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# Changes in water clarity of the Bohai Sea: Observations from MODIS

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A B S T R A C T

Water clarity, which is commonly and widely represented by the Secchi depth ($Z_{sd}$), is an important quality parameter for all aquatic environments. To evaluate the variation of water clarity of the Bohai Sea (BHS) in the past decade (2003–2014), $Z_{sd}$ is derived from MODIS-Aqua ocean color data with an innovative mechanistic model. The resulted $Z_{sd}$ product from MODIS is found within 23% differences of match-up in situ measurements that span a range of 2–12 m. Based on this validated MODIS $Z_{sd}$ product of the BHS, valuable findings regarding water clarity of the BHS over the period of 2003–2014 are obtained for the first time. For the central BHS, the climatological mean $Z_{sd}$ in August of 2003–2014 (3.9 m) is found strikingly lower than that observed in situ in August of 1982–1983 (8.7 m), 1959–1979 (8–12 m) and 1972–1987 (8–14 m). This implies substantial deterioration of water clarity in the central BHS after the late 1980s, an unpleasant byproduct of rapid economic development in the BHS surrounding regions initiated in the mid-1980s. On the other hand, no significant variations in $Z_{sd}$ in the central BHS is detected for the period of 2003–2014, suggesting deterioration of water clarity of this water body is not continued. Results from this effort highlight the value of both the analytically-derived $Z_{sd}$ product and satellite ocean color remote sensing in monitoring water quality of coastal seas.



## 1. Introduction

The Bohai Sea (BHS) is a large (77,000 km$^2$) and shallow (~18 m on average) semi-enclosed marginal sea surrounded by one of the heavily industrialized and densely populated regions in China (Fig. 1) - the "Bohai-Rim Economic Circle." The BHS includes three bays (Bohai Bay, Laizhou Bay and Liaodong Bay), which serve as primary receivers of >17 rivers (e.g., Zhang et al., 2007). Among these rivers, the Yellow River is the largest and empties itself into the Laizhou Bay with an annual discharge at the magnitude of 10$^{10}$ m$^3$ and an annual sediment load estimated at 10$^9$ tons (Milliman and Meade, 1983). The Bohai Strait, with maximum water depth of ~70 m, is the only channel allowing water mass exchanges between the BHS and the neighboring Yellow Sea (YS) (e.g., Xu et al., 2009). The BHS is also under the influence of monsoons, with strong northerly winds prevailing in winter and weak and less persistent southerly winds in summer (Lee and Chao, 2003).

Following the economic reform in the "Bohai-Rim Economic Circle" initiated in 1985 (http://baike.baidu.com/view/48598.htm), various impacts on the BHS water, resulting from the intense urbanization and rapid industrialization, have emerged. The BHS receives ~40% of the direct discharged sewage from the entire country every year, although it takes up just 2.6% of the sea area of China (China Environment Yearbook, Volume 4). In the meantime, most rivers discharging into the BHS have been dammed for the purposes of irrigation and municipal water supply (Fuggle and Smith, 2000). It was suggested that the damming of rivers has resulted in the increasing trend in dissolved inorganic nitrogen, temperature, and salinity in the BHS over 1960–1996 (Ning et al., 2010). Fishery biomass in 1998 was only ~5% of that in 1959, accompanied by a decreasing trend of primary productivity from 1959 to 1998 (Tang et al., 2003). Bottom acidification was observed in the western BHS in summer 2011. It has been suggested that the acidification was induced by remineralization of local biogenic organic matters originating from frequent harmful algae blooms and intensive aquaculture (Zhai et al., 2012). In general, it has been recognized that the BHS ecosystem is being rapidly degraded (Gao et al., 2014; Liu et al., 2011; Xu, 2011).

However, while these changes in the ecosystem of the BHS over the past decades are of serious concern, the current status and the change in water quality over time have not been characterized in detail. One of the key water quality parameters is water clarity, which not only affects our visual perception of the water environment, but also provides important information on light availability to the aquatic ecosystems.

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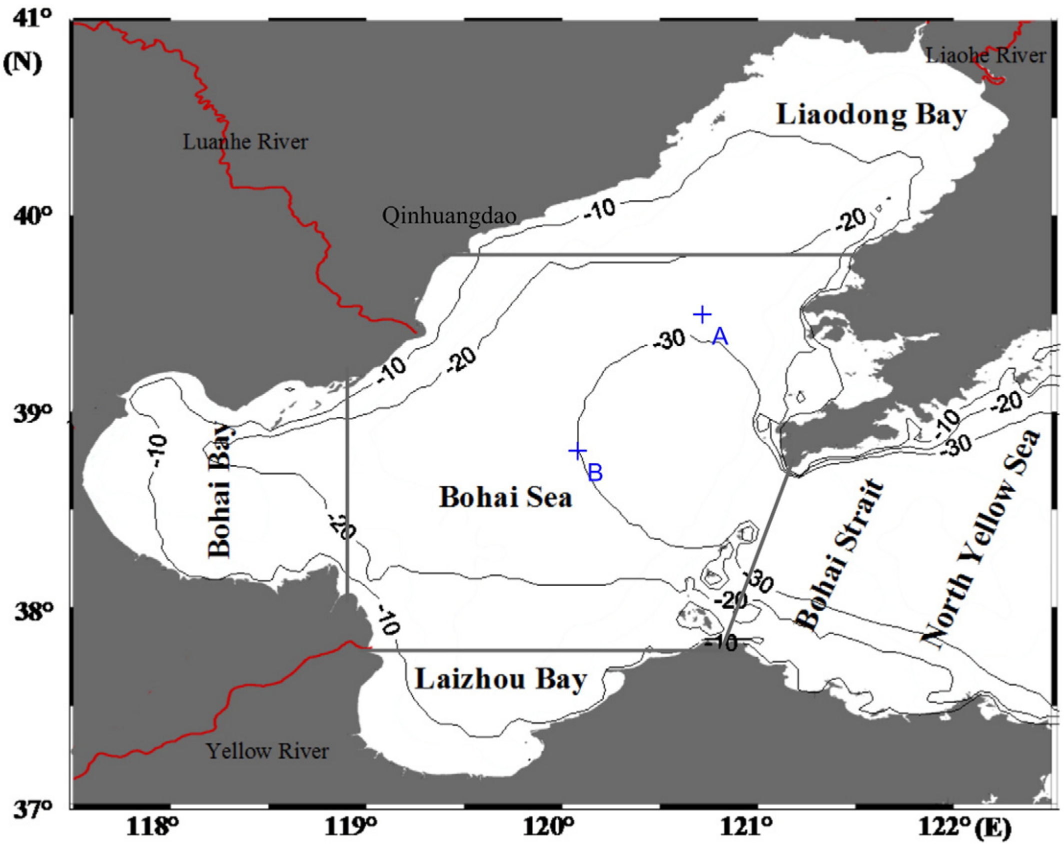


**Fig. 1.** Bathymetry of the Bohai Sea, with 17 rivers around it, most of which have been dammed and thus only three of which are annotated. The grey lines are the boundaries for calculation of spatial means of $Z_{sd}$ for the central BHS and the three bays, respectively. Station A and B are two sampling stations in Zhu and Zhao (1991), the only ones located in the central BHS with a monthly record of $Z_{sd}$.

