CHARACTERIZATION OF DOWNWELLING SPECTRAL IRRADIANCE FLUCTUATIONS

DAVID A. SIEGEL AND T. D. Dickey
Ocean Physics Group
Department of Geological Sciences
University of Southern California
Los Angeles, California 90089-0740

Abstract
Profiles of downwelling spectral irradiance fluctuation \( e'(z,\lambda) \) are determined from data taken during the Optical Dynamics Experiment in the North Pacific Ocean. These vertical profiles are based upon values of \( e'(z,\lambda) \), defined as the root mean square deviations of the instantaneous irradiance from the smoothed (9m running mean) irradiance. Time scales associated with these deviations range from \(-1\) to \(13s\) and are probably associated with surface gravity wave processes. Vertical variations of attenuating materials are minimal as data are from the upper mixed layer (upper 50m). Profiles indicate that \( e'(z,\lambda) \) decreases nearly exponentially with depth and can be modeled with the form \( e'(z,\lambda) = A(\lambda) \exp(-B(\lambda)z) \). This simple expression accounts for at least 90% of the observed vertical variations of \( e'(z,\lambda) \). The ensemble mean \( A(\lambda) \) is roughly 5% of the mean spectral irradiance just beneath the sea surface. The mean \( B(\lambda) \) varies from about 1 to 2 times the mean diffuse spectral attenuation coefficient, with the largest values occurring for the most penetrating wavelengths of light. Possible mechanisms contributing to the observed variations and their relationships with other parameters are discussed.

Introduction
The characteristics of the mean downwelling spectral irradiance are reasonably well-documented (Tyler and Smith, 1970; Jerlov, 1976; Smith and Baker, 1978; Baker and Smith, 1980; Siegel and Dickey, 1987a, 1987b). However, the character of the deviations from this mean state has received less attention and is not well understood (Dera and Gordon, 1968; Snyder and Dera, 1971; Gordon et al., 1971; Weidemann et al., 1987). Relatively high frequency fluctuations of the downwelling irradiance (temporal scales less than \(\sim10s\)) are commonly associated with the alteration of the sea surface by surface waves (Cox and Munk, 1955; Phillips, 1980; Preisendorfer and Mobley, 1986). Irradiance fluctuations can also have important biological implications by affecting rates of photosynthesis (e.g., Walsh and Legendre, 1983) and yields of stimulated chlorophyll fluorescence (e.g., Abbott et al., 1982). Further, the characterization of these high frequency irradiance fluctuations can be used to design systems to sample both optical and surface wave properties.

Previous observations of downwelling irradiance fluctuations have shown that the amplitudes of the fluctuations decay nearly exponentially with depth below a very shallow subsurface maximum (Dera and Gordon, 1968). The fluctuation maximum occurs below an optical depth of \(\sim0.25\) and is thought to be caused by surface wave induced focusing of light rays (Dera and Gordon, 1968; Snyder and Dera, 1971). For the present case, this optical depth corresponds to a physical depth of \(\sim7m\) for the most penetrating wavelengths (441 to 488nm; Siegel and Dickey, 1987a). At the subsurface maximum, the amplitude of the fluctuation is reported to vary from 55 to 85% of the mean \textit{in situ} irradiance and to increase with increasing water clarity (Dera and Gordon, 1968). Beneath this subsurface maximum, the amplitude of fluctuation relative to the mean \textit{in situ} irradiance decreases rapidly (Dera and Gordon, 1968). This indicates that the vertical attenuation rate for the fluctuation is significantly greater than that for the mean \textit{in situ}
irradiance. Recent moored spectroradiometer observations (Booth et al., 1987) have shown that the shapes of the root mean square (rms) irradiance fluctuation spectra (normalized by the mean) are similar to observed diffuse attenuation coefficient spectra.

Observations

Measurements of downwelling spectral irradiance ([Ed(z,λ)]λ) were made between October 25 and November 7, 1982 from the sea surface to a nominal depth of 150m, near 33°N, 142°W in the North Pacific Ocean (Dickey and Siegel, 1988). The measurements were made using a Biospherical Instruments Inc. (San Diego, California) MER-1010 spectroradiometer which samples vector downwelling irradiance at 12 discrete (10nm bandwidth) wavebands (specifically: 410, 441, 465, 488, 520, 540, 560, 589, 625, 671, 694, and 767nm; Smith et al., 1984; Siegel and Dickey, 1987a). Profiles of the diffuse attenuation coefficient spectrum (Kd(z,λ)) and values of [Ed(0+,λ)]λ were determined by using the smoothed [Ed(z,λ)]λ profiles and linear regression techniques (Siegel and Dickey, 1987a, 1987b). Only casts with nearly constant incident solar irradiance ([Ed(0-)λ]) were chosen for analysis, because incident irradiance variations during a cast invalidate the calculation procedures. A total of 32 casts was selected for this analysis. The environmental conditions for the spectroradiometer casts encompassed high and low sun altitude angles and cloud amounts. During these observations, a full suite of meteorological and radiative flux determinations along with physical and bio-optical measurements were also made (Dickey and Siegel, 1988).

