Prediction of Asian Dust Days over Northern China Using the KMA-ADAM2 Model

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(Manuscript received 9 February 2019, in final form 7 August 2019)

ABSTRACT

This study evaluates the Korea Meteorological Administration (KMA) Asian Dust Aerosol Model 2 (ADAM2) for Asian dust events over the dust source regions in northern China during the first half of 2017. Using the observed hourly particulate matter (PM) concentration from the China Ministry of Environmental Protection (MEP) and station weather reports, we find that a threshold value of \( \text{PM}_{10-2.5} = 400 \ \mu g \ m^{-3} \) works well in defining an Asian dust event for both the MEP-observed and the ADAM2-simulated data. In northwestern China, ADAM2 underestimates the observed dust days mainly due to underestimation of dust emissions; ADAM2 overestimates the observed Asian dust days over Manchuria due to overestimation of dust emissions. Performance of ADAM2 in estimating Asian dust emissions varies quite systematically according to dominant soil types within each region. The current formulation works well for the Gobi and sand soil types, but substantially overestimates dust emissions for the loess-type soils. This suggests that the ADAM2 model errors are likely to originate from the soil-type-dependent dust emissions formulation and that the formulation for the mixed and loess-type soils needs to be recalibrated. In addition, inability to account for the concentration of fine PMs from anthropogenic sources results in large false-alarm rates over heavily industrialized regions. Direct calculation of PM2.5 in the upcoming ADAM3 model is expected to alleviate the problems related to anthropogenic PMs in identifying Asian dust events.

1. Introduction

Asian dusts composed of dry sands, clay, and loam, exert great social and economic impacts on East Asia (EA). Severe Asian dust events often lead to canceled flights and adversely affect the manufacturing of semiconductors and precision instruments (Shao and Dong 2006). Increased optical thickness by Asian dusts inhibits photosynthesis, causing plant growth disorders and ecosystem disturbances (Huang et al. 2006; Kim et al. 2005). Previous studies also showed that Asian dusts cause a number of adverse effects on human health (Giannadaki et al. 2014; Hong et al. 2010; Kashima et al. 2016; Kwon et al. 2002; Zhang et al. 2016).

In northeastern Asia regions, Asian dust events are most frequent in spring, from March to May (Chun et al. 2001; Kim 2008; Shao et al. 2013). However, changes in the wind field and precipitation patterns due to desertification and climate change in northern China may reduce or enlarge major Asian dust source regions to alter the intensity and frequency of Asian dust events (Kim 2008; Kurosaki and Mikami 2003; Kurosaki et al. 2011; Lee and Sohn 2011; Wang et al. 2006; Zhang et al. 2003). Forecasting and early warning of severe dust events are critical for alleviating the adverse impacts of Asian dusts

Denotes content that is immediately available upon publication as open access.

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DOI: 10.1175/WAF-D-19-0008.1

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on the economy and environment in EA. Despite its importance, current Asian dust forecasting suffers from large uncertainties (Lee et al. 2017; Shao et al. 2003; UNEP, WMO, and UNCCD 2016).

The Korea Meteorological Administration (KMA) employs the Asian Dust Aerosol Model 2 (ADAM2) (In and Park 2003; Park et al. 2010; Park and In 2003) to forecast Asian dust events. The model has been used in various Asian dust studies: simulation of dry deposition of Asian dusts in EA (Park et al. 2011; Lee et al. 2005), the effects of particulate matter (PM) assimilation on Asian dust forecasting (Lee et al. 2013a), and intercomparison of Asian dust simulations using ADAM2 and Lagrangian models (Kim and Lee 2013). ADAM2 is also a current Asian dust forecasting model at the Mongolia National Agency for Meteorology and Environmental Monitoring (Lee et al. 2013b).

The Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Asian node of the World Meteorological Organization (WMO) intercompares and manages Asian dust predictions at KMA, China’s Ministry of Environmental Protection (MEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the National Centers for Environmental Prediction (NCEP). The Dust Model Intercomparison Project (DMIP) has intercompared the performance of several Asian dust models including ADAM (Park and In 2003), Chemical Weather Forecasting System (CFORS; Uno et al. 2004), Model of Aerosol Species in the Global Atmosphere (MASINGAR; Tanaka and Chiba 2005), and Chinese Unified Atmospheric Chemistry Environment for Dust (CUACE/Dust; Gong and Zhang 2008; Uno et al. 2006) in simulating Asian dust events. Previous studies compared Asian dust simulations against those from the Global Telecommunications System (GTS) synoptic observatories or PM observations at limited observatories (Zhou et al. 2008). However, most of the early Asian dust model evaluation was performed in the regions downstream of the source regions where dust storms affect large populations; evaluation of Asian dust forecast models against observations in the Asian dust source regions is not available in previously published studies.

This study aims to evaluate ADAM2, the current KMA Asian dust forecast model, using the hourly PM$_{10}$ and PM$_{2.5}$ observations from MEP for the dust source region within $35^\circ$N–$50^\circ$N and $75^\circ$E–$130^\circ$E during the first half of 2017. This study first establishes a threshold value for identifying an Asian dust day for the PM values from the MEP observations and ADAM2 simulations. The threshold value is subsequently used to analyze the observed and simulated dust days to examine the model performance in simulating Asian dust events in the Asian dust source regions in northern China. This study further examines the model performance according to regions and soil types.

2. Data and analysis methods

a. ADAM2

The ADAM2 model was developed by incorporating the Asian dust emissions algorithm (In and Park 2003; Park and In 2003) into the U.S. Environmental Protection Agency (EPA) Community Multiscale Air Quality (CMAQ) model, version 4.1.7 (Byun and Schere 2006). In the model, calculations for the atmospheric chemistry and transports of air pollutants are carried out by the CMAQ model and the dust generation algorithm calculates the amount of dust emissions for given meteorological conditions and soil types. Note that the dust emissions algorithm in ADAM2 is not a part of any EPA CMAQ versions. The meteorological fields to drive ADAM2 for the operational Asian dust forecasting are obtained from the Unified Model (UM) of the Met Office (Davies et al. 2005) that is the current global forecast model at KMA. To run the KMA Asian dust forecasts, the UM forecast data are interpolated onto the ADAM2 grid using the UM Meteorology–Chemistry Interface Processor (MCIP) conversion system of the Aeolus and the National Center for Atmospheric Science (Taylor 2006). The current operational forecast performs 84-h forecast cycles at 6-h intervals over an EA domain covered horizontally by a 25-km resolution $340 \times 220$ (north–south) grid using the Lambert conformal cone projection and vertically by irregularly spaced 47 layers.

The Asian dust algorithm in ADAM2 calculates particulates in 11 particle size bins. The particle size distribution is adjusted by a weighting function based on the friction velocity using the logarithmic minimum and maximum variance distributions (Park and Lee 2004). A basic framework for the Asian dust algorithm was developed by studying the critical friction of the Asian dust phenomenon in the EA region (In and Park 2002). The Asian dust algorithm in ADAM2 has been improved by considering the reduction factor to account for the seasonal variations in the vegetation cover (Park et al. 2010).

The Asian dust source regions are largely limited to northern China, Mongolia, northern India, and central Asia (Fig. 1). Details on the Asian dust source regions and the formulations for dust emission used in the model are described in Park et al. (2010), and will not be elaborated in this paper. The colored areas indicate soil types used in ADAM2: Gobi (black), sand (yellow), loess (red), mixed (blue), and Tibetan (green). Different
critical values for wind speeds, humidity, and surface temperature are assigned according to soil types.

b. PM-based Asian dust threshold value

To determine the threshold for determining an Asian dust event, we first examine the ratio of Asian dust events to the total weather events. Figure 2 shows the percentages of the Asian dust events in the GTS synoptic observations over the region 35°–50°N and 75°–130°E during the first half of 2017. Figure 2a shows the ratio of the Asian dust events when the weather codes 7 and 8 are selected as Asian dust events. Of the total 19,958 weather events reported in terms of the codes, 651 are codes 7 and 8 (3.26%) with high values occurring in and near the Gobi Desert. Using only the codes 7 and 8 to define Asian dust days is likely to underestimate the total Asian dust days because these two weather codes represent only the events related to local sources due to updrafts. Figure 2b shows the percentage of the Asian dust days determined by considering the codes 6, 7, 8, 9, 30, 31, 32, 33, 34, 35, and 98 as Asian dust events. Unlike in the previous estimate based
solely on the codes of 7 and 8 (Fig. 2a), these cases include not only the Asian dust events from local origins but also those due to dusts transported into the region. These cases occupy 1665 out of the 19,958 events (8.34%) with high ratios in and near the Gobi and Taklamakan Deserts. Based on these observation-based estimates, we assume that Asian dust events represent 5% of the entire weather types in the dust emission region.