There are many ways to quantify water clarity. These include the Secchi depth ($Z_{sd}$, m), the diffuse attenuation coefficient ($K_d$, $m^{-1}$), and the euphotic zone depth, with the Secchi depth having the longest record of water clarity (e.g., Boyce et al., 2012; Capuzzo et al., 2015; Fleming-Lehtinen and Laamanen, 2012; Philippart et al., 2013). For the BHS, a large quantity of in situ $Z_{sd}$ is available, covering four periods: 1959–1979 (Zhang, 1983), 1972–1987 (Zhu and Zhao, 1991), 1982–1983 (Fei, 1986), and 2003–2009 (Qin et al., 2014; Xue et al., 2015). These data, however, due to the inherent limitations of ship surveys, are discrete and sporadic in nature, which thus prevent a thorough and objective evaluation of the temporal variations of water clarity of the entire BHS.

As demonstrated decades ago, repetitive measurements from satellite sensors are the only feasible means to observe and evaluate the temporal variations of geophysical properties of large regions (e.g., Behrenfeld et al., 2001; Chavez et al., 1999; McClain, 2009; Yoder et al., 2002). The study of water clarity is done the same way (e.g., Hicks et al., 2013; Weeks et al., 2012). There have been some reports on the water clarity of the entire China seas using remote sensing approaches. For example, the BHS was found having the shallowest Secchi depth or euphotic depth among the China seas (He et al., 2004; Shang et al., 2011). Nevertheless, no detailed evaluations and analyses about the changes of BHS water clarity are available yet.

In this paper, taking advantage of the MODIS $Z_{sd}$ time series of 2003–2014 generated using a new mechanistic model (Lee et al., 2015), together with historical records of in situ $Z_{sd}$ dated back to 1959, we seek to address the changes of water clarity over the entire BHS during the past decades, and try to provide a comprehensive understanding of the forces driving the changes. Considering the well-recognized degradation of the BHS ecosystem, we hypothesize that the contemporary water clarity of the BHS is also decreasing, at least compared to the era prior to the mid-1980s when economic reform had not been initiated in the BHS surrounding region. In short, the aim of this study is to evaluate the change of water clarity before and after economic development, and to see if the trend of change continues to the present. Results of this study may guide future economic development of the BHS surrounding regions to be conducted in a more environmental friendly way, and may serve as an example for other coastal seas under severe stresses from human activities.

## 2. Data and methods

### 2.1. Algorithm to retrieve $Z_{sd}$

Recently, Lee et al. (2015) found that the classical underwater visibility theory (Preisendorfer, 1986) cannot interpret exactly the sighting of a Secchi disk by a human eye, and developed an innovative and mechanistic model based on radiative transfer for the estimation of $Z_{sd}$ from ocean color measurements by MODIS:

$$Z_{sd} = \frac{1}{2.5\,\mathrm{Min}(K_d(443, 488, 531, 547, 665))} \ln\left[\frac{|0.14 - R_{rs}^{tr}|}{C_t^r}\right] \quad (1)$$

Here $R_{rs}^{tr}$ is the remote-sensing reflectance ($sr^{-1}$) at the transparent window of the water body (the wavelength corresponding to the maximum transparency), and $C^r_t$ is the contrast threshold of a human eye for Secchi disk observation and an average of 0.013 $sr^{-1}$ was taken based on measurements of Blackwell (Blackwell, 1946). This model was validated with >300 concurrent global measurements of both $R_{rs}$ and $Z_{sd}$ covering oceanic to coastal to inland waters, including nearly 200 match-ups of $R_{rs}$ and $Z_{sd}$ from the China seas, resulting in an average difference ~ 18% between the estimated $Z_{sd}$ from $R_{rs}$ and the measured $Z_{sd}$ (Lee et al., 2015). Note that this 18% difference includes > 10% uncertainty in situ $Z_{sd}$. We thus implemented this new model (Eq. (1)) to generate MODIS $Z_{sd}$ products for the BHS, rather than any traditional empirical algorithms (e.g., Chen et al., 2007; Morel et al., 2007) or previous semi-analytical algorithms based on the classical visibility theory (e.g., Doron et al., 2011). The empirical approaches are generally applicable to the locations (and/or seasons) used for the development of the empirical relationship but prone to errors and uncertainties when the same empirical formula is applied to other water bodies (or the same water body but at a different season). Details of implementing Eq. (1) can be found in Lee et al. (Lee et al., 2015; Lee et al., 2016).

### 2.2. Satellite data

Both MODIS-Aqua Level-2 daily and Level-3 monthly mean remote-sensing reflectance ($R_{rs}$) data, processed with the most recent updates in calibration and algorithms (reprocessing R2014.0), were obtained from the NASA Ocean Biology Processing Group (OBPG, http://oceancolor.gsfc.nasa.gov/) where the spatial resolution is approximately 1 km by 1 km and 4 km by 4 km, respectively. Monthly mean backscattering coefficient of particles at 443 nm ($b_{bp}(443)$) were derived from monthly mean MODIS $R_{rs}$ using QAA (Lee et al., 2002).

Monthly mean wind field data were obtained from QuikScatterometer (QuikSCAT) observations from 2003 to 2009 when the data were available (http://podaac.jpl.nasa.gov), with a spatial resolution of 0.25° by 0.25° (equivalent to ~25 km by ~25 km). Calculation of wind stress from wind speed is detailed in Shang et al. (2011).

### 2.3. Calculation of mean and anomaly

Temporal and spatial means and anomalies of various properties are commonly used to address the spatio-temporal variations of geophysical properties (e.g., Behrenfeld et al., 2006; McClain, 2009; Shang et al., 2011). Following this convention, we calculated temporal and spatial means and anomalies of $Z_{sd}$, $b_{bp}$ (443), and wind stress, respectively. Approaches to calculate these means and anomalies are detailed in Shang et al. (2011).

## 3. Results

### 3.1. Evaluation of MODIS $R_{rs}$ and $Z_{sd}$

The performance of the innovative $Z_{sd}$ algorithm of Lee et al. (2015) (Eq. (1)) was evaluated with concurrent in situ measurements of $R_{rs}$ and $Z_{sd}$. Excellent results were achieved. Here its performance is further evaluated with MODIS and in situ match-ups in order to ensure the quality of MODIS $Z_{sd}$ product for spatial-temporal studies.

In situ measurements were made during 2011–2012, with in situ $Z_{sd}$ being measured with a conventional all-white Secchi disk (reflectance is ~0.85) with a diameter of 30 cm, and in situ $R_{rs}$ being measured using a GER 1500 spectroradiometer (Spectra Vista Corporation, USA) as detailed in Shang et al.(Shang et al., 2011; Shang et al., 2014).

