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# Deposition of duststorm particles during 2000–2012 in the South Yellow Sea, China based on satellite data

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**Abstract**

In this study, about 220 satellite images between 2000 and 2012 were obtained from FY-series, MODIS, CBERS, HJ-1A and HJ-1B to estimate the impact of duststorms on the South Yellow Sea (SYS), which serve as an important source of particles there. The analyzing results from the images support a total occurrence of 88 duststorms (including the locally-generated dusty weather) that affected the SYS during 2000–2012. The annual occurrence was about 4–10 times (10 times in 2000 and 2004; four times in 2009 and 2012), predominantly in March (29%), April (33%) and May (22%). By mapping the distribution of their frequency, the duststorms influencing the SYS were found primarily moving from the northwest (39 times, 44.3%) and west (37 times, 42%) to the study region with only 11 duststorms (12.5%) coming from the north and 1 duststorm (1%) from the southwest. We estimated that an annual amount of 0.5–3.5 million tons of sediment particles was brought to the SYS by the duststorms during 2000–2012.

**Key words:** duststorm particle, deposition, satellite data, South Yellow Sea

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## 1 Introduction

In recent years, the northern Jiangsu Shoal has received an increasing attention given that it is likely to be enclosed as a landform for regional marine economic development. An important issue that remains to be resolved is whether the northern Jiangsu Shoal is expanding or retreating, as the enclosed land may be eroded within a few years if it is retreating. Most researchers believe that the northern Jiangsu Shoal has been in a state of retreat after the Huanghe River (Yellow River) changed its path to the northeast in 1855 (Zhang and Chen, 2013), resulting in a shortage of sediment input into the South Yellow Sea (SYS). It is significant to identify the sources of sediment particles to determine the expansion or retreating of the northern Jiangsu Shoal.

Asian duststorms are considered as an important sediment source for the SYS (Kok et al., 2012). The dust is carried across the coastal waters from North and Northwest China (Mukai et al., 1990). It has been reported that the annual-mean dust emission flux is 1 015.34 mg/(m$^2$·d), of which 62.4% and 2.3% are re-deposited onto the continent of East Asia through dry and wet deposition processes, respectively, and the rest 35.3% is remained in the atmosphere or subject to long-range transport (Su and Wang, 2012). A large portion of the sediment in the SYS, which is located within the path of duststorm long-range transport, originates from these duststorms. Of all of the East Asia dust weather, about 63.9% are likely to affect the seas in China and 30.9% influenced the SYS during 2000–2002 (Zhang et al., 2005). Wet deposition contributes substantially to the total amount of dust deposition in the seas, in particular, the SYS, the East China Sea and the northwestern Pacific Ocean.

A variety of estimations for the amount of duststorm particles that are deposited in the SYS were provided by different researchers, as summarised below. In March 2010, the monthly mean value of dust concentration in the SYS was 62 μg/m$^3$ and the total amount was about 2.33 t/km$^2$, with a dry deposition of 1.36 t/km$^2$ and wet deposition of 0.97 t/km$^2$ (Park et al., 2011). During December 20–29, 2009, the 10-day total dust deposition in the downwind domain of the SYS was found to be 2.44 t/km$^2$ (Park et al., 2013). The annual maximum dust deposition in the downwind region of the SYS was 19 t/km in total in 2007 (Park et al., 2010) and 27 t/km$^2$ in 2010 (Park et al., 2011). Gao et al. (1992) estimated that the atmospheric dust deposition into the SYS was about 9–76 g/(m$^2$·a) (or 4–33 Tg/a). Zhang et al. (2004) reported a dry deposition flux into the SYS of 51.3 g/(m$^2$·a), an atmospheric flux of 0.20 g/(m$^2$·a) in spring, and total dry deposition into the SYS was 7.58×10$^5$ g/d (about 276.67 tons annually). An annual maximum wet deposition of 71 t/km$^2$ into the SYS in total was re-

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ported by Satake et al. (2012). Some of the researchers only used data from a single duststorm event based on a point observation, which is not adequate for calculating the contributions of all duststorms in terms of dust particle deposition in the SYS with high accuracy. The difficulties to collect *in situ* observations over the sea and the lack of systematic observations with a wide spatial coverage are likely to result in errors or uncertainties in the estimation of the dust deposition into the sea and thus the gaps as large as over four orders among the estimations provided by different researchers. From these works, we can see variations in the reported amount of dust particles deposited in the SYS.

