



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



Shaoling Shang^{a,*}, Zhongping Lee^{b,*}, Lianghai Shi^a, Gong Lin^a, Guomei Wei^{c,d}, Xueding Li^e

^a State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen 361005, China

^b School for the Environment, University of Massachusetts Boston, Boston, MA 02125, United States

^c Key Laboratory of Underwater Acoustic Communication and Marine Information Technology (Xiamen University), the Ministry of Education, Xiamen 361005, China

^d Research and Development Center for Ocean Observation Technologies, Xiamen University, Xiamen 361005, China

^e Fujian Marine Forecast, Fuzhou 350000, China

ARTICLE INFO

Article history:

Received 28 April 2016

Received in revised form 16 July 2016

Accepted 11 August 2016

Available online 19 August 2016

Keywords:

Water clarity

Secchi depth

Environmental change

Bohai Sea

MODIS

ABSTRACT

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.

© 2016 Xiamen University. Published by Elsevier Inc. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

The Bohai Sea (BHS) is a large (77,000 km²) 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 10¹⁰ m³ and an annual sediment load estimated at 10⁹ 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.

* Corresponding authors.

E-mail addresses: slshang@xmu.edu.cn (S. Shang), ZhongPing.Lee@umb.edu (Z. Lee).

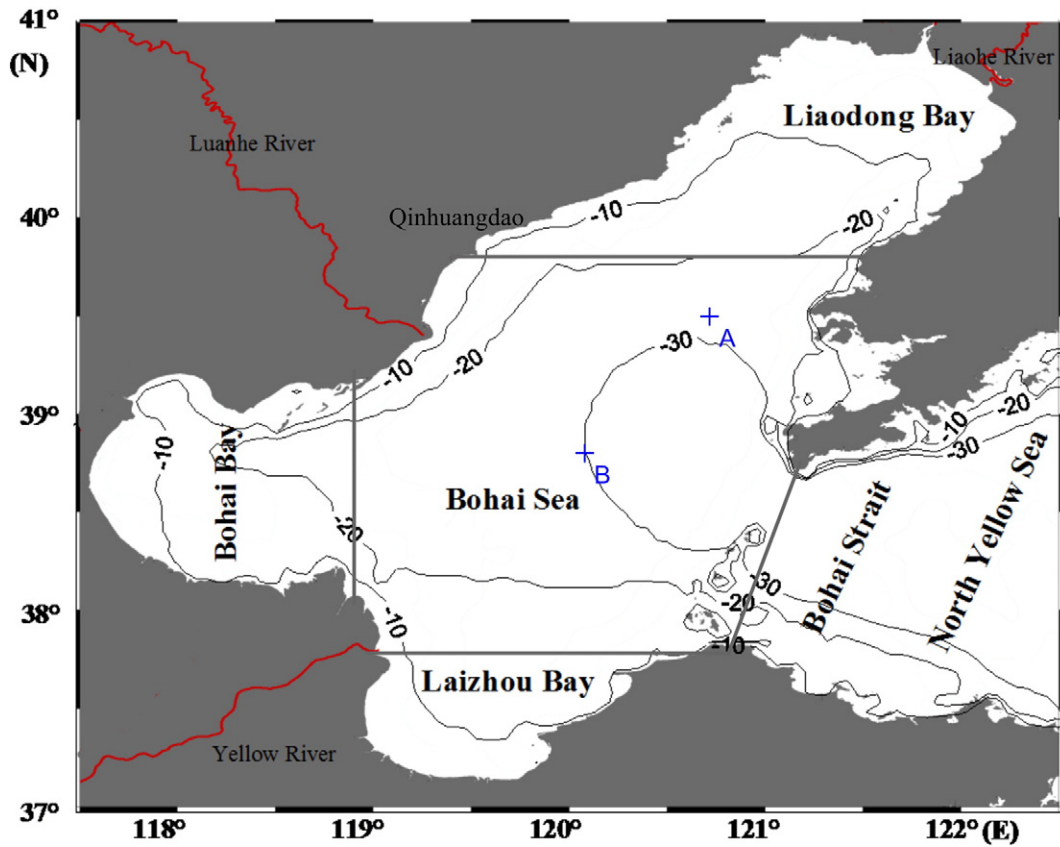


Fig. 1. Bathymetry of the Bohai Sea, with 17 rivers around it, most of which have been dammed and thus only three of which are annotated. The grey lines are the boundaries for calculation of spatial means of Z_{sd} for the central BHS and the three bays, respectively. Station A and B are two sampling 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:

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

Here R_{rs}^t is the remote-sensing reflectance (sr^{-1}) at the transparent window of the water body (the wavelength corresponding to the maximum transparency), and C_t^r 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 km²) 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 (ε):

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

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

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.iocccg.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 ε 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 (± 0.4) m in winter and 5.2 (± 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.

