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Coupling ocean models and satellite derived optical fields to estimate LIDAR penetration and detection performance

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ABSTRACT

A global-scale climatological assessment of the temporal and spatial relationships between physical and optical ocean layers was previously performed to determine LIDAR efficiency for measuring the 3D Ocean. That effort provided estimates of laser sensor penetration depth (PD) in the global oceans and identified critical coupling between Mixed Layer Depth (MLD) and Optical Depth (OD) based on potential laser power and ensuing attenuation. We make use of a Bio-Physical ocean model configured for the Gulf of Mexico (GOM) along with remotely sensed satellite measurements to examine LIDAR performance in the Gulf of Mexico coastal regions. The 4Km GOM ocean model runs in near-real-time and produces physical and bio-optical fields which are coupled to in-house derived satellite bio-optical products such as the Diffuse Attenuation Coefficient at 490 nm (Kd_{490}). PD and MLD are coupled to determine laser power efficiency rates across multiple attenuation lengths. The results illustrate the potential utilization of space-borne oceanographic LIDAR to penetrate through the water column, elucidating its applicability for a variety of scientific (**characterization of the ocean subsurface layers)** and applied (**target detection**) objectives.

Keywords: LIDAR, Attenuation Length, Optical Depth, Penetration Depth, Mixed Layer, Gulf of Mexico

1. INTRODUCTION

Passive radiometric instruments, such as the Sea-viewing Wide Field-of-view Sensor (SeaWIFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS), have given us unparalleled insight and understanding of the seas, but these instruments only measure an integrated signal of the upper ocean, heavily weighted towards the surface and entirely missing vibrant ecological areas, deep bio-active layers, and productive zones. In prior work[1,2,3], we elucidated the utility of oceanographic LIDAR by assessing its potential penetration at global and climatological scales. That work was primarily a theoretical evaluation of the capabilities of space-borne oceanographic LIDAR that was motivated by the scientific rewards achieved by the only known LIDAR in space: NASA's CALIPSO-CALIOP (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations - Cloud-Aerosol LIdar with Orthogonal Polarization). However, CALIPSO-CALIOP was designed to target the atmosphere, not the ocean.

In this assessment, we implement similar analysis, but with focus on the Gulf of Mexico. We estimate the number of attenuation lengths needed for a LIDAR to penetrate to the Mixed Layer Depth (MLD) using diffuse attenuation coefficients from MODIS-Aqua, and mixed layer depths computed directly from NRL's Gulf of Mexico Modeling System (GOMMS)[4] temperature and salinity daily-averaged fields. Climatological (2002-2011) means are shown and discussed for general assessment and comparison to previous global studies, while real-time in-house-derived imagery and corresponding model-derived MLD products are used on an experimental operational basis.

2. METHODOLOGY

The diffuse attenuation coefficient provides a measurement of water turbidity impacting light penetration into the upper ocean. The mixed layer, generally considered a quasi-uniform layer owing its existence to turbulent mixing due to air/sea energy exchanges, influences the majority of the upper ocean bio-optical-physical interactions, impacting light and nutrient distribution; and hence, we explore these interactions by assessing LIDAR configurations to penetrate to or below the Mixed Layer Depth (MLD).

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The diffuse attenuation coefficient for downwelling irradiance, K_d (m^{-1}), is an important parameter for remote sensing of ocean color and a frequently used property of seawater. K_d at the 490 nm wavelength, $K_d(490)$, is a commonly available quantity frequently derived from satellite observations, and because it is strongly correlated to phytoplankton chlorophyll concentrations, it provides a connection between optics and biology[5,6,7,8]. Using K_d in connection with the subsurface physical structure, such as the MLD, enables coupling of optics, biology, and physics. Figure 1 illustrates the differences and similarities among the biological (Chlorophyll), optical ($K_d(490)$), and physical (MLD) fields for the 2002-2011 seasonal climatology (data sources described in section 2.1 and 2.2 and summarized in table 1). Consequently, satellite-derived $K_d(490)$ and model-derived MLD are used in this study to obtain estimates for the assessment of oceanographic LIDAR potential aptitude in the Gulf of Mexico.