The direction of an incoming duststorm is important for calculating the amount of duststorm particles that are deposited in the seas. Geng and Sheng (2006) used statistics for the direction of duststorms over Qingdao and found that the duststorms came from north and northwest 118 times out of a total of 158 times, which is 74.8% of the total number of East Asia duststorms occurring from 1961–2004. Considering that the duststorms entering the SYS are mainly from northwest, west and north, Qingdao and Korea provide important locations for ground measurements. In March and April, mass concentrations of coarse particles in Qingdao account for 80% and 62% of the total duststorm occurrence, respectively. The dry deposition flux in Qingdao is between 0.06–0.20 g/(m$^2$·d), with an average value of 0.13 g/(m$^2$·d) (Zhang et al., 2004). However, since some duststorms that entered the SYS did not pass over Qingdao, these results can only partially explain the amount of sediment deposition in the SYS. At the ground sampling sites on the Korean Peninsula, high dust concentrations of up to 1 110 μg/m$^3$ have been observed, with dust sources in North China and Mongolia (Chung, 1992).

At present, the estimation of the quantity of duststorm particles deposited into the SYS is mainly derived from models. Yang et al. (2010) adopted a two-layer model, which includes the deposition processes of turbulent transfer, Brownian diffusion, impaction and gravitational settling over the sea surface, and calculated the mean value of dry deposition flux into the SYS as (5.05±2.49) μg/(m$^2$·s). Along the main paths of the duststorms, more deposition was found. You et al. (1991) simulated particle deposition and observed that about 25% was deposited within the range of 250 km from the source, 50% within 1 000 km and only 20% transported to areas beyond 10 000 km. These results are important for calculating duststorm particle deposition into the SYS in the most recent decade. Boundary conditions, however, were relatively difficult to determine for the modeling of duststorm deposition.

Duststorms, one of the most important particle sources of the SYS, can provide particles for maintaining the stability of the northern Jiangsu Shoal. Dust concentration and deposition flux are determined not only by duststorm density, but also by transportation paths and processes (Arimoto, 2001). Owing to its ability to detect duststorms with a high accuracy, satellite remote-sensing serves as a useful tool to calculate the sediment content of duststorms precisely and to constrain the transport directions and pathways. In this study, we identified the duststorms that influenced in the SYS from 2000 to 2012 with the corresponding ten-year's satellite data and provided an accurate estimation of duststorms' contribution to sediment deposition into the SYS.

## 2 Materials and methods

### 2.1 *Study area*

The Yellow Sea, located between China and South Korea (Fig. 1), extends about 960 km from north to south and about 700 km from east to west. It has an area of about 380 000 km$^2$ and a volume of about 17 000 km$^3$. Its depth is only 44 m on average, with a maximum of 152 m. The sea was named after the dust particles from the Gobi Desert duststorms that gave the surface of the seawater a golden-yellow color, and hence the name "Yellow