When conducting match-ups of daily MODIS $R_{rs}$ data (Level 2) at original resolution (approximately 1 km$^2$) with in situ $R_{rs}$ and $Z_{sd}$, it is difficult to strictly follow the methods recommended in Bailey and Werdell (2006) due to heavy and frequent cloud cover over the study region. To allow for a larger number of matchups for statistical analysis, the temporal difference was relaxed to ≤6 h with no relaxation of the spatial window (i.e. MODIS data centered on the location of in situ measurements were retrieved), and the region was extended to the neighboring YS (12 stations). Finally, a total of 20 match-ups were compiled (see Fig. 2 for the location of these match-ups). For statistical evaluations, three indicators were calculated as a measure of consistency between the field measured ($f$) and the satellite data products ($s$), following community-accepted standards (e.g., Hooker et al., 2002; Lee, 2006; Mélin et al., 2007; Moore et al., 2009). These standards were the correlation coefficient (r) of the data pairs, the root mean square error in log scale (*RMSE*) and averaged unbiased percentage difference ($\varepsilon$):

$$\varepsilon = \left[\frac{1}{n}\sum_{i=1}^{n}\left|\frac{s_i - f_i}{s_i + f_i}\right|\right] \times 200\% \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\log_{10}(s_i) - \log_{10}(f_i)\right)^2} \tag{3}$$

Here n is the total number of match-up observations.

Before the evaluation of the analytically-derived MODIS $Z_{sd}$, we evaluated the data quality of the standard Level 2 daily MODIS $R_{rs}$ products in the BHS and YS. The latest MODIS $R_{rs}$ over this region was found having high quality (Fig. 3), with *RMSE* ranging between 0.051 and 0.197 for MODIS ocean-color bands (412–667 nm), comparable and consistent with those found in other seas and the open ocean (e.g., Antoine et al., 2008; Bailey et al., 2010; Chaves et al., 2015; Mélin et al., 2007).

Following the description of Lee et al. (2015), daily MODIS $R_{rs}$ was fed into the latest version of QAA (v6, Lee et al., 2015, http://www.ioccg.org/groups/software.html) to derive the total absorption and backscattering coefficients of the MODIS bands. These inherent optical properties were further converted to the diffuse attenuation coefficient ($K_d$) for the sun angle at the time of observation for each sampling station based on a semi-analytical model (Lee et al., 2013), and the minimum $K_d$ within the MODIS bands of each station was determined. Subsequently, $Z_{sd}$ was derived according to Eq. (1), which was further compared with corresponding in situ measurements. An *RMSE* of 0.126 and an $\varepsilon$ of 23% were obtained for $Z_{sd}$ in a range of ~2–12 m (Fig. 4). This provides the necessary confidence to examine the spatio-temporal variations of water clarity in the BHS based on MODIS $Z_{sd}$ time series derived with this new mechanistic algorithm.

### 3.2. Comparison of $Z_{sd}$ in the Bohai Sea between 2003–2014 and 1959–1987

With the confidence on $Z_{sd}$ product from MODIS, monthly mean $Z_{sd}$ of 2003–2014 for the BHS was produced following the same procedure described above with the MODIS Level 3 monthly mean $R_{rs}$ as the input. These $Z_{sd}$ products are specific for a sun angle of 0° (Sun at zenith), and the likely variation of visibility due to changes in the sun angle, is thus removed (Philippart et al., 2013).

A distinct spatio-temporal pattern of $Z_{sd}$ is manifested in the monthly climatology images, such as summer high and winter low, and higher values in the central BHS than in the bays (see Fig. 5). To better interpret the spatial and temporal variations, the monthly spatial means (Fig. 6) were derived separately for the central BHS and the three bays (separated by the grey lines in Fig. 1). As shown in Fig. 6, the central BHS shows the largest seasonality, with $Z_{sd}$ ranging between 0.9 ($\pm$0.4) m in winter and 5.2 ($\pm$1.5) m in summer. The Liaodong Bay appears to be the clearest among the three bays ($Z_{sd}$ ranging between 0.7 $\pm$ 0.3 m in winter and 3.6 $\pm$ 2.0 m in summer). $Z_{sd}$ in the other two bays - Bohai Bay and Laizhou Bay - maintains at a lower level throughout the year. Specifically, it is below 2 m through the year in the Bohai Bay, except in July (2.1 $\pm$ 1.3 m), while the Laizhou Bay has only three months of $Z_{sd}$ exceeding 2 m (May–July). A big industrial city, Tianjin, is located on the shore of the Bohai Bay, and the Laizhou Bay receives the Yellow River of very high sediment load. This most probably result in the lower water clarity in the Bohai Bay and the Laizhou Bay compared to the Liaodong Bay.

While the basin-scale spatio-temporal features of $Z_{sd}$ in 2003–2014 (Figs. 5 and 6) are, in general, consistent with those observed in situ decades ago (Fei, 1986; Zhang, 1983; Zhu and Zhao, 1991) and a survey conducted in 2006–2007 (Xue et al., 2015), significant and striking deterioration of water clarity in the BHS was found (see Fig. 6), as detailed below.

