# Probing the subsurface ocean processes using ocean LIDARS

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## ABSTRACT

Subsurface profiling LIDAR systems extend our understanding of ocean processes "below" the ocean surface of SST and ocean color. Time-gated LIDAR backscattering intensity has been shown to define the bio-optical ocean layers and characterize subsurface processes. The interaction between the mixed layer depth (MLD) using vertical temperature structures and LIDAR optical layers provides a critical link between physical and bio-optical processes. We evaluated the capability of LIDAR penetration to reach the MLD on a global basis. Penetration depths of LIDAR were estimated using attenuation depths derived from global monthly ocean color averages which were assumed vertically homogenous. Climatology of LIDAR penetration depth was combined with the monthly mixed layer depth determined from the Global NCOM ocean circulation model. Global NCOM output was used to construct monthly averaged MLD climatologies from 2002 to 2010. Results show how monthly changes in MLD and LIDAR penetration depths are coupled for different regions of the global ocean. For example, the time-lag in LIDAR penetration depths is linked to shallowing of the MLD in the North Atlantic Bloom. We estimate the percentage of global ocean waters where different LIDAR system configurations can reach below the MLD. Results illustrate the potential performance of LIDAR systems to "probe" the subsurface for global waters which help in LIDAR design. Subsurface processes such as mixing and biological growth and decay have significant impact on what we observe at the ocean surface. LIDAR profiling should provide the new dimension for monitoring global ocean processes.

**Keywords:** *LIDAR, Mixed Layer Depth, Optical layers, subsurface Ocean Structure, Climatology*

## 1. INTRODUCTION

Ocean LIDAR can provide a new capability to sensing the subsurface structure of the ocean. Characterizing the time-gated return of the LIDAR scattering enables remote sensing of the subsurface scattering layers. Scattering layers in the ocean waters have shown to characterize the relationship between the biological layers and physical processes. These optical layers are known to have extensive coverage and to have different vertical thicknesses from "thin" (< 20cm) to much larger. Many of these particle layers are associated with biological particle layers from phytoplankton and zooplankton in addition to detrital particle layers[9,4]. Additionally, these optical layers are responsive to the particle density and water density stratification and turbulence. Thus, these optical layers have an inter-relationship with the ocean's physical processes such as the mixed layer and mixing regime.

LIDAR return signatures from these optical scattering layers represent interaction of in-water particles with the LIDAR photon scattering and thus are dependent on particle composition (i.e. index of refraction), and size distribution etc. New methods to characterize the LIDAR return scattering using polarization (horizontal and vertical) in addition to backscattering intensity are all used to understand the optical layers and their composition. These methods are key to defining new approaches to enhance our capability to define the subsurface layers and the interaction of the biological and physical processes [10] .

Airborne LIDAR's have been used to characterize the subsurface structure of phytoplankton and zooplankton layers[3] These airborne LIDAR systems have been shown to penetrate to a depth of approximately three optical depths. These optical conditions are high variable and seasonal changing.

The LIDAR's capability to characterize subsurface processes is dependent on the LIDAR's depth of penetration. Specifically, the mixed layer depth (MLD) is a key parameter which is used in defining physical processes and it also has significant impact on biological activities, such as the nutricline, chlorophyll maximum, and upper ocean processes. Our objective is to determine if a LIDAR is capable of penetrating to the mixed layer depth. We will assess the global and seasonal distribution of LIDAR penetration depth by making some assumptions on the vertical optical homogeneity and LIDAR characteristics.

The development and erosion of the mixed layer and the resulting layer deepening and shallowing through seasonal cycles is known to impact the development of phytoplankton blooms and decay. The capability of a LIDAR to detect these subsurface processes can provide a new capability to understand the coupling between physical and optical layers. For example, the spring bloom in the North Atlantic occurs with the shallowing of the MLD into the euphotic zone which results in increased surface phytoplankton and decreases optical transparency ( i.e. "turbidity"). The LIDAR has unique ability to monitor subsurface layers and determine the relationship between these optical layers and MLD. Additionally, reduced LIDAR penetration depth is an indicator of the optical feedback of the decreased penetration depth of the LIDAR resulting from increased "turbidity" of the bloom. This study will identify how these changing conditions of the physical environment and the changing water "turbidity" or optical depths are coupled and how these conditions (physical and optical) impact the LIDAR penetration to the mixed layer depth.

