A Study on Three Factors Influencing Uptake Rates of Nitric Acid onto Dust Particles

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ABSTRACT

Recent studies have indicated that the observed nitric acid (HNO3) uptake rates (RHNO3) onto dust particles are much slower than RHNO3 used in the previous modeling studies. Three factors that possibly affect RHNO3 onto dust particles are discussed in this study: (1) the magnitude of reaction probability of HNO3 (γHNO3), (2) aerosol surface areas, and (3) gas-phase HNO3 mixing ratio. Through the discussion presented here, it is shown that the use of accurate γHNO3 is of primary importance. We suggest that the use of γHNO3 values between ~10^{-2} and ~10^{-3} produces more realistic results than the use of γHNO3 values between ~10^{-1} and ~10^{-2} does, more accurately modeling the nitrate formation characteristics on/in dust particles. We also discuss two different types of aerosol surface area, active and geometric, since the use of different aerosol surface areas often leads to an erroneous result in RHNO3. In addition, the levels of the gas-phase HNO3 are investigated with the example cases of TRACE-P DC-8 flights in East Asia. The HNO3 levels were found to be relatively high, indicating that they can not limit nitrate formation in dust particles.

Key words: Reaction probability, Dust particles, Nitric acid, Uptake rates, Aerosol surface area

1. INTRODUCTION

Recently, several studies have reported that although East Asian dust particles have sufficient chemical aging (or contacting) times (say, 1-4 days) with atmospheric air pollutants, they were found to contain only small amounts of nitrate (and/or sulfate) (Song et al., 2007; Song et al., 2005; Maxwell-Meier et al., 2004). This fact possibly indicates that the gas-to-particle nitric acid (HNO3) uptake rates (RHNO3) onto dust particles are slower than previously estimated. This could also be an important correction to the results from previous studies (Meskhidze et al., 2003; Song and Carmichael, 2001; Zhang and Carmichael, 1999; Dentener et al., 1996). For example, Meskhidze et al. (2003) inferred from the data of TRACE-P DC-8 Flight #13 that total nitrate (=HNO3(g)+NO3−(p)) distribution between gas phase and East Asian dust particles reaches a near equilibrium (refer to Fig. 4 in Meskhidze et al. (2003)). Their work supported the opposite idea that dust particles could contain a quite large amount of nitrate that could completely neutralize dust-originated cationic components such as Ca^{2+} and Mg^{2+}. This study, therefore, intends to discuss possible causes of this discrepancy in order to offer a convincing explanation.

Closely connected with this issue, controversy has continued regarding the magnitude of reaction probability of HNO3 (γHNO3) onto dust particles. Several research groups measured γHNO3 onto various types of dust particle, from proxy species of dust particles (e.g., α-Al2O3, SiO2, CaCO3 etc) to authentic Saharan and Gobi dust. However, a large difference in the magnitude of γHNO3 onto dust particles has been reported (Johnson et al., 2005; Umann et al., 2005; Harnisch and Crowley, 2001a, b; Underwood et al., 2001a, b; Fenter et al., 1995), as presented in Table 1. Here, the first group of γHNO3 has an order of magnitude from ~10^{-1} to ~10^{-2} (Umann et al., 2005; Harnisch and Crowley, 2001a, b; Fenter et al., 1995), compared to a range from ~10^{-3} to ~10^{-5} for the second group (Johnson et al., 2005; Underwood et al., 2001a, b).

The ultimate purpose of estimating (or measuring) γHNO3 is to apply the result to the chemistry-transport modeling studies. However, because of the large differences in the magnitude of γHNO3 onto dust particles, atmospheric modelers have been confused about which value should be adopted in their modeling studies (Song et al., 2007; Bauer et al., 2004; Zhang and Carmichael, 1999; Dentener et al., 1996; and also the third group of γHNO3 as presented in Table 1). In addition, it appears that the parameterizations (or estimation method) for γHNO3 for describing the heterogeneous interac-
tion between HNO₃ and dust particles are questionable. Therefore, an impartial discussion is urgently required about both the magnitudes of γ HNO₃ onto dust particles and the parameterizations for the heterogeneous interactions between HNO₃ and dust particles. In this study, we discuss all the relevant and yet contentious issues regarding the heterogeneous processes between gas-phase HNO₃ and dust particles. In addition, through this study we wish to provide a modeler’s perspective regarding the chemical evolution of dust particles and the magnitude of γ HNO₃ onto dust particles.

