

Modeling CMAQ dry deposition treatment over Western Pacific: A distinct characteristic of mineral dust and anthropogenic aerosol

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Abstract. Dry deposition plays a vital role in the aerosol removal process from the atmosphere. However, the chemical transport model (CTM) is sensitive to the dry deposition parameterization and yet remains to be determined due to the limited particle deposition measurement. By utilizing the CMAQv5.4 with the refined dust emission treatment, the East Asian dust (EAD) simulation during January 2023 was constructed to evaluate the performance of four dry deposition parameterizations, namely PR11, E20, S22, and P22. The result showed that the dry deposition parameterization could significantly improve the CMAQ dust emission treatment. By implementing the E20 dry deposition scheme, the CMAQ simulation performance of the surface PM₁₀ has been considerably improved with the NMB of -41.9 %, as compared to the dry deposition proposed by PR11 (54.05 %), S22 (-47.01 %) and P22 (-53.90 %). The modeled PM₁₀ pattern by E20 at the upper level (700 hPa) was mostly consistent with the observed PM₁₀ at the Lulin Atmospheric Background Station (LABS; 23.47° N, 120.87° E; 2862 m a.s.l.) where is a typical background site at Western Pacific, particularly in capturing the peak value. The high-altitude correlations (R) were well performed for E20 by 0.55, as compared to PR11 (0.47), S22 (0.54) and P22 (0.46). Moreover, E20 improved the simulated PM₁₀ concentrations and aerosol optical depth (AOD) value over the Asian Continental during the multiple dust episodes in spring 2021. The noticeable deduction of the coarse mode particle's deposition velocity (V_d) was responsible for reducing the PM₁₀ simulation underestimation. Moreover, the significant improvement of the modeled PM₁₀ was also shown by the PM_{2.5} simulation. On 22-31 January 2023, the *in-situ* measurement of the upper level observed the possibility of natural dust and anthropogenic aerosol. This is consistent with the CMAQ, which shows

31 that both aerosol types displayed a clear "long dust-black carbon belt" along the 15°N. We proposed
32 implementing the E20 dry deposition approach, narrowing the uncertainty of the CMAQ dust emission
33 treatment.

34 **1 Introduction**

35 The chemical transport model (CTM) is a powerful tool for comprehending air pollution, encompassing
36 emission, transport, radiative impact, and removal mechanisms at various grid scales. Among
37 these, particle dry deposition is a crucial aerosol removal process and an important sink for particles in
38 the model. The derivation of the dry deposition is based on the resistance framework and
39 electrical analogue, but its implementation can vary across models (Wesley, 1989; Giardina and Buffa,
40 2018; Gaydos et al., 2007; Khan and Perlinger, 2017; Shu et al., 2017). A key challenge in dry deposition
41 simulation is the scarcity of measurement data for model verification, underscoring the necessity for
42 further research to enhance the accuracy of air quality modeling.

43 An immense range of dry deposition parameterization has been implanted in the model. The
44 deposition mechanism by Slinn (1982) includes the deposition process such as turbulent transfer,
45 Brownian diffusion, impaction, interception, gravitational settling, and particle rebound, where the
46 particle grows under humid conditions. Zhang et al. (2001) suggested the dry deposition scheme is
47 sensitive to land use category and several parameters. For instance, due to the particle growth, the
48 deposition velocity (V_d) over the ocean is much higher than on another land surface, as the V_d increased
49 rapidly with the increase of particle size. However, Zhang et al. (2001) parameterization still
50 underestimated the global $PM_{2.5}$ concentration. The latest dry deposition scheme revision by Emerson et
51 al. (2020) has reduced the uncertainty, marking a significant step forward in our quest for more accurate
52 air quality modeling.

53 An updated deposition scheme that reduces the dependence of the deposition velocity on the aerosol
54 mode width has been proposed (Shu et al., 2022). Indeed, the approach suggested that vegetation
55 dependence increased the V_d for submicrons and decreased for large particles by 37 % and -66 %,
56 respectively. It also reduced the functional biases by 56-97 % for vegetated land-use type and equivalence

57 performance over the water. Moreover, adding the second inertial impaction term for microscale obstacles
58 such as leaf hairs, microscale ridges, and needle leaf edge effects managed to increase the mass dry
59 deposition of the accumulation mode aerosols in the model (Pleim et al., 2022). These modifications
60 reduced the average PM_{2.5} in the atmosphere during July 2018 over the contiguous United States.

61 With a plethora of deposition approaches in use, it becomes paramount to comprehend their impact
62 on model performance in predicting aerosol behavior. The surface fine particle concentrations can vary
63 up to 5-15 %, and the particle dry deposition has more than 200 % discrepancy due to the different dry
64 deposition schemes. (Saylor et al., 2019). A comprehensive evaluation of five different parameterizations
65 has been conducted, with the simplest and most effective deposition mechanism suggested for the CTM
66 (Khan and Perlinger, 2017). However, the model's reliance on meteorological factors such as frictional
67 velocity, relative humidity, rainfall, or wind speed, which can significantly influence
68 the model's accuracy, remains a challenge (Kong et al., 2021).

69 Besides the model bias on PM_{2.5}, the simulation of PM₁₀ has been underestimated due to the
70 uncertainty of the deposition mechanism, particularly over the western Pacific (Kong et al., 2021). The
71 V_d is overestimated for coarse particles, where the dry deposition velocity is too high for coarse particles
72 when the frictional velocity is large, which is why the surface PM₁₀ concentration is underestimated (Ryu
73 and Min, 2022). The model performance of PM₁₀ simulation that is widely influenced by the dust
74 treatment embedded within CMAQ has been revised (Dong et al., 2016; Liu et al., 2021; Kong et al.,
75 2021, 2024) and are found to effectively simulate the PM₁₀ over the western Pacific region such as
76 Taiwan. However, the issue regarding the deposition algorithm's impact on the model performance at the
77 corresponding region needs to be discussed. The present research intends to evaluate the CMAQ model
78 performance due to the different deposition schemes on aerosols in the Taiwan region.

79 The model performance in Taiwan is paramount in our study, as the area is equipped with a substantial
80 number of well-maintained surface observation sites, providing comprehensive coverage. The LABS
81 station in the high-altitude subtropical western North Pacific region serves as the sole background station

82 for monitoring transboundary pollutants. This station is crucial in our research as it provides unique data
83 on the long-range transport of pollutants, further underscoring the relevance of our study.

84 The transboundary pollutants mechanisms have been widely discussed through LABS measurements,
85 cooperating with the backward trajectory, reanalysis dataset, and modeling approach. Previous research
86 reveals that LABS pollutants could be associated with severe fire emissions from northern Peninsular
87 Southeast Asia (Huang et al., 2020; Ooi et al., 2021) and Indonesia (Ravindra Babu et al., 2023).
88 Moreover, the intense wind speed in northwest China could transport the mineral dust through the surface
89 and high-altitude layer detected at LABS (Kong et al., 2021; Kong et al., 2022). Additionally, the transport
90 process of East Asian haze due to the cold surge from the Asian Continental industrial region towards
91 Taiwan has been widely discussed (Chuang et al., 2020). Instead of pure aerosol, the coexistence of dust
92 and biomass burning over Taiwan, a condition discovered in previous research, has significant
93 implications for the regional climate (Dong et al., 2018; Dong et al., 2019). However, the high-altitude
94 synoptic pattern associated with the coexistence between natural dust and anthropogenic pollutants
95 remains unknown due to a lack of observations at the upper layers.

96 This study used the chemical transport model to investigate the long-range transport of East Asian
97 dust (EAD) that occurred on 22-31 January 2023 and 12 March-20 April 2021. Due to the limitation of
98 the dust model, the CMAQ version 5.4, embedded with four types of dry deposition schemes, was
99 implemented to justify the effectiveness of improving our latest refined dust model (Kong et al., 2024).
100 LABS detected the recent transboundary episode in January 2023 as a mixing aerosol type (see Section
101 3.1), which has not been widely discussed, and the multiple dust storm episodes mentioned by Kong et
102 al. (2024) provide an opportunity to model the EAD over the downwind region. Recognizing the
103 significant transboundary events detected through Taiwan's observations, the improvement of the CMAQ
104 dust model by the dry deposition schemes, and its application in characterizing the transport mechanism
105 can be vital. The paper is organized as follows. The model setup and ancillary datasets are discussed in
106 Sect. 2. The results and discussion are presented in Sect. 3, followed by the conclusions in Sect. 4.

107 **2 Data and Methodology**

108 2.1 Dust emission treatment

109 Before delving into the details, it's important to understand the process of dust transport. Dust is primarily
110 transported by wind through a process known as sandblasting (Kok et al., 2012). For dust to be uplifted,
111 the horizontal wind speed must exceed a certain threshold frictional velocity ($u_{*,t}$), which is estimated by
112 the model as follows:

$$113 \quad u_{*,t} = u_{*,to} f_m f_r \quad (1)$$

114 Where $u_{*,to}$ is the ideal threshold friction velocity, while f_m and f_r are the correction factors of soil
115 moisture and surface roughness, respectively.

116 Through a collaborative effort, the windspeed, soil texture, soil moisture, and surface roughness
117 length derived from field and laboratory studies have been integrated into the windblown dust treatment,
118 which is now a part of the Community Multiscale Air Quality (CMAQ) modeling system (Foroutan et
119 al., 2017). This model, developed and evaluated over the continental United States, has also been extended
120 to the East Asia region (Dong et al., 2016; Liu et al., 2021; Kong et al., 2021, 2024). Kong et al. (2024)
121 have proposed further improvements, including the integration of the revised soil moisture fraction, dust
122 emission speciation profile, and bulk soil density, to enhance the representation of the Asian dust
123 simulation. This ongoing collaboration is crucial for the continuous improvement of our understanding
124 and management of dust emissions.

125 2.2 Particle dry deposition schemes

126 Particle dry deposition is a complex process relating to the deposition velocity, particle size, source and
127 composition, land use surface, and meteorological condition. Generally, the flux of the particle mass
128 through the surface boundary layer is estimated as:

$$129 \quad F = C \times V_d \quad (2)$$

130 where F is the deposition flux, C is the particle concentration at the surface layer, and V_d is the deposition
131 velocity.

132 The difference in the particle concentration and deposition prediction among the various
133 atmospheric chemistry models was probably due to the algorithm of the dry deposition particle. The
134 algorithm describing particle deposition velocity as a function of particle size in almost all current air
135 quality model systems is descended from Slinn (1982). The particle deposition according to vegetative
136 canopies formulated the deposition velocity as:

$$137 \quad V_d = V_s + \frac{1}{R_a + R_s} \quad (3)$$

138 where V_s is the gravitation settling velocity, R_a is the resistivity aerodynamic and R_s is the surface
139 resistivity. The V_s is calculated according to Stokes's Law as:

$$140 \quad V_s = \frac{p_p D_p^2 g C_c}{18\eta} \quad (4)$$

141 where, p_p is the density of the particle; D_p is the diameter of the particle; g is gravitational acceleration;
142 C_c is the Cunningham correction factor for small particles; and, η is the dynamic viscosity of air.

143 CMAQ is embedded with M3Dry dry deposition calculation that implements the scheme of Pleim
144 and Ran (2011), which is based on Slinn (1982). As noted by Pleim and Ran (2011), chemical surface
145 flux modeling has become an essential process in the air quality model. For instance, the linkages of
146 ambient concentration levels to the deposition of SO_x and NO_x . Moreover, Surface Tiled Aerosol and
147 Gaseous Exchange (STAGE) deposition has been implemented within the CMAQv5.3, where estimated
148 fluxes from sub-grid cell fractional land-use values, aggregate the fluxes to the model grid cell and unifies
149 the bidirectional and unidirectional deposition schemes using the resistance framework (Massad et al.,
150 2010; Nemitz et al., 2001). The updated STAGE version in CMAQv5.4 could aggregate the grid-scale
151 values that match the grid-scale values from most kinds of Land Surface Model of WRF (Hogrefe et al.,
152 2023).