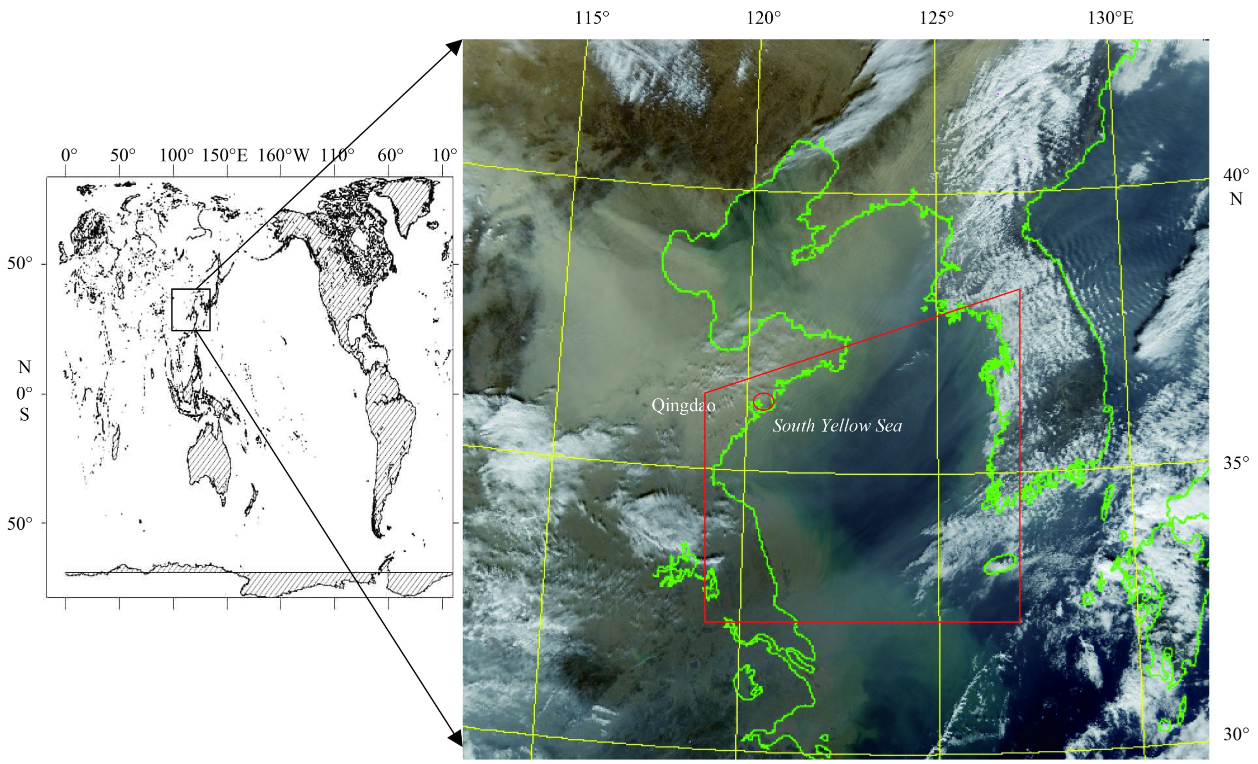


**Fig. 1.** Studied area of the SYS. The coastal ground observation site in Qingdao (for color-web) is also shown.

China Sea". The seabed slope is relatively small toward the mainland of China but it is large toward the Korean Peninsula. The water depth gradually increases from north to south. The sea bottom and shores are dominated by dust and silt from rivers (http://en.wikipedia.org/ wiki/Yellow_Sea).

The Yellow Sea can be divided into the North Yellow Sea (NYS) and the SYS at the narrowest width between the east top of the Jiaozhou Peninsula and the Korea Peninsula. The SYS is an area more susceptible to duststorms. The duststorms from the deserts in Mongolia and in West and North China (mainly the Taklimakan and Badain Juran, respectively) move eastward. The SYS is an important pathway for duststorm particle transport towards the east (Zhang, 2007).

### 2.2 *Satellite data obtaining and processing*

#### 2.2.1 *Satellite data*

Satellite data from China's FY-series, MODIS (http://modis.gsfc.nasa.gov/data/), CBERS (China–Brazil Earth Resources Satellite program), HJ-1A and HJ-1B are used to detect duststorms that affected the SYS during 2000–2012. About 220 satellite images of these data sets were gathered in this study. The quasi-real-time images are produced with medium resolutions for more than twice a day in order to minimize the amount of missed duststorm events.

#### 2.2.2 *Satellite data processing*

The process of satellite data processing is presented in Fig. 2.

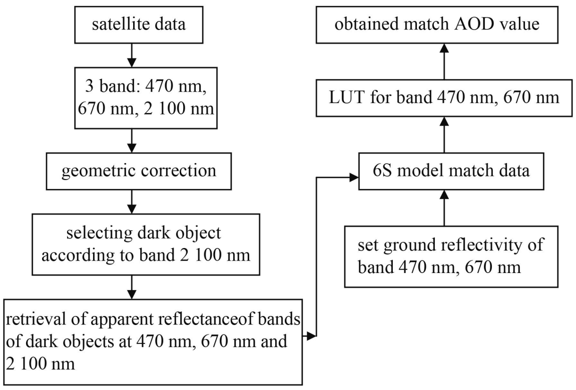


**Fig. 2.** Flow chart (based on Liu and Yang, 2013) of atmospheric optical depth retrieval (AOD is aerosol optical depth).

Duststorm atmospheric optical depth (AOD) can be divided into atmospheric optical depth-of-dust ($\tau_{\text{dust}}$) and free-of-dust ($\tau_{\text{free}}$):

$$\tau_t = \tau_{\text{dust}} + \tau_{\text{free}}. \tag{1}$$

The atmospheric optical depth of free-of-dust mainly contains Rayleigh scattering ($\tau_{\text{Ray}}$), water vapour ($\tau_{\text{H}_2\text{O}}$), oxygen ($\tau_{\text{O}_2}$), and ozone ($\tau_{\text{O}_3}$):

$$\tau_{\text{free}} = \tau_{\text{Ray}} + \tau_{\text{H}_2\text{O}} + \tau_{\text{O}_2} + \tau_{\text{O}_3}. \tag{2}$$

In the winter of middle latitude, $\tau_{\text{Ray}}$=0.056 8, $\tau_{\text{H}_2\text{O}}$=0.003 1, $\tau_{\text{O}_2}$=0.000 7, and $\tau_{\text{O}_3}$=0.034 2 (Ignatov and Stowe, 2002). Therefore, the atmospheric optical depth of duststorms can be accurately detected by satellite remote sensing.

