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The vertical attenuation of irradiance as a function of turbidity: a case of the Huanghai (Yellow) Sea in spring

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Abstract

The planar photosynthetically available radiation (PAR), turbidity and concentration of chlorophyll a (chl a), were measured at 26 stations in the Huanghai (Yellow) Sea during a cruise of China SOLAS from 19 to 27 March 2005. Due to low chl a (<0.35 mg·m^{-3}) in upper layers (above 5 m), suspended particulate matter became the major factor that influenced the turbidity in early spring. The calculated vertical diffuse attenuation coefficient of PAR, $K_{\rm PAR}$, varied with water depths with a maximum value in the upper 5 m layer. The mean $K_{\rm PAR}$ in survey area was 0.277±0.07 m^{-1} that is considerably higher than most of the other case 2 waters. Within the survey area, $K_{\rm PAR}$ also showed distinct regional characteristics, corresponding to the distribution of turbidity. Based on measurements, the relationship between $K_{\rm PAR}$ and turbidity as well as chl a was established. It was suggested that suspended particulate matter plays an important role in light attenuation in the Huanghai (Yellow) Sea in spring.

Key words: Photosynthetically available radiation, Diffuse attenuation coefficient, Turbidity, Chlorophyll a, the Huanghai (Yellow) Sea

1 Introduction

Light is essential for photosynthetic plants and aquatic algae. Besides nutrients, temperature and salinity, due to the rapid attenuation in water, light is often a limiting factor to the primary production in aquatic environment (Fisher et al., 1999). Light availability also influences species composition (Rijstenbil, 1987; Jones and Gowen, 1990) and many other biological and chemical processes, such as behavior of organisms (e.g., Graham et al., 2001; Dieguez and Gilbert, 2003), phytoplankton physiological response (Cullen and Lewis, 1988) and photochemical degradation (Anning et al., 2000).

In the visible part of light spectrum, the light with wavelengths between 400 and 700 nm, termed PAR (Photosynthetically Avaliable Radiation) is utilized by phytoplankton for photosynthesis (Falkowski and Raven, 1997). The light attenuation underwater occurs mainly due to four factors: water molecule, phytoplankton, colored dissolved organic material (CDOM) and suspended particulate matter (SPM). The last factor, i.e., SPM, has a close relationship with turbidity (Jones and Wills, 1965). Through light, these factors are related to the rates of primary production. Therefore, correct representation of underwater light field is a key issue in modeling the biogeochemical processes and primary production in aquatic ecosystems.

Because the incident PAR at air-water interface can be measured or calculated quite accurately (Fisher et al., 2003), the main difficulty in calculating underwater light field is to correctly estimate vertical light attenuation coefficient (K). The vertical light attenuation coefficient can be decomposed to a set of partial attenuation coefficients, each characterizing absorption and scattering by a different waterborne material.

Attenuation depends on wavelength of light and an accurate underwater model for attenuation coefficient must consider light spectrum. Recently, spectral bio-optical models have been developed and applied to various kinds of water bodies (Platt et al., 1988; Gallegos et al., 1990; Arrigo et al., 1994; Lee et al., 2005). On the other hand, because of its simple principle and easy measurement, non-spectral bio-optical models

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have had a long history and have also been broadly used (Morel, 1988; Varela et al., 1992; Radach et al., 1993; Mcgillicuddy et al., 1995; Wong et al., 1995; Loukos et al., 1997). However, most of them, no matter spectral or non-spectral models, did not include the effects of SPM. In the open ocean, this assumption is acceptable where the concentration of SPM is very low. However, in coastal waters, the concentration of SPM is relatively high and it is therefore necessary to consider the influence of SPM on the light attenuation underwater. This is particularly true in the Huanghai (Yellow) Sea, where SPM and turbidity is high (Su and Yuan, 2005).

The Huanghai Sea is semi-enclosed water surrounded by China, DPR Korea and RO Korea. The average water depth of Huanghai Sea is nearly 44 m and the maximum depth is above 140 m. The connection line between Cheng Shanjiao, China and Changsangot, DPR Korea divides the Huanghai Sea into two parts, north Huanghai Sea and south Huanghai Sea (Su and Yuan, 2005). The Huanghai Sea receives Yellow River diluted water from west (Wang et al., 2008) and Changjiang (Yangtze River) diluted water from south (Zhu et al., 1998; Pu et al., 2002), and consequently large amounts of sediment was sent to the sea (Pang et al., 2003). In addition, the resuspension of sediment offshore the old Yellow River mouth and the terrestrial input from Huai, Han, and Yalv rivers also contribute to the SPM distribution in the Huanghai Sea. The Huanghai Sea therefore has been considered as one of the most turbid water in the world (Sun et al., 2000).

There is still no a simple model or a function to link with turbidity and chl a for the Huanghai Sea. However, such a function is expected to give a more reasonable estimation of underwater light field than a constant light attenuation coefficient, which is important to the ecological modeling study. In this study, based on the field data in the Huanghai Sea, a linear function was established and the effects of SPM and chl-a on light attenuation were discussed.