153 **2.3 CMAQ model design**

154 This study applied WRF v4.0 for the meteorological field parameters and CMAQv5.4 to simulate the
155 transboundary East Asian dust episodes on 22-31 January 2023, and the multiple dust storm episodes
156 during 12 March-20 April 2021. The modeling domain was set up to cover the Taklamakan and Gobi
157 Desert, with a resolution of 45 km, and nested towards Taiwan at a resolution of 15 km (d02) and 5 km
158 (d03) (Fig .1, Table 2). Also, as Taiwan is influenced by biomass burning, the domain covers up to the
159 peninsular Southeast Asia (PSEA), which will be carried out in the future (Ooi et al., 2021). The model
160 consisted of 40 vertical layers, with eight layers below ~1 KM altitude, 13 layers below ~3 KM altitude,
161 and 27 layers covering the upper layer to ~21 KM. The model's initial and lateral boundary
162 conditions were constructed using the National Centers for Environmental Prediction (NCEP) Final
163 Analyses (FNL) reanalysis dataset on a $0.5^\circ \times 0.5^\circ$ grid. The data assimilation was conducted by grid
164 nudging in all the domains. The CB06 gas-phase chemical mechanism and the AERO7 aerosol module
165 model were implemented in CMAQ for the present study.

166 The anthropogenic emission inventories in East Asia, crucial for our research, were obtained from
167 the MICS-Asia (Model Inter-Comparison Study for Asia) Phase III emission inventory (Li et al., 2017).
168 The emissions of SO₂, NO_x, NMVOC, NH₃, CO, PM₁₀, PM_{2.5}, BC, OC and CO₂ has been meticulously
169 modified, taking into account of the relative changes in China's anthropogenic emissions between 2010
170 and 2017 (Zheng et al., 2018). Additionally, the modified emission of NO₂ was adjusted further by the
171 satellite imagery OMI-NO₂ in January 2023 (Huang et al., 2021). Biogenic emissions for Taiwan were
172 prepared by the Biogenic Emission Inventory System version 3.09 (BEIS3, Vukovich and Pierce, 2002)
173 and, for regions outside Taiwan, by the Model of Emissions of Gases and Aerosols from Nature v2.1
174 (MEGAN, Guenther et al., 2012). TEDS 10.0 (Taiwan Emission Database System, TWEPA, 2011;
175 <https://erdb.epa.gov.tw/>, last access: 18 January 2024) was used for domain 3 (d03).

176 To ensure the precision of the multiple dry deposition parameterizations, the present research
177 conducted six simulation scenarios, namely CMAQ_Off_PR11, CMAQ_Dust_PR11, CMAQ_Dust_E20,
178 CMAQ_Dust_S22 and CMAQ_Dust_P22. The CMAQ_Off_PR11 scenario did not include the inline
179 dust calculation (Table 2). Meanwhile, the latest refined integrated dust treatment was implemented in
180 the CMAQ_Dust_PR11 scenario (Kong et al., 2024). Indeed, both CMAQ_Off_PR11 and
181 CMAQ_Dust_PR11 used the dry deposition mechanism by Pleim and Ran (2011). The dry deposition

182 mechanism of Emerson et al. (2020), Shu et al. (2022), and Pleim et al. (2022) were implemented in
183 CMAQ_Dust_E20, CMAQ_Dust_S22, and CMAQ_Dust_P22 scenarios, respectively.

184 **2.4 Ancillary dataset**

185 PM₁₀ (particulate matter ≤ 10 μm in aerodynamic diameter) and PM_{2.5} (particulate matter ≤ 2.5 μm in
186 aerodynamic diameter) concentrations during the dust events in January 2023 were obtained from Lulin
187 Atmospheric Background Station (LABS; 23.47° N, 120.87° E, 2862 m MSL) and Cape Fuguei (25.30°
188 N, 121.54° E, 10 m MSL). In addition, the hourly PM₁₀ and PM_{2.5} of nearly 100 sites distributed over
189 mainland China (Fig. S1), covering the period of 12 March-20 April 2021, obtained from the Chinese air
190 quality online monitoring analysis platform's website (www.aqistudy.cn/). The Modern Era
191 Retrospective-analysis for Research and Application version 2 (MERRA-2) reanalysis data was used to
192 demonstrate the spatiotemporal distribution of dust, compare with the air quality model, irrespective of
193 the influence of clouds. MERRA-2 (Gelaro et al., 2017) is a NASA reanalysis utilizing Goddard Earth
194 Observing System Data Assimilation System Version 5 (GEOS-5) and covering the data assimilated
195 system at a native spatial resolution of $0.5^\circ \times 0.625^\circ$. Also, Moderate Resolution Imaging
196 Spectroradiometer (MODIS) Terra satellite images and the level-3 MODIS AOD at 550 nm
197 (MYD08) were obtained from the U.S. National Aeronautics and Space Administration
198 (<https://worldview.earthdata.nasa.gov/>).

199 **3 Results and Discussion**

200 **3.1 Observed air quality and weather conditions**

201 Figure 2 shows the dust outbreak over East Asia, displayed by the MODIS Terra sensor and MODIS
202 AOD at 550 nm from 22-31 January 2023. The satellite image showed dust induced by a high-pressure
203 system on 24-25 January (Fig. 2a3, 2a4). The next day, the same region was covered by a thick cloud,
204 and dust was again widely distributed from 27-30 January 2023. Using MODIS AOD to verify the dust
205 plume (Han et al., 2012; Kong et al., 2021), the dust plume was distributed in Central China and northern
206 Taiwan on 24 January 2023. Moreover, the most intense dust plume in the eastern China and East China
207 Sea region was observed on 27 January. Fig. S2 shows the synoptic weather map across the study domain.

208 On 22-23 January, the southward high-pressure system was responsible for pushing the pollutant across
209 the Asian Continent, which is consistent with Chuang et al. (2018) and Kong et al. (2021, 2022, 2024)
210 (Fig. S1a-b). The high-pressure system that moved southward will then move eastward toward the western
211 Pacific Ocean (Fig S1c-d). Meanwhile, the high-pressure system on the northwest side again expands in
212 the southeast direction. The second high-pressure system again pushed the pollutant for the second time
213 and caused the high pollutant problem on 27 January.

214 The impact of East Asian dust on the air quality over the high-altitude western Pacific region was
215 widely discussed (Kong et al., 2022). Two interesting high pollution events at Mt. Lulin (2,862 m above
216 sea level) during 24-26 Jan and 27-30 January, respectively, are shown in Fig. 3. The latter event was
217 more intense compared to the earlier one, where the maximum PM₁₀ concentration can reach up to 35 µg
218 m⁻³. Moreover, it was observed that the black carbon concentrations could reach up to a maximum of 400
219 ng m⁻³. Based on the *in-situ* measurement, it was interesting to find the mixing state between dust, black
220 carbon, and brown carbon (Fig. 3c). Different from what has been discussed by Kong et al. (2022), the
221 long-range transport air pollution at the high-altitude not just merely EAD, but also included the
222 anthropogenic pollutant from mainland China.

223 3.2 Evaluation of CMAQ dust emission and dry deposition parameterizations

224 Table 3 shows the statistical analysis of PM₁₀ and PM_{2.5} concentrations over Cape Fuguei (northern
225 Taiwan) from 22-31 January under the multiple deposition mechanisms. The threshold of the statistical
226 index is based on Emery (2001). CMAQ_Off_PR11, the PM₁₀ simulation presented without the inline
227 dust calculation, recorded the normalized mean bias (NMB) of -57.59 %. CMAQ_Dust_PR11 improved
228 the simulation over Cape Fuguei (northern Taiwan) by -54.05 % as we included the refined dust treatment
229 (Kong et al., 2024). However, the improvement is insignificant due to the weak intensity dust episodes
230 and the limitation due to the excessive deposition mechanism within the model (Kong et al., 2021). Hence,
231 we expanded the sensitivity simulation to examine the impact of the deposition algorithm on the aerosol
232 prediction. CMAQ_Dust_E20 simulations utilizing the Emerson et al. (2020) approach increased the
233 modeled PM₁₀ simulation by NMB of -41.9 %. In addition, the deposition algorithm proposed by

234 CMAQ_Dust_S22 (Shu et al., 2022) and CMAQ_Dust_P22 (Pleim et al., 2020) has reduced the NMB by
235 -47.01 % and -53.90 %, respectively.

236 Instead of PM₁₀ simulation, the present study found that the inline dust treatment and deposition
237 algorithms could influence PM_{2.5} simulation performances. For instance, the modeled PM_{2.5} improved
238 from -19.55 % (CMAQ_Off_PR11) to -16.53 % (CMAQ_Dust_PR11). Meanwhile, the deposition
239 algorithm embedded in CMAQv5.4 has further enhanced the modeled PM_{2.5} by -10.65 %, -15.22 %, and
240 -8.84 % under CMAQ_Dust_E20, CMAQ_Dust_S22 and CMAQ_Dust_P22, respectively. This incident
241 suggested that the East Asian dust from northwest China transported to the Western Pacific Ocean could
242 also carry the anthropogenic emission of East China.

243 Figure 4 shows the time series of hourly PM₁₀ and PM_{2.5} concentrations over Cape Fuguei
244 (northern Taiwan) and LABS (high altitude region) from 22-31 January 2023 under the multiple
245 deposition mechanisms. Generally, all the patterns of PM₁₀ simulations were consistent with the observed
246 PM₁₀, especially in capturing the peak value. For instance, the maximum observed (CMAQ_Dust_E20)
247 PM₁₀ concentrations at the surface during Jan 24 and 27 were 141 (102.6) $\mu\text{g m}^{-3}$ and 114 (163.2) $\mu\text{g m}^{-3}$,
248 respectively. A similar time-series pattern was found for the PM_{2.5} simulation (Fig. 4b).

249 More importantly, the CMAQ model performance over the high-altitude region needed to be
250 carried out and discussed. The biomass-burning episode of the northern PSEA over Mt. Lulin has been
251 finely correlated by plume rise injection (Chuang et al., 2016; Ooi et al., 2021). From Fig. 4c, the modeled
252 PM₁₀ pattern for CMAQ_Dust_Off could not correlate well with observed PM₁₀ over Mt. Lulin, with a
253 poor correlation of 0.17. The correlation was increased for CMAQ_Dust_PR11 (0.47), CMAQ_Dust_S22
254 (0.54), CMAQ_Dust_P22 (0.46), and primarily well performed for CMAQ_Dust_E20 (0.55). The
255 modeled result was somehow consistent with the surface PM₁₀ simulation at Cape Fuguei. The high
256 observed PM₁₀ episodes during 27-28 January with a maximum of 34.5 $\mu\text{g m}^{-3}$ was only 53.3 % higher
257 than CMAQ_Dust_E20 of 22.5 $\mu\text{g m}^{-3}$. For the CMAQ PM_{2.5}, the simulation generally underestimated the
258 observed PM_{2.5}.

