mainly the Gobi and Taklimakan
234 Deserts) at middle latitudes and high altitudes.

235 **Conclusions**

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

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

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

257 human activities on air quality and climate dynamics.

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

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

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

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

281 In conclusion, this study contributes significantly to our understanding of the complex relationships
282 between aerosols, atmospheric systems, and climate dynamics in the Gobi Desert region. By
283 bridging critical knowledge gaps and providing evidence of changing aerosol compositions and

284 their impacts, our findings offer valuable insights for refining climate models, informing policy
285 decisions, and developing strategies to mitigate the effects of climate change. As we continue
286 to grapple with the challenges of a changing climate, research such as this will be instrumental in
287 guiding our efforts to create a more sustainable and resilient future.

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

294 2. Summarize the main findings Novel conclusions: that change/advance our understanding of
295 the field

296 3. Interpret the results within a broader context

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

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

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

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

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

328 4. Point limitations/alternate interpretations

329 5. Describe implications for other systems

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

335 7. Suggest areas for future research

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

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

349 **Study materials and Methods**

350 **A description of study sites**

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

355 Ulaanbaatar (47.92°N, 106.92°E): The capital city, situated at an elevation of 1350 m,
356 characterized by high urban activity and associated air pollution.

357 Dalanzadgad (43.57°N, 104.42°E): A Gobi Desert town at an elevation of 1470 m, representing
358 arid and sparsely populated areas.

359 Sainshand (44.87°N, 110.12°E): Located at an elevation of 947 m, featuring semi-arid conditions.

360 Zamyn Uud (43.72°N, 111.90°E): A border town at 967 m elevation, characterized by cross-border
361 trade activities.

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

366 **Data**

367 **Data Collection**

368 Particulate matter with aerodynamic diameters less than 2.5 (PM2.5) and 10 micrometers (PM10)
369 were measured at these sites using an instrument that measures light scattering by air-borne
370 particulates. Meteorological parameters, including wind speed, wind direction and visibility were
371 determined by automatic instruments and are detailed in previous articles (Jugder et al., 2011,

372 2012; Nishikawa, Sugimoto). The instruments for measuring particulate matters were placed 2
373 m above the ground level (AGL) at Dalanzadgad, Sainshand and Zamyn-Uud (Table 2.1). Wind
374 sensors and visibility (meteorological optical range-MOR) sensors with a maximum measurement
375 range of 20 km were installed at a height of 3 m AGL at the three Gobi sites. At the Ulaanbaatar
376 site, the wind sensor height and a visibility sensor was placed at 15 m AGL. Datasets were
377 obtained from measurements at Dalanzadgad, Sainshand, and Zamyn-Uud from January 2009
378 to May 2018, and at Ulaanbaatar from the end of April 2008 to May 2020.

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

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

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

398 The MTSDI method (Junger, Santos, and Ponce de Leon (2003), Junger and Leon (2012)) uses
399 the EM algorithm with the Autoregressive Integrated Moving Average (ARIMA) method, also known

400 as Box–Jenkins model (Box et al. (2015), Meyler, Kenny, and Quinn (1998)). The data provided by
401 ARIMA (p, d, q) depend on the number of autoregressive terms (p), the number of differences (d),
402 and the number of terms in the moving average (q) (Meyler, Kenny, and Quinn (1998)). Default
403 configuration was used. The mtdsi method is widely used to impute missing data like in cosmic
404 data Fernandes, Lucio, and Fernandez (2017). Similar multiple imputation methods have been
405 applied for multivariate solar data Zhang et al. (2020), highly univariate seasonal data even with
406 the large amount of missing data Chaudhry et al. (2019), missin data imputation and modeling
407 for leaching processes He et al. (2017). Recently, Motesaddi Zarandi et al. (2022b) used the
408 mtdsi method to imputing missing data air pollution in Tehran (We used the complete data of
409 temperature (°C), relative humidity (RH) (%), wind speed (m/s), barometric pressure (BP) (mbar),
410 PM10, PM2.5, NO2, CO, and CVD variables to impute SO2 and O3 with the mtdsi R package.).