The optical depth-of-dust retrieved in the paper can be used directly to calculate dust content in the columns of duststorms using Eq. (3) below, following Kaufman (1987) and Zheng et al. (2008):

$$M = 0.04 f_{\text{d}} \omega_0 \tau_{\text{dust}} \ \ (0.61\ \mu\text{m}), \tag{3}$$

where unit of $M$ is g/m$^2$ and $f_{\text{d}}$ can be calculated using

$$f_{\text{d}} = 1.43(1 - h_{\text{r}})^{0.7} \ \ (0.4 \leqslant h_{\text{r}} \leqslant 0.9), \tag{4}$$

where $h_{\text{r}}$ is relative humidity at 8:00 am; and $\omega_0$ is the single reflection at 0.64 μm, whose value is about 0.96 (Tanré et al., 1997).

When the satellite data are used for calculating dust content, the directions and pathways of duststorms can be retrieved directly. Software of 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) is used to retrieve AOD with Eq. (1).

### 2.3 *Collection of ground truth data*

Ground truth for dust particle deposition data was gathered mainly from dustfall jars for the years between 2005 and 2009. Qingdao City was chosen for collecting these samples for its being located on the northwest coast of the SYS, where originates most of the duststorms influencing SYS.

### 2.4 *Statistical methods for determining duststorm frequency*

Satellite remote sensing data on a 1°×1° grid was used for obtaining the statistics of duststorm distribution in the SYS. If the grid of the remote sensing image shows a duststorm, it is recorded as 1; otherwise, it is 0 (the density of duststorms were not considered). The geographic distribution of duststorms above the SYS and the Bohai Sea was examined annually using the Kriging interpolation algorithm (SURFER 8 Golden Software, Colorado). The area of a duststorm can be calculated by summing up the grids of 1 multiplied by a geographical coefficient (111×111cos$\alpha$, where $\alpha$ refers to latitude).

### 2.5 *Deposition calculation*

According to Han et al. (2008), the relationship between dust particle content in a duststorm and distance from the duststorm is described as

$$y = 4\,336.5 e^{-0.022\,3x}, \tag{5}$$

where $y$ (μg/m$^3$) is the dust particle content in a duststorm compared with that at the source site, and $x$ is the distance from the source duststorm. Thus, the deposition of duststorm particles in the study area can be calculated using the following equation:

$$y_1 = 4\,336.5(e^{-0.022\,3(x_1)} s_1 h - e^{-0.022\,3(x_2)} s_2 h), \tag{6}$$

where $y_1$ (μg) is quantity of dustfall; $x_1$ and $x_2$ are the distances from the source duststorm; $s_1$ and $s_2$ are duststorm areas at $x_1$ and $x_2$, respectively; and $h$ is the height of the duststorm. In the paper, we regard $h$ as a constant.

Considering that duststorms mainly come from the northwest, west and north, a ground truth observation site in Qingdao is used for validating the satellite data.

## 3 Results

### 3.1 *Duststorm pathways to the SYS*

Four types of duststorm pathways to the SYS are identified as: duststorm from the north (primarily, Mongolia), northwest

(Central Asia), west and southwest (Fig. 3). Duststorms originating from Central Asia primarily follow the northwest pathways, whereas duststorms originating from Mongolia predominate the north pathways. Some duststorms from Central China, such as South Shandong, and a great part of Shanxi, Gansu, and Inner Mongolia, use west pathways. The southwest pathway is occasionally used by the duststorms that scarcely occurred under some particular meteorological conditions.