259 During the spring of 2021, a series of dust storms (15 March, 27 March, and 18 April) occurred
260 over the Gobi area, with one of the most significant dust storms in the past decade (15 March, the “3.15”
261 dust storm hereafter) causing environmental impact over the continental (Jin et al., 2022; Gui et al., 2022;
262 He et al., 2022; Liang et al., 2022; Tang et al., 2022). More interestingly, one of the multiple dust storm
263 episodes reached western Pacific Ocean due to the extreme typhoon episode (Kong et al., 2024). Hence,
264 we intend to re-emphasize the precision of various deposition schemes on the CMAQ for the recent dust
265 storm episode over the Asian Continental highlighted by Kong et al. (2024). We evaluated the CMAQ
266 simulations with the different dry deposition schemes for the 40-day sensitivity test on 12 March-20 April
267 2021 against measured PM_{10} and $PM_{2.5}$ concentrations across the observation sites in mainland China
268 (Table 4). The observation sites used for the model comparison are marked in Fig. S1. Generally, the
269 evaluation results for Taiwan and mainland China were consistent. During the 40 days of Spring 2021,
270 the CMAQ PM_{10} of NMB was the highest for Off_PR11 (NMB = -79.19 %), followed by Dust_PR11 (-
271 60.53 %). The latest inline dust emission scheme embedded with E20 dry deposition scheme for PM_{10}
272 was well performed by NMB of -25.43 %, compared to the Dust_S22 (-45.97 %) and Dust_P22 (-59.82
273 %). For the $PM_{2.5}$ simulation, Dust_PR11 has been improved from Dust_Off, and Dust_S22 was slightly
274 better than Dust_E20.

275 Figure 5 shows the scatter plot of simulated and observed PM across mainland China. The
276 correlation coefficient (R), a factor of two (FAC2), and the mean observed and simulated PM are marked
277 in Figure 5. The modeled PM_{10} without the dust scheme had the lowest correlation, followed by
278 Dust_PR11. Among all of these simulations, Dust_E20 performed the best correlation ($R > 0.3$) compared
279 to Dust_PR11, Dust_S22 and Dust_P22. However, for $PM_{2.5}$, the correlation between the model and
280 measured values was similar for all the dry deposition schemes. The statistical index of FAC2 was used
281 in the present work since either low or high outliers less influence it (Chan and Hanna, 2004). The dataset
282 is reliable for FAC2 values between 0.5 and 2.0, with the ideal model of 1.0. The simulated PM_{10} by E20
283 performed well, with a nearly perfect value of 1.1. Meanwhile, the $PM_{2.5}$ by S22 simulation was slightly
284 better than E20 but much better than the other experiments.

285 The comparison of AOD between CMAQ and MODIS for the three dust storm episodes: 14-16
286 March 2021 (“3.15” dust storm), 26-28 March 2021 (“3.27” dust storm), and 17-19 April 2021 was
287 shown (“4.18” dust storm) (Table 4). Overall, CMAQ Dust_E20 above 30°N has evaluated well the
288 MODIS AOD by NMB of -26.2 %, as compared to PR11 (-37.4 %), S22 (-32.0 %) and P22 (-35.8 %).
289 The CMAQ AOD by E20 during the most intense Super Dust Storm in 3.15 has significantly improved
290 over northern China, the dust source region, as shown in the red dash rectangular box (Fig. S3).
291 Additionally, the modeled AOD by E20 over the western Pacific Ocean (shown in red dash rectangular
292 box) increased in episode 4.18, reporting a value of 0.7 compared to 0.4 by PR11. Significantly, the E20
293 deposition scheme has primarily enhanced the PM₁₀ prediction over the marine boundary layer,
294 addressing the model uncertainty due to the typhoon mentioned by Kong et al. (2024) and demonstrating
295 the practical implications of our research.

296 The present work is consistent with the dust scheme in the WRF-Chem, where the dust loading is
297 very sensitive to the dry deposition schemes and dust emission schemes, especially over the downwind
298 region (Zeng et al., 2020). Fig. 6 shows the CMAQ estimated ten days averaged mean PM₁₀ and PM_{2.5}
299 for the PR11 deposition scheme and its corresponding change by E20, S22, and P22,
300 respectively. Generally, the spatial distribution of the high PM₁₀ concentrations by $> 80 \mu\text{g m}^{-3}$ was
301 distributed over northwest China, which is the dust source region's location, consistent with the simulation
302 suggested by Kong et al. (2021, 2022, 2024). Such high particulate matter dissipated to east China,
303 indicating the transport pathway in the southeastern direction towards the western Pacific (Fig. 6a). The
304 difference between E20 and PR11 suggested the high PM₁₀ $> 50 \mu\text{g m}^{-3}$ distributed over northwest China,
305 meaning E20 successfully increased the PM₁₀ concentrations. As compared to the S22 deposition scheme,
306 it also increased the PM₁₀ over northwest China by around $30 \mu\text{g m}^{-3}$ but was not as intense as E20. For
307 P22, the difference of PM₁₀ between PR11 and P22 was less than $10 \mu\text{g m}^{-3}$, indicating less efficiency of
308 P22 in improving the PM₁₀. Another fascinating fact about E20 was that the PM₁₀ increased over the
309 southern South China Sea. For the modeled PM_{2.5} concentrations, the high concentration was
310 distributed over the Asian Continental. Under the E20 mechanism, the modeled PM_{2.5} has been
311 increased over PSEA. For S22, such improvement of PM_{2.5} was more intense over a similar region.

312 Meanwhile, the $PM_{2.5}$ simulated by P22 didn't have much difference compared to PR11, which showed
313 consistency as the PM_{10} simulation.

314 **3.3 Impact on the CMAQ ambient particle concentrations**

315 Figure 7 shows the boxplot of the 10-day averaged simulated V_d for the Aitken, accumulation, and coarse
316 particles modes under multiple deposition schemes, namely PR11 (Pleim and Ran, 2011), E20 (Emerson
317 et al., 2020), S22 (Shu et al., 2022) and P22 (Pleim et al., 2022). Different dry deposition treatments
318 substantially impact aerosol profile, altering the ambient total dry deposition regionally. As shown in the
319 figure, the median of E20, S22, and P22 increased the deposition velocity of the Aitken (accumulation)
320 modes particle as compared to PR11 by 22.56 (11.32) %, 117.76 (86.43) % and 2.5 (7.52) % respectively.
321 For coarse-mode particles, the P22 simulation median V_d increased by 14.36 % compared to PR11. On
322 the other hand, E20 and S22 showed a different simulation by the median V_d reduction by -9.1 % and
323 -12.1 %, respectively. Also, the 75th percentile V_d of the coarse mode has been significantly reduced by -
324 50.57 % (E20) and -58.27 % (S22), respectively. The result suggested that the reduced V_d of the coarse
325 mode particle was responsible for reducing the PM_{10} simulation underestimation of PR11, consistent with
326 the simulation by Shu et al. (2022) and Ryu and Min (2022). The slow V_d means the total loss of aerosol
327 to the surface has been minimized, leading to increased aerosol concentration.

328 We estimated the CMAQ averaged particle modes for the PR11 dry deposition scheme and the
329 corresponding percentage changes using E20, S22, and P22 (Fig. 8 and Fig. S4). By using E20 and S22,
330 we found that the V_d corresponding to the Aitken and accumulation modes has been increased by >100
331 % over most of the CMAQ domain, which was most obvious over Asian continent (Fig 8b, c, f, g).
332 Meanwhile, the variation of V_d distribution was insignificant for P22 (Fig. 8d, h, i). For the coarse mode
333 particles, the V_d has been tremendously reduced for E20 and S22 compared to PR11. However, for S22,
334 the V_d has increased by >100 % over northwest China, which is the dust source region (Fig.
335 8k). This leads to a significant deposition over the desert before transporting it to the downwind region,
336 causing less PM_{10} simulated by S22 than E20. A previous study proposed the V_d for the aerosol at the
337 water surface was associated with the CTM uncertainly at the downwind region (Kong et al., 2021, 2024;
338 Ryu and Min, 2022). The V_d of Aitken and accumulation modes at land and water surfaces increased

generally, except E20 at the water surface. Interestingly, the coarse mode V_d at the water surface for E20 and S22 decreased significantly by -44.65 % and -21.44 %, respectively, suggesting that both deposition schemes, particularly E20, could resolve the excessive deposition over the marine boundary layer (Table 5). Such minimal deposition velocity distributing over a large part of the western Pacific Ocean, including the Sea of Japan, Yellow Sea, East China Sea, and South China Sea, might be responsible for reducing the modeled PM_{10} underestimation over Taiwan (Fig.8j, k), as mentioned by Kong et al. (2021).

3.4 CMAQ of dust and black carbon synoptic pattern at the upper level

Black carbon, often known as elemental carbon, released from the biofuels, fossil fuels and biomass burning, has been proven to impact the radiative budget and regional climate (Ramanathan, V and Carmichael, 2008; Pani et al., 2016, 2020). In the meantime, China has been a significant contributor to global anthropogenic black carbon emission, particularly in the cities of the northern part (Xiao et al., 2023; Wang et al., 2024). During the severe dust episodes in the spring of 2023, the contribution of black carbon brought by EAD was captured in North China (Wang et al., 2024). As depicted in Fig. 2, the transboundary episode observed in the upper level of Taiwan during this event could be the mixing of the natural dust and anthropogenic haze episodes, which demonstrates the consistency. Additionally, blending mineral dust with anthropogenic transport due to the north easterly wind, a wind that blows from the northeast, has been a subject of extensive discussion (Lin et al., 2007, 2012; Li et al., 2012). During the EAD, the dust from the Gobi Desert that was transported towards the western Pacific region could also carry anthropogenic aerosol, contributing to different levels of pollutant concentration. However, the distinct transport pathway at the high altitude between both aerosol types is a topic that has received less attention but is of significant importance to our understanding of atmospheric dynamics.

Figure 9 illustrates mineral dust concentration's spatial and temporal distribution under the CMAQ_Dust_E20 scenario at 700 hPa from 24-30 January. The model reveals a high proportion of modeled dust aerosol (red dash circle) at the source region, indicating an uplift from the surface to 700 hPa (Fig. 9a, b). This uplift, driven by the strong pressure gradient at the surface and the 'eastward moving trough system' at the upper level (700 hPa), is a key factor in the eastward and southward transfer of the dust (Fig. 9c, d). The high dust fraction reappears at the source region (Fig. 9e-f) and is transported

366 eastwardly by the similar upper-level trough (Fig. 9g-j), causing a long dust belt at 15°N, distributing
367 over central Asia continental, Taiwan Straits, Taiwan and large part of western Pacific Ocean. (Fig. 9i, j).
368 On 29 January, the model of E20 clearly predicted that the dust plume moved in the southward direction
369 toward the South China Sea (Fig. 9k, l). The dust aerosol was left distributed at a certain part of the
370 northern South China Sea and the Philippine Sea until it totally dissipated (Fig. 9m, n). This interesting
371 result suggests the possible EAD at the longer distance at the upper level, which is a topic for further
372 investigation.

373 The southward high-pressure system responsible for the long-range transport haze episode has
374 been widely discussed (Chuang et al., 2008; Kong et al., 2021)—however, the upper-level transboundary
375 transport needs to be addressed more. While focusing on CMAQ_Dust_E20, we attempted to characterize
376 the long-range transport of modeled black carbon at the upper level (700 hPa) (Fig. 10). As shown in Fig.
377 10(c, e), the modeled black carbon concentration is shown to be significantly distributed at central China.
378 The black carbon transport pattern followed the eastward-moving trough system as the plume moved
379 eastward and southward (Fig. 10g-l). Interestingly, the long black carbon belt is consistent with the long
380 dust belt, as shown in Fig. 9. For instance, both modeled dust and black carbon were distributed at the
381 western Pacific Ocean (Fig. 9i, j; Fig. 10i, j) and South China Sea (Fig. 9m, n; Fig 10m, n). This means
382 that the black carbon due to the anthropogenic emission and the natural EAD shared a similar transport
383 pattern at the upper level, driven by the trough system. Such consistency has been verified by the
384 MERRA-2 dust and black carbon mass column over the region (red dash rectangular in Fig. S5).