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

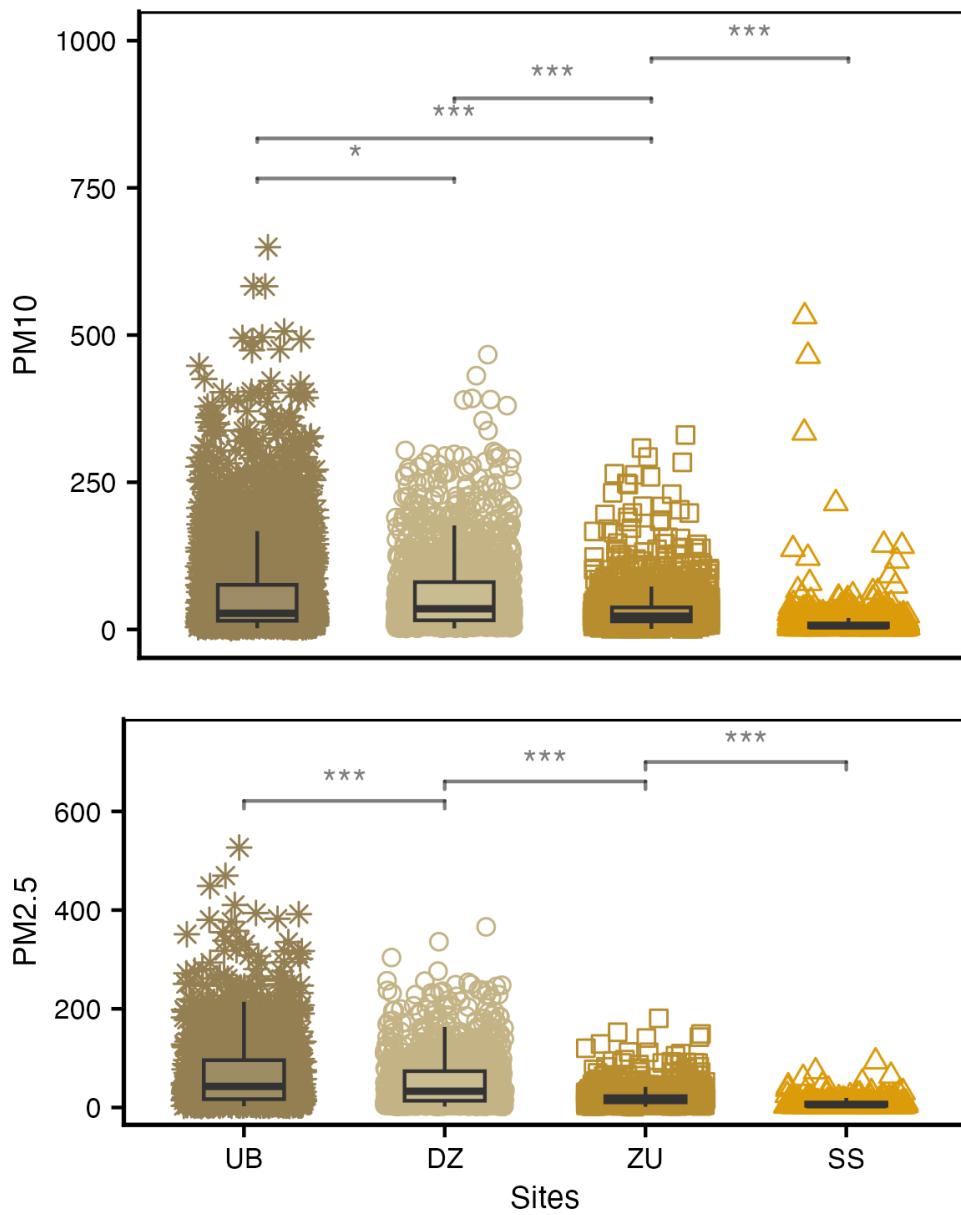


Figure 1: Distinct concentrations of coarse and fine particulates among sites

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