2 Materials and methods

2.1 *Observations*

The survey in spring was carried out in an area from 121°E to 124°E and 33°N to 39°N as the first cruise of China SOLAS (Surface Ocean-Lower Atmosphere Study) project from 19 to 27 March, 2005 (Fig. 1) on board R/V Dongfanghong II. Observations were conducted at 26 stations, among which A1 and A2 were anchor stations and measurements were carried out every two hours during the 25-hour anchored period. At all stations, CTD measurements were performed down to 2 m above the bottom with XR-620CTD probe (RBR Ltd., Canada), which measures conductivity, temperature and pressure with a maximum sampling rate of 6Hz. The LICOR PAR sensors (LI-192SA) were placed on the CTD probe to measure downwelling planar irradiance profiles in the water. Chlorophyll a and turbidity were measured using Seapoint sensors attached to the CTD probe. During each CTD casting, the ship was oriented to minimize the influence of ship shadow and all the instruments were lowered from a crane which stretched out 2 m from the ship's side. Dark values were measured at the beginning of each casting and subtracted from all the readings.

Compared with traditional fluorescence analysis (chl a_{FLUO}), the values measured by CTD probe (chl a_{CTD}) were lower, but they have similar spatial pattern. The linear regression between them is expressed as equation (1) (with a credible degree of 95%). The good linear regression relation between C_{chlaCTD} and C_{chaFLUO} indicates that the use of C_{chlaCTD} is acceptable.

$$\begin{aligned}&\text{chl a}_{\mathrm{CTD}} = 0.174\text{chl a}_{\mathrm{FLUO}} \times 0.087\\&R^2 = 0.68\end{aligned} \quad (1)$$

In the survey, 17 CTD castings were carried out during daytime and table 1 shows the measurement time and dates of these castings.

2.2 *Data processing*

Light intensity decreases approximately exponentially with depth in water (Kirk, 1994),

$$E_{\mathrm{d}}(z) = E_{\mathrm{d}}(0) \times \exp(-K_{\mathrm{PAR\cdot z}}) \quad (2)$$

where $E_{\mathrm{d}}(z)$ is downward irradiance at depth z, $E_{\mathrm{d}}(0)$ is downward irradiance just beneath air-water interface, K_{PAR} is the average value of vertical attenuation coefficient over the distance from surface to water depth z. Equation (2) can be rearranged to calculate K_{PAR}:

$$K_{\mathrm{PAR}} = -\frac{1}{z}\ln(E_{\mathrm{d}}(z)/E_{\mathrm{d}}(0)) \quad (3)$$

For our calculations to examine the vertical of K_{PAR}, z is the distance between the upper and lower levels

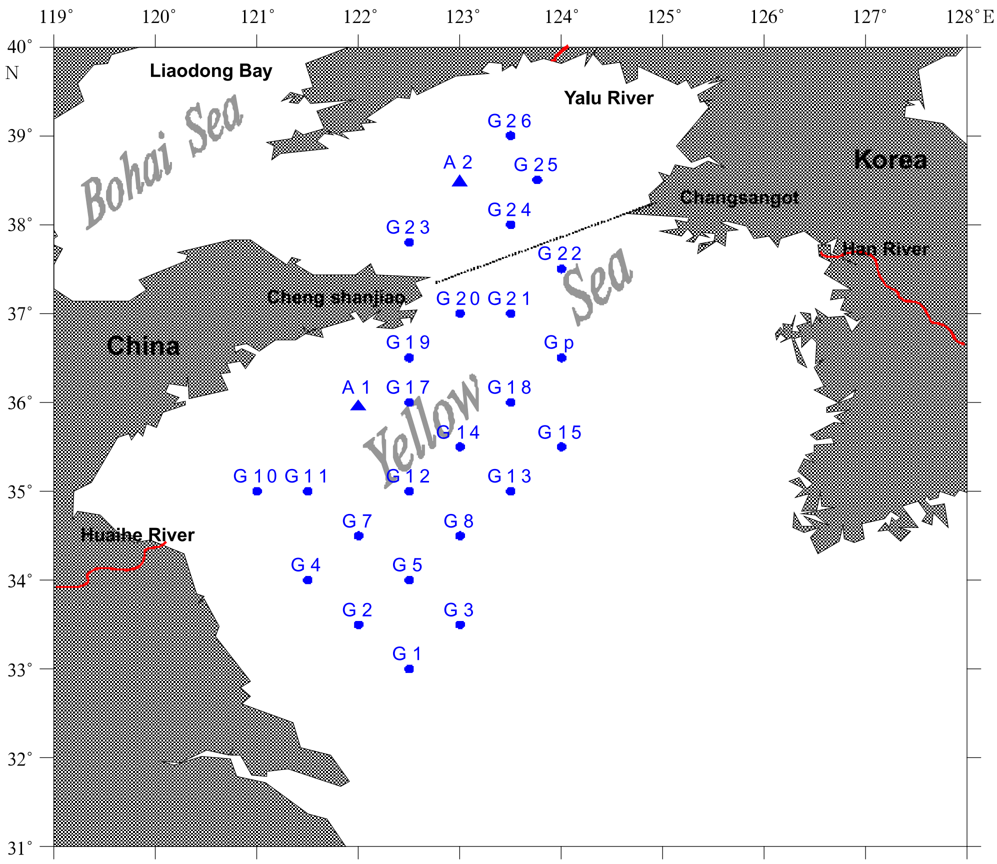

Fig.1. Area and stations of the first China SOLAS cruise. The dot with a name denotes the stations from 19 to 27 March, 2005. The broken line between Cheng Shanjiao, China and Changsangot, DPR korea separates the Huanghai Sea into north Huanghai Sea and south Huanghai Sea.

of PAR measurement, $E_{\rm d}(z)$ is the lower PAR measurement, and $E_0(z)$ is the upper PAR measurement.