Calculation and Interpretation of e'(z,λ)

We interpret the profile of root mean square deviations of the in situ [Ed(z,λ)]λ from a smoothed profile ([Ed(z,λ)]λ) as a profile of high frequency irradiance fluctuations. The method for calculating the rms deviation profile is illustrated for λ=441nm in figure 1. The data were sampled by the spectroradiometer at 64Hz and averaged as 1s (~1.5m) averages. These data were log-transformed, interpolated to 1m depth intervals, and then smoothed using a 9m width boxcar filter. Deviation profiles were made by calculating the rms difference between the exponentiated smoothed and raw irradiance values. These data were then averaged over 10m intervals, which overlapped by 5m. These irradiance fluctuations are denoted e'(z,λ). The shallowest depth bin which is evaluated for e'(z,λ) is at 5m. Thus, the subsurface fluctuation maximum (e.g., Dera and Gordon, 1968) is not resolved with the present observations.

Proper interpretation of the observed downwelling irradiance fluctuations requires knowledge of the time scales associated with e'(z,λ). The deviation profile should be associated with physical process time scales less than the time required to profile 9m (~13s). The time scale for e'(z,λ) will also be greater than 1s because of the sample averaging by the spectroradiometer. Thus, the sampled irradiance fluctuations are associated with processes whose temporal scales are bounded by 1 and 13s.

It is likely that these in situ irradiance fluctuations are caused by surface wave processes, because cloud-induced variations of the incident solar radiation are not likely to be important at these relatively high frequencies (Abbott et al., 1982). Surface waves can alter the instantaneous downwelling irradiance by three fundamental processes. Sea surface elevation changes alter the mean path length between the sea surface and the irradiance sensor, surface slope variations create glitter patterns at depth by nearly randomly refracting light rays, and sea surface curvature can focus light rays towards (or away from) the irradiance sensor. Although the distinctions among these various surface wave processes cannot be made with the present data set, their joint effects on the instantaneous downwelling irradiance values can be characterized.

In order to characterize e'(z,λ), conceptual models of the physical processes controlling the irradiance fluctuations are used to help define possible parametric dependencies. For example, the amplitude of e'(z,λ) should decay with depth (Dera and Gordon, 1968). An increase in the incident solar irradiance (Ed(0+)λ) should increase the amplitude of e'(z,λ). The effects of variations of the incident radiation field may also be studied using the observed cloud amount or the downwelling irradiance spectrum just beneath the sea surface ([Ed(0-,λ)]λ). The amount of clouds may also have some influence
Figure 1: Construction of $e'(z,441\text{nm})$ for cast 298e (Day 298, 1856 UT, 1982). First panel displays both sampled ($[E_d(z,441\text{nm})]_\lambda$) (thin line) and 9m vertically smoothed ($[E_d(z,441\text{nm})]_\lambda$) (thick line) downwelling spectral irradiance. Second panel shows the absolute difference between $[E_d(z,441\text{nm})]_\lambda$ and $[E_d(z,441\text{nm})]_\lambda$. The third panel displays the vertically binned $e'(z,441\text{nm})$ data (thick line) with the exponential fit (thin line). The relationship between $A(441\text{nm})$ and $B(441\text{nm})$ and the $e'(z,441\text{nm})$ profile is also indicated. The units for all panels are W m$^{-2}$ nm$^{-1}$.

on the proportion of incident diffuse light. Variations in $e'(z,\lambda)$ caused by surface waves may depend upon the amplitude and character of wind waves and hence the local wind speed. However, observed sea surface swell motions with periods of $O(10s)$ are likely to be caused by distant storms. The mean solar altitude angle may also have an effect upon the observed distributions of $e'(z,\lambda)$ by altering the incident radiance distribution and the reflection and refraction properties of the sea surface. These conceptual parametric dependencies can aid in the characterization of $e'(z,\lambda)$.

