An air quality forecasting system in Beijing – Application to the study of dust storm events in China in May 2008

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Abstract
An air pollution forecast system, ARIA Regional, was implemented in 2007–2008 at the Beijing Municipality Environmental Monitoring Center, providing daily forecast of main pollutant concentrations. The chemistry-transport model CHIMERE was coupled with the dust emission model MB95 for restituting dust storm events in springtime so as to improve forecast results. Dust storm events were sporadic but could be extremely intense and then control air quality indexes close to the source areas but also far in the Beijing area. A dust episode having occurred at the end of May 2008 was analyzed in this article, and its impact of particulate matter on the Chinese air pollution index (API) was evaluated. Following our estimation, about 23 Tg of dust were emitted from source areas in Mongolia and in the Inner Mongolia of China, transporting towards southeast. This episode of dust storm influenced a large part of North China and East China, and also South Korea. The model result was then evaluated using satellite observations and in situ data. The simulated daily concentrations of total suspended particulate at 6:00 UTC had a similar spatial pattern with respect to OMI satellite aerosol index. Temporal evolution of dust plume was evaluated by comparing dust aerosol optical depth (AOD) calculated from the simulations with AOD derived from MODIS satellite products. Finally, the comparison of reported Chinese API in Beijing with API calculated from the simulation including dust emissions had showed the significant improvement of the model results taking into account mineral dust correctly.

Key words: dust; particulate matter; modeling; Beijing; air quality forecast and analysis system
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Introduction
In the context of increasing preoccupation about air pollution in China, an air quality modeling system ARIA REGIONAL was developed over China to forecast and analyze both gas phase and particulate pollutants. The system has been working automatically at the Beijing Municipality Environmental Monitoring Center (BMEMC), providing daily forecast of nitrogen oxides (NO and NO2), carbon monoxide (CO), sulfur dioxide (SO2), ozone (O3), as well as anthropogenic and biogenic particulate matter (PM). The objective of this work is to study the performance of the modeling system in restituting dust events affecting periodically China and especially Beijing. Beijing is the political and cultural center of China, including more than 16 millions of inhabitants. Air quality problem is a topic of major concern in Beijing, together with a strong socio-economic growth in the last 20 years. Beijing is located in a basin area, surrounded by the Taihang Mountain on the south-west and Yan Mountain on the north-west. High observed pollution levels can be due to meteorological situation induced by its geographical situation (Chen et al., 2009). Farther in this direction, large desert areas of Northern China and Mongolia, for instance, the Gobi desert and sandy lands (Fig. 1), constitute important mineral dust sources (Laurent et al., 2005; Gong and Zhang, 2008; Wang et al., 2008) among the main sources on Earth. Dust storms often affect the PM measurements and air quality in East Asia, China, Korea and Japan, in spring and early summer (e.g. Uno et al., 2001). Dust particles severely decrease atmospheric visibility (Wang et al., 2005). Located downwind of dust sources regions, Beijing is affected by dust storms from those arid areas of Northern China and Mongolia in spring and early in summer (Zhang et al., 2005; Wang et al., 2006). Additionally with anthropogenic pollution due to local emissions and regional transported pollution (An et al., 2007), it leads to heavy pollution level of particulate matter with aerodynamic diameter less than 10 micrometers (PM10) in Beijing. Human health could be gravely affected during dust storm events. In order to study and forecast dust storms in real-time, remote sensing methods (Hsu et al., 2004; Gautam et al., 2009), numerical modeling approaches (Uno et al., 2001; Gong et al., 2003; Shao et al., 2003; Laurent et al., 2006, 2008) and detailed dust emission schemes (Marticorena and Bergametti, 1995; Shao et al., 2003) have been utilized.

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have specifically analyzed previous dust events in Beijing (Sugimoto et al., 2003; Zhang et al., 2005; Wu et al., 2009). Modeling studies have shown that continuous dust emission upper than 10 Tg during several days could lead to severe dust storm in China (Shao et al., 2003; Laurent et al., 2006). Thus, chemistry-transport model (CTM) in which dust emissions are not calculated may underestimate PM concentrations during heavy dust pollution episode (An et al., 2007). Therefore, it is necessary to include the dust term source in models to improve forecast results of PM<sub>10</sub> even for less important dust storm episode. In this work, the goal is to take into account the dust contribution to the air quality of China. For this purpose, the process-oriented dust emission model MB95 (Marticorena and Bergametti, 1995; Marticorena et al., 1997a, 1997b) using a soil characteristic database (Laurent et al., 2005, 2006) have been integrated into the CHIMERE CTM.