It is commonly assumed that the average $K_{\rm PAR}$ can be decomposed as a set of partial attenuation coefficients. In addition to the contribution of water itself, $K_{\rm PAR}$ is often modeled as a linear function of another three substances' concentration (Smith, 1982) including phytoplankton (and, if any, macrophytes), SPM and CDOM (Kirk, 1994). Consequently, $K_{\rm PAR}$ can be approximated as

$$K_{\rm PAR} = K_{\rm w} + Kc_{\rm chl\ a} + K_{\rm SPM} + K_{\rm CDOM}, \tag{4}$$

Where $K_{\rm w}$ is the attenuation due to water, and $Kc_{\rm chl\ a}$, $K_{\rm SPM}$ and $K_{\rm CDOM}$ are the specific attenuation coefficients for phytoplankton, SPM and CDOM, respectively. Theoretically, the estimation of $K_{\rm chl\ a}$, $K_{\rm SPM}$ and $K_{\rm CDOM}$ is quite challenging in the Huanghai Sea because the temporal and spatial variations of phytoplankton, SPM and CDOM are large.

The above empirical, non-spectral approach (Eq. 4) has been widely used to study the relation between light attenuation and water component concentrations in many different marine systems (Smith, 1982; McMahon et al., 1992; Wang et al., 1996, Gallegos and Moore, 2000). It is indicated that if one can simultaneously measure both $K_{\rm PAR}$ and water component concentrations, the values of specific attenuation coefficients can be obtained by multiple linear regression method. In this study, we also used such multiple linear regression method to obtain the relation between $K_{\rm PAR}$ and water component concentrations including those of chlorophyll a and SPM. The CDOM is not included in our analysis for lack of the data. With the calculation using field survey data, we compare the influence of chlorophyll a with that of SPM on the attenuation of PAR to find out which one is the major factor affecting the light attenuation in the Huanghai Sea.

3 Results

3.1 *Horizontal and vertical distributions of chlorophyll a and turbidity*

The chlorophyll a concentration chl a was generally lower than 0.35 mg·m^{-3} in the surface layer (Fig. 2). Such low chl a was kept in the middle and bottom layers at most stations except for stations G23, A2-13, G17, and A1-12, where the chl a increased with depth. In north Huanghai Sea, chl a varied largely among stations. The chl a was higher at inshore stations (A2, G23) than those at offshore stations (G22, G21) (Fig. 3a). In south Huanghai Sea, all the stations except for station A1 presented a similar low level of chl a in the vertical (Fig. 3b). At station A1-12, an inshore station, the chl a was low in the surface layer, but rapidly increased with depth and reached a maximum of 3.18 mg·m^{-3} down to about 37 m (data not shown due to range used in figure).

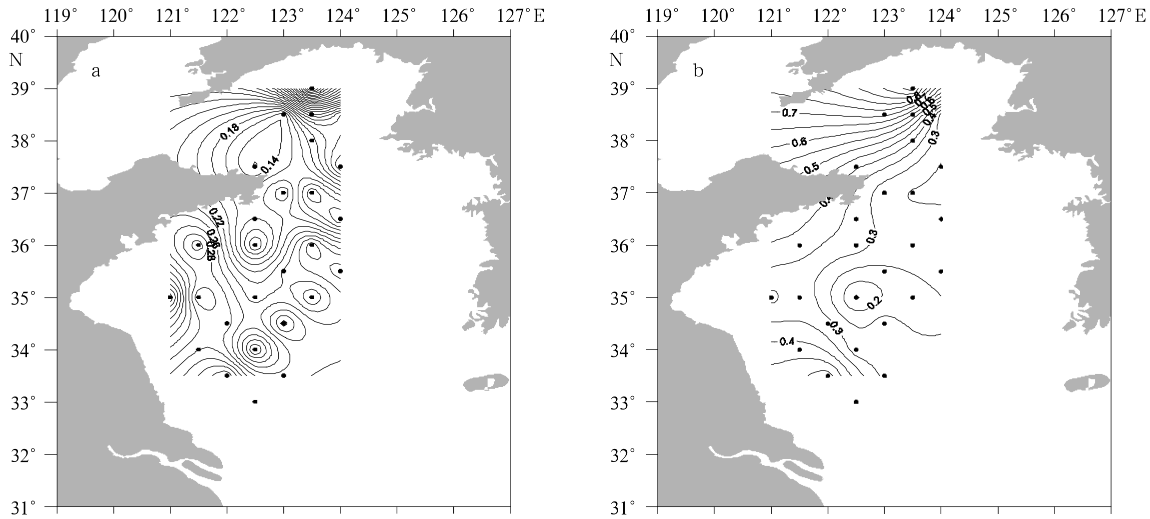

Fig.2. Horizontal distribution of chlorophyll a concentration (mg·m^{-3}) (a) in the surface layer and (b) in the bottom layer.

The vertical profiles of turbidity in north and south Huanghai Seas were shown in Fig. 3c and Fig. 3d. There were essentially two types of turbidity profiles in the water column. One was that turbidity shows a uniform value in the vertical, such as stations G10, G14, G17, and Gp in south Huanghai Sea and stations G21 and G23 in north Huanghai Sea. The other was that turbidity is uniform in the upper few meters and increased with depth in the bottom layer, such as stations G12 and A1-12 in south Huanghai Sea and stations A2-13 and G22 in north Huanghai Sea.

