Variations in the downwelling diffuse attenuation coefficients in the northern South China Sea

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ABSTRACT The diffuse attenuation coefficient for downwelling irradiance ($K_d(\lambda)$) is an important parameter for ocean studies. Based on the optical profile data measured during three cruises in the northern South China Sea in autumn from 2003 to 2005, variations in the $K_d(\lambda)$ spectra were analyzed. The variability of $K_d(\lambda)$ shows much distinct features both in magnitude and spectra shape. The $K_d(\lambda)$ value are much higher in costal waters than that of open oceanic waters and the blue-to-green(443/555) ratios of $K_d(\lambda)$ tends to increases with the chlorophyll a concentration ([Chl a]) from open ocean to coastal waters. These characteristics can be explained primarily by the increasing of $a_{w+p}(443)/a_{w+p}(555)$ with [Chl a]. In the short waveband, the relation between $K_d(\lambda)-K_w(\lambda)$ and [Chl a] can be well described by a power law function, suggesting the large contribution of phytoplankton to the variations in $K_d(\lambda)$. As for the spectral model of the diffuse attenuation coefficient, there are good linear relationships between $K_d(490)$ and $K_d(\lambda)$ at other wavelengths, with the slope parameter and the intercept following linear functions within the spectral range 412~555 nm. These variabilities of $K_d(\lambda)$ provided much useful information for us to study the bio-optical properties in the northern South China Sea.

Key words The northern South China Sea, The downwelling diffuse attenuation coefficient, Cholorophyll a, Bio-optical model

1. Introduction

In ocean color remote sensing, the commonly used quantity is the vertically averaged value of diffuse attenuation coefficient in the surface mixed layer. The estimation of $K_d(\lambda)$ from ocean color remote sensing is a practical and useful way for us to study the ocean optical properties of the world ocean on large spatial and temporal scales. During the past decades, several empirical methods and semi-analytical algorithms have been built up to derive the $K_d(\lambda)$ from ocean color remote sensing data. For CZCS ocean color data, Austin and Petzold (1986; 1990) estimated $K_d(490)$ from the empirical algorithm based on the relationship between $K_d(490)$ and the blue-to-green ratio of the water leaving radiance ($L_W(443)/L_W(550)$), and the derived $K_d(490)$ can be further used to estimate the $K_d(\lambda)$ at other wavelengths based on the relationship between $K_d(490)$ and $K_d(\lambda)$; also Mueller et al (1997; 2000) built similar empirical algorithms for SeaWiFS satellite data using the ratio bands of 490 and 555nm. Another kind of empirical algorithms relies on the relationship between $K_d(\lambda)$ and [Chl a] for the open oceanic waters, since [Chl a] can be estimated from an empirical algorithm (O'Reilly et al., 1998) based on the blue-to-green ratio of remote sensing reflectance, the $K_d(\lambda)$ value could be derived from these bio-optical models. In recent years, Lee et al (2002; 2005a; 2005b) presented the semi-analytical model based on the numerical simulations of radiative transfer in the seawater to calculate $K_d(\lambda)$ from $R_{rs}(\lambda)$, this method derived the absorption and backscattering coefficient from $R_{rs}(\lambda)$ firstly using a quasi-analytical model, and then these two coefficients were input into a semi-analytical model to estimate the $K_d(\lambda)$ value. Lee et al (2005b) pointed out that the standard empirical method could produce satisfactory estimation of $K_d(\lambda)$ in oceanic waters where the attenuation was relatively low but resulted significant errors in coastal waters, while their own semi-analytical algorithm has no such limitations. The error of empirical methods used in coastal waters may come from the range of the data sets.

So far, some researchers have made great efforts on the study of the diffuse attenuation coefficient variations and the vertical distributions in the sea around Nansha Island (Zhong et al., 1982; Zhang et al., 2003). Based on the data collected from 3 cruises between 2003 and 2005, the main goal of the present paper is to study the variations of $K_d(\lambda)$ for different areas in the northern South China Sea.