The LIDAR capability to probe the subsurface is dependent on the "turbidity" or optical depth of the water. Airborne systems have used the rule of thumb that conventional LIDARs (NgYaG 532 nm) can probe to a depth of approximately three optical depths (Churnside personnel communication). An optical depth or water transparency is defined as the depth which subsurface irradiance is reduced to the natural logarithm of the surface intensity. In these clear waters, with a diffuse attenuation coefficient at 490 nm (K490) of 0.04, three optical depths is (1/.04) x3 = ~ 106 meters. Correspondingly, three optical depths in coastal waters with a K(490) of 0.5 is 1/0.5*3 = 6 meters. We are using this assumption between LIDAR penetration depth and the diffuse attenuation coefficient, and we recognize that other characteristics such as LIDAR pulse shape and intensity and frequency all impact this 3 OD assumption. Additionally, we recognize that in-water particles properties and their vertical distribution will also impact that LIDAR depth of penetration.

## 2. WATER TRANSPARENCY AND MIXED LAYER DEPTH CLIMATOLOGY:

Ocean color satellite data can be used to estimate the diffuse attenuation coefficient [1, 6] . The SeaWIFS Global monthly retrievals of the diffuse attenuation coefficient were averaged from 2002–2009 from Ocean Biology Processing Group (OBPG) NASA at a spatial resolution of 9 km. The derived K490 represents the first optical depth, since this is the depth the satellite is observing. The global monthly K490 climatology for April is shown in *Figure 1* with a color scale representing 1, 2, and 3 optical depths. We are assuming that the K490 remains constant below the second and third optical depths in order to determine the LIDAR penetration depth estimate. This assumption may not always be valid for global optical conditions, 1) especially where the chlorophyll maximum occurs below the satellite sensing or 1$^{st}$ optical depth and penetration depth will be overestimated and 2) regions where surface phytoplankton blooms results in turbid surface layers and penetration depth is underestimated in the 2 and 3 OD.

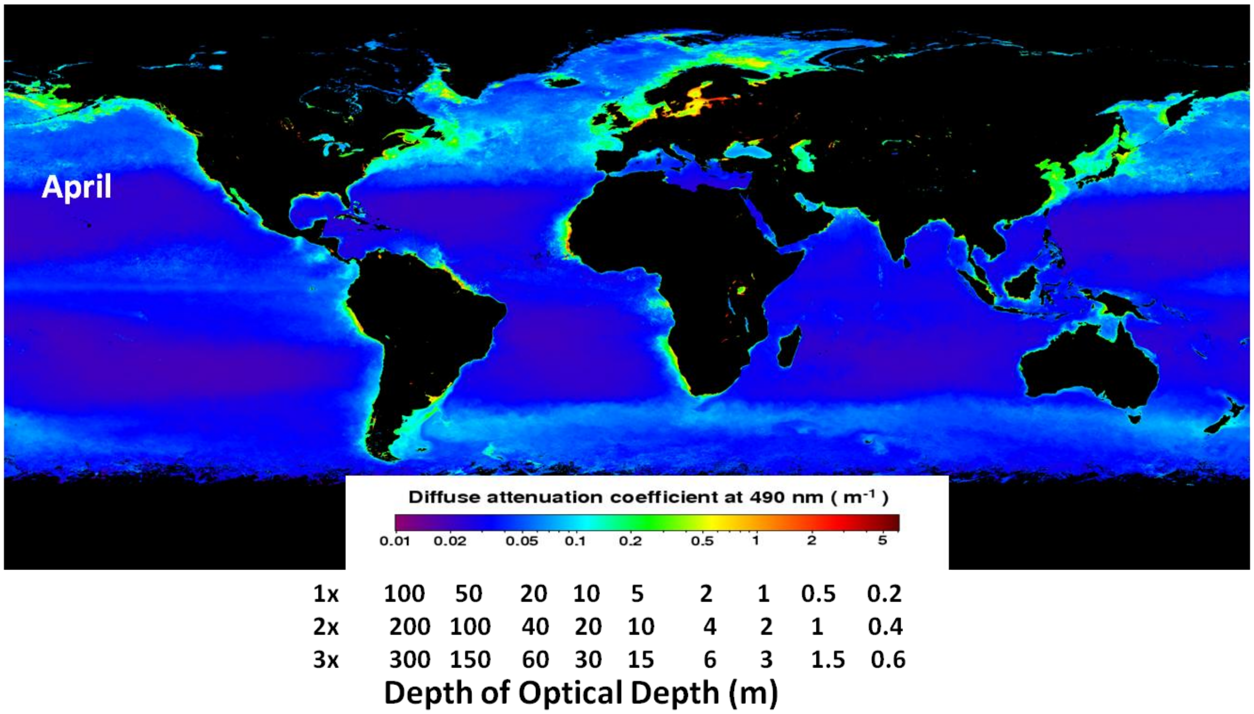



**Figure 1. SeaWIFS Climatology of the Diffuse Attenuation Coefficient at 490 for April from 2002 - 2009. The legend indicates the depth in meters for 1, 2, and 3 optical depths (OD).**