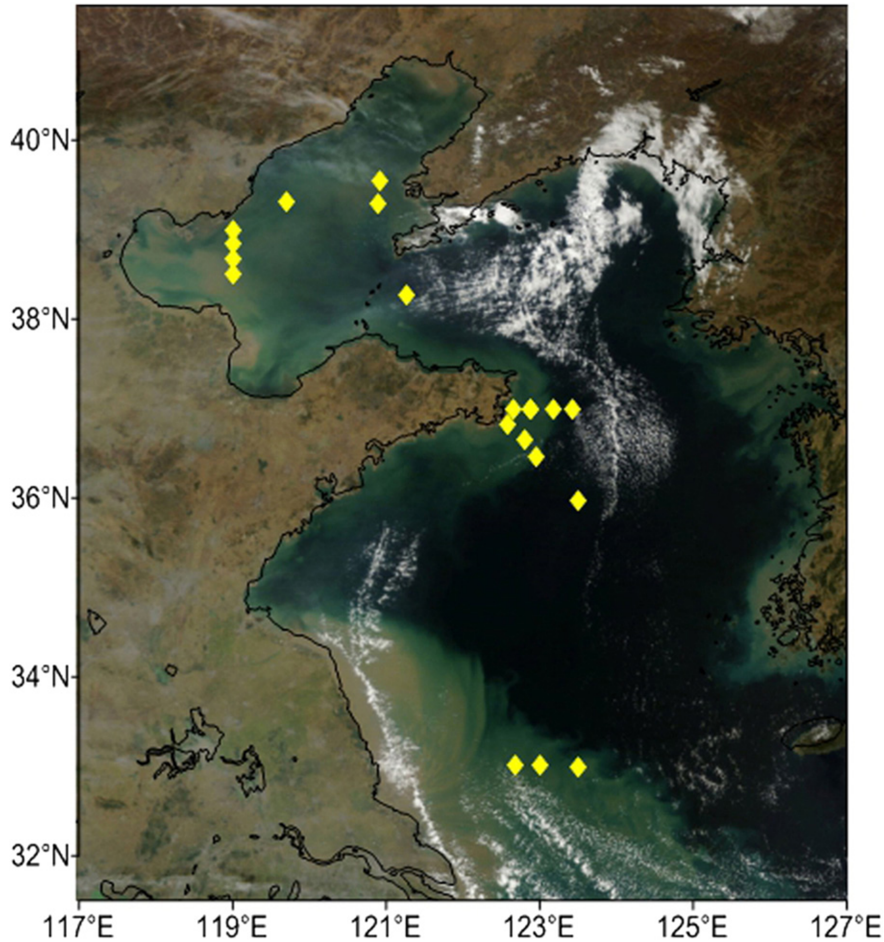


**Fig. 2.** Locations of sampling stations for match-ups of MODIS $R_{rs}$ and in situ $R_{rs}$ and $Z_{sd}$, overlaid with a MODIS RGB image of October 25, 2012 (http://www.eosnap.com/image-of-the-day/sediments-in-bohai-sea-and-from-yangtze-river-china/).

- First, a comparison of the record of 1982–1983 (Fei, 1986) with 2003–2014 monthly climatology (see the first row of Fig. 6) indicates: (1) in the summer, the water appeared much clearer in 1982–1983 than in 2003–2014, except the Bohai Bay. Specifically, in the central BHS, the averaged values of $Z_{sd}$ for summer (June–August) were 7.3 m in 1982–1983 vs 4.5 ± 1.4 m in 2003–2014; the greatest difference occurred in August, with $Z_{sd}$ up to 8.7 m in 1982–1983 vs 3.9 ± 1.3 m in 2003–2014; (2) in winter, almost no change of $Z_{sd}$ was seen between 1982–1983 and 2003–2014 for the entire BHS; (3) in 1982–1983, the Bohai Bay was the least clear water body year round ($Z_{sd}$ was 0.7 m for the Bohai Bay, and 2.8 m and 3.0 m for the other two bays); however, it was no longer the case during 2003–2014. The three bays are now almost at a similar level in terms of $Z_{sd}$ (1.0 ± 0.4 m for the Bohai Bay; 1.4 ± 0.6 m and 1.7 ± 0.7 m for the other two bays).
- The water appeared much clearer in summer of 1959–1979 and 1972–1987 than in summer of 2003–2014, at least in the central BHS. Specifically, the $Z_{sd}$ in the central BHS in August was up to 8–12 m over the period of 1959–1979 and 8–14 m during 1972–1987, and the $Z_{sd}$ in the three bays were in general <4 m in August for those periods (Zhang, 1983; Zhu and Zhao, 1991). Note that these in situ reports use climatology of almost 30 years in combination.
- The above two comparisons are simply for the spatial means of $Z_{sd}$ for either the central BHS or the three bays. Separately, there is a record of in situ $Z_{sd}$ monthly climatology at two stations located in the central BHS (Stations A and B, see Fig. 1 for the locations) for the period of 1972–1987 (Fig. 3 of Zhu and Zhao, 1991). MODIS $Z_{sd}$ monthly climatology of 2003–2014 at these two stations were then derived and compared to the in situ record. Again, considerable differences emerged in the summer, particularly in August (10.7 m in 1972–1987 vs 4.9 m in 2003–2014 at Station A, and 7.0 m vs 3.1 m at Station B) (Fig. 6, see the second row).

To summarize, there is no doubt that compared to the period prior to the late 1980s, the water clarity of 2003–2014 in the central BHS in the summer has substantially reduced, particularly in August, a time the $Z_{sd}$ of 2003–2014 was halved compared to decades ago. Xue et al. (2015) also suggested a decrease of $Z_{sd}$ in the BHS when compared their survey data of 2006–2007 with a climatology compiled for the 1907–1986 period.

### *3.3. Variations of $Z_{sd}$ in the central Bohai Sea during 2003–2014*

Monthly means $Z_{sd}$ for each year were averaged for the central BHS to get a spatial mean for each month, and then, the means were used for an estimation of the temporal trend of $Z_{sd}$ during 2003–2014 with a linear regression analysis using Grapher (Golden Software, inc., Version 9.1, Fig. 7). The three bays were excluded from this analysis because of the scarcity of valid data available for all months of each year, making it impossible to obtain meaningful spatial averages. No statistically significant slope was obtained from this analysis either (p-value >0.05), suggesting that water clarity in the central BHS remains nearly the same in the period of 2003–2014.

The above analysis is simply based on the spatial means of each month. To further clarify whether there are any trends of $Z_{sd}$ in specific

