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Evaluation of Dust Emission and Land Surface Schemes in Predicting a Mega Asian Dust Storm over South Korea Using WRF-Chem (v4.3.3)

Ji Won Yoon[1,2], Seungyeon Lee[2,3], Ebony Lee[2,3], Seon Ki Park[1,2,3*]

[1]Center for Climate/Environment Change Prediction Research, Ewha Womans University, Seoul, 03760, Republic of Korea.
[2]Severe Storm Research Center, Ewha Womans University, Seoul, 03760, Republic of Korea.
[3]Department of Climate and Energy Systems Engineering, Ewha Womans University, Seoul, 03760, Republic of Korea.

Correspondence to: Seon Ki Park (spark@ewha.ac.kr)

Abstract. This study evaluates the performance of the Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem) in forecasting a mega Asian Dust Storm (ADS) event that occurred over South Korea on March 28–29, 2021. We specifically evaluated a combination of five dust emission schemes and four land surface schemes, which are crucial for predicting ADSs. Using in-situ and remote sensing data, we assessed surface meteorological and air quality variables, including 2 m temperature, 2 m relative humidity, 10 m wind speed, particulate matter 10 (PM10), and aerosol optical depth (AOD) over South Korea. Our results indicate that prediction of surface meteorological variables is more influenced by the land surface scheme than by the dust emission scheme---generally showing good performance when dust emission schemes are combined with the Noah land surface model with Multiple Parameterization options (Noah-MP). In contrast, prediction of air quality variables, including PM10 and AOD, is strongly affected by the dust emission schemes, which is directly related to the generation and amount of dust through interaction with surface properties. Among the total of 20 available scheme combinations, the University of Cologne 2004 combined with the Community Land Model version 4.0 (UoC04-CLM4) showed the best performance, closely followed by the University of Cologne 2001 combined with CLM4 (UoC01-CLM4). UoC04-CLM4 outperformed the other scheme combinations by reducing the root mean square errors of PM10 up to 29.6 %. However, both UoC04-CLM4 and UoC01-CLM4 simulated values closest to the MODIS AOD but tended to overestimate the AOD in some regions during the origination and transportation processes. In contrast, other scheme combinations significantly underestimated the AOD throughout the entire simulation process of ADSs.

1 Introduction

The sand dust storms (SDSs), originating from arid or semi-arid regions, can be lifted to several kilometers and then transported over long distances, sometimes crossing continents (Zhang et al., 2018). They can contain fine particulates, pollutants, and biological materials such as bacteria, viruses, and mold spores (WMO, 2020)---exerting significant impacts

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on human life and health. Therefore, accurate prediction of SDSs is essential to mitigate their impact on public health risks, quality of life, and economic loss.

The SDSs occur in many places around the world, including East Asia (He et al., 2022; Lee et al., 2015; Lee and Lee 2022), where they are also called Asian dust storms (ADSs), Southwest Asia, the Sahel, the Middle East, and the Mediterranean (Behrooz et al., 2022; Darvishi Boloorani et al., 2021; Su and Fung, 2015; Wu et al., 2016; Yu et al., 2018). In East Asia, the Taklimakan and Gobi Desert account for about 40 % of global dust emissions (Kok et al., 2021). The ADSs occur most often during the spring season, when surface conditions are dry and wind speeds are strong (Kurosaki and Mikami, 2005; Sun et al., 2001).

Located in East Asia, South Korea is geographically situated within the westerly wind belt; it is predominantly affected by ADSs originating from the Gobi Desert/Inner Mongolia region during the spring season (Lee et al., 2013). The SDSs are also named *Hwangsa* in Korean, literally meaning 'yellow sands' (Chun et al., 2008; In and Park, 2002; Park and Lee, 2004). It is noted that, of the ADS events that affected South Korea from 2002 to 2021, 82.4 % originated from the Gobi Desert/Inner Mongolia region and 64.7 % occurred in spring (Boo et al., 2022).

The Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem; Grell et al., 2005) has been extensively employed for simulating and forecasting the weather and air quality (i.e., trace gases, aerosols, etc.) variables. Since the WRF-Chem incorporates multiple parameterization schemes concerning the planetary boundary layer, land surface, dust emission, radiation, and other physical processes, its performance relies on the combination of parameterization schemes employed in the simulation (Najafpour et al., 2023; Parra, 2023; Rizza et al., 2018; Yuan et al., 2019: Zhao et al., 2020). Therefore, in order to understand the model responses to different parameterization schemes and to enhance the model performance, it is crucial to conduct the sensitivity experiments on the parameterization schemes for the targeted regions and variables.

The SDSs occur when wind speed exceeds a certain threshold value, eroding the soil and releasing dust particles (Chun et al., 2001). In WRF-Chem, the dust emission flux mainly depends on the soil type and the near-surface winds (Kok et al., 2012; Shao, 2008) within the dust emission scheme. Conversely, soil moisture, vegetation, and snow can influence changes in dust emission flux (Ginoux et al., 2001; Park et al., 2010), and they are primarily associated with the land surface scheme in WRF-Chem. For this reason, numerous studies have investigated the sensitivity of different parameterization schemes of the dust emission or land surface processes on simulating SDSs using WRF-Chem.

Yuan et al. (2019) investigated the sensitivity of a severe dust storm that occurred in Central Asia to three different dust emission schemes and showed that the sensitivity results varied across regions, indicating that significant differences in dust emission schemes essentially depend on the sensitivities of threshold friction velocity to surface properties. Najafpour et al. (2023) also examined the accuracy of five different dust emission schemes in estimating dust concentration for a severe SDS in Tehran, Iran; they found that the Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) and Air Force Weather Agency (AFWA) schemes had the best performance compared to the in-situ measurements. Zhao et al. (2020) studied the ability of five dust emission schemes to simulate dust emission and transport processes in northwest China; they

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identified that each of the five schemes had its own strengths and weaknesses, in terms of spatial pattern of dust source region, aerosol optical depth (AOD), aerosol extinction coefficient, and surface PM10 concentrations. Lee et al. (2022) conducted WRF-Chem simulations by changing the five dust emission schemes for severe wintertime ADS events over South Korea, noting that the University of Cologne 2001 (UoC01) and University of Cologne 2004 (UoC04) schemes were the most successful in simulating severe wintertime Asian dust events while the University of Cologne 2011 (UoC11), GOCART (GO01), and AFWA (GA19) schemes failed to predict them. Rizza et al. (2018) simulated AOD and PM10 for a severe Saharan dust event over southern Italy using three land surface schemes within the WRF-Chem model and reported that the Rapid Update Cycle (RUC) scheme significantly overestimated dust emissions, whereas Noah and Noah land surface model with Multiple Parameterization options (Noah-MP) performed better; they demonstrated the impact of the choice of land surface scheme on the prediction of dust emissions. Parra (2023) emphasized the critical importance of accurately representing surface-atmosphere interactions for numerical air-quality modeling by conducting sensitivity experiments on four land surface schemes within the WRF-Chem model.

Despite the direct influence of surface properties such as soil moisture, vegetation cover, snow, soil type, and near-surface wind on the dust emission flux, most of these sensitivity experiments focused solely on either dust emission or land surface schemes. Therefore, there were limitations in obtaining the best scheme combination that considers interaction between dust emissions and surface conditions. Furthermore, in the event of severe dust storms deviating from typical conditions, there may be discrepancies in outcomes compared to existing sensitivity studies. Hence, it is necessary to evaluate and propose schemes or combinations through appropriate sensitivity experiments.

In this study, we evaluated the performance of scheme combinations---five for dust emission schemes and four for land surface schemes---for meteorological and air quality variables in a mega ADS event, specifically on March 28–29, 2021, by using in-situ, including the Automated Surface Observing System (ASOS) and Asian dust observation data, remote sensing data, including the AErosol RObotic NETwork (AERONET) and the MODerate resolution Imaging Spectroradiometer (MODIS), and reanalysis data such as Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2), over South Korea.

Section 2 describes the ADS event and methodology, including parameterization schemes in WRF-Chem, and Section 3 describes the evaluation results. Conclusions are given in Section 4.

2 Methodology

2.1 Mega Asian dust event

Since South Korea is geographically located in the westerly wind zone, it is often affected by the ADSs that occur mainly in the Gobi and Inner Mongolia deserts in spring (March to May) (Lee et al., 2013). Consequently, the government of South Korea introduced the “ADS Crisis Warning System (ACWS)” in 2015. Additionally, the government and local authorities

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have prepared for health and safety problems that may arise among the population by utilizing the "ADS Response Manual" during the occurrence of ADSs.

The ACWS is divided into four-stage crisis warnings---Attention, Caution, Alert, and Severe. These stages are determined by the hourly average concentrations of PM10: 1) the Attention stage when hourly average concentrations of PM10 are expected to exceed 150 $\mu g\ m^{-3}$; 2) the Caution stage, more than 300 $\mu g\ m^{-3}$ for longer than 2 hours; 3) the Alert stage, more than 800 $\mu g\ m^{-3}$ for longer than 2 hours; 4) the Severe stage, more than 2,400 $\mu g\ m^{-3}$ for 24 hours and then expected to remain at that level for next 24 hours, or more than 1,600 $\mu g\ m^{-3}$ for 24 hours and then expected to maintain at that level for 48 hours. Generally, in South Korea, the PM10 concentrations more than 300 $\mu g\ m^{-3}$ indicate a high level, whereas those more than 800 $\mu g\ m^{-3}$ are considered a very high level (Boo et al., 2021).

On March 29, 2021, a mega ADS with the PM10 concentrations more than 1,000 $\mu g\ m^{-3}$ were observed in some regions of the Yellow Sea and South Korea. For the first time following the introduction of the ACWS in 2015, the Ministry of Environment of South Korea issued the Caution stage warning to 17 cities and provinces nationwide (Kim et al., 2022). Fig. 1 shows that the highest PM10 concentration was recorded at 1,491 $\mu g\ m^{-3}$ at Heuksando, an island located in the Yellow Sea, at 1800 UTC on March 29, 2021 (0300 LST on March 30). During this period, 9 out of 25 Asian dust observation stations from Korea Meteorological Administration (KMA) exceeded 800 $\mu g\ m^{-3}$, indicating a very severe ADS event in South Korea. Based on these findings, we selected this ADS event for this study, which occurred on March 29-30, 2021, and significantly impacted the air quality of South Korea.