To determine the threshold PM values for identifying the Asian dust events, the cumulative distribution function (CDF) of the MEP-observed daily coarse particle concentration values (PM$_{10}$–PM$_{2.5}$) are compared against the collocated ADAM2-simulated values within the dust source region, 35°–50° N and 75°–130° E, in the first half of 2017 (Fig. 3a). Compared to using the PM$_{10}$ values, using the PM$_{10}$–PM$_{2.5}$ value as the threshold for identifying the Asian dust days helps to reduce the possibility of mistakenly identifying haze-dominated days as Asian dust days; haze is mainly affected by fine PMs of anthropogenic origins that contribute mostly to PM$_{2.5}$ values. The PM$_{10}$–PM$_{2.5}$ values in Fig. 3a are selected for the days on which observations were taken for more than 12 h or PM$_{10}$ values exceeded 200 μg m$^{-3}$ for over 3 h. The 95th percentile values of the observed CDF of PM$_{10}$–PM$_{2.5}$ (i.e., the upper 5% of the total weather events that are regarded as Asian dust days in the weather-code-based Asian dust days, is 369 μg m$^{-3}$); the corresponding value in ADAM2 simulations is 385 μg m$^{-3}$. Based on this analysis, we adopt PM$_{10}$–PM$_{2.5}$ = 400 μg m$^{-3}$ as the threshold for identifying Asian dust days for both observed and simulated PM data for simplicity. The threshold value obtained here is larger than PM$_{10}$ = 200 μg m$^{-3}$ used in Wang et al. (2008) for identifying Asian dust days, but is in line with the PM$_{10}$ = 400 μg m$^{-3}$ traditionally used to identify Asian dust days (Lee et al. 2012). Figure 3b shows a box-and-whisker plot of the PM$_{10}$ concentrations for the Asian dust days and non-Asian dust days from the MEP data and the ADAM2 simulations determined by applying PM$_{10}$–PM$_{2.5}$ = 400 μg m$^{-3}$ as the threshold value. Using the threshold value, PM$_{10}$ concentrations for the Asian dust days are clearly separated from those for the non-Asian days in both observations and simulations.

3. Analysis and discussion

The Asian dust day threshold value obtained in section 2 is used to analyze the Asian dust events in the observed and simulated data. There are 355 MEP data points in the Asian dust source region located within 35°–50° N and 75°–130° E. When the maximum PM$_{10}$–PM$_{2.5}$ value satisfies the Asian dust threshold value even for a single hour, the day is considered as an Asian dust day. Figure 4a shows the MEP-observed Asian dust days. The highest Asian dust frequencies are observed in northwestern China near the border with Kyrgyzstan, Tajikistan, and Pakistan, as well as in Inner Mongolia around the Badain Juran and Tengger Deserts. Asian dust days are also frequent in the vicinity of the four provinces around the Huabei Plain. The PM$_{2.5}$/PM$_{10}$ value is known to decrease to below 0.4 because large size particles are dominant in Asian dust events.
events (Claiborn et al. 2000). Figure 4c shows the ratio PM$_{2.5}$/PM$_{10}$ (%) when an Asian dust day was identified in the MEP data. The PM$_{2.5}$/PM$_{10}$ values are in the four provinces near the Huabei Plain and northeastern China are generally larger than in other regions due to the effects of anthropogenic aerosols from industrial sources. Although anthropogenic aerosols are screened using the PM$_{10}$–PM$_{2.5}$ threshold, as shown in Plaza et al. (2011), nitrates, one of the major anthropogenic aerosols, sometimes occur in the range 3.2–5.6 μm, leading to overestimation of Asian dust days for the heavily industrialized four provinces in the Huabei Plain. Similar to the observation, the simulation shows (Fig. 4b) a large number of Asian dust days in the Badain Juran and Tengger Deserts inInner Mongolia; however, the number of Asian dust days for northwestern China is well below the MEP observations. The simulation overestimates the observed Asian dust days in northeastern China.

