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Characteristics of dry deposited mineral particles associated with weather conditions in the adjacent sea areas of East China during a cruise in spring 2011

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ABSTRACT

Dry deposited particles, larger than 1.3 μm, were collected under clear, cloudy, and foggy conditions during a cruise, traversing the Yellow Sea and the East China Sea from 23 March to 8 April 2011. In these areas, air masses are influenced by pollution outflows from the Asian continent. The size and elemental composition of dry deposited particles were investigated using a scanning electron microscope. Number–size distributions of these particles were approximately lognormal. Under clear conditions, the mode size was about 5.0 μm, with a mean diameter of 6.9 μm. Under cloudy and foggy conditions, the mean diameters were 5.7 and 6.0 μm, respectively, but the mode sizes were vague. Non-mixed mineral particles, sea salt, and mixed mineral–sea salt particles were the major particle types. Correspondingly, Al and Si were the most frequently detected elements. Frequencies of K-, Ca-, and S-containing particles were highest under foggy conditions, while the frequency of Na-containing particles was lowest. These results indicate that fog favored sulfate production on the particles and led to the deposited mineral particles more abundant in secondary salt, suggesting the importance to consider the dependence of the composition of deposited mineral particles on weather as well as particle size.

Introduction

Atmospheric deposition is one of the most efficient pathways for some natural substances to enter open oceans (Kocak et al., 2015; Zhang & Gao, 2007; Zhang, Yu, Ma, & Chen, 2010). Thus, the composition, size, and shape of airborne particles in the marine boundary layer determine part of the input of particulate matter into the ocean (Osada et al., 2014). Typically, aerosols in the marine atmosphere comprise particles emitted from ocean surfaces, land surfaces, and anthropogenic activities; these may be primary particles, or particles produced via gas-to-particle conversions in the air, which are known as secondary particles (Ye & Chen, 2009; Zhang et al., 2012). Their deposition in the ocean affects marine ecosystems, and consequently the Earth's biogeochemical cycle (Cropp et al., 2013; Gao, Arimoto, Duce, Lee, & Zhou, 1992; Xie, Chi, Meng, Guo, & Wang, 2015).

Aerosol particles deposited onto sea surface have been studied in various contexts (Al-Taani, Rashdan, & Khashashneh, 2015; Zhang, Shi, Gao, Zhang, & Yao, 2013). The dry deposition of particles is dependent on their size and density, as well as meteorological conditions and the surface resistance of the ocean (Nho-Kim, Michou, & Peuch, 2004; Pan & Wang, 2015). A number of measurements have been carried out at coastal sites to evaluate the deposition flux of dust and particulate species to adjacent sea areas (Qi, Li, Li, Feng, & Zhang, 2005; Zhang, Wang, Sheng, Yutaka, & Astuyuki, 2004). Yang et al. (1994) reported that the percentage of atmospheric dust settling onto the sea surface is 1%–35% of the total mass input into the East China Sea. Liu, Zhang, and Yu (1998) estimated that the annual atmospheric dust input into the Yellow Sea was 6.0×10^{11}–90.0×10^{11} g/a, which is equivalent to 4%–38% of the annual river sediment input into the sea. However, in contrast to particulate input from rivers, dry deposition from the atmosphere is not limited to coastal regions, but can occur even in remote open ocean (Hsu et al., 2010). Aerosols deposited into the ocean promote plankton growth in sea surface water, influencing the marine ecosystem (Fung et al., 2000; Hsu et al., 2010). In

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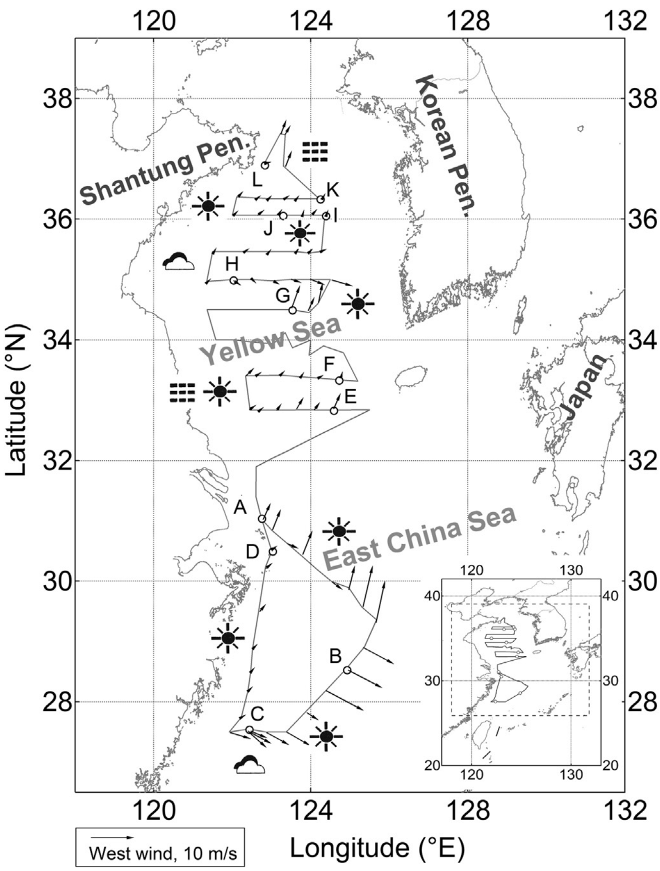

