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Daily Spectral Ocean Surface Albedo due to Small Chlorophyll Concentrations and Cloudy Conditions for 440 nm Wavelength in Coastal Waters

(Permukaan Lautan Spektrum Harian Albedo disebabkan oleh Kepekatan Klorofil Kecil dan Keadaan Mendung untuk Panjang Gelombang 440 nm di Perairan Pantai)

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ABSTRACT

The spectral daily Ocean Surface Albedo (OSA) is a sensitive parameter dependent on sea surface bio-optical properties and solar radiation distribution due to the transmissivity of the atmosphere. We analyzed the OSA sensitivity to the small concentrations of sea surface phytoplankton due to cloudy conditions, based on measured half-hourly global radiation data, and phytoplankton variability represented by chlorophyll-a concentrations at the upper layers over the Malacca Strait. The influence of the sea surface phytoplankton was examined by using the chlorophyll-a maximum absorption wavelength (440 nm) for a detailed examination of the real phytoplankton impact presented by small concentrations (0.39 - 0.69 mg/m^3). The atmosphere transmittance determination was made over the period from January 2016 to March 2016 and January 2017 to March 2017 using hourly clearness index (K_{Th}) estimation. The aim of current study was to examine the influence of sea surface phytoplankton concentrations on the radiation budget and to account the role that the phytoplankton plays in detail short-scale OSA parameterization. Daily timescale spectral OSA includes the bio-optical modelling part, which allowed us to investigate the patterns of diurnal variability of the main reflectance parameters, using Jin et al. scheme for albedo components (direct and diffuse) estimation, was computed. The OSA variability analysis confirmed the bio-optical feedback presented by apparent properties of the coastal waters for the observed conditions. The proposed calculation scheme accounted for the sea surface optical behavior with low concentrations of chlorophyll-a and suggests that albedo variability depends not only on the angle factors, even with the low phytoplankton influence (less than 1 mg/m^3). It was found that the phytoplankton pigment absorption properties have less effect in albedo parameterization while the chlorophyll-a concentrations are less than 0.5 mg/m^3.

Keywords: Clearness index; ocean surface albedo; ocean upper-layers; photosynthetically active radiation; phytoplankton influence

ABSTRAK

Spektral harian Albedo Permukaan Lautan (OSA) adalah suatu parameter sensitif yang bergantung kepada ciri bio-optik lautan dan taburan radiasi solar radiasi berdasarkan ketransmisian atmosfera. Kajian ini menganalisis kesensitifan OSA terhadap kepekatan rendah fitoplankton permukaan lautan keadaan awan berdasarkan data cerapan radiasi global setengah-jam dan juga keragaman fitoplankton yang diwakili oleh kepekatan klorofil-a lapisan atas permukaan Laut China Selatan. Pengaruh fitoplankton permukaan lautan adalah dikaji berasaskan panjang gelombang serapan maksimum (40 nm) untuk mendapatkan gambaran jelas impak sebenar fitoplankton kepekatan rendah (0.39 - 0.69 mg/m^3). Penentu transmisi atmosfera dihasilkan dalam tempoh Januari 2016 ke Mac 2016 dan juga dari Januari 2017 ke Mac 2017 dengan menggunakan jangkaan indeks kecerahan (K_{Th}) berjam. Tujuan kajian ini adalah untuk mengkaji pengaruh fitoplakton permukaan laut ke atas bajet radiasi serta menentukan peranan fitoplankton dalam pemparameteran OSA skala pendek. Spektral OSA berskala harian dihitung termasuk bahagian permodelan bio-optik yang membolehkan kajian corak keragaman diurnal parameter pantulan utama menggunakan skema Jin et al. untuk komponen albedo (langsung dan sebaran). Analisis keragaman OSA mengesahkan bahawa suap-balik bio-optik wujud bagi ciri perairan persisiran keadaan cerapan. Skema pengiraan yang dicadangkan ini mengambi kira ciri optik permukaan laut dengan kepekatan klrofil-a rendah dan mencadangkan bahawa perubahan albedo bukan sahaja bergantung kepada faktor sudut walaupun dengan pengaruh rendah fitoplankton (kurang daripada 1 mg/m^3). Didapati ciri serapan pigmen fitoplankton mempunyai kesan kecil terhadap pemparameteran albedo apabila kepekatan klorofil-a adalah rendah daripada 0.5 mg/m^3.

Kata kunci: Albedo permukaan laut; indeks kecerahan; lapisan atas lautan; pengaruh fitoplankton; radiasi aktif fotosintesis

Introduction

The ocean surface optical properties are affected by many factors. Most of these factors are related to sunlight propagation within different sky condition, ocean surface's reflectance ability and specific bio-optical impact. The bandwidth ranges of Photosynthetically Active Radiation (PAR) not widely used for examination of daily scale Ocean Surface Albedo (OSA) variability with chlorophyll-a concentrations and daily clearness index changes (K_T) in the current statement (Okogbue et al. 2009; Santos, Pinazo & Canada 2003; Somayajula et al. 2018). However, the variability of phytoplankton may change the diffuse component of reflectance, from 0.005 to 0.1, just below the surface (Patara et al. 2012; Tetsuichi et al. 2002; Ye et al. 2017). The changes in phytoplankton biomass result in the variability of the ocean biological and bio-chemical processes (Yoder & Kennelly 2003). However, the phytoplankton organisms as a basic marine ecosystem component have some key characteristics that cause the biological radiative heating (Patara et al. 2012) within the Earth's climate system. Moreover, the indirect influence of the phytoplankton on the radiative heating in the near-surface ocean may cause the rise in sea surface temperature by overall ~0.5 °C. Since the bio-optical modelling development in radiation studies included the spectral dependencies of the phytoplankton effect presented by chlorophyll-a absorption and backscattering properties (Bricaud et al. 2004; Frouin & Iacobellis 2002; Gordon 1987; Jin et al. 2011, 2004; Loisel & Morel 1998; Morel 1988; Morel & Maritorena 2001; Morel & Prieur 1977; Pope & Fry 1997; Smith & Baker 1981), the daily time scale studies allowed examining the sensitivity of the corresponding parameters. Therefore, most of the previous studies confirmed the decrease of the outgoing radiative flux globally and annually (Golovchenko et al. 2020; Seferian et al. 2018) forced by phytoplankton effect in high-latitude regions (Jin et al. 2011; Seferian et al. 2018). Hedges and Keil (1995) stated that coastal waters are characterized by large variations of properties related to biological, physical and chemical specific properties, the highly productive coastal waters characterized by a significant fraction of organic matter produced in surface waters, that reach the bottom sediments of coastal margins and usually become buried. Oceanic water usually divided into Case 1 and Case 2 waters (Morel & Prieur 1977). Coastal and inland waters usually referred to as Case 2 waters, characterized by additional seawater constituents such as suspended sediments, and dissolved organic matter (Sathyendranath 2000). Therefore, the phytoplankton in the upper-layers of the ocean has a potential impact on the optical properties.

The major part of solar radiation entering the upper-layers of the ocean, which interacts with marine biological light-sensitive materials like phytoplankton (Seferian et al. 2018). The variations in optical properties associated to biological pigments may affect the transparency at sea surface. Moreover, studies in the equatorial Pacific recorded the increase in the heat trapped in the upper ocean of the order of 10 Wm^{-2}, as a result of increase in chlorophyll-a concentrations (Lewis et al. 1990).

Light absorption by particulate material, including phytoplankton, plays a significant role in light attenuation primary production and remote sensing of pigment biomass in mixed ocean layer heating (Sosik & Mitchell 1991). In a biological oceanographic study, Siegel et al. (1995) attempted to quantify the biophysical effect related to the phytoplankton pigments absorption properties in the equatorial Pacific Ocean. The phytoplankton blooms reduced the penetrative heat flux by 5.6 Wm^{-2} at 30 m depth and presented the increasing effect of the heating rate of the mixed layer by 0.13 °C per month. These observations showed the significant role of biogeochemical processes on thermal climate. Moreover, most studies that are related to the modeling of climate change have started taking into consideration the absorption and backscattering properties of phytoplankton particles (Carruthers et al. 2001; Ohlmann et al. 2000; Sanusi et al. 2015).

The high variability of the reflectance components of the upper layers of the coastal waters needs the daily examination of the phytoplankton concentrations (Gupta et al. 1999; Tan et al. 2005). The ocean surface albedo includes the complex calculations related to the spectral distribution of the reflectance properties driven by the sea surface phytoplankton coverage. Moreover, the spectral distribution of the OSA also varies with direct and diffuse components (Angstrom 1924; Ideriah & Suleman 1989). The irradiance reflectance (R_0) and the spectral attenuation coefficient (K_d) for downward irradiance, commonly used in ocean color algorithms, depend on spectral variability of bio-optical properties (Bricaud et al. 2004; Morel & Maritorena 2001).

The data used for this daily timescale variability parameterization study is the *in situ* measurements taken from an observational pier located on the island of Pulau Pinang (5°26′53″ N, 100°11′36″ E). Thus, the sky conditions should include the sky conditions parameterization in case of the transparency of the atmosphere to examine the cloud influence. In terms of knowledge of the global solar radiation, the clearness index (K_T) is a measure of solar radiation attenuation, which includes effects due to clouds and radiation interaction with other atmospheric constituent parts. Moreover, the clearness index is a widely used parameter for solar radiation studies and depends on global solar radiation surface measurements (Maleki et al. 2017). In the current study, the determination of the hourly clearness index (K_{Th}) used to define the cloudy periods ($K_{Th} \leq 0.4$) over the study area for further calculations.

