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Lidar Measurements of the Diffuse Attenuation Coefficient in Yellowstone Lake

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Abstract: Airborne lidar study of lake ecosystems is still a relatively unexplored field. In this paper we present measurements of the diffuse attenuation coefficient of downwelling irradiance (K_d) obtained using a 532 nm airborne lidar in flights during the years 2004 and 2016 over Yellowstone Lake, Yellowstone National Park, Wyoming, USA. We compare the lidar measurements with MODIS K_d data, discuss the impact that local weather and river inflows/outflows may have had on the data, compare to previous models of the diffuse attenuation coefficient, and examine several published relationships converting K_d to Secchi disk depth.

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1. Introduction

Study of the spatial heterogeneity of species and biological processes is an important component of limnology that is just beginning to receive attention. While in the past many authors have assumed lakes to be spatially homogeneous, recent research has highlighted the importance of spatial heterogeneity of trophic parameters [1–3]. In this paper we discuss direct measurements of the diffuse attenuation coefficient of downwelling irradiance (K_d) obtained using airborne lidar in flights during September 2004 and September 2016 over Yellowstone Lake, Yellowstone National Park, Wyoming, USA. This work is an extension of lidar attenuation coefficient measurements in Yellowstone Lake previously reported in [4].

These data are presented to expand the base of optical data available from lakes, specifically from Yellowstone Lake. Previous optical measurements in Yellowstone Lake consist solely of Secchi disk measurements which were made at intermittent intervals in limited locations [5, 6]. This work represents the first fully quantitative measurements of the optical properties of Yellowstone Lake and the largest body of optical measurements in Yellowstone Lake to date.

2. Background

On September 21, 2004 and September 28, 2016, we undertook flights of Yellowstone Lake using the National Oceanic and Atmospheric Administration (NOAA) Fish Lidar and the Montana State University (MSU) Fish Lidar, respectively. The NOAA lidar was operated at 532 nm with a 100 mJ pulse energy and 30 Hz pulse repetition frequency (PRF). At the time of these measurements, the lidar had a single receiver channel, which was sensitive to either the co- or cross-polarized light [7, 8]. Later versions of the lidar added a second channel for simultaneous measurements of the co- and cross-polarized signal [9, 10]. The measurements reported here were obtained from the cross-polarized return. Note that the difference in attenuation observed using the cross-polarized return, the co-polarized return, or the total unpolarized return is small [11, 12]. The beam spot diameter on the water was five meters, and the lidar was mounted to point 15° off nadir to reduce unwanted reflection from the surface. The typical flight altitude was 300 m, but portions of the flight were run at 150 m. Typical flight speed was 40 m/s, resulting in 73%

overlap between adjacent shots.

The details of the MSU Fish Lidar have been reported previously in [13], and we will only briefly summarize its design here. The MSU Fish Lidar is a 532 nm, direct-detection, pulsed lidar, with a 26 mJ pulse energy and 50 Hz PRF. The MSU Fish Lidar measured both co- and cross-polarized backscatter signals simultaneously. Spot diameter on the water surface is 5 m, and penetration depth is typically between 6 and 12 m. Flight altitude was 300 m and speed was 40 m/s. The high PRF and slow aircraft speed led to 84% overlap of neighboring shots. The primary purpose of this flight was to survey for invasive lake trout [14], and we also recorded the first-known lidar measurements of hydrothermal vents [15].

To compute the diffuse attenuation coefficient, the co- and cross-polarized signals from the MSU Fish Lidar were summed (for the 2004 NOAA Fish Lidar only the cross-polarized signal was available) to produce an unpolarized signal $S(z)$. This signal is given by

$$S(z) = A\beta \exp\left(-2 \int_0^z K_d dz'\right), \quad (1)$$

where A is a calibration constant resulting from the parameters of the lidar and β is the volume scattering coefficient at angle π [11, 16, 17]. We assume that both β and K_d are nearly constant over the penetration depth, and thus derive a depth-averaged attenuation coefficient. No additional homogeneity is assumed.