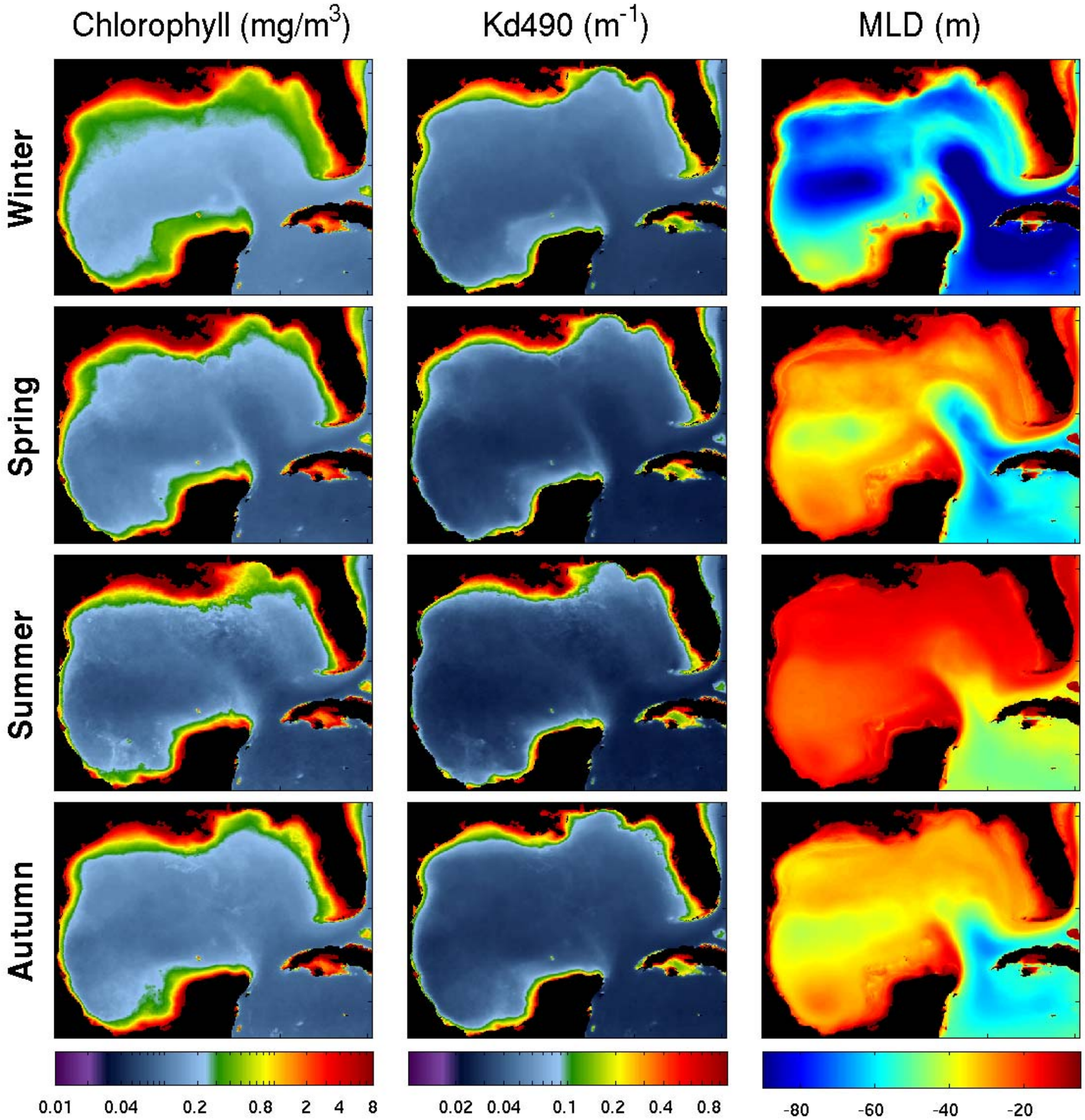

Figure 1. 2002-2011 seasonal (Winter: Dec-Feb, Spring: Mar-May, Summer: Jun-Aug, Autumn: Sep-Nov) climatology comparison of biological (chlorophyll-a from MODIS-Aqua), optical ($K_d(490)$ from MODIS-Aqua), and physical (Mixed Layer Depth from GOMMS) illustrating the linkage among these fields, most notably in the loop current regimes and the upwelling coastal zones.