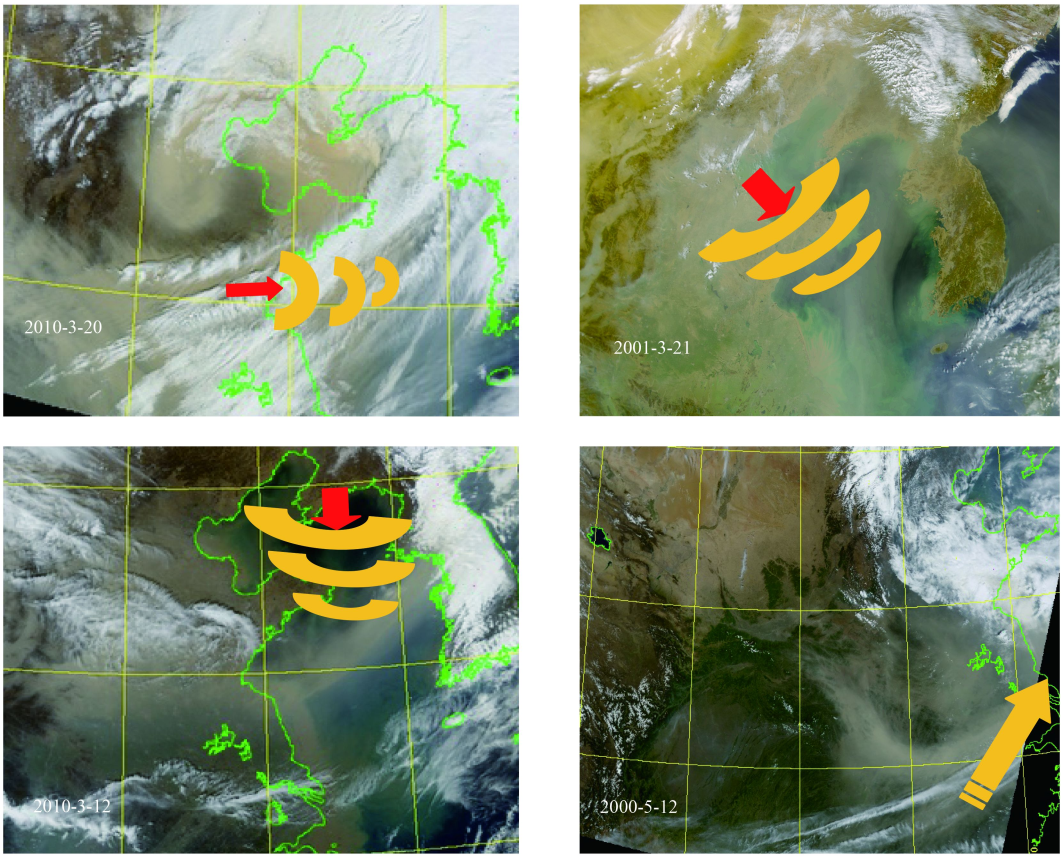


**Fig. 3.** Directions of sandstorms to the SYS (for color-web). a. West, b. northwest, c. north, and d. southwest.

Statistically, the satellite data during 2000–2012 revealed that 39 duststorms (44.3%) came from the northwest, 37 (42%) from the west, 11(12.5%) from the north times and only once from the southwest (1%). Apparently, the northwest and west were the dominant directions where duststorms come from.

### 3.2 *Duststorm frequency to the SYS*

3.2.1 *Yearly and monthly occurrences of duststorms in the SYS*

We found that 88 duststorms that affected the SYS occurred in total during 2000–2012 and that the annual occurrence was about 4–10 times (10 times in 2000 and 2004; four times in 2009 and 2012). The reduced number of duststorms after 2004 (Fig. 4) implies that there has been less annual dust particle deposition in the SYS in recent years.

Statistics from the monthly data show that duststorm intrusion into the SYS occurred mainly in January, February, March, April, May, November and December, among which duststorm occurred more frequently in March, April, and May. The percentage of monthly duststorm occurrences was 29% in March, 33% in April, 22% in May, and 7% in November (Fig. 5). A comparison of duststorm occurrences in different months indicates that the total number of duststorm occurrences in the SYS in these three months accounts for about 82% of the total yearly duststorm occurrences. There were almost no duststorms during June–October.

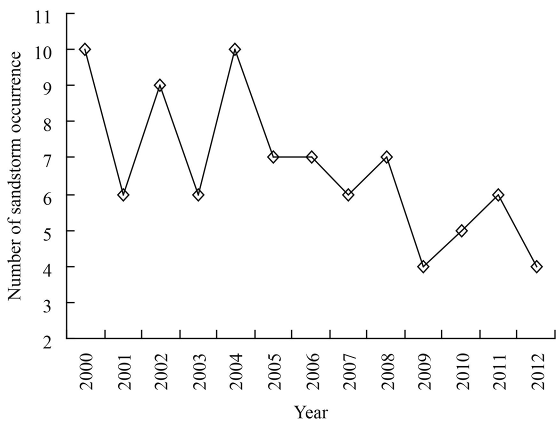


**Fig. 4.** Yearly occurrences of sandstorms in the SYS during 2000–2012.

3.2.2 *Spatial distribution of duststorm occurrence in the SYS.*

In order to map dust deposition in the SYS, satellite data from 2000–2012 were used to retrieve the frequencies of duststorms above the SYS (Fig. 6). In addition to a highly frequent occurrence of the duststorms on the east of the Jiaozhou Peninsula (a.k.a. the north part of the SYS) in recent years (2001–2011, except for 2009) (Fig. 6), the results indicate a large annual variety

