Measurements of Wave-Induced Fluctuations in Underwater Radiance Under Various Surface Boundary Conditions

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LONG-TERM GOALS

This project is part of the Radiance in a Dynamic Ocean (RaDyO) program which aims at developing an understanding of variability in underwater radiance distribution and its relation to dynamic processes within the ocean-atmosphere boundary layer.

OBJECTIVES

The principal objective of our project is to measure wave-induced fluctuations in underwater light field under various sea-surface boundary conditions. The specific objectives include the characterization of wave-induced fluctuations in downwelling irradiance and radiance as a function of various environmental parameters such as wind/wave conditions, sky radiance distribution, direction of radiance observation, depth of observation, and water optical properties. The central theme of our study is to characterize light fluctuations at shallow depths caused by surface wave focusing under clear skies. The focusing events are the most intense fluctuations that occur on temporal scales of a fraction of a second. The most prominent manifestation of this phenomenon is high-amplitude short-duration pulses of focused light, which we refer to as light flashes (Dera and Stramski, 1986; Stramski, 1986).

The two primary objectives for this reporting period were: (i) analysis of data collected during the RaDyO experiment in the Santa Barbara Channel in September 2008, and (ii) collection of data during the Hawaii RaDyO experiment in August-September, 2009.

APPROACH

The basic component of our approach involves in situ measurements of high-frequency fluctuations in underwater light field produced by surface waves under various boundary conditions. As reported previously, we developed the Underwater Porcupine Radiometer System, which includes twenty three light sensors providing a capability to measure downwelling irradiance and downwelling radiance with a high sampling frequency of 1 kHz. Sixteen sensors measure radiance at a single waveband (532 nm)

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at different zenith angles within two orthogonal azimuthal planes. Seven sensors measure downwelling plane irradiance at different wavelengths (365, 410, 443, 488, 532, 610, and 670 nm). In addition, the underwater unit is equipped with a depth sensor, temperature sensor, compass, and a rotator that allows us to control the spatial orientation of radiance sensors with respect to azimuthal direction.

Our approach to conduct field experiments involves the acquisition of time-series data (typically 10-min time-series) of light fluctuations at various depths with a 1 kHz sampling rate. The typical 10-min time-series includes 600,000 data points for each sensor. These data are acquired at depths ranging from about 0.5 m to 20-30 m. Most measurements are taken at shallow depths within the top 5 m of the ocean where wave-induced light fluctuations are most intense. The actual strategy for acquiring the data in the field is adjusted during experiments depending on variations in environmental conditions (wind, waves, sky conditions, etc.). This strategy may, for example, consist of the acquisition of successive time-series over a prolonged period of time (hours) at a single depth (e.g., 1 m) or a change of the measurement depth after every 10-min time series. With regard to data analysis, our approach involves the use of various statistical methods for the analysis of stochastic time-series data. The traditional analysis of random processes provides several statistical characteristics of light fluctuations such as statistical moments, probability density function, and frequency spectral density function. Special methods, referred to as the threshold analysis, are used to provide the statistics describing the frequency and duration of wave-focused pulses of focused light, i.e., light flashes.

This project is conducted in collaboration with the Institute of Oceanology, Polish Academy of Sciences (IOPAS) and the new instrumentation was developed at IOPAS. The key participants in the project from IOPAS are Dr. Miroslaw Darecki and an electro-optical engineer Mr. Maciej Sokolski.

WORK COMPLETED

During the first RaDyO experiment in the Santa Barbara Channel in 2008, we collected nearly 230 time-series of light fluctuations from FLIP (M. Darecki and M. Sokolski worked on FLIP). Data processing and computations of the statistics of light flashes caused by wave focusing has been completed during the reporting period. The analysis is underway. This data set was used in collaboration with Dr. George Kattawar's group to compare our measurements of wave focusing with their model that coupling radiative transfer and surface waves. This collaboration has resulted in a manuscript, which will be submitted for publication soon.

During the Santa Barbara Channel experiment we also measured the absorption and scattering properties and particle size distribution (PSD) of discrete water samples on KILO MOANA. R. Rottgers, S. Yildiz, and myself worked on KILO MOANA. In collaboration with Drs. Svein Vagle and Oliver Wurl, we also made experiments to characterize PSD and optical properties of surface microlayer. While our activities on FLIP are funded by the RaDyO program, our research activities on KILO MOANA are not supported by the RaDyO program nor any other grant or agency. We decided to provide this additional contribution to the field experiment in the Santa Barbara Channel because the RaDyO program had no plan for the analysis of discrete water samples. Such analysis provides essential data to support the interpretation of in situ optical measurements. Here we report only on the results of light fluctuations from measurements on FLIP.