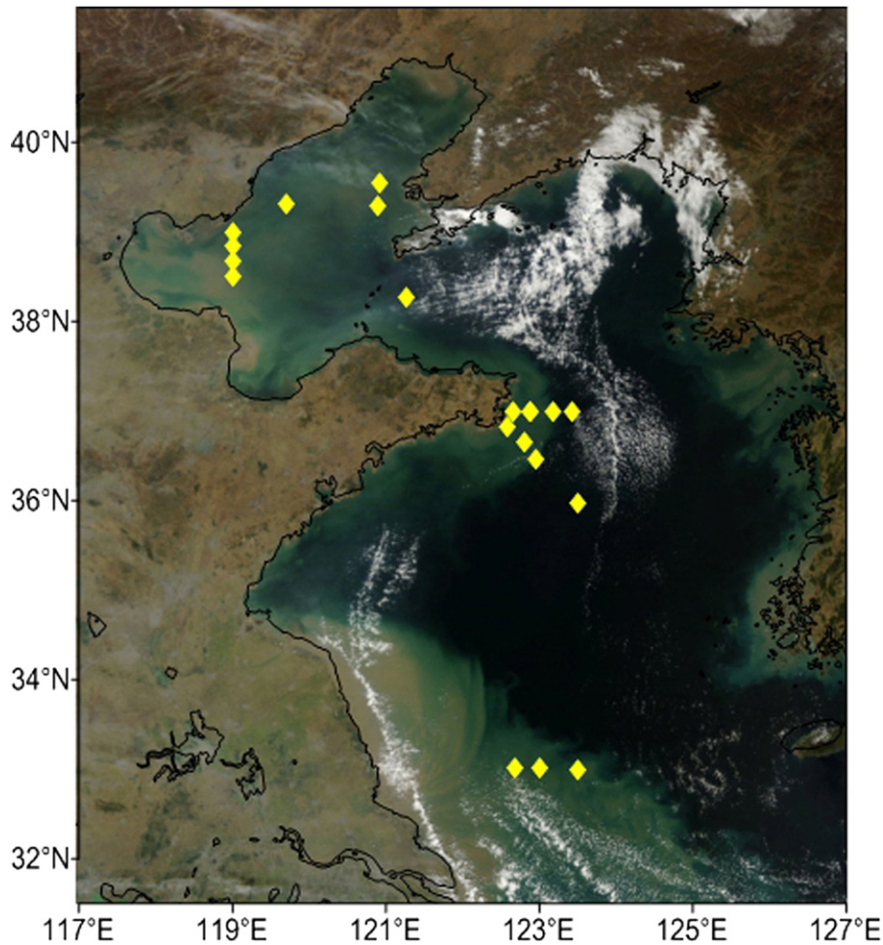


Fig. 2. Locations of sampling stations for match-ups of MODIS R_{rs} and in situ R_{rs} and Z_{sd} , overlaid with a MODIS RGB image of October 25, 2012 (<http://www.eosnap.com/image-of-the-day/sediments-in-bohai-sea-and-from-yangtze-river-china/>).