385 Dust aerosol vertical profiles (Fig. 11) show the large dust fraction was distributed over the Asian
386 Continent (Fig. 11a, b), according to the transect drawn as a red-dash line in Fig. 1. Due to the westerly
387 winds as illustrated in Fig. 9, the aerosol plume transported at the eastward direction toward the western
388 Pacific Ocean, that vastly accumulated along the 700 hPa altitude. Another plume was found across the
389 ocean on the east side of Taiwan Island (Fig. 11b). The plume was moved eastward (Fig. 11c-f). During
390 00 UTC on 27 January, another large fraction of dust covered the Asian Continent (Fig. 11g); in the next
391 12 hours, the model showed an apparent dust plume located in the Western Pacific Ocean, with much
392 higher dust concentrations compared to Fig. 11b. The plume again distributed eastward showed a clear

393 dust dome (Fig. 11i-j). Then, due to the westerly airflow, the dust aerosol slowly dissipated at the upper
394 layer of the western Pacific.

395 The vertical profile of the modeled black carbon has a similar transport pattern as mineral dust
396 (Fig. 12). As shown in Fig. 12d, the modeled black carbon was found distributed at the western Pacific
397 Ocean. In Fig. 12e, a clear black carbon dome was distributed along 700 hPa, showing a similar pattern
398 as dust. This simulation proposes the consistency of the “double dome” mechanism of Asian dust and
399 biomass burning episodes (Dong et al., 2018; Huang et al., 2019). The issue regarding whether or not
400 such a mechanism could cause the warming effect can be considered as a future study. However, the
401 difference is that the dust dome contains a higher fraction of concentrations as compared to the black
402 carbon dome. Considering the maximum height, the present simulation suggests the dust aerosol can reach
403 up to 500 hPa, which is consistent with Kong et al. (2021). Contrary, the black carbon plume was slightly
404 lower with approximately 600 hPa of the maximum height under the same meteorological condition. As
405 this section essentially discusses the similarity and distinctiveness of natural dust and anthropogenic
406 aerosol at the upper level, we are interested in characterizing the synoptic pattern. Hence, the present
407 simulation did not consider the two-way coupling model, and it is strongly suggested for future study.

408 **4.0 Summary and Conclusions**

409 The chemical transport model is considered sensitive to the dry deposition parameterization besides the
410 dust emission treatment. The present study demonstrates the impact of the four dry deposition
411 parameterizations on aerosol performance in East Asia. It provides a significant analysis of the
412 transboundary transport of East Asian Dust to Taiwan from a case study of 22-31 January 2023. The
413 incorporation of the latest dust emission treatment with PR11 (Pleim and Ran, 2011; Kong et al., 2024)
414 to the CMAQ slightly improved the model performance to -54.05 % from -57.59 %. By implementing
415 the E20 dry deposition scheme, characterized by adding the collection efficiency by interception across
416 the land surface, the CMAQ simulation of the surface PM₁₀ has been improved by NMB of -41.9 %, as
417 compared to the dry deposition proposed by S22 (-47.01 %) and P22 (-53.90 %). Moreover, the modeled
418 PM₁₀ pattern by CMAQ_Dust_E20 at the upper level (700 hPa) was mostly consistent with the observed
419 PM₁₀, especially in capturing the peak value. The dry deposition of E20 was correlated well with the high

altitude in-situ by 0.55, as compared to PR11 (0.47), S22 (0.54) and P22 (0.46). Such a significant difference in PM_{10} improvement has also been shown by modeled $PM_{2.5}$. The simulation of surface $PM_{2.5}$ by PR11 has been improved to -16.53 % from -19.55 %, after using the latest dust treatment, and further enhanced by E20 (-10.65 %), S22 (-15.22 %) and P22 (-8.84 %). Additionally, the simulations of the multiple dust episodes in spring 2021 were re-constructed to evaluate the CMAQ performance over the Asian Continental. The E20 dry deposition scheme outperformed the other schemes with the lowest NMB value in simulating PM_{10} (-25.4 %) and AOD (-26.2%). For the modeled $PM_{2.5}$, S22 performed slightly better than E20, with NMB of -36.29 % and -37.5 %, respectively.

The previous CMAQ model, modulated by Kong et al. (2021; 2024), showed excessive deposition at the marine boundary layer, leading to an underestimation of the modeled surface PM_{10} . However, our updated model, using the E20 and S22 schemes over the entire model domain, has not just reduced, but significantly reduced the 75th percentile of V_d by -50.57 % and -58.27 %, respectively. This precise reduction of V_d of the coarse mode particle, responsible for resolving the PM_{10} simulation underestimation, has not just minimized, but effectively minimized the total loss of aerosol to the surface, leading to a concentration increment. Furthermore, the intense decrease of modeled V_d across the water surface by E20 could play a crucial role in resolving the excessive aerosol deposition over the ocean layer.

In addition, the updated CMAQ was used to investigate the synoptic pattern at the upper level. The transboundary transport of EAD from the Asian Continent towards the western Pacific Ocean at the upper level was associated with the eastward moving trough system. Such transport mechanism is found to bring along the black carbon aerosol, which is primarily the main element of China's human-made emissions. More interestingly, both aerosol profiles created a "long dust-black carbon belt" along the 15°N. The 'double dome mechanism', a concept proposed by Huang et al. (2019) that depicts the superposition of the two types of aerosol, was also simulated in the present study. However, since the present work did not consider two-way radiative impact, the issue of warming/cooling is proposed in the future study.

446 **Data Availability**

447 MERRA-2 data are available online through the NASA Goddard Earth Sciences Data Information
448 Services Center (GES DISC; <https://disc.gsfc.nasa.gov>; last access: 01 August 2024). MODIS data used
449 in this study are available at <https://asdc.larc.nasa.gov/>(last access: 01 August 2024). The observational
450 data at LABS can be ordered by contacting corresponding authors.

451 **Author Contribution**

452 **Steven Soon-Kai Kong:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology;
453 Software; Validation; Visualization; Writing – original draft; Writing – review and editing.

454 **Joshua S. Fu:** Conceptualization; Investigation; Methodology; Formal analysis; Writing – review and
455 editing.

456 **Neng-Huei Lin:** Conceptualization; Visualization; Supervision; Funding acquisition; Resources; Writing
457 – review and editing.

458 **Guey-Rong Sheu:** Funding acquisition; Resources.

459 **Wei-Syun Huang:** Data curation; Software.

460 **Competing Interests**

461 Some authors are members of the editorial board of journal ACP.

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641 **Table 1.** Model settings.

Model setting	Descriptions
Period	12 March-20 April 2021 and 22-31 January 2023
Domain	d01, d02, and d03 with 45 KM, 15 KM, and 5 KM of the resolutions, respectively
Boundary condition	NCEP FNL lateral boundary condition
Surface and land surface model	NOAH
Numerical weather model	WRF v40, including grid and observation nudging at d01.
Chemical transport model	CMAQ v5.4
Gas-phase chemistry and aerosol mechanism	CB06e51 + AE7
Emission Inventory	MICS-ASIA III emission in 2023, adjusted from the emission in 2017 (Zhang et al., 2018) based on the OMI-NO _x satellite (Huang et al., 2021).
Online dust treatment	The windblown dust treatment suggested by Kong et al. (2024).
Dry deposition option	M3DRY (PR11) and STAGE (E20, S22 and P22).

642
643 **Table 2.** Simulation scenarios used in this present study.

Scenarios	Descriptions
CMAQ_Off_PR11	Without in-line dust calculation, with the M3DRY dry deposition algorithm by Pleim and Ran (2011).
CMAQ_Dust_PR11	Implement the latest refined dust treatment proposed by Kong et al. (2024), with the M3DRY dry deposition algorithm by Pleim and Ran (2011).
CMAQ_Dust_E20	Same as CMAQ_Dust_PR11, but with the STAGE dry deposition algorithm by Emerson et al. (2020).
CMAQ_Dust_S22	Same as CMAQ_Dust_PR11, but with the STAGE dry deposition algorithm by Shu et al. (2022).
CMAQ_Dust_P22	Same as CMAQ_Dust_PR11, but with the STAGE dry deposition algorithm by Pleim et al. (2022).

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656 **Table 3.** Statistical evaluation for PM₁₀ and PM_{2.5} concentrations during 22-31 January 2023 for Cape
 657 Fuguei under the multiple simulation scenarios.

Benchmark		CMAQ-M3DRY				CMAQ-STAGE					
		Off	PR11	Dust	PR11	Dust	E20	Dust	S22	Dust	P22
PM ₁₀											
MeanObs		49.97		49.97		49.97		49.97		49.97	
MeanMod		21.19		22.97		29.04		26.48		23.04	
NMSE		0.82		0.71		0.49		0.56		0.71	
NMB	± 85%	-57.59		-54.05		-41.90		-47.01		-53.90	
R	> 0.35	0.41		0.44		0.52		0.46		0.42	
NMBF		-1.36		-1.18		-0.72		-0.89		-1.17	
PM _{2.5}											
MeanObs		15.52		15.52		15.52		15.52		15.52	
MeanMod		12.48		12.95		13.86		14.15		13.16	
NMSE		0.31		0.29		0.29		0.30		0.31	
NMB	± 85%	-19.55		-16.53		-10.65		-8.84		-15.22	
R	> 0.35	0.52		0.55		0.53		0.53		0.52	
NMBF		-0.24		-0.20		-0.12		-0.10		-0.18	

658 Note: the definition of the statistical formulas NMSE: Normalized Mean Square Error; NMB: Normalized
 659 Mean Bias; R: Correlation Coefficient and NMBF: Normalized Mean Bias Factor

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 661 **Table 4.** CMAQ evaluation for PM₁₀ and PM_{2.5} against the averaged 100 observation sites across
 662 mainland China (Fig. S1) and AOD against MODIS daily observation near the dust source region (above
 663 30°N) with Normalized Mean Bias (NMB) under the multiple simulation scenarios (Fig. S3). Spring
 664 2021, 3.15, 3.27, and 4.18 represent the evaluation period by 12 March-20 April 2021, 14-16 March 2021,
 665 26-28 March 2021, and 17-19 April 2021, respectively.