In this article, after a brief description of the model system, we focus on a severe dust storm episode originated from arid areas of North China and Mongolia at the end of May 2008. This severe dust storm episode has influenced air quality in Beijing during 3 days (http://www.forestry.gov.cn). This event has also been described by Kim et al., (2010) who have reported observations of dust storm from 29 to 31 May 2008 in Seoul, South Korea.

1 Modeling approach

1.1 CHIMERE model configuration

The operational ARIA Regional system is composed of the MM5 meteorological model (Dudhia, 1993) and the CHIMERE eulerian CTM (http://euler.lmd.polytechnique.fr/chimere/). The CHIMERE model is widely used for operational regional air quality simulations and forecast (Honore et al., 2008; http://www.prevair.org). Since many years, the model has been operationally applied for modeling and forecasting gas phase and particulate matter pollution in Europe (Schmidt et al., 2001; Bessagnet et al., 2009).

The CHIMERE v.2006 model is used in the frame of the present study, performing over 3 successively nested domains, the largest continental one covering (29°N–46.5°N; 72°E–126.5°E) with a spatial resolution of 0.5°, a regional one covering North China with a spatial resolution of 0.15° and a smallest one focusing on Beijing, Tianjin and Hebei areas with a resolution of 0.05°. The choice of the dimension of these nested domains was oriented to take into account the background pollution level controlled by the incoming pollutants from other regions. It thus covers the most populated areas and also the main deserts. Eight hybrid-sigma vertical layers are used, with the first layer at about 40 m, extending to 500 hPa.

Meteorological parameters are given as input to the CTM. They are provided from the PSU/NCAR MM5 model (Dudhia, 1993), using the grid nudging (grid FDDA) option for the nested domains. MM5 runs with a resolution of 100 km with 33 vertical layers up to 100 hPa for the largest domain with 2 nested grids at 15 km (North China) and 5 km resolution (Beijing, Tianjin and Hebei). For the largest domain, CHIMERE simulations use boundary condition from monthly climatologies of GOCART and LMD-INCA2 chemistry transport models.

Anthropogenic emissions such as NO<sub>x</sub>, PM, SO<sub>2</sub>, CO and volatile organic compounds (VOCs) are interpolated from the REAS Asia emission inventory (with a 0.5° spatial resolution) over the 3 simulated domains in the forecast system and scaled to hourly emissions applying temporal profiles provided by IER (Friedrich, 1997). Local traffic emissions data for the center of Beijing are integrated into the smallest domain simulation. Tropospheric photochemistry is represented using the reduced MELCHIOR chemical mechanism (Lattuati, 1997; Derognat et al., 2003), including 120 reactions and 44 prognostic gaseous species. Six particulate species are included in the sectional aerosol module: primary particle material, nitrate, sulfate, ammonium, anthropogenic secondary organic aerosol (SOA), and water. The thermodynamic mechanism of inorganic species (sulfate, nitrate and ammonium) is simulated with ISORROPIA model (Nenes et al., 1998). Simplified scheme for SOA formation is implemented in CHIMERE, where a temperature dependent partitioning coefficient is used to calculate the thermodynamic equilibrium between the gas phase and the particulate phase. A detailed description of gas and particulate phase modeling can be found on CHIMERE website (http://euler.lmd.polytechnique.fr/chimere/).

1.2 Coupling CHIMERE with dust emission model MB95

To simulate dust emissions, the calculation of mineral dust source term is developed by coupling CHIMERE with the process-oriented dust emission scheme called MB95 (Marticorena and Bergametti, 1995) (Fig. 2) and the relevant soil and surface data base over Asia (Laurent et al., 2006). Three processes (erosion threshold, saltation and sandblasting) are parameterized in MB95. The horizontal flux (G) is calculated with input parameters meteorological...
fields (wind speed, soil moisture and snow cover) and ground surface characteristics such as the aerodynamic roughness lengths \(z_0\) for the overall surface, and \(z_0\) for the erodible part of the surface), the particle size distribution of the soil aggregates \(D_P\). \(G\) is calculated as a function of the wind friction velocity \(U^*\) and include a wind threshold friction velocity \(U^*\text{th}\):