In August-September 2009, we participated in the RaDyO field experiment off Hawaii Islands on both FLIP and KILO MOANA (our team consisted of 4 people, M. Darecki and M. Sokolski on FLIP, and P. Gernez and myself on KILO MOANA). Our field work during the Hawaii experiment was similar to that carried out during the Santa Barbara Channel experiment. We collected about 200 time series (each of 10-min duration) of light fluctuations during the Hawaii experiment.

In addition, during the reporting period we conducted a 7-day experiment from the Aqua Alta Research Platform in the Adriatic Sea off Venice. We acquired over 100 time-series (each of 10-min duration) with the Porcupine instrument. The main objective of this experiment was to test the influence of the collector size on the measured fluctuations in downwelling plane irradiance.

RESULTS

Figure 1 shows example probability distributions of downwelling irradiance measured at different depths. These measurements were made under environmental conditions that favor strong wave focusing, that is under clear skies and relatively weak winds. The distributions show characteristic changes from highly asymmetric distributions at shallow near-surface depths to more symmetric, Gaussian-like, distributions at increasing depths. The high asymmetry at near-surface depths is indicative of the presence of high-amplitude pulses of light due to wave focusing.

Figure 2 shows statistical parameters of irradiance fluctuations as a function of depth. The intensity of fluctuations decreases rapidly with depth as indicated by the vertical profiles of the coefficient of variation. The relative intensity of fluctuations is higher for longer wavelengths (the red portion of the spectrum) compared with shorter wavelengths (the blue portion of the spectrum). This can be attributed to higher contribution of diffuse light to total irradiance at shorter wavelengths compared with longer wavelengths, which results from wavelength-dependent light scattering in atmosphere and water. The values for the skewness and kurtosis parameters indicate that light fluctuations were non-Gaussian at shallow depths at least down to 5-10 m (depending on light wavelength) under the conditions of measurements. The rate of this depth transition from non-Gaussian to Gaussian distribution will depend on environmental parameters, for example the optical properties of seawater.

The power spectra of irradiance fluctuations show significant contribution to the variance at frequencies above 1 Hz and a clear reduction of high-frequency content of the signal with depth (Fig. 3). The reduction of the high-frequency components of light fluctuations with depth can be attributed to scattering of direct solar photons as they propagate throughout the water column.

Figure 4 shows example results from threshold analysis of light flashes, specifically the frequency distributions of light flashes measured at different depths. The exponential function provides a good fit to the experimental data of flash frequency versus flash amplitude. The flash amplitude is expressed as a ratio of instantaneous irradiance, E_d, to time-averaged irradiance, $\langle E_d \rangle$ (the averaging time is 2 min). Our results show that the frequency of flashes at the amplitude level $1.5\langle E_d \rangle$ can exceed 500 per minute at shallow depths less or about 1 m under environmental conditions that favor strong wave focusing. The maximum flash amplitudes can be as high as 10 times the average irradiance. These extremely intense pulses of focused light occur at low frequencies of about 1 flash per 10 minutes or less. The frequency and maximum amplitude of flashes decrease rapidly with depth.

Also, these flash parameters are reduced at winds increasing beyond 5-6 m s^{-1}, as seen from a comparison of left-hand panels (weaker winds) and right-hand panels (somewhat stronger winds) in Fig. 4. The durations of individual flashes are on the order of 10 ms and tend to increase with depth (Fig. 5).

The preliminary results from the Santa Barbara Channel experiment shown in this report point to a wealth of novel information about the time-dependent underwater light field. For example, the very high amplitudes of wave-focused pulses of irradiance as shown in Fig. 4 have never been reported in the past. These pulses represent the highest transient concentrations of solar energy that occur in nature, which likely have important implications to photochemical reactions within the near-surface layer of the ocean.