To examine the real influence of the phytoplankton on sea surface reflectance properties due to cloudy conditions, we estimated the solar radiation in PAR range, using clearness index, for the detailed analysis of the maximum absorption wavelength (440 nm). Since the clearness index affected the OSA parameterization, the sky conditions included the global radiation (PAR fractions) parameterization in case of the transparency of the atmosphere to examine the cloud influence. In the context of the global solar radiation, the clearness index (K_T) is a measure of solar radiation attenuation, which includes the effect due to clouds and radiation interaction with other atmospheric constituents. Moreover, the clearness index is a widely used parameter for solar radiation studies and depends on global solar radiation surface measurements. Compared to wind speed (presented here as a roughness parameterization), the clearness index influences the solar radiation distribution and indicates the atmospheric transparency. The wavelength 440 nm was chosen to evaluate the effectiveness of the proposed examination. Photosynthetically active radiation (PAR) has wavelengths of 400-700 nm, is part of the light spectrum used by plants for photosynthesis (Santos, Pinazo & Canada 2003; Somayajula et al. 2018) and widely used in land surface analysis and marine ecosystem productivity monitoring. Furthermore, we chose the marine biological pigment influence parameterization, which is defined by its chlorophyll-a content and the function of seawater and biological pigment backscattering (β (η, μ)), stated by Morel and Maritorena (2001). On daily timescales, solar radiation absorbed into the ocean surface layers affects the stability of the ocean mixed layer (Gordon 1987). Therefore, the daily timescale analysis of the solar radiation fluxes (Qs) absorbed in the coastal area upper layers water represents the sea surface absorption ability within the phytoplankton impact in the sea surface due to cloudy conditions. Therefore, we also focus on the changes in the surface reflectance due to phytoplankton to analyze the importance of even small concentrations (0.1 - 1.1 mg/m^3) at a coastal area.

OSA determines the reflectance components dependent on the variability of the optical properties related to atmosphere - ocean interactions. Analytical scheme optimization for short-scale OSA variability incorporates the solar radiation attenuation and atmospheric transparency (K_T) as an additional significant mechanism in the current research. Clearness index affects albedo parameterization in combination with other reflectance properties such as spectral and angular dependencies, backscattering and absorptions coefficients, refractive index and diffuse fractions. The proposed OSA scheme emphasizes the phytoplankton influence even within low atmospheric transparency (cloudy conditions) and low chlorophyll-a concentrations.

Materials and Methods

In this section, we described the datasets and OSA calculation properties that were used for the parameterization in the present study. The hourly dataset of global radiation data was used for the experiment validation and cloudy period detection. The detailed methodology of OSA parameters is well described by Golovchenko et al. (2020) in a previous study related to daily OSA variability in the Strait of Malacca. Here, the Albedo's dependence on clearness index (K_T) was examined based on measured global radiation data and phytoplankton variability influence represented by chlorophyll-a concentration at the upper layers over the Malacca Strait. Half-hourly global solar radiation (at 5◦26′ 53″ N, 100◦11′ 36″ E) measurement over the period from January to October 2017 was analyzed to investigate the correlation between clearness index and ocean surface albedo (OSA) in case of phytoplankton influence in Malacca Strait coastal waters. Parameterization of OSA study (Golovchenko et al. 2020) includes the solar zenith angle (SZA), ocean roughness (wind speed), wavelength, chlorophyll-specific coefficients (absorption and backscattering) and some other radiative parameters that allow us to include detail processes in every step of the calculation. Overall, the datasets involved in current study is summarized in Table 1.

TABLE 1. Data and sources used in the presented work

Data	Source
Solar radiation: Global Radiation (RG), Net Radiation (RN),	Obtained from natural observations
Clearness index (K_T)	Calculated
Photosynthetically Active Radiation (PAR_H)	Obtained from natural observations
Photosynthetically Active Radiation (PAR)	Calculated from PAR_H
Chlorophyll-a concentration (C)	Obtained from The Ocean Colour Climate Change Initiative project (ESA OC-CCI) (Sathyendranath et al. 2021) for monthly-mean chlorophyll-a concentration in seawater.
Solar radiation fraction	Calculated
Bio-optical properties (absorption and backscattering)	Modeled
Ocean Surface Albedo (OSA)	Modeled
Absorbed solar radiation fluxes (Q_s)	Calculated

GLOBAL RADIATION DATA

Global radiation measurements were made at the Muka Head station continuously using a pyranometer (LI-200R, LI-COR, USA) for the years 2016 and 2017. The LI-200R measures the global solar radiation – the combination of direct and diffuse solar radiation – in the 400 to 1100 nm range. The observation point was located in the Island of Pulau Pinang (5°26′53″ N, 100°11′36″ E) at the edge of a concrete pier (Figure 1). The system of sensors is called Biomet, which included a pyranometer (RG) (LI-200SL model, from LI-COR, Inc., USA; with an error of <5%), and a net radiometer (RN) (NR LITE 2 model, from Kipp & Zonen, Inc., USA; and sensitivity of about 13.6 μV W-1 m-2). The sensors were at positioned 4.1 m above the sea surface. A data logger recorded the data (9210b Xlite model, from Sutron Corporation, USA), at a sampling frequency of 1 min and averaged in 30-min blocks. The station's instruments and sensors were powered by a constant alternating -current power supply.

PARAMETERIZATION

The parameterization part of the current study includes the analysis of the two-year (2016 and 2017) global solar radiation data, cloudy conditions period determination and spectral OSA calculation with chlorophyll-a concentration (C) variability.

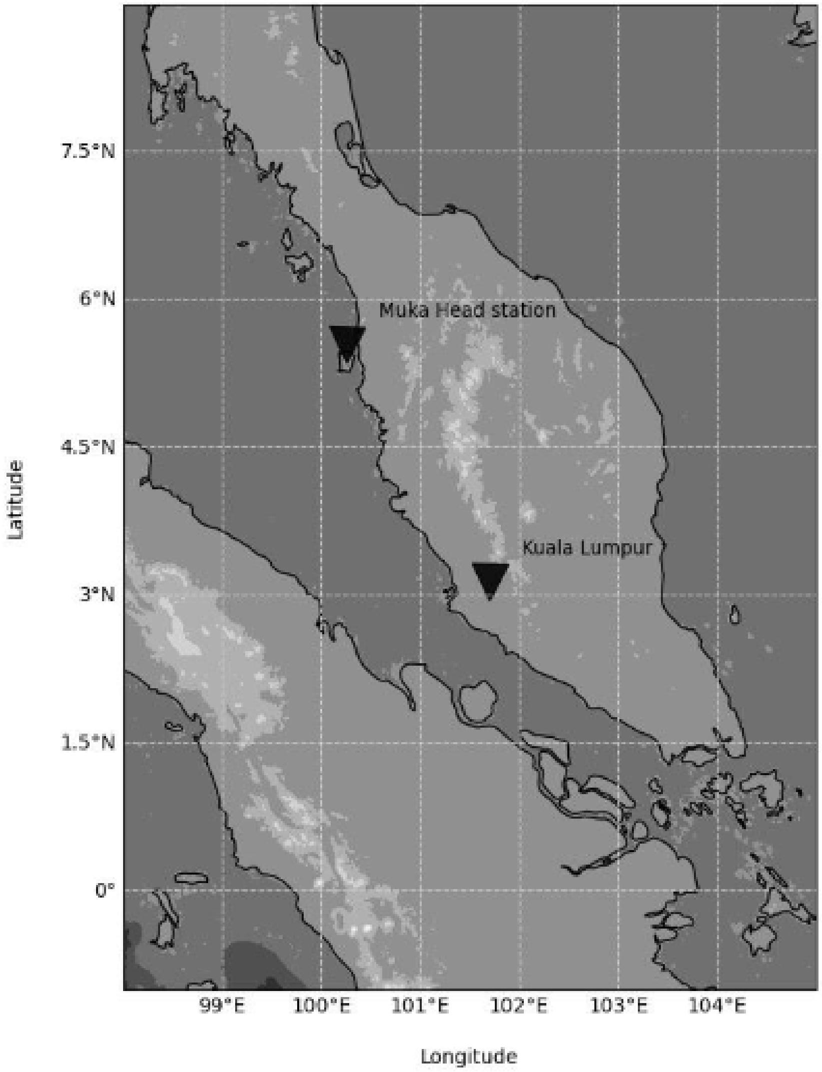

FIGURE 1. Observation point of study area (Muka Head station, Pulau Pinang, Malaysia)

Preliminaries and notations

Each year dataset (2016 and 2017) contains hourly values of the Global Radiation data for the daytime period from 8:00 to 19:00 to prevent the nighttime solar radiation data with $G_{RH} \approx 0$ W/m^2. For further calculations and detailed analysis, the dataset reduced to the time from 12:00 to 17:00 to avoid the solar angles (elevation and azimuth angles) confusion and the low Global radiation values, that usually attribute to the low solar elevation angle values, in case of overcast conditions. Those values obtained from continuous half-hourly data obtained at the Muka Head station.

The current parameterization includes the mean slope distribution (σ), which is defining the surface roughness and related to wind speed (w), the roughness parameter used instead of wind speed and stated by Jin et al. (2011):

$$\sigma^2 = 0.003 + 0.00512\, w \tag{1}$$

The solar elevation (ε_s) and azimuth angles (ϕ) were obtained from NOAA Solar Calculator to avoid the errors caused by wrong $\cos(\theta_s)$ determination in 1-hour step parameterization.