In seawater, and pertinent to this analysis, the relative importance of K_d is related to the power, measured in attenuation lengths or optical depths, of an instrument. Waters of varying turbidity have varying degrees of attenuation values which are directly related to the ocean bio-active layers predominantly concentrated within the euphotic zone in the upper 100m, but more precisely in the mixed layers which vary greatly, as shown in Figure 1, according to season, latitude, and other factors. Thus, given the power of a laser instrument, we make use of MODIS-Aqua derived $K_d(490)$ to calculate penetration depths and attenuation lengths needed to reach the Mixed Layer Depth.

2.1 Methods

From Beer-Lambert Law[9],

$$E_d(\lambda, z) = E_d((\lambda, z{=}{\sim}0)\ e^{-Kd(\lambda,z)\,z}, \quad (1)$$

where, for any wavelength λ, the spectral downwelling irradiance E_d (at depth z) is exponentially proportional to that of its near surface value $E_d(z{=}{\sim}0)$ by the diffuse attenuation coefficient K_d, the physical penetration depth (z) can be estimated by:

$$\frac{\tau}{K_d(\lambda)} = z\ , \quad (2)$$

where τ is the optical depth, and $K_d(\lambda)$, is the diffuse attenuation coefficient valid at the surface and assumed vertically homogeneous through the water column.

Since satellite sensor power is nominally measured in integral (i.e. 1,2,3) attenuation lengths (AL) --equivalent to optical depths, equation 2 can readily be written as:

$$PD = \frac{AL}{K_d(\lambda)}, \quad (3)$$

where PD is the Penetration Depth of a laser having AL power and penetrating water of turbidity prescribed by $K_d(\lambda)$.

Current lasers are ranging at about 3 optical depths, capturing 3-dimensional vertical structure by measuring the time-space dependent return intensity of the light pulses they actively emit --the higher the pulse frequency, the higher the vertical resolution represented. Presently, due to the maturity, relatively inexpensive cost, and widespread applicability of the technology, most LIDAR systems use diode pumped (Neodymium-Doped Yttrium Aluminium Garnet) Nd:YAG lasers, and inherent of this material is its fundamental 1064nm frequency that is frequency doubled to 532 nm to penetrate water with much less attenuation than at 1064nm[10,11]. We, therefore, focus our analysis on the 532 nm wavelength and explore implications at 490 nm. Since the objective here is to assess the theoretical potential of LIDAR to penetrate to the MLD, equation 3 is solved for AL, and MLD is substituted for PD, in order to derive the number of attenuation lengths needed to reach the mixed layer depth; that is:

$$AL = \text{MLD} \times K_d(\lambda). \quad (4)$$

2.2 Data: Diffused attenuation coefficient (K_d)

The MODIS-Aqua 4 Km monthly climatology (2002-2011) of the downwelling diffused attenuation coefficient at 490 nm $K_d(490)$ was downloaded from NASA's Ocean Color website[12]. For the near-real-time assessment, the 7-day latest pixel (most recent pixel over the last 7 days) composites for $K_d(490)$ were in-house derived using the Automated Processing System[13] for the latest (near-real-time) date (September 6, 2012 at the time of this paper).

K_d at the 532 nm wavelength, was derived using the well adopted empirical equations of Austin and Petzold (A&P)[14,15],

$$K(\lambda') = M(\lambda')\ [K(\lambda_{ref}) - Kw(\lambda_{ref})] + Kw(\lambda'), \quad (5)$$

The resulting K_d values represent the first optical depth as measured by the satellite, and for this analysis are assumed homogeneous for the entire water column. The seasonal climatology (2002-2011) of the Penetration Depth, as computed by equation 3, using $K_d(490)$ and $K_d(532)$ are shown in Figure 2.