\[
G = E \frac{D_p}{g} U^* \sum_{i} \left(1 + \frac{U^*_i \left(D_p, Z_0, z_i\right)}{U^*} \right) \times \\
\left(1 - \frac{U^*_i \left(D_p, Z_0, z_i\right)}{U^*} \right)^2 dS_{rel}(D_p) dD_p
\]

where, \(E\) is the fraction of erodible to total surface, \(\rho_a\) is the air density and \(S_{rel}\) is the relative surface covered by particles of diameter \(D_p\).

The horizontal flux \(G\) is then used to derive the vertical dust flux \(F\) following an empirical relation between the sandblasting efficiency and soil texture proposed by Marticorena and Bergametti (1995). The computed dust flux is distributed into the 3 aerosol particle populations that can be released from arid soils following the sandblasting model of Alfaro and Gomes (2001). To compute dust emissions, up-to-date and surface and soil databases were used: \(Z_0\) values are derived from POLDER-1 surface products (Laurent et al., 2005) while soil size distribution and texture are derived from in-situ sampling (Laurent et al., 2006) for the main Chinese arid areas presented in Fig. 1.

To simulate correctly the mass and size distribution of dust particles during their transport and deposition, Gong et al. (2003) reported a minimal number of 12 particle size bins when using an isolog bin scheme for size distribution. Foret et al. (2006) performed sensitivity test on the number of bin and required to properly represent dust mass and number concentration and optical depth that was further extended to 3-D simulations by Menut et al. (2007). Here in the model, 12 aerosol size bins following iso-log bin scheme are distributed for dust particles as well as for other aerosol species.

Dry deposition velocity of particulate is calculated following a resistance analogy as a function of the friction velocities and stability of the lowest model layer (Wesely, 1989).

The deposition of particles scavenged by rain drops is described as a function of grid-averaged precipitation rates and cloud water content as described by Tsyro (2002) and Loosmore and Cederwall (2004).

### 1.3 Model aerosol optical depth

Aerosol optical depth (AOD) derived from satellite measurements provides quantitative information on the vertically integrated amount of atmospheric particles. It is widely used to evaluate model results (Moulin et al., 1998; Papayannis et al., 2007; Schepanski et al., 2009).

From the CHIMERE simulated atmospheric concentrations, dust AOD is calculated as follows:

\[
\tau = \sum_{j} h_j \sum_{i} C_{ij} \sigma_{ij}
\]

where, \(n\) is the number of vertical levels, \(m\) is the number of size bins, \(h_j\) is the altitude of \(j\)th vertical level, \(C_{ij}\) is the particulate concentration of bin \(i\) in level \(j\) and \(\sigma_{ij}\) is the mass cross extinction coefficient.

AOD is both particle size and wavelength dependent. Figure 3 presents \(\sigma_{ij}\) of dust at 550 nm. The wavelength dependent \(\sigma_{ij}\) can be calculated for each size bin from the Mie theory assuming spherical particles (Van de Hulst, 1957). Following Foret et al. (2006), in our simulations the AOD is computed at the reference solar wavelength of 550 nm and using a dust complex refractive index of 1.5-i0.002.

We calculate AOD only for dust aerosol because during the studied dust storm event it constitutes the major contribution to AOD high values observed compared to other aerosol species.

### 1.4 Air pollution index

The Chinese air pollution index (API) is officially reported for the principal pollutant in a city (www.zhb.gov.cn). It is calculated from the daily mean concentration (from 12:00 the day before to 12:00 on this day) of the responsible principal pollutant among SO\(_2\), nitrogen dioxide (NO\(_2\)) and PM\(_{10}\) measured at main monitoring sites throughout each city. As it is a mean value from all measurement stations, API is an indicator representing the daily air quality at the level of a city. API has pollution levels for each pollutant with a maximum value of 500 which is equal to or superior than 600 \(\mu g/m^3\) (Table 1). API under 50 represents good air quality in a city, each concentration