### 2. DISCUSSION

#### 2.1 Research and Theoretical Background

The HNO₃ uptake into dust particles causes the replacement of carbonate (CO₃²⁻) originally associated with crustal Ca²⁺ (and/or Mg²⁺) in dust particles via the following reaction:

\[
\text{CaCO}_3 + 2\text{HNO}_3 \rightarrow \text{Ca(NO}_3)_2 + \text{H}_2\text{O} + \text{CO}_2 \quad (\text{R-1})
\]

Similar carbonate replacement reactions occur with the uptake of other acidic substances such as H₂SO₄ and SO₂. Based on this mechanism, Table 2 presents the “dust chemical aging index”, defined as the ratio of estimated CO₃²⁻ equivalence ([CO₃²⁻] in μeq/m³) to crustal cation equivalence ([Ca²⁺] + [Mg²⁺]) at several different locations in East Asia (Song et al., 2007; 2005). As presented in Table 2, the ratios range from 0.39 to 0.87, indicating that the remaining carbonate fractions in the dust particles range from 39-87% respectively, even after the chemical aging times of 24-84 hrs. Several single particle chemical analysis studies with East Asian dust particles reached the same conclusions (Rö et al., 2005; Zhang et al., 2003; Zhang and Iwasaka, 1999). The replaced CO₃²⁻ fractions of 13-61% are believed to be released from dust particles by nitrate (and/or sulfate) formation. The small percentages of the replaced carbonate, even with the long chemical aging times, are obvious evidence of slow RHNO₃ onto dust particles.

Assuming pseudo first-order kinetics (eqn. 1), RHNO₃ can be calculated by eqns. (1) and (2). In the equations, the magnitude of RHNO₃ can be affected by three factors: i) γ HNO₃; ii) aerosol surface density (Sₐ); and iii) gas-phase HNO₃ concentration (C_HNO₃):

\[
\frac{dC_{\text{HNO}_3}}{dt} = kC_{\text{HNO}_3}
\]  

#### Table 1. Reaction Probability of HNO₃ onto dust particles.

<table>
<thead>
<tr>
<th>γ HNO₃</th>
<th>Type of Dust</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 × 10⁻²</td>
<td>Marble powder</td>
<td>Low pressure-flow reactor</td>
<td>Fenter et al. (1995)</td>
</tr>
<tr>
<td>7.1 × 10⁻²</td>
<td>CaCO₃</td>
<td>Knudsen cell</td>
<td>Harnisch and Crowley (2001a)</td>
</tr>
<tr>
<td>7.6 × 10⁻²</td>
<td>Na₂CO₃</td>
<td>Knudsen cell</td>
<td>Harnisch and Crowley (2001b)</td>
</tr>
<tr>
<td>1.5 (±0.3) × 10⁻¹</td>
<td>CaCO₃ (humid)</td>
<td>Knudsen cell reactor</td>
<td></td>
</tr>
<tr>
<td>6.0 × 10⁻²</td>
<td>CaCO₃ (dried)</td>
<td>Field study</td>
<td>Umann et al. (2005)</td>
</tr>
<tr>
<td>13.6 × 10⁻²</td>
<td>Saharan Dust</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>17.1 (±3) × 10⁻²</td>
<td>Chinese Dust</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>14.0 (±1.5) × 10⁻²</td>
<td>Dolomite</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>11 (±3) × 10⁻²</td>
<td>Saharan Dust</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>6 (±1.5) × 10⁻²</td>
<td>Arizona Dust</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>10 (±2.5) × 10⁻²</td>
<td>CaCO₃ (heated)</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>18 (±4.5) × 10⁻²</td>
<td>CaCO₃ (unheated)</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>13 (±3.3) × 10⁻²</td>
<td>Al₂O₃</td>
<td>Field study</td>
<td>Umann et al. (2005)</td>
</tr>
<tr>
<td>5.2 (±0.3) × 10⁻⁵</td>
<td>Gobi Dust</td>
<td>Knudsen cell</td>
<td>Underwood et al. (2001a)</td>
</tr>
<tr>
<td>2.0 (±0.1) × 10⁻⁵</td>
<td>Saharan Dust</td>
<td>Knudsen cell</td>
<td>Underwood et al. (2001b)</td>
</tr>
<tr>
<td>1.4 × 10⁻²</td>
<td>MgO (wet condition)</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>1.6 × 10⁻²</td>
<td>CaO (wet condition)</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>2 × 10⁻² × R₉</td>
<td>Saharan Dust</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>1.1 × 10⁻²</td>
<td>China Loess</td>
<td>Knudsen cell</td>
<td></td>
</tr>
<tr>
<td>7 (±4) × 10⁻⁴</td>
<td>Dolomite</td>
<td>Knudsen cell</td>
<td>Johnson et al. (2005)</td>
</tr>
<tr>
<td>1.5 (±0.4) × 10⁻³</td>
<td>CaCO₃</td>
<td>Modeling study</td>
<td>Dentener et al. (1996)</td>
</tr>
<tr>
<td>0.1</td>
<td>Dust</td>
<td>Modeling study</td>
<td>Zhang and Carmichael (1999)</td>
</tr>
<tr>
<td>0.01</td>
<td>Dust</td>
<td>Modeling study</td>
<td>Bauer et al. (2004)</td>
</tr>
<tr>
<td>0.1</td>
<td>Dust</td>
<td>Modeling study</td>
<td>This study</td>
</tr>
<tr>
<td>10⁻³-10⁻⁵</td>
<td>Dust</td>
<td>Modeling study</td>
<td></td>
</tr>
</tbody>
</table>

