DOWNWELLING DIFFUSE ATTENUATION COEFFICIENTS FROM IN SITU MEASUREMENTS OF DIFFERENT WATER TYPES

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Abstract. Process of light reduction or loss (attenuation) by scattering and absorption is affected by solar zenith, time, depth, and seawater constituents. Downwelling diffuse attenuation coefficient ($K_d$) is important to understand for light penetration and biological processes in ocean ecosystem. It is, therefore, important to know the $K_d$ value and its variability in ocean ecosystem. The objective of this study was to determine downwelling diffuse attenuation coefficients and its variability form in situ measurements of different water types. In situ downwelling irradiances ($E_d$) were measured using a submersible marine environmental radiometer instrument (MER) during a clear sky, calm water condition, and at the time range of 10:30 a.m. up to 14:00 p.m. local time in the northeastern Gulf of Mexico in April 2000. In general, $E_d$ values decreases exponentially with depth. $E_d$ at 380 nm exhibited the lowest attenuation (the most penetrative light), while $E_d$ at 683 nm exhibited the highest attenuation (the most light loss at the top of water column). Overall, the $K_d$ patterns tended to decrease from 380 nm to 490 nm (blue-green wavelength), and increase from 490 nm to 683 nm (green-red wavelength). $K_d$ values in offshore region were relatively lower than in coastal region. $K_d$ can be used to determine the depth of euphotic zone in offshore or teh case-1 water type and the depth of one optical depth (the water column depth where the ocean color satellite can possibly sense).

Keywords: $E_d$, $K_d$, euphotic zone, one optical depth, NEGOM.

1 INTRODUCTION

The downwelling diffuse attenuation coefficient ($K_d$) is an important element of seawater optical properties related to light penetration and availability in aquatic ecosystems. The determination of $K_d$ is critical to understand not only physical processes such as the heat transfer in the upper layer of the water column (Nechad and Ruddick, 2010; Wu et al., 2007; Lee et al., 2007, 2005; Kirk, 1994; Mobley, 1994; Morel and Antoine, 1994; Sathyendranath et al., 1991; Lewis et al., 1990), but also biological processes such as phytoplankton photosynthesis and primary production in the ocean euphotic zone (Nechad and Ruddick, 2010; Kirk, 1994; Mobley, 1994; Platt et al., 1988; Sathyendranath et al., 1989).

$K_d$ is generally defined as the differentiation of downwelling irradiances between two layers (depths) as formulated as follows:

$$K_d(z, \lambda) = -\frac{1}{E_d(\lambda)} \frac{dE_d}{dz}$$

where $K_d(\lambda)$ is downwelling diffuse attenuation coefficient (m$^{-1}$), $E_d(\lambda)$ is downwelling irradiance (W m$^{-2}$); and $z$ is water column depth (m).

As a penetrative component of solar radiation, $K_d$ is affected by depth, solar zenith, time, and seawater constituents (Lee et al., 2002, 2005, Mobley, 1994, Kirk, 1994). The effect of solar zenith (elevation) on $K_d$ is relatively small in the lower (blue-green or <500 nm) wavelengths and relatively larger in the higher (yellow-green or >500 nm) wavelength (Lee et al., 2002; Stramska and Frye, 1997; Kirk, 1991; Gordon, 1989). $K_d$ can also be used to derive water clarity by determining the ability of light transmission (penetration) in the water column using Secchi disc equipment with the following equation:

$$K_d = k/SD$$

where SD is Secchi Depth (m) and k is assumed to be constant (Jamu et al. 1999).
From the above equation, it can be concluded that the deeper the secchi disc observed from the surface water, the clearer the seawater or the smaller the value of \(K_d\).

Approximately 90% of the diffuse reflected light from a water body comes from a surface layer of water within a depth of \(1/K_d\) (Lee et al., 2002). This condition can also be interpreted that the ocean color satellite can only sense the seawater column at the most within the depth of \(1/K_d\). Therefore, \(K_d\) is an important parameter for remote sensing reflectance \((R_o)\) of ocean color satellite.

Liu et al. (2005) correlated the diffuse attenuation coefficient with seawater quality parameters such as total suspended solid (TSS), Secchi Depth (SD), and salinity. They found that SD measurements had a negative linear relationship with \(K_d\), salinity with positive linear relationship, and no good relationship with TSS. Jacobson (2005) found that variability of \(K_d\) was more significantly affected by chlorophyll-a concentration than TSS concentration variabilities. \(K_d\) had the highest correlation with chlorophyll-a concentration at 443 nm wavelength \((r^2=0.65)\), while the highest correlation of \(K_d\) with TSS found at 710 nm wavelength \((r^2=0.4)\).