Surface and bottom detection was performed on the summed signal, and the result was used to determine the penetration depth. If a bottom was detected, the penetration depth was from the surface to the bottom; otherwise the penetration depth was from the surface to the tail of the reflected pulse. The slope of the linear regression of $\ln S(z)$ was calculated to compute K_d , an extension of the slope method used in atmospheric lidar [11, 17]. The constants A and β become a constant offset in the regression and do not affect the slope. Regressions with $r^2 < 0.9$ and penetration depths < 1 m were excluded from the results. The condition that r^2 be high ensures that the assumption that both β and K_d are nearly constant is satisfied for the data used in the analysis.

3. Results

Figures 1 and 2 show raster images of the diffuse attenuation coefficient data from the 2004 and 2016 flights, respectively. These images were created using inverse-distance-weighted interpolation from the flight data, so data points far from the flight path should be treated with caution.

The 2016 map shows many areas of local variability in attenuation and some spatially homogeneous areas (notably the West Thumb). Some areas of high attenuation are associated with river and creek inlets and known underwater hydrothermal vents, which may result in the locally higher attenuation observations, and these areas are called out on the map.

Figures 3 and 4 show histogram plots of the shot penetration depth, bottom depth, and K_d for the 2004 and 2016 flights, respectively. The purpose of these figures is to present the lake-wide measurements for each year. Due to the differing flight paths, direct comparison of the 2004 and 2016 data is not possible.

For 2004, the mean K_d was 0.13 m^{-1} (std. 0.04 m^{-1}) and the median was 0.12 m^{-1} . For 2016 the mean K_d was 0.28 m^{-1} (std. 0.26 m^{-1}) and the median was 0.17 m^{-1} . Previously in [13] we modeled K_d using two different methods and arrived at values of 0.25 m^{-1} and 0.27 m^{-1} for the 2016 conditions, both of which are well within one standard deviation of the 2016-measured mean here.

4. Discussion

We compared the calculated lidar K_d values with eight-day-averaged K_d measurements retrieved by the Moderate Resolution Imaging Spectrometer (MODIS). The MODIS K_d measurements at 490 nm were corrected to 530 nm using a model from [18]. Table 1 compares the lidar and MODIS measurements of K_d .

For the 2004 data we retrieved an eight-day-average K_d measurement from MODIS starting on September 21, 2004, the day of the flight, as daily data for that day were unavailable. The mean MODIS K_d for Yellowstone Lake was 0.14 m^{-1} (std. 0.08 m^{-1}), with min/max of 0.08/0.31. For this flight the MODIS-measured value corresponds closely to the values measured by the lidar. Weather conditions at the lake during the MODIS measurement window largely matched those immediately prior to the flight.

For the 2016 data we retrieved an eight-day-average K_d measurement from MODIS ending on September 28, 2016 (the 2016 lidar flight day). The mean MODIS K_d for Yellowstone Lake was 0.50 m^{-1} (std. 0.09 m^{-1}) with min/max of 0.39/0.63. The lidar measurements still agree with MODIS to within one standard deviation, although MODIS had only two pixels on the lake, so it recorded massively less spatial variability than the lidar. This flight had many areas of locally high attenuation that were not resolved by the satellite sensor.

During the eight-day-averaged MODIS measurement window for the 2016 flight, the lake received several days of heavy rain; however, for three days prior to the flight there was no