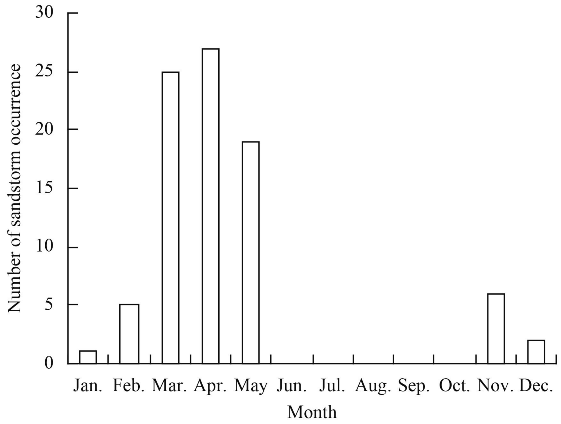


**Fig. 5.** Monthly occurrences of sandstorms in the SYS during 2000–2012.

of the numbers and densities of duststorms with a higher frequency of occurrence.

The duststorms in the SYS in 2000 and 2012, however, differed slightly, with higher duststorm occurrences shifting to the south of the Jiaozhou Peninsula. In 2009, higher duststorm occurrences mainly appeared in the Bohai Sea. A northward shift of duststorms in the SYS was obvious during 2009–2011, compared with other years concerned in the study.

The area in the SYS under the influence of duststorms was quantified as ranging from 6 480 $km^2$ up to 380 000 $km^2$, with an average of 108 000 $km^2$.

### 3.3 *Amount of duststorm particle deposition in the SYS*

#### 3.3.1 *Duststorm particle deposition at the sampling sites in Qingdao*

The deposition flux in Qingdao was used as an important index to identify the dust particle deposition in the SYS. Based on the analysis of the ground truth data collected in Qingdao (Fig. 7), we found that the monthly deposition amount ranged from 3.48 to 13.76 $g/m^2$. Dust depositions in April and May were relatively greater than that in other months, reaching as high as 13.76 $g/m^2$.

We determined that the deposition during 2005–2009 in Qingdao ranged from 64.31 to 85.92 $g/m^2$, which is equal to 7–9 million tons of dust particles deposited in the SYS annually given an average duststorm occurrence area of 108 000 $km^2$.

The relationship between ground sampling data in Qingdao and satellite-retrieved data was regressed (Fig. 8). We observed that the two data sets were in the same order of magnitude, although there was only a weak relationship them.

#### 3.3.2 *Duststorm deposition in the SYS based on satellite data*

Dust content in duststorms can be calculated by Eq. (2), using the area of duststorm dust deposition and atmospheric optical depth. The area of duststorm dust deposition into the SYS can be obtained from satellite remote sensing data (Fig. 6). Each satellite remote sensing data was processed, and dust content was calculated.

Considering duststorm direction and diffusion path, the duststorm deposition in the SYS was determined as illustrated in Fig. 9. The duststorms brought about 0.5–3.5 million tons of particles to the SYS annually during 2000–2012.

## 4 Discussion

How many duststorm particles are deposited in the SYS annually? The results provided by different researchers vary greatly. In some cases, the differences of these results are up to four orders of magnitude. This paper examined the duststorm particles deposited into the SYS using satellite remote sensing data. These data are more precise because the pertinent information, such as the range and density of duststorms, provided by the satellite data is more accurate than modeling.

The duststorm particles deposited into the North Pacific Ocean were evaluated as about 400–500 Tg of dust deposition annually by the World Meteorological Organization (WMO) (GESAMP, 1989). In the central North Pacific, the estimated deposition rate ($6\times10^{12}$–$12\times10^{12}$ g/a) and measured deposition rate ($20\times10^{12}$ g/a) of mineral aerosols could account for a substantial fraction of the non-biogenic portion of deep-sea sediments. In fact, sedimentologists previously estimated that 75%–95% of the surface sediments in the region was derived from atmospheric dust fallout (Blank et al., 1985).

Based on the 44-year averaged dust transportation for the model domain from East Asia to western North America, Zhao et al. (2006) estimated that 26% was exported by the Asian Subcontinent to the Pacific Ocean. In total, 16% of Asian dust aerosol emissions were deposited into the North Pacific whereas 3% was carried to North America via the trans-Pacific transport pathway (Zhao et al., 2006). We thus concluded that about 7% of the world's duststorm particles were deposited in the China's seas. Husar et al. (2001) reported that an Asian dust event in April 1998 was responsible for the high dust concentration over the east coast of the United States, which was in the range of 20–50 $g/m^3$ with local peaks of 100 $g/m^3$.