2. Data and Methods

Optical measurements were made during the daytime within the photic zone in close time and space to water samples collected with the Niskin bottles. We used a freefall spectroradiometer (Satlantic, Inc.) to measure vertical profiles of the downwelling spectral irradiance $E_d(z,\lambda)$ and upwelling spectral radiance $L_u(z,\lambda)$ at 7 wavebands (412, 443, 490, 520, 555, 620, 683 nm) away from the ship shadow, and the surface incident spectral irradiance $E_s(0,\lambda)$ was recorded simultaneously. The data with the profiler tilt <5°for Case I waters and <7°for Case II waters are considered acceptable. Before the calculation, we have to make depth correction and data smoothing. Then according to the data process described in the SeaWiFS ocean optical protocols (Mueller et al., 2002), the vertically averaged diffuse attenuation coefficient for downwelling irradiance ($K_d(\lambda)$) in the surface mixed layer can be calculated. Details of the data process can be found in the previous paper (Tang et al, 1998).

3. Results and Discussion

3.1 Spatial variations of the diffuse attenuation coefficient

The diffuse attenuation spectra for downwelling irradiance ($K_d(\lambda)$) of CWGD and NSCS cruise were shown in Figure 2a. We can find that there are some distinct differences between the coastal and open oceanic waters. Take the $K_d(490)$ as an example, for CWGD cruises it lies between 0.222 and 0.852 m^{-1} with the averaged value being 0.484 m^{-1}; while for the NSCS cruise waters, $K_d(490)$ ranges from 0.034 to 0.193 m^{-1} averaged only about 0.073 m^{-1}, of which most samples are less than 0.092 m^{-1} except two coastal stations. We can clearly see that in coastal waters $K_d(\lambda)$ is much higher than that of open oceanic waters. According to the Jerlov's (1976) classification of water types, most of the stations in NSCS can be classified as oceanic water type IA and type Ⅱ, while the other two nearshore stations with $K_d(490)$ being higher than 0.190 m^{-1} and the CWGD waters are typically the coastal waters. Except for the magnitude, $K_d(\lambda)$ also varies in the spectra shape. For CWGD waters, in the spectral range 412 to 555 nm $K_d(\lambda)$ tends to decrease with the wavelength, while in the spectral range 555~700 nm it tends to increase with the wavelength. For NSCS waters, $K_d(\lambda)$ doesn't have much variations between 412~555 nm, and from 555 to 700 nm it has the similar trends with that of CWGD waters, so that the wavelength 555 nm could be taken as a key turning point.

So we used the blue-to-green ratio (443/555) of $K_d(\lambda)$ to describe these spectral variabilities from coastal to open oceanic waters. In CWGD waters, $K_d(443)/K_d(555)$ lies between 1.348~2.188 and the mean value is about 1.732, which is much higher than that of NSCS waters (0.370-1.474). With the increasing of [Chl a] from open ocean to coastal waters, the $K_d(443)/K_d(555)$ also tends to increase, and the relationship fits a power law function well with the determination coefficient being up to 0.93(Figure 2b).

According to the Gordon's (1989) study, $K_d(\lambda)$ is primarily dependent on the absorption coefficient of the sea water and the light field distribution. As a result, we concluded that the variability of blue-to-green ratio of $K_d(\lambda)$ could be explained primarily by the absorption coefficient (Stramska et al., 2003). Based on the in situ measurement of total suspended particles absorption coefficient, we illustrated the impact of the absorption by pure seawater plus particles (a_{p+w}) or plus phytoplankton (a_{ph+w}). As illustrated in Figure 2c, the blue-to-green ratio (443/555) of a_{p+w} and a_{ph+w} vary gradually with [Chl a], and there are good power law functions between a_{p+w}/a_{ph+w} and [Chl a]. Then we could find the linear relationship between $a_{p+w}(443)/a_{p+w}(555)$ and $K_d(443)/K_d(555)$ (figure 2d), and this suggests that the blue-to-green absorption ratio is an important factor driving the increase of the blue-to-green diffuse attenuation ratio with [Chl a]. The $K_d(443)/K_d(555)$ value is a little higher than $a_{p+w}(443)/a_{p+w}(555)$ which illustrates the spectral variability of yellow substances absorption and the backscattering coefficient of seawater (Stramska et al., 2003). There are similar linear relationship between $K_d(443)/K_d(555)$ and $a_{ph+w}(443)/a_{ph+w}(555)$, and for higher values of $K_d(443)/K_d(555)$ in coastal waters the deviation tends to be larger, which shows that the absorption by non-algal particles also contributes a lot to the variability.