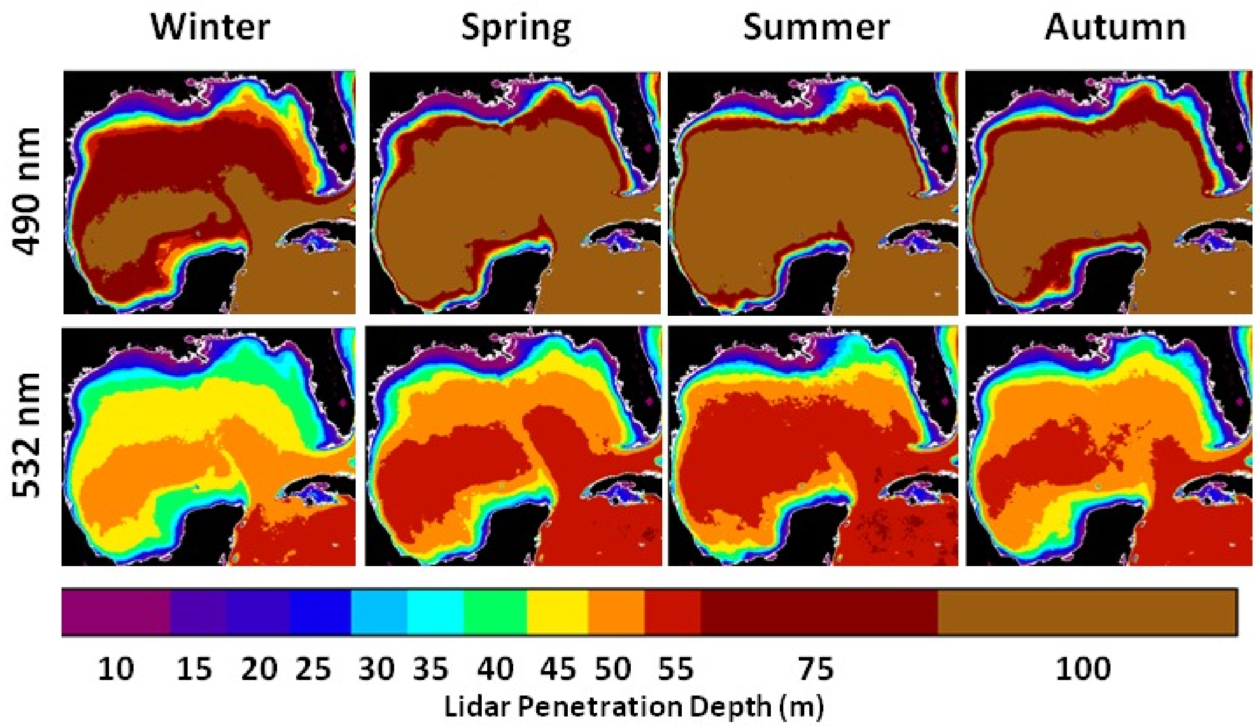

Figure 2. A seasonal climatology comparison of the penetration depth ($PD = AL/ K_d(\lambda)$) afforded by the 490 nm (top) and 532 nm (bottom) wavelengths at 3 attenuation lengths (AL) –the nominal power of current laser technology. The 490 nm band, better suited for CASE I waters, dominates the deeper open ocean.

2.3 Data: Mixed Layer Depth (MLD)

The Naval Research Laboratory (NRL) has been running a bio-optical-physical Gulf of Mexico ocean model (18ºN - 31ºN, 77ºW - 98ºW) interannually since 2000 and extending into near-real-time. The model has a 4Km horizontal resolution which coincides with the MODIS-Aqua 4Km dataset. The model is data-assimilative and has been shown to well-represent the circulation of the Gulf[4]. We make use of these data to construct a mixed layer depth dataset that is temporally and spatially coincident to the satellite derived K_d values.

For reasons explained in the literature[3], in order to properly account for those regions significantly influenced by salinity fluxes and thermohaline circulation, we compute a density-based MLD for the Gulf of Mexico from the model daily-averaged temperature and salinity fields using the difference criteria described in Kara et al.[16]. Table 1 summarizes the $K_d(490)$ and MLD datasets used in this work.

Table 1. Summary of the datasets used in this analysis. Monthly Climatologies are monthly averaged values across several years; 2002 to 2011 for all datasets. Latest Pixel Composites and MLD daily values are in-house products produced in near real-time for nowcasting/forecasting purposes.