- 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

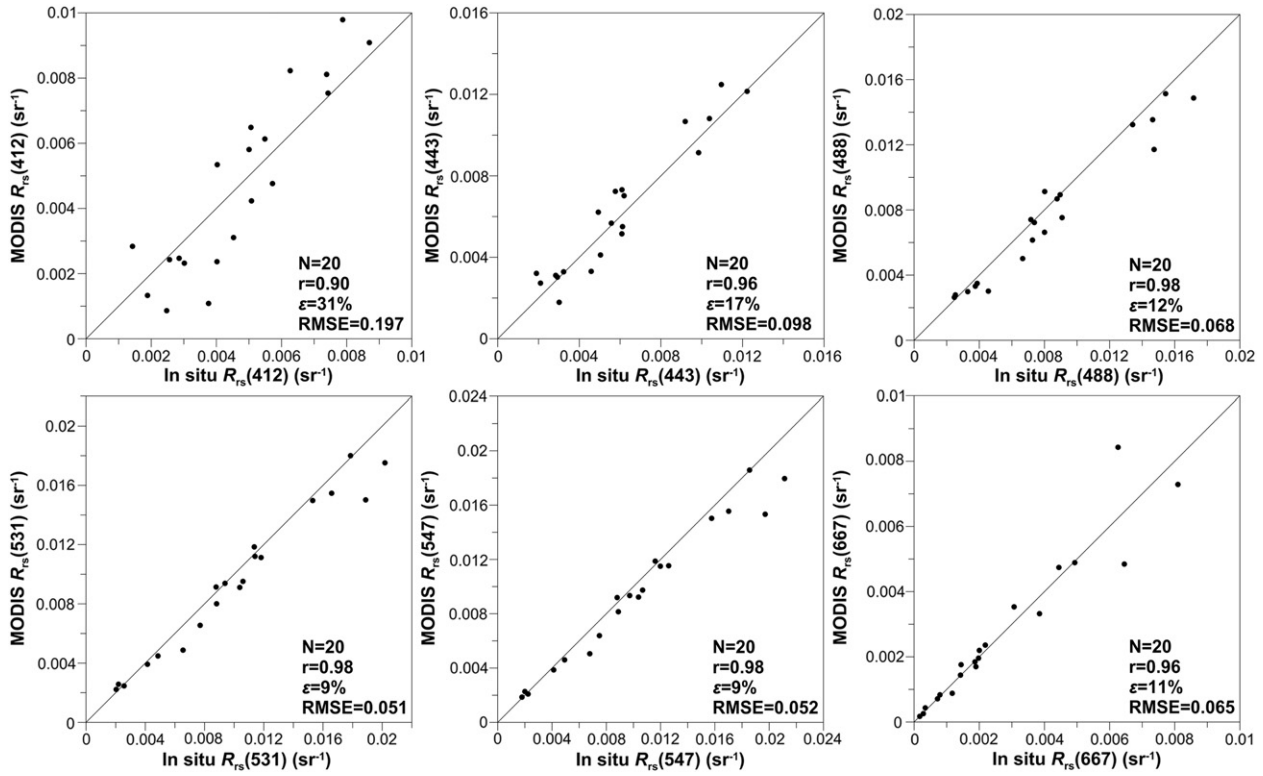


Fig. 3. MODIS R_{rs} versus in situ R_{rs} in the Bohai Sea and the Yellow Sea.

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

(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

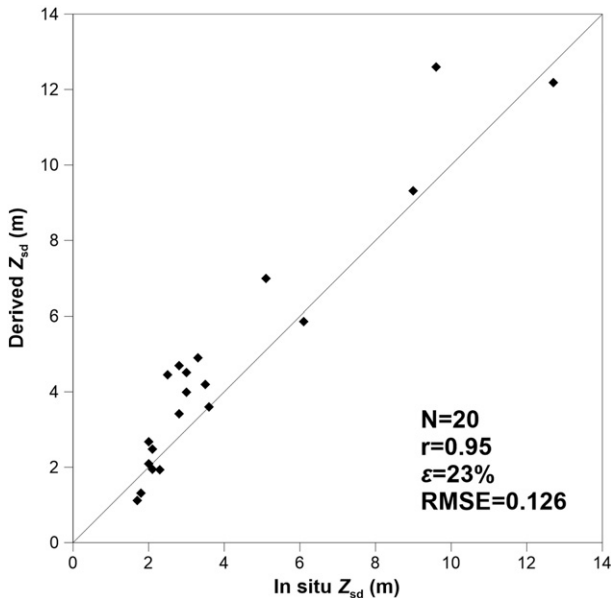


Fig. 4. In situ Z_{sd} compared to Z_{sd} derived from MODIS R_{rs} using the algorithm of Lee et al. (2015).