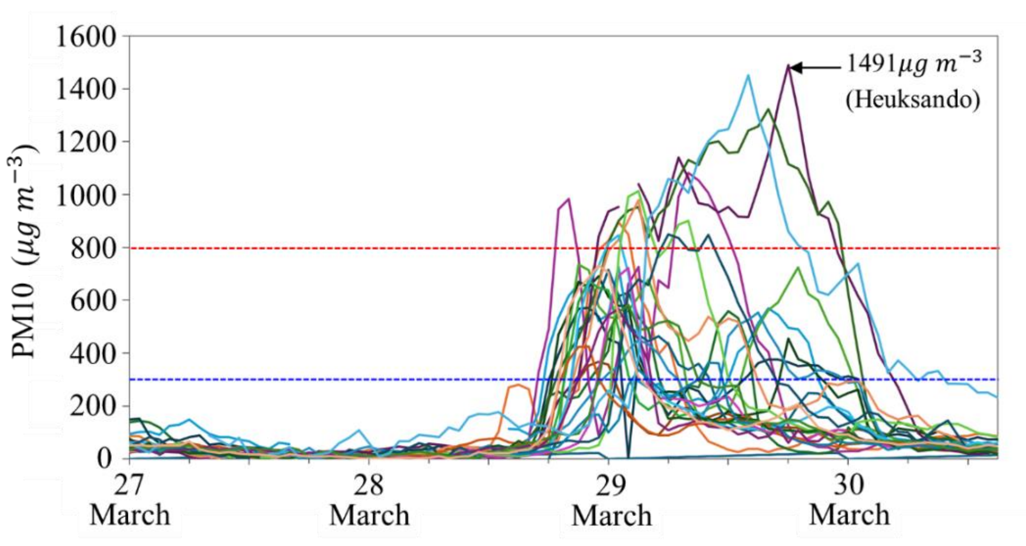

Figure 1: Time series of the hourly averaged PM10 concentrations from 0000 UTC (0900 LST) on March 27 to 1500 UTC on March 30 (0000 LST on March 31) at 25 Asian dust observation stations operated by KMA. Colored solid lines represent the PM10 concentrations at each Asian dust observation station. Blue and red dashed lines indicate the thresold values for the ACWS: the Caution (≥ 300 μg m^{-3}) and Alert (≥ 800 μg m^{-3}) stage, respectively.

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Figure 2 shows surface weather charts associated with the ADS from March 26 to 29, 2021. Here, the source region and site observations of ADSs are identified by the orange shaded area and red circles, respectively. At 1800 UTC on March 26, 2021, the ADS originated along the high pressure gradient side of a low pressure system in Mongolia (Fig. 2a). At 1200 UTC on March 27, as the low-pressure center moved to the eastern Mongolia and Inner Mongolia, the ADS moved to the Gobi Desert/Inner Mongolia (Fig. 2b). At 0600 UTC on March 28, the low-pressure center moved toward north of Manchuria, forming a northwest wind that could carry the sand dusts to South Korea; thus, the ADS moved toward the Bohai Bay, including the Liaodong Peninsula (Fig. 2c). Finally, by 0000 UTC on March 29, the ADS affected the entire areas of the Shandong Peninsula and South Korea (Fig. 2d).

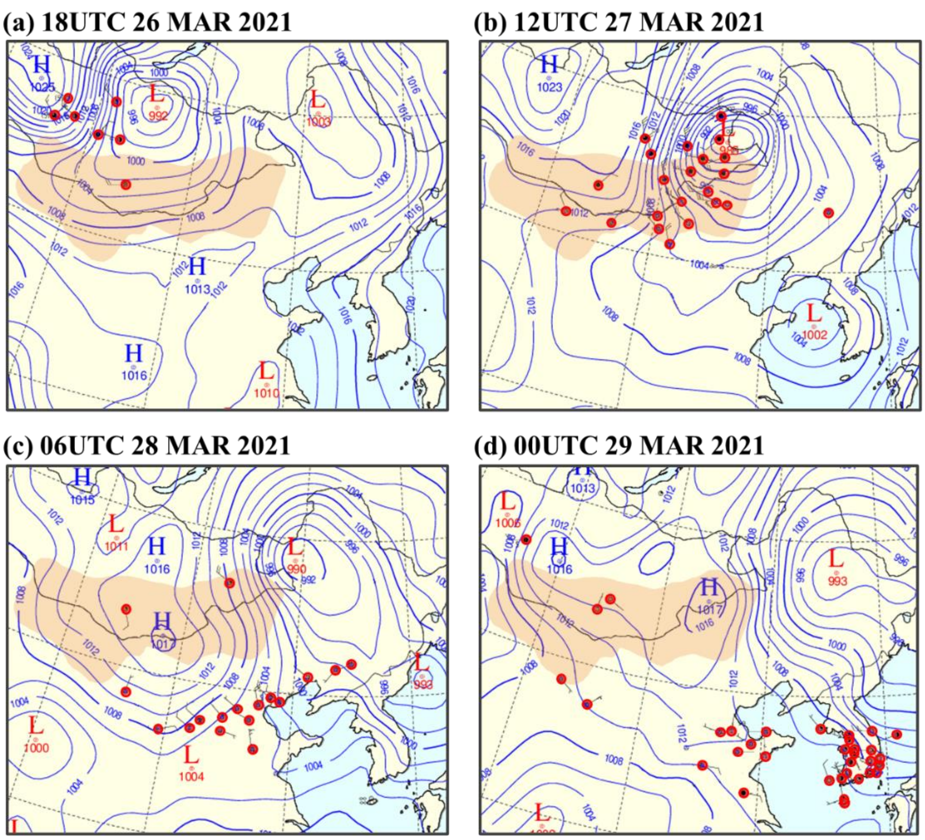

Figure 2: Surface weather charts indicating the source region (orange shading) and site observations (red circles) of the ADS event, along with the sea-level pressure (solid lines; in hPa for (a) 1800 UTC on 26 March, (b) 1200 UTC on 27 March, (c) 0600 UTC on 28 March, and (d) 0000 UTC on 29 March 2021. The source region represents the Gobi Desert, including part of Inner Mongolia. Modified from the weather charts by KMA (https://data.kma.go.kr/cmmn/main.do).

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2.2 WRF-Chem

In this study, we utilized the WRF-Chem model version 4.3.3, a fully coupled meteorology-chemistry model that accounts for interactions between meteorological and chemical processes (Grell et al., 2005). The model domain covers most of East Asia, focusing on the source regions and transport route of ADSs impacting South Korea (refer to Fig. 3), with a grid spacing of 30 km and 50 vertical levels up to 50 hPa.

The meteorological initial and boundary conditions are obtained from the global final analysis (FNL) dataset with a resolution of 0.25° × 0.25°, produced by the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP); the boundary conditions are updated every 6 h. The chemical initial and boundary conditions are derived from the Community Atmosphere Model with Chemistry (CAM-chem), part of the National Center for Atmospheric Research (NCAR)'s Community Earth System Model (CESM) and are produced using the mozbc pre-processing tool.

The physical and chemical schemes used in the study, excluding the dust emission and land surface schemes, are detailed in Table 1. The default physics schemes are as follows: Grell 3D ensemble for cumulus parameterization (Grell and Dévényi, 2002), Morrison two-moment scheme for cloud microphysics (Morrison et al., 2009), Mellor-Yamada-Nakanishi-Niino level 2.5 (MYNN2; Nakanishi and Niino, 2006) for planetary boundary layer processes, and the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) for both shortwave and longwave radiation (Iacono et al., 2008). For chemistry option, MOZCART is selected, which merges the Model for Ozone and Related Chemical Tracers (MOZART) gas-phase chemistry module (Emmons et al., 2010) with the GOCART aerosol module (Chin et al., 2000a, b; Ginoux et al., 2001; Chin et al., 2002). The global emission inventory for anthropogenic emissions is obtained from the Emission Database for Global Atmospheric Research developed for the Hemispheric Transport of Air Pollutants assessment (EDGAR-HTAP; Janssens-Maenhout et al., 2015), and the updated Tropospheric Ultraviolet Visible (TUV; Madronich et al., 2002) scheme for photolysis is used.

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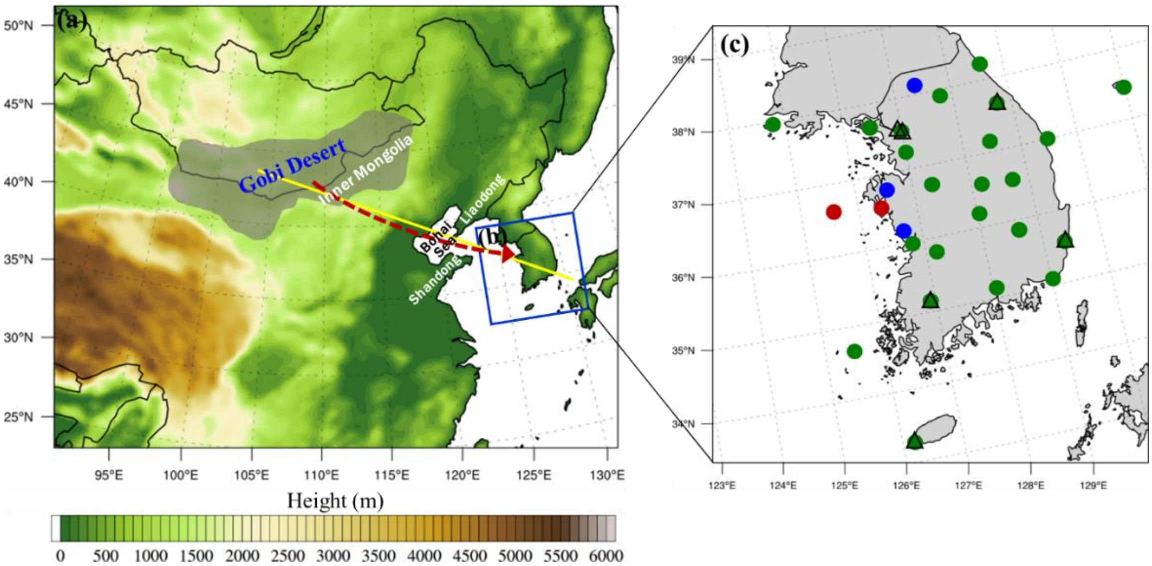

Figure 3: The computational domain with WRF-Chem for (a) simulation, (b) verification against in-situ and AERONET data in South Korea, and (c) locations of the ASOS, Asian dust observation stations, and AERONET used for verification: In (a), the gray shadings represent the ADSs source regions for this study case, and the red dashed arrow indicates the main route of ADSs. The solid yellow line denotes the location for vertical cross-section analysis (see Fig. 11 and Fig. S7). In (c), the green circles indicate the locations where the ASOS and Asian dust observation stations coexist---23 stations; the blue circles represent ASOS stations only---3 stations; the red circles depict Asian dust observation stations only---2 stations; and the black triangle indicates AERONET sites---6 sites.

Table 1: The default physical and chemical schemes used in WRF-Chem simulations.

	Processes	Schemes / Options
Physics	Microphysics	Morrison double-moment
	Cumulus	Grell 3D ensemble
	PBL	MYNN2
	Shortwave radiation	RRTMG
	Longwave radiation	RRTMG
Chemistry	Gas phase chemistry/Aerosols	MOZCART
	Anthropogenic	EDGAR-HTAP
	Photolysis	Updated TUV

We run WRF-Chem with a 1-hour interval from the occurrence of ADSs in the source region to their complete disappearance in South Korea, including a spin-up time of 72 hours; therefore, the model run period is from 1200 UTC

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March 24 to 0000 UTC on March 31, 2021. Note that the 72-hour spin-up time is not included in the evaluation process whose performance are calculated every hour and summed up for the total analysis period.