Dataset	Source
MODIS-Aqua Monthly Climatology K_d (490)	Downloaded from web[12]
MODIS-Aqua daily (latest pixel composites) K_d (490)	In-housed derived via APS[13]
Mixed Layer Depth (Monthly Climatology and daily)	GOMMS derived via Kara[16]
Monthly Climatology and daily K_d (532)	Derived from K_d (490) via A&P[14,15]

3. RESULTS AND DISCUSSION

Given the ocean model derived MLD and the satellite-derived MODIS-Aqua $K_d(490)$ and ensuing $K_d(532)$ fields, we computed the attenuation lengths (ALs) required to reach the MLD for the seasonal climatology (Figure 3), and a selected (nearly cloud free) 7-day composite image (September 1-6, 2012), which at the time of this paper, was the latest up-to-date image.

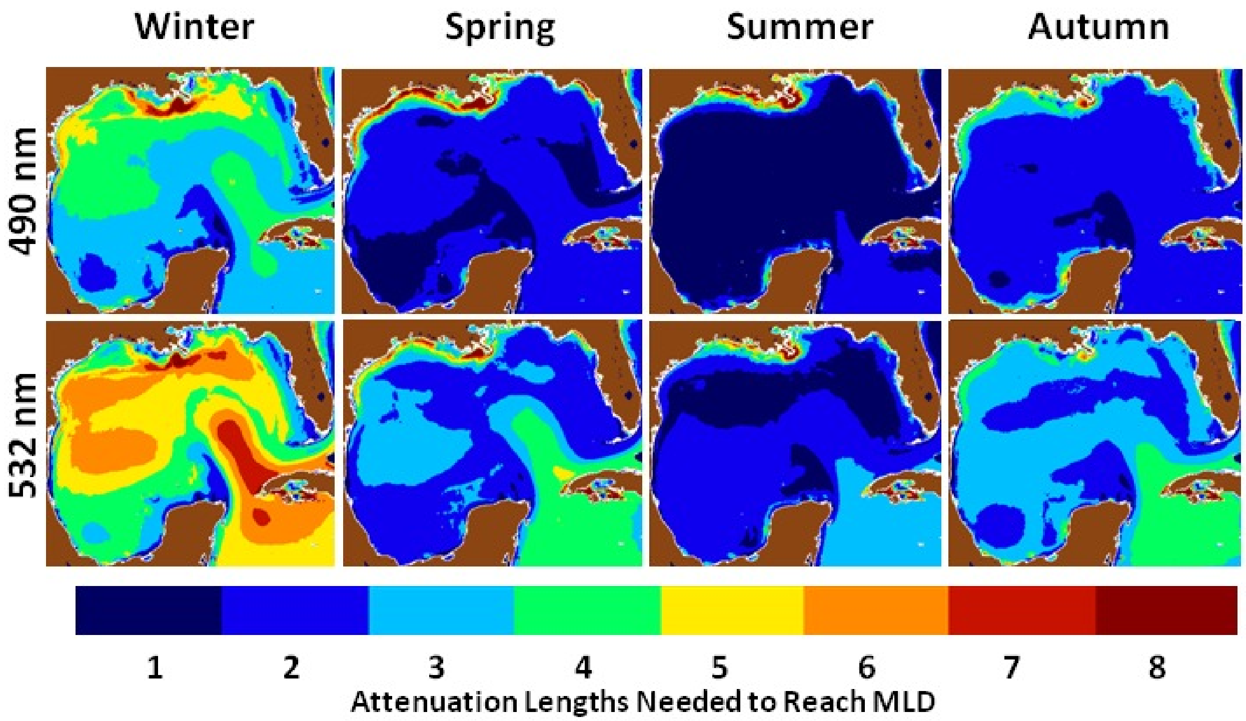

Figure 3. The seasonal (2002-2011 climatology) attenuation lengths to reach the MLD are shown for 490 nm (top) and 532 nm (bottom). This figure summarizes this study showing the number of attenuation lengths a LIDAR would need to penetrate to or beyond the mixed layer. As expected, most of the CASE I waters can be "seen" by LIDAR at less than 3 ALs regardless of spectral band. Coastal zones, however, become more challenging as the turbity increases significantly enough to need higher power (> 5 ALs) to be penetrated.