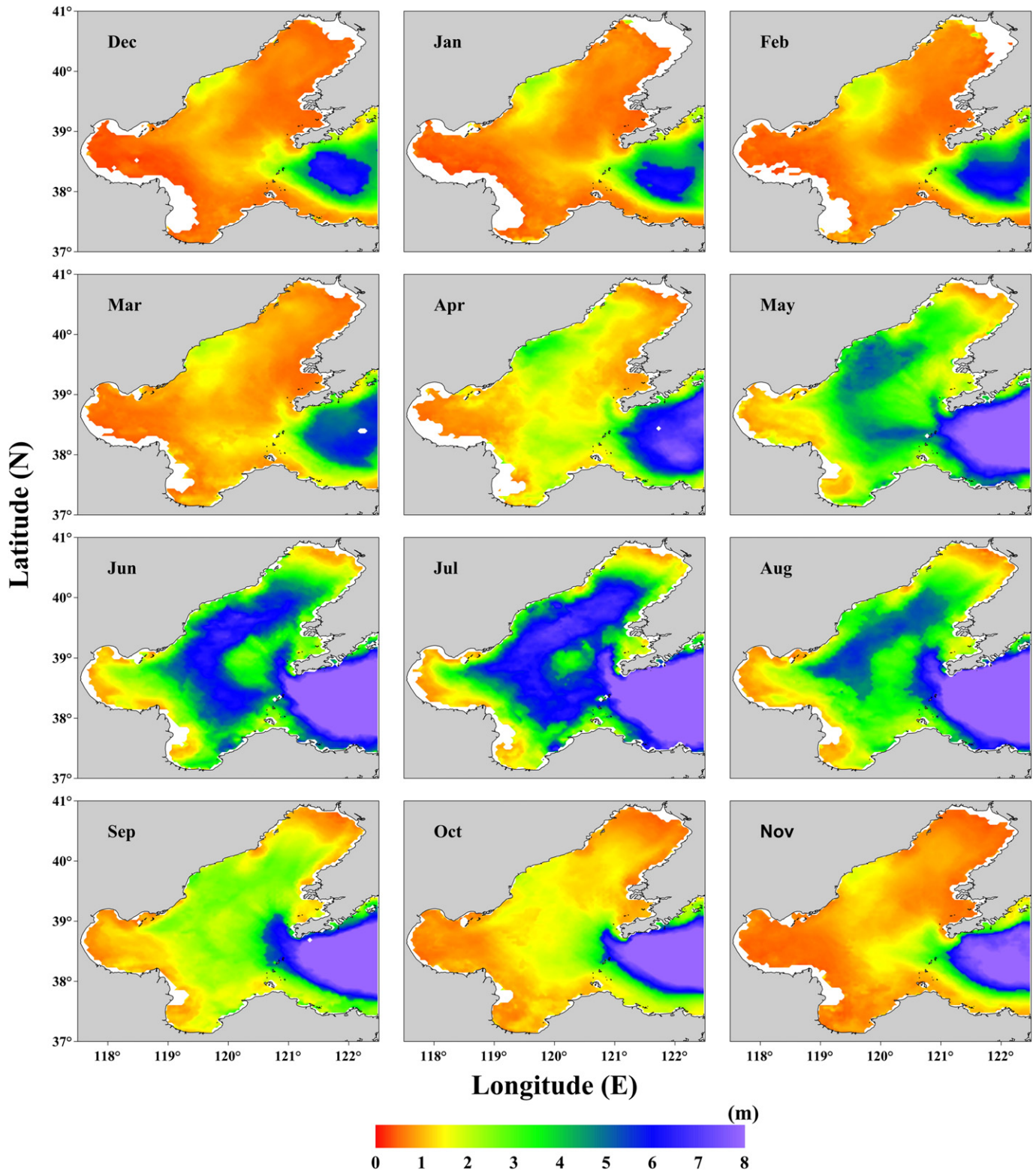


Fig. 5. Climatological monthly mean Z_{sd} in the Bohai Sea during 2003–2014.

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.