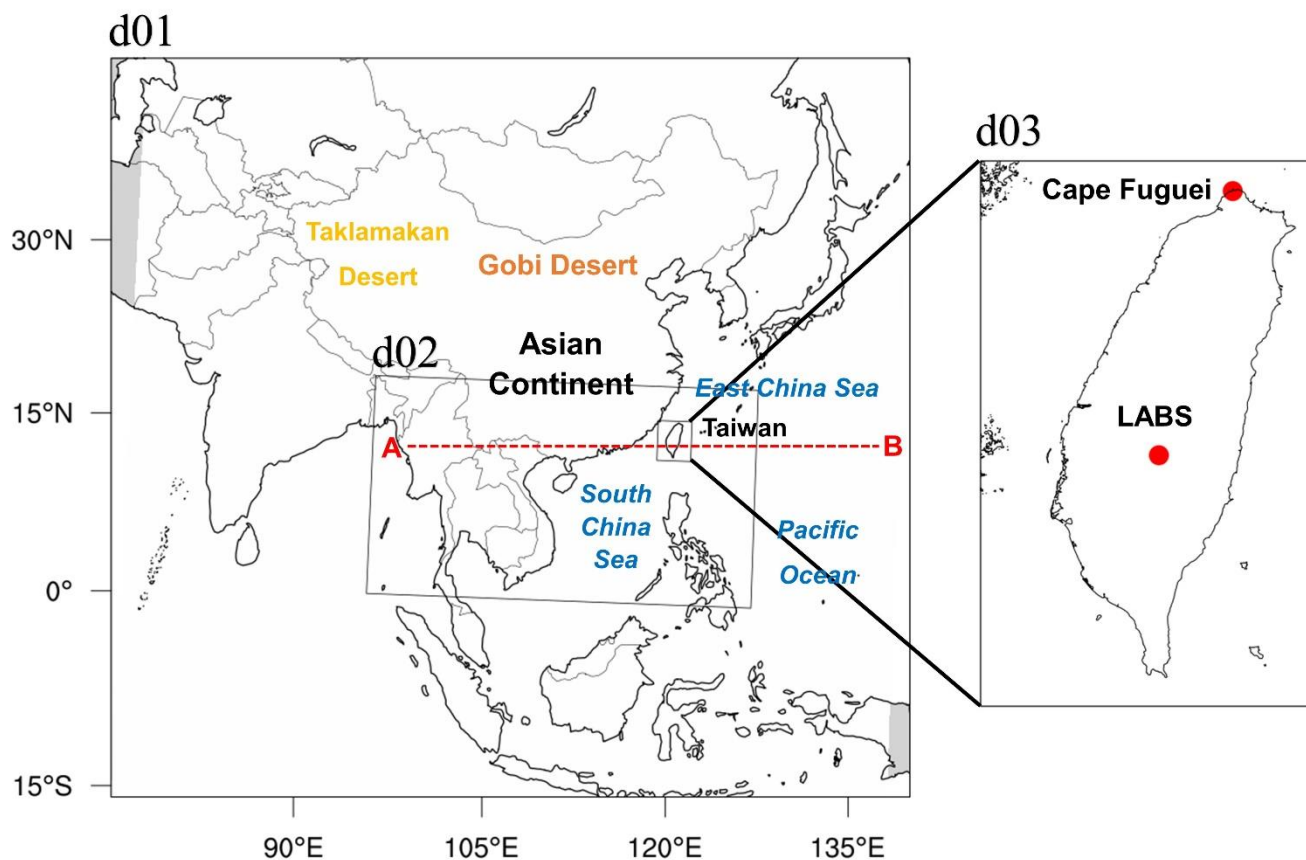
Parameters	Period	CMAQ-M3DRY			CMAQ-STAGE		
		Off_PR11	Dust_PR11	Dust_E20	Dust_S22	Dust_P22	
PM ₁₀	Spring 2021	-79.15	-60.53	-25.43	-45.97	-59.82	
PM _{2.5}	Spring 2021	-60.94	-44.84	-37.50	-36.29	-42.47	
AOD	3.15	-81.92	-49.54	-38.97	-46.41	-48.45	
	3.27	-75.10	-46.12	-36.39	-41.84	-44.52	
	4.18	-55.88	-16.49	-3.20	-7.83	-14.52	
	Mean AOD	-70.97	-37.38	-26.19	-32.03	-35.83	

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670 **Table 5.** Average deposition velocity and the percentage change by PR11 corresponding to E20, S22, and
 671 P22, for Aitken, Accumulation, and Coarse modes over land and ocean boundary layer, respectively.

Dry deposition schemes	Aitken		Accumulation		Coarse	
	Land	Ocean	Land	Ocean	Land	Ocean
PR11 (cm s ⁻¹)	0.080	0.062	0.061	0.042	0.264	0.109
E20 (cm s ⁻¹)	0.090	0.074	0.065	0.040	0.139	0.060
S22 (cm s ⁻¹)	0.219	0.117	0.120	0.064	0.078	0.085
P22 (cm s ⁻¹)	0.085	0.062	0.072	0.043	0.290	0.116
Δ E20 (%)	12.66	20.06	5.43	-5.19	-47.10	-44.65
Δ S22 (%)	173.74	89.45	96.52	52.35	-70.29	-21.44
Δ P22 (%)	6.10	1.37	17.66	1.52	10.06	6.86

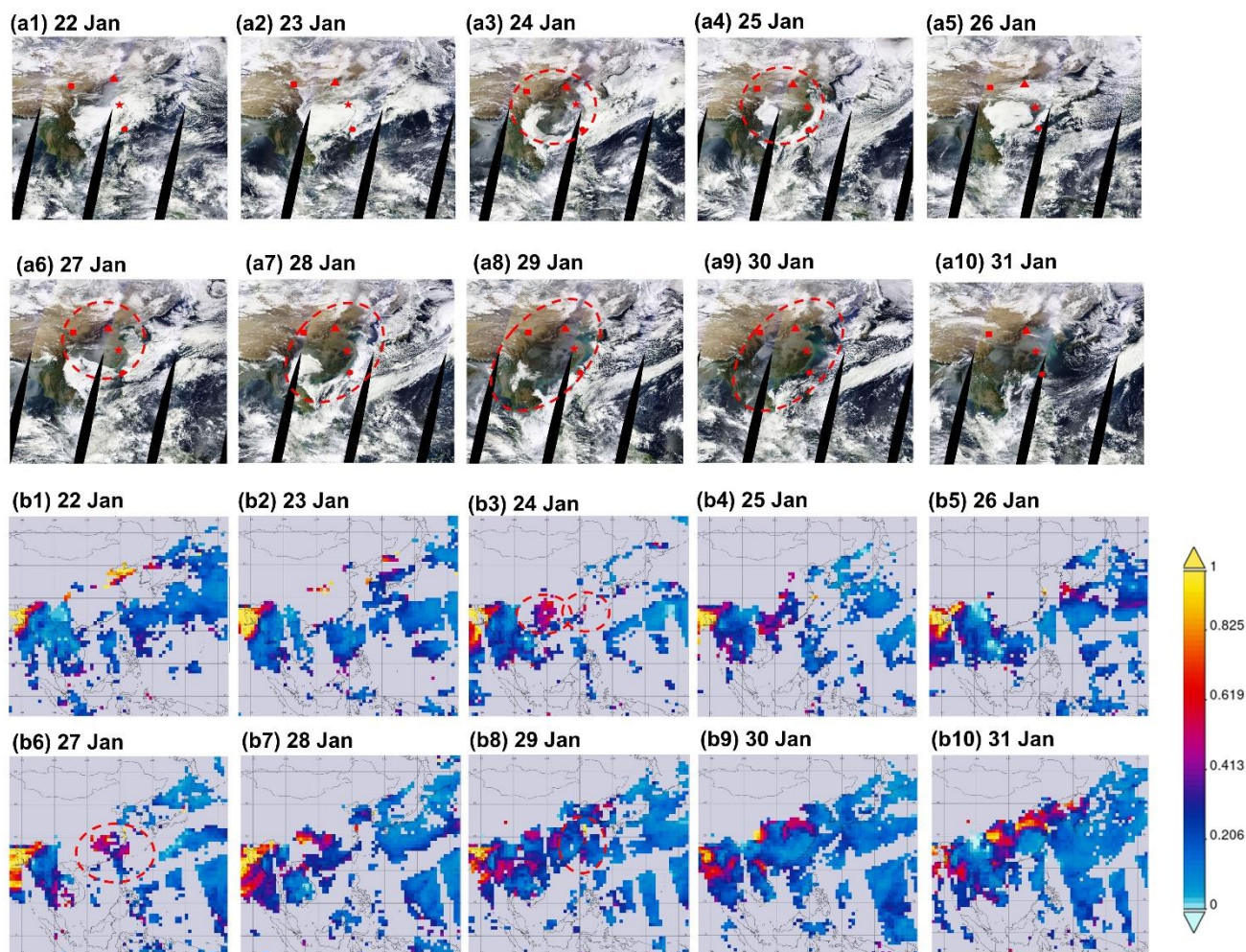
672 Note: the Δ represents the percentage change by PR11 relative to E20, S22, and P22.
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677 **Figure 1:** Modeling domain configuration in East Asia. Ground-based air quality stations in Taiwan at
 678 Cape Fuguei and Lulin Atmospheric Background Station (LABS) are shown in the zoomed panel. The
 679 red dash line (A→B) represents the transects that the aerosol plumes traveled along in this study and that
 680 are discussed in Section 3.4;

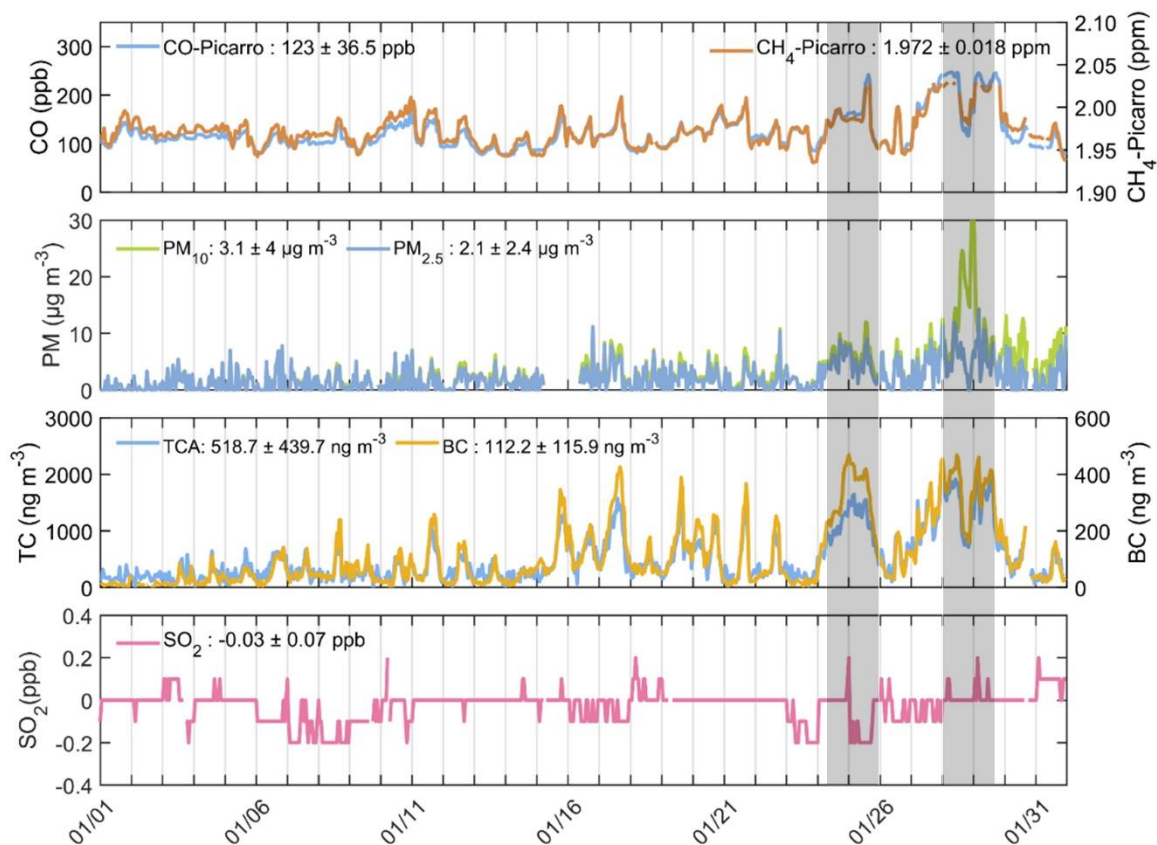
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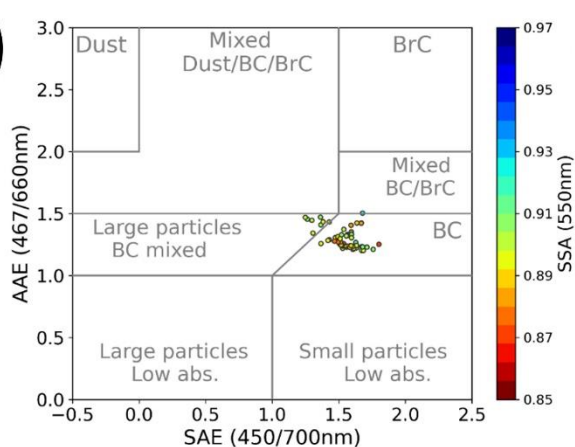
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 683 **Figure 2:** MODIS Terra images (a1-a10) and MODIS aerosol optical depth AOD at 550 nm (b1-b10)
 684 showing dust outbreak across East Asia during 22-31 January 2023. Red Rectangular, triangle, star and
 685 circle indicate Lanzhou, Beijing, Shanghai and Taiwan. The red circle with dash line indicates the dust
 686 plume.