2.3 Dust emission and land surface schemes

In this study, the sensitivity experiments of scheme combinations are performed for a total of 20 combinations of five dust emission and four land surface schemes in WRF-Chem: the dust emission scheme include the GOCART (Ginoux et al., 2001), AFWA (LeGrand et al., 2019), and 3 versions of University of Cologne schemes---UoC01, UoC4, and UoC11 (Shao, 2001, 2004; Shao et al., 2011); the land surface schemes include Noah land surface model (Noah; Chen and Dudhia, 2001; Ek et al., 2003), Rapid Update Cycle (RUC; Benjamin et al., 2004), Noah land surface model with multiple parameterization options (Noah-MP; Niu et al., 2011), and Community Land Model version 4.0 (CLM4; Oleson et al., 2010). Table 2 lists the parameterization schemes used in the above-mentioned description. Hereinafter, in order to distinguish between different scheme combinations, each sensitivity experiment is named in the following format: 'dust emission scheme-land surface scheme' (e.g., GOCART-Noah, GOCART-RUC, AFWA-Noah, etc.).

Table 2: Parameterization schemes of WRF-Chem used for the sensitivity experiment: the dust emission and land surface schemes. The option numbers are the same as in the *namelist* of WRF-Chem.

Dust emission scheme		Land surface scheme	
Scheme	**Option** (dust_opt / dust_scheme)	**Scheme**	**Option** (sf_surface_physics)
GOCART	1 / -	Noah	2
AFWA	3 / -	RUC	3
UoC01	4 / 1	Noah-MP	4
UoC04	4 / 2	CLM4	5
UoC11	4 / 3		

2.3.1 Dust emission schemes

The GOCART scheme calculates the dust emission flux based on 10 m wind speed and soil wetness for five bin sizes of dust particles: 0.73 μm (0–1 μm), 1.4 μm (1–1.8 μm), 2.4 μm (1.8–3 μm), 4.5 μm (3–6 μm), and 8.0 μm (6–10 μm). The dust emission flux at each bin size is estimated as function of F_p (Ginoux et al., 2001)

$$F_p = \begin{cases} CS s_p u_{10m}^2 \left(u_{10m} - u_t\right) & \text{if } u_{10m} > u_t \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

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where C is an empirical constant (0.8); S is dust erodibility factor; s_p is the fraction of each bin size class---it is fixed as 0.1 for 0.73 μm and 0.25 for the other bin sizes; u_{10m} is the horizontal wind speed at 10 m height above ground level; u_t is the threshold velocity, a minimum wind speed at which dust emission can occur, and it depends on particle size and soil wetness. The AFWA scheme was updated version based on the Marticorena-Bergametti (MB) dust emission scheme (Marticorena and Bergametti, 1995) in GOCART scheme (Chin et al., 2000). It uses friction velocity (u_*) to calculate saltation flux from the surface for a particular dust size as (White, 1979)

$$H(D_p) = \begin{cases} C\frac{\rho_a}{g}\left(1+\frac{u_{*t}}{u_*}\right)\left(1-\frac{u_{*t}^2}{u_*^2}\right) & u_* \geq u_{*t} \\ 0 & u_* < u_{*t}, \end{cases} \tag{2}$$

where $H(D_p)$ is the saltation flux; C is an empirical constant (1.0); ρ_a is the air density; g is gravitational acceleration; u_* is the friction velocity; u_{*t} is threshold friction velocity---a function of particle size, air and soil density, soil moisture, and roughness. The total horizontal saltation flux calculated as follows:

$$G = \sum_s H(D_p) dS_{rel}(D_p), \tag{3}$$

where G is total horizontal saltation flux considering the sum of each particle size (D_p); s represents 9 sand particles that are composed of 1 Clay, 5 Silt, and 3 Sand particles, each defined by specific particle density and effective diameter; dS_{rel} is relative weighting factor for each particle size bin (D_p). The vertical dust flux is then calculated as (Marticorena and Bergametti, 1995)

$$F_{bulk} = GS\beta, \tag{4}$$

where F_{bulk} is the vertical dust flux---a dust emission flux; S is the erodibility function; β is the sandblasting efficiency factor (Gillette, 1979)---an empirical function of soil properties (Marticorena and Bergametti, 1995)

The UoC01, UoC04, and UoC11 are three versions of dust emission schemes based on Shao (2001), Shao (2004) and Shao et al. (2011), respectively. This latter is further divided into three emission parameterizations with an increasing level of simplification (Shao, 2001, 2004; Shao et al., 2011). The calculation of dust emission flux for UoC01 is as follows:

$$F(d_i, d_s) = c_y\left[(1-\gamma) + \gamma\frac{p_m(d_i)}{p_i(d_i)}\right]\frac{Q_{ds}g}{u_*^2 m}\left(\rho_b \eta_{fi}\Omega + \eta_{ci} m\right), \tag{5}$$

where $F(d_i, d_s)$ is the vertical dust flux of particle size (d_i) generated by the saltation of particle size (d_s); c_y is a dimensionless coefficient; γ is the weight factor related to dust particle size distribution, $p_m(d_i)$ and $p_i(d_i)$ are minimally and fully disturbed particle size distribution of the parent soil, respectively; ρ_b is the soil density; m is dust particle mass; Ω is the volume removed by an impacting saltation particle; η_{fi} is the mass fraction of dust that can be discharged; η_{ci} is the mass fraction of the aggregated dust; Q is the saltation flux of particles of size d_s.

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The dust emission flux in UoC04 is simplified compared to that in the UoC01 scheme (Shao, 2004). The calculation is as follows:

$$F(d_i, d_s) = c_y \eta_{fi}\left[(1-\gamma) + \gamma\sigma_p\right]\frac{Q_{ds}g}{u_*^2}(1+\sigma_m), \tag{6}$$

$$\sigma_p = \frac{p_m(d_i)}{p_i(d_i)}, \tag{7}$$

where σ_p is the mass ratio of free and aggregated dust; σ_m is the bombardment efficiency.

The UoC11 scheme is further simplified based on the UoC04 scheme. In this scheme, γ is set to 1, and the dust emission flux is determined as follows:

$$F(d_i, d_s) = c_y \eta_{fi}\sigma_p\frac{Q_{ds}g}{u_*^2}(1+\sigma_m) \tag{8}$$

2.3.2 Land surface schemes

The Noah scheme assesses soil moisture and temperature in four soil layers with thicknesses of 10, 30, 60, and 100 cm, incorporating vegetation and snow dynamics. It uses equations for soil thermal diffusion and hydrology to determine soil moisture and temperature while accounting for surface energy and water balance. Moreover, it explicitly includes physics related to vegetation and hydrological processes such as evapotranspiration, canopy resistance, surface runoff, soil drainage, albedo, and the influence of urban canopies.

The RUC scheme demonstrates various phases of soil surface water, vegetation effects, and canopy water dynamics; it calculates heat diffusion and moisture transfer through nine soil layers from 0 to 300 cm, with a focus on soil temperature, soil moisture, and snow dynamics (Smirnova et al., 2016). This scheme features a thin surface layer that covers half of the first atmospheric layer and half of the topsoil layer, ensuring accurate representation of the energy budget and incorporates the part of canopy moisture and soil texture to reflect the effect of vegetation on evaporation.

The Noah-MP scheme built on the Noah framework but includes updates in physics that encompass dynamic vegetation and ecological processes, as well as snow and underground water processes. This scheme allows flexibility in selecting from multiple options for each physical parameterization. In this study, the default options for each parameterization in the WRF-Chem model are used.

The CLM4 is applied in climate studies because of its advanced handling of hydrology, biogeochemistry, biogeophysics, and dynamic vegetation. Its vertical structure consists of a single-layer vegetation canopy, a ten-layer soil column, and a five-layer snowpack (Skamarock et al., 2008). It employs a conceptual Topography-based Hydrological Model (TOPMODEL) to calculate overland flow, focusing on the biogeophysics of the land surface and vegetation dynamics.

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2.4 Evaluation data and methods

2.4.1 Surface observation data

The surface meteorological variables, including 2 m temperature (T2m), 2 m relative humidity (RH2m), 10 m wind speed (WS10m) and surface PM10 concentration, obtained from the ASOS and the Asian dust observation stations (see Fig. 3c) as operated by KMA, were used to evaluate the performance of scheme combinations during the mega ADS event. The T2m and RH2m were utilized as observation data collected at hourly intervals. Due to fluctuations, the WS10m were used as the 10-minute average wind speed before each hourly. Since the PM10 concentrations were collected at 5-minute intervals, the analysis was conducted using the hourly average concentrations.

2.4.2 Remote sensing data

The AERONET is a global network of ground-based remote sensing aerosol and provides a long-term database of globally distributed aerosol optical properties---AOD, single scattering albedo, and particle size distribution (Holben et al., 1998). In this study, we utilized the Angström exponent (AE) between 440 and 675 nm and AOD at 500 nm, collected from six sites over South Korea (see Fig. 3c), to calculate the AOD at 550 nm for evaluation. The conversion formula is as follows:

$$AOD(550) = AOD(500) \times \left(\frac{550}{500}\right)^{-\alpha}, \tag{9}$$

where α indicates AE between 440 and 675 nm, and $AOD(500)$ and $AOD(550)$ represents AOD at 500 and 550 nm, respectively.

The MODIS instruments on the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites observe and monitor Earth's changes with high spatial resolution. They provide near-daily global coverage, allowing the monitoring of various phenomena such as tropospheric aerosols (Kaufman et al., 1997). The MODIS Deep Blue algorithm enables the retrieval of AOD data even over high-albedo surfaces such as deserts and snow-covered areas (Hsu et al., 2006), with a spatial resolution of 10 × 10 km^2 at 550 nm. In this study, the AOD data retrieved from Terra Collection 6.1 Level 2 MODIS Deep Blue algorithm (MOD04_L2) are used to assess the time-varying horizontal distribution of simulated AOD by scheme combinations.

2.4.3 Reanalysis data

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), represents the latest atmospheric and aerosol reanalysis product from NASA's Global Modeling and Assimilation Office (Gelaro et al., 2017). The MERRA-2 is derived from the Goddard Earth Observing System, version 5 (GEOS-5) (Molod et al., 2015; Rienecker et al., 2008), utilizing the GOCART model (Chin et al., 2002) aerosol module (Buchard et al., 2017; Randles et al., 2016) and offers a spatial resolution of 0.5° latitude by 0.625° longitude, with 72 vertical layers from the surface up to 0.01 hPa. The MERRA-2 assimilates AOD from a variety of ground-based and remote sensing sources, including the AErosol RObotic

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NETwork (AERONET; 1999–2014), Advanced Very High Resolution Radiometer (AVHRR), Multiangle Imaging SpectroRadiometer (MISR; 2000–2014), and MODIS on both Terra (2000–present) and Aqua (2002–present) satellites (Buchard et al., 2017; Gelaro et al. 2017). In this study, MERRA-2 is employed to compare the AOD spatial distribution with the AOD simulated by various scheme combinations.