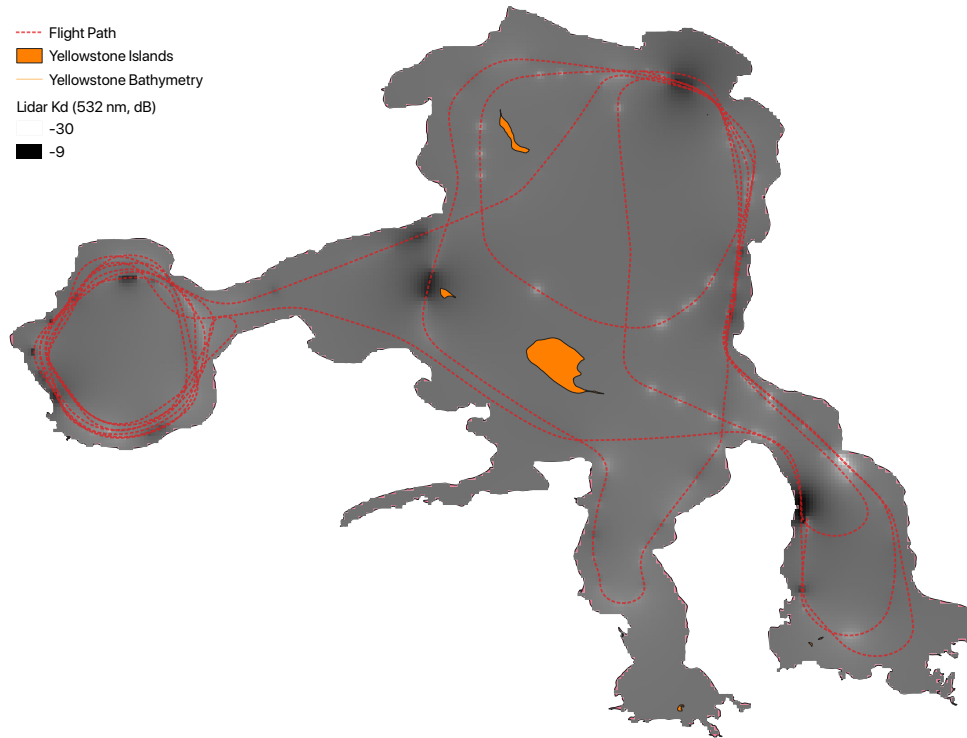


Fig. 1. Map of the diffuse attenuation coefficient in Yellowstone Lake from the September 21, 2004 flight in units of dB (re 1 m^{-1}) to increase the image contrast, calculated using inverse-distance-weighted interpolation. Data far from the flight path should be treated with caution.

precipitation. Heavy rainfall events wash particulate matter into the lake in a runoff plume [19,20], which has been shown to temporarily increase K_d [21], and which could help explain the higher K_d seen in the MODIS measurement window.

The only previous optical measurements in Yellowstone Lake are Secchi disk depths, z_S . Theriot et al. performed a long-term study of limnological parameters in Yellowstone Lake and found a mean Secchi disk depth of 8.1 m (std. 2.6 m) [5]. To compare our measured lidar attenuation with these values, a relationship between z_S and K_d is required. A recent theoretical investigation concluded that Secchi depth could be well approximated by $z_S = 0.95/K_d$ [12]. Here, K_d is the minimum value at several wavelengths across the visible range. The value at 532 nm is very close to this minimum, except in clear open-ocean waters. With this relationship, we infer Secchi depth values of 7.3 m and 3.4 m for the 2004 and 2016 averages.

The Secchi depth values estimated from the lidar are a little less than the Secchi disk measurements, so we considered relationships explicitly derived for lakes. Arst et al. [18] obtained a relationship between z_S and K_d for several lakes in Finland and Estonia. They found $z_S = 2.178 K_d(\text{PAR})^{-1.4769}$, where $K_d(\text{PAR})$ is the attenuation coefficient of Photosynthetically Active Radiation (400-700 nm). We used the spectral model of Morel and Maritorena [22] to relate the lidar measurements to $K_d(\text{PAR})$, with the result $K_d(\text{PAR}) = 1.28 K_d(532) + 0.102$.