Note: ¹Values of 0.017-0.054 were reported; ²Surface roughness factor; ³Values recommended by this study.
2). For example, when $HNO_3$ levels of 1-3 ppb were frequently observed with high dust concentrations over the downwind areas from the polluted regions in East Asia (this will be discussed in more detail in section 2.4; also refer to Bauer et al. (2004)). However, such large amounts of nitrate have never been found in dust particles, particularly in East Asia (Song et al., 2007; Ro et al., 2005; Song et al., 2005; Zhang et al., 2003). In contrast, when $\gamma_{HNO_3} = 10^{-1}$, $R_{HNO_3}$ becomes much slower ($\tau_{10}=3.1-91.8$ days). With the initial $C_{HNO_3}$ of 1-3 ppb and $\gamma_{HNO_3}$ of $10^{-4}$, the converted amount of nitrate after the interacting times of 8 hours is 0.095-0.29 $\mu g/m^3$, which is

\[ k = \frac{1}{4} v_{HNO_3} \gamma_{HNO_3} S_a \]  

(2)
equivalent to an hourly averaged $R_{\text{HNO}_3}$ of 0.01-0.04 μg/m³·hr. Such slow $R_{\text{HNO}_3}$ are more consistent with the slow chemical evolution of dust particles observed in the field measurements. For example, in Table 2, we estimated the possibly maximum nitrate concentrations ($[\text{NO}_3^-]_{\text{max}}; [\text{NO}_3^-]_{\text{max}} = [\text{NO}_3^-]+[\text{SO}_4^{2-}]$). The measurement data used in Table 2 were obtained from the ACE-ASIA C130 flight campaign conducted over the Yellow sea on April 11-13, 2001, and a measurement campaign conducted in Seoul in April, 2005. We selected the data from the dust storm periods of the campaigns. In this calculation, while we cannot estimate the individual amounts of nitrate and sulfate, we can estimate the combined amounts of “nitrate+sulfate” concentration in the dust particles by equating the replaced carbonate equivalents to the “nitrate+sulfate” equivalences. In an extreme case, carbonate in dust particles could be replaced only by NO$_3^-$. These amounts ($([\text{NO}_3^-]_{\text{max}} = [\text{NO}_3^-]+[\text{SO}_4^{2-}])$ are then divided by chemical aging times to obtain the maximum possible nitrate uptake rates. As shown in Table 2, the rates range from 0.01 to 0.26 μg/m³·hr. These values are in general comparable to the estimated rates above (0.01-0.04 μg/m³·hr), particularly for the cases of ACE-ASIA C-130 Flights #6, #7, and #8 which recorded results in the range 0.05-0.07 μg/m³·hr (again, it is important to remember that the average uptake rates actually represent the production rates of NO$_3^-$+$\text{SO}_4^{2-}$).