During the Hawaii experiment in August-September 2009, the most significant challenge for maximizing the collection of wave focusing data was associated with weather conditions. The collection of meaningful data for statistical analysis of wave focusing requires stable sky conditions with clear (unobstructed by clouds) sun disk persisting at least for a duration of acquisition of our single time series data file, which is 10 minutes. The highly variable sky conditions, both on within-day and day-to-day time scales, were associated typically with a complex mix of different types of clouds, such as Cu, Ci, Cs, As, Ac. These sky conditions resulted in variable degree of diffuseness of irradiance incident on the sea surface. These variations in irradiance diffuseness occurred typically on relatively short time scales on the order of minutes or less, which seriously challenged our strategy for acquiring wave focusing data. These sky conditions also limited the amount of meaningful wave focusing data that could be collected during the Hawaii experiment.

One of the most interesting and significant aspects of our research is the analysis of the relationships between the statistics of light flashes and wind-wave parameters. With regard to that analysis, we also expect limitations associated with a narrow range of variability in wind-wave conditions throughout the Hawaii experiment. The winds were typically about or above 10 m/s. The wave breaking and significant small-scale roughness were prominent features of surface wave field throughout the entire experiment. Under such conditions, the sea surface is efficiently diffusing the incident direct solar radiation, and as a result the focusing effects underwater are greatly reduced. The maximum focusing effects occur at weak winds up to about 5 m/s with no wave breaking at the surface (Dera and Stramski, 1986; Stramski, 1986). Unfortunately, the high winds experiment off Hawaii will not allow us to reveal the most interesting relationships between wave-induced light fluctuations and the wave field parameters across a broad range of conditions from weak winds accompanied by small surface wave slopes and curvatures to higher winds with steeper slopes and larger curvatures. Nearly all our data from the Hawaii experiment represent similar wind-wave conditions under which wave focusing effects are significantly reduced compared to most favorable weak wind conditions.

In order to maximize the potential for novel scientific analysis of Porcupine data collected on FLIP under the prevailing sky conditions and intermittent cloud cover during the Hawaii experiment, we acquired several long continuous time-series of irradiance fluctuations at a fixed depth near the surface (~1 - 2 m). These time-series lasted 2-6 hours but the data were still collected at a high sampling frequency of 1 kHz. This strategy was adopted to enable the characterization of a broad spectrum of light fluctuations ranging from low-frequency components due to the passage of scattered cumulus (Cu) clouds across the sun disk to high-frequency components due to surface waves, especially pronounced when sun disk is clear and wave focusing of direct sunlight dominates. A 10-min portion of these time-series data is shown in Figure 6. The segments of the data with intense high-frequency fluctuations associated with wave focusing correspond to clear sun disk when direct sunlight dominates the total downward irradiance incident upon the surface. The segments of the data with relatively low irradiance and very small fluctuations correspond to time periods when sun was blocked by Cu cloud and the total irradiance incident upon the surface was dominated by diffuse light.

IMPACT/APPLICATIONS

The major impact of this project is to provide novel data and understanding of wave-induced fluctuations in underwater light field. This phenomenon has been scantily investigated in the past. Our measurements are expected to provide critical information for achieving science objectives of the RaDyO program, including the development and validation of time-dependent coupled surface wave-radiative transfer model. Our findings are also expected to have broader implications beyond the disciplines of ocean optics and physics, specifically in the areas of ocean biology and photochemistry.

RELATED PROJECTS

This effort is related to other projects funded through the RaDyO program.

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Stramski, D. 1986. Fluctuations of solar irradiance induced by surface waves in the Baltic. *Bulletin of the Polish Academy of Sciences, Earth Sciences,* 34, 333-344.

PUBLICATIONS

None.