Gao et al. (1997) reported that the total atmospheric dust deposition into the China's seas is 67 Tg/a, accounting for 14% of the total atmospheric dust deposition into the entire North Pacific. Considering the annual total amount of ca. 800 Tg of Asia dust deposition is (Andreae, 1995; Duce, 1995), about 56 Tg duststorm particles is deposited into the China's seas. Zhang et al. (1997) estimated that about 240 Tg of dust is deposited onto the Chinese deserts, about 73 Tg onto the Huangtu Plateau and 68 Tg onto the historical deposit area, and they estimated about 26.7 Tg of the total 381 Tg, duststorm particles are deposited into the China's seas. In spite of the great variety of the exact values, these results agree that a broad range of duststorm particles is deposited into the China's seas, which covers the estimation of the annual amount of duststorm particles deposited in the SYS obtained in this study.

The results from most recent years (2001–2011, except for 2009) demonstrated that the Jiaozhou Peninsula acted as the most important bridge for duststorm particles deposited into the SYS. In 2000 and 2012, the amount of duststorms from the west overweigh those in the other years. In 2009, the duststorms partially passed over the Bohai Sea and originated from the southeast as a rare case.

Although we obtained the number of duststorms in the SYS during the past 13 years, the sediment deposition from these duststorms was still difficult to determine given the various density of each duststorm. In this study, an average duststorm density was used for mapping duststorm particle deposition.

Our estimate of dust particles deposited into the SYS is about 9–12 million tons each year based on the data collected from sites in Qingdao. Since 44.3% of the duststorms in the SYS were from the northwest and that the duststorms from the north and west also passed over Qingdao, the results from sampling sites in