Seasonal SeaWIFS chlorophyll-a data variation over 5-year composite of monthly mean studies made by Tan et al. (2005) records a peak of concentration in the area of study from January to March around Penang to Langkawi Island. Chlorophyll concentrations (C) for the current study were derived from The Ocean Colour Climate Change Initiative project (ESA OC CCI) at the study area to include the real concentrations (Table 2). Moreover, the following maximum chlorophyll-a concentration months were used for further OSA estimation with the bio-optical part in the current experiment, January, February and March in 2016 and 2017. Considering the aim of the present parameterization, we decided to use the hourly clearness index (K_{Th}) to determine the dataset with cloudy sky conditions. For the current experiment, we assume that $K_{Th} \leq 0.4$ indicates the overcast circumstances for the observed area.

Photosynthetically Active Radiation is used because of its closest (visible) range to the absorption range of the chlorophyll pigments. The PAR/G_{RH} ratio estimations using clearness index (K_{Th}) were made by empirical model described below and included the verification with the real PAR measurements (PAR_H) for the area of observations.

TABLE 2. Data from The Ocean Colour Climate Change Initiative project (ESA OC CCI) for monthly-mean chlorophyll-a concentration in seawater (2016-2017) for Peninsular Malaysia and the Strait of Malacca

	Month	Dates	Chlorophyll-a concentration (mg/m^3)	$K_T \leq 0.4$
2016	January	02, 10, 11, 14, 15, 16, 17, 19, 22, 25-28, 31	0.59	0.25
	February	04 - 07, 09 – 11, 14, 25, 27	0.69	0.24
	March	08, 18, 22 – 24, 28 - 30	0.53	0.29
2017	January	01 – 09, 11, 13, 16, 19 -28, 31	0.39	0.24
	February	01 – 06, 10, 11, 19 – 23, 25, 27, 28	0.44	0.25
	March	01 – 02, 07, 09, 14, 16, 18, 20-21, 26 – 27, 29 - 31	0.44	0.18

Solar position angles

The albedo parameterization includes the solar geometry for better understanding of the solar irradiance distribution. Therefore, the solar angles and their properties vary from hour to hour being the driving force for the OSA estimation.

The declination angle (δ) varies every season (from -23.5 to 23.5 degrees) due to the Earth rotation around the sun and the Earth on its axis of rotation, presented by following equation:

$$\delta = -23.44 \cos(360 / (365 \times (d + 10))) ; \quad (2)$$

where d is the day of year (e.g., 21 January is 21). The hour angle (H) represents the angle between an observer's meridian and the hour circle, expressed in hours and minutes:

$$H = 15 \text{ (LST-12)} ; \quad (3)$$

where the local solar time (LST) presented as follows:

$$LST = LT + (TC / (60)) ; \quad (4)$$

LT is the local time in a place of observation and TC – the time correction factor

$$TC = 4 \times (\varphi - LSTM) + EoT ; \quad (5)$$

LSTM presents the local solar time meridian; EoT is the equation of time, widely used for the description of the discrepancy between two kinds of solar time:

$$LSTM = 15 \times TZ ; \quad (6)$$

$$EoT = 9.873 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B); \quad (7)$$

where TZ is the time zone (8 – for the region of the study) and B is the time special factor.

$$B = (360\ (d-81))\ /\ (365.) \quad (8)$$

The solar zenith angle θ_s) obtained from the solar elevation angle by (ε_s), $\theta_s = 90 - \varepsilon_s$.

Global radiation and clearness index

The clearness index (K_{Th}) estimation is used here as a major instrument to achieve the diffuse fraction of global radiation and overcast condition determination. Moreover, the clearness index defined as the ratio of the global solar radiation measured at the surface to the total solar radiation at the top of the atmosphere, it is also a veritable tool in the determination of sky conditions in case of atmosphere transmittance (Ideriah et al. 1989). In the current study, the Ångström model (1924) used to derive the clearness index from measured Global radiation for time (08:00 – 19:00) using one-hour time step:

$$K_{Th} = \frac{G_{RH}}{G_{ext\_H}}; \quad (9)$$

$$G_{on} = G_{SC}\left(\frac{1 + 0.333\cos(360d)}{365}\right); \quad (10)$$

$$G_{ext\_H} = G_{on}(\cos(\psi)\cos(\delta)\cos(HRA) + \sin(\psi)\sin(\delta)). \quad (11)$$

where G_{ext_H}) is the hourly extraterrestrial solar radiation; ψ is the latitude of the observation point; G_{on} is the exact incident irradiation on a surface; and = 1367 W/m^2 – Solar constant.

Diffuse fraction

Among the existing parameterizations (Maleki et al. 2017), the diffuse fraction of Global radiation (K_d) estimated using the Erbs model formulation (Erbs, Klein & Duffie 1982) with two different options for the specific

K_{Th} range:

for $K_{Th} \leq 0.22$:

$$K_d = 1\text{-}(0.0\ K_{Th}), \quad (12)$$

for $K_{Th} > 0.22$:

$$K_d = 1.317 - 3.023\ K_{Th} + 3.372\ K_{Th} - 1.769\ K_{Th}{}^3. \quad (13)$$

Photosynthetically active range (PAR) estimation

The photosynthetically active radiation (PAR) is defined as the wavelength band between 400 nm and 700 nm (visible solar radiation). The conversion factor PAR/G_r that varies with water vapor amount from 0.45 to 0.49, obtained statistically to achieve an accuracy in the relation between global radiation (G_r) and PAR for further estimation of the PAR amount (W/m^2). PAR as a component of global radiation and can be calculated using empirical modeling and special coefficients for the study area. However, most climate models assume an invariant value of PAR/ G_r ratio of 0.49 (Carruthers et al. 2001; Gupta et al. 1999; Maleki et al. 2017):

$$PAR = G_r\ (G_{PAR}) = G_r \times 0.49; \quad (14)$$

The reappraisal of hourly PAR/G_r estimation models allowed us to design the new empirical model. Therefore, for the current study, the empirical model for PAR/G_r estimation designed for Malacca Strait coastal area, to achieve the accuracy in PAR amount presentation. The relationship between global PAR and clearness index was estimated as a simple function, using the method proposed by Orgill and Hollands (1977) and tested by Tsubo and Walker (2004). This method includes averaged values of PAR/G_r for each K_T interval (Figure 2(A)) of 0.1 to estimate the accuracy for coefficients calculation in the quadratic equation. We used the dataset of hourly Global and PAR data (390 values) measured by Photosynthetically Active Radiation (PAR_H) sensor (LI-190R model, LI-COR, Inc., USA; sensitivity 5 µA to 10 µA per 1000 µmol s^{-1} m^{-2}) for the ratio calculation and plotted averaged PAR/G_r against the values of PAR/G_r for the mid-point interval (Figure 2(B)).

Hourly basis PAR/G_r ratios correlated for Malacca Strait showed the acceptable result, compared to Tsubo and Walker's scheme calculation (2004) for an hourly basis, where ratios difference reaches 0.2. The correlation for the current empirical model is moderate (Chaddock scale), r = 0.375 for PAR/G_r ratios. The proposed empirical model divided into three sky conditions:

1) cloudy ($0 \leq K_T \leq 0.25$):

$$\frac{PAR}{G_r} = 0.041\ K_{Th}^2 + 0.323\ K_{Th} + 0.445, \quad (15)$$

1) partial cloudy ($0.25 < K_T \leq 0.5$):

$$\frac{PAR}{G_r} = 0.041\,K_{Th}^2 + 0.140\,K_{Th} + 0.445, \qquad (16)$$

1) partial clear sky ($K_T > 0.5$):