It should be noted that only data from the upper 50m of the water column are used for the present analysis. For these depths, few significant variations of $K_d(z,\lambda)$ were observed (Siegel and Dickey, 1987a). Thus, minimal vertical gradients of attenuating materials should not affect the interpretation of the vertical structure of $e'(z,\lambda)$. $K_d(\lambda)$ is defined here as the average diffuse attenuation coefficient for the upper 30m.

Results

Vertical profiles of $e'(z,\lambda)$ for $\lambda=441\text{nm}$ and $\lambda=560\text{nm}$ are shown in figures 2a and 2b. The trends of decreasing fluctuation amplitudes with depth suggest that these profiles may be described by an exponential fit. Although, individual values of $e'(z,\lambda)$ can vary by an order of magnitude among the various casts, the rate at which the fluctuations decay with depth does not appear to vary to the same degree. This suggests that the amplitudes
of these fluctuations may be controlled by the intensity of surface processes, however their attenuation rates appear to be less affected by these processes.

The reduction of $e'(z,\lambda)$ values with depth suggests that $e'(z,\lambda)$ may be modeled using the exponential form, $A(\lambda)e^{(-B(\lambda)z)}$. This expression allows both the amplitude ($A(\lambda)$) and the vertical attenuation coefficient ($B(\lambda)$) of the fluctuations to be considered as functions of atmospheric forcing and wavelength. This model accounts for at least 95% of the observed variance for almost all of the profiles analyzed.

The exponential model simplifies the characterization of the observed $e'(z,\lambda)$ profiles by allowing the amplitude ($A(\lambda)$) and vertical attenuation rate ($B(\lambda)$) to be considered separately. Simple correlation analyses were performed by comparing the values of $A(\lambda)$ and $B(\lambda)$ for the 32 profiles with values for other environmental parameters (i.e., $E_d(0^+)$, $[E_d(0^-)\lambda]$, $K_d(\lambda)$, cloud amount, sun altitude angle, and wind speed). The resulting correlation coefficients are shown in table 1 for $A(\lambda)$ and in table 2 for $B(\lambda)$.

It should be noted that significance levels were assigned to the observed correlations based upon the assumption that each cast was an independent event. However, the casts analyzed were frequently made contiguously (Siegel and Dickey, 1987b). Assigning one degree of freedom for each set of casts taken within an hour of each other, the number of degrees of freedom used in determining the significance levels may be better defined as...
Significant correlations must be greater than 0.59 at the 95% confidence interval and greater than 0.46 at the 90% confidence interval. It should be noted that this does not alter the interpretation of the present results.

Table 1: Correlation coefficients for $A(\lambda)$ vs. environmental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>410nm</th>
<th>441nm</th>
<th>465nm</th>
<th>488nm</th>
<th>520nm</th>
<th>540nm</th>
<th>560nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[E_d(0^-,\lambda)]_x$</td>
<td>0.73</td>
<td>0.74</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.74</td>
<td>0.75</td>
</tr>
<tr>
<td>$E_d(0^+)$</td>
<td>0.70</td>
<td>0.71</td>
<td>0.71</td>
<td>0.72</td>
<td>0.73</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Sun angle</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Cloud amount</td>
<td>-0.72</td>
<td>-0.74</td>
<td>-0.74</td>
<td>-0.75</td>
<td>-0.78</td>
<td>-0.78</td>
<td>-0.79</td>
</tr>
<tr>
<td>Wind speed</td>
<td>-0.32</td>
<td>-0.34</td>
<td>-0.36</td>
<td>-0.36</td>
<td>-0.35</td>
<td>-0.34</td>
<td>-0.34</td>
</tr>
</tbody>
</table>

(Value for significant correlation at the 95% confidence interval is 0.41)
(Value for significant correlation at the 90% confidence interval is 0.33)

The correlation coefficients (between the fluctuation amplitude spectrum ($A(\lambda)$) and each environmental parameter) are found to have similar values for the different wavelengths examined (table 1). High positive correlation coefficients are observed between $A(\lambda)$ and those parameters which describe the amount of incident irradiance ($[E_d(0^-,\lambda)]_x$, and $E_d(0^+)$; a significant negative correlation coefficient is found using variations of the cloud amount). This implies that the amount of incident solar radiation controls the amplitude of the in situ irradiance fluctuations to first order. Correlation coefficients relating $A(\lambda)$ and the solar altitude angle are found to be insignificant.