Fig. 1. Cruise track (from position A to position L), sampling areas (along the lines connecting the marked positions), wind direction and speed (shown as vectors), and corresponding weather conditions (clear, cloudy, and foggy marked with weather symbols). Ten samples were collected as the cruise ship moved between two marked positions, or remained at one position: A–B (Mar. 23 9:30–Mar. 25 22:30), B–C (Mar. 25 23:25–Mar. 26 15:10), C (Mar. 26 15:30–Mar. 27 18:50), C–D (Mar. 27 18:55–Mar. 28 18:03), E–F (Mar. 30 09:25–Mar. 31 12:35), G–H (Apr. 03 8:05–Apr. 04 8:40), H–I (Apr. 04 9:20–Apr. 05 10:08), I–J (Apr. 05 10:55–Apr. 05 17:25), J–K (Apr. 06 18:45–Apr. 07 15:35), and K–L (Apr. 07 16:15–Apr. 08 16:00). The times shown are Beijing Standard Time (GMT + 8).

particular, Shi et al. (2012) observed a phytoplankton bloom following a dust storm, and found that the atmospheric deposition of mineral particles dominated the supply of nutrients to the central East China Sea during dust events.

Many observations record particles deposited onto or near the sea surface (Gabric et al., 2015; Tu, Hao, & Pan, 2015; Zhang et al., 2012). However, the physical and chemical characteristics of these dry deposited particles are not well defined because of a lack of observational data at the individual particle scale. Clearly, bulk measurements of integrated samples cannot accurately characterize these particles (Yang, Liu, & Chen, 2010). To obtain accurate physical and chemical information on particles settling into the sea, we used an electron microscope to quantify the size and elemental compositions of dry deposited particles from the marine boundary layer. The particles were collected during a cruise in areas adjacent to East China from 23 March to 8 April 2011 under clear, cloudy, and foggy weather conditions. These areas are significantly influenced by heavy pollution outflows from the Asian continent. To date, little information is available on the nature of the dry deposited mineral particles off the East China coast, over the Yellow Sea and the East China Sea. To our knowledge, work characterizing dry deposited mineral particles under various weather conditions is rare. Here, the number–size distribution and the elemental composition of such dry deposited particles under various weather conditions are presented.

Sample collection and analysis

The research vessel, Dong Fang Hong 2, cruised in the off shore areas of the Yellow Sea and the East China Sea from 23 March to 8 April 2011. The cruise track, showing sampling areas, wind direction, wind speed, and corresponding weather conditions, is shown in Fig. 1. Dry deposited particles were collected using a Sigma-2 sampler, fixed at about 8.0 m above sea level. The Sigma-2 sampler is a passive sampler for collecting dry deposited particles with a geometrical diameter larger than 1.3 μm (for a density of 2.3 g/cm^3). Hence, this sampler efficiently collects long-distance transported dust particles because such particles typically have sizes larger than 1 μm, with a mode size of around 3–4 μm (Zhang, Iwasaka, & Shi, 2005). Sampler design and performance were described by Schultz (1993) and Guéguen, Stille, Millet, Dietze, and Gieré (2010) in detail. The sampler was covered with plastic bags whenever the vessel stopped or sailed toward the wind direction to avoid possible contamination from the vessel's exhaust. No obvious influence of seawater droplets or ship emissions were encountered during sampling. Particles were collected directly onto Ti grids having a 3-mm diameter, which were placed on the top of pin stubs for electron microscopy analysis. The stubs were subsequently fixed to the bottom of the sampler. After particle collection, each stub with a grid was sealed in a plastic stub box. The boxes were stored in sealed bags with silica gel and were later stored in a laboratory refrigerator. Consequently, the particles were dehydrated when analyzed.

We analyzed the particles of six samples collected under clear conditions, and two samples each collected under cloudy and foggy

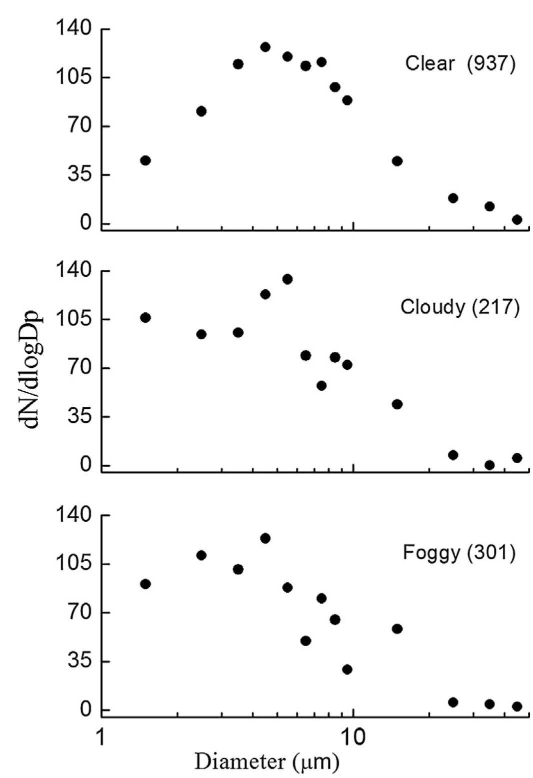

Fig. 2. Number–size distributions for dry deposited particles collected under different weather conditions: clear, cloudy, and foggy. Numbers of particles analyzed are shown in parentheses.