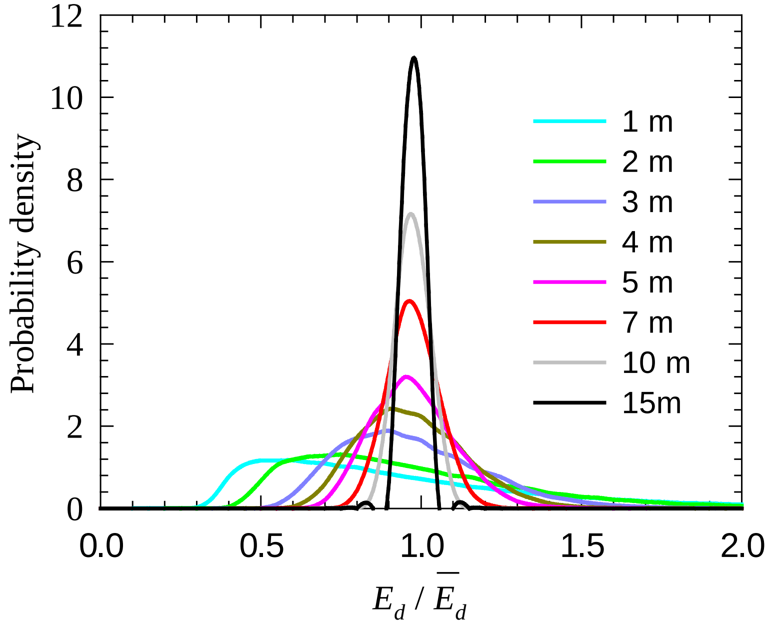

Figure 1. Example probability distributions of downwelling irradiance (normalized to time-averaged irradiance) obtained from time-series measurements at different depths during the Santa Barbara Channel experiment on September 11, 2008. The results are for the light wavelength of 532 nm. The measurements were made under clear skies, sun zenith angle between 31 and 35^o, and wind speed between 4 and 6.5 m s^{-1}.

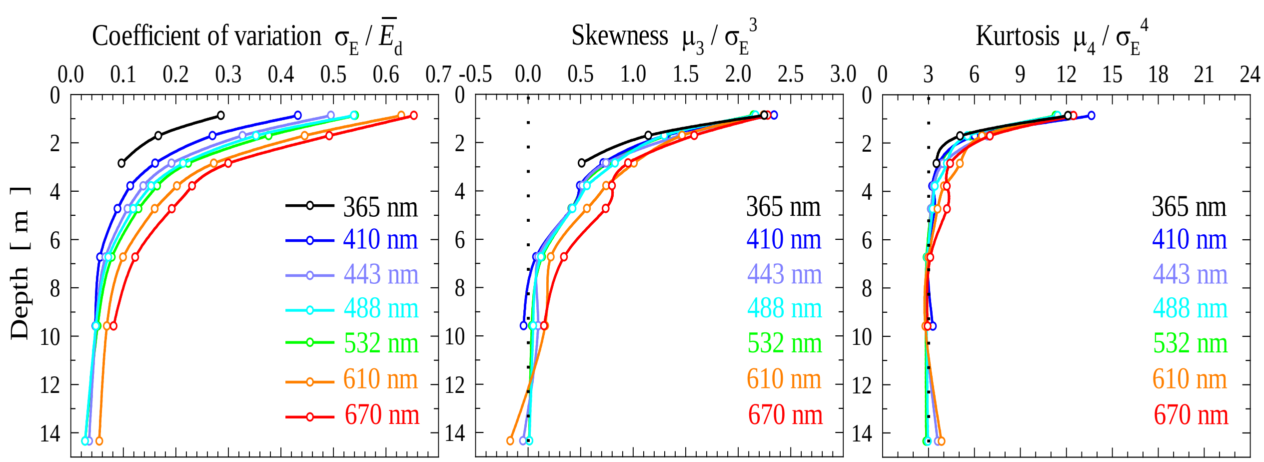

Figure 2. Coefficient of variation, skewness, and kurtosis as a function of depth, as derived from measurements of irradiance fluctuations at different light wavelengths made during the Santa Barbara Channel experiment on September 11, 2008. The measurements were made under clear skies, sun zenith angle of 31 - 35^o, and wind speed of 4 - 6.5 m s^{-1}.