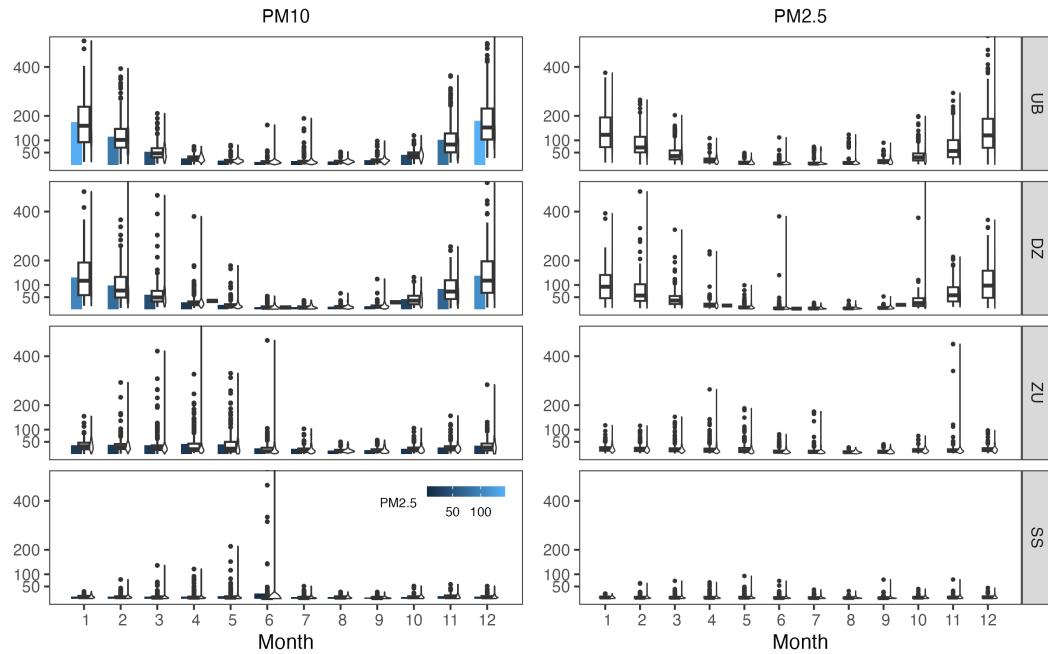


Figure 2: Annual variations of \$PM_{10}\$ and \$PM_{2.5}\$

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

Daily variations of PM₁₀ and PM_{2.5} concentrations

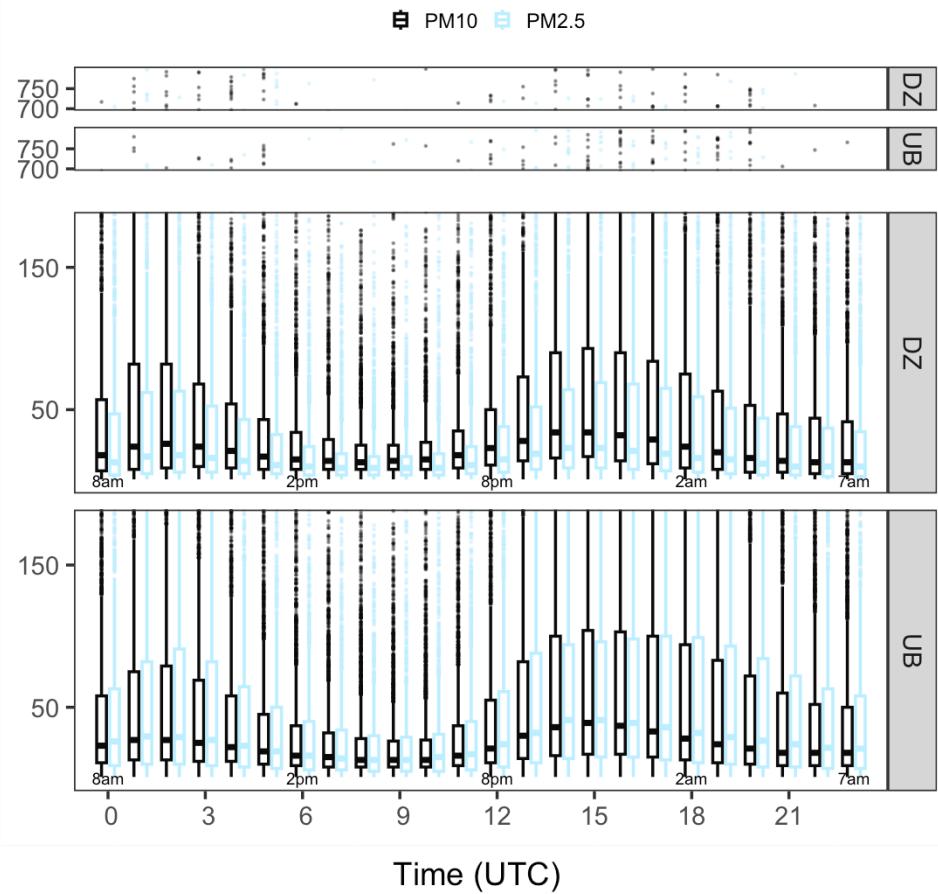