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(a)



(b)



(c)

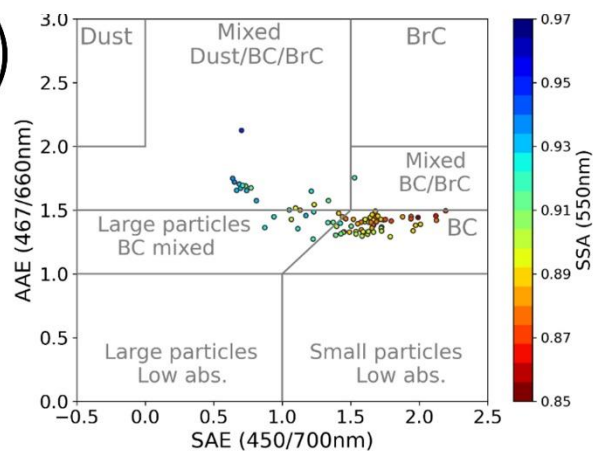


Figure 3: (a) Time series of observed pollutants over LABS during January 2023. The aerosol radiation properties during (b) 24-26 January and (c) 27-30 January 2023.

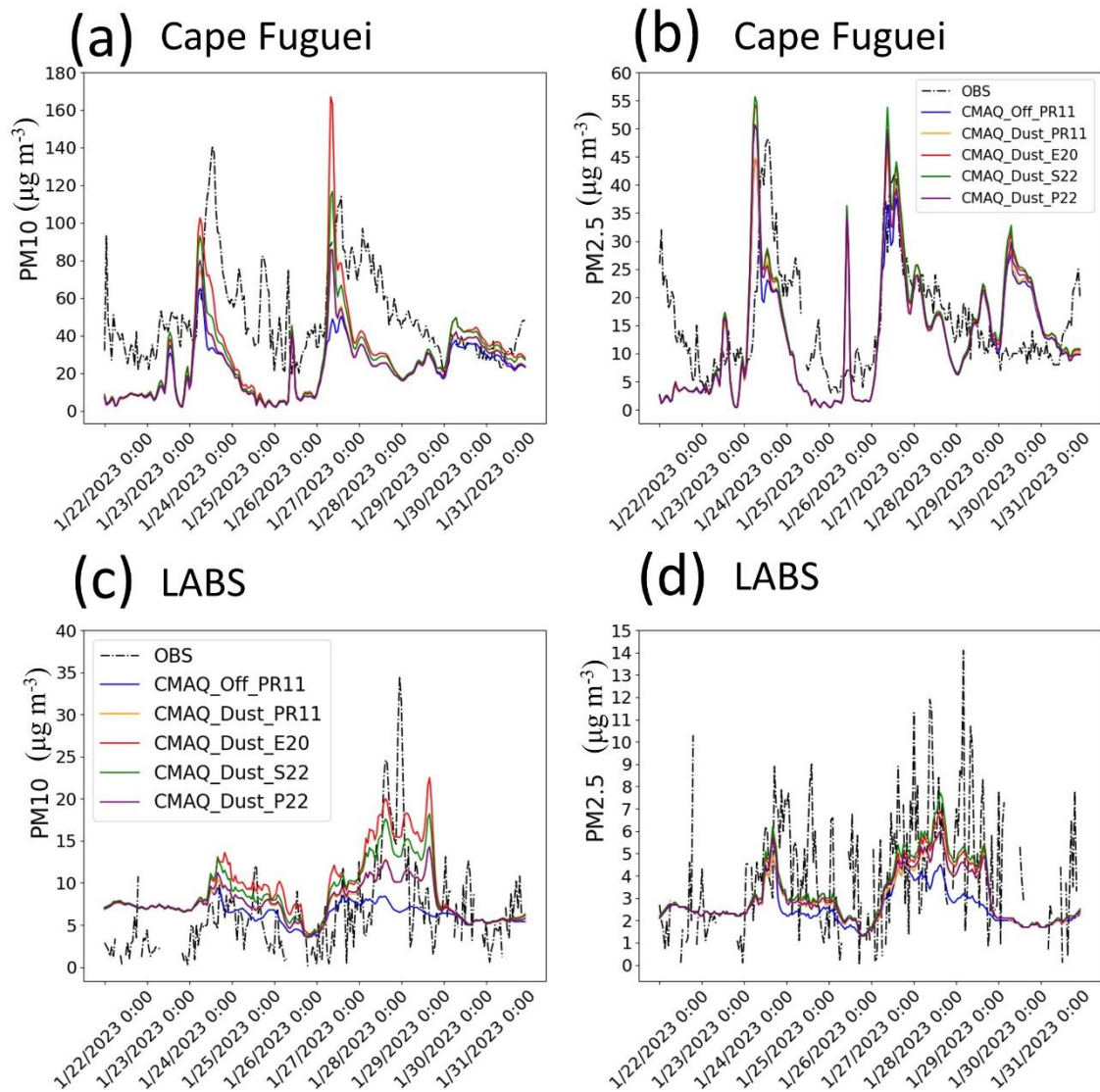
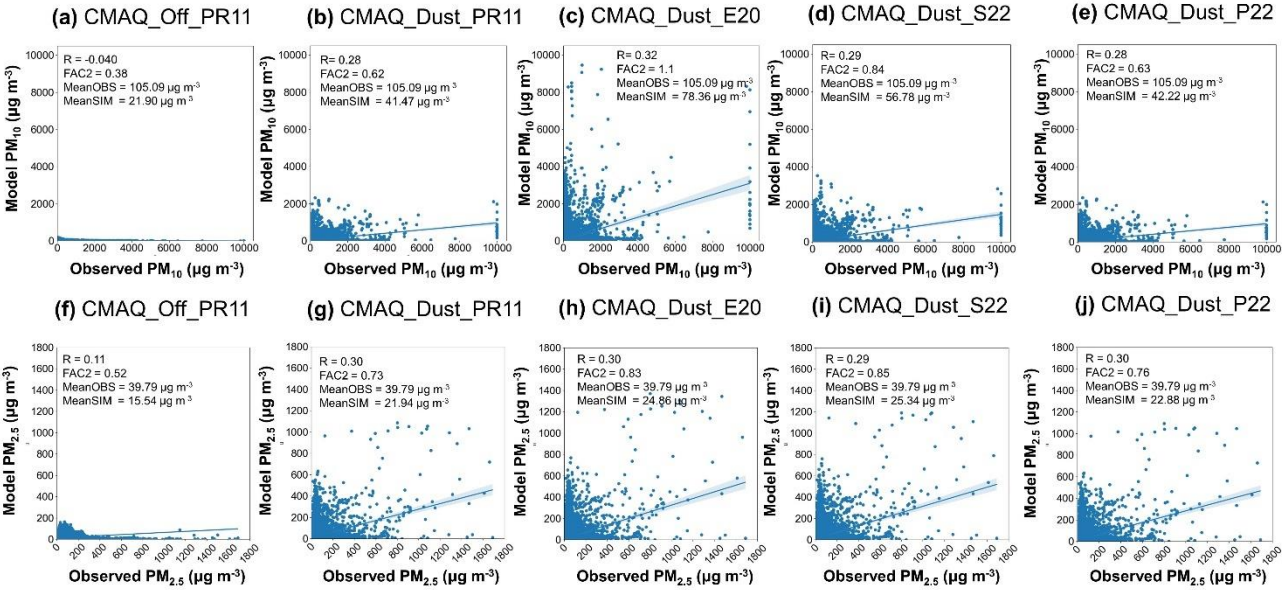


Figure 4: Time series of PM₁₀ (left panel) and PM_{2.5} (right panel) concentrations during 22-31 January 2023 under multiple deposition schemes over the Cape Fuguei (upper panel) and LABS (lower panel), representing the surface and high altitude, respectively.



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703 **Figure 5:** The scatter plot of the observed against modeled PM_{10} (a-e) and $PM_{2.5}$ (f-j) for
704 CMAQ_Off_PR11 (a, f), CMAQ_Dust_PR11 (b, g), CMAQ_Dust_E20 (c, h), CMAQ_Dust_S22 (d, I
705 and CMAQ_Dust_P22 (e, j), at the 100 sites of the mainland China on 12 March-20 April 2021
706 (<http://www.aqistudy.cn/>). R is the correlation coefficient between the observation and model; FAC2 is
707 the factor of two; MeanOBS and MeanSIM are the mean of PM from observation and model, respectively.