The 1/8° Global Navy Coastal Ocean Model (NCOM) was used to determine the climatology of the subsurface density field and the mixed layer depth. NCOM is a 40 layer primitive equation model [7,8] which is data assimilating of satellite sea surface height and sea surface temperature. Global NCOM temperature and salinity 3-dimensional output from 2002 to 2009 was used to derive monthly climatologies of the Mixed Layer Depth at the same spatial resolution of the satellite k490 products. The MLD was derived following the density-based definition of Kara et al. [5]. In brief, MLD is defined as the depth where the Density ($\sigma_t$) has changed by a difference ($\Delta\sigma_t$ ) from the $\sigma_t$ at a prescribed Reference Depth ($(\sigma_t)_{RefDepth}$). $\sigma_t$ is computed from Temperature (T) and Salinity (S) using the UNESCO equation of state independent of Pressure (i.e. P=0) and $\Delta\sigma_t$ is thus computed using:

$$\Delta\sigma_t = \sigma_t(T_{RefDepth} + \Delta T, S_{RefDepth}, P) - \sigma_t (T_{RefDepth}, S_{RefDepth}, P) \quad (1)$$

For this analysis, the criteria RefDepth = 0m and $\Delta T = 0.8$ was used.

The monthly climatology of the MLD from was determined from NCOM from 2002 to 2009 to coincide with the spatial and temporal (monthly) resolution the satellite K490 from SeaWIFS.

## 3. LIDAR PENTRATION

K490 is selected since this frequency (blue green) is the maximum penetration wavelength in clear ocean waters. For traditional LIDARs operation at the 532, this reduced the penetration depth for ocean waters. The conversion of the K490 to K532 was estimated by Austin and Petzold [2] to be:

$$K532 = 0.68052 * (K490 - 0.0224) + 0.05356 \quad (2)$$

We applied this conversion to the SeaWIFS diffuse attenuation coefficient climatology to estimate a 532 nm LIDAR penetration depth.

By combining the MLD and the diffuse attenuation coefficient at 532 from SeaWIFS, we determined the number of optical depths required to reach the mixed layer depth for the month of May (figure 2). Note that the large areas in dark blue are < 3 optical depths and cover a significant area of ocean waters. The clear waters of the gyres indicate approximately 2 optical depths to reach the mixed layer. Figure 2 represents planning or a design tool to determine what penetration depth is required to reach the MLD at 532 nm. Note the red areas (>9 optical depths) are indications of either turbid waters and / or very deep MLD.