2.4.4 Evaluation Metrics

In this study, the simulated surface meteorological variables and PM10 concentrations were compared with observation data using two types of evaluation methods: 1) Using the difference between predicted and observed values---Pearson's correlation coefficient (PCC) represents the level of linear relationship between the forecasts and observations; mean bias error (MAE) is the arithmetic average of the differences between forecasts and observations; root mean square error (RMSE) estimates the average error of the model and uses the square of the difference between the forecasts and observations; 2) Determining detection success using an arbitrary threshold (categorical metrics)---this method requires a threshold for binary classification using a 2 x 2 contingency table (see Table 3) and was applied for only PM10 evaluations in this study.

For categorical metrics, we considered the threshold values of the Fine dust alert and ACWS provided by the Atmospheric Environment Administration of South Korea---the threshold values are 80 $\mu g\ m^{-3}$ (poor air quality due to fine dust), 150 $\mu g\ m^{-3}$ (very poor air quality due to fine dust; Attention), 300 $\mu g\ m^{-3}$ (Caution), and 800 $\mu g\ m^{-3}$ (Alert), respectively. In Table 3, 'Hit' and 'Correct rejection' indicate accurate predictions, whereas 'False alarm' and 'Miss' suggest inaccurate predictions. The Probability Of Detection (POD) evaluates the ratio of accurate forecasts to observed events, indicating how often an event is predicted correctly when it occurs. It ranges from 0 to 1, with 1 indicating a perfect forecast and below 0.5, poor performance. Note that POD does not account for events without observed events, which means that an increased tendency to overestimate the frequency of events can lead to an artificial improvement in performance. The False Alarm Rate (FAR) is utilized to assess the ratio of false alarms to events, predicting an event when it is not observed. FAR also ranges between 0 and 1, where values closer to 0 indicate better forecast skill. In contrast to POD, since FAR does consider events without observed events, an increased tendency to underestimate the frequency of non-events can result in an artificial skill improvement. Therefore, it is essential to consider FAR with POD to address these limitations. The formulas for POD and FAR are as follows:

$$POD = \frac{a}{a+c} \tag{10}$$

$$FAR = \frac{b}{b+d} \tag{11}$$

Table 3: Contingency table for forecast evaluation: this table categorizes the outcomes of forecasts versus actual observations into four distinct types---Hit (a), when both the forecast and observation agree on the event occurring; False alarm (b), when the

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forecast predicts an event that does not occur; Miss (c), when an event occurs but is not forecasted; and Correct rejection (d), when neither the forecast nor the observation indicates the occurrence of an event.

		Observation	
		Yes	**No**
Forecast	**Yes**	Hit (a)	False alarm (b)
	No	Miss (c)	Correct rejection (d)

3 Results

3.1 Verification with in-situ data

The verification against the in-situ data (i.e., ASOS and Asian dust observation stations) is conducted for T2m, RH2m, WS10m, and surface PM10 concentrations at the given observational stations in South Korea. The values are averaged over the stations (see the station locations in Fig. 3c).

3.1.1 Surface meteorological variables

Figure 4 shows PCC for all scheme combinations. Since surface meteorological variables are primarily influenced by the land surface scheme, the performance differences caused by the dust emission schemes were very small in the validation results. The scheme combinations generally have good performance with high to moderate PCCs for surface meteorological variables: 0.73−0.77 for T2m, 0.73−0.77 for RH2m, 0.58−0.62 for WS10m (Fig.4). More details are as follows: 1) For T2m, the best performance is achieved by scheme combinations based on Noah-MP (0.77), followed by CLM4 (0.74−0.75), Noah (0.74), and RUC (0.72−0.73) (Fig 4a); 2) For RH2m, the best performance is also shown by combinations based on Noah-MP (0.77), followed by CLM4 (0.74−0.75), Noah (0.74−0.75), and RUC (0.72−0.73) (Fig. 4b); 3) For WS10m, similar performance is achieved by scheme combinations based on Noah-MP (0.61−0.62), RUC (0.61−0.62), and CLM4 (0.61), followed by Noah (0.58−0.60) (Fig. 4c).

Figure S1 shows the RMSE for all scheme combinations: 1) For T2m, Noah-MP-based combinations showed the best performance, followed by Noah-, CLM4-, and RUC-based combinations (Fig. S1a); 2) For RH2m, Noah-MP- and Noah-based combinations showed similarly good performance, followed by CLM4- and RUC-based combinations (Fig. S1b); 3) For WS10m, Noah-MP-based combinations still showed the best performance, followed by RUC-based combinations (Fig. S1c). Fig. S2 shows the MBE for all scheme combinations: 1) For T2m, Noah-MP- and Noah-based combinations showed similarly large MBEs, with a negative trend across all experiments (Fig. S2a); 2) For RH2m, Noah-MP- and Noah-based combinations also showed similarly good performance, with positive bias across all experiments (Fig. S2b); 3) For WS10m, Noah-MP-based combination showed the best performance, with positive bias (Fig. S2c).

Overall, for surface meteorological variables, the Noah-MP-based combinations showed the best performance. The Noah-MP scheme provides reliable lower boundary conditions by accurately representing surface variables through more precise calculations of heat and moisture fluxes compared to other land surface schemes within the planetary boundary layer (Rizza et al., 2018; Wang et al., 2023).

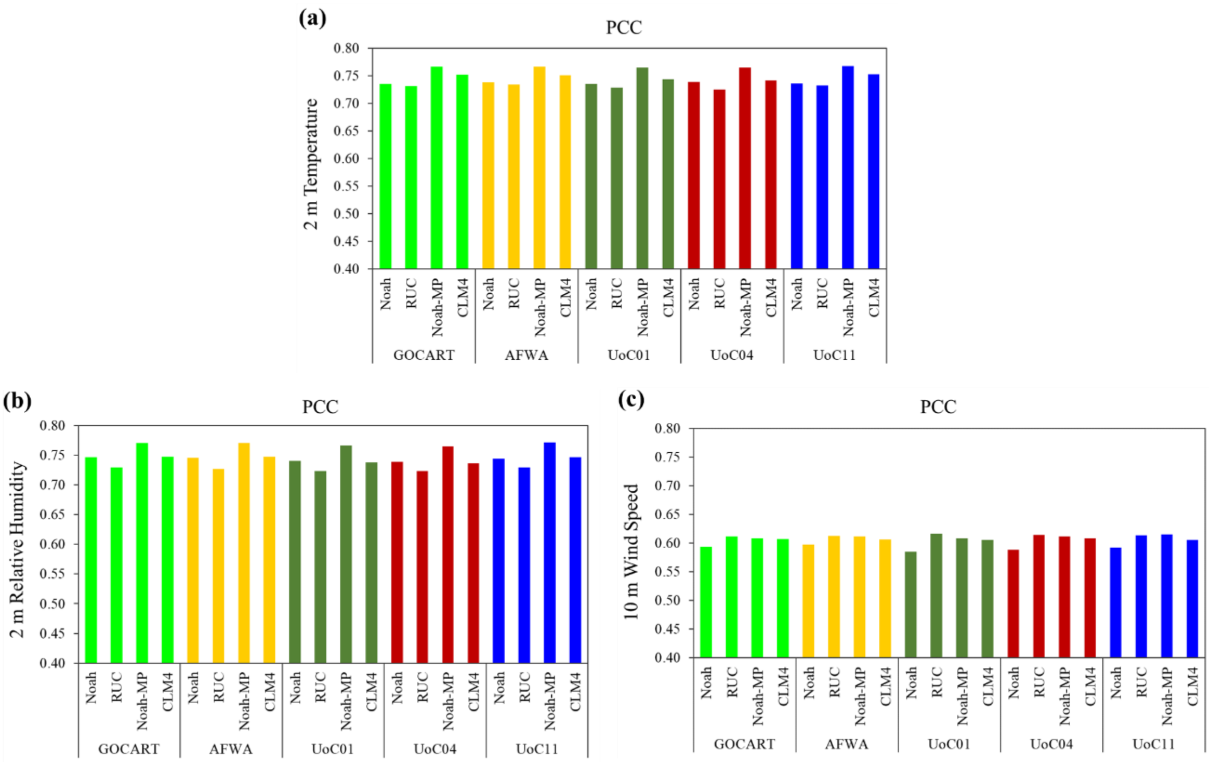

Figure 4: Pearson's correlation coefficient (PCC) of all scheme combinations for (a) T2m, (b) RH2m, and (c) WS10m, respectively, using the ASOS data. The y-axis represents values greater than 0.4, indicating the minimum threshold for a weak correlation. The values are averaged over the stations (see Fig. 3c).

Figure 5 shows the scatter diagram for T2m of Noah-MP-based combinations, which exhibited the best performance for T2m, RH2m, and WS10m in the verification. Consistent with the verification results, the dust emission scheme does not significantly impact the linear correlation between observed and simulated surface meteorological variables. Similar outcomes were observed for RH2m and WS10m (not shown).