Figure 3: Daily variations of PM₁₀ and PM_{2.5} at UB and DZ sites

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

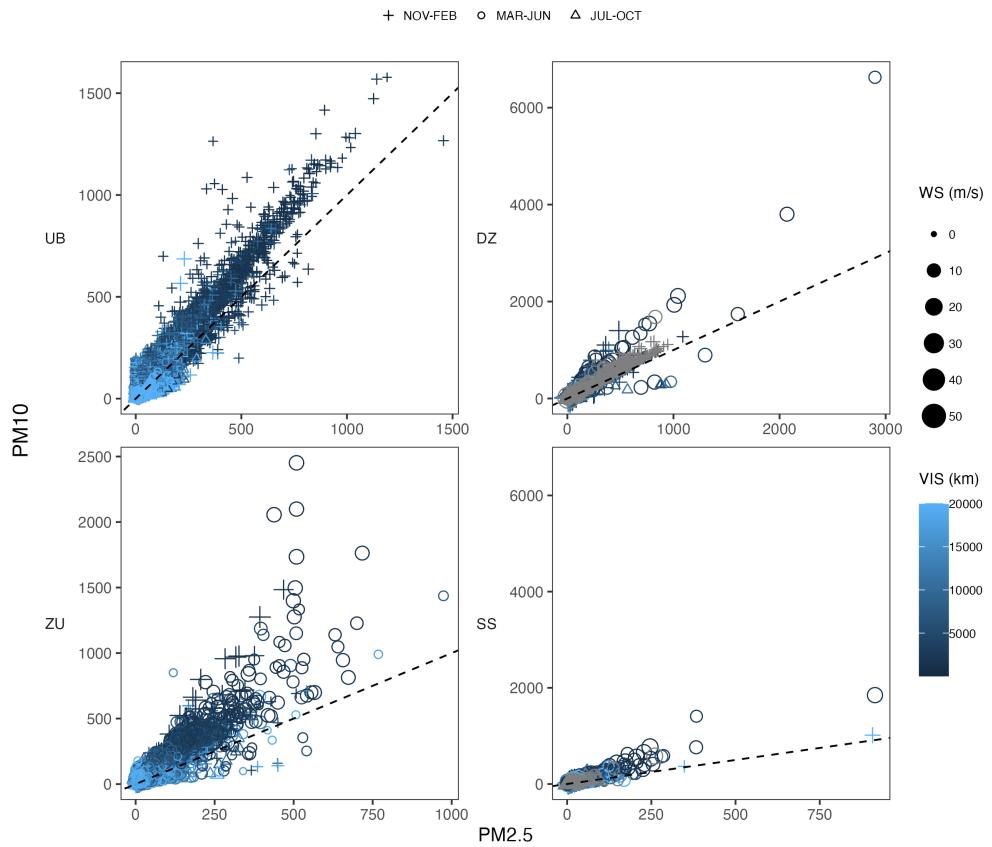


Figure 4: Relationships between meteorological major factors and variations of PM_{10} and $PM_{2.5}$.