$$\frac{PAR}{G_r} = 0.041\,K_{Th}^2 + 0.245K_{Th} + 0.323. \qquad (17)$$

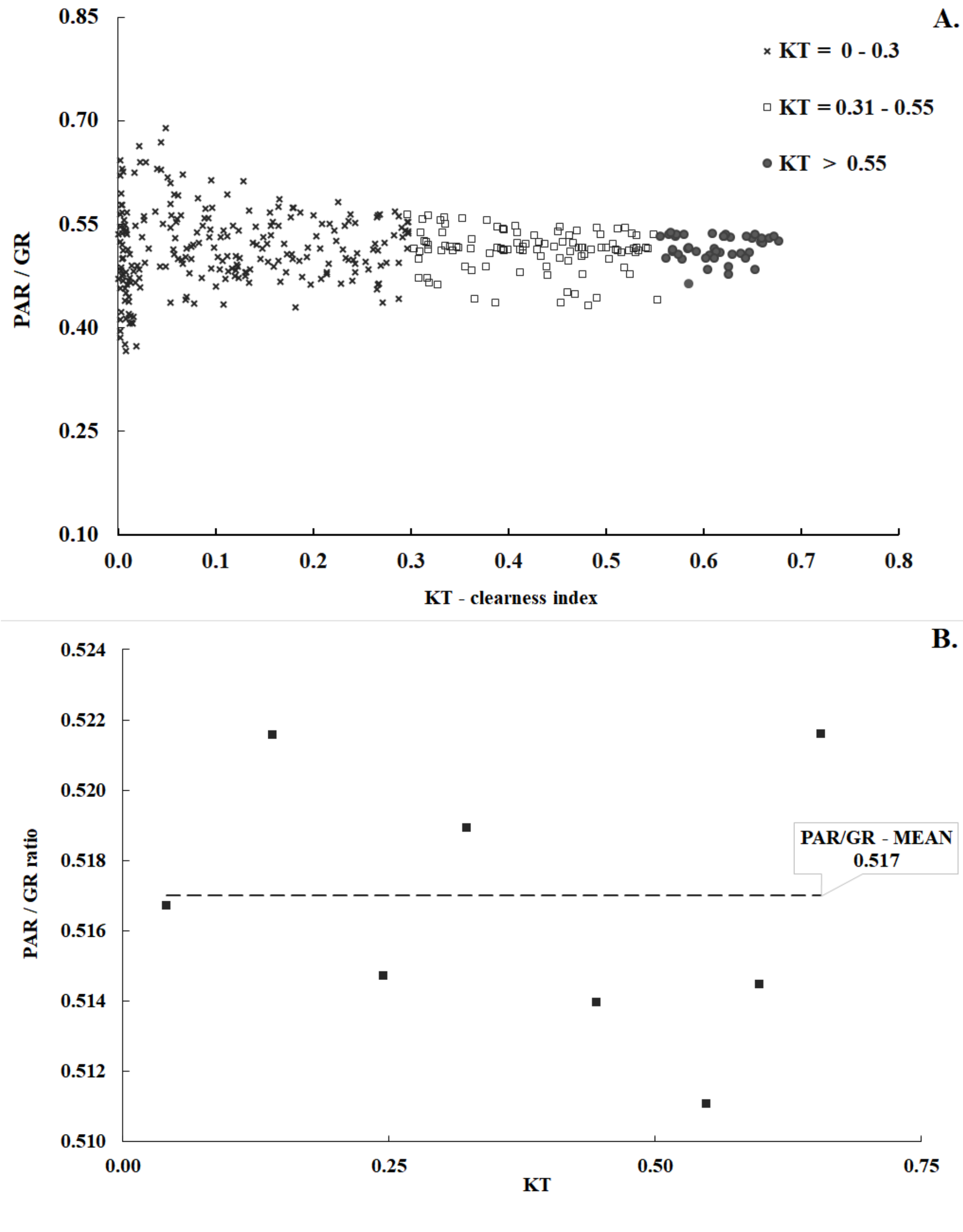

FIGURE 2. Relationship between the ratios of measured PAR to global solar radiation and clearness index. A – Distribution of the PAR/G_r ratio values in K_T ranges. B – Averaged values of PAR/G_r for each K_T interval of 0.1

Bio-optical part

The spectral optical properties related to the phytoplankton were widely studied by Morel and Maritorena (2001) in which these properties were statistically related to chlorophyll-a concentration and specified wavelength. All of the formulations are valuable for range 0.02 - 2 mg/m^3 of the chlorophyll-a concentrations (C). Bio-optical model for spectral absorption coefficient in Case 1 waters stated by Prieur and Sathyendranath (1981) and modified by Morel and Gentili (1991) accordingly to specific bio-optical coefficients is expressed as:

$$a(\lambda) = \left(a_w(\lambda) + 0.06\, a_{phy}(\lambda)\, [C]^{0.65}\right)\left(1 + 0.2\exp^{(-0.014(W-440))}\right); \tag{18}$$

$$a_{bp}(\lambda) = 0.06\, a(\lambda)\, [C]^{0.65} + 0.2(0.00635 + 0.06[C]^{0.65}\left(e^{(0.014\times(400-W)}\right). \tag{19}$$

where a (λ) and a_{bp} (λ) are absorption coefficients of seawater (m^{-1}) and chlorophyll-a biological pigment, respectively, C – phytoplankton concentration (mg/m^3), λ – is specific wavelength (nm). Considering the light absorbing properties of seawater phytoplankton, chlorophyll-specific absorption coefficient of phytoplankton (a_{phy}(λ)) included in the parameterization of contributions by pure-water (Morel 1988) can be written as:

$$a_{phy}(\lambda) = [C]a^*{}_{phy}(\lambda). \tag{20}$$

Previous studies using a wide range of observation data obtained from different regions showed that a^*_{phy} (λ) is not a constant and decreases rather regularly from oligotrophic to eutrophic waters. According to research made by Bricaud et al. (2004), the value of a^*_{phy} (λ) varies between 0.18 and 0.01 m^{2}mg^{-1} (the value a^*_{phy} (λ) = 0.18 is used in this study). Moreover, the absorption coefficient, a_w, for pure water represented by Pope and Fry (1997) as a function of wavelength. The backscattering (b_{bp}) coefficient expressed in terms of single biological variable, the phytoplankton pigment concentration (C) and modelled in accordance to the study of Morel and Maritorena (2001):

$$b_{bp} = 0.416[C]^{0.766}(0.002 + (1/100)(0.50 - 0.25(\log[C])\left(\frac{\lambda}{550}\right)^{(0.5(\log[C]-0.3)}. \tag{21}$$

The function of seawater and biological pigment backscattering (β (η, μ)) presented as

$$\beta\,(\eta,\mu) = 0.6270 - 0.2227\eta - 0.0513\eta^2 + (0.2465\eta - 0.3119)\mu\,. \tag{12}$$

The ratio of backscattering by water molecules to total backscattering, defines the apparent optical properties of seawater (η) and reflectance (R_0) represent the functions (Bricaud et al. 2004) that depend on the wavelength, cos (θ_s) and the chlorophyll-a concentration (C):

$$\eta = 0.5\, b_w/(0.5b_w + b_{bp}); \tag{23}$$

$$R_0(\lambda,\mu,\eta,C) = \beta\left(\frac{0.5b_w + b_{bp}}{a_w + a_{bp}}\right). \tag{24}$$

The backscattering coefficient, b_w, of seawater selected in accordance to the specific coefficient for 440 nm wavelength stated by Smith and Baker (1981) (Table 1).

Direct and diffused OSA components

The proposed OSA calculation scheme is divided into direct and diffuse albedo components according to Jin et al. (2004) statement. The direct OSA component presented by the surface reflection equals to Fresnel (R_f) reflectance (in case of flat surface condition, stated before) and expressed according to Haltrin, McBride III and Arnone (2001) as:

$$R_f = \frac{1}{2}\left[\left(\frac{\cos(SZA) - \sqrt{n_0^2 - \sin^2(SZA)}}{\cos(SZA) + \sqrt{n_0^2 - \sin^2(SZA)}}\right)^2 + \left(\frac{n_0^2\cos(SZA) - \sqrt{n_0^2 - \sin^2(SZA)}}{n_0^2\cos(SZA) + \sqrt{n_0^2 - \sin^2(SZA)}}\right)^2\right]; \tag{25}$$

In the current study, refractive index (n_0) of seawater is chosen to be 1.341.

Since Morel and Gentili (1991) expressed the water-to-water reflectance at the air-water interaction border for upwelling diffuse incidence from water below (r_w) as a function of surface roughness (Equation 26), following Jin et al. (2004), we assumed the roughness parameter σ = 0 and water-to-water reflectance can be written as follows:

$$r_w = 0.4817 - 0.0149\sigma - 0.207\sigma^2. \tag{26}$$

The OSA component (α_{Sdir}) applicable to the surface Fresnel reflection of the direct solar incidence presented as:

$$\alpha_{Sdir} = R_f \ . \qquad (27)$$

The ocean interior reflectance (R_f) for effective incidence direction (47.47 degrees) based on Morel and Gentili (1991). Consequently, the formulation of the diffuse water albedo (α_{Wdif}) component is expressed as direct water albedo (α_{Wdir}) with cos (θ_s) = 0.676 (Equation 29) in case of an effective angle of incoming radiation proposed by Morel and Gentili formulation and employed by Jin et al. (2004) in COART modeling study as:

$$\alpha_{Wdir}(\mu, W, C) = \frac{R_0(1 - r_w)(1 - \alpha_{Sdir})}{1 - r_w R_0}; \qquad (28)$$

$$\alpha_{Wdif}(\mu, W, C) = \alpha_{Wdir}(W, C, \mu = 0.676). \qquad (29)$$

Absorbed solar radiation fluxes

For better examination of the small chlorophyll-a in the bio-optical parameterization, we used the solar radiation fluxes absorbed by every square meter (Q_s) of the sea surface, proposed by Dera (1992). Dera stated the following formulation for the daytime estimation for the sea surface level (h = 0), in the 'small-scale air-sea interaction' research:

$$Q_s = E_q \downarrow (h = 0)[1 - \alpha]. \qquad (30)$$

In the current study, we used the estimated PAR spectrum data instead of E_q irradiance and albedo (α) calculated according to the scheme described previously.

Results and Discussion

In this section, we will characterize the results of spectral OSA parameterization for the cloudy period due to the chlorophyll-a concentration impact into the bio-optical modelling part. The calculated data consists of two datasets, 2016 (86 values) and 2017 (178 values) for January, February and March, accordingly to hourly clearness index $K_{Th} \leq 0.4$, for 12:00 – 17:00 time interval, for Malacca Strait coastal region (the Island of Pulau Pinang).

Since the clearness index calculation related to Global radiation data input, the trend of K_{Th} (Figure 3) is similar to the estimated PAR amount (W/m^2). In terms of clearness index determination, the low values explained by extinction in the atmosphere, which includes the clouds effect and other atmospheric constituents. Considering that, the solar radiation and clearness index sharp decreasing caused by angular dependencies, the lowest Global radiation (11.5 - 55.5 W/m^2) values registered for the local noon (LT = 12:00) and nearby the sunset time (17:00) for the observed period, with the low clearness index around 0.01 - 0.02.