<table>
<thead>
<tr>
<th>PM(_{10}) ((\mu g/m^3))</th>
<th>0 &lt; C ≤ 50</th>
<th>50 &lt; C ≤150</th>
<th>150 &lt; C ≤350</th>
<th>350 &lt; C ≤420</th>
<th>420 &lt; C ≤500</th>
<th>500 &lt; C ≤600</th>
<th>C ≥ 600</th>
</tr>
</thead>
<tbody>
<tr>
<td>API = f(C)</td>
<td>C</td>
<td>C/2+25</td>
<td>C/2+25</td>
<td>C*10/7–300</td>
<td>C*5/4–225</td>
<td>C–100</td>
<td>500</td>
</tr>
<tr>
<td>API range</td>
<td>0–50</td>
<td>51–100</td>
<td>101–200</td>
<td>201–300</td>
<td>301–400</td>
<td>401–500</td>
<td>500</td>
</tr>
</tbody>
</table>
of 3 principal pollutants $\text{SO}_2$, $\text{NO}_2$ and $\text{PM}_{10}$ being under 50 $\mu$g/m$^3$. API of 100 for PM corresponds to 150 $\mu$g/m$^3$. Above that value is corresponding to a polluted level of PM in a city. The API derived from model is calculated in the same way as is done for station measurements. Detailed information about the calculation of API values from $\text{PM}_{10}$ is presented in Table 1.

### 2 Studied dust event in China from 26 to 30 May 2008

Weather records (http://www.forestry.gov.cn) report a dust storm episode between 26 and 29 May 2008 in North China with visibility less than 1 km in certain regions. The severe dust event developed under a strong cold air flow associated with a Mongolian Cyclone in Mongolia and Inner Mongolia of China on 26 May 2008. Beijing was influenced by this dust storm event during these days, and API values are controlled by the $\text{PM}_{10}$ concentrations.

In fact, API values reported by Chinese Ministry of Environment (SEPA) (http://www.mep.gov.cn) in 2 main cities of North China, Beijing and Tianjin, are higher than 150 from 27 to 29 May, which means daily average $\text{PM}_{10}$ concentration over city was about 250 $\mu$g/m$^3$ (Fig. 4). Values around 400 were reported in Beijing on 27 and 29 May and in Tianjin on 29 May indicating severe dust pollution influence in this region from later 26 to 29 May. In comparison, API in another megacity Shanghai, located in East China is less important, under 100 (150 $\mu$g/m$^3$) for the all period. The API value in Shanghai on 29 May is not presented in Fig. 4, as the principal pollutant controlling the API by $\text{SO}_2$ during these days.

During this identified dust event, the daily Aerosol Indexes (AI) from OMI satellite products (Levetl et al., 2006; http://jwockey.gsfc.nasa.gov/aerosol/) also qualitatively indicate that the presence of dust increases in the arid area of Mongolia and North of China. The AI over the south of Mongolia, north of Inner Mongolia and Taklimakan Desert increases on 26 May. The AI over the south of Mongolia keeps increasing and expend toward north of China on 27 May. It decreases on 28 May when the second dust storm occurs in Inner Mongolia. It then starts to disappear on 29 May. This dust episode started to influence the air quality in the Beijing region on 27 May.

In this study, a 5-day simulation with the same configuration as described in the forecast system from 26 to 30 May was applied to analyze this dust episode. The simulated dust emissions for the 26–29 May period are presented. Wind speeds and directions are also analyzed because they drive the dust emission processes and then the transport of dust plume. Model results are compared to meteorological airport report (METAR) data which are free but with a coarse precision of $\pm 1$ m/sec for wind speed and $20^\circ$ for wind direction. During this dust event period, daily AI from OMI satellite products at 6:00 UTC (14:00 local time) are compared with modeled column concentrations of total suspended particulate (TSP).

### 2.1 Emissions and wind surface parameters

Figure 5 shows the daily total dust emissions from 26 to 29 May 2008. The model simulates important amount of dust emissions during the 26–28 May period. For the complete studied period, about 21 Tg and 2 Tg of dust particles are produced from Gobi Desert and the arid area of Badain Jaran Desert and Tengger Desert in the model, respectively. This severe dust storm was mainly due to emissions from Gobi desert on 26 and 27 May. Then it was more related to emissions from Badain Jaran Desert and Tengger Desert on 28 and 29 May. The location of dust emission sources and the range of emission quantity are in agreement with previous studies (Shao et al., 2003; Laurent et al., 2006).