Complementing Figure 1 and 2, Figure 3 further exposes the relationships between physical and biogeochemical ocean processes, such as temperature gradients, water characteristics, and nutrient upwelling in the coastlines. Chlorophyll (plankton) concentrations are higher in coastal areas than they are in the open ocean affecting the turbidity of the water and therefore the penetration of LIDAR. Clearly, as expected, the 490 nm is superior in class I waters and in general, but 532 nm does slightly better in the "greenest" of coastal waters as depicted in the summer (Figure 3) around the Mississippi River plume.

The blue-green visible spectra are optimal for remote sensing of the oceans. K_d at 490 nm (blue) is particularly well suited for the maximum penetration of the open "blue" ocean waters as seen in the central Gulf (Figures 3,4) with a clear difference in the summer. The green (532 nm) is better suited for optimum penetration in shallower coastal eutrophic waters, which are dominated by seasonal blooms and river fluxes, specifically, runoff from the Mississippi River. Neglecting any consideration for scattering, in the Gulf of Mexico, the 490 nm frequency has a deeper penetration in a larger percent of the ocean and performs better in general, but since 532 nm constitutes the fundamental laser frequency for current lasers whose nominal power is estimated at 3 attenuation lengths, the estimation of 50-60% (on average) penetration to the MLD is perhaps the best current technology can do. Auspiciously, "tunable" lasers are already being developed and future LIDAR technologies may allow spatio-temporal tuning of their bands.