Mishra et al. (2005) reported that from in situ measurements in Roatan island waters the diffuse attenuation coefficient values were relatively low in the blue and green wavelength, and increase above 750 nm.

Informations related \(K_d\) values and its variabilities are considered very little, while the use of \(K_d\) informations are increasingly important specifically for the use and development of bio-optical model algorithms in ocean color satellites.

2. MATERIALS AND METHOD

2.1 Study area

The study was conducted in the region of Northeastern Gulf of Mexico (NEGOM) extending from the Mississippi River Delta to the West Florida Shelf off Tampa Bay within coordinate of 27°18’ - 30°42’ N and 82°36’ - 89°36’ W (Figure 1). In situ downwelling irradiance measurements were conducted in April 2000 and concentrated in four designated region i.e., coastal region or case-2 water (A; stations 3, 4, 12, and 13), continental shelf region or transition from case-2 to case-1 water (B; stations 7 and 15 and C; stations 8, 10, and 11), and offshore region or case-1 water (D; stations 1, 2, 5, 6, 9, 14, and 16). The study regions limited within 10 m isobath in coastal region up to 1000 m isobath in offshore (Figure 1).

2.2 In situ data collection

The data used in this study were the in situ measurements of downwelling irradiance \((E_d)\) at various depths in April 2000. The data were used to calculate the value of the downwelling diffuse attenuation coefficients \((K_d)\). Downwelling irradiances \((E_d)\) were collected using a submersible marine environmental radiometer instrument (MER). Before measurements in the field, the MER equipment was calibrated in the laboratory. Dark measurements were also conducted during the night time for dark current calibration. The measurements were casted from the ship deck during a relatively calm water condition (wave height < 0.5 m), relatively clear sky (cloud covered < 30%), and from about 10:30 a.m. to 14:00 p.m. local time.

Data measured by the equipments were upwelling radiance \((L_u)\), downwelling radiance \((L_d)\), upwelling irradiance \((E_u)\), and downwelling irradiance \((E_d)\) for wavelength of 380 nm, 412 nm, 443 nm, 455 nm, 475 nm, 490 nm, 510 nm, 532 nm, 555 nm, 589 nm, 665 nm, 683 nm, and Photosynthetically Active Radiation (PAR).
Figure 1. Study area map exhibited the four groups of in situ measurement of coastal region or case-2 water (A), continental region or mixture/transition of case-1 and case-2 waters (B and C), offshore region or case-1 water (D).

Data were recorded for both upcast and downcast. In this study, we used downcast data of downwelling irradiances measurements. The downcast could be extended up to the maximum of 250 m deep with 0.5 m integration depth.

Locations of data collection were divided into four locations i.e., region A (stations 3, 4, 12, and 13), region B (stations 7 and 15), region C (stations 8, 10, and 11), and region D (stations 1, 2, 5, 6, 9, 14, and 16). Region A represented the coastal water type or case-2 water type, region B and C represented the mixture/transition of coastal water and offshore water or mixture/transition of case-2 and case-1 water type, while region C represented offshore water or case-1 water type. The division was done based on the location of stations where downwelling irradiance measurements were taken and it was assumed that within one region the water constituents or type were similar. We compared the $K_d$ values at the locations of different water type.

### 2.3 Data Analyses

Raw MER data were processed through standard processing MER data by converting binary data to csv format data applying dark current calibration and laboratory standard calibration. Data were also fitted using curve fitting tool to eliminate noise caused by ship movement during casting. Exponential equation of $E_d$ produced by fitting processing was used to extrapolate $E_{sd}$ at the surface. The compensation depth (the depth where downwelling irradiances remain 1% of downwelling irradiance received at the surface) and depth of one optical depth were also determined using the following equations:
Z_k (1%) = \frac{4.6}{Kd(z, \lambda)} \quad \text{............... (3)}

\eta_d (m) = \frac{1}{Kd(z, \lambda)} \quad \text{............... (4)}

where \( Z_k \) (1%) is the compensation depth, \( \eta_d \) (m) is the depth of one optical depth, and \( K_d \) is the downwelling diffuse attenuation coefficient.

