Supporting Information for

A Global-scale Mineral Dust Equation

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Introduction

This supporting information provides a text description to address adsorbed water and salt minerals for special types of dust, followed by two text descriptions about the processing of the soil data set reported by Engelbrecht et al. (2016) and the anthropogenic dust data from the SPECIATE database used in this study, figures to complement the main manuscript, and a table listing the SPECIATE speciation profiles selected.

Text S1.

To develop a framework to address adsorbed water for special types of dust, we began with the single hygroscopicity parameter $\kappa$ (Kreidenweis et al., 2008; Snider et al., 2016), and derived a water adjustment factor (WAF) as:

$$WAF = 1 + \left( \kappa \frac{RH}{100 - RH} \right) \times \left( \frac{\rho_{\text{water}}}{\rho_{\text{dust}}} \right)$$

where RH is relative humidity and $\rho$ is density. The overall $\kappa$ of dust can be obtained from hygroscopic growth measurements or estimated using mineralogical composition and known $\kappa$ values of each mineral. For common desert dust, WAF approaches unity.

To account for salt minerals in special types of dust, we expanded the expressions of the MAL ratio, CF, and the global dust equation given that some elements can be associated...
with other anions besides carbonate and these anions are not considered for common desert dust.

The expanded expression of MAL is shown below:

\[
MAL = [(x+1.20(1 - x)) K/Al + [y+1.66(1 - y)] Mg/Al + [z+1.35(1 - z)] Na/Al]/1.89 \\
= [(1.20 - 0.20x) K/Al+(1.66 - 0.66y) Mg/Al+(1.35 - 0.35z) Na/Al]/1.89
\]

The variables \(x\), \(y\), and \(z\) represent mass ratios of K, Mg, and Na ions that exist in salt minerals apart from carbonates to total K, Mg, and Na, respectively. Specific mineralogical information is needed to estimate \(x\), \(y\), and \(z\). For common desert dust, \(x\), \(y\), and \(z\) approach zero, which reduces the equation to the original expression of MAL where K, Mg, and Na are only included as oxides.

The expanded expression of CF combined with WAF is shown below:

\[
CF = \frac{100 \text{ wt} \%}{100 \text{ wt} \% - [1 \text{ wt} \% + \text{CO}_2(\text{wt}\%) + \text{Cl}^-(\text{wt}\%) + \text{F}^-(\text{wt}\%) + \text{SO}_4^{2-}(\text{wt}\%) + \text{NO}_3^-(\text{wt}\%)]} \times \text{WAF}
\]

Carbonate is incorporated as CO\(_2\) as in the original expression of CF. Specific mineralogical information is needed to estimate the abundance of all salt minerals. For common desert dust, the water content and salt minerals apart from carbonates are negligible, which reduces the equation to the original expression of CF.

The expanded global equation with expanded MAL and CF is shown below:

\[
\text{Dust}=\{1.89\text{Al}\times(1+\text{MAL})+\{\alpha+2.14(1 - \alpha)\}\text{Si}+\{\beta+1.40(1 - \beta)\}\text{Ca}+1.36\text{Fe}+1.67\text{Ti}\}\times\text{CF}
\]
\[
=\{1.89\text{Al}\times(1+\text{MAL})+(2.14 - 1.14\alpha)\text{Si}+(1.40 - 0.40\beta)\text{Ca}+1.36\text{Fe}+1.67\text{Ti}\}\times\text{CF}
\]

The variable \(\alpha\) represents the mass ratio of Si in fluorides to total Si for volcanic dust. The variable \(\beta\) represents the mass ratio of Ca ions that exist in salt minerals apart from carbonates to total Ca for saline dust, volcanic dust, aged dust, etc. Specific mineralogical information is needed to estimate \(\alpha\) and \(\beta\). For common desert dust, \(\alpha\) and \(\beta\) approach zero, which reduces the equation to the original expression of the global equation.

**Text S2.**

We used an available data set (Engelbrecht et al., 2016) with chemical and mineralogical measurements of PM\(_{10}\) and PM\(_{2.5}\) surface soil samples from 65 sites worldwide to investigate the mass ratio of total CO\(_2\) to CO\(_2\) in CaCO\(_3\) as well as the effects of particle size on the elemental ratios and CO\(_2\) content. Since we are interested in desert dust, we excluded samples that are local soils in Europe, lakebed or riverbed deposits, soils collected from roads and artillery firing pads, and special types of soil including red clay
and green dust. We were therefore left with 38 samples in the final data set. This data set is missing measurements of Na, so we used available ICP-OES measurements of Na\(^+\) as the substitute. For calculating the mass ratio of total CO\(_2\) to CO\(_2\) in CaCO\(_3\) in dust source regions, we excluded the samples with desert soil in non-source regions (the Atlantic islands) and averaged the data of soils with the same particle size from the same site. Hence, 13 more samples were omitted.