Figure 5 evaluates the accuracy index of the simulated Asian dust days against the observed data using a contingency table constructed as follows: When a day is identified as an Asian dust day in both the observation and the simulation, it is counted toward the hit (H); if an observed Asian dust day is not an Asian dust day in the

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**Fig. 4.** Dust days in the first half of 2017 derived from (a) MEP observations and (b) the ADAM2 simulation. (c) Average PM$_{2.5}$/PM$_{10}$ ratio in the first half of 2017 obtained from MEP observations during dust events.

**Fig. 5.** Hit rate, threat score, probability of detection, and false-alarm ratio of the dust simulation in ADAM2 compared with those in the MEP observations in the first half of 2017.
simulation, it is a miss (M); when a non-Asian dust day in the observations is an Asian dust day in the simulations, it is a false alarm (FA); when both the observations and simulations indicate a non-Asian dust day, it is a correct rejection (CR). For a total number of forecasts \( n \), \( n = H + M + FA + CR \), the hit rate (HR) is \( HR = (H + CR)/n \), the threat score (TS) is \( TS = H/(H + M + FA) \), the probability of detection (POD) is \( POD = H/(H + M) \), and the false-alarm rate (FAR) is \( FAR = FA/(H + FA) \). To examine the ADAM2 performance in simulating Asian dust events according to regions, the dust source region in northern China is divided into four regions (Fig. 5): the northwestern China region (region A), the Inner Mongolia region (region B); the four provinces near the Huabei Plain (region C), and the Manchuria region (region D). Note that region C and region D include heavily industrialized areas and thus the aerosol concentration in these regions is strongly affected by anthropogenic sources. The HR values are relatively high except for northwestern China (region A); that is, ADAM2 substantially underperformed in detecting the Asian dust days in region A compared to other regions.

The TS values are high in Badain Juran and Tengger Desert in Inner Mongolia (region B) and in Manchuria (region D). The TS values are relatively low in the four provinces around the Huabei Plain (region C). Similar to HR, the TS values are low in northwestern China (region A). The POD values are high in Inner Mongolia (region B) and Manchuria (region D) and are relatively low in the four provinces around the Huabei Plain (region C). POD values are low in northwestern China (region A). FAR values are large in region D. The POD values are also high in region D, implying that ADAM2 substantially overestimates Asian dust days in the region.

To examine the effect of anthropogenic aerosols in determining Asian dust days in the four regions, the variations of the model errors according to PM\(_{2.5}\)/PM\(_{10}\), an approximate measure of the portion of anthropogenic aerosols within PM\(_{10}\), on the observed Asian dust days are summarized in Fig. 6. As the PM\(_{2.5}\)/PM\(_{10}\) ratio increases, the simulation overestimates the Asian dust days; this is common in all four regions. This may be due to the combined effects of the model overestimating the downstream transport of Asian dusts and the
observation overestimating Asian dust days by inaccurately counting anthropogenic aerosols toward large mineral dust particles. This also implies that the threshold for identifying Asian dust days does not work well when anthropogenic particulate concentration is very high as often occurring in heavily industrialized regions. Regionally, the model tends to underestimate Asian dust days in northwestern China (region A), but the PM2.5/PM10 values in region A are small, indicating that most of the Asian dusts in the region are large particles of natural origins. The PM2.5/PM10 values are small in Inner Mongolia (region B), and the model error in the number of Asian dust days for region B is smaller than that in the Taklamakan Desert. Major simulation errors occur in the four provinces near the Huabei Plain (region C). This indicates using the Asian-dust detecting threshold value based on PM10–PM2.5 may overestimate Asian dust days in the regions of heavy anthropogenic aerosols. To examine the possibility of erroneously overestimating Asian dust days due to heavy concentrations of anthropogenic particles, we examine the average PM2.5/PM10 values in each region. Compared with the entire distribution, high PM2.5/PM10 ratios of 0.4–0.45 are mostly found in the regions C and D that include heavily industrialized areas. As the PM2.5/PM10 value increases in region D, the number of Asian dust days in the simulation is slightly larger than in the observation; this also contributes to the tendency of the model to overestimate the Asian dust events for the region.