Kruskal-Wallis test was used to determine the significant different of \( K_d \) mean values among different region or different water types.

3 RESULTS AND DISCUSSION

3.1 Downwelling irradiance (\( E_d \))

In general, \( E_d \) values were exponentially decrease with depth and significantly decrease at the top layer of the water column (Figure 2). \( E_d \) graphs at the four represented stations (region) exhibited similar pattern that decreases exponentially with depth. However, the results showed that the gradient of \( E_d \) at the red wavelength (> 600 nm) declined sharper than in the blue-green wave length (<600 nm). This occurred because the water body absorbed more in red wavelength than in the blue-green wavelength range (Kirk, 1994, Moblye, 1994).

The sharp decrease of \( E_d \) at the top layer of water column occurred as a result of quick absorption of water body and scattering of light due to present of suspended materials and dissolved organic matter in this layer (Figure 2). In station 3 and 8 (Figure 2), the \( E_d \) plots were sharply decrease at the top layer of the water column as a result of the relatively high concentration of suspended materials and dissolved organic matter originated from riverine input near to the stations such as Choctawhatchee and Escambia River located near to station 3 and Apalachicola river located near to the station 8 (Nababan et al., 2011; Nababan, 2005). Phytoplankton biomass that in general higher in the coastal region than in the offshore also helped light attenuation due to its scattering and absorption specifically in blue-green wavelength in the top layer of the water column (Zhai et al. 2011; Nababan et al., 2011, 2009; Mishra et al., 2005). The chlorophyll-a concentrations in the region A were generally >1 mg/m\(^3\) or high productivity (Nababan et al., 2011; Nababan, 2005).

Location D was a region with generally low primary productivity (phytoplankton <1 mg/m-3). The stations in this region were far enough from the coast resulted in low nutrient from riverine inflow. Therefore, relatively low chlorophyll-a concentration and low organic matter in this region produced less absorption and scattering by phytoplankton and organic matter, causing \( E_d \) gradient less sharp compared with \( E_d \) in station A, B, and C. NEGOM waters are strongly influenced by large rivers that flow into the region. The large flow of waters from rivers brought particles and nutrients from the mainland into the coastal region in the NEGOM and affecting \( E_d \) profile (Nababan et al., 2011; Nababan, 2005).

In general, \( E_d \) of 380 nm of all stations exhibited similar patterns and had the lowest gradient energy changes indicating the strongest light penetration. Meanwhile, \( E_d \) of 665 and 668 nm of all stations exhibited similar patterns and had the highest gradient energy changes indicating the weakest light penetration or the strongest light absorbed by water (Figure 2).

The patterns of \( E_d \) on each station within the same region were in general similar, while the patterns of \( E_d \) on each station within different region exhibited some differences in the values and their slopes indicating different water type and water constituents in different regions (Figure 2).
Figure 2. Some examples of downwelling irradiance $E_d$ plots representing the four groups of stations (region). Station 3 represents coastal region or case-2 water type, stations 15 and 8 represent continental shelf region or transition between case-1 and case-2 water type, station 6 represents offshore region or case-1 water type.
3.2 Attenuation coefficient ($K_d$)

In general, attenuation coefficient values at each station exhibited a decrease trend in the range of 380-490 nm and followed by an increase trend in the range of 490-683 nm (Figure 3). The highest value of $K_d$ occurred at the red wavelength (665 and 683 nm) as a result of the sharpest gradient of Ed specifically at the top layer of water column (see Figure 2). Similar $K_d$ patterns were reported by Mishra et al. (2005) showing an increase pattern in the red wavelength and and decrease trend in green-blue wavelength.

In each station, the lowest Kd value was generally found at the green wavelength of 490 nm and the highest Kd value was generally found at the red wavelength of 683 nm (Figure 3). The lowest Kd value (0.014 m$^{-1}$) at 490 of all station was found at station 1 and 5 of region D where the clearest or case-1 water type was found, while the highest $K_d$ value (0.137 m$^{-1}$) was found at station 12 of region A where the possible highest suspended material and organic matter or case-2 water type was found (Figure 3).

In region A (coastal water), Kd values of station 3 ranged of 0.050 - 0.096 m$^{-1}$, station 4 with range of 0.039 - 0.101 m$^{-1}$, station 12 with range of 0.048 - 0.058 m$^{-1}$, and station 13 with range of 0.069 - 0.137 m$^{-1}$. Overall, the $K_d$ values of all stations in region A were relatively higher than in all other stations of region B, C, and D. This occurred due to the highest suspended materials and organic matters found in this region. Brito et al. (2013) also reported that in general the highest $K_d$ values were found in shallow water near to the estuary and river mouth.