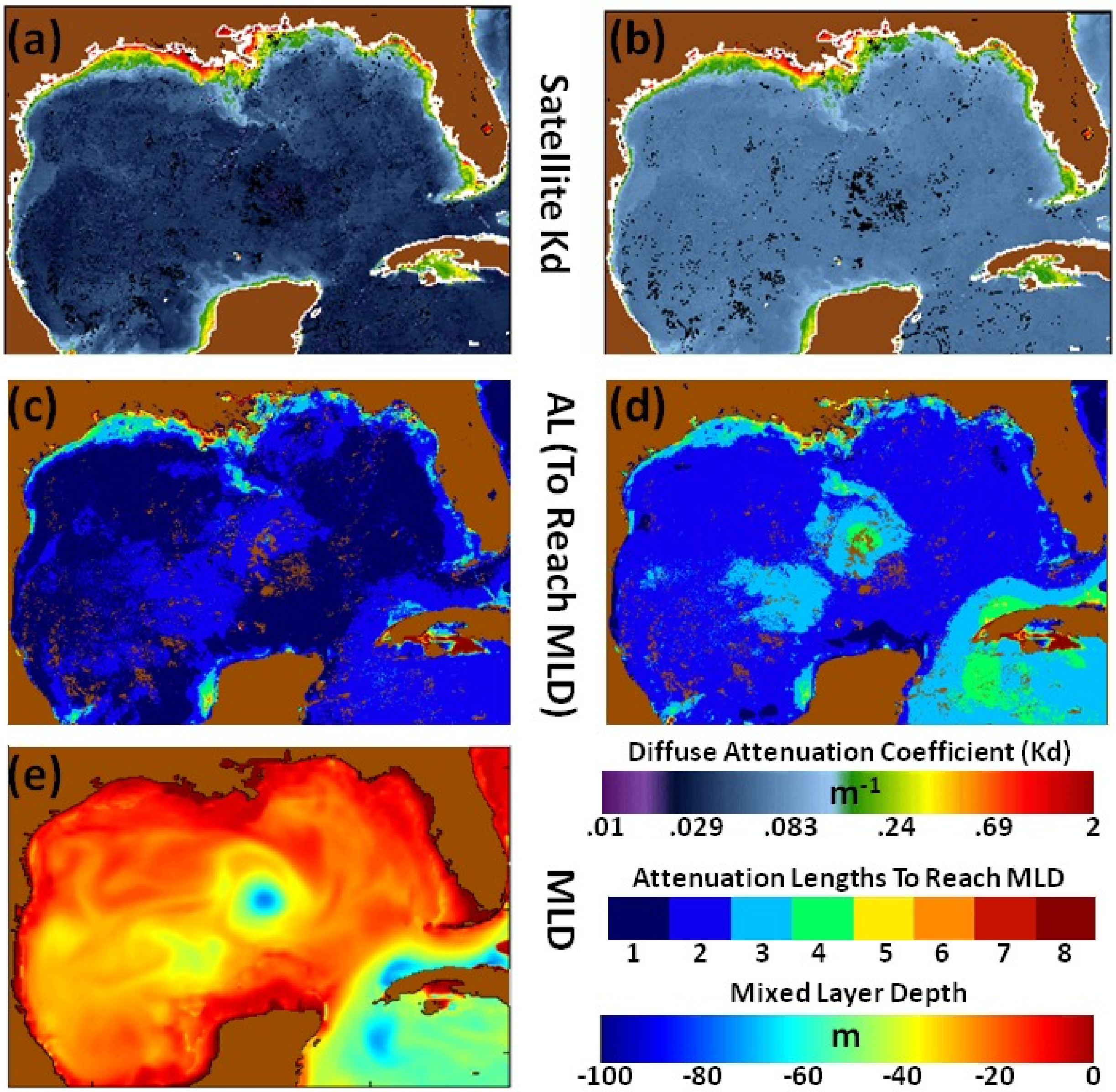

Figure 4. MODIS-Aqua 7-day-latest-pixel composites of (a) Kd at 490 nm and (b) Kd at 532 nm illustrating the satellite diffuse attenuation values coupled with the (e) MLD to determine the Attenuation Lengths at (c) 490 nm and (d) 532 nm necessary to reach the (e) MLD. This figure demonstrates a real-time capability for the utilization of space-borne LIDAR and how it is impacted by the ocean optical environment. A blue (490 nm) LIDAR, outperforms a blue-green (532 nm) LIDAR by penetrating deeper into the water column using less attenuation lengths --as exemplified by the deepening of the mixed layer (e) in the warm-core eddies clearly seen in the central Gulf.

Many assumptions have taken place in this work. Austin and Petzold equations[14,15], though suitable for the Gulf of Mexico mid latitudes, are only accurate for CASE 1 waters. We have assumed that the K_d values are constant with depth, and have neglected any consideration for scattering, atmospheric correction, noise, and related issues associated with remote sensing. These assumptions can lead to over or under estimation of penetration, especially where deep layers and biomass maxima occur below the MODIS satellite sensing depth of $1/K_d$. Furthermore, shallow coastal regions abundant in organic and inorganic matter can result in gross underestimation of penetration depth, increasing the uncertainly of the results. However, seasonal/inter-annual trends of penetration coverage (%) in the Gulf were found to be correlated with the expected seasonal variability of the fields (K_d and MLD) as shown in Figure 5. These results, although highly theoretical, can be of seminal use when building sensors of specific power to provide optimal coverage and penetration.