Figure 3 represents the distribution of the albedo in the wavelength of maximum chlorophyll-a absorption. The albedo decreasing with the low solar radiation values nearby to sunset time (17:00 for this study). The minimum and maximum of the albedo estimation indicated as 0.096 and 0.104, respectively, for the chlorophyll-a concentrations that were assumed before (Table 1). However, the peaks of the clearness index distribution do not always indicate the same trend in albedo. The albedo parameterization proposed in the current research includes the bio-optical parameterization of the reflectance property due the phytoplankton impact.

The reflectance (R_0 in Equation 24) presented in the current research, defines the apparent optical properties of the seawater, stated by Morel and Maritorena (2001). The presented reflectance (R_0) defines the apparent optical properties and determines the backscattering and absorption properties included in OSA calculation. For the further analysis, we selected the datasets with extreme chlorophyll-a concentrations for representative comparison of the parameters related to the bio-optical part. Each albedo dataset consists of 37 values of the main apparent and inherent optical properties for C = 0.39 and C = 0.69 mg/m^3 (January 2017 and February 2016).

Figure 4 indicates the same albedo distribution trends on both plots (C = 0.39 and C =0.69), but the smaller concentration of the chlorophyll-a has a less effect on the hourly reflectance. Thus, the difference in the reflectance consists of 0.01 – 0.05 for the low albedo values (≈ 0.096) and 0.02 for the albedo peak (0.101 and 0.104). The reflectance, $R_0(\beta(\eta, \mu), \lambda, C)$ proposed accordingly to Morel and Maritorena (2001) depends on the function (Equation 22) of seawater and biological pigment backscattering ($\beta(\eta, \mu)$) and the chlorophyll-a concentration. In this case, the same datasets with $\beta(\eta, \mu)$ parameter were chosen (Figure 5).

The backscattering function in conditions of two extreme concentrations (C) for the observed period (Figure 5) contains the particle and seawater scattering ability. The albedo decreases up to 0.104, as it was mentioned before, with a parallel backscattering increasing, which reaches its maximum with β = 0.39. Moreover, the C = 0.69 mg/m^3 dataset consists of many backscattering peaks, mainly for albedo in the range 0.096 – 0.098. The function β (η, μ) varies from 0.33 to 0.39 for high albedo values and increasing proportionally when the albedo values getting lower than 0.98. The sharp peaks of the backscattering function match with significant albedo decrease for C = 0.69 mg/m^3 dataset, but peaks are smoothed out with the small chlorophyll-a concentration.

Consequently, to quantify the impact of chlorophyll-a concentration (C) into the ocean surface albedo for 440 nm due the cloudy conditions, we parameterized the solar radiation fluxes absorbed by every square meter (Equation 30), defined as Q_s (Figure 6). Figure 6 represents the distribution of the calculated albedo and absorbed solar fluxes for two datasets with the chlorophyll concentrations and clearness indexes mentioned above (Table 1). The maximum peaks (≈ 265 J/s m^2) match with for the 2016 dataset, with C = 0.69 mg/m^3, but the same absorption peaks for 2017 vary from range, with C = 0.39 mg/m^3.

Previous studies related to the variations of light absorption (Bricaud et al. 1998; Morel & Maritorena 2001; Prieur & Sathyendranath 1981) in Case 1 waters had presented a valuable relationship between particulate absorption (440 nm) and chlorophyll-a concentration for bio-optical analytical modelling. In studies, mentioned above, 440 nm wavelength characterized as a wavelength, in which absorption coefficients of particles are near their maximum. In this case, the short scale analysis of the diurnal parameterized spectral albedo is a key instrument in bio-optical modeling of the sea surface. The sensitivity of the OSA parameterization due to the absorbed solar radiation in the PAR range, the further analysis includes albedo comparison for the extreme C values within the mentioned datasets (Figure 7).

The solar absorption range varies from 4.5 to 269 J/s m^2 due to the different albedo values. For C = 0.39 mg/m^3, the amount of the solar fluxes absorbed in the sea surface reaches the peak at 224 J/s m^2. The minimum of the absorption recorded at Q_s = 34 with and reflectance equal to 0.09 (Figure 7). The low albedo values, for C = 0.69 mg/m^3 match with the low absorbed amount of solar fluxes. However, the reflectance (Figure 8) for both concentrations increase rapidly with the downward Q_s trend.

The difference in reflectance and albedo sensitivity (Figure 8) explained by backscattering component in R_0 estimation. The reflectance calculation proposed in the current research depends not only on the chlorophyll-a concentration. The cosine (μ) of solar zenith angle (Equation 22) included in β (η, μ) dominates within the impact of the small concentration of chlorophyll-a the estimation (0.1 – 1.1 mg/m^3). Therefore, the albedo for the chosen wavelength (Figure 6) demonstrates the small difference in absorption abilities of the sea surface. The maximum amount of 269 J/s m^2 registered for the highest albedo (0.1) within the 440 nm for C = 0.69 mg/m^3 dataset. The highest peak of absorption in lower concentration (C = 0.39) registered for for α = 0.104 and R_0 = 0.089. Summarizing the distribution of these parameters, it becomes obvious that concentration values below C = 0.5 mg/m^3 can be neglect for the OSA parameterization within sky condition and solar angles variability.

The OSA scheme estimation proposed for the chlorophyll maximum absorption wavelength due to cloudy conditions in Malacca Strait presented. Moreover, the parameterization includes the main absorption and backscattering bio-optical properties related to phytoplankton properties for the wavelength that we stated before. The minimum of the parameterized albedo is recorded for the 16:00 – 17:00 time interval, this value explained by the low amount of the Global radiation for this time (12 – 85 W/m^2). However, the high peaks (α = 0.102 - 0.104) of the spectral albedo registered in both datasets (2016 and 2017) for the period with the maximum daylight activity ($G_r \geq 400$ W/m^2). The detailed analysis with two representative concentrations (C = 0.39 and C = 0.69 mg/ m^3) for the daytime interval shown the representative estimation (Figures 4 & 5), which is characterized by the variability of the parameters within the cloudy period ($K_{Th} \leq 0.4$).

During the chosen period in accordance with maximum sea chlorophyll coverage in the upper layers of the observed area (January, February and March in 2016 and 2017), the daily scale reflectance and spectral albedo (440 nm) were parameterized. The reflectance (Equation 24) defined as a function of the phytoplankton bio-optical properties and varies slightly with parallel albedo increasing until for both datasets (Figure 8). The fluctuations of the reflectance increased rapidly for in the 2017 dataset with C = 0.53 – 0.69 mg/m^3, while R_0 ranged from 0.085 to 0.090. However, the 2016 dataset varies widely in reflectance range from 0.081 (with) until 0.1 (with03).

Therefore, we assumed the low effect of the chlorophyll-a concentrations below 0.55 mg/m^3, even for the maximum absorption wavelength (440 nm), and the phytoplankton impact under the cloudy skies conditions can be neglected with C ≤ 0.5 mg/m³. The parameterized reflectance, presented in the current work, in accordance with Morel and Maritorena formulation (2001), strongly depends on the absorption and backscattering properties of the phytoplankton particles. As to the OSA estimation, the albedo divided into direct and diffused parts (Jin et al. 2011) also showed the smoothed distribution in 2017 dataset with C ≤ 0.5 mg/m³, compared to 2016 albedo fluctuations (Figure 9).

The maximum amount of the fluxes absorbed by sea surface (Q_s = 269 W/m²) in PAR range (Figure 5) registered for 2016 dataset. Moreover, the analysis of the extreme C values (Figure 7), showed that surface reflectance (R_0) recorded the sharp downward trend for the maximum chlorophyll values within the observed period, at the same time the absorption reached the peak during the daily distribution. The albedo distribution registered by the smooth decrease for C = 0.69, compared to the minimum concentration values (Figure 7).