Although in this study we do not intend to estimate $\gamma_{\text{HNO}_3}$ onto dust particles, one of the objectives of this study is to decide which values of “already-measured” $\gamma_{\text{HNO}_3}$ in Table 1 can be adopted in the dust chemistry modeling studies. Based on the calculations above, the modeling studies with $\gamma_{\text{HNO}_3}$ of $\sim 10^{-3}$-$10^{-5}$ could produce more consistent results with the field measurement data.

### 2.3 Surface Area

There is another possible mechanism that could slow down $R_{\text{HNO}_3}$ into dust particles: the application of a smaller surface area to eqn. (2). For example, in an estimating procedure of $\gamma_{\text{HNO}_3}$, Umann et al. (2005) introduced an “active surface area ($S_A$)” (for greater detail, refer to both Umann et al. (2005) and Matter Engineering, Appendix IV of Operating Instructions LQ1-DC, SKM990318-7b). A similar type of active surface area, so-called “Fuchs surface”, was also introduced by Pandis et al. (1991) and Shi et al. (2001). Whichever active surface area is used, $S_A$ has a tendency to become smaller than the “geometric surface area” ($S_G$), when the coarse-mode fraction is large, such as in dust and sea-salt aerosol cases. Therefore, if we use $S_A$ instead of $S_G$ for the gas-to-particle mass transfer process, $R_{\text{HNO}_3}$ could become slower. Table 3 presents the typical ratios of $S_A$ to $S_G$ for dust and sea-salt particle distributions (Sander and Crutzen, 1996; Zhang et al., 1994; Jaenicke, 1993). The ratios range between 0.11 and 0.41. In particular the ratio is 0.11 for the two typical dust cases, indicating that $R_{\text{HNO}_3}$ become slower by a factor of 0.11, even if the same $\gamma_{\text{HNO}_3}$ is used. Here, the relevant question is whether $S_A$ can be applied to eqn. (2). Umann et al. (2005) used $S_A$ with the concept of the “actual surface area” that is accessible for impinging gas molecules that can typically be measured by a BET (Brunauer, Emmett and Teller) type of instrument. However, both the active (μm$^2$/cm$^3$) and Fuchs (1/cm$^3$) surface areas are not the “actual/accessible surface area”, but an imaginary aerosol-surface area conveniently adjusted to consider the changing mechanism in the gas-to-particle mass transfer in accordance with the aerosol size changes (Pandis et al., 1991). For the fine particles, the gas-to-particle mass transfer (uptake) rates are proportional to the second moment (i.e., surface area), whereas for the coarse particles, $R_{\text{HNO}_3}$ are proportional to the first moment (i.e., radius). Therefore, the $S_A$-$to-S_G$ ratios are small when the coarse aerosol fraction is large, whereas the ratios are close to unity when the fine fraction is dominant. The variation in uptake mechanism with the aerosol size can be taken into account by the use of Fuchs and Sutugin kinetics (1971) or other

### Table 3. Mass transfer coefficients with different types of surface area ($\gamma_{\text{HNO}_3}=0.033$).

<table>
<thead>
<tr>
<th>Aerosol type and size distribution</th>
<th>$S_G$ (μm$^2$/cm$^3$)</th>
<th>$S_A$ (μm$^2$/cm$^3$)</th>
<th>$S_A/S_G$</th>
<th>$k_A$ (1/s)</th>
<th>$k_G$ (1/s)</th>
<th>$k_F$ (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaenicke (1993)</td>
<td>149.48</td>
<td>16.65</td>
<td>0.11</td>
<td>4.26×10$^{-5}$</td>
<td>3.82×10$^{-4}$</td>
<td>2.63×10$^{-4}$</td>
</tr>
<tr>
<td>Zhang et al. (1994)</td>
<td>137.07</td>
<td>15.72</td>
<td>0.11</td>
<td>4.02×10$^{-5}$</td>
<td>3.50×10$^{-4}$</td>
<td>3.12×10$^{-4}$</td>
</tr>
<tr>
<td>Sea salt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaenicke (1993)</td>
<td>44.54</td>
<td>18.06</td>
<td>0.41</td>
<td>4.97×10$^{-5}$</td>
<td>1.36×10$^{-4}$</td>
<td>1.15×10$^{-4}$</td>
</tr>
<tr>
<td>Sander and Crutzen (1996)</td>
<td>71.08</td>
<td>5.15</td>
<td>0.07</td>
<td>1.32×10$^{-5}$</td>
<td>1.82×10$^{-4}$</td>
<td>1.45×10$^{-4}$</td>
</tr>
</tbody>
</table>