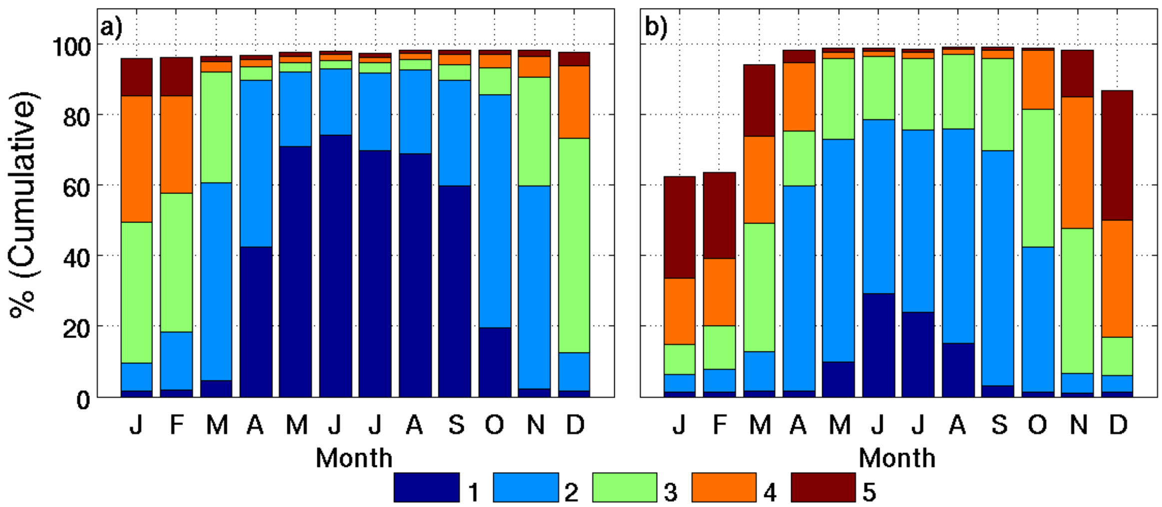

Figure 5. The figure illustrates the percentage (y-axis) of the ocean (Gulf of Mexico) where the penetration computed for attenuation lengths 1-5 (1:blue, 2:light-blue, 3:green, 4:orange, 5:red, shown) has reached the MLD for both 490 nm (a) and 532 nm (b). This effectively shows the impact of the inter-annual variability of the optical and physical environment on LIDAR efficiency. In the summer months (M-May, J-June, J-July, A-August, S-September), a shallowing mixed layer decreases the attenuation lengths needed to penetrate (to the MLD) 70% of the Gulf at only 1 attenuation length (blue). In the winter, however, due to deep convective mixing and therefore, in part, to a deepening mixed layer, higher attenuation lengths are needed. LIDAR penetration at 490 nm for 1-4 AL's reaches the MLD for 85-90% while at 532 nm, especially in the winter months, it consistently requires more attenuation lengths than at 490 nm.

We recognize there is a difference between the beam attenuation and $K_d(490)$. In open ocean water, the $K_d(490)$ is representative of the absorption and attenuation, and as expected, it performs better in transparent CASE 1 waters, which accordingly, comprise the majority of the Gulf domain. The higher the K_d values (i.e. eutrophic waters), the shallower the penetration of a laser. Similarly, lower K_d values are indicative of clear oligotrophic waters and naturally much deeper laser penetration is seen in the Yucatan Strait and in the central Gulf. What is of notable interest in this analysis is the spatio-temporal variability in this region which can be useful in future oceanographic research as more sophisticated sensors and space-borne LIDAR technology becomes available.

4. CONCLUSION

Significant insight can be realized by coupling the physical ocean mixed layer dynamics to satellite-derived optical products. The Gulf of Mexico encompasses many aspects of a typical subtropical system, with rich coastal biogeochemistry, and high nutrient content in riverine and coastal areas. It is representative of a variety of fronts, eddies and complex coastal and open waters interactions and therefore, it provides an ideal environment for measuring instrument capabilities. Using the relatively high-resolution (4Km) satellite and model data permits the study of meso-scale ocean features and their impact on LIDAR subsurface penetration depth. We made use of high-resolution satellite-derived diffuse attenuation coefficients (K_d) along with Mixed Layer Depth (MLD) derived from a Gulf of Mexico numerical ocean model to estimate fundamental parameters (e.g. attenuation lengths, penetration depth) for consideration in the design and development of next-generation ocean probing laser systems. This assessment illustrates potential LIDAR performance to probe the ocean subsurface, and reveals connections between MLD and LIDAR penetration for optically different regions of the Gulf.

LIDAR sensors have the potential capability to penetrate deep into the water column, but their penetration depth will be dictated not only by the instrument specifications (power, frequency) and its associated hardware/software, but also by the ocean optical conditions (attenuation, scattering, absorption) which are geographically and temporally dependent. Our analysis demonstrates the fundamental parameters and environmental considerations that can aid in design of next generation sensors. In return, LIDAR sensors will provide data to assimilate into numerical models, evaluate their skill, and mend deficiencies in their parameterization, allowing enhanced ocean and weather forecasting. Space-borne LIDAR technology will increase our understanding of ocean biogeochemical processes, ecosystem dynamics, marine trophics, primary productivity, CO_2 sequestration, and other vital air/sea processes which passive sensors have hardly tapped.

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