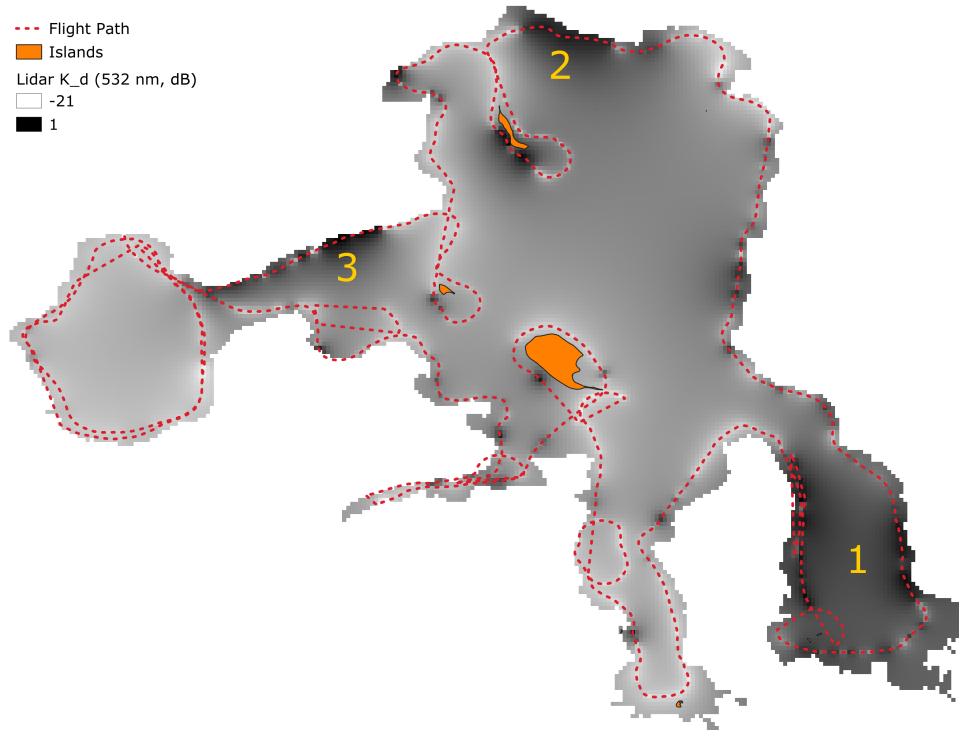


Fig. 2. Map of the diffuse attenuation coefficient in Yellowstone Lake from the September 28, 2016 flight in units of dB (re 1 m^{-1}) to increase the image contrast, calculated using inverse-distance-weighted interpolation. Higher attenuation in the Southeastern Arm (1) and the northern portion of the lake (2) is likely associated with the inlet of the Yellowstone River and Pelican Creek, respectively, and the higher attenuation at (3) is may be the result of a series of hydrothermal vents directly under the flight path in that area. Data far from the flight path should be treated with caution.