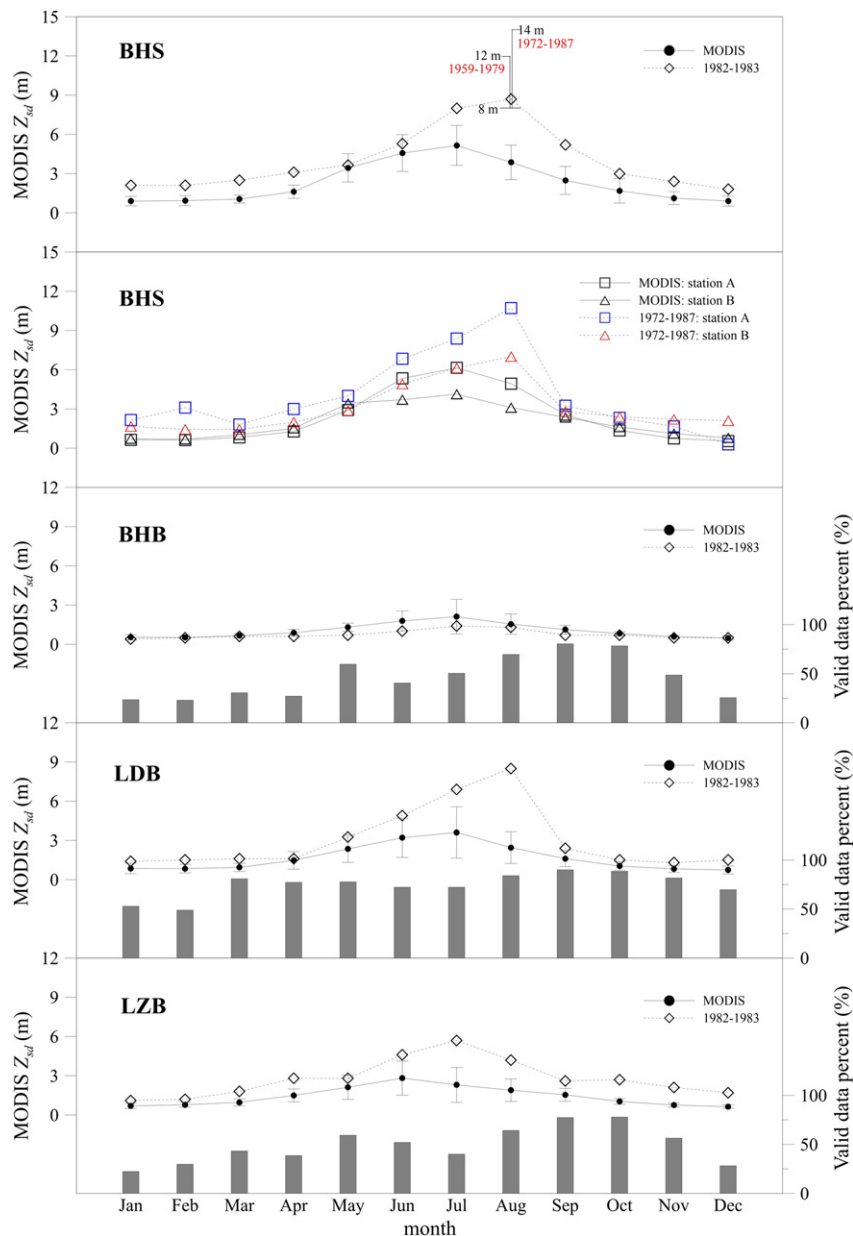


Fig. 6. Climatological seasonal patterns of Z_{sd} (solid circles), std (error bars) and the valid data percent (= numbers of valid retrievals / total pixels, see grey bars) in the three bays, namely, the Bohai Bay (BHB), Laizhou Bay (LZB) and Liaodong Bay (LDB), and in the central Bohai Sea (BHS; percentage 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 1×10^8 tons during 1985–1992, increasing to 1×10^9 tons in 2000 and to 3.5×10^9 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.

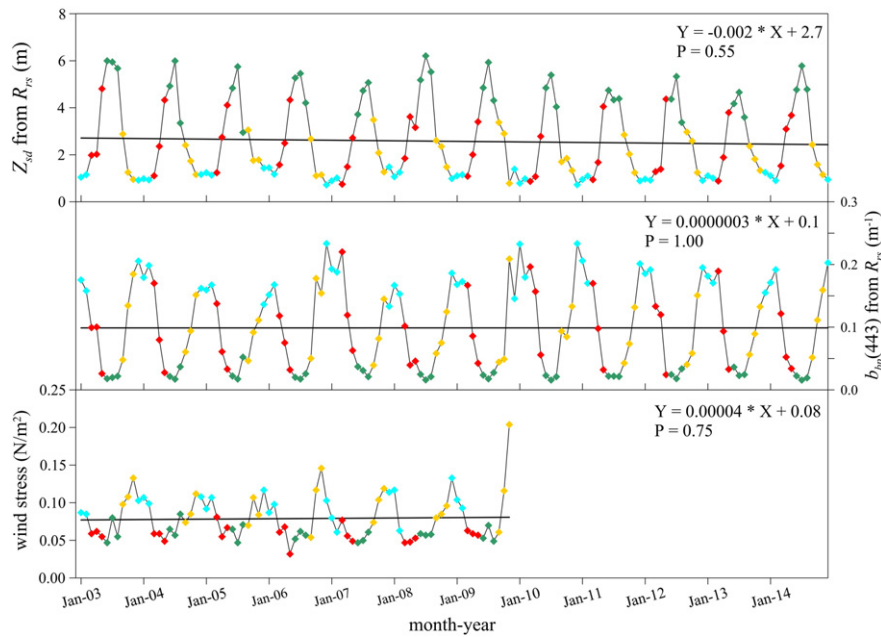


Fig. 7. MODIS monthly-mean time series and linear regression line of Z_{sd} and $b_{bp}(443)$ during 2003–2014, and QuikSCAT wind stress during 2003–2009 (the only time this dataset is available), in the central Bohai Sea (excluding the three bays). Solid lines are results of linear regression, with 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).

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).

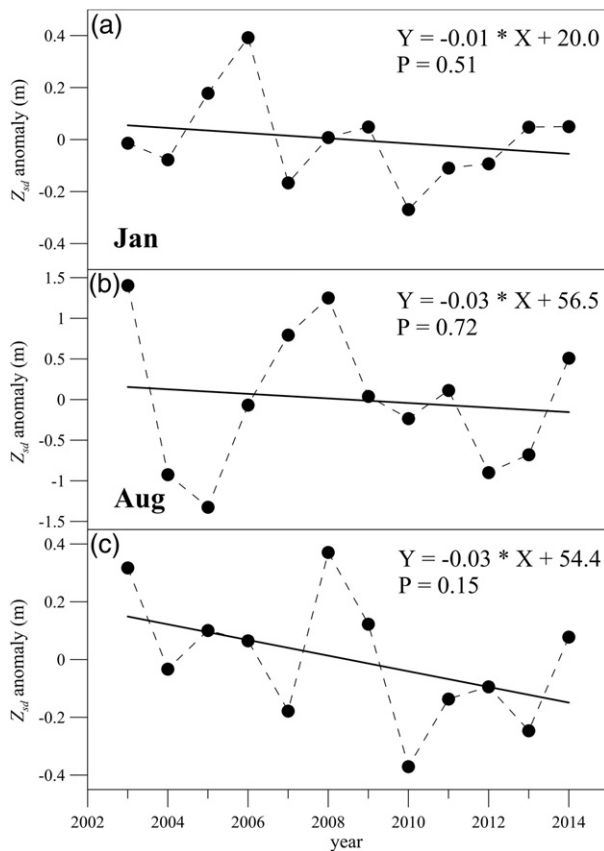


Fig. 8. Temporal anomalies of Z_{sd} for the central BHS during 2003–2014. Solid lines are results of linear regression, with equations and p values shown on the upper right of each panel. (a) January; (b) August; (c) annual mean.

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.