1) The parameters have also appeared in Seinfeld and Pandis (1998) (see p. 430)
2) $n=7.98; r_p=0.88 \mu m; \log \sigma_p=0.23$
3) $n=1.40, r_p=1.66 \mu m; \log \sigma_p=0.19$
similar kinetics (e.g., see p. 604 in Seinfeld and Pandis, 1998). In Table 3, the Fuchs-Sutugin mass transfer coefficient \( k_F \) is compared with \( k_A \) (\( k \) from eqn. 2 with \( S_A \) for \( S_A \)) and \( k_G \) (\( k \) from eqn. 2 with \( S_G \) for \( S_G \)). As shown in Table 3, the values of \( k_G \) are consistent with \( k_F \), whereas the values of \( k_A \) are smaller than \( k_F \) by a factor of \( \approx 0.1 \). Meanwhile, the use of \( S_A \) in eqn. (2) also leads to an erroneous estimation of \( \gamma_{HNO_3} \). One example of the erroneous results is shown in Fig. 2. Umann et al. (2005) estimated \( \gamma_{HNO_3} \) from the field measurements in Sahara desert, using equations (1) and (2) with \( S_A \). We selected three dust episodes (E3, E4, and E5) from Umann et al.’s work (2005), and then re-estimated \( \gamma_{HNO_3} \) with \( S_A \) and \( S_G \). As shown in Fig. 2, when \( S_G \) is used instead of \( S_A \), the values of \( \gamma_{HNO_3} \) are decreased down to 0.004-0.02, which are smaller than Umann et al.’s values \( \gamma_{HNO_3}=0.03-0.18 \). These values are also closer to the second group of \( \gamma_{HNO_3} \), in Table 1 that we recommended to be used in the future dust chemistry modeling studies.

2.4 \( \text{HNO}_3 \) Concentration in the Gas Phase

\( \text{C}_{\text{HNO}_3} \)

The third factor that could affect \( R_{\text{HNO}_3} \) into dust particles is \( C_{\text{HNO}_3} \) (from eqn. 1). If \( C_{\text{HNO}_3} \) is low, \( R_{\text{HNO}_3} \) becomes slow. Or, if the amounts of \( \text{HNO}_3 \) are not sufficient, the amounts of nitrate formed in dust particles can be limited by the insufficient the amounts of \( \text{HNO}_3 \), even with fast \( R_{\text{HNO}_3} \). Particularly, extremely low \( C_{\text{HNO}_3} \) could occur over the areas where \( \text{NH}_3 \) concentrations are high. Over such areas, \( \text{HNO}_3 \) can be depleted by the reaction of \( \text{HNO}_3(g) + \text{NH}_3(g) \rightarrow \text{NH}_4\text{NO}_3(aerosol) \). For example, East Asia has large \( \text{NH}_3 \) emissions (Kim et al., 2006). Fig. 3 presents \( C_{\text{HNO}_3} \) and the \( \text{Ca}^{2+} \) concentrations measured by TRACE-P DC-8 Flights #9 and #13 over the Yellow Sea and East China Sea (see panels (c) and (g)). As presented in panels (d) and (h), the air masses originated from the Gobi desert and the arid areas in Inner Mongolia, and then passed through the highly polluted, high \( \text{NO}_x \) and \( \text{NH}_3 \) emission areas in China such as Beijing, Tianjin, Qindo, Dalian, Nanjing, and Shanghai, as well as various Chinese agricultural areas (Kim et al., 2006). The high levels of \( \text{Ca}^{2+} \) indicate that the air masses intercepted by DC-8 Flights #9 and #13 contained high levels of dust particles. In the two flights, the observed levels of \( \text{HNO}_3 \) were increased up to as high as 7 ppb (see panel (g)). The typical \( \text{HNO}_3 \) levels reported from other TRACE-P DC-8 and P3-B flights in the boundary layer under the continental outflow situations ranged between \( \approx 1 \) ppb and \( \approx 3 \) ppb. Despite the coexistence of the high levels of dust particles and \( \text{HNO}_3 \), Song et al. (2007; 2005) reported very low nitrate (and/or sulfate) concentrations inside dust particles over the areas close to the flight paths of TRACE-P DC-8 Flights #9 and #13. This is an important correction to the results from Meskhidze et al. (2003). They insisted that the coexistence of high levels of \( \text{Ca}^{2+} \) and \( \text{HNO}_3 \) in the TRACE-P DC-8 Flight #13 was firm evidence that \( \text{HNO}_3 \) had already filled up the dust particles (i.e., complete neutralization of \( \text{Ca}^{2+} \) or 100% carbonate replacement had occurred).