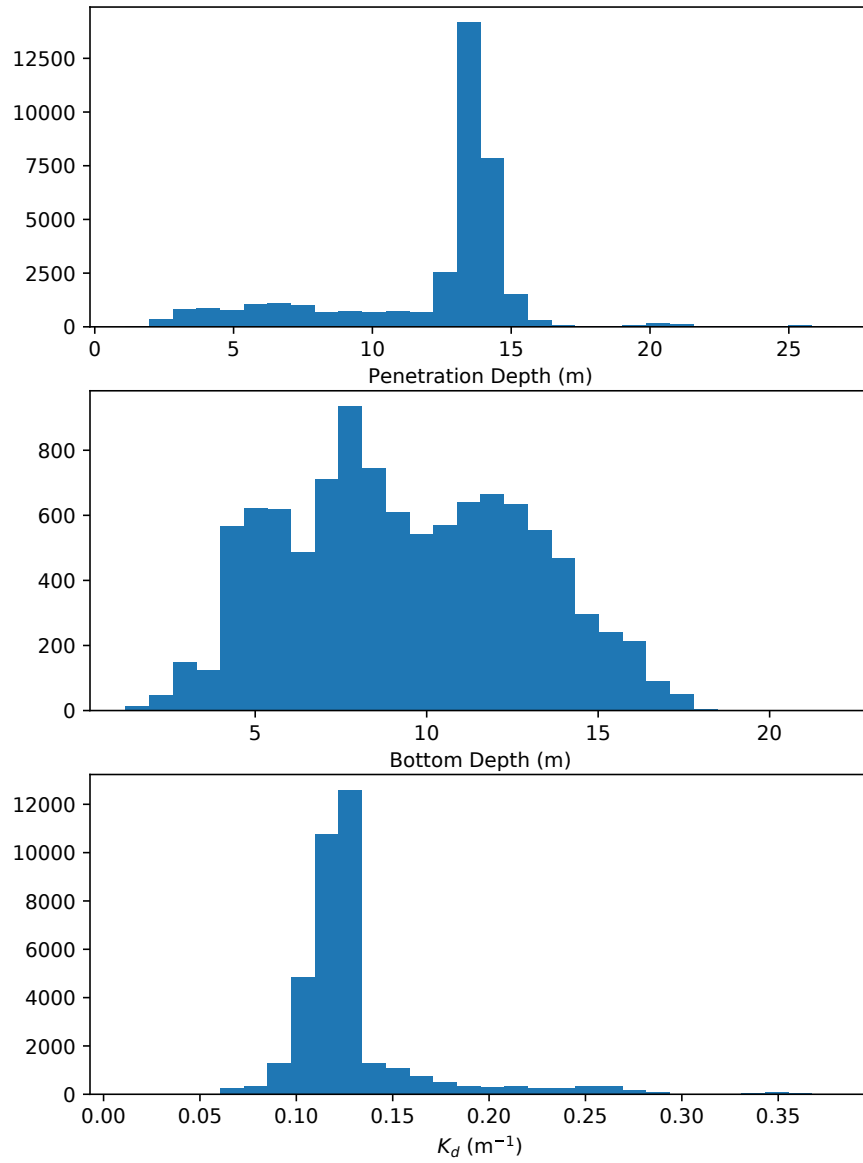


Fig. 3. Histogram plots of the shot penetration depth, the bottom depth, and the calculated K_d from the 2004 flight. The NOAA lidar had a more powerful laser and larger telescope than the MSU lidar, which allowed it to achieve greater penetration depths.