From the above analysis, we can conclude that the variability of the blue-to-green absorption ratio by pure seawater plus particles is an important factor driving the increase of $K_d(443)/K_d(555)$ with [Chl a]. In open oceanic waters, the absorption by phytoplankton and pure seawater contribute a lot to the variations of diffuse attenuation coefficient, while for coastal waters the absorption by non-algal particles also has much contributions.

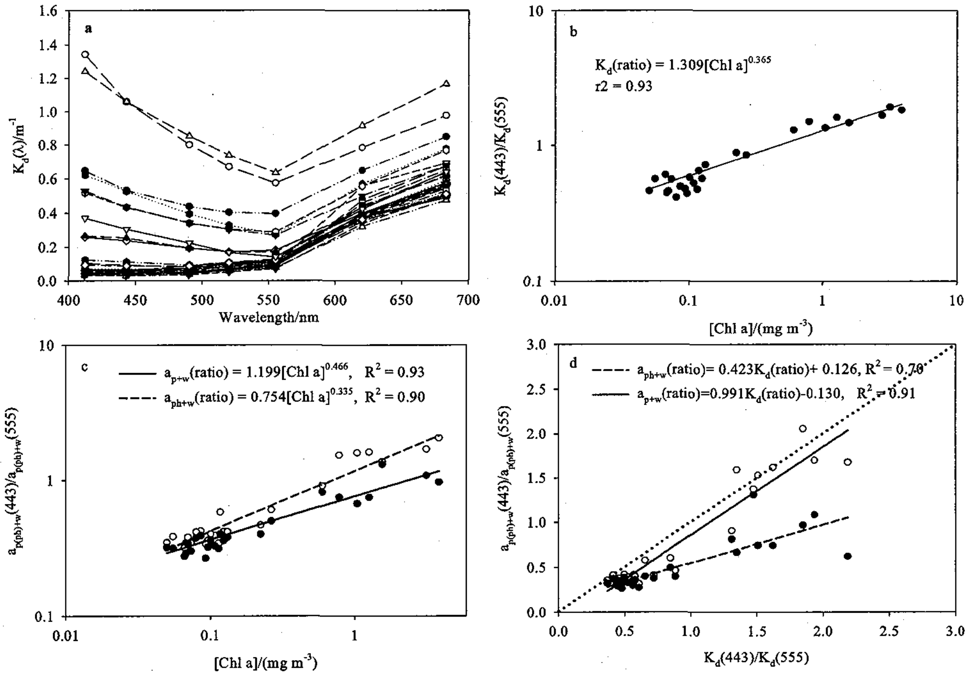

Figure 1: (a) The diffuse attenuation coefficient spectrum in CWGD and NSCS cruises; (b) the diffuse attenuation coefficient ratio $K_d(443)/K_d(555)$ as a function of [Chl a]; (c) Absorption ratio by pure seawater plus particles ($a_{p+w}(443)/a_{p+w}(555)$)and plus phytoplankton ($a_{ph+w}(443)/a_{ph+w}(555)$) as functions of [Chl a]; (d) $K_d(443)/K_d(555)$ versus $a_{p+w}(443)/a_{p+w}(555)$ and $a_{ph+w}(443)/a_{ph+w}(555)$, the dotted line represents y=x.

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References

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