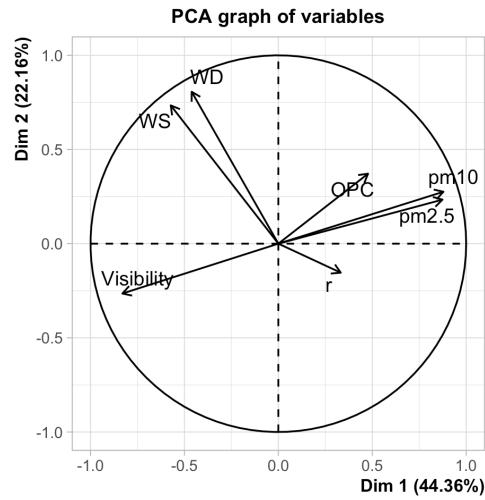


Figure 5: Spatio-temporal distinct feature of variations of PM_{10} and $PM_{2.5}$ with PCA analysis

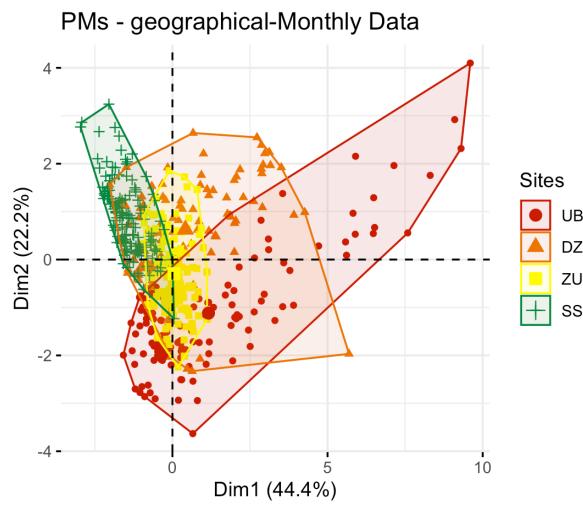
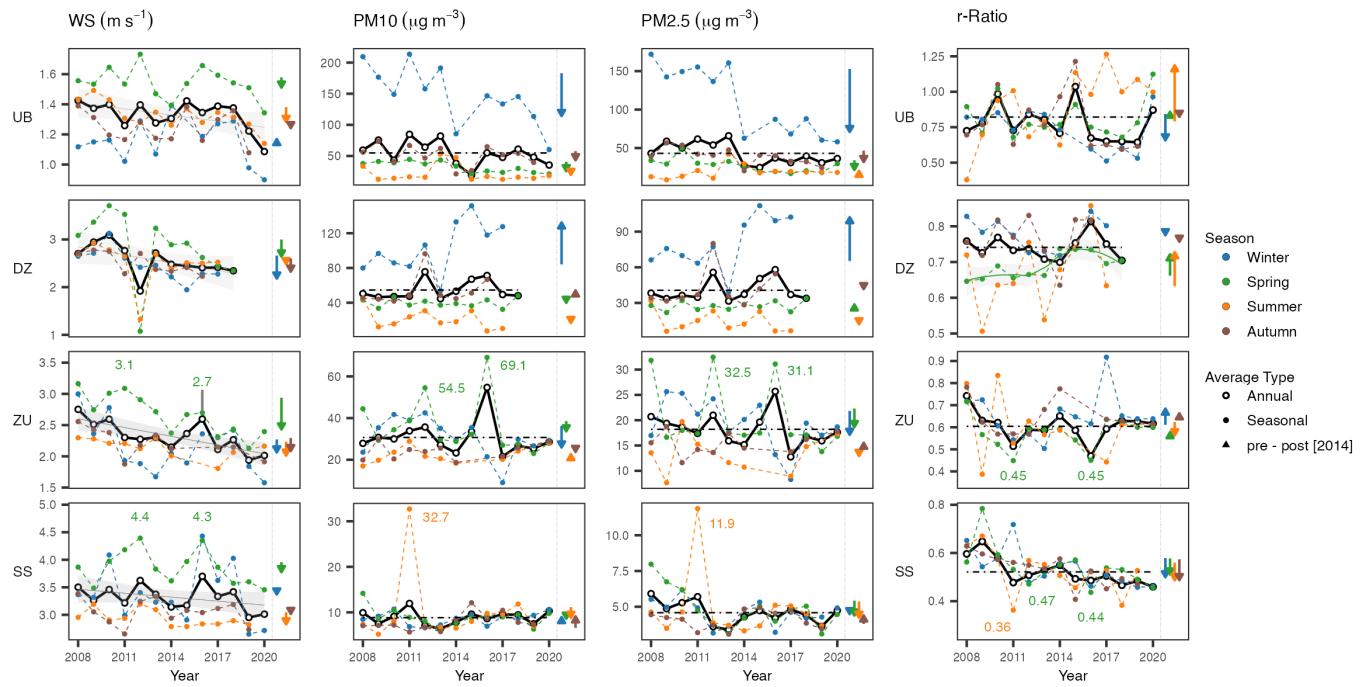
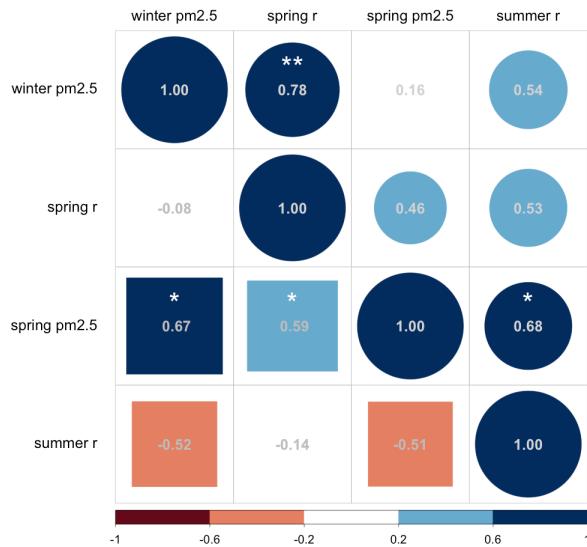