The horizontal distribution of turbidity was shown in Fig. 4. In the surface layer, G23, a station in north Huanghai Sea, showed the most turbid water. The maximal turbidity appeared in the area east of Cheng Shanjiao, China. The clearest water in the study area in south Huanghai Sea located at stations G17 and Gp. In the bottom layer, there were two maximum turbid areas: one was corresponding to that in the surface layer, the other appeared in the middle area of south Huanghai Sea.

Station G12 presents the largest vertical change in turbidity whose value varied from about 0.8 to 7.9 NTU. In the horizontal, turbidity ranged from about 0.03 to 5.8 NTU in the surface layer and from about 0.9 to 7.9 NTU in the bottom layer. Therefore, turbidity looks like changed at the same order in the vertical and in the horizontal.

The mean values of turbidity and chl a in the surface layer averaged are presented in Table 2, and from which, an interesting trend can be found. The averaged turbidity decreased from north Huanghai Sea to south Huanghai Sea. In contrast, the averaged chl a was higher in south Huanghai Sea than in north Huanghai Sea.

In the Huanghai Sea, the inshore water had distinct optical properties from the offshore water (Table 2). All of K_{PAR}, turbidity and chl a were higher at inshore stations than at offshore stations. The influence of bathymetry on currents or sediment transport looks like partly response for the optical difference between inshore and offshore waters.

3.2 *Vertical profile of* K_{PAR}

Generally, the value of K_{PAR} can be considered as a constant in the entire euphotic zone if the water component concentrations do not change significantly in the vertical water column. To examine this in the

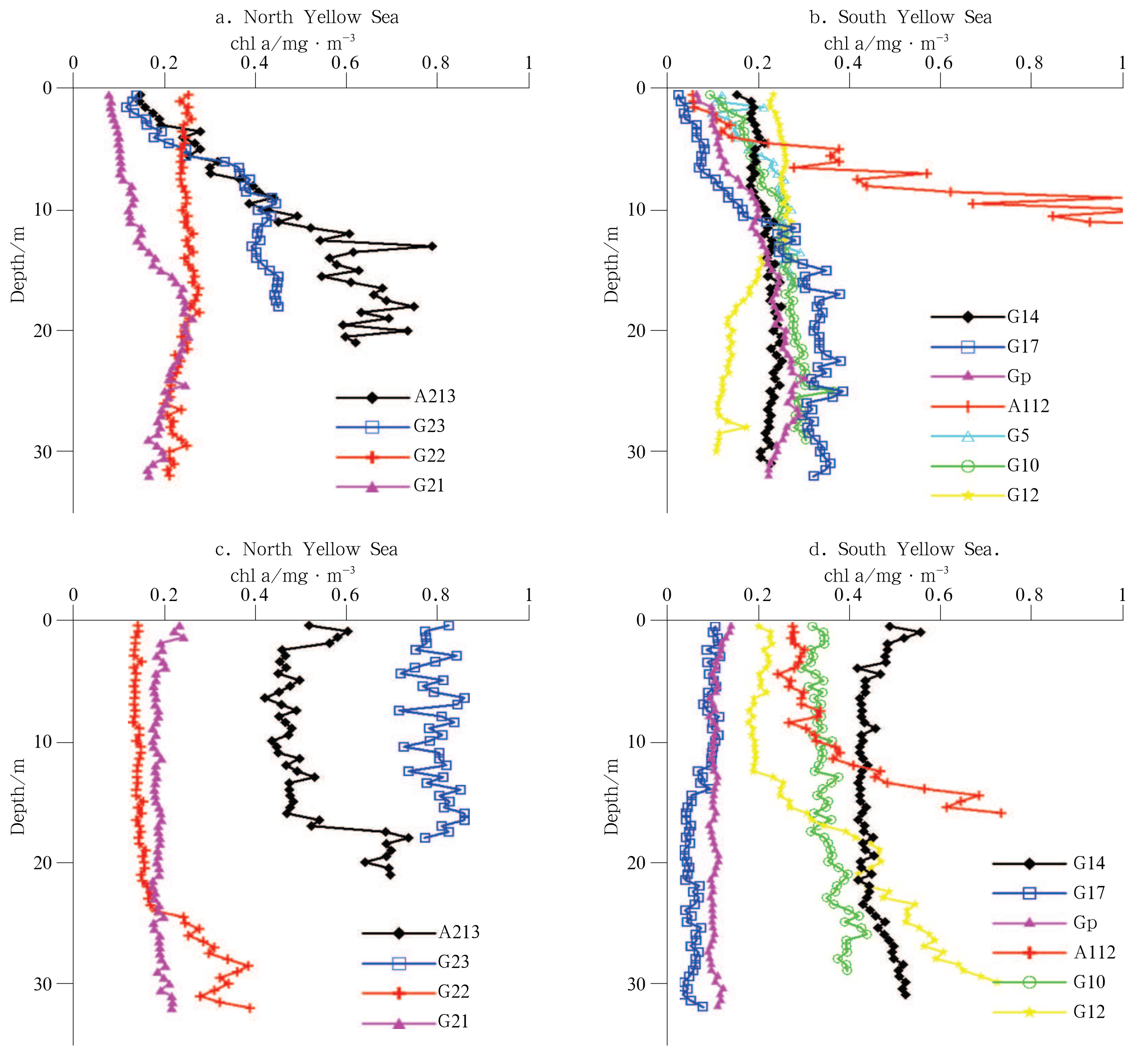

Fig.3. Vertical profiles of (a, c) chlorophyll a concentration (mg·m^{-3}) and turbidity (NTU) at the stations in north Huanghai Sea and (b, d) south Huanghai Sea (see Fig.1 for their locations).