Again, the presence of high \( \text{HNO}_3 \) levels indicates that the low nitrate concentrations in the dust particles were not a result of the low \( C_{\text{HNO}_3} \) levels, but were rather due to the small \( \gamma_{HNO_3} \) that was reduced even smaller than \( 10^{-3} \).

3. CONCLUSIONS

The observed \( R_{\text{HNO}_3} \) onto dust particles were much slower than previously estimated. In addition, \( R_{\text{HNO}_3} \) have been overestimated in several previous dust
modeling studies, for which three possibilities were discussed here: (1) the magnitude of $\gamma_{\text{HNO}_3}$, (2) aerosol surface area, and (3) $C_{\text{HNO}_3}$. Regarding the second factor, we suggested that $S_G$ should be used in eqn. (2) instead of $S_A$, which had been used, for example, in Umann et al.’s study (2005). With respect to the third factor, we showed that the observed $C_{\text{HNO}_3}$ was relatively high, sometimes increasing up to as high as $\sim$7 ppb in the marine boundary layer in East Asia, for example. $C_{\text{HNO}_3}$ can not limit nitrate formation in dust particles.

The over-predicted $R_{\text{HNO}_3}$ onto the dust particles may have been caused by the first factor-overestimated $\gamma_{\text{HNO}_3}$ values ($\gamma_{\text{HNO}_3}=10^{-1}$-$10^{-2}$). In the previous modeling studies of Dentener et al. (1996), Zhang and Carmichael (1999), and Bauer et al. (2004), $\gamma_{\text{HNO}_3}$ values of 0.1 and 0.01 were used. In contrast to these overestimated $\gamma_{\text{HNO}_3}$ values, smaller $\gamma_{\text{HNO}_3}$ values within the range $10^{-2}$-$10^{-3}$ have also been reported by Underwood et al. (2001a, b) and Johnson et al. (2005). In this study we concluded that the use of $\gamma_{\text{HNO}_3}$ values between

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Fig. 3. The HNO$_3$ and Ca$^{2+}$ concentrations encountered by TRACE-P DC-8 Flights #9 and #13: (a) and (e) flight paths; (b) and (f) altitudes of the flights; (c) and (g) HNO$_3$ and Ca$^{2+}$ concentrations; and (d) and (h) five-day backward trajectory analyses, respectively, using the HYSPLIT model and meteorological data available on the NOAA/ARL web site (Draxler and Hess, 1998).
~10^{-3} and ~10^{-5} could produce more realistic results than those within the range of 10^{-1}-10^{-2} could, by more accurately predicting the nitrate formation characteristics in dust particles.

ACKNOWLEDGEMENTS

This work was financially supported by the Mid-Career Research Program, through a National Research Foundation of Korea (NRF) grant from the Ministry of Education, Science and Technology (MEST) (2010-0014058); and a National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST) (No. R17-2008-042-01001-0).

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(Received 4 April 2011, accepted 22 April 2011)