Table 2: Correlation coefficients for $B(\lambda)$ vs. environmental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>410nm</th>
<th>441nm</th>
<th>465nm</th>
<th>488nm</th>
<th>520nm</th>
<th>540nm</th>
<th>560nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[E_d(0^-,\lambda)]_x$</td>
<td>-0.46</td>
<td>-0.54</td>
<td>-0.58</td>
<td>-0.61</td>
<td>-0.17</td>
<td>0.14</td>
<td>0.34</td>
</tr>
<tr>
<td>$E_d(0^+)$</td>
<td>-0.44</td>
<td>-0.54</td>
<td>-0.57</td>
<td>-0.57</td>
<td>-0.03</td>
<td>0.22</td>
<td>0.41</td>
</tr>
<tr>
<td>$K_d(0^-,\lambda)$</td>
<td>-0.35</td>
<td>-0.39</td>
<td>-0.42</td>
<td>-0.44</td>
<td>0.08</td>
<td>0.34</td>
<td>0.55</td>
</tr>
<tr>
<td>Sun angle</td>
<td>-0.33</td>
<td>-0.17</td>
<td>-0.16</td>
<td>-0.16</td>
<td>-0.61</td>
<td>-0.60</td>
<td>-0.57</td>
</tr>
<tr>
<td>Cloud amount</td>
<td>0.32</td>
<td>0.50</td>
<td>0.55</td>
<td>0.58</td>
<td>-0.10</td>
<td>-0.41</td>
<td>-0.61</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.01</td>
<td>0.14</td>
<td>0.18</td>
<td>0.19</td>
<td>-0.12</td>
<td>-0.20</td>
<td>-0.26</td>
</tr>
</tbody>
</table>

(Value for significant correlation at the 95% confidence interval is 0.41)
(Value for significant correlation at the 90% confidence interval is 0.33)

Significant negative correlation coefficients (at the 90% confidence level) between $A(\lambda)$ and wind speed are observed. This suggests that the fluctuation amplitude decreases with increasing wind speed. Partial correlation analysis techniques (Bendat and Piersol, 1986) were used to remove the dependence of $A(\lambda)$ upon $E_d(0^+)$, however the partial correlation coefficients were found to be insignificant. Thus, the observed negative correlation between $A(\lambda)$ and the wind speed is likely to be caused by the significant negative correlation between the wind speed and $E_d(0^+)$ during the 32 spectroradiometer casts ($r=-0.49$).

The spectral character of the correlation coefficients determined between the irradiance fluctuation attenuation spectrum ($B(\lambda)$) and the various environmental parameters are different from those observed between $A(\lambda)$ and the same parameters (table 2). In general, correlation coefficients found using the blue-green wavebands (410-488nm) are opposite from those determined using the yellow-orange wavebands (540-560nm). For the blue-green wavebands, a significant negative correlation is observed between $B(\lambda)$ and those parameters which describe the amount of incident
irradiance (i.e., $E_d(0^+)$, $[E_d(0^-,\lambda)]_\lambda$, and cloud amount). This implies that as the incident irradiance intensity increases, the rate at which the blue-green fluctuations decay with depth decreases, allowing the irradiance fluctuation to reach greater depths. However for the orange 560nm waveband, the fluctuation will be attenuated faster with increasing light intensity.

The spectral behavior for the correlations between $B(\lambda)$ and the other parameters may be influenced by the rate at which the mean light field is attenuated with depth ($K_d(\lambda)$). Values of $K_d(\lambda)$ are roughly the same for wavelengths between 400 and 500nm, however they increase rapidly above 500nm (fig. 3b). The observed spectral variations of $B(\lambda)$ suggest that the magnitude of the mean *in situ* irradiance may control fluctuation attenuation. Also, the spectral similarities between the correlation coefficients relating $E_d(0^+)$ and $[E_d(0^-,\lambda)]_\lambda$ and both $A(\lambda)$ and $B(\lambda)$ imply that the spectral quality of the incident irradiance has little bearing on the observed irradiance fluctuations and their spectral distribution.

![Graphs showing spectral distributions and ratios](image_url)

**Figure 3:** Ensemble mean spectral distributions for $A(\lambda)$, $[E_d(0^-,\lambda)]_\lambda$, $B(\lambda)$, and $K_d(\lambda)$. a) Mean spectra for $A(\lambda)$ (open circles) and $[E_d(0^-,\lambda)]_\lambda$ (solid circles). Units are W m$^{-2}$ nm$^{-1}$. b) Mean spectra for $B(\lambda)$ (open circles) and $K_d(\lambda)$ (solid circles). Units are m$^{-1}$. c) Ratio of the mean $A(\lambda)$ and $[E_d(0^-,\lambda)]_\lambda$ spectra. d) Ratio of the mean $B(\lambda)$ and $K_d(\lambda)$ spectra.