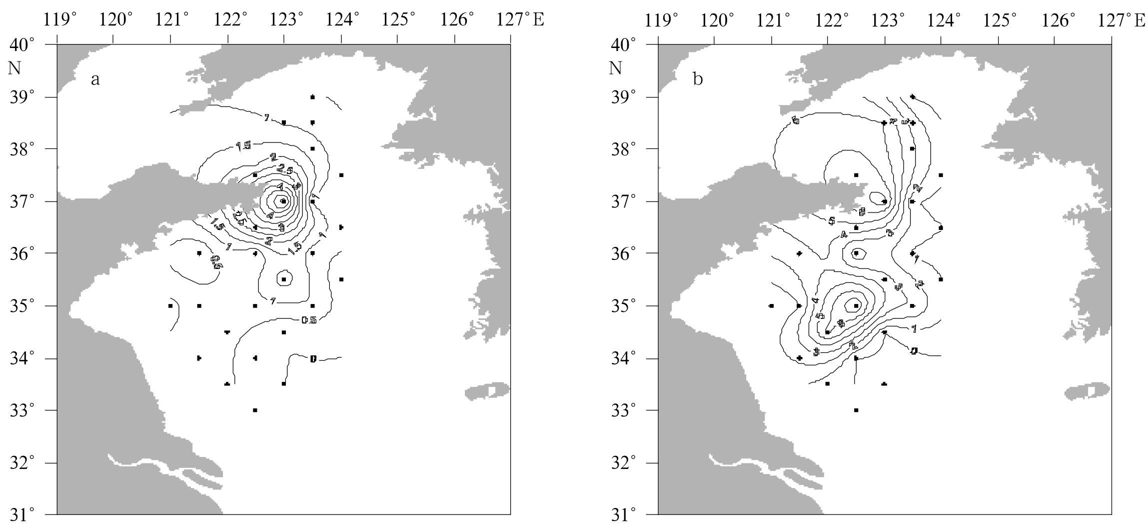

Fig.4. Horizontal distribution of turbidity (NTU) (a) in the surface layer and (b) in the bottom layer.

Table 1. Observation time and geographic location of the stations with PAR measurements in the first China SOLAS cruise on March 2005 in the Huanghai Sea. Four measurements at different time were performed at stations A1 and A2, respectively. Among total 11 stations, stations A2, G23, G22 and G21 are located in north Huanghai Sea; stations Gp, G14, G17, A1, G5, G10 and G12 in south Huanghai Sea.

Number	Station	Longitude (°E)	Latitude (°N)	Local Time	Date (March 2005)
01	A2-11	122°59'008	38°29'009	09:26	21
02	A2-12	122°59'008	38°29'009	11:45	21
03	A2-13	122°59'008	38°29'009	13:33	21
04	A2-14	122°59'008	38°29'009	15:13	21
05	G23	122°30'002	37°47'008	09:44	20
06	G22	124°00'099	37°29'930	07:34	22
07	G21	123°30'000	36°59'008	11:38	22
08	Gp	123°59'009	36°30'002	15:45	22
09	G14	122°59'896	35°29'819	07:34	23
10	G17	122°30'035	35°59'932	11:54	23
11	A1-10	121°34'849	35°54'062	09:18	27
12	A1-11	121°34'849	35°54'062	11:23	27
13	A1-12	121°34'849	35°54'062	13:17	27
14	A1-13	121°34'849	35°54'062	15:10	27
15	G5	122°30'101	33°59'890	16:09	25
16	G10	121°00'154	33°59'890	08:30	26
17	G12	122°30'082	34°59'846	16:48	23

Table 2. Mean concentrations of turbidity and chlorophyll a, and mean values of K_{PAR} in the surface layer of the Huanghai Sea.

	North Huanghai Sea	South Huanghai Sea	Inshore stations	Offshore stations
Turbidity (NTU)	1.699	0.692	1.481	0.906
$c_{\mathrm{chl\ a}}$ (mg·m^{-3})	0.158	0.262	0.260	0.210
K_{PAR} (m^{-1})	0.259	0.241	0.333	0.244

Huanghai Sea, we calculated the value of K_{PAR} every 0.5 meters using measured downwelling planar PAR. The calculation shows a relatively large K_{PAR} in the upper layer and low K_{PAR} in the lower layer (Fig.5), which can be confirmed in both inshore stations (Fig. 5a) and offshore stations (Fig. 5b). More specifically, K_{PAR} has a maximum value of 0.5–0.7 m^{-1} in the surface, decreases sharply to a value of 0.3 m^{-1} in the upper few meters between 1 and 5 m. Under the depth of 5 m, it decreases gradually to a low value of 0.2 m^{-1}.