In region B, $K_d$ values of station 7 ranged of 0.031 - 0.037 m$^{-1}$ and station 15 in range of 0.026 - 0.060 m$^{-1}$. In region C, $K_d$ values of station 8 ranged of 0.016-0.025 m$^{-1}$, station 10 with range of 0.015-0.036 m$^{-1}$, and station 11 with range of 0.017-0.030 m$^{-1}$. Regions B and C were a transition region from coastal water to offshore water. Therefore, the water properties in this region was a transition between case-1 water and case-2 water.

In region D (offshore water), $K_d$ values at station 1, 2, 5, 6, 9, 14, and 16 ranged of 0.014-0.022 m$^{-1}$, 0.016-0.039 m$^{-1}$, 0.014-0.017, 0.016-0.032 m$^{-1}$, 0.017-0.040, 0.018-0.049 m$^{-1}$, and 0.016-0.018 m$^{-1}$, respectively. Overall, Kd values in this region were relatively low compared to other regions (A, B, and C).

$K_d$ values of PAR wavelength in region A ranged of 0053-0096 m$^{-1}$, while in other regions (B, C, and D), $K_d$ values ranged of 0015-0033 m$^{-1}$ (Figure 3). The average values of $K_d$ of 380-683 nm and Kd PAR in each station of all regions are presented in Table 1. This Table showed that the average values of Kd PAR and $K_d$ 380-683 nm were not significantly different.

Lugo-Fernandez et al. (2012) calculated $K_d$ in the northern Gulf of Mexico by dividing the water column into multiple layers, showed that at a depth of <15 meters, $K_d$ ranges from 0.5 - 1.0 m$^{-1}$, decreased at a depth of 20-100 meters of 0.1 - 0.3 m$^{-1}$, and above 100 meters obtained $K_d$ range 0.05 - 0.2 m$^{-1}$. This showed that a lot of the absorption occurred in the surface layer of water. In addition, the results showed that the $K_d$ in coastal waters was greater than the value of $K_d$ in the waters off the coast.

Based on Kruskall-Wallis test and Box & Whisker Plot, $K_d$ values of each wavelength was significantly different within the different regions or different water types i.e., case-1, case-2, and transition water types (significantly different in 95%).

The trend of Kd values decreased from the coastal region toward offshore region, therefore, euphotic zone and the depth of one optical depth increased from from teh coastal region toward offshore region which will be discussed in the sub-chapter.

3.3 Euphotic zone and one optical depths

The optical depth is general closely related to water transparency. The clearer the waters, the deeper the ocean color satellite sensor can sense. Region A was expected to...
Figure 3. $K_d$ values with respect to wavelength in each station of region A, B, C, and D.
Table 1. Kd PAR and Kd 380-683 average in each station of all regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Station</th>
<th>Kd PAR (m⁻¹)</th>
<th>Average Kd 380-700 nm (m⁻¹)</th>
<th>difference (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3</td>
<td>0.0639</td>
<td>0.0643</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0529</td>
<td>0.0546</td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.0533</td>
<td>0.0526</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.0957</td>
<td>0.0927</td>
<td>0.0030</td>
</tr>
<tr>
<td>B</td>
<td>7</td>
<td>0.0330</td>
<td>0.0337</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.0331</td>
<td>0.0347</td>
<td>0.0016</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
<td>0.0187</td>
<td>0.0187</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.0197</td>
<td>0.0208</td>
<td>0.0011</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.0234</td>
<td>0.0225</td>
<td>0.0009</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>0.0178</td>
<td>0.0171</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0207</td>
<td>0.0221</td>
<td>0.0014</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.0153</td>
<td>0.0149</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.0198</td>
<td>0.0203</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.0223</td>
<td>0.0234</td>
<td>0.0011</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.0256</td>
<td>0.0262</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.0184</td>
<td>0.0171</td>
<td>0.0013</td>
</tr>
</tbody>
</table>

be more turbid than other regions. We derived the euphotic zone based on equation (3) assuming the water depth was limitless. From the calculation, in region A, the depth of euphotic zone depth ranged of 45.5-264.1 m. The results of the euphotic zone estimation in coastal region were beyond the maximum depth (the maximum depth in region A was about 50 m deep in station 4 and about 30 m in station 12 (Nababan, 2005)). Therefore, the estimation of euphotic zone in coastal region or case-2 water type was not accurate. Meanwhile, the depth of one optical depth in region A (coastal water) ranged of 7.30-25.41 meters. This result indicated the ocean color satellite could sense the water column from surface up to the sea floor in coastal region or case-2 water type. This result also supported theory that ocean color satellite could sense bottom reflectance.