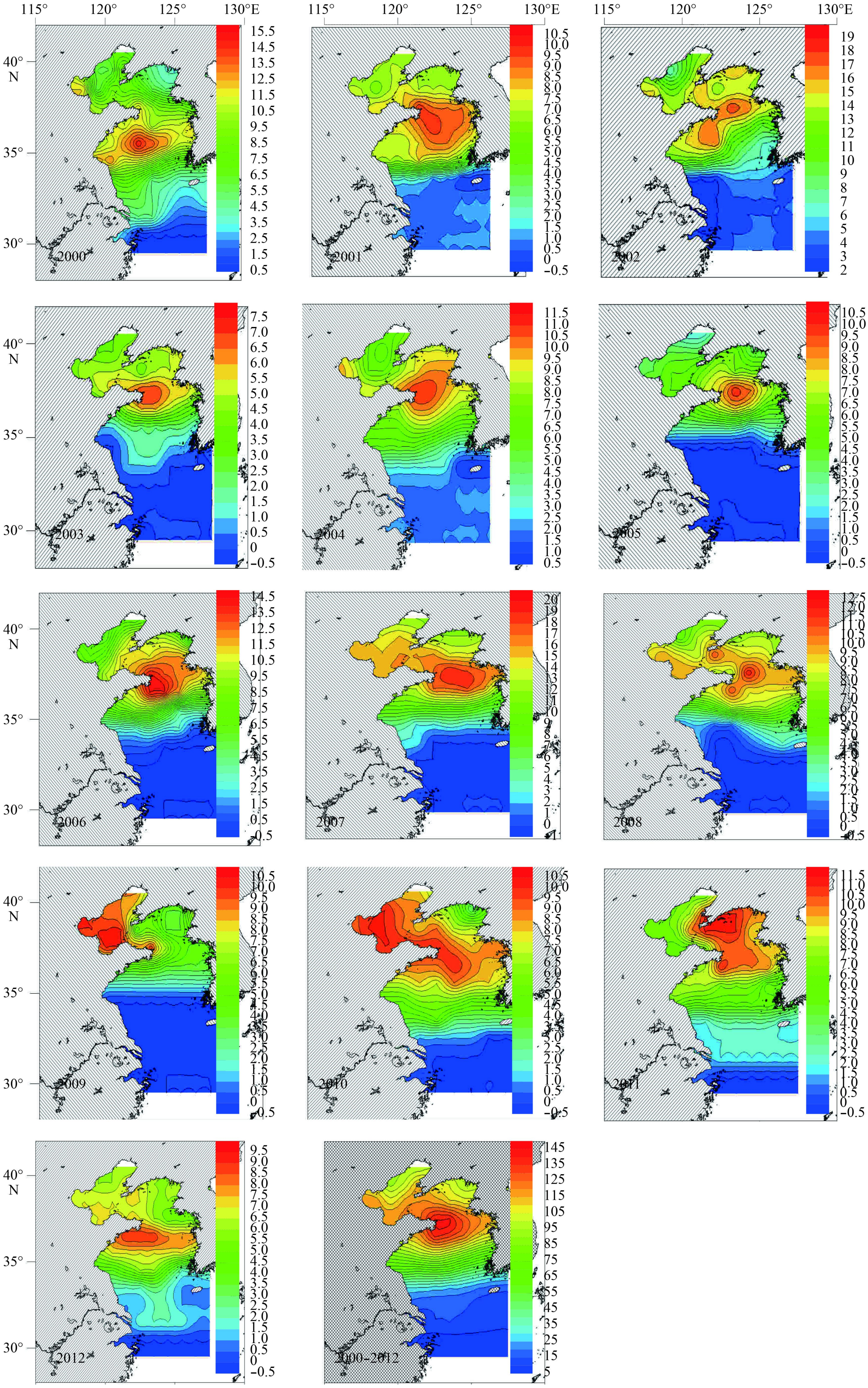


**Fig. 6.** Frequency of sandstorm occurrences above the SYS during 2000–2012 (for color-web).

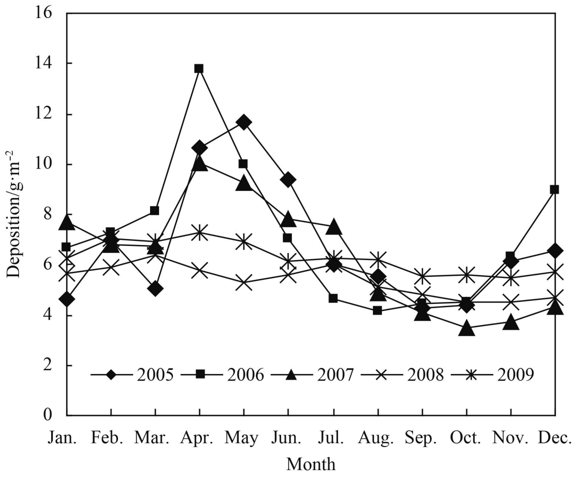


**Fig. 7.** Monthly deposition flux in Qingdao.

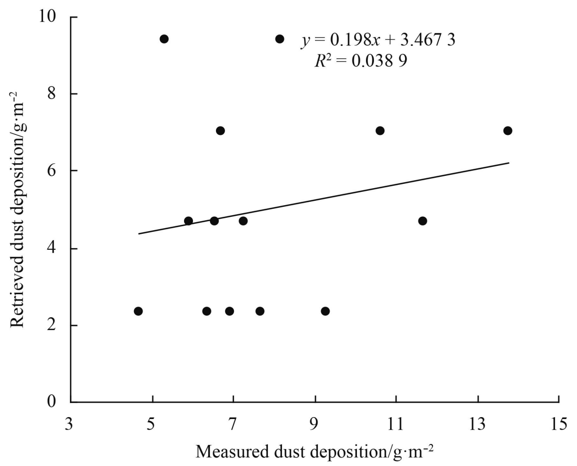


**Fig. 8.** Relationship between measured and retrieved dust deposition data sets.

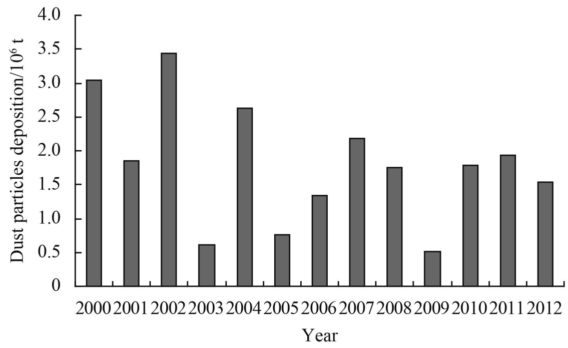


**Fig. 9.** Amount of sand particles deposited in the SYS during 2000–2012.

Qingdao could account for about 75% of the duststorm particle deposition into the SYS. In contrast, some locally-raised dust would cause an over-estimation of the duststorm deposition into the SYS. A shortcoming of estimating the duststorm particles deposited into the SYS, according to the data collected at the sampling sites in Qingdao, is that the deposition amount in every square meter is assumed to be identical, which leads to a larger estimate than that derived from the ground truth observation. In contrary, satellites remote sensing imagines can provide a more accurate estimation of the duststorm deposition in the SYS as demonstrated in this study.

## 5 Conclusions

Duststorms makes a considerable contribution to sediments deposited in the SYS. Based on the data from 220 satellite images, we reported that 88 duststorms that affected the SYS occurred in total during 2000–2012 with an annual occurrence of 4–10 times. Duststorms occurred mainly in March (29%), April (33%), May (22%) and November (7%). The pathways of duststorm intrusion into the SYS are primarily from the northwest and west (the combination of which accounting for about 86.3% of the sum) with minority coming from the north and rare from the southeast. On average, we estimated that 0.5–3.5 million tons of particles are brought into the SYS annually by the duststorms.

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