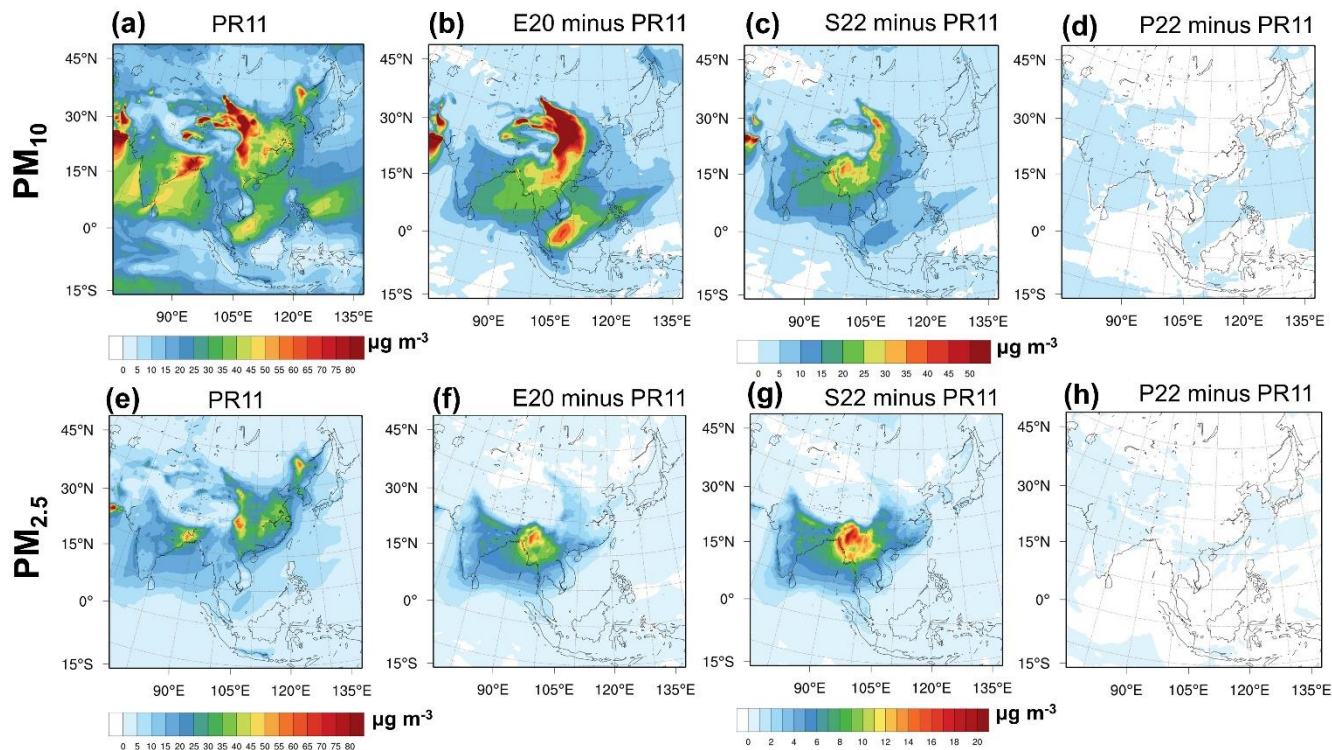
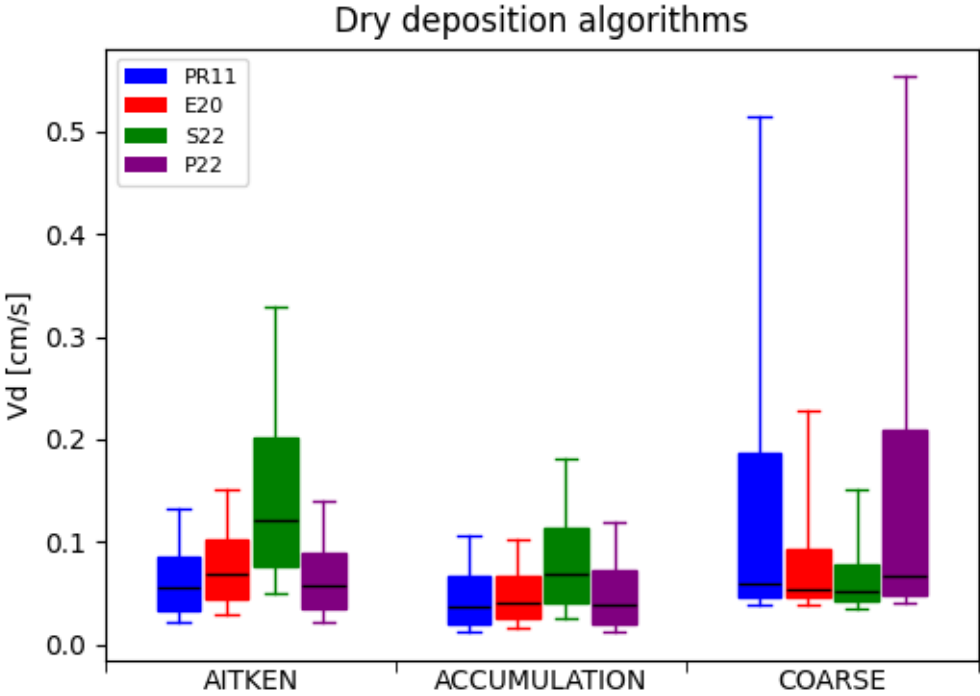


Figure 6: CMAQ estimated 10 days (22-31 January 2023) averaged mean (a-d) PM_{10} and (e-h) $PM_{2.5}$ for (a, e) PR11 dry deposition scheme and the corresponding concentration changes using (b, f) E20, (c, g) S22 and (d, h) P22 schemes.



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725 **Figure 7:** 10-days averaged dry V_d predicted by CMAQv5.4 for the Aitken, accumulation, and coarse
726 particle modes using the PR11(blue), E20(red), S22(green) and P22(purple) particle dry deposition
727 schemes. The variability illustrated by the boxes and whiskers corresponds to spatial variability in
728 annually averaged values throughout the CMAQ domain.

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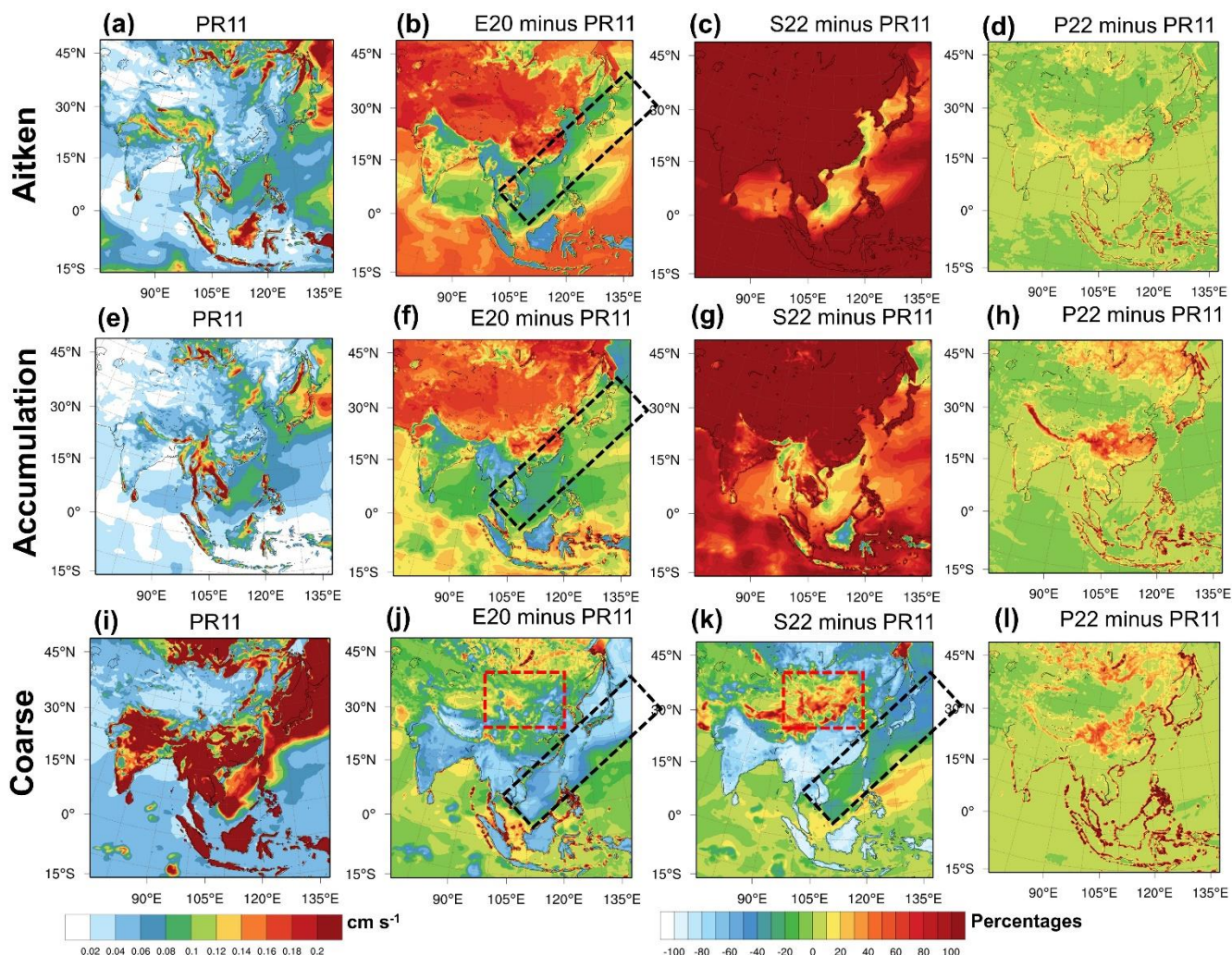
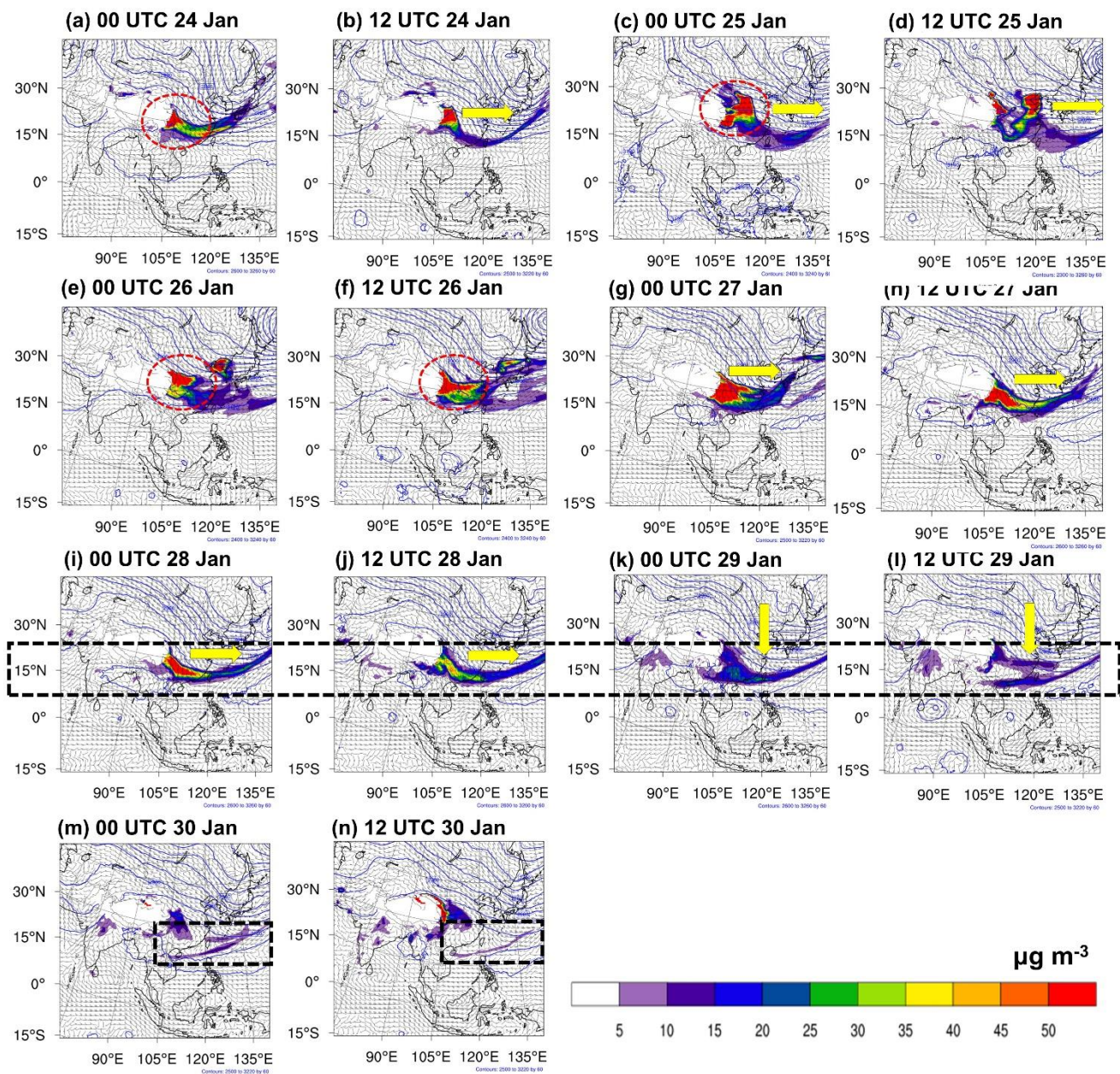


Figure 8: CMAQ estimated 10 days (22-31 January 2023) averaged for the (a-d) Aitken, (e-h) accumulation, and (i-l) coarse particle modes for PR11 dry deposition scheme (a, e, i) and the corresponding concentration percentage changes (%) using (b, f, j) E20, (c, g, k) S22 and (d, h, l) P22 schemes. Red-dash rectangular indicates the region across northwest China; Black-dash rectangular indicates the marine boundary layer.