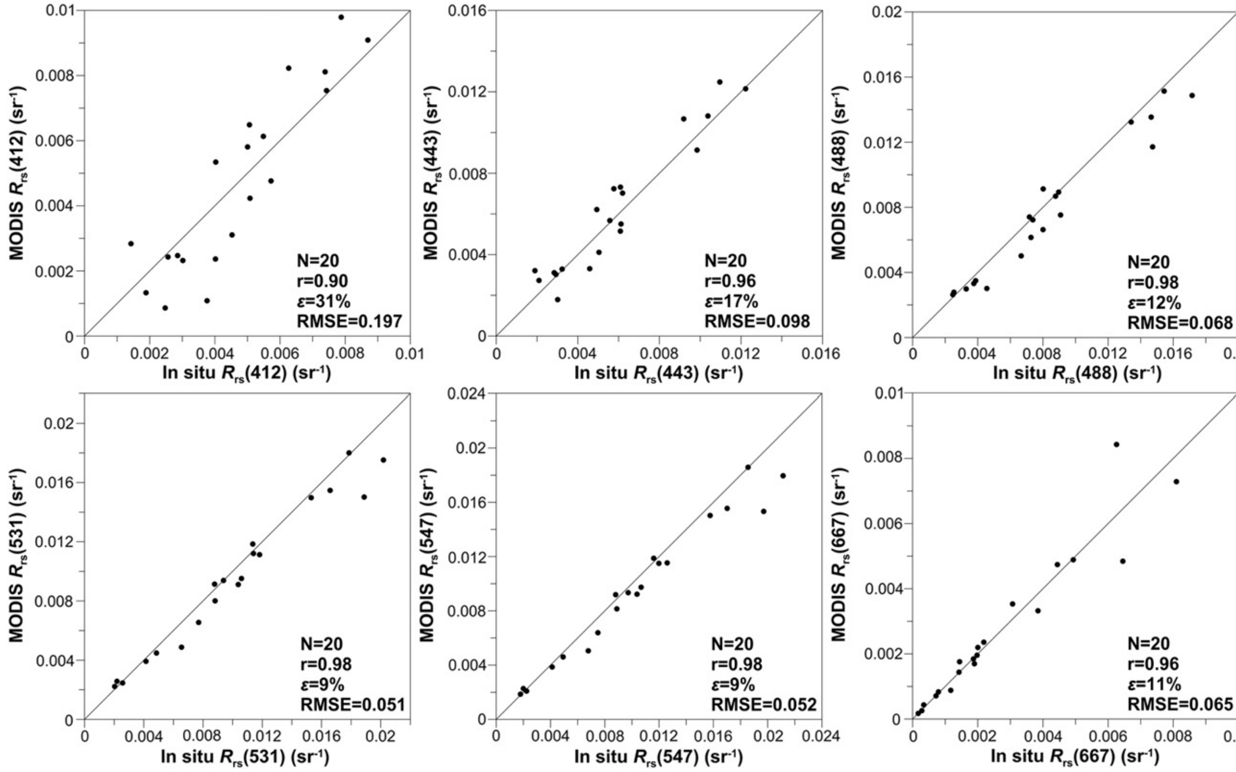


**Fig. 3.** MODIS $R_{rs}$ versus in situ $R_{rs}$ in the Bohai Sea and the Yellow Sea.

seasons, changes in January and August, representative months for winter and summer, were analyzed. To highlight the change, following conventional practice (e.g., Behrenfeld et al., 2006), temporal anomalies rather than spatial means of $Z_{sd}$ were used in the linear regression analysis, and a minor decreasing trend emerged but this "trend" is still insignificant (p-value >0.05, Fig. 8). In addition, temporal anomalies of annual mean $Z_{sd}$ also show an insignificant decreasing "trend" (Fig. 8).

Furthermore, a generalized additive mixed model (GAMM, Philippart et al., 2013) was also applied on this dataset to evaluate the temporal variations. It resulted in a decreasing trend of 0.02 m/year

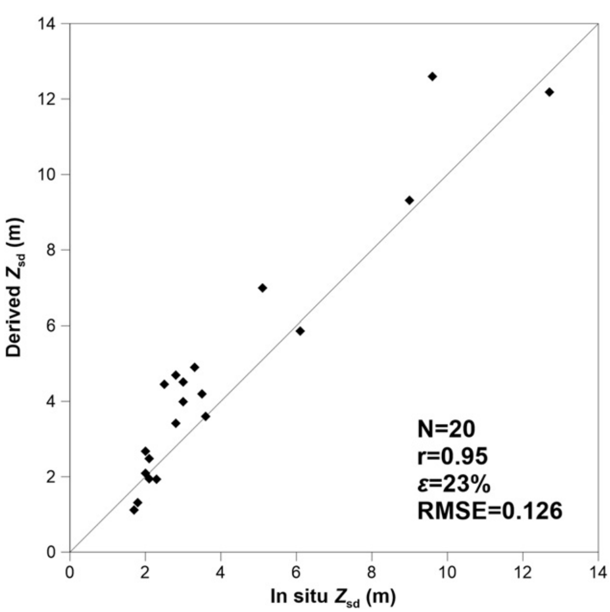


**Fig. 4.** In situ $Z_{sd}$ compared to $Z_{sd}$ derived from MODIS $R_{rs}$ using the algorithm of Lee et al. (2015).

(figures not shown to save space), consistent with the linear regression results.

All the above analyses lead to the conclusion that the central BHS has maintained a certain $Z_{sd}$ level over the period of 2003–2014.

## 4. Discussion

Based on a newly derived MODIS $Z_{sd}$ time series for the period of 2003–2014, as well as historical in situ $Z_{sd}$ records dated back to the 1950s, for the first time, we found two interesting results regarding the changes of $Z_{sd}$ in the BHS. The basin-wide water clarity of the BHS in the summers of 2003–2014 is substantially worsened compared to the time before the late 1980s. However, the deteriorating scenario has not persisted: the water clarity in the central BHS has remained at a certain level over the past decade (2003–2014). Further discussions on the quality of MODIS $Z_{sd}$ data products used in this study, and the reasons to account for our observations, are detailed below.

### *4.1. MODIS data products*

The algorithm used to derive $Z_{sd}$ from MODIS ocean color measurements is the innovative mechanistic model of Lee et al. (2015), and the result in Fig. 4 indicates successful retrievals of high quality $Z_{sd}$ product from MODIS for the interested region. Note that the ~23% difference includes contributions from uncertainties in field $Z_{sd}$ measurements (usually around 10%) and uncertainties due to the spatial-temporal mismatches between satellite and in situ data (could be very high in coastal regions). It thus indicates a high fidelity of the analytically-derived MODIS $Z_{sd}$ product. However, it must be pointed out that there were no matchup data yet to verify the $Z_{sd}$ product in the three bays (Bohai Bay, Laizhou Bay and Liaodong Bay) (see Figs. 1 and 2), leaving difficulties to know the data quality of the MODIS $Z_{sd}$ for waters in the three inner bays.

In addition, there are fewer valid MODIS retrievals in the three bays (see the grey bars for the valid data percent in Fig. 6) compared to the