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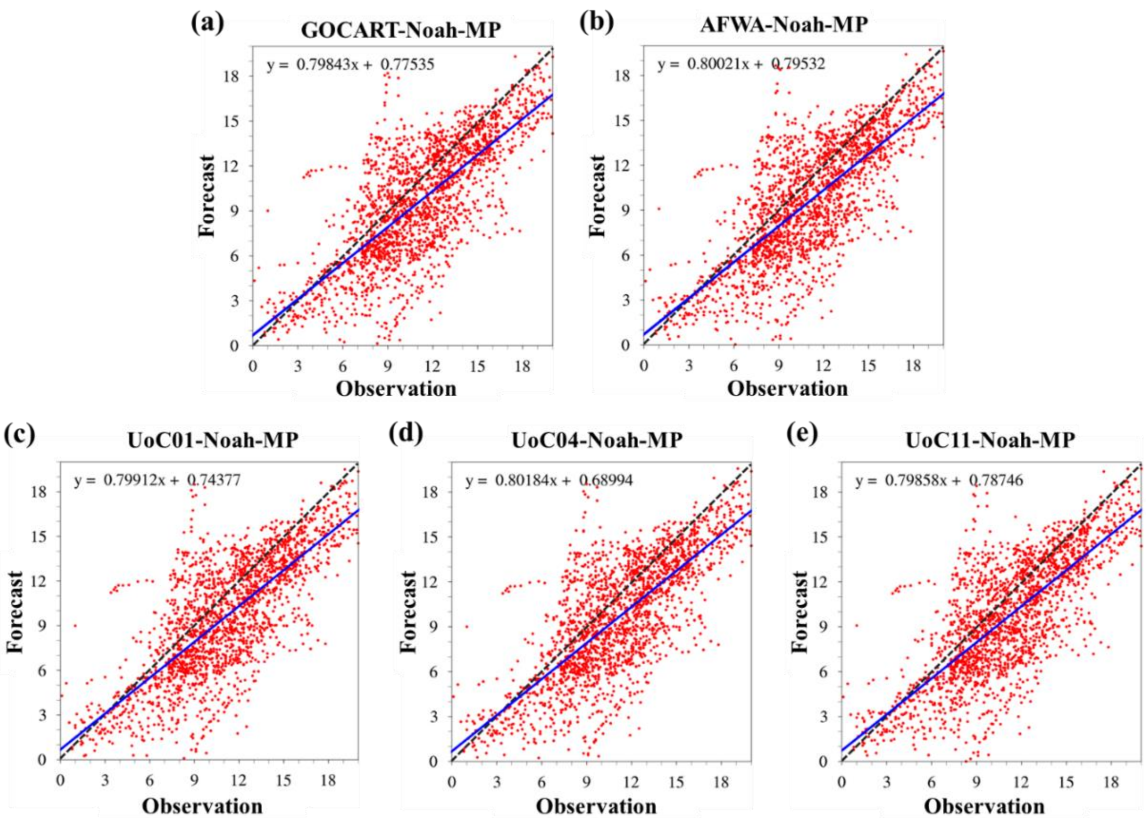

Figure 5: Scatter plots showing the relationship between observed and forecasted values for T2m, using Noah-MP-based combinations. Each panel represents a different scheme combinations: (a) GOCART-Noah-MP, (b) AFWA-Noah-MP, (c) UoC01-Noah-MP, (d) UoC04-Noah-MP, and (e) UoC11-Noah-MP. The black dashed line represents that the forecast perfectly matches the observation. The blue line indicates the linear regression fit to the data, providing relationship between the observed and forecasted values.

3.1.2 Surface PM10 concentrations

We compared the PM10 prediction performance of all scheme combinations against in-situ data---Asian dust observation station (see the station locations in Fig. 3c). Fig. 6 shows PCC, RMSE, and MBE for all scheme combinations. Overall, UoC04-CLM4 showed the best performance, followed by UoC01-CLM4. The UoC04-RUC and UoC01-RUC also showed good performance compared to other scheme combinations. Conversely, the combinations of UoC01 and UoC04 with Noah and Noah-MP, as well as the combinations of GOCART, AFWA, and UoC11 with all land surface schemes, performed poorly. The detailed descriptions of the verification results are as follows: 1) For PCC (Fig. 6a), UoC04-CLM4 showed the highest value (0.61), indicating the best performance, followed by UoC01-CLM4 (0.60), UoC04-RUC (0.47), and UoC01-RUC (0.44). In all scheme combinations except for combinations of UoC04 and UoC01 with CLM4 and RUC, PCC was below 0.4, indicating very weak or almost no correlation; 2) For RMSE (Fig. 6b), UoC04-CLM4 showed the lowest value

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(199.59), indicating the best performance, followed by UoC01-CLM4 (201.618), UoC04-RUC (242.40), and UoC01-RUC (247.25). The other scheme combinations exhibited high values ranging 271−284, indicating relatively poor performance; 3) For MBE (Fig. 6c), all scheme combinations showed negative values, indicating an underestimation. UoC04-CLM4 showed the best performance (-6.29), followed by UoC01-CLM4 (-21.31), UoC04-RUC (-85.08), and UoC01-RUC (-90.28). In scheme combinations, excluding combinations of UoC04 and UoC01 with CLM4 and RUC, relatively small negative values (-137−-120) were exhibited, indicating a significantly low performance compared to UoC04-CLM4, which had the larger negative MBE value.

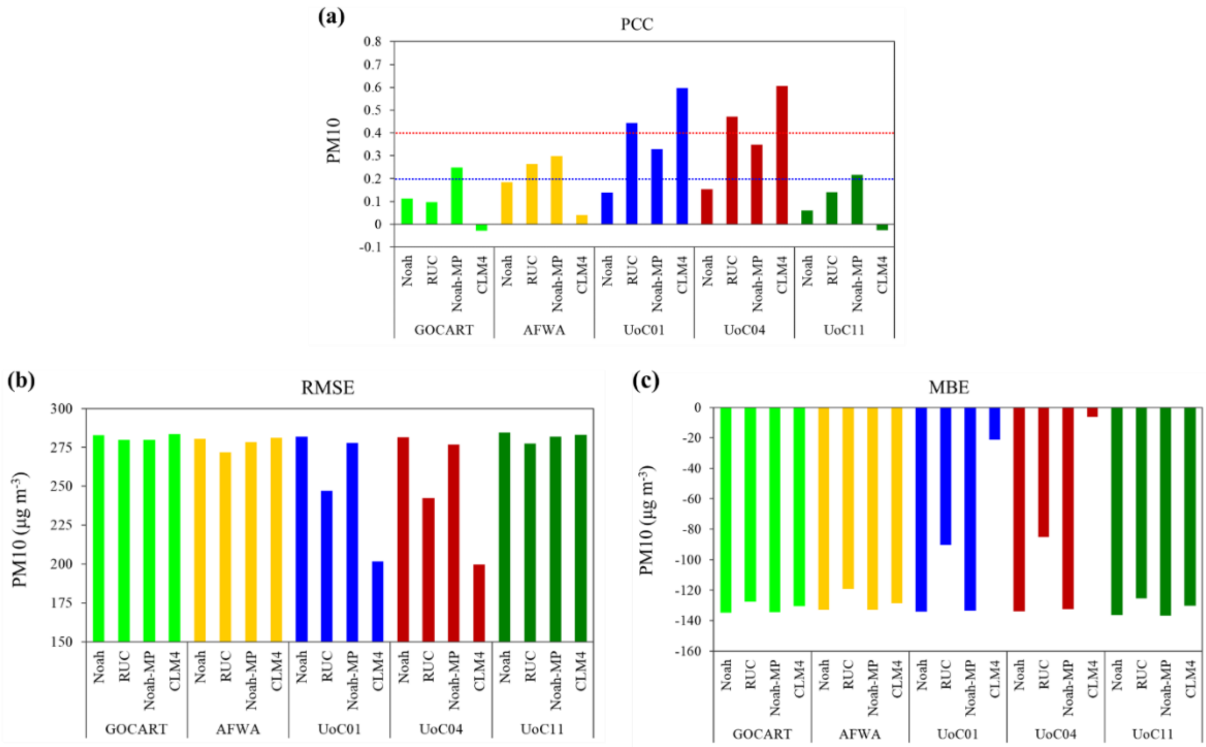

Figure 6: The verification results of all experiments for PM10 concentrations; (a) PCC, (b) RMSE, and (c) MBE, respectively, using the in-situ data. The blue dashed line represents the baseline indicating no correlation, while the red dashed line denotes the threshold for a weak correlation. The values are averaged over the stations (see Fig. 3c).

Figure 7 shows a scatter diagram for CLM4-based combination---the land surface scheme that showed the best prediction performance when combined with UoC04 and UoC01 in the verification (see Fig. 6). The x-axis represents PM10 observations, while the y-axis indicated the predicted values of PM10 for each experiment. The red circles represent the predicted PM10 values corresponding to observations. The scheme combinations UoC04-CLM4 (Fig. 7c) and UoC01-CLM4 (Fig. 7d) showed similarly good performances while the other three combinations showed no correlations between observations and forecasts (Fig. 7a, b, and e): UoC04-CLM4---the best performance in verification---primarily showed

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overestimation for values below approximately 180 $\mu g\ m^{-3}$ and wider dispersion with underestimation tendencies for values above 180 $\mu g\ m^{-3}$.

Fig. S3 shows a scatter diagram for UoC04-based combination---the dust emission scheme that showed the best prediction performance when combined with CLM4 in the verification (see Fig. 6). As mentioned earlier, the UoC04-CLM4 combination exhibited the highest correlation, followed by UoC04-RUC. In contrast, the UoC04-Noah and UoC04-Noah-MP showed no linear correlation (Figs. S3a, and c).

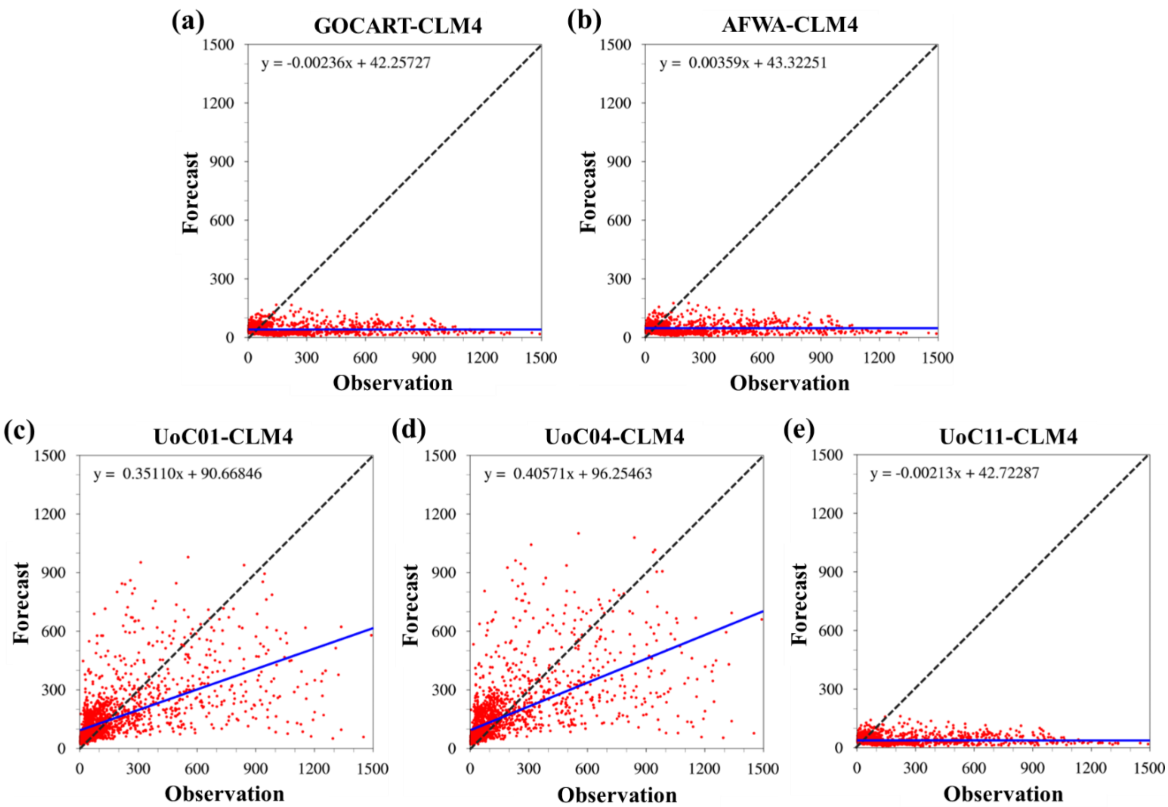

Figure 7: Same as in Fig. 5 but for PM10 concentration, using CLM4-based combinations: (a) GOCART-CLM4, (b) AFWA-CLM4, (c) UoC01-CLM4, (d) UoC04-CLM4, and (e) UoC11-CLM4.