**Text S3.**

We collected measured PM\(_{2.5}\) and PM\(_{10}\) data of paved road, unpaved road, and agricultural soil dust from the EPA’s SPECIATE5.0 database. The concentrations of species are given in the weight fraction form. Speciation profiles that are composites of other profiles were discarded to avoid double weighting. Data without information on the sampling date were excluded. We calculated the “residual mass” (RM) using the following equation:

\[
RM = 100\% - OC \times (OM/OC) - EC - SO_4^{2-} - NO_3^- - NH_4^+ - 1.8Cl^- (or Cl) - PBW
\]

When the measurement of NH\(_4^+\) is unavailable, we use 1.375SO\(_4^{2-}\) and 1.29 NO\(_3^-\) in the equation assuming (NH\(_4^+)\)_2SO\(_4\) and NH\(_4\)NO\(_3\) referring to the IMPROVE algorithm. The common humidity protocol (35%) was adopted for calculating the PBW. Table S1 provides information about the selected data.

**Figures**

![Graphs](image)

**Figure S1.** The median and interquartile range of elemental ratios and MAL in six dust source regions and the average global continental crust. The six dust source regions include the Middle East (ME), Sahara, Sahel, Australia, East Asia (EA), and Southwest US (SW US).
Figure S2. The single silicon coefficient $M$ (total dust mass / Si) in six dust source regions and the average global continental crust shown on a log scale. The dashed line indicates the median coefficient $M$ (3.4) in continental crust of four data sources.

Figure S3. The MSI ratio of $(K_2O+MgO+Na_2O)/SiO_2$ in six dust source regions and the average global continental crust shown on a log scale. The dashed line indicates the median MSI ratio (0.15) in continental crust of four data sources.
Figure S4. The distribution of CaCO₃ content (wt%) in topsoil from the Harmonized World Soil Database (HWSD version 1.21).

Figure S5. The mass ratio of total CO₂ to the CO₂ associated with CaCO₃ using measured data collected from the literature (Boose et al., 2016; Engelbrecht et al., 2016; Shen et al., 2009). Soils from islands were excluded and duplicated samples were averaged.
Figure S6. Particle size effect on elemental ratios of dust using a dataset of surface soil from arid regions (Engelbrecht et al., 2016). ICP-OES measurements of Na\(^+\) were used to calculate Na/Al. Data points are jittered to avoid overlap. The number of asterisks indicates the significance level (* \(P < 0.05\); ** \(P < 0.01\); *** \(P < 0.001\)) of the difference between two groups using the paired-sample Wilcoxon test.

Figure S7. Comparison of the dust mass calculated by the global equation with the “residual mass” using dust-dominated (SOIL > 50% RCFM) PM\(_{2.5}\) data during 2008-2010 (red circles) and 2011–2013 (black crosses) from the U.S. IMPROVE network.
Figure S8. Mean fractional bias (MFB) for the dust mass calculated by (a, b) the global equation and (c, d) the IMPROVE equation compared to (a, c) the “total mineral mass” and (b, d) the “residual mass” at IMPROVE sites using daily-integrated dust-dominated (SOIL $>$ 50% RCFM) PM$_{2.5}$ speciation data in 2011–2018 from the U.S. IMPROVE network. Only the sites with $\geq$5 data points were used to ensure representativeness. The number of selected IMPROVE sites is 95.
Figure S9. Comparison of the dust mass calculated by the global equation and the IMPROVE equation with the “total mineral mass” for PM$_{10}$ data measured at EMEP sites during Saharan dust events (17-23 June 2012 and 28 June to 7 July 2012). Inset statistics are the normalized mean bias (NMB) and mean fractional bias (MFB) of using the two equations. The residual-mass approach was not applied because of insufficient measurements of other PM$_{10}$ species.

Figure S10. The ratio of the dust mass calculated by the global equation and the IMPROVE equation to the “total mineral mass” for African dust over the Atlantic islands as well as Asian dust over Japan and Korea. The amounts of dust elements are given in mass concentration or mass fraction, so only the mass ratios were shown in the plot for comparison.
| Dust Type         | SPECIATE Profile Code | Sampling Region |
|-------------------|-----------------------|-----------------|
| Paved Road        | 4204, 4206, 4208, 4210, 4212 | Texas           |
| Unpaved Road      | 4217, 4219, 4221, 3966, 3968 | Texas, Illinois |
| Agricultural Soil | 3297, 3298, 3307, 3308, 3312, 3313, 3332, 3333, 3337, 3338, 3357, 3358, 3392, 3393 | California     |

*Mg and Na data are missing. The average elemental ratios of Mg/Al (0.07) and Na/Al (0.02) from another study (Chow et al., 2003) in the same location were therefore applied. Table S1. Anthropogenic dust data from the SPECIATE5.0 database used in this study*
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