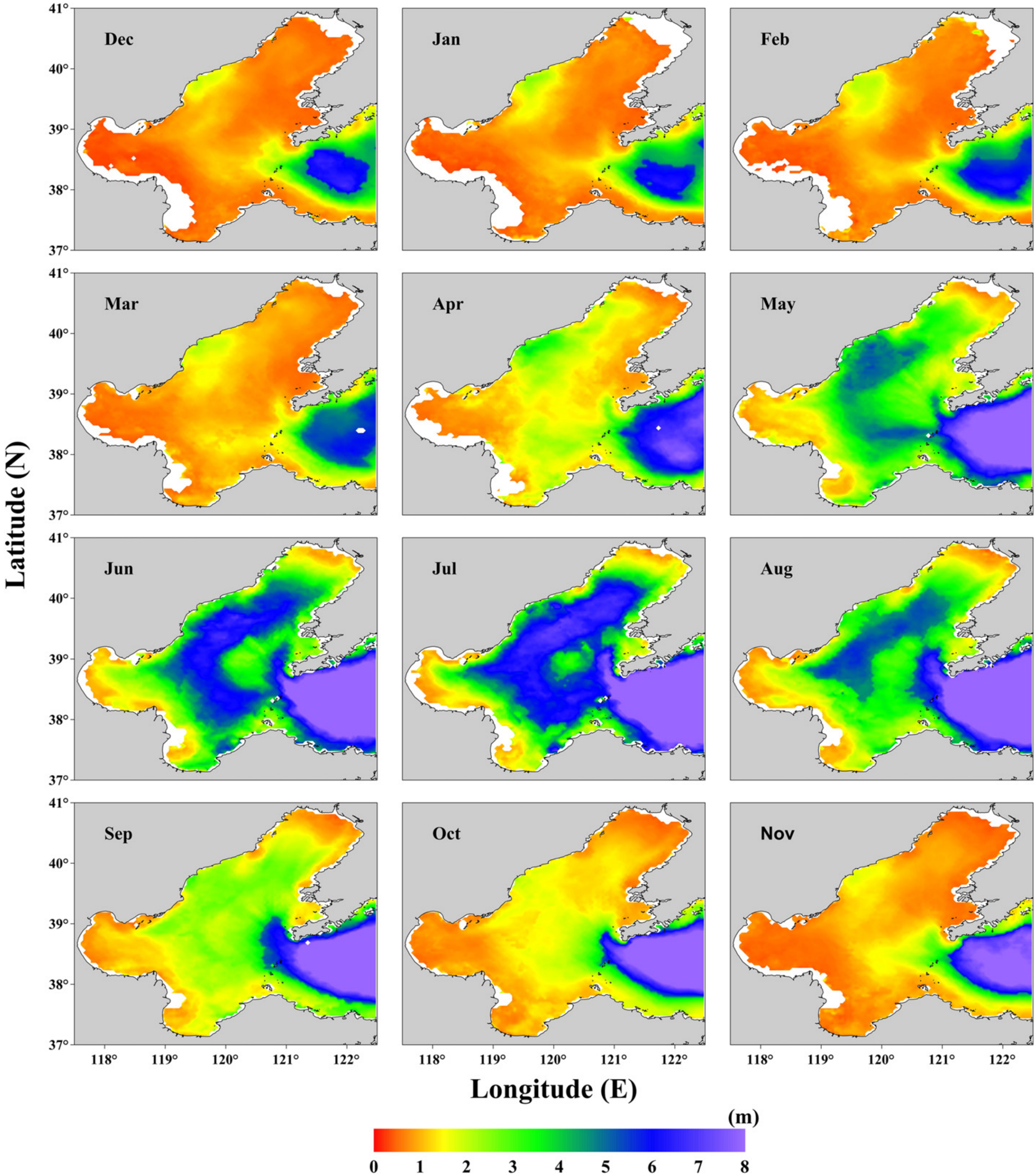


**Fig. 5.** Climatological monthly mean $Z_{sd}$ in the Bohai Sea during 2003–2014.

central BHS, most probably due to failure in atmospheric correction over turbid nearshore waters. For example, in July, only about 40% of the Laizhou Bay has valid MODIS products, where the high sediment load Yellow River empties itself. Here a valid $Z_{sd}$ is simply a positive (>0 m) retrieval calculated from valid (positive) monthly mean MODIS $R_{rs}$ provided by the NASA OBPG. Although the atmospheric correction algorithm employed by the NASA OBPG has included an optical model for turbid and optically complex waters, which results in significant reductions in the number of negative $R_{rs}$ retrievals (Bailey et al., 2010), low valid data percent in the three bays of the BHS certainly advocates using more sophisticated atmospheric correction schemes developed for extremely turbid waters (e.g., Shi and Wang, 2014) in the future.

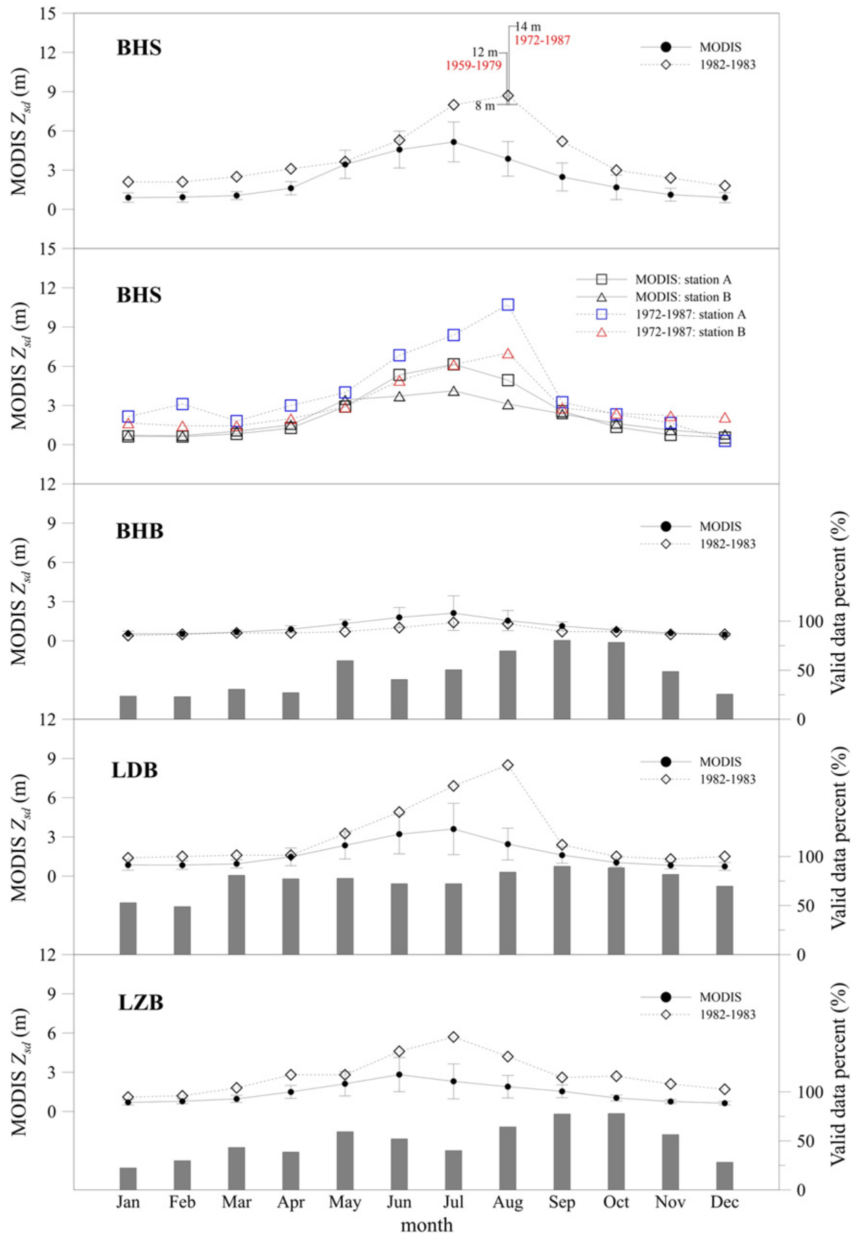


**Fig. 6.** Climatological seasonal patterns of $Z_{sd}$ (solid circles), std (error bars) and the valid data percent (= numbers of valid retrievals / total pixels, see grey bars) in the three bays, namely, the Bohai Bay (BHB), Laizhou Bay (LZB) and Liaodong Bay (LDB), and in the central Bohai Sea (BHS; percentage of valid retrievals not shown because it is nearly 100% year round). For the BHS results, the diamonds are data obtained by reading Fig. 3 of Fei (1986), an in situ dataset collected during 1982–1983; the blue and red symbols are data obtained by reading Fig. 3 of Zhu and Zhao (1991), an in situ dataset collected during 1972–1987. The diamonds of BHB, LZB and LDB are also in situ data obtained by reading Fig. 3 of Fei (1986).