Table 4 shows the POD and FAR, calculated based on the PM10 thresholds using the Fine dust alert and ACWS in South Korea. A higher POD and a lower FAR indicate better prediction performance. Typically, a POD value below 0.5 indicates a failure to detect the observed events. The POD values for all scheme combinations at each threshold are as follows: 1) At 80 $\mu g\ m^{-3}$, UoC04-CLM4 exhibited a very high POD (0.928), followed by UoC01-CLM4 (0.918), UoC04-RUC (0.544) and UoC01-RUC (0.516). The other experiments failed to predict the observed events, with POD ranging from 0.031 to 0.223; 2)

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At 150 $\mu g\ m^{-3}$, UoC04-CLM4 also showed a high POD (0.799), followed by UoC01-CLM4 (0.758). Conversely, other experiments failed to detect the observed events or did not predict at all; 3) At 300 $\mu g\ m^{-3}$, only UoC04-CLM4 achieved a POD of 0.520, surpassing the minimum detection threshold of 0.5; 4) At 800 $\mu g\ m^{-3}$, UoC04-CLM4 failed to forecast the observed events while the others did not predict at all. Overall, in terms of POD, UoC04-CLM4 showed the best prediction performance, with a POD of exceeding 0.5 up to 300 $\mu g\ m^{-3}$.

The FAR close to 0 indicates a low probability of false alarms. Note that FAR could lead to a decrease as the frequency of non-events increases because FAR considers non-events. The FAR values of all experiments for each threshold are as follows: 1) At 80 $\mu g\ m^{-3}$, overall, Noah and Noah-MP-based combinations showed relatively lower FAR than RUC and CLM4-based combinations; 2) At 150 $\mu g\ m^{-3}$, combinations of all dust emission schemes with RUC and CLM4 showed FARs ranging from 0.063 to 0.500. Notably, the AFWA-RUC showed the lowest FAR (0.063). Other combinations could not predict dust events---thus, calculating their FAR was impossible. 3) At 300 $\mu g\ m^{-3}$, combinations of UoC01 and UoC04 with the RUC and CLM4 yielded FAR ranging from 0.048 to 0.325. Significantly, the UoC04-RUC achieved the lowest FAR (0.037). As with the threshold of 151 $\mu g\ m^{-3}$, other combinations were unable to simulate exceeding 300 $\mu g\ m^{-3}$ of PM10, making FAR calculations impossible; 4) At 800 $\mu g\ m^{-3}$, FAR was calculated only for UoC01-CLM4 and UoC04-CLM4, showing high values exceeding 0.7.

When non-events occur frequently, FAR may falsely indicate skill improvement---highlighting the importance of considering both POD and FAR when evaluating prediction capability of detection. Therefore, considering both POD and FAR, UoC04-CLM4 demonstrated the best performance, followed by UoC01-CLM4.

Table 4: POD and FAR values for each PM10 threshold across all scheme combinations. The bold numbers indicate POD greater than 0.5. The dashes '-' indicate POD and FAR values that cannot be calculated.

		> 80 μg m^{-3}		> 150 μg m^{-3}		≥ 300 μg m^{-3}		≥ 800 μg m^{-3}	
		POD	FAR	POD	FAR	POD	FAR	POD	FAR
GOCART	Noah	0.055	0.164	-	-	-	-	-	-
	RUC	0.097	0.221	-	-	-	-	-	-
	Noah-MP	0.114	0.120	-	-	-	-	-	-
	CLM4	0.079	0.298	0.002	0.500	-	-	-	-
AFWA	Noah	0.090	0.128	-	-	-	-	-	-
	RUC	0.223	0.256	0.027	0.063	-	-	-	-
	Noah-MP	0.126	0.103	-	-	-	-	-	-
	CLM4	0.110	0.264	0.007	0.333	-	-	-	-
UoC01	Noah	0.076	0.171	-	-	-	-	-	-
	RUC	**0.516**	0.401	0.251	0.305	0.057	0.048	-	-
	Noah-MP	0.138	0.073	-	-	-	-	-	-

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	CLM4	**0.918**	0.297	**0.758**	0.351	0.448	0.325	0.034	0.727
UoC04	Noah	0.077	0.169	-	-	-	-	-	-
	RUC	**0.544**	0.407	0.282	0.331	0.075	0.037	-	-
	Noah-MP	0.152	0.093	-	-	-	-	-	-
	CLM4	**0.928**	0.310	**0.799**	0.378	**0.520**	0.320	0.069	0.714
UoC11	Noah	0.031	0.257	-	-	-	-	-	-
	RUC	0.149	0.225	-	-	-	-	-	-
	Noah-MP	0.060	0.138	-	-	-	-	-	-
	CLM4	0.071	0.298	0.002	0.500	-	-	-	-

Figure 8 compares the PM10 time series between observations and forecasts, using combinations of all dust emission schemes and CLM4, at six Asian dust observation stations in South Korea---Seoul, Suwon, Yeongwol, Andong, Cheonan, and Mungyeong: UoC04-CLM4 and UoC01-CLM showed excellent performance in PM10 prediction and effectively captured the onset and peak PM10 concentrations when ADSs entered South Korea. During the analysis period, UoC04-CLM4 simulated slightly higher PM10 concentrations than UoC01-CLM4 and approached the peak of PM10 concentrations closer to observations. Conversely, GOCART-CLM4, AFWA-CLM4, and UoC11-CLM4 poorly simulated and significantly underestimated PM10 concentrations throughout the forecast hours, leading to failure in predicting PM10 concentrations during the mega ADS event in South Korea.

Figure S4 compares observations and forecasts of PM10 concentrations for combinations of land surface schemes and UoC04. Note that PM10 concentrations are substantially different for PM10 for different land surface schemes. As noted in Fig. 8, UoC04-CLM4 simulated most similarly to observations, followed by UoC04-RUC. However, other scheme combinations, including UoC04-RUC, notably underestimated the PM10 concentrations.

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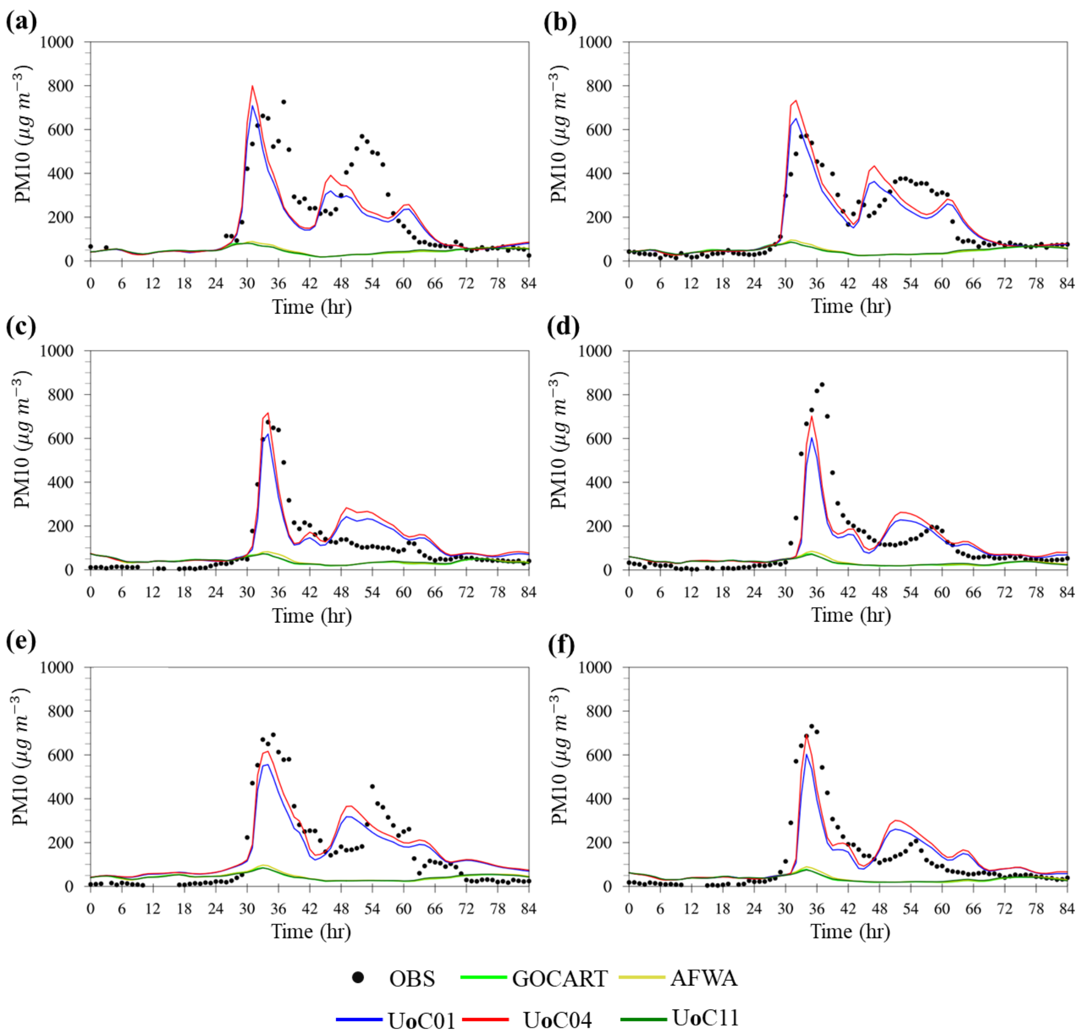

Figure 8: Time series comparison of PM10 concentrations between observations and combinations of all dust emission schemes and CLM4 for (a) Seoul, (b) Suwon, (c) Yeongwol, (d) Andong, (e) Cheonan, and (f) Mungyeong. The black dots represent the observed PM10 concentrations, while the colored lines depict various scheme combinations: the lime green for GOCART-CLM4, the yellow for AFWA-CLM4, the blue for UoC01-CLM4, the red for UoC04-CLM4, and the green for UoC11-CLM4.

3.2 Evaluation with remote sensing data

3.2.1 Time series comparison of AOD: AERONET

Figure 9 shows the comparison of AOD time series between observations and predictions, using combinations of all dust emission schemes and CLM4, at six AERONET sites in South Korea: Overall, UoC04-CLM4 and UoC01-CLM4 showed better agreement with observation than other experiments across all sites. On March 29th, a significant dust event, with AOD values exceeding 0.9, was observed at the Gwangju (Fig. 9c), Ulsan (Fig. 9e), and Gosan (Fig. 9f) sites. All experiments indicated underestimation, but GOCART-CLM4, AFWA-CLM4, and UoC11-CLM4 showed notably more significant underestimation than UoC04-CLM4 and UoC01-CLM4.