The mean vertical profile of K_{PAR} (Fig. 6), which was obtained by averaging the K_{PAR} shown in Fig. 5 at the same depth over all the stations, can be approximately expressed by an exponential function between K_{PAR} and depth (D) as equation (5).

$$K_{\mathrm{PAR}} = 0.352\exp(0.026 \times D), \quad R^2 = 0.95 \tag{5}$$

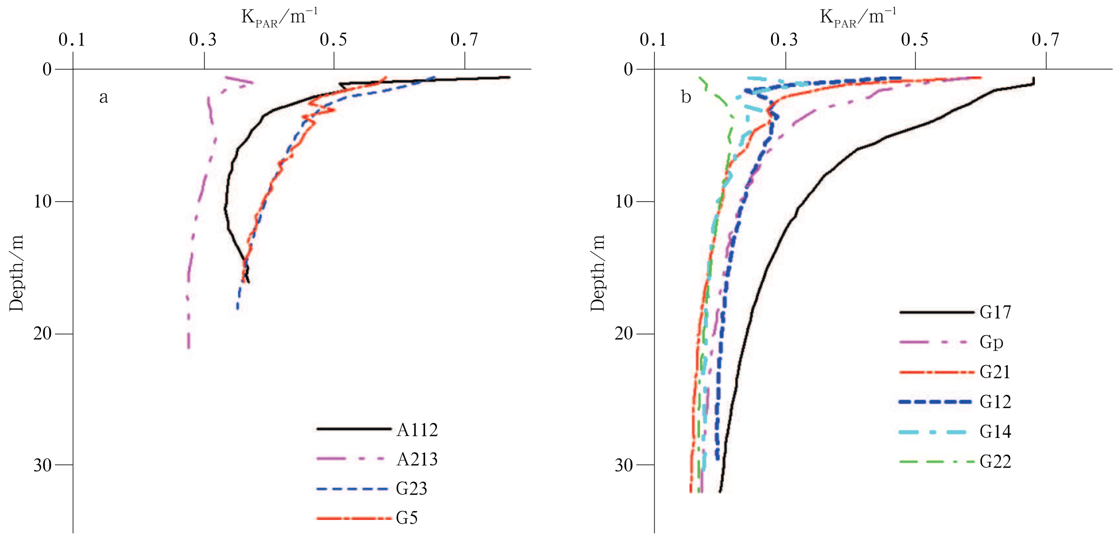

Fig.5. The diffuse attenuation coefficients K_{PAR} (m^{-1}) versus depth (m) at (a) inshore stations and (b) offshore stations in the Huanghai Sea.

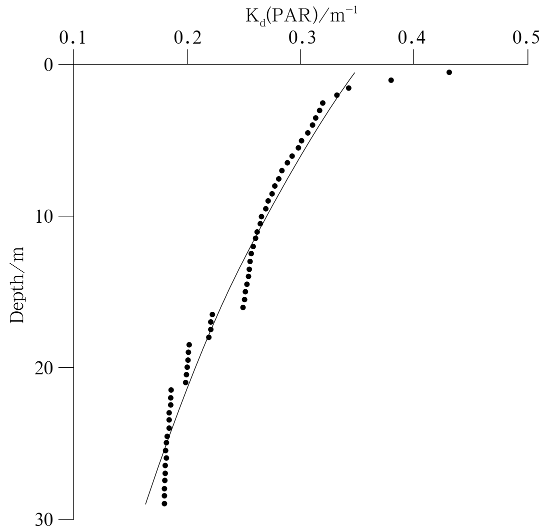

Fig.6. The averaged diffuse attenuation coefficients $K_{\rm PAR}$ as a function of depth for the entire area. (dot represents measured value; line represents regressive value).

3.3 *Depth-averaged* $K_{\rm PAR}$ *versus depth averaged* $c_{chl\ a}$ *and turbidity*

Although we can not obtained a correlation between depth-dependent $K_{\rm PAR}$ and $C_{\rm chl\ a}$ or turbidity, we find a really good correlation between depth-averaged $K_{\rm PAR}$ and depth-averaged turbidity (Fig. 7). The values were averaged in the whole euphotic zone that is determined by the calculated depth-dependent $K_{\rm PAR}$ at each station.

According to Fig. 7, depth-averaged $K_{\rm PAR}$ has good positive correlation with turbidity with a credible degree of 95% and the correlation coefficient R^2 is 0.68. The linear relationship is expressed as,

$$K_{\rm PAR} = 0.142 \times T + 0.07 \quad R^2 = 0.68(6) \qquad (6)$$

Where T is the value of turbidity, ranging from 0.48 to 2.5 NTU.

According to the measurements, there were essentially two types of turbidity profiles in the water column. The first was that turbidity showed a uniform value in the vertical, such as at stations G17, G21, G23 and Gp, and the second was that turbidity was uniform in the upper few meters and increased with depth to the bottom layer, such as at stations A112, A213 and G12. We made liner regression between $K_{\rm PAR}$ and turbidity in the two different areas. The results were that:

$$K_{\rm PAR} = 0.11 \times T + 0.07 \quad R^2 = 0.83 \qquad (7)$$

which applied to the first area. And

$$K_{\rm PAR} = 4.31 \times T + 0.11 \quad R^2 = 0.8 \qquad (8)$$

which applied to the second area.