Further, because the BHS freezes to varying degrees every winter for about 3–4 months (Su and Wang, 2012), ice coverage reduces valid MODIS retrievals in the BHS.

Consequently, due to concerns regarding the MODIS $Z_{sd}$ quality in the inner bays and the long period of ice coverage, the monthly means and anomalies of $Z_{sd}$ in each year were calculated only for the central BHS with the three inner bays excluded (see Fig. 7), and the discussion below regarding Fig. 6 will also only focus on the central BHS.

### *4.2. Reasons for the water clarity difference between 2003–2014 and 1959–1987*

Based on the validated water clarity data, it is now confirmed that the central BHS was much clearer in summer in the era prior to the late 1980s than in the period of 2003–2014. It is interesting that the economic reform in the region surrounding the BHS, i.e. "Bohai-Rim Economic Circle", was initiated in 1985 (http://baike.baidu.com/view/48598.htm). This indicates that a significant change of the water clarity in the BHS is a byproduct of the economic development. According to Miyazaki et al. (Miyazaki et al., 2005), the development of economy induced massive poorly treated sewage waste entering the Chinese coastal regions. In the beginning of the 1980s, the total volume of industrial and municipal waste waters entering the Chinese coastal waters was about 6.5 billion tons per year, and this number reached 8 billion tons per year in 1990 with an average increase of 0.15 billion tons per year. Among Chinese coastal waters, the Bohai Sea accounted for about half of the total waste discharges. The annual sewage produced by cities around the BHS was around $1 \times 10^8$ tons during 1985–1992, increasing to $1 \times 10^9$ tons in 2000 and to $3.5 \times 10^9$ tons in 2007 (Xu et al., 2010). These may not be the waste amount discharged into the BHS, yet suggest the increasing load of wastes the BHS received in the past decades.

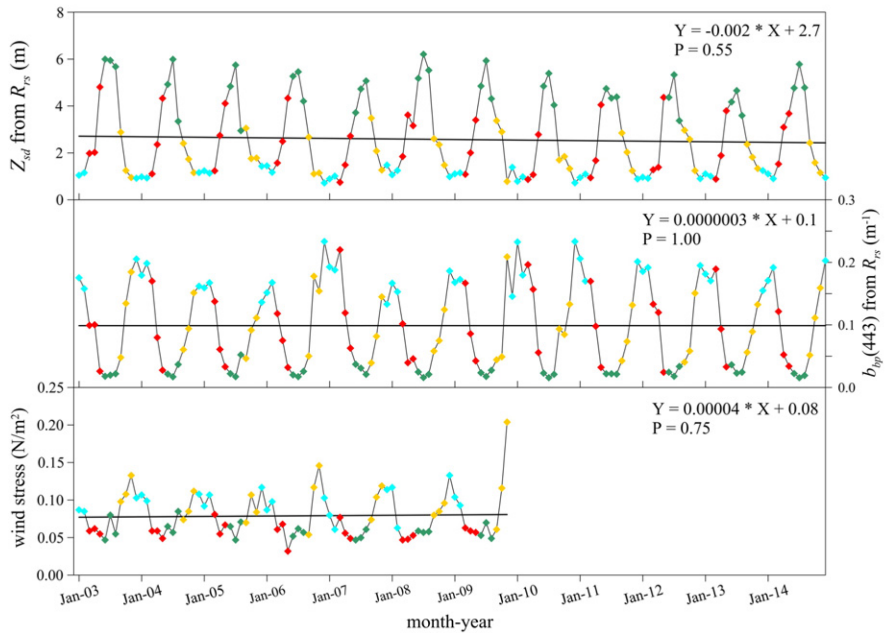


**Fig. 7.** MODIS monthly-mean time series and linear regression line of $Z_{sd}$ and $b_{bp}(443)$ during 2003–2014, and QuikSCAT wind stress during 2003–2009 (the only time this dataset is available), in the central Bohai Sea (excluding the three bays). Solid lines are results of linear regression, with equations and p values shown on the upper right of each panel. Blue: December-February; Red: March-May; Green: June-August; Yellow: September-November

In addition, the decrease in water clarity may also be partially attributed to the damming of the surrounding rivers. Most rivers discharging into the BHS have been dammed (Fuggle and Smith, 2000), and the annual discharge from the Yellow River has been continuously declining from the 1950s to the early 2000s. For example, it was up to 50 billion m$^3$ in the 1950s, but was reduced to ~30 billion m$^3$ in the 1980s (Li and Zhang, 2001) and ~20 billion m$^3$ during 2000–2004 (Wang et al., 2007). Although decline of the sediment flux into the sea will help to increase the water clarity, decline of the freshwater flux would lead to less flushing of the seas receiving plenty of waste and thus decreasing water clarity. In fact, in many reports, degrading of the BHS ecosystem and worsening of the BHS water quality have been attributed to the reduction of river discharges (e.g., Lei et al., 2007; Ning et al., 2010; Tang et al., 2003).

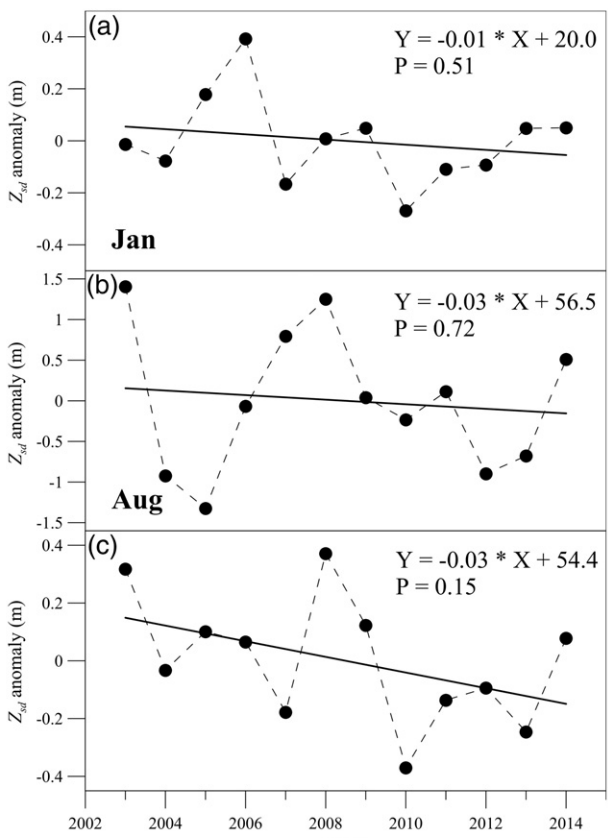


**Fig. 8.** Temporal anomalies of $Z_{sd}$ for the central BHS during 2003–2014. Solid lines are results of linear regression, with equations and p values shown on the upper right of each panel. (a) January; (b) August; (c) annual mean.