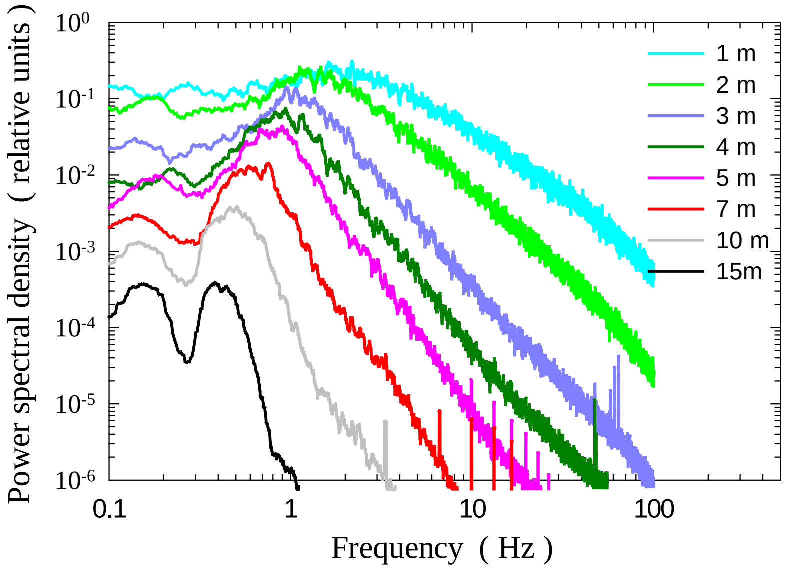

Figure 3. Example power spectral density functions of irradiance fluctuations obtained from time-series measurements at different depths during the Santa Barbara Channel experiment on September 11, 2008. The results are for the light wavelength of 532 nm. The measurements were made under clear skies, sun zenith angle of 31 - 35^o, and wind speed of 4 - 6.5 m s^{-1}.