Figure 6: Patterns of meteorology and PMs at the 4 sites

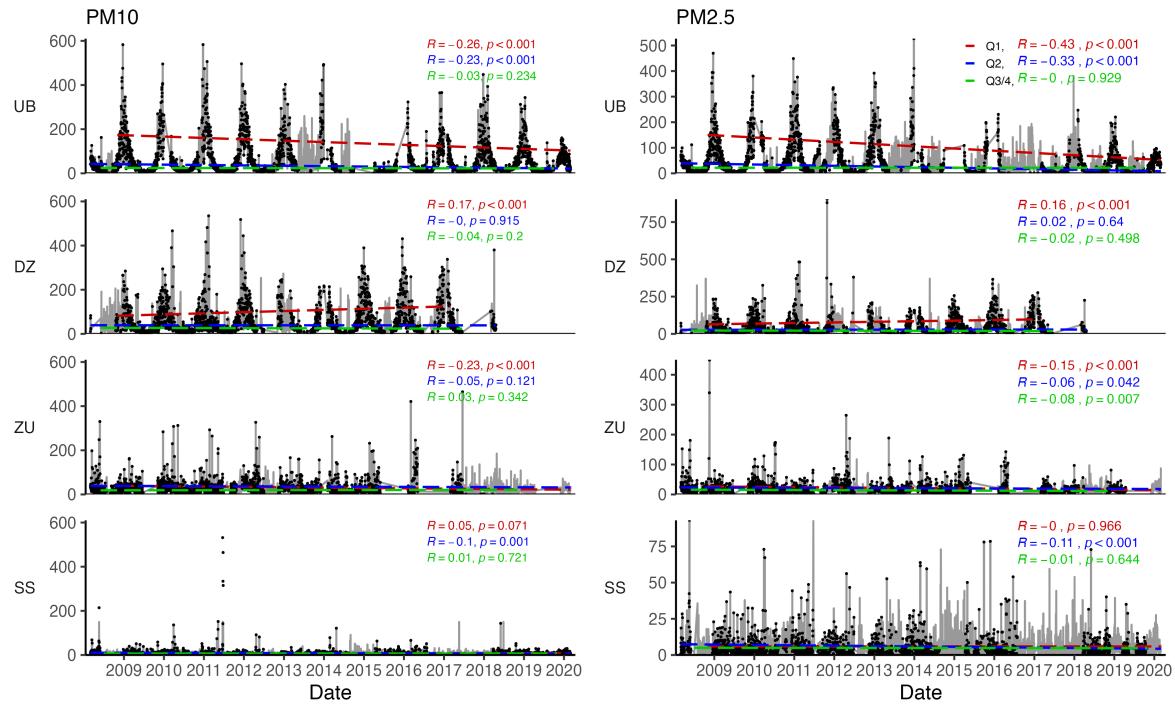
419 Trends



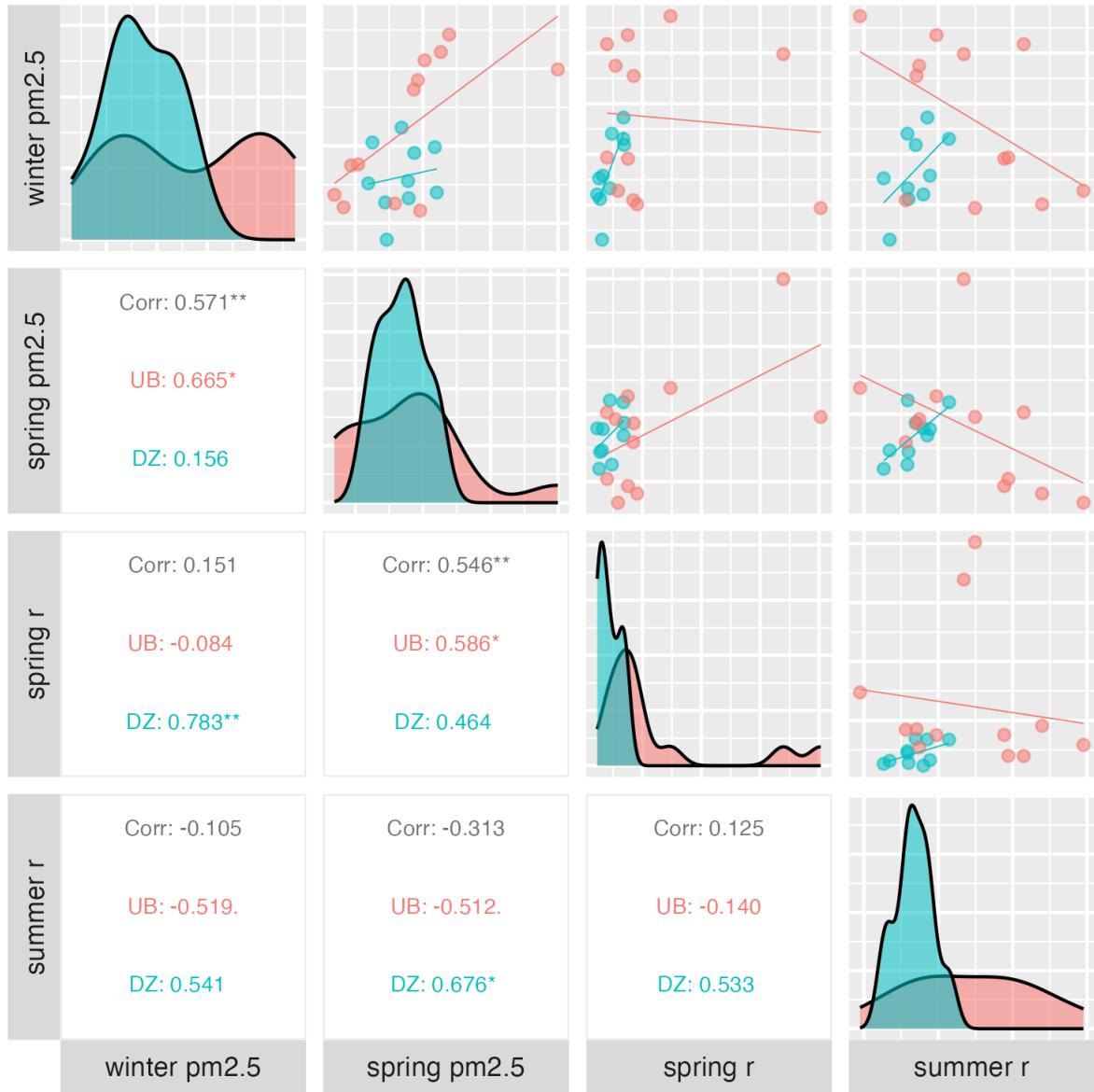
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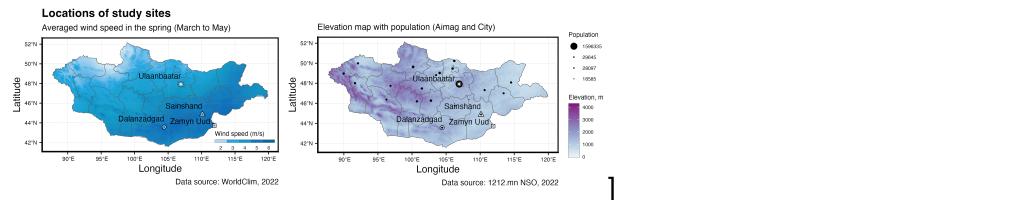
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422



