Spectral variability of in-water downwelling irradiance induced by wave focusing

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Motivation

Campaigns
Small boat in shallow areas of 3 German lakes
421 data sets, 4375 spectra at 0–5 m depth

Observation
Reflectance spectra (in shallow water) can vary strongly in magnitude and spectral shape – why?

Due to variability of downwelling irradiance
Spectral variability of downwelling irradiance in water induced by wave focusing

- Wave focusing induces large fluctuations
- Statistics is well known
- Wavelength dependency?
- Other sources of variability?


Very complete book on the topic:
Spectral variability of downwelling irradiance in water induced by wave focusing

Wavelength dependency of $E_d$ variability (Type 1)

- Smooth spectral shape across VIS
  - no spectral fine structures from $E_d$
  - power law
- Relevance in our data set
  - $\gamma_{VIS}$ average = 5.4 %
  - little depth dependency

$$\gamma_{VIS,i} = \frac{E_{d,i}(400)}{E_d(400)} - \frac{E_{d,i}(700)}{E_d(700)}$$
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Wavelength dependency of $E_d$ variability (Type 2)

- **Characteristic feature in NIR**
  - dominated by water absorption
- **Relevance in our data set**
  - 0–1 m: $\gamma_{\text{NIR}}$ average = 5.7 %
  - > 1 m: $\gamma_{\text{NIR}}$ average = 3.7 %

\[
\gamma_{\text{NIR,i}} = \frac{E_{d,i}(755)}{E_d(755)} - \frac{E_{d,i}(700)}{E_d(700)}
\]
Irradiance model

Irradiance is sum of a direct and a diffuse component

\[ E_d(\lambda, z) = f_{dd} E_{dd}(\lambda, z) + f_{ds} E_{ds}(\lambda, z) \]

- \( E_d \): downwelling irradiance
- \( E_{dd}, E_{ds} \): direct / diffuse component of \( E_d \)
- \( f_{dd}, f_{ds} \): actual fraction of \( E_{dd}, E_{ds} \)

**Wave focusing changes** \( f_{dd} \) and \( f_{ds} \)

Depth dependency of each component according to Lambert-Beer law

\[ E_{dd}(\lambda, z) = E_{dd}(\lambda, 0-) \exp\left\{-\left[a(\lambda)+b_b(\lambda)\right]z\cos\theta_{sun,w}\right\} \]

\[ E_{ds}(\lambda, z) = E_{ds}(\lambda, 0-) \exp\left\{-\left[a(\lambda)+b_b(\lambda)\right]z l_{ds}\right\} \]

- \( l_{ds} \): average path length of diffuse radiation.
- \( z \): water column thickness above sensor.

**Waves alter** \( z \).
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Illustration of irradiance model

\[ E_d(\lambda, z) = f_{dd} E_{dd}(\lambda, z) + f_{ds} E_{ds}(\lambda, z) \]
Inversion of irradiance measurements

WASI software

ftp.dfd.dlr.de/pub/wasi
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Sources of irradiance variance (from model)

1. Changes of direct radiation due to waves
2. Changes of direct radiation due to sensor tilt
3. Changes of diffuse radiation due to waves
4. Changes of sensor depth due to waves and swaying boat

\[
\text{var} \left[ \frac{\Delta E_d(\lambda, z)}{E_d(\lambda, z)} \right] = \left[ \frac{r_d(\lambda, z)}{r_d(\lambda, z) + 1} \right]^2 \text{var} \frac{\Delta f_{dd}}{f_{dd}} + \left[ \frac{r_d(\lambda, z)}{r_d(\lambda, z) + 1} \right]^2 \left( \frac{1}{r_d(\lambda, z) + 1} \right)^2 \text{var} \frac{\Delta f_{ds}}{f_{ds}} + \left[ \frac{1}{r_d(\lambda, z) + 1} \right]^2 \left[ a(\lambda) + b_d(\lambda) \right]^2 \left[ \frac{r_d(\lambda, z)}{\cos \theta_{sun} + l_{ds}} \right]^2 \text{var}[z]
\]
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Importance of sources

1: Changes of direct radiation due to waves
2: Changes of sensor depth due to waves and swaying boat
3: Changes of diffuse radiation due to waves

$\text{Coefficient of determination (r}^2\text{)}$

- $r^2(\text{var}[\Delta E_d/E_d], \Delta f_{dd}/f_{dd})$
- $r^2(\text{var}[\Delta E_d/E_d], \Delta z)$
- $r^2(\text{var}[\Delta E_d/E_d], \Delta f_{ds}/f_{ds})$
Summary and conclusion

3 relevant sources of irradiance variability (intensity and spectral shape)

- Rank 1: Changes of direct radiation due to waves. $\text{var } E_d \sim \left[\frac{1}{(r_d+1)}\right]^2$. Typical: $\pm 5\%$ across VIS.
- Rank 2: Changes of sensor depth due to waves and swaying boat. $\text{var } E_d = f(r_d, a, b, \theta_{\text{sun}}, l_d)$. Typical: $\pm 6\%$ across NIR.
- Rank 3: Changes of diffuse radiation due to waves. $\text{var } E_d \sim \left[\frac{1}{(r_d+1)}\right]^2$

Assignment of "best" in-water measurement requires above-water measurement in order to determine the actual values $f_{dd}$, $f_{ds}$.