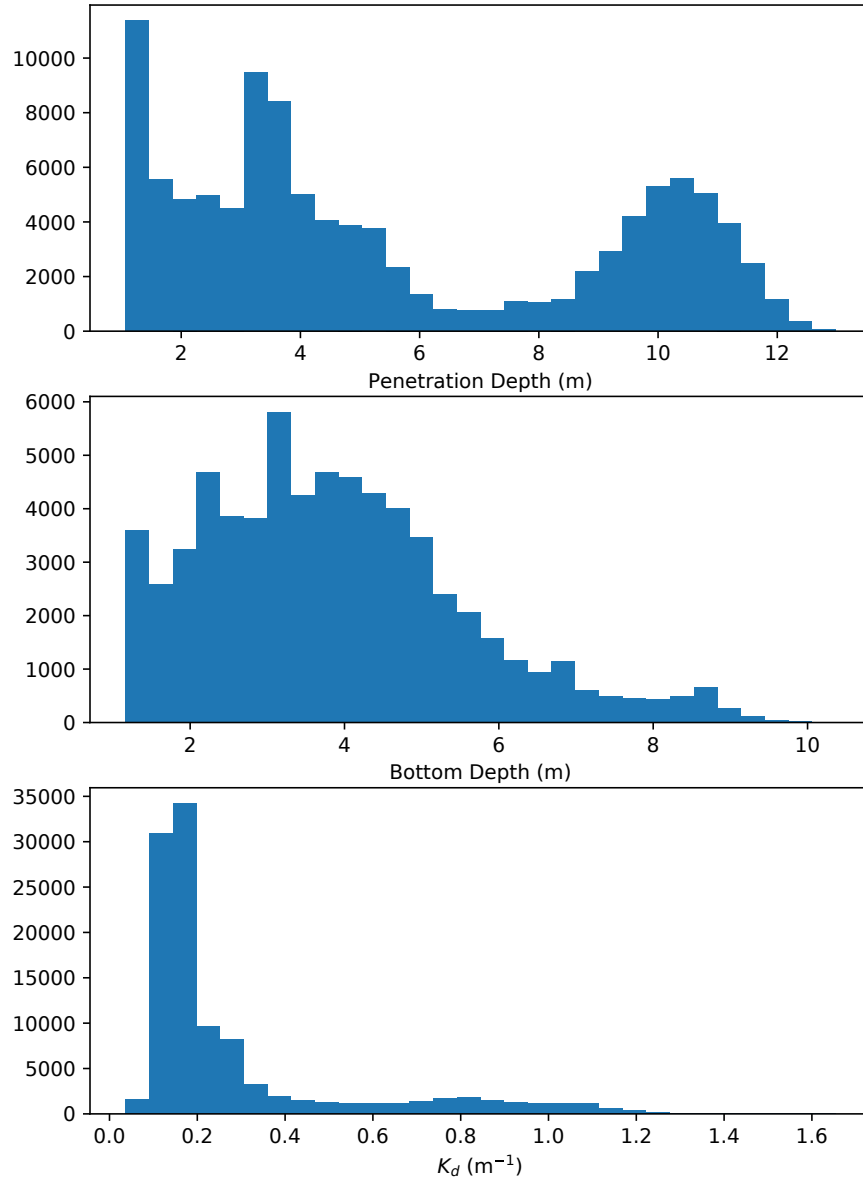


Fig. 4. Histogram plots of the shot penetration depth, the bottom depth, and the calculated K_d from the 2016 flight. The bimodal penetration depth distribution results from a combination of high K_d and/or the bottom limiting penetration depths, and low K_d and a deep bottom allowing deeper penetration depths.

		Mean (m^{-1})	Median (m^{-1})	Std. (m^{-1})
2004	Lidar	0.13	0.12	0.04
	MODIS	0.14		0.08
2016	Lidar	0.28	0.17	0.26
	MODIS	0.50		0.09

Table 1. This table summarizes the lidar and MODIS measurements of K_d for 2004 and 2016. The differing flight paths flown each year precludes direct comparison of the 2004 and 2016 lidar data.

This provided estimates for Secchi depths of 15.2 m and 6.8 m for 2004 and 2016.

Finally, we consider a relationship derived for Lake Baikal, Russia [23]. They found that $Z_s = 1.146/(K_d(480) - 0.01)$. After using our measurements of $K_d(532)$ to estimate $K_d(480)$, we obtain mean Secchi depths of 8.7 m and 3.1 m for 2004 and 2016. The mean Secchi depths from the 2004 lidar measurements are close to the average measurements using the theoretical expression [12] and the Lake Baikal measurements [23]. The 2016 lidar measurements provide Secchi depths that are less than the Secchi disk values, possibly because the 2016 flights were generally closer to the shore. Research to develop a relationship specific to Yellowstone Lake is recommended.

5. Conclusion

We have presented two sets of airborne lidar data where we derived the diffuse attenuation coefficient of downwelling irradiance (K_d) in Yellowstone Lake. Previous measurements of optical properties in Yellowstone Lake are few and consist solely of Secchi disk depth measurements.

In the 2016 flight we saw significant geographic variability and proposed that areas of locally high attenuation could be the result of river and creek inflows and hydrothermal vents.

We compared our measurements to MODIS measurements of K_d at 490 nm. Using a relationship developed by Arst et al., we converted these measurements to 530 nm for comparison. Our 2004 results agreed with the MODIS measurements, and the 2016 flight measured a lower attenuation coefficient than MODIS, which may have been the result of heavy rain prior to the flight causing runoff that elevated the MODIS measurements over the 8-day averaging window.

Using several published relationships, we converted our K_d measurements to Secchi disk depth. The 2004 results were consistent with mean Yellowstone Lake Secchi depths using a theoretical relationship and one based on measurements at Lake Baikal.

The data presented here represent the largest body of optical measurements in Yellowstone Lake to date, and are the first large-scale study of the spatial heterogeneity of the optical attenuation in Yellowstone Lake. Airborne lidar enables the collection of data over large areas of water at significantly lower cost than traditional methods, and may allow for better understanding of how limnological processes vary over much finer spatial and temporal scales than previously understood, especially given that airborne lidar provides many orders of magnitude higher spatial resolution than current satellite remote sensing capabilities.

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Disclosures

The authors declare no conflicts of interest.

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