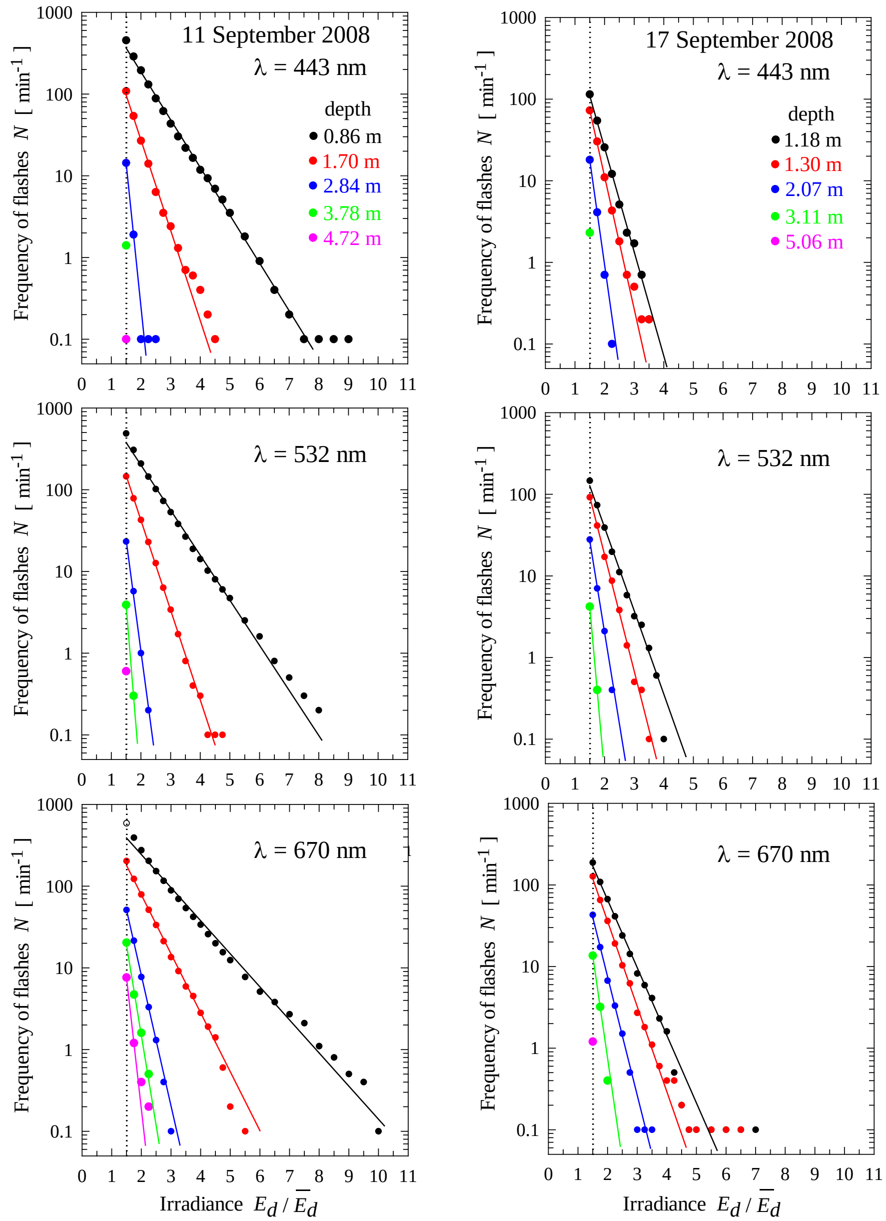

Figure 4. Frequency distributions of light flashes derived from threshold analysis of time-series measurements made during the Santa Barbara Channel experiment. Each graph shows distributions for several depths at a selected light wavelength, as indicated. The left-hand panels represent data obtained on September 11, 2008 under clear skies and wind of 4.1-5.6 m s^{-1}. The right-hand panels represent data obtained on September 17, 2008 under clear skies and wind of 6.7-7.5 m s^{-1}. The instantaneous irradiance at the horizontal axis is normalized to the time-averaged irradiance. The circles represent the actual data and the solid lines are the best-fit exponential function to the data.

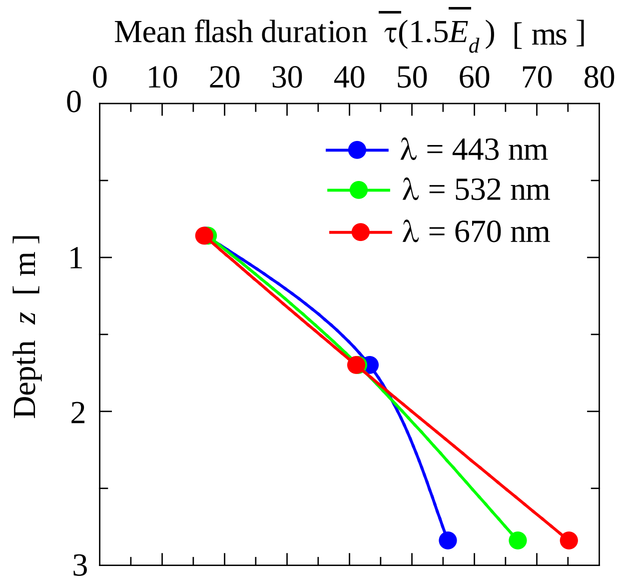

Figure 5. Mean duration of light flashes measured at the amplitude level 1.5<E$_d$>, where <E$_d$> is the time-average downwelling irradiance. The results are shown for three light wavelengths as a function of depth. The measurements were made during the Santa Barbara Channel experiment on September 11, 2009.

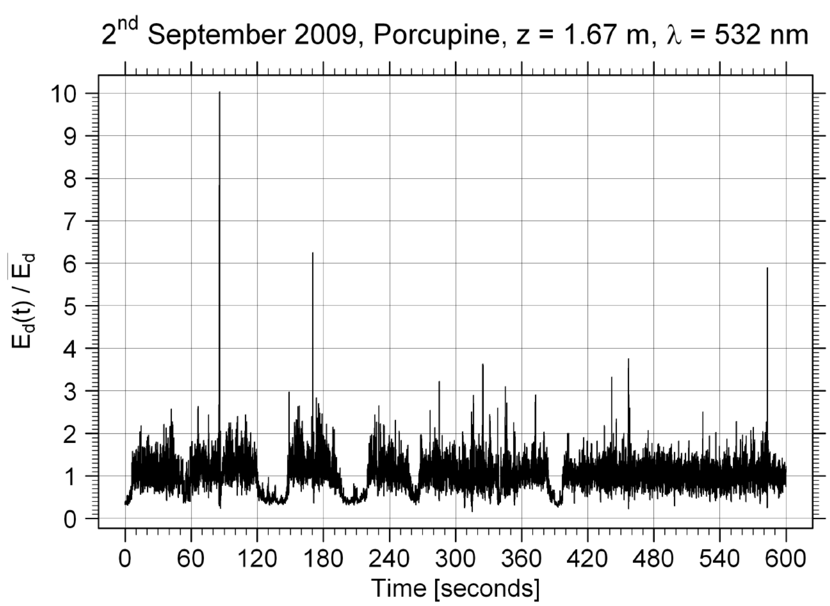

Figure 6. Example 10-min time series of downward irradiance fluctuations measured at a "mean" depth of 1.67 m below the sea surface under typical sky conditions characterized by the presence of scattered cumulus clouds in the sky during the Hawaii experiment.