Acknowledgements

This study was supported by the Chinese Ministry of Science and Technology (#2016YFA0601201), the NSF-China (#41576169), the National Aeronautic and Space Administration (NASA) Ocean Biology and Biogeochemistry and Water and Energy Cycle Programs (NNX14AK08G, NASA-NNX15AC84G, Lee), and the University of Massachusetts Boston (P20120000019675, Lee). In situ surveys were jointly supported by the NSFC Open Ship-Time Projects and the National Basic Research Program of China (2009CB421201). We thank Mr. Jushi Zhang for in situ data collection, Ms. Yanshuang Xie for processing QuikSCAT data, and Dr. Weidong Zhai for help to improve the presentation of this manuscript.

References

- Aksnes, D.L., Dupont, N., Staby, A., Fiksen, Ø., Kaartvedt, S., Aure, J., 2009. Coastal Water Darkening and Implications for Mesopelagic Regime Shifts in Norwegian Fjords.
- Antoine, D., d'Ortenzio, F., Hooker, S.B., Bécu, G., Gentili, B., Tailliez, D., Scott, A.J., 2008. Assessment of uncertainty in the ocean reflectance determined by three satellite ocean color sensors (MERIS, SeaWiFS and MODIS-A) at an offshore site in the Mediterranean Sea (BOUSSOLE project). *J. Geophys. Res. Oceans* 113.
- Bailey, S.W., Werdell, P.J., 2006. A multi-sensor approach for the on-orbit validation of ocean color satellite data products. *Remote Sens. Environ.* 102, 12–23.
- Bailey, S.W., Franz, B.A., Werdell, P.J., 2010. Estimation of near-infrared water-leaving reflectance for satellite ocean color data processing. *Opt. Express* 18, 7521–7527.
- Behrenfeld, M.J., Randerson, J.T., McClain, C.R., Feldman, G.C., Los, S.O., Tucker, C.J., Falkowski, P.G., Field, C.B., Frouin, R., Esaias, W.E., 2001. Biospheric primary production during an ENSO transition. *Science* 291, 2594–2597.
- Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., Boss, E.S., 2006. Climate-driven trends in contemporary ocean productivity. *Nature* 444, 752–755.
- Blackwell, H.R., 1946. Contrast thresholds of the human eye. *J. Opt. Soc. Am.* 36, 624–643.