The accuracy indices in each region are summarized in Table 1 with the corresponding formulations. The highest HR value of 96.6% appears in the four provinces near the Huabei Plain (region C), and the lowest value is 88.1% in northwestern China (region A). The TS value is highest in Inner Mongolia (region B) (30.5%), followed by Manchuria (region D) (25.5%). This yields a high POD value (65.2%) for region D, but FAR is also large (70.5%). FAR is 50.0% in Inner Mongolia (region B), comparable to that in region D, leading to the largest TS. In northwestern China (region A), the simulation substantially underestimates Asian dust days to result in the smallest POD value (5.5%); the smallest FAR also occurs (28.6%) in the region. The large amount of anthropogenic aerosol emission in region C yields large FAR (73.1%) and small POD.

To further examine the relationship between soil types and the regional variations of model performance, the ratio of the soil types in each region is examined (Fig. 7). In the study area, mixed soil and loess are the most common soil types. In the Tibetan Plateau area, there are no observation stations, so it is difficult to determine whether Asian dust was present. Thus, we exclude the Tibetan soil type in discussion. In the northwestern region (region A), sand is most dominant, and mixed and Gobi are most dominant in Inner Mongolia (region B). Mixed soil and loess are present in region C. Last, Manchuria (region D) shows a pattern similar to that in the Huabei Plain (region C), but the sand type is also present in region D.

To determine the accuracy index of the model according to soil types, an analysis similar to that in Table 1 is performed for each soil type (Table 2) in all regions except for northwestern China (region A) where the model performance is problematic. There are only a few HR

<table>
<thead>
<tr>
<th>Region</th>
<th>H</th>
<th>M</th>
<th>FA</th>
<th>CR</th>
<th>HR (%)</th>
<th>TS (%)</th>
<th>POD (%)</th>
<th>FAR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1014</td>
<td>1151</td>
<td>1782</td>
<td>54012</td>
<td>94.3</td>
<td>23.3</td>
<td>39.5</td>
<td>63.7</td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>519</td>
<td>12</td>
<td>3900</td>
<td>88.1</td>
<td>5.4</td>
<td>5.5</td>
<td>28.6</td>
</tr>
<tr>
<td>B</td>
<td>455</td>
<td>582</td>
<td>454</td>
<td>14756</td>
<td>93.6</td>
<td><strong>30.5</strong></td>
<td>43.9</td>
<td>50.1</td>
</tr>
<tr>
<td>C</td>
<td>160</td>
<td>253</td>
<td>434</td>
<td>19258</td>
<td><strong>96.6</strong></td>
<td>18.9</td>
<td>38.7</td>
<td><strong>73.1</strong></td>
</tr>
<tr>
<td>D</td>
<td>369</td>
<td>197</td>
<td>882</td>
<td>16098</td>
<td>93.9</td>
<td>25.5</td>
<td><strong>65.2</strong></td>
<td>70.5</td>
</tr>
</tbody>
</table>

FIG. 7. Surface soil over regions A, B, C, and D categorized as Gobi (black), sand (yellow), loess (red), mixed (blue), and Tibetan (green) soil types.
values in the Gobi area because of a small number of samples, but the Gobi area shows the second largest TS value (29.0%). The largest TS (39.2%) appears for the sand type. In conjunction with very small FAR (36.8%), this indicates that the model simulates Asian dust events well for the sand type soil. Thus, ADAM2 is found to work well for the Gobi and sand types. For the loess type, the FAR value is largest (71.9%), showing that the area in which Asian dusts occur excessively in the current soil classification system is the loess area. Considering the overestimation of Asian dusts in region D, this result means that Asian dusts that originating in the regions of loess and mixed soil types (the ADAM2 soil types in region D) need to be reduced.