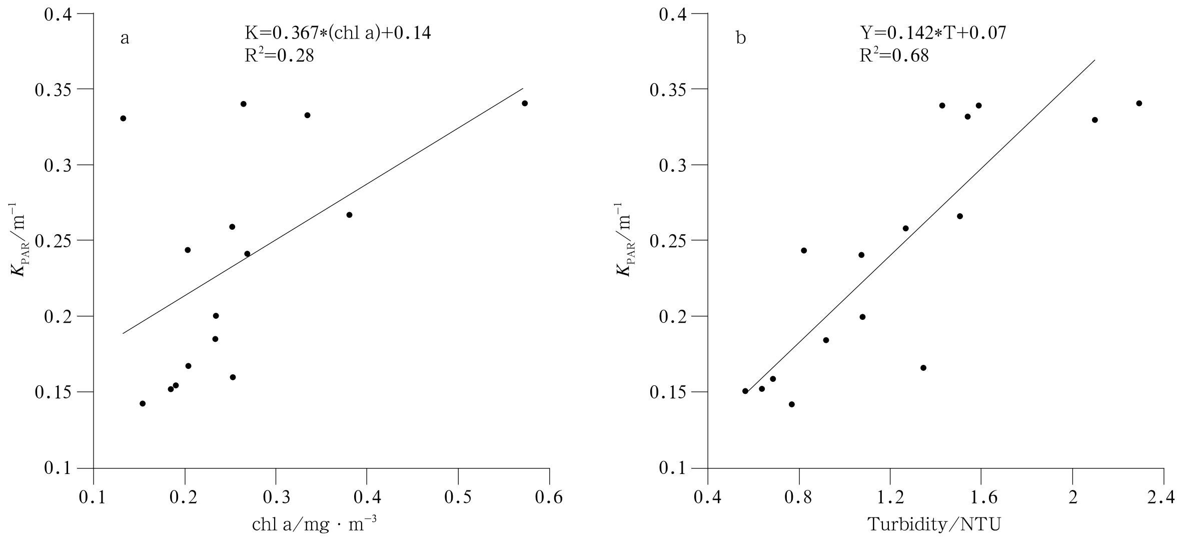

Fig.7. The linear relationship (a) between $K_{\rm PAR}$ and chl-a (mg·m^{-3}) and (b) between $K_{\rm PAR}$ and turbidity (NTU).

The two correlation coefficients R^2 were both higher than that in equation (6), which implied that it is more precise to divide the Huanghai sea according to the turbidity profiles in the water column.

Usually, phytoplankton is also an important factor affecting light attenuation. In Fig. 7, however, there is no apparent correlation between K_{PAR} and chl a, indicating that phytoplankton was not the major factor affecting light attenuation during our cruise period.

To consider the contribution of both chl a and turbidity to light attenuation with one equation, we conducted a multiple regression of K_{PAR} with chl a and turbidity. The depth-averaged K_{PAR} is expressed as,

$$K_{\mathrm{PAR}} = K_{\mathrm{w}} + Kc_{\mathrm{chl\ a}} \times [C_{\mathrm{chl\ a}}] + K_{\mathrm{t}} \times T \qquad (9)$$

where K_{w} is the attenuation part due to water plus CDOM. Based on all the measurements of our survey, the regression of depth-averaged K_{PAR} against depth-averaged chlorophyll a and depth-averaged turbidity yields (with a credible degree of 95%),

$$K_{\mathrm{PAR}} = 0.03 + 0.13C_{\mathrm{chl\ a}}[C_{\mathrm{chl\ a}}] + 0.23T$$
$$R^2 = 0.89 \qquad (10)$$

Where chl a and T have the units of mg·m^{-3} and NTU, respectively.

According to equation (10), the specific coefficient of turbidity is much larger than that of chlorophyll a, suggesting a possibility that the light attenuation effect of SPM is more important than that of phytoplankton in the Huanghai Sea. To examine this possibility, we substituted depth-averaged turbidity and depth-averaged chl a observed at all the stations into equation (10). The ratio of K_{PAR} due to chl a is among 0.05-0.21 while the ratio of K_{PAR} due to turbidity is 0.62-0.86 (Fig. 8). Clearly, the attenuation of light was influenced more by SPM than by chlorophyll a.