As already mentioned, the meteorological parameters, especially the wind fields, control the dust emissions and their transport. A meteorological study is conducted comparing the MM5 simulated winds with the observed winds at 2 METAR stations: ZBAA in Beijing, and ZBHH in Hohhot which is located near the dust source area in the province of Inner Mongolia of China (Fig. 1). Hohhot is about 450 km on the northwest of Beijing. The Hohhot station is located on the pathway of dust plumes coming from Gobi and North China deserts and transported to Beijing. Modeled meteorological parameters are compared to the METAR measurements using a 10 best-fit-point method. Figure 6 displays the comparison of wind speed and wind direction at these two stations. The MM5 simulated winds well capture the high wind intensity episodes as well as the change of wind direction during the studied period.
The computed wind direction is given with a 20° error. The absolute error on the wind speed is about 0.5 m/sec higher, in particular on 27 and 29 May. The computed wind speeds have a determination correlation coefficient of 0.78 with the ones reported at the studied METAR stations.

2.2 Dust plume transport over China

Figure 7 shows the OMI Aerosol Index (AI) (http://jwocky.gsfc.nasa.gov/aerosols/) and the computed column concentrations of total suspended particulates (TSP) at 6:00 UTC from 26 to 29 May. The computed column concentrations of TSP show similar patterns as the OMI AI. On 26 May, dust is observed in source areas on the south of Mongolia, north of Inner Mongolia and from Taklimakan Desert. The modeled TSP plume from the south of Mongolia and the north of Inner Mongolia is then transported to the north of China on 27 May, but with a light shift to the south with respect to the AI pattern due to a bias on the wind direction. Meanwhile, a modeled dust plume over eastern central China (32°N, 36°N) does not appear from AI observation (Fig. 7b at 27 May). This is probably due to the OMI observation deficiency as OMI is not always able to capture the aerosol pattern below 1000 m above the ground surface. The METAR reported horizontal visibility can also be used to complete the information on dust at the ground level. In fact, close to dust areas the decrease of the horizontal visibility can be considered as an indicator of a dust event (Laurent et al., 2006). A visibility less than 5 km can be referred as a floating dust event, and a visibility less than 1 km can be referred as a heavy dust storm (Mahowald et al., 2007) which can occur when concentration dust particles is about 500 g/m³ (Song et al., 2007). In this region, the reported visibilities close to 5 km seem to indicate that of a dust event is occurring. On the contrary, the model underestimates aerosols located in the Taklimakan Desert on 27 and 29 May while OMI AI is about 2. A dust plume is transported over the sea on 28 May when the second dust emission is simulated on the north of Inner Mongolia of China and transported towards to southeast on 29 May. This simulated plume (Fig. 7b at 29 May) appeared in East China when the observed one (Fig. 7a at 29 May).
3 Evaluation and discussion of the results

In this section, hourly TSP concentrations are compared to METAR observations of visibility at three stations for a first qualitative analysis. AOD derived from satellite observations are then compared to dust AOD calculated in the model, allowing a more quantitative evaluation of the model performance. Finally, the improvement of model simulations with the dust emission module is analyzed, computing agreement factors between the modeled and reported API values.

3.1 Comparison of ground total suspended particles with visibility decrease in China

Temporal variations of visibility and ground TSP concentrations at three METAR stations: ZBHH in Hohhot, ZBAA in Beijing and ZSQD in Qingdao, located all along the dust plume trajectory from north to south and from west to east are presented in Fig. 8. As mentioned above, the decrease of the visibility less than 5 km close to source areas can be a good indicator of a dust plume. The comparison can be focused on dust storm periods, i.e. on 26 May at ZBHH, between the 26 and 27 May in ZBAA and since 27 May at ZSQD (the reported corresponding daily mean API being also higher than 100, i.e. > 150 μg/m³). At the ZBHH station, which is the closest station to dust source areas, modeled TSP concentrations reach high values of 6000 μg/m³ when visibility reported at METAR station is less than 1 km. At the ZBAA and ZSQD stations, which are located on the transport pathway of the dust plume, the reported visibility less than 5 km is well correlated with the high modeled TSP concentrations (up to 1500 μg/m³). Even if the relative variations can be different, we can notice that for all these stations the reported visibilities decrease when the simulated ground TSP concentrations increase (> 300 μg/m³). This seems to confirm that the model captures at the right moment the dust plume transport in these areas.