423

**Table 1. Measured data**

SITE	Location		Measured and collected data						Missing data	
	COORDINATE	ELEVATION	TOTAL ¹	WS&WD ²	VIS ³	OPC ⁴	PM2.5 ⁵	PM10 ⁶	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%

¹Equipment height: 15 meter at urban site (Ulaanbaatar), 2 meter at Gobi sites (Dalanzadgad, Sainshand and Zamyn Uud); ²Measurement range: 0–60 m/s; 0–365 degrees. Instrument model: Wind speed and direction PGWS-100, Gill, England; ³Range: 10–20 000 m. Visibility meter PWD10, Vaisala, Finland; ⁴Optical Particle Counter; ⁵Range: 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

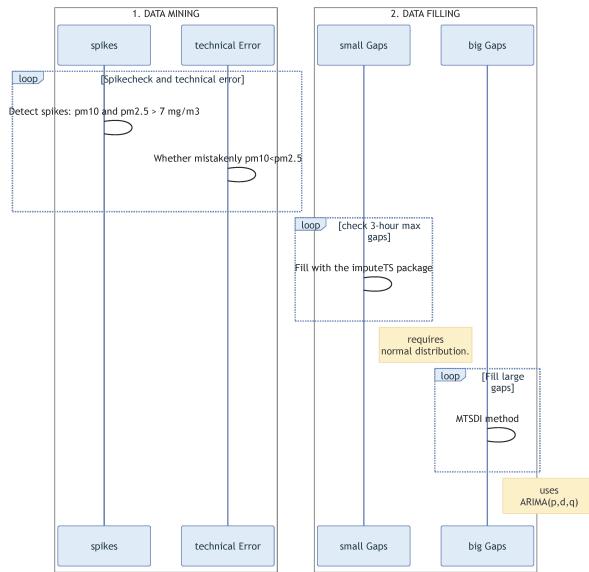


Figure 8: Scheme 1. Data handling procedure

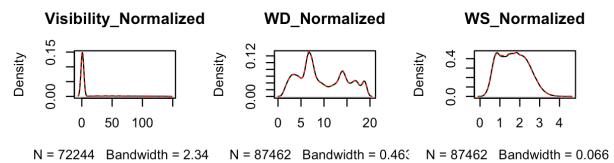


Figure 9: Figure 2. Data gap filling

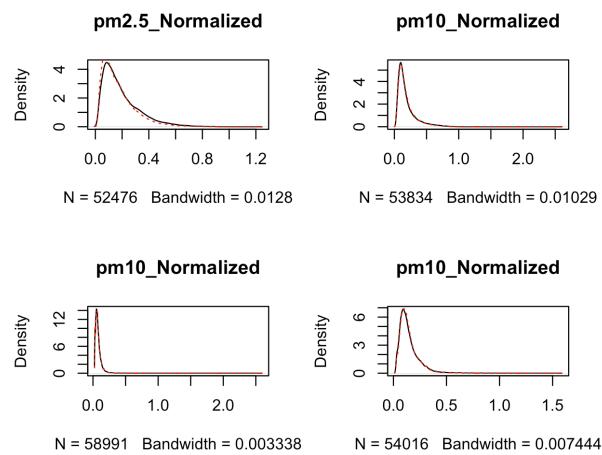


Figure 10: Figure 2b. Data gap filling

425 (1)

426 **References**

- 427 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.