Region B as the transition region had euphotic zone depth in range of 77.1-175.2 m and one optical depth with range of 16.76-38.09 meters (Table 2). The estimation of euphotic zone in this region was also considered to inaccurate because the maximum depth within region B was less than 100 m (Nababan, 2005). Region C as the transition region had euphotic depth with range of 128.2-298.6 m and one optical depth with range of 27.88 - 64.92 m (Table 2). This zone is closer to the case-1 water type than to the case-2 water type. Therefore, the estimation of euphotic zone in this region was more reliable. Region D where the highest level of brightness, lowest suspended materials, and lowest organic matter had the depth of euphotic zone in the range of 94.6-340.6 m. This estimation exhibited was more reliable because the maximum depth in thi region was about 500-1000 m deep (Nababan, 2005). Meanwhile, the depth of one optical depth in region D was with the range of 20.57-74.04 m (Table 2). This result indicated that ocean color satellite can sense the water column in this region or the case-1 water type up to 74.04 m. The result also showed that the depth of one optical depth was increase from coastal region toward the offshore region.
Table 2. Range of $K_d$, the depth of euphotic zone, and the depth of one optical depth.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Station</th>
<th>$K_d \text{ (m}^{-1}\text{)}$</th>
<th>Depth of euphotic zone (m)</th>
<th>Depth of one optical depth ($\mu$) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3</td>
<td>0.050 - 0.096</td>
<td>48.0 - 91.5</td>
<td>10.43 - 19.89</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.039 - 0.101</td>
<td>45.5 - 116.9</td>
<td>9.89 - 25.41</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.069 - 0.137</td>
<td>79.9 - 95.4</td>
<td>7.30 - 14.54</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.048 - 0.058</td>
<td>155.8 - 264.1</td>
<td>17.38 - 20.73</td>
</tr>
<tr>
<td>B</td>
<td>7</td>
<td>0.031 - 0.037</td>
<td>125.0 - 147.7</td>
<td>27.17 - 32.10</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.026 - 0.060</td>
<td>77.1 - 175.2</td>
<td>16.76 - 38.09</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
<td>0.016 - 0.025</td>
<td>180.9 - 288.2</td>
<td>39.34 - 62.66</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.015 - 0.036</td>
<td>128.2 - 298.6</td>
<td>27.88 - 64.92</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.017 - 0.030</td>
<td>155.8 - 264.1</td>
<td>33.87 - 57.41</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>0.014 - 0.022</td>
<td>213.7 - 319.6</td>
<td>46.46 - 69.48</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.016 - 0.039</td>
<td>118.9 - 279.2</td>
<td>25.85 - 60.69</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.014 - 0.017</td>
<td>275.2 - 340.6</td>
<td>59.83 - 74.04</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.016 - 0.032</td>
<td>145.9 - 288.8</td>
<td>31.71 - 62.78</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.017 - 0.040</td>
<td>113.6 - 263.4</td>
<td>24.70 - 57.26</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.018 - 0.049</td>
<td>94.6 - 258.2</td>
<td>20.57 - 56.13</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.016 - 0.018</td>
<td>249.1 - 294.3</td>
<td>54.15 - 63.98</td>
</tr>
</tbody>
</table>

4 CONCLUSION

In general, $E_d$ values decreased exponentially with depth. $E_d$ at 380 nm exhibited the lowest attenuation (the most penetrative light), while $E_d$ at 683 nm exhibited the highest attenuation (the most light loss at the top of water column).

Overall, the $K_d$ patterns tended to decrease from 380 nm to 490 nm (blue-green wavelength), and the $K_d$ patterns tend to increase from 490 nm to 683 nm (green-red wavelength). $K_d$ values in offshore region were relatively lower than in coastal region.

$K_d$ can be used to determine the depth of euphotic zone in teh case-1 water type and the depth of one optical depth (the depth where the satellite can possibly sense).

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