3.2 Comparison of modeled AOD with MODIS AOD in China

During dust events, dust particles constitute the main contribution of aerosol concentrations with hundreds to thousands μg/m³ with respect to 150 μg/m³ for a heavy anthropogenic pollution case. Thus, modeled AOD is only calculated from dust particle concentrations for our studied period with an hourly time step. As the MODIS AQUA satellite passes above North of China at about
6:00 (UTC) every day, the modeled dust AOD is also presented for the same hour in Fig. 9a with reported visibility at METAR stations from 26 to 29 May. Both the collection 5.1 low-resolution AOD and AOD retrieved from deep blue method from AQUA satellite data at 550 nm (http://gdata1.sci.gsfc.nasa.gov/) are presented in Fig. 9b and c with a 1° spatial resolution.

We can notice that the order of magnitudes and the spatio-temporal variability of the modeled and observed AOD are similar. Dust emissions from Gobi desert lead to AOD higher than 1.2 near the source areas, while modeled AOD is above 1.5.

Model AOD values are higher in Mongolia, but less intense over the north of Inner Mongolia of China. The model simulates correctly the beginning of the dust event on 26 May at the border between Mongolia and China. AOD retrieved from observations on 26 May show values higher than 1.5, even 2 in the regions on the east coast of China (Fig. 9b, c at 26 May), whilst the visibility in some cities there upper than 5 km means that no dust event occurred (Fig. 9a at 26 May). Moreover, API value in Shanghai within that region is lower than 100 (< 150 g/m³) (Fig. 2b). These high values are probably due to the influence of a source existing before the beginning of our simulations on 26 May. As the dust plume was transported towards southeast from emission sources in Mongolia on 27 May, values upper than 2 patterned as a plume are found in East China where the visibility is below 5 km (Fig. 9a at 27 May); meanwhile another plume originated from Mongolia was modeled and transport to China with a slight shift of wind direction to south. Both the model and satellite observations (Fig. 9b, c at 27 May) show these
Discussion and conclusions

An operational modeling forecast system was implemented to simulate dust emissions. The API estimated from simulations highly improves our ability to simulate dust emissions. Taking into account mineral dust in the city, the score reaches 72.7% for the simulations without dust emissions well representing PM levels. These two different modeled API are compared with the API estimated from station measurements. For a city, if the daily modeled API and the reported API from measurements are both higher or lower than 100, we note one agreement. Twenty and 32 agreements are from measurements during this dust episode. CHIMERE simulations of dust concentrations were assessed through comparisons with the OMI Aerosol Indexes (AI). With these day-by-day satellite data, we assessed qualitatively the dust emissions simulated and the smog transport. In agreement with the observations, the model well simulated an important dust emission episode on 26 May. The dust plume transports and affects most part of North China in the 3 following days. Another dust emission episode occurred on 28 May and dust concentrations decreased on 29 May. Reported decrease of horizontal visibilities of METAR stations were also used to complete surface observations. High simulated ground level TSP concentrations in Beijing, Hohhot and Qingdao on the plume transport pathway are correctly correlated with the decrease of the reported visibilities. Furthermore, an analysis of the modeled AOD versus the MODIS AOD was also performed. The results have shown that the model well-reproduced the spatial pattern of the plume and its temporal evolution. In Beijing, the model has well simulated the dust plume transport. Dust particulate is the major contributor to PM10 concentrations during this period in the simulation. Taking into account the dust emissions in the simulations greatly improved the agreement between the modeled API and the reported API from in-situ measurements during this dust episode.

In conclusion, with the recent coupling of CHIMERE with the dust emission model MB95, ARIA Regional system has shown its capability to reproduce spring dust storm events in terms of timing, duration and intensity, which highly improves API values derived from PM10 forecast results in Beijing. A next step in the validation of this regional prevision system would be to evaluate statistically its capability to simulate the dust event occurrence at the annual and inter-annual scale. As a perspective, more in-situ satellite observations will be very useful to constrain the model meteorological fields and dust simulations, and the interaction between dust and photochemistry.
will be taken into account in the model system.

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