However, the change of water clarity is more obvious in the summer, with nearly unnoticeable change in the winter. This is fundamentally due to that water clarity is determined by suspended and dissolved constituents, changes of these constituents could be from either human activities or natural forcing. The BHS is a shallow sea (~18 m on average) with its bottom mostly covered by fine-grained sediments (e.g., Qiao et al., 2010). In the winter, the BHS region is characterized by strong winds, thus re-suspending the sediments in this shallow water body (e.g., Jiang et al., 2000), which then dominates the variation of $Z_{sd}$ in the BHS (e.g., Fei, 1986). The impact of increasing sewage discharge on winter water clarity is thus considered to be a minor factor compared to wind-driven sediment re-suspension. Therefore, if there are no changes in winter winds to drive changes in sediment re-suspension, there will be little chance to observe changes in winter water clarity; or if there is a decreasing trend in winter winds, there will be an increasing trend in $Z_{sd}$. Indeed, no report on any changes in the wind field over the BHS during the past three decades could be found, but a decreasing trend of winds over the lands surrounding the BHS was observed during 1957–2011 (Yang and Yang, 2012) and 1961–2000 (Yang et al., 2009). The only available remote sensing wind data (see Fig. 7) shows no change in winds over the BHS during 2003–2009, but the observation time is relatively short. On the other hand, during the summer, when wind is weak (Lee and Chao, 2003), the impact of increasing sewage discharge on summer water clarity likely overwhelms wind-driven sediment re-suspension. This can also be evidenced from comparing $b_{bp}(443)$ derived from MODIS, an indicator of the concentration of suspended particulate matters, between summer and winter. For the central BHS, $b_{bp}(443)$ in the summer is only 0.02 m$^{-1}$ on average but its value is 0.18 m$^{-1}$ in winter (Fig. 7).

In summary, it is apparent that the increased waste water and river damming are the reasons for the decreased summer clarity in the central BHS between the periods prior to the late 1980s (1959–1987) and the past decade (2003–2014).

### 4.3. Mechanisms for stable water clarity during 2003–2014

While a substantial change in summer water clarity is observed between 2003–2014 and the era prior to the late 1980s, our findings show that water clarity was maintained at a certain level during 2003–2014 (Figs. 7 and 8). In other words, although summer $Z_{sd}$ in the central BHS is substantially lower in 2003–2014 compared to the era before the late 1980s, it was found that this decline has plateaued during the past decade (2003–2014).

To better understand the reasons accounting for this hiatus, we analyzed the change of suspended particulate matter during 2003–2014 with MODIS $b_{bp}(443)$. The correlation coefficient between the monthly time series of MODIS $Z_{sd}$ and MODIS $b_{bp}(443)$ is 0.98, further proving that suspended particulate matters as a dominant determinant of $Z_{sd}$ in the BHS (Fei, 1986). Meanwhile, $b_{bp}(443)$ shows no detectable trend in the past decade (Fig. 7).

We believe there are several reasons for the stable $b_{bp}(443)$ during this period. (1) The primary factors for the variations of $b_{bp}(443)$ in the BHS are the wind and the fine-grained sediment covered shallow bottom (e.g., Qiao et al., 2010). Under such conditions, particulates can be easily introduced into the water column due to wind-driven re-suspension. At the same time, there are no reports of significant change in wind patterns in the BHS during 2003–2014. This is further supported by the nearly stable monthly wind stress during 2003–2009, derived from QuikSCAT data (Fig. 7). (2) River discharge brings suspended sediments into the sea while flushing the sea with its freshwater. There is no report about further decline of river runoffs discharging into the BHS over the past decade, and thus, no changes in $b_{bp}(443)$ associated with river discharge could be expected. (3) Discharge of wastewater is an important factor that could elevate $b_{bp}(443)$. Since the BHS receives increasing amounts of sewage water year after year, the Chinese government has recognized the severity of the environmental and ecological problems and has initiated a series of measures to save this important water body since 2001. Some of these include legal and regulatory measures that wastewater must be treated and controlled, and that more environmentally friendly industries need to be developed. These measures might have reduced the discharge of solid waste, and thus helped maintain annual suspended particulates ($b_{bp}(443)$) at a certain level in the past decade. We may thus conclude that a combination of no changes in large-scale wind patterns and the lessening of human disturbances (control of sewage and river dams) might have helped to prevent the increase of particulates in the central BHS during 2003–2014, and to maintain its water clarity from worsening for this period.

### 4.4. Change of water clarity in other seas compared to the Bohai Sea

It is noticeable that other coastal seas and inland waters under pressure from human activities like the BHS are also experiencing similar changes, showing a decrease in water clarity (e.g., Aksnes et al., 2009; Capuzzo et al., 2015; Dupont and Aksnes, 2013; Fleming-Lehtinen and Laamanen, 2012; Kemp et al., 2005; Olmanson et al., 2008). Specifically, Capuzzo et al. (Capuzzo et al., 2015) analyzed in situ Secchi depth records in the North Sea, making a comparison between pre-1950 and post-1950. They found that the central and southern North Sea have become significantly less clear in the post-1950 era, and suggested that these changes in water clarity were more likely driven by an increase in the concentration of suspended sediments attributed to changes in sea-bed communities and in weather patterns, decreased sink of sediments in estuaries, and increased coastal erosion. These findings, along with results of this study, do imply that human activities are indeed making coastal waters deteriorated and more efforts are certainly necessary to help sustain healthy coastal ecosystems. Also, more investigations are needed in order to grasp the whole picture of the global water clarity, especially with a global $Z_{sd}$ product produced with ocean color satellites such as MODIS.

## 5. Conclusions

Using MODIS $Z_{sd}$ data from 2003 to 2014, we found that the water clarity in the central BHS has not changed during 2003–2014; but the water clarity in summer time is roughly half of that observed in situ prior to the late 1980s (1959–1987). This result, proving our hypothesis, reflects a negative byproduct of the economic development in the BHS surrounding regions, initiated in the mid-1980s that accompanied by rapid expansion of urbanization and not well controlled wastewater treatment. On the other hand, with technology and management tools in place, especially with an emphasis on the health of the environment and the ecosystem, the water clarity in the BHS maintained at its current level in the period of 2003–2014. It is interesting that our hypothesis on continuous decreasing $Z_{sd}$ in the BHS was not proved. We think this highlights the importance and contributions of sound management on the quality of aquatic ecosystems, and we expect to see further improvements in water quality in the BHS after more stringent enforcement of environmental measures.

Although it has been a century-old practice to monitor water quality with Secchi disk measurements, it has only focused on various discrete locations via surveys. The solid performance of the newly developed mechanistic algorithm for $Z_{sd}$ for this marginal sea with MODIS measurements indicates the value and the important application of satellite ocean color measurements for monitoring the quality of large-scale water bodies with a $Z_{sd}$ product. It is thus logical to expect a routine generation and distribution of $Z_{sd}$ product from all ocean color missions, which in turn demands improved atmospheric correction for turbid coastal waters whereas the quality of $R_{rs}$ is the key for the derivation of water-quality products.

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