Figure 8 compares the simulated number of Asian dust days to that in the MEP observations according to soil types and regions. The number of the simulated Asian dust days agrees closely with that of the observation for the Gobi and sand types. Unlike for the mixed and loess soil type which show large spread, the model tends to overestimate the number of Asian dust days for the loess type. As shown in Fig. 8b, the model overestimates the observed number of Asian dust days in region D. This means that, in the model, Asian dust emission needs to be modified for the mixed and loess soil types. The systematic model errors according to soil types appear to be the main cause of the regional variations of model errors as the model performed poorly in the regions of the mixed and loess soil types.

The observed and simulated PM$_{10}$ concentration distributions are analyzed according to the $H$, $M$, FA, and CR values in the three regions except for region A (Fig. 9). In Inner Mongolia (region B), the simulated PM$_{10}$ concentrations agree closely for $H$ and CR although the high-concentration events are underestimated. For $M$ and FA, the model underestimates and overestimates the observed PM$_{10}$ concentrations, respectively. For the Huabei Plain (region C), the model simulations notably underestimate the observed mean and high percentile of PM$_{10}$ values for the $H$ and CR cases. The exact cause for this model bias is not clear, however, the lack of consideration of the dusts generated in Mongolia and subsequently transported into the region as well as the dusts from agricultural activities in the simulation may have contributed to the underestimation. Because of high concentrations of anthropogenic PMs in the four provinces around the Huabei Plain (region C), the $M$ and FA cases in the region may be due to the inability of ADAM2 in simulating anthropogenic PMs. Unlike for other regions, the simulation overestimates the observed PM$_{10}$ values in
the $H$ cases for Manchuria (region D); the mean and the upper/lower limit of the PM$_{10}$ concentration in the CR cases are underestimated for this region like for other regions. This may be the consequence of the soil-type-dependent ADAM2 model errors characterized by overestimation and underestimation of dust emission over loess/mixed soil types and Gobi/sand types, respectively.

4. Conclusions

Using the hourly PM observations and ADAM2 simulations in the first half of 2017, we have developed a threshold value for identifying Asian dust days from the observed as well as the ADAM2-simulated PM data. The threshold value in turn is applied to evaluate the fidelity of ADAM2 in simulating Asian dust days in the dust source regions in northern China. Based on the Asian dust events reported at the GTS stations, we have estimated that 5% of all weather events correspond to Asian dust days in the source region. Based on the weather-code deduced Asian dust days, the daily maximum PM$_{10}$ = 400 $\mu$g m$^{-3}$ is adopted as a threshold value for identifying an Asian dust day in the ADAM2 simulations and the MEP observations. The model performance in identifying Asian dust days are evaluated based on the accuracy index according to regions and soil types based on the threshold value.

The ADAM2 model notably underestimates the Asian dust days in northwestern China and overestimates in Manchuria. Both the probability of detection and false-alarm rate are high in the Manchuria, resulting in overestimation of Asian dust days. In terms of the threat score, the model fidelity for the number of Asian dust days is highest in Inner Mongolia. The predictability index for the number of Asian dust days according to soil types shows that the model performance in identifying Asian dust days varies quite systematically according to soil types: good performance for the sand-type soil and poor performance for the mixed and loess-type soil. The regional variations in ADAM2 performance appear to be related to the dependence of the model performance according to soil types. For example, the large FAR value in the Manchuria appears to result from overestimation of dust emissions in the source algorithm. Another source of the ADAM2 model errors may be due to inadequate handling of anthropogenic PMs, most seriously for the heavily industrialized Huabei Plain in which large PM$_{2.5}$ concentrations of anthropogenic PMs can yield large PM$_{10}$=PM$_{2.5}$ values to meet the Asian dust day threshold when the concentration of large dust particles is small. This problem will be alleviated in the upcoming ADAM3 model that simulates anthropogenic PMs.

As alterations in winds, vapor transports, and precipitation are expected due to future climate change, the proposed threshold value in the current Asian dust algorithm may not work well in future Asian dust forecasting. Thus, in addition to the model improvements listed above, it is necessary to regularly verify the threshold value for identifying an Asian dust forecast day. Continued evaluations and verifications of Asian dust simulations are important for improving Asian dust forecasts.

Acknowledgments. This work was funded by the Korea Meteorological Administration Research and Development Program “Development of Asian Dust and Haze Monitoring and Prediction Technology” under Grant 1365003013.

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