- Boyce, D.G., Lewis, M., Worm, B., 2012. Integrating global chlorophyll data from 1890 to 2010. *Limnol. Oceanogr. Methods* 10, 840–852.
- Capuzzo, E., Stephens, D., Silva, T., Barry, J., Forster, R.M., 2015. Decrease in water clarity of the southern and central North Sea during the 20th century. *Glob. Chang. Biol.* 21, 2206–2214.
- Chaves, J.E., Werdell, P.J., Proctor, C.W., Neeley, A.R., Freeman, S.A., Thomas, C.S., Hooker, S.B., 2015. Assessment of ocean color data records from MODIS-Aqua in the western Arctic Ocean. *Deep-Sea Res. II Top. Stud. Oceanogr.* 118, 32–43.
- Chavez, F., Strutton, P., Friederich, G., Feely, R., Feldman, G., Foley, D., McPhaden, M., 1999. Biological and chemical response of the equatorial Pacific Ocean to the 1997–98 El Niño. *Science* 286, 2126–2131.
- Chen, Z., Muller-Karger, F.E., Hu, C., 2007. Remote sensing of water clarity in Tampa Bay. *Remote Sens. Environ.* 109, 249–259.
- Doron, M., Babin, M., Hembise, O., Mangin, A., Garnesson, P., 2011. Ocean transparency from space: Validation of algorithms estimating Secchi depth using MERIS, MODIS and SeaWiFS data. *Remote Sens. Environ.* 115, 2986–3001.
- Dupont, N., Aksnes, D.L., 2013. Centennial changes in water clarity of the Baltic Sea and the North Sea. *Estuar. Coast. Shelf Sci.* 131, 282–289.
- Fei, Z., 1986. Study on the water color and transparency in the Bohai Sea. *J. Oceanogr. Huang Hai Bohai Sea* 4, 33–40.
- Fleming-Lehtinen, V., Laamanen, M., 2012. Long-term changes in Secchi depth and the role of phytoplankton in explaining light attenuation in the Baltic Sea. *Estuar. Coast. Shelf Sci.* 102, 1–10.
- Fuggle, R., Smith, W., 2000. Large Dams in Water and Energy Resource Development in the People's Republic of China (PRC). Country review paper prepared as an input to the World Commission on Dams, Cape Town.
- Gao, X., Zhou, F., Chen, C.-T.A., 2014. Pollution status of the Bohai Sea: an overview of the environmental quality assessment related trace metals. *Environ. Int.* 62, 12–30.
- He, X., Pan, D., Huang, E., Zhao, Y., 2004. Monitor of water transparency in the China Sea by using satellite remote sensing [J]. *Eng. Sci.* 9, 006.
- Hicks, B.J., Stichbury, G.A., Brabyn, L.K., Allan, M.G., Ashraf, S., 2013. Hindcasting water clarity from Landsat satellite images of unmonitored shallow lakes in the Waikato region, New Zealand. *Environ. Monit. Assess.* 185, 7245–7261.
- Hooker, S.B., Lazin, G., Zibordi, G., McLean, S., 2002. An evaluation of above-and-in-water methods for determining water-leaving radiances. *J. Atmos. Ocean. Technol.* 19, 486–515.
- Jiang, W., Pohlmann, T., Sündermann, J., Feng, S., 2000. A modelling study of SPM transport in the Bohai Sea. *J. Mar. Syst.* 24, 175–200.
- Kemp, W.M., Boynton, W.R., Adolf, J.E., Boesch, D.F., Boicourt, W.C., Brush, G., Cornwell, J.C., Fisher, T.R., Glibert, P.M., Hagy, J.D., 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. *Mar. Ecol. Prog. Ser.* 303, 1–29.
- Lee, Z., 2006. Reports of the International Ocean-Colour Coordinating Group. IOCCG, Dartmouth, NS.
- Lee, H.-J., Chao, S.-Y., 2003. A climatological description of circulation in and around the East China Sea. *Deep-Sea Res. II Top. Stud. Oceanogr.* 50, 1065–1084.
- Lee, Z., Carder, K.L., Arnone, R.A., 2002. Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters. *Appl. Opt.* 41, 5755–5772.
- Lee, Z., Hu, C., Shang, S., Du, K., Lewis, M., Arnone, R., Brewin, R., 2013. Penetration of UV-visible solar radiation in the global oceans: insights from ocean color remote sensing. *J. Geophys. Res. Oceans* 118, 4241–4255.
- Lee, Z., Shang, S., Hu, C., Du, K., Weidemann, A., Hou, W., Lin, J., Lin, G., 2015. Secchi disk depth: a new theory and mechanistic model for underwater visibility. *Remote Sens. Environ.* 169, 139–149.
- Lee, Z., Shang, S., Qi, L., Yan, J., Lin, G., 2016. A semi-analytical scheme to estimate Secchi-disk depth from Landsat-8 measurements. *Remote Sens. Environ.* 177, 101–106.
- Lei, K., Meng, W., Zheng, B., Hou, X., Sun, Y., 2007. Variations of water and sediment discharges to the western coast of Bohai Bay and the environmental impacts. *Acta Sci. Circumst.* 27, 2053–2059.
- Li, F., Zhang, X., 2001. Impact of variation of water and sediment fluxes on sustainable use of marine environment and resources in the Huanghe River estuary and adjacent sea II. Variation of marine environment due to water flow cut-off and decrease greatly the volume of water imputed the sea from the Huanghe River. *Studia Marina Sinica* 43, pp. 60–67.
- Liu, S., Lou, S., Kuang, C., Huang, W., Chen, W., Zhang, J., Zhong, G., 2011. Water quality assessment by pollution-index method in the coastal waters of Hebei Province in western Bohai Sea, China. *Mar. Pollut. Bull.* 62, 2220–2229.
- McClain, C.R., 2009. A decade of satellite ocean color observations*. *Ann. Rev. Mar. Sci.* 1, 19–42.
- Mélin, F., Zibordi, G., Berthon, J.-F., 2007. Assessment of satellite ocean color products at a coastal site. *Remote Sens. Environ.* 110, 192–215.
- Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. *J. Geol.* 1–21.