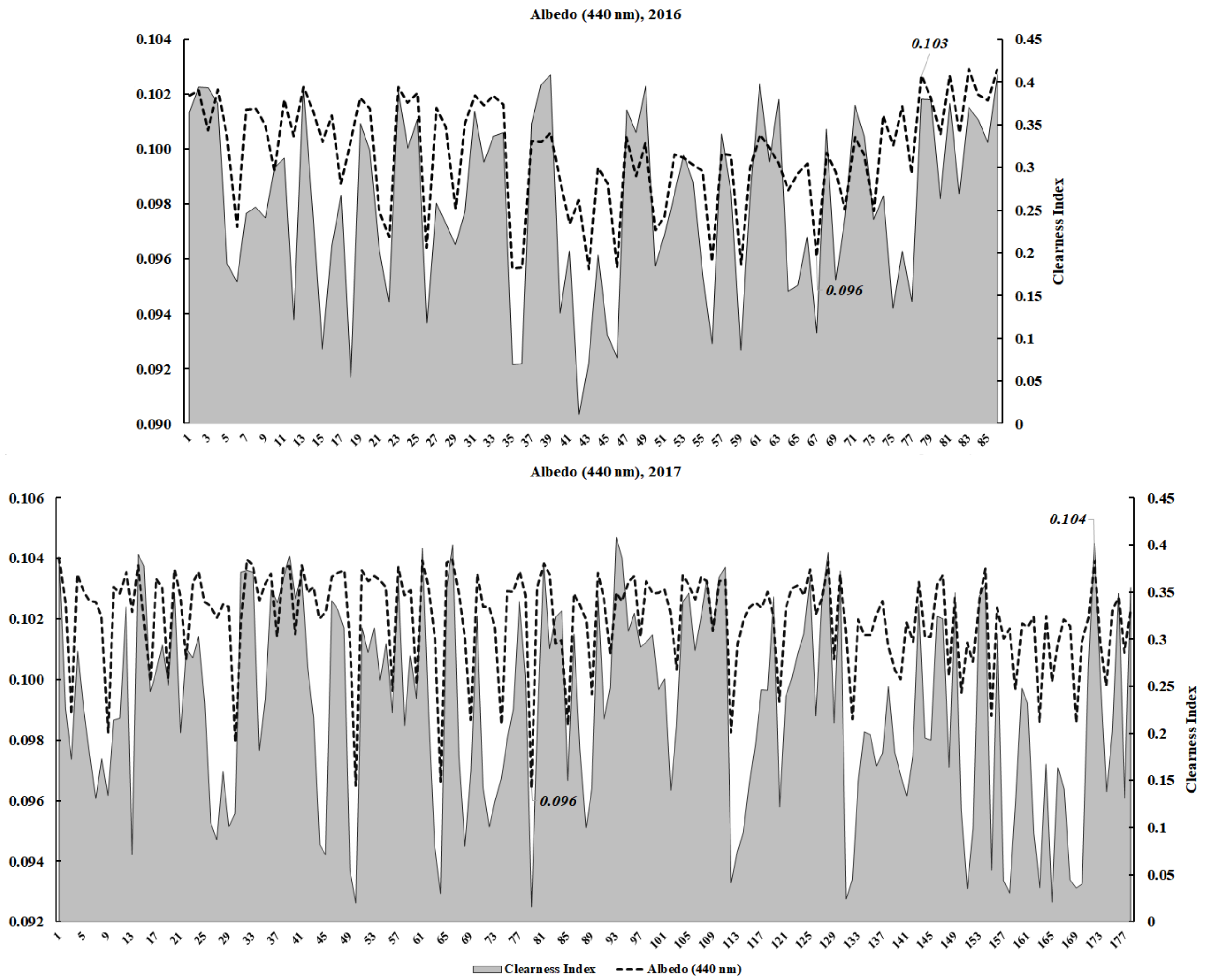

FIGURE 3. Plots of the hourly clearness index (K_{Th}) and sea surface albedo (dotted line) for 440 nm wavelength, for the selected dates, in 2016 and 2017, respectively

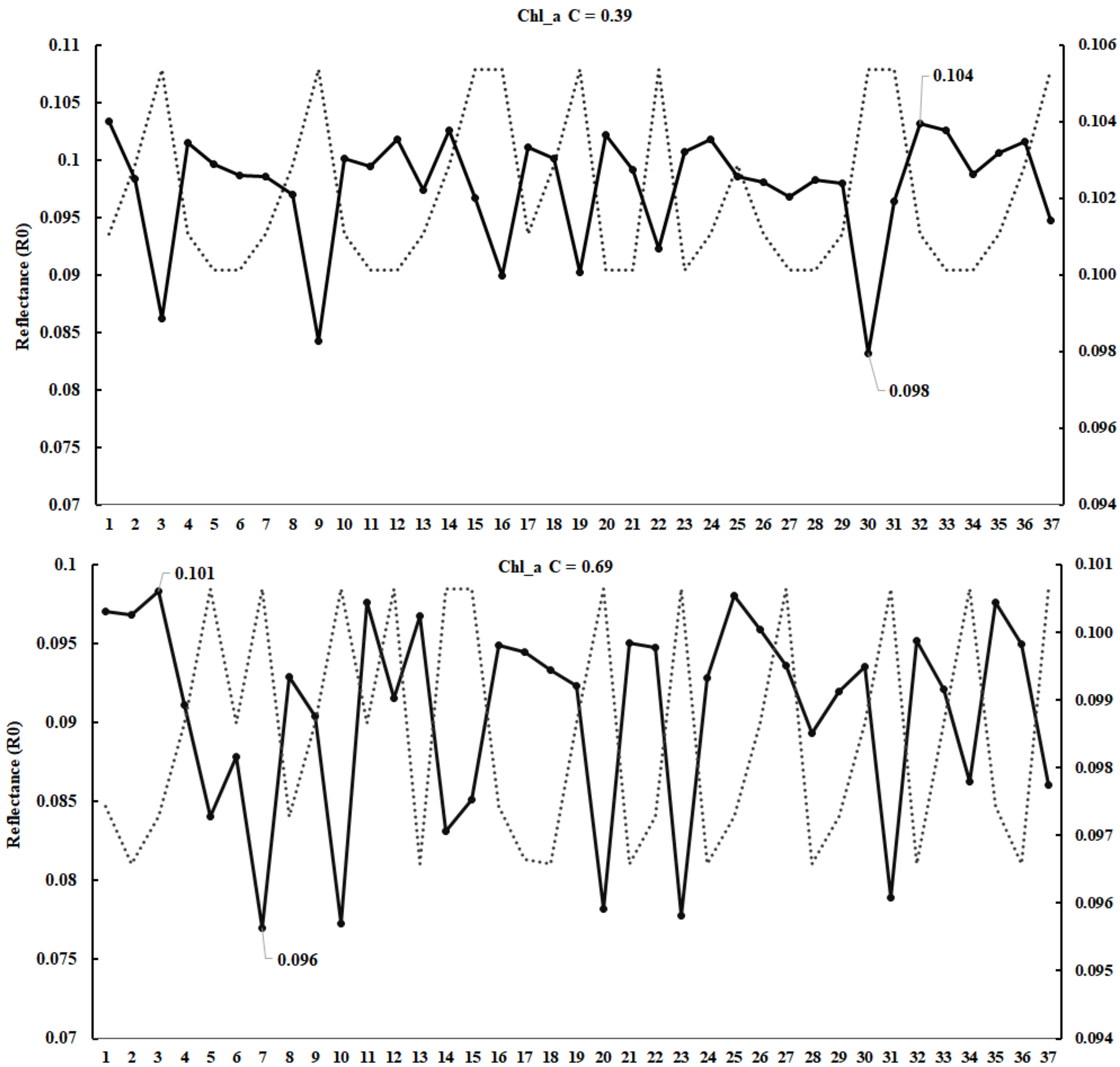

FIGURE 4. Plots of the hourly reflectance, R_0 (dashed line) and sea surface albedo for 440 nm wavelength (solid line) estimated for the chlorophyll-a concentrations, C = 0.39 mg/m^3 and C = 0.69 mg/m^3

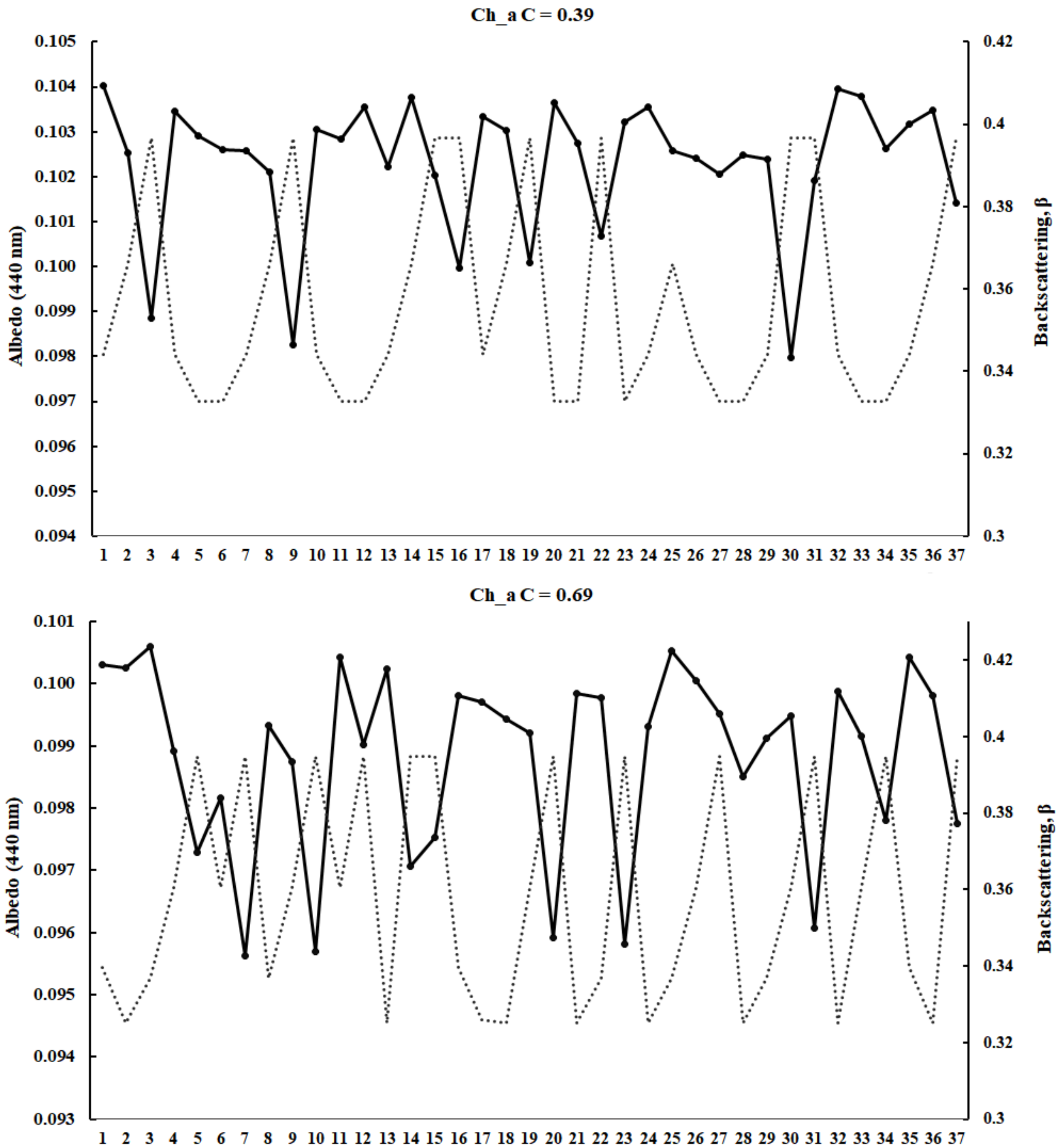

FIGURE 5. Plots of the hourly seawater and biological pigment backscattering (β (η, μ)) function (dashed line) and sea surface albedo for 440 nm wavelength (solid line) estimated for the chlorophyll-a concentrations, C = 0.39 mg/m^3 and C = 0.69 mg/m^3