Fig. S5 shows same as Fig.9 except for combinations of all surface schemes and UoC04: Overall, both UoC04-RUC and UoC04-CLM4 effectively captured the peak of ADSs around March 29th in South Korea---especially UoC04-RUC, which accurately simulated the AOD peak at the Ulsan site (Fig. S5e). However, UoC04-Noah and UoC04-Noah-MP significantly underestimated the peak, resulting in poorer AOD prediction performance.

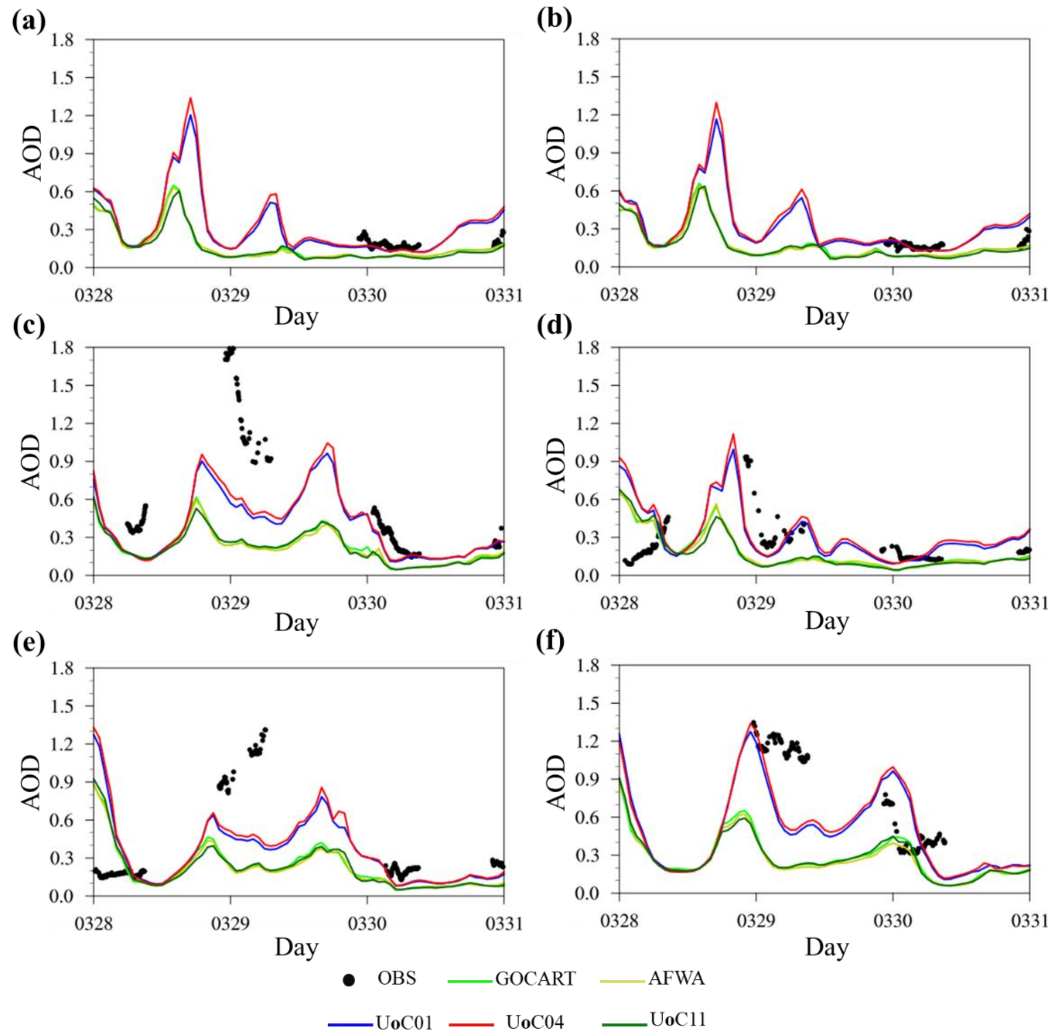

Figure 9: The hourly time series of AERONET and simulated AOD in (a) Yonsei University, (b) Seoul, (c) Gwangju, (d) Gangneung, (e) Ulsan, and (f) Gosan in South Korea. The black dots represent AERONET AOD values, and the colored lines depict various scheme combinations---the lime green for GOCART-CLM4, the yellow for AFWA-CLM4, the blue for UoC01-CLM4, the red for UoC04-CLM4, and the green for UoC11-CLM4.

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3.2.2 Spatial distribution of AOD

Figure 10 shows the spatial distribution of AOD depicting the processes of dust origination (Fig. 10a), transportation (Fig. 10b), and appearance in South Korea (Fig. 10c) in comparison of MODIS (i.e., observation) with MERRA-2 (i.e., reanalysis) and combinations of dust emission schemes and CLM4 (i.e., model results). The comparison for each stage is as follows: 1) At 0500 UTC on March 27, 2021 (Fig. 10a), dust origination stage, MODIS AOD notably exceeded 1.8 over the Gobi Desert/Inner Mongolia. UoC01-CLM4 and UoC04-CLM4 showed AOD values similar to MODIS with over 1.8. In contrast, MERRA-2, GOCART-CLM4, AFWA-CLM4, and UoC11-CLM4 showed significantly low values below 0.5, failing to simulate the dust origin; 2) At 0300 UTC on March 28, 2021 (Fig. 10b), while maintaining high values (>1.8), MODIS AOD moved towards the Bohai Bay, including the Shandong and the Liaodong Peninsulas. UoC01-CLM4 and UoC04-CLM4 showed spatial distribution similar to MODIS AOD. However, MERRA-2 and the other scheme combinations did not simulate the dust transportation due to the absence of dust origination in the source region; 3) At 0300 UTC on March 29, 2021 (Fig. 10c), as the dust inflows the inland of South Korea, the MODIS AOD exceeded 1.0 in the southern and southwestern regions of South Korea. MERRA-2, UoC01-CLM4 and UoC04-CLM4 underestimated AOD compared to MODIS, particularly in the southern and southwestern regions (≤ 0.6); the other scheme combinations failed in AOD simulation (≤0.3). In summary, while UoC01-CLM4 and UoC04-CLM4 effectively simulated the processes of dust origin, transportation, and appearance in South Korea similar to MODIS AOD, they showed a tendency to overestimate. Conversely, MERRA-2, GOCART-CLM4, AFWA-CLM4, and UoC11-CLM4 failed to predict AODs at all three processes, with a substantial underestimation.

Figure S6 shows the same features as in Fig. 10 except for combinations of land surface schemes and UoC04. The MERRA-2, UoC04-Noah and UoC04-Noah-MP tended to underestimate and consequently failed to simulate the dust storm accurately. In contrast, UoC04-RUC and UoC04-CLM4 exhibited a strong tendency to overestimation. Nevertheless, from the origin of the source region to the appearance in South Korea, their simulations were closer to MODIS than those from other experiments.

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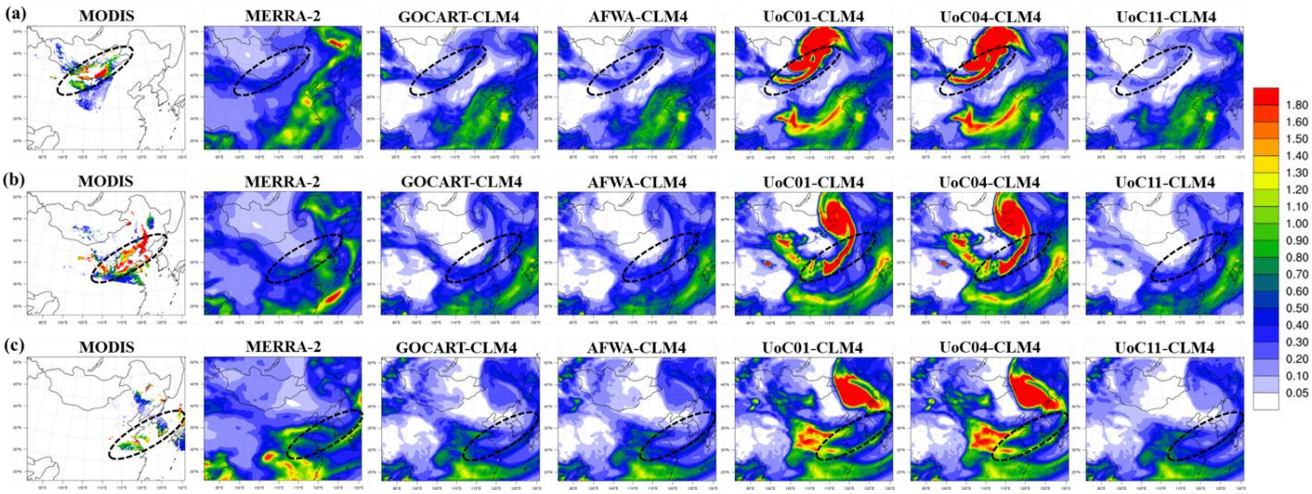

Figure 10: Spatial distribution of AOD in the model domain for MODIS, MERRA-2, and combinations of all dust emission schemes and CLM4: (a) dust origination in the Gobi/Inner Mongolia desert at 0500 UTC on March 27, (b) transport towards the Bohai Sea at 0300 UTC on March 28, (c) appearance in South Korea at 0200 UTC on March 29, 2021. The black dashed circles represent the main comparison regions of MODIS and each experiment.

3.2.3 Vertical distributions of dust concentrations

Figure 11 shows the vertical distributions of dust concentrations along the main route of the ADS from the dust source regions to South Korea (see Fig. 2a), representing the total dust concentrations from all particle size bin in WRF-Chem. The comparisons of combinations of dust emission schemes and CLM4 are as follows: 1) At 1200 UTC on March 27, 2021, GOCART-CLM4 and AFWA-CLM4 simulated dust concentrations very weakly (≤ 450 $\mu g\ kg^{-1}$) from the dust source region (Fig. 11a). In contrast, UoC01-CLM4 and UoC04-CLM4 showed dust concentrations surpassing 3000 $\mu g\ kg^{-1}$ up to 9.5 km over the dust source region, more than six times higher than those of GOCART-CLM4 and AFWA-CLM4. The UoC11-CLM4 simulated dust concentrations higher than GOCART-CLM4 and AFWA-CLM4 but lower than UoC01-CLM4 and UoC04-CLM4. During this period, westerly winds prevailed in the source region, while easterly winds persisted over the Bohai Sea and Yellow Sea (Fig. 11a); 2) At 0200 UTC on March 28, UoC01-CLM4 and UoC04-CLM4 indicated a shift from easterly winds to westerly winds over the Bohai and Yellow Sea, which initiated the movement of dust from the source region, with both having very similar patterns. Overall, the maximum altitude of dust has decreased, and dust concentrations above 1000 $\mu g\ kg^{-1}$ were simulated up to approximately 6 km. Since other experiments simulated very low dust concentrations in the source region, almost no transportation was observed (Fig. 11b); 3) At 1200 UTC on March 28, while westerly winds persisted in UoC01-CLM4 and UoC04-CLM4, dust concentrations exceeding 1000 $\mu g\ kg^{-1}$ passed through the Yellow Sea at altitudes of approximately 4.5 km (Fig. 11c); 4) At 0200 UTC on March 29, dust concentrations exceeding 500 $\mu g\ kg^{-1}$ was simulated at the lowest altitude as the ADS reached South Korea (Fig. 11d).