- Miyazaki, Y., Kondo, Y., Takegawa, N., Weber, R., Koike, M., Kita, K., Fukuda, M., Ma, Y., Clarke, A., Kapustin, V., 2005. Contribution of particulate nitrate to airborne measurements of total reactive nitrogen. *J. Geophys. Res. Atmos.* 110.
- Moore, T.S., Campbell, J.W., Dowell, M.D., 2009. A class-based approach to characterizing and mapping the uncertainty of the MODIS ocean chlorophyll product. *Remote Sens. Environ.* 113, 2424–2430.
- Morel, A., Huot, Y., Gentili, B., Werdell, P.J., Hooker, S.B., Franz, B.A., 2007. Examining the consistency of products derived from various ocean color sensors in open ocean (case 1) waters in the perspective of a multi-sensor approach. *Remote Sens. Environ.* 111, 69–88.
- Ning, X., Lin, C., Su, J., Liu, C., Hao, Q., Le, F., Tang, Q., 2010. Long-term environmental changes and the responses of the ecosystems in the Bohai Sea during 1960–1996. *Deep-Sea Res. II Top. Stud. Oceanogr.* 57, 1079–1091.
- Olmanson, L.G., Bauer, M.E., Brezonik, P.L., 2008. A 20-year Landsat water clarity census of Minnesota's 10,000 lakes. *Remote Sens. Environ.* 112, 4086–4097.
- Philippart, C.J., Salama, M.S., Kromkamp, J.C., van der Woerd, H.J., Zuur, A.F., Cadée, G.C., 2013. Four decades of variability in turbidity in the western Wadden Sea as derived from corrected Secchi disk readings. *J. Sea Res.* 82, 67–79.
- Preisendorfer, R.W., 1986. Secchi disk science: visual optics of natural waters. *Limnol. Oceanogr.* 31, 909–926.
- Qiao, S., Shi, X., Zhu, A., Liu, Y., Bi, N., Fang, X., Yang, G., 2010. Distribution and transport of suspended sediments off the Yellow River (Huanghe) mouth and the nearby Bohai Sea. *Estuar. Coast. Shelf Sci.* 86, 337–344.
- Qin, P., Xiao, Y., Cui, T., Liu, R., Bing, M.U., 2014. Validation of main semi-analytical retrieval algorithms of transparency in the Bohai and Yellow Sea. *Acta Laser Biology Sinica* 23, 516–522.
- Shang, S., Dong, Q., Lee, Z., Li, Y., Xie, Y., Behrenfeld, M., 2011. MODIS observed phytoplankton dynamics in the Taiwan Strait: an absorption-based analysis. *Biogeosciences* 8, 841–850.
- Shang, S., Wu, J., Huang, B., Lin, G., Lee, Z., Liu, J., Shang, S., 2014. A new approach to discriminate dinoflagellate from diatom blooms from space in the East China Sea. *J. Geophys. Res. Oceans* 119, 4653–4668.
- Shi, W., Wang, M., 2014. Ocean reflectance spectra at the red, near-infrared, and short-wave infrared from highly turbid waters: a study in the Bohai Sea, Yellow Sea, and East China Sea. *Limnol. Oceanogr.* 59, 427–444.
- Su, H., Wang, Y., 2012. Using MODIS data to estimate sea ice thickness in the Bohai Sea (China) in the 2009–2010 winter. *J. Geophys. Res. Oceans* 117.
- Tang, Q., Jin, X., Wang, J., Zhuang, Z., Cui, Y., Meng, T., 2003. Decadal-scale variations of ecosystem productivity and control mechanisms in the Bohai Sea. *Fish. Oceanogr.* 12, 223–233.
- Wang, M., Tang, J., Shi, W., 2007. MODIS-derived ocean color products along the China east coastal region. *Geophys. Res. Lett.* 34.
- Weeks, S., Werdell, P.J., Schaffelke, B., Canto, M., Lee, Z., Wilding, J.G., Feldman, G.C., 2012. Satellite-derived photic depth on the Great Barrier Reef: spatio-temporal patterns of water clarity. *Remote Sens.* 4, 3781–3795.
- Xu, S., 2011. Decline mechanisms of fishery resources in the Bohai Sea under anthropogenic activities. Doctoral Dissertation, Graduate University of Chinese Academy of Sciences. 2011 Available: <http://www.cnki.net/KCMS/detail/detail.aspx>.
- XU, L.-I., WU, D.-X., LIN, X.-P., CHAO, M., 2009. The study of the Yellow Sea Warm Current and its seasonal variability. *J. Hydrodyn. Ser. B* 21, 159–165.
- Xu, S., Song, J., Li, X., Yuan, H., Li, N., Duan, L., Sun, P., 2010. Changes in nitrogen and phosphorus and their effects on phytoplankton in the Bohai Sea. *Chin. J. Oceanol. Limnol.* 28, 945–952.
- Xue, Y.H., Xiong, X.J., Liu, Y.Q., 2015. Distribution features and seasonal variability of the transparency in offshore waters of China. *Advances in Marine Science*.
- Yang, H., Yang, D., 2012. Climatic factors influencing changing pan evaporation across China from 1961 to 2001. *J. Hydrol.* 414, 184–193.
- Yang, Y., Zhao, N., Hao, X., Li, C., 2009. Decreasing trend of sunshine hours and related driving forces in North China. *Theor. Appl. Climatol.* 97, 91–98.
- Yoder, J.A., Schollaert, S.E., O'Reilly, J.E., 2002. Climatological phytoplankton chlorophyll and sea surface temperature patterns in continental shelf and slope waters off the northeast US coast. *Limnol. Oceanogr.* 47, 672–682.
- Zhai, W., Zhao, H., Zheng, N., Xu, Y., 2012. Coastal acidification in summer bottom oxygen-depleted waters in northwestern-northern Bohai Sea from June to August in 2011. *Chin. Sci. Bull.* 57, 1062–1068.
- Zhang, X., 1983. On distribution characteristics of water transparency in the East China Sea. *Mar. Sci. Bull.* 2, 21–24.
- Zhang, L., Xia, B., Gui, Z., Jiang, C., 2007. Contaminative conditions evaluation of sixteen main rivers flowing into sea around Bohai Sea, in summer of 2005. *Environ. Sci.* 28, 2409–2415.
- Zhu, L., Zhao, B., 1991. Distribution and variations of the transparency in the Bohai Sea, Yellow Sea and East China Sea. *Transactions of Oceanology and Limnology* 3, 1–11.