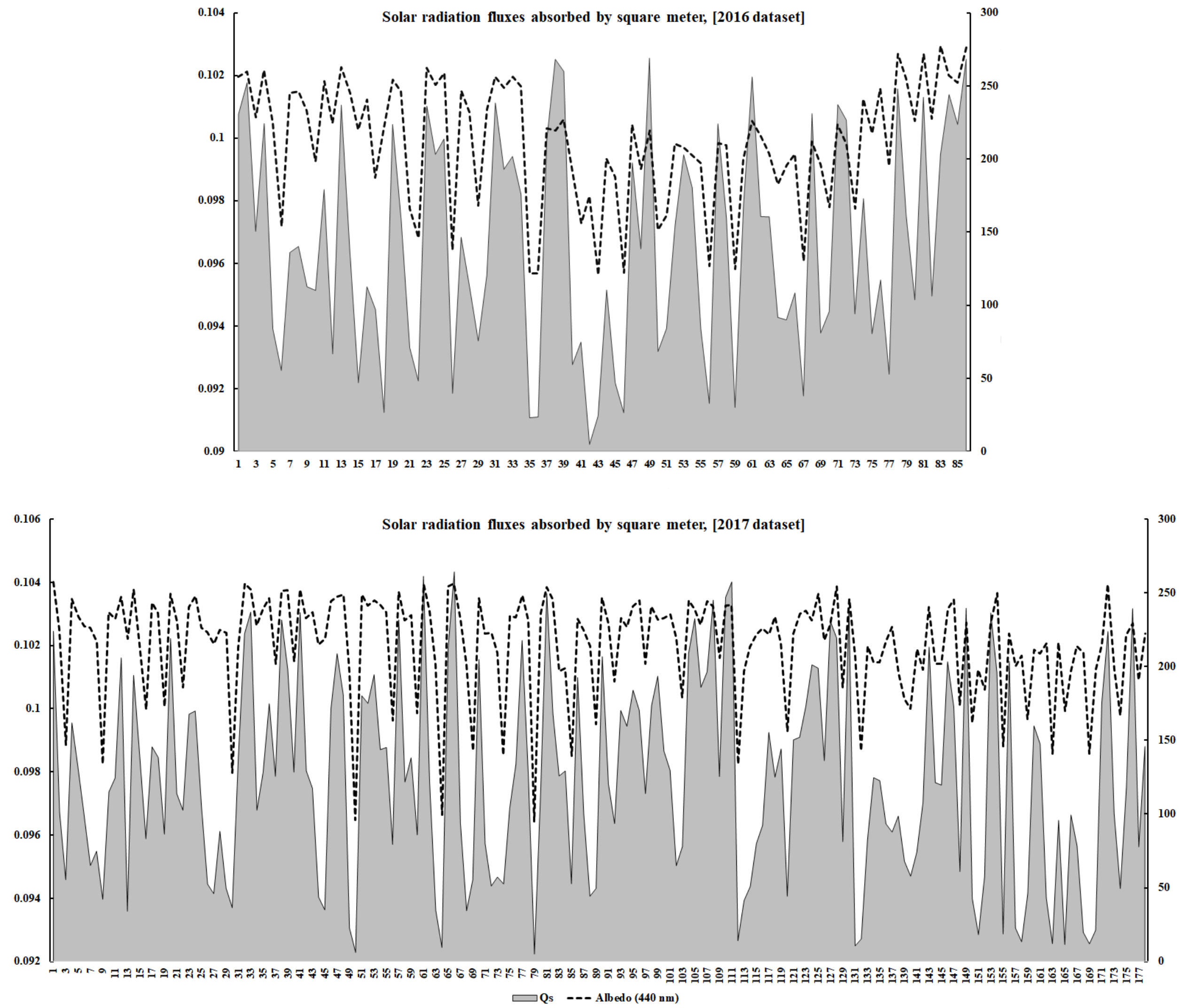

FIGURE 6. Sea surface albedo (440 nm) against the solar radiation fluxes absorbed by square meter [J/s m^2] for the time interval 12:00 – 17:00 due the cloudy conditions, 2016 and 2017 datasets

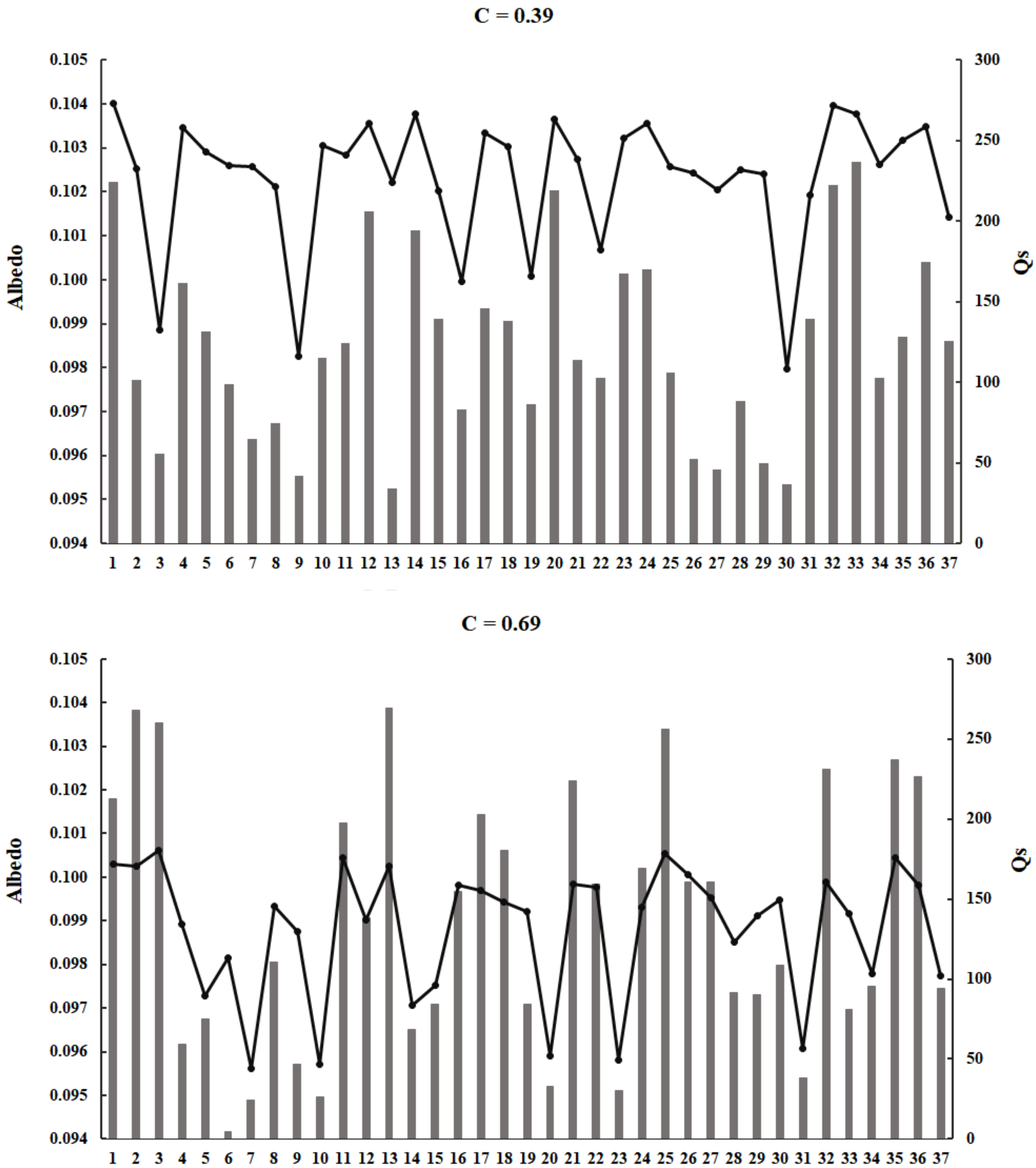

FIGURE 7. Sea surface albedo for 440 nm, (solid line) against the solar radiation fluxes (grey column plot) absorbed by square meter [J/s m^2] for the time interval 12:00 – 17:00 due the cloudy conditions, C = 0.39 mg/m^3 and C = 0.69 mg/m^3