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Figure S7 shows same as Fig. 11 except for combinations of land surface schemes and UoC04: 1) At 1200 UTC on March 27, 2021, UoC04-RUC and UoC04-CLM4 simulated dust concentrations above 3000 $\mu g\ kg^{-1}$ from the source region, with UoC04-RUC simulating dust to higher altitudes than UoC04-CLM4. In contrast, UoC04-Noah and UoC04-Noah-MP simulated significantly weaker dust concentrations; 2) At 0200 UTC on March 28, UoC04-RUC and UoC04-CLM4 simulated dust transport towards the Bohai Sea by westerly winds. Once dust reached the Bohai Sea, UoC04-RUC showed primarily higher concentrations in the upper levels, while UoC04-CLM4 revealed higher concentrations at lower altitudes. UoC04-Noah and UoC04-Noah-MP did not simulate significant dust emissions from the source region, resulting in no simulated dust transport; 3) At 1200 UTC on March 28, as the dust passed over the Yellow Sea, UoC04-RUC simulated dust concentrations above 1500 $\mu g\ kg^{-1}$ up to approximately 9.5 km altitude. Meanwhile, UoC04-CLM4 simulated similar concentrations up to about 5 km, primarily at lower altitudes; 4) At 0200 UTC on March 29, as dust flowed into South Korea, UoC04-CLM4 simulated higher concentrations than UoC04-RUC, and dust was also simulated over the Yellow Sea. UoC04-Noah and UoC04-Noah-MP did not simulate any dust in South Korea.

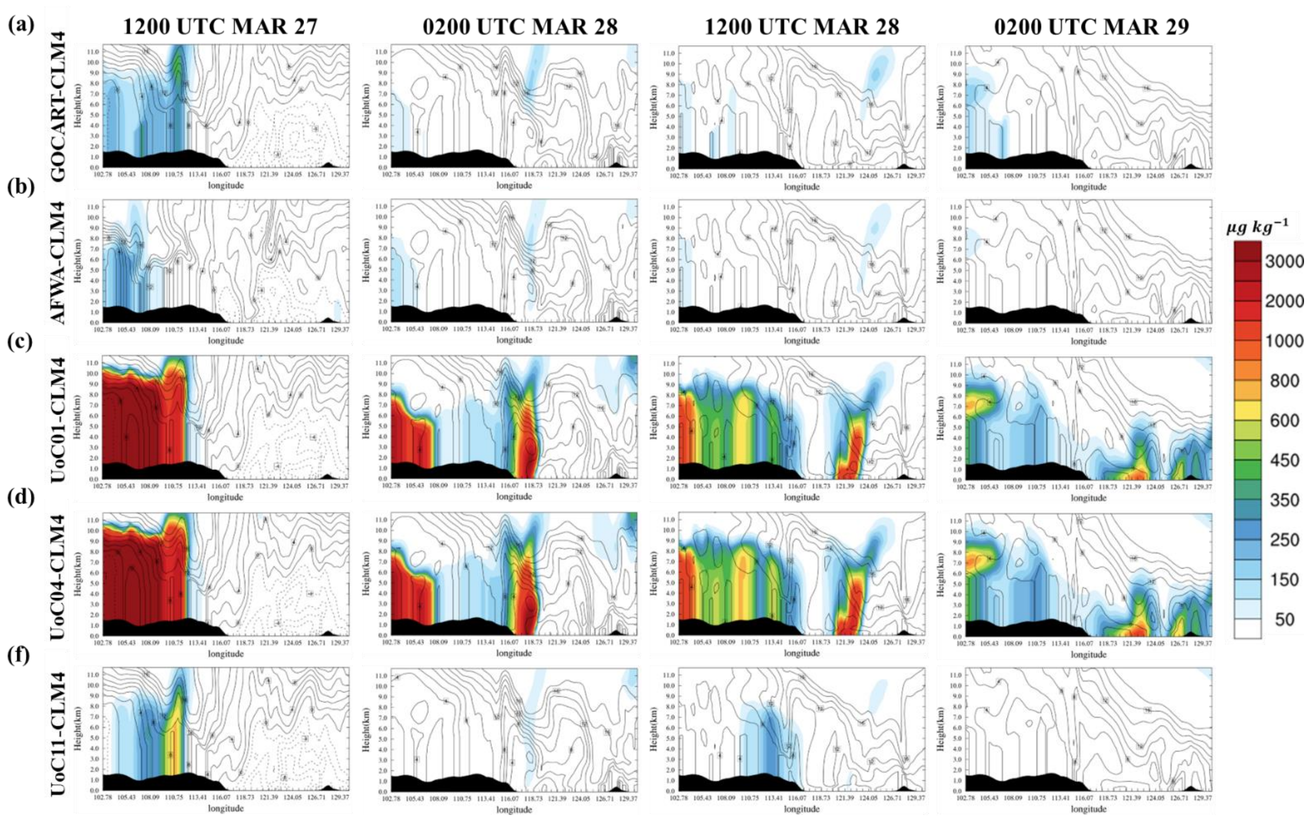

Figure 11: Vertical distributions of the total dust concentrations simulated by the combinations of all dust emission schemes and CLM4 for (a) GOCART-CLM4, (b) AFWA-CLM4, (c) UoC01-CLM4, (d) UoC04-CLM4, and (e) UoC11-CLM4, for given different times. The black solid lines and dashed lines denote the westerly and easterly wind speeds, respectively. The colored

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shading represents the total dust concentration. The black shading indicates topographic height. The location of the cross section is referenced in Fig. 3a.

4 Conclusion

This study aims to evaluate the performance various combinations of parameterization schemes---five for dust emission and four for land surface schemes---in the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) for a mega Asian dust storm (ADS) event (i.e., 28-29 March 2021) over South Korea. Since the introduction of the ADS Crisis Warning System (ACWS) in South Korea in 2015, a nationwide Caution stage was announced for the first time in six years on March 29, 2021. The PM10 concentrations in Heuksando, located in the westernmost part of South Korea, were recorded as high as 1,491 $\mu g\ m^{-3}$---one of the record-breaking events of severe Asian dust storms (ADSs) in South Korea. We evaluated the performance of various scheme combinations in WRF-Chem for this mega ADS event in the following steps.

First, we evaluated the performance of all scheme combinations in forecasting the surface meteorological variables related to dust storms---air temperature at 2 m (T2m), relative humidity at 2 m (RH2m), and wind speed at 10 m (WS10m)---and surface PM10 concentrations. They were verified against surface observation data using various static metrics: 1) It turns out that the land surface schemes have a greater effect on surface meteorological variables than the dust emission schemes---showing little difference in model performance using different dust emission schemes. Additionally, the combinations of all dust emission and Noah-MP schemes, known for its excellence as a land surface scheme, showed the best performance; 2) For surface PM10 concentrations, we observed significant variations of prediction performance across different scheme combinations, as the dust emission schemes directly influence the generation of dust storms. UoC04-CLM4 showed the best performance, followed by UoC01-CLM4, UoC04-RUC, and UoC01-RUC. In contrast, other scheme combinations showed very poor performance and failed to predict PM10 in this study.

Second, we also compared the time series of simulated PM10 and AOD with the in-situ and remote sensing data: 1) For surface PM10 concentrations, UoC04-CLM4 and UoC01-CLM4, which demonstrated good performance through verification, effectively captured the timing of dust inflow into South Korea and the peak PM10 concentrations, with little difference between the two scheme combinations. However, the other experiments exhibited significant underestimations and completely failed to predict PM10 concentrations.; 2) For AOD, when strong dust storms occur and the AERONET AOD value is high, all experiments were underestimated, with combinations of UoC01- and UoC04-based RUC and CLM4 showing the simulations most similar to the AERONET AOD.

Finally, we found that UoC01-CLM4 and UoC04-CLM4 effectively simulated the three processes of origination, transport, and appearance in South Korea, similar to MODIS AOD, but with a tendency to overestimate these processes. In contrast, MERRA-2 and other scheme combinations failed to predict those processes, with significant underestimations. These findings highlight prominent differences in the capabilities among different scheme combinations, specifically dust emission and land surface schemes, in forecasting dust storms.

Since this study focuses on the selected parameterization schemes within the WRF-Chem model, it may just partially consider important factors that could affect the accuracy of ADS forecasting. Additionally, the evaluation is made for a specific mega ADS event, which may limit the generalization of the findings to other ADS events or regions. Nonetheless, this study provides valuable insights into the capabilities of various scheme combinations, thus laying a foundation for improvements in forecast skills for ADSs. Further research is needed to explore additional factors influencing dust storm forecasting accuracy and to generalize our findings to diverse weather conditions and regions.

Code and data availability

The base version (V4.3.3) of the WRF-Chem is publicly released and available at https://github.com/wrf-model/WRF/releases/tag/v4.3.3. The FNL data set for the meteorological initial and boundary conditions is available from the National Centers for Environmental Prediction (NCEP) at https://rda.ucar.edu/datasets/ds083.3/dataaccess. The Community Atmosphere Model with Chemistry (CAM-chem) data for the chemical initial and boundary conditions is provided by the National Center for Atmospheric Research (NCAR) at https://www.acom.ucar.edu/cam-chem/cam-chem.shtml. The mozbc utility is available for download at https://www.acom.ucar.edu/wrf-chem/download.shtml. The surface weather charts (Fig. 1), meteorological variables, and PM10 are provided by the Korea Meteorological Administration (KMA) Weather Data Service at https://data.kma.go.kr/cmmn/main.do. The AERONET, MODIS, MERRA-2 data sets for evaluating the model are available at https://ladsweb.modaps.eosdis.nasa.gov/search, https://aeronet.gsfc.nasa.gov/new_web/download_all_v3_aod.html, and https://disc.gsfc.nasa.gov/datasets?project=MERRA-2, respectively. All data used in this study can be downloaded from https://zenodo.org/records/11649488.

Author contributions

Ji Won Yoon: Conceptualization, Methodology, Software, Analysis, and Writing - Original Draft, Review and Editing; Seungyeon Lee: Software and Validation; Ebony Lee: Software and Validation; Seon Ki Park: Conceptualization, Methodology, Software, and Writing - Review and Editing. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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