741
 742 **Figure 9:** CMAQ mineral dust aerosol concentration at the 700 hPa during 24-30 January 2023. The
 743 yellow arrows highlight the trough moving direction. The dash-black rectangular box highlights the dust
 744 belt.
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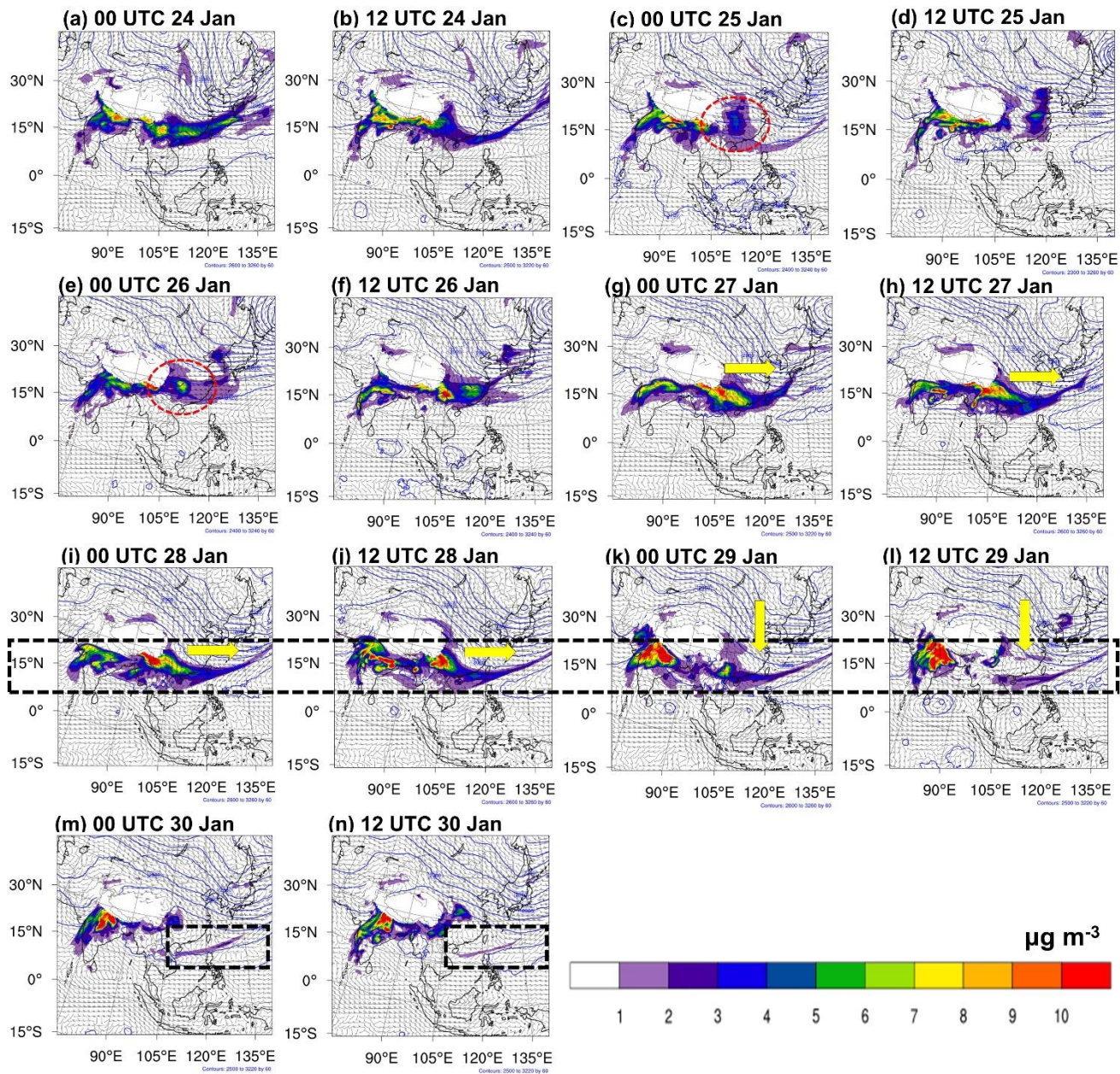


Figure 10: CMAQ black carbon concentration at the 700 hPa during 24-30 January 2023. The yellow arrows highlight the trough moving direction. The dash-black rectangular box highlights the dust belt.

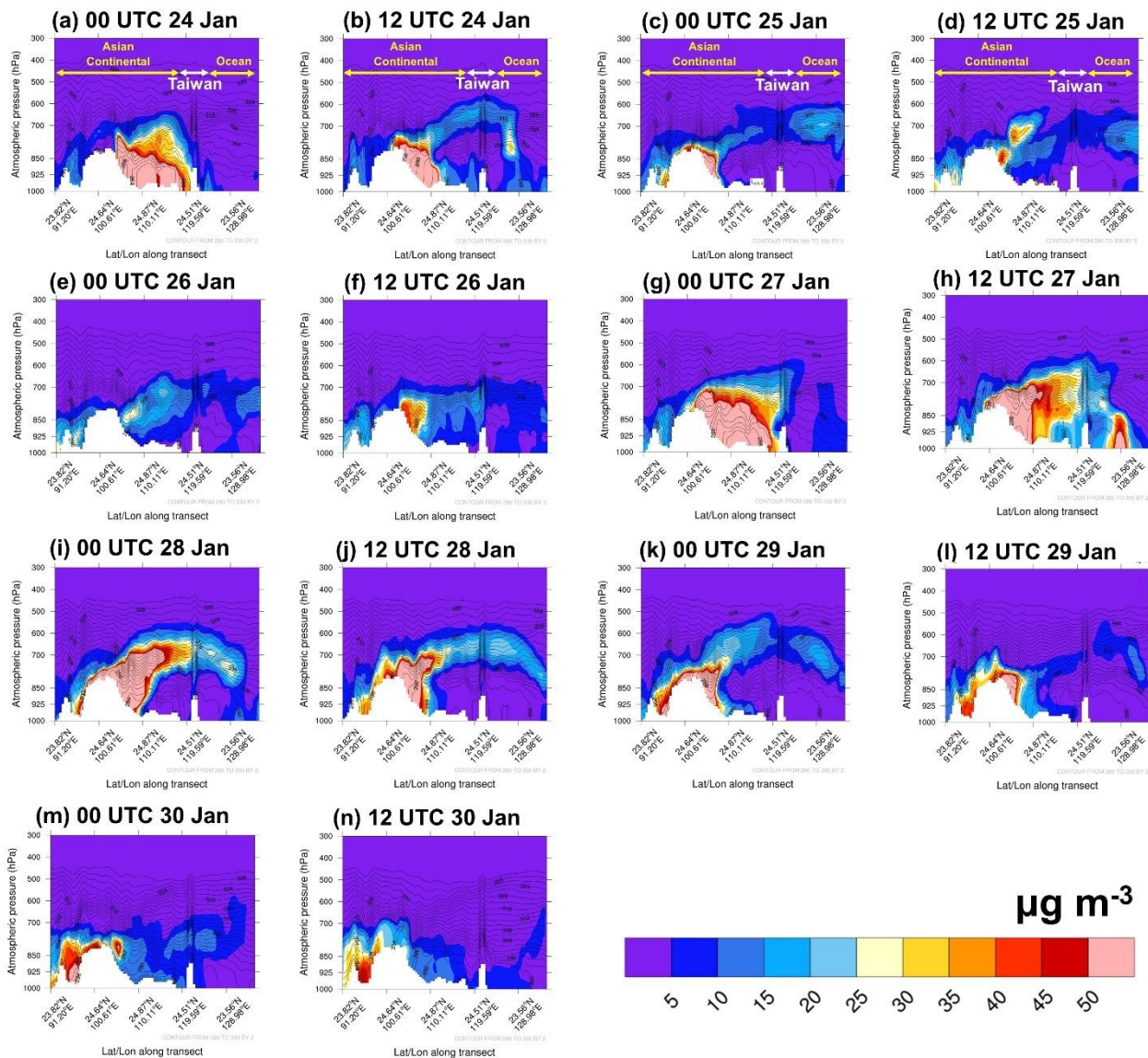


Figure 11: Vertical profile of simulated dust aerosol for the CMAQ simulation during 24-30 January 2023.

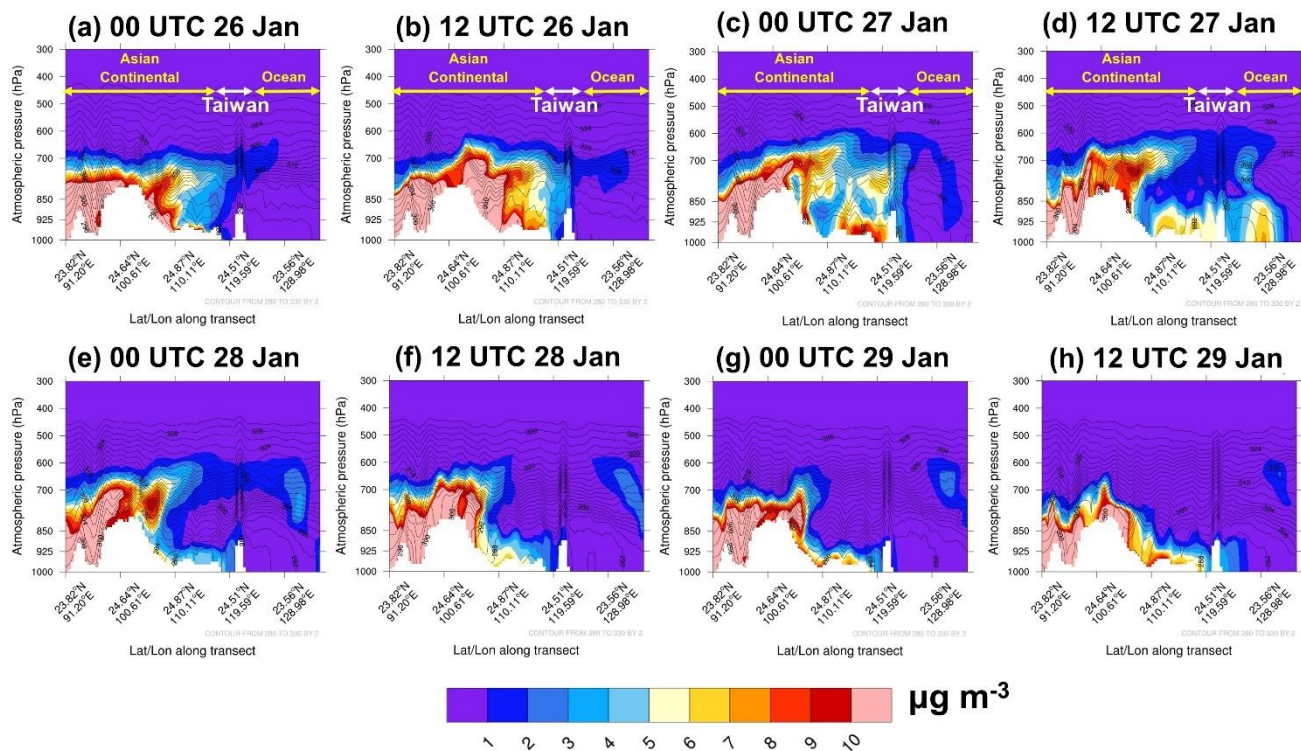


Figure 12: Vertical profile of simulated black carbon aerosol for the CMAQ simulation during 26-29 January 2023.