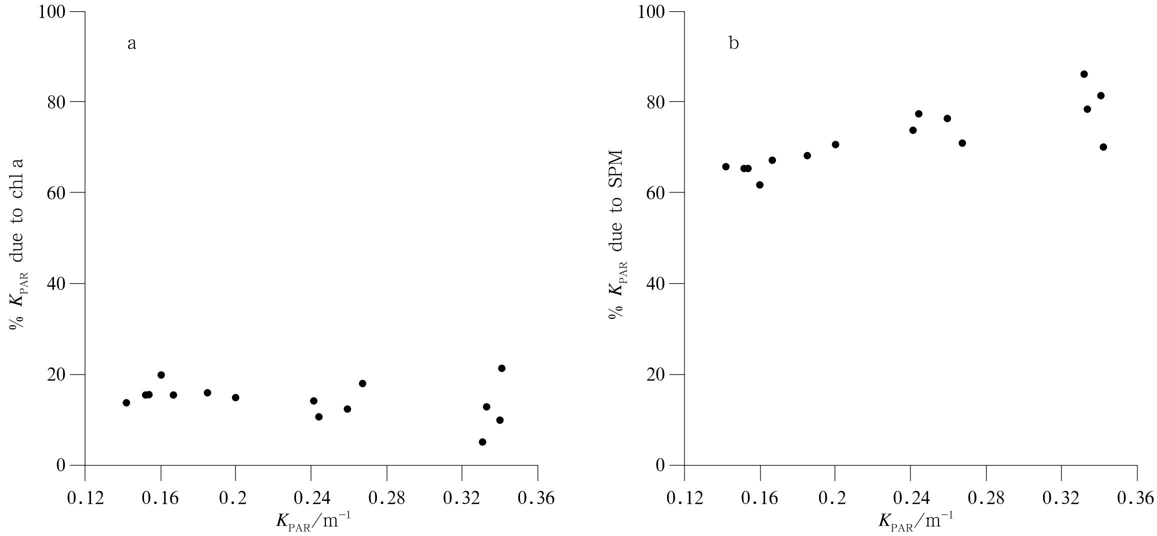

Fig.8. The relative contributions of chlorophyll a (a) and turbidity (b) to K_{PAR}.

In order to further verify equation (10), we applied it to the data in the Huanghai Sea from another cruise in spring, the third cruise of China SOLAS from 17 to 30 on April 2006 (Table 3). The survey was

Table 3. Diffuse attenuation coefficients K_{OPAR} and K_{TPAR} at 10 stations in the Huanghai Sea, computed by the observed data and equation (10), respectively. The Turbidity and chl a data were obtained from the third cruise of China SOLAS from 17 to 30 April 2006.

Station	chl a (mg·m^{-3})	Turbidity (NTU)	K_{OPAR} (m^{-1})	K_{TPAR} (m^{-1})	Δ
A1	1.181	0.789	0.341	0.359	0.053
A2	0.318	0.913	0.285	0.278	0.025
G10	0.438	0.531	0.214	0.206	0.037
G25	0.515	0.93	0.271	0.306	0.129
G26	0.604	0.499	0.25	0.219	0.124
G27	0.375	1.346	0.375	0.383	0.021
G28	0.689	0.281	0.221	0.181	0.181
G34	0.251	0.835	0.289	0.251	0.131
G37	0.256	1.289	0.333	0.355	0.066
G40	0.304	0.651	0.253	0.216	0.146

carried out in an area from 121°E to 124°E and 32.5°N to 39°N and observations were conducted at 45 stations (locations were not shown here). At all the stations, CTD measurements were similarly performed with those in the first cruise, including conductivity, temperature, pressure, downwelling planar irradance, chlorophyll a concentration and turbidity. The relative error Δ is calculated by equation (11), in which $K_{\rm OPAR}$ denotes the values calculated from observed PAR data on April 2006 and $K_{\rm TPAR}$ calculated by equation (10) with the simultaneously observed data of turbidity and chl a.

$$\Delta = |K_{\rm OPAR} - K_{\rm TPAR}|/K_{\rm OPAR} \qquad (11)$$

As shown in Table 3, the value of Δ was within 20% at most stations. Therefore, we conclude that equation (10) is able to estimate reasonably the vertical attenuation of irradiance in the turbid Huanghai Sea, at least works well for spring.

4 Summary and conclusion

Up to now, $K_{\rm PAR}$ used in many marine ecosystem models is usually expressed as a linear function of the concentration of chlorophyll a (Megard et al., 1980; Morel, 1988; Radach et al., 1993) or phytoplankton biomass and detritus (Mcgillicuddy, 1995; Wong et al., 1995). Varela et al. (1992) has proposed an equation of $K_{\rm PAR}$ for a study of deep-chlorophyll maximum and suggested that the extinction of light is not only affected by pure water and chlorophyll a but also by other factors that could be related to the chlorophyll a or other particles, but still not explicitly include the effects of SPM. In most Chinese coastal waters such as the Bohai Sea, Huanghai Sea and East China Sea, in addition to the large amount of terrestrial input of sediments from Yellow River and Changjiang, the resuspension of sediments due to strong tidal currents and strong winds in shallow shelf also maintain the high concentrations of SPM. However, SPM concentration is not easily measured by normal marine observational instruments, turbidity is though to be a reasonable alternate parameter which can be easily obtained by multi functional CTD or water quality monitor, and it also has good correlation with SPM in coastal waters (Jones and Wills, 1965; Su et al., 2001).

Based on the observations in early spring in the Huanghai Sea, we presented a function for the attenuation of PAR by turbidity and chl a. The results suggested that SPM affects more on light attenuation than phytoplankton. The direct cause for this conclusion is that the concentration of suspended particles is high during the observations. Since our equation has been verified by independent data from another cruise in the Huanghai Sea, the conclusion that SPM plays an important role in light attenuation in spring looks reasonable. An extension of this conclusion is that any ecosystem model for the Huanghai Sea needs to consider the influence of SPM on light attenuation.

Like any studies based on field measurements, the data used in this study was unavoidably limited in terms of time and space. For example, our stations are biased to Chinese side of the Huanghai Sea and it could be therefore to obtain a little different result for the Korea side of the Huanghai Sea. In addition, the turbidity and chl a in the Huanghai Sea vary significantly from season to season (Qin et al., 1989; Sun et al., 2000). Finally, $K_{\rm PAR}$ has a close relation with the solar zenith angle (Gordon, 1989; Kirk, 1991) that we did not consider. All of these factors suggest the necessity of further efforts to parameterize the relation of $K_{\rm PAR}$ with turbidity, chl a and other water properties in the turbid Huanghai Sea.

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