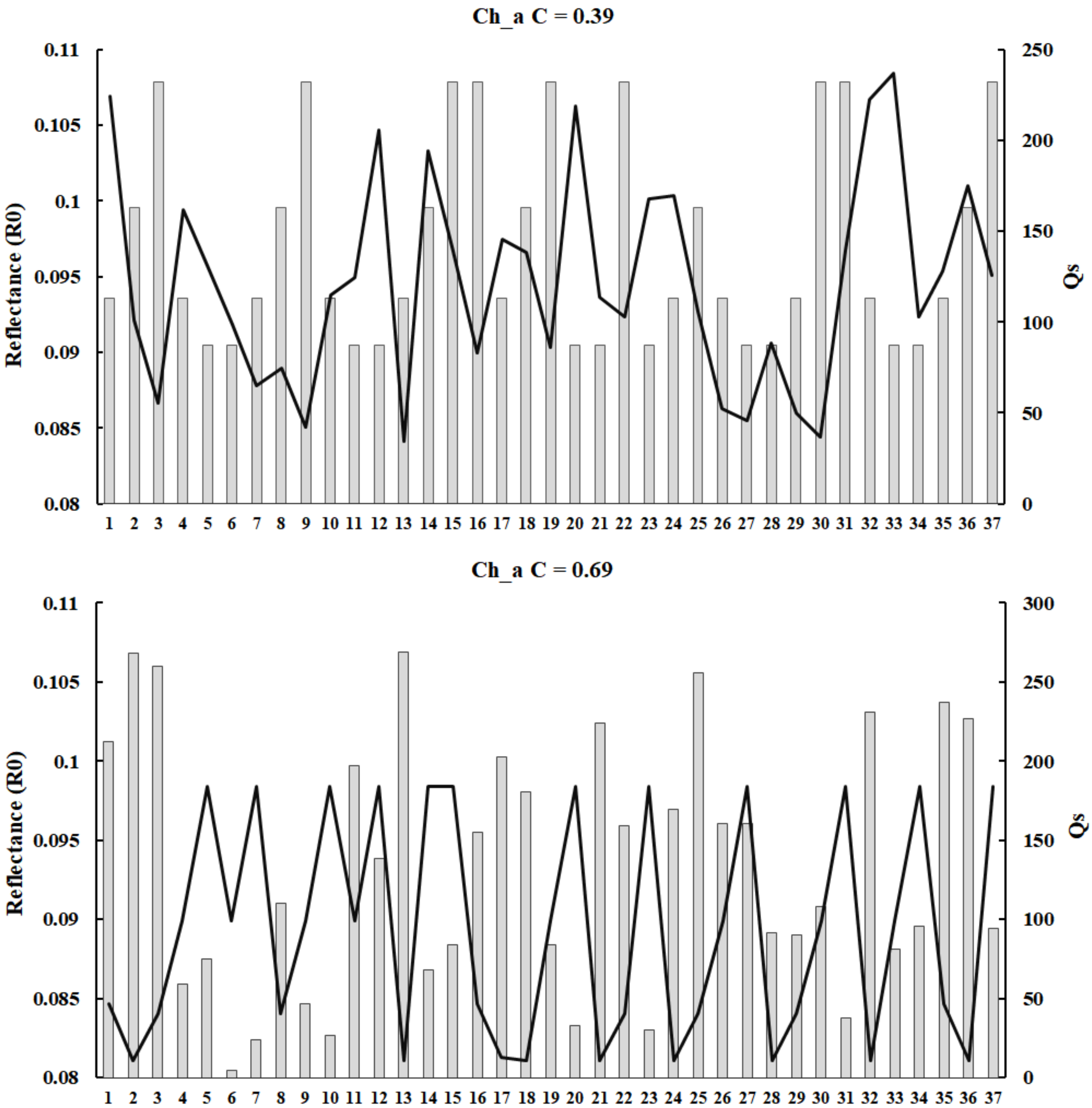

FIGURE 8. Sea surface reflectance (R_0) for 440 nm, (solid line) against the solar radiation fluxes (grey column plot) absorbed by square meter [J/s m^2] for the time interval 12:00 - 17:00 due the cloudy conditions, C = 0.39 mg/m^3 and C = 0.69 mg/m^3

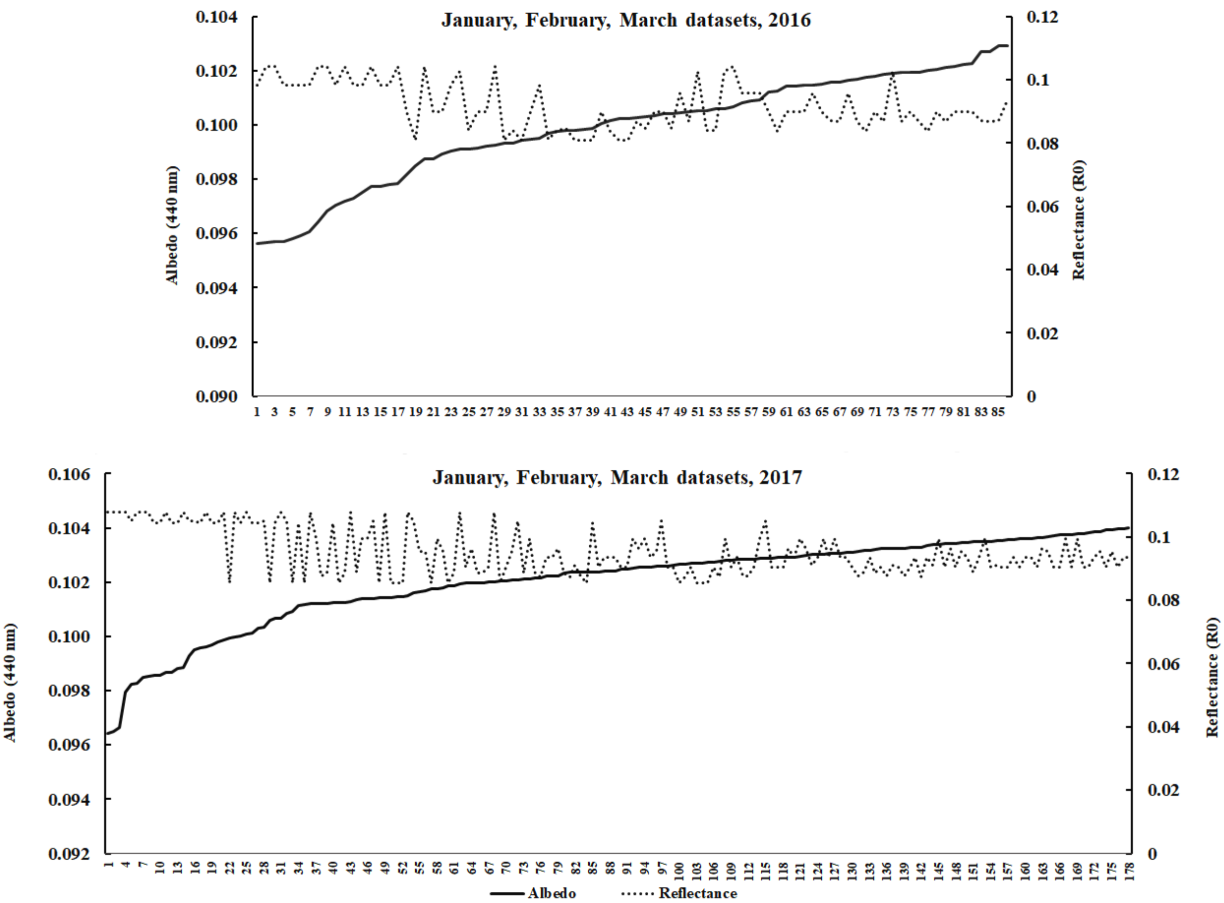

FIGURE 9. Plots of the hourly reflectance (R_0) and sea surface albedo (solid line) for 440 nm wavelength, for the selected dates, in 2016 and 2017, respectively

Conclusions

The methods of the spectral OSA estimation, provided in the current research, showed valuable parameterization using bio-optical modeling coupled with clearness index influence. The bio-optical input as a key tool for feedback mechanism understanding used in the current work. The main parameter responsible for the apparent optical properties in OSA calculation is reflectance, presented as a function of the absorption and backscattering abilities of the chlorophyll pigments. The extreme atmospheric transmittance ($K_{Th} \leq 0.4$) used for better understanding of the phytoplankton impact in the solar radiation modelling. Furthermore, we used the monthly averaged chlorophyll-a concentrations and natural Global radiation measurements with correlated PAR estimation for Malacca Strait, to examine the real approach for the coastal marine ecosystem. The chlorophyll-a as a key driving mechanism, can be neglected for the spectral approach, when the concentration $C \leq 0.5$ mg/m^3, in the further bio-optical estimations in climate modelling. Daily OSA parameterization provides an advantage for detailed and complex analysis of spectral surface radiation in the equatorial coastal waters. The analytical bio-optical model used to explain the chlorophyll impact on spectral ocean surface albedo estimation characterized by absorption and backscattering properties of the phytoplankton. Moreover, 440 nm wavelength analysis allowed us to provide an indicative approach of the sea surface chlorophyll feedback resulting in the change of absorbed fluxes variability. OSA, as a solar radiation dependent scheme needs the proper cloud formulation for further spectral analysis. The *in situ* coastal chlorophyll-a measurements should be a valuable suggestion for the spectral bio-optical scheme correlation for the coastal area modeling.

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