Mean spectra for $A(\lambda)$ and $[E_d(0^-,\lambda)]_\lambda$ and for $B(\lambda)$ and $K_d(\lambda)$ are shown in figures 3a and 3b, respectively. The shapes of the two sets of spectra are similar, although the properties which describe the mean light field (i.e., $[E_d(0^-,\lambda)]_\lambda$ and $K_d(\lambda)$) have larger relative spectral variations than those which describe the fluctuating light field ($A(\lambda)$ and $B(\lambda)$). Generally, there is little spectral variation for the mean $A(\lambda)$, whereas values of $B(\lambda)$ increase rapidly for wavelengths of light greater than 500nm.

The relationships between the optical properties of the mean and fluctuating irradiance distributions may be examined by using their mean ratios. The ratio of the mean $A(\lambda)$ to the mean $[E_d(0^-,\lambda)]_\lambda$ is shown in figure 3c. The mean $A(\lambda)$ varies from 5.2 to 6.5% of the downwelling irradiance spectrum just below the sea surface with a maximum at 488nm. The mean $B(\lambda)$ spectrum normalized by the mean $K_d(\lambda)$ spectrum is shown in
The B(λ) spectrum is nearly twice the mean K_d(λ) spectrum for the blue-green wavebands, however at 560nm they are roughly equal. A breakpoint wavelength of roughly 500nm is observed. The location of the breakpoint is consistent with the change of correlation coefficients discussed previously.

Discussion

The previous analysis indicates that the magnitude of the incident solar radiation plays a major role in the observed irradiance fluctuations. It appears to affect both the fluctuation amplitude and its vertical attenuation rate. Increased incident solar radiation causes the fluctuation amplitude (A(λ)) to increase as expected. However, the complex relationships among the fluctuation attenuation rate (B(λ)), the wavelength of light examined, and the magnitude of the incident solar irradiance suggest that variations of B(λ) are the result of an intricate interplay of surface wave and optical processes.

Values of the fluctuation amplitude (A(λ)) increase with increased solar fluxes as expected. The spectral character of the correlation coefficients between A(λ) and E_d(0+) and between A(λ) and [E_d(0-,λ)] are found to be insignificantly different indicating that to first order the wavelength of light has little bearing upon this relationship. Similar spectral variations are found between A(λ) and cloud amount suggesting that the proportion of diffuse light also has little influence upon A(λ).

The observed mean values of the fluctuation attenuation coefficient (B(λ)) are roughly twice the diffuse attenuation coefficient (K_d(λ)) for the blue-green waveband, however for the green-yellow band the mean values of B(λ) are about the same as K_d(λ) (figs. 3b and d). It is hypothesized that the spectral variations of the mean B(λ) are the result of a combination of wave induced light path variations and the optical properties of the near-surface mixed layer. This may be illustrated by considering a geometric model for the fluctuation light field. The locations on the sea surface from which the light rays originate will be distributed over a circular region above the irradiance sensor. On the average, the distance traversed by fluctuation light rays to the underwater irradiance sensor is further than the light path of the mean irradiance. Thus, the attenuation coefficient for the fluctuation (B(λ)) should be greater than that for the mean irradiance (K_d(λ)). This is the case observed for the blue-green waveband (410-488nm).

For the green-yellow waveband (520-560nm), mean values of B(λ) approach values of K_d(λ). This suggests that the fluctuation light rays may be attenuated rapidly because of the mean absorbing and scattering properties of the mixed layer. Contributions may also be made by inelastic scattering processes (i.e., pigment fluorescence or Raman scattering) which can convert a small fraction of the blue-green fluctuating irradiance to the green-yellow waveband (Yentsch and Yentsch, 1979; Sugihara et al., 1984; Siegel et al., 1986; Stavn and Weidemann, 1988). The distinctions among these effects cannot be made with the present data, however it is unlikely that pigment fluorescence makes important contributions (Yentsch and Yentsch, 1979; Siegel et al., 1986).

The relationship between the fluctuation attenuation coefficient (B(λ)) and the magnitude of the incident solar radiation (E_d(0+)) is particularly curious. The blue-green waveband is negatively (and significantly) correlated with the amount of incident irradiance while the yellow-green waveband tends to show a positive correlation. The cause of the variations of B(λ) may be caused by a complicated interplay of attenuating, inelastic scattering, and incident irradiance variations. An unambiguous interpretation of these variations is not possible with the present data set, suggesting that detailed optical data sets be obtained.

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References