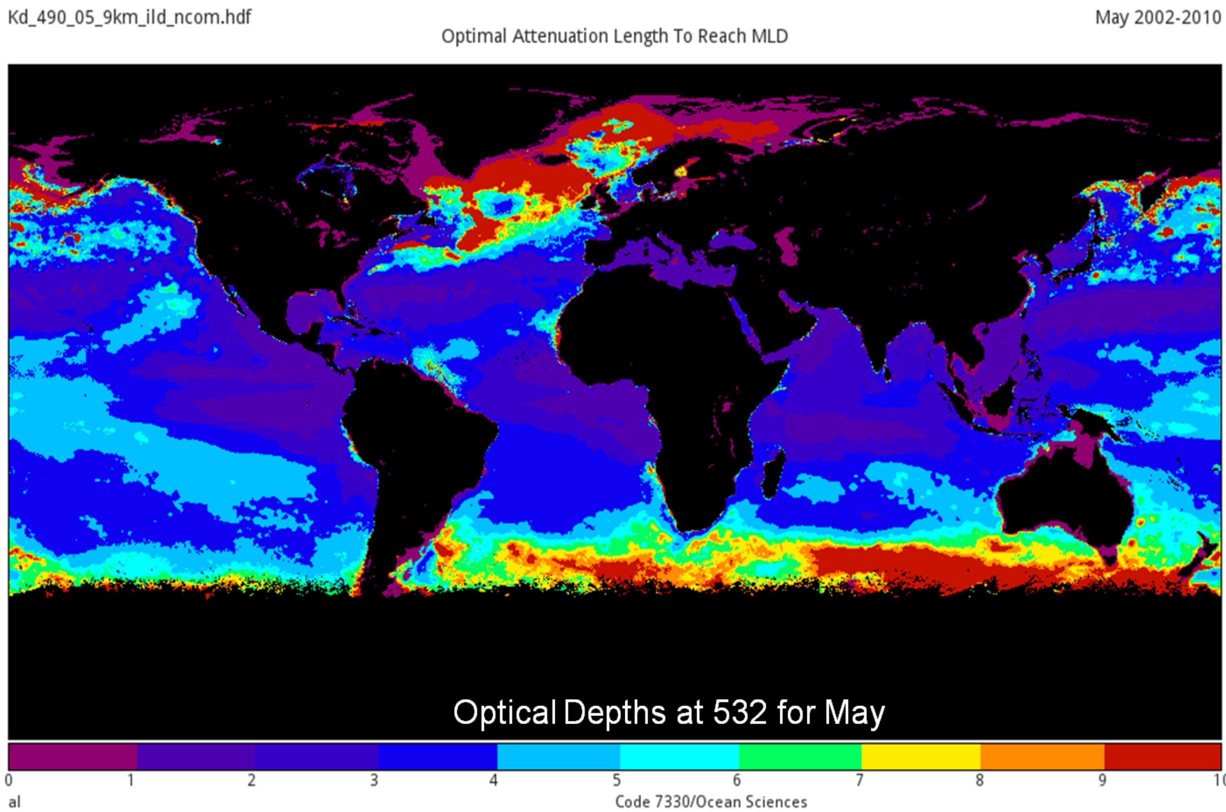
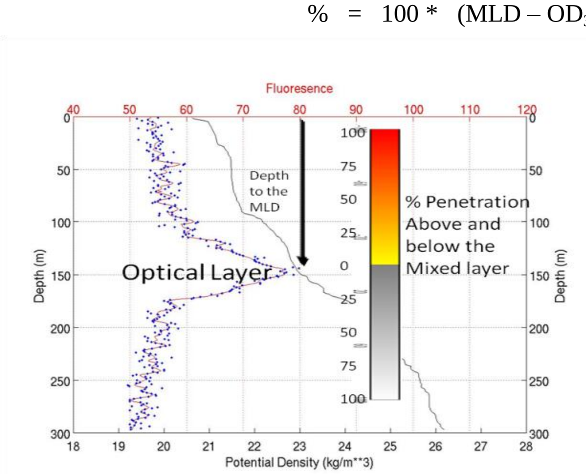



**Figure 2 - Global estimate of the number of Optical Depths at 532 nm to reach the Mixed Layer depth for May 2002 - 2010**

## 3. REACHING THE MIXED LAYER DEPTH

Using these monthly climatology of MLD and the diffuse attenuation coefficient, the percentage of penetration, above and below the MLD was estimated by:

$$\% = 100 * (MLD – OD_{3(\lambda)} / MLD) \quad (3)$$




where $OD_3$ is three optical depths and is dependent on the K532 or K490.

So if the MDL equals three optical depths then a '0' percent penetration is determined. A positive 100 percent, estimates that the LIDAR penetration is double (2x) the depth of the MLD, and conversely a -50% indicates that the penetration is only one half the depth to the MDL. The color scale used in Figure 3 show positive values (i.e. penetration to or below the MLD ) in white to black, and negative percentages, (i.e. percentages not reaching the MLD) are colored yellow to red.

Figure 3. Scaling for reaching the Mixed layer depth. The percentage above (color) and below (gray) the Mixed Layer Depth

This color scaling for the percentage of the penetration to the MLD was applied to the May Climatology (2002 – 2010) from the Global NCOM and SeaWIFS K490 and K532. The colored areas (red to yellow) in Figure 4 and 5 indicate that three optical depths did **not** reach the mixed layer; whereas the white to gray areas are regimes where three optical depths reached to and below the mixed layer.

Note that for K490 (Figure 4) there is increased coverage of the globe where penetration reaches the mixed layer (gray areas). This reflects the spectral dependence of penetration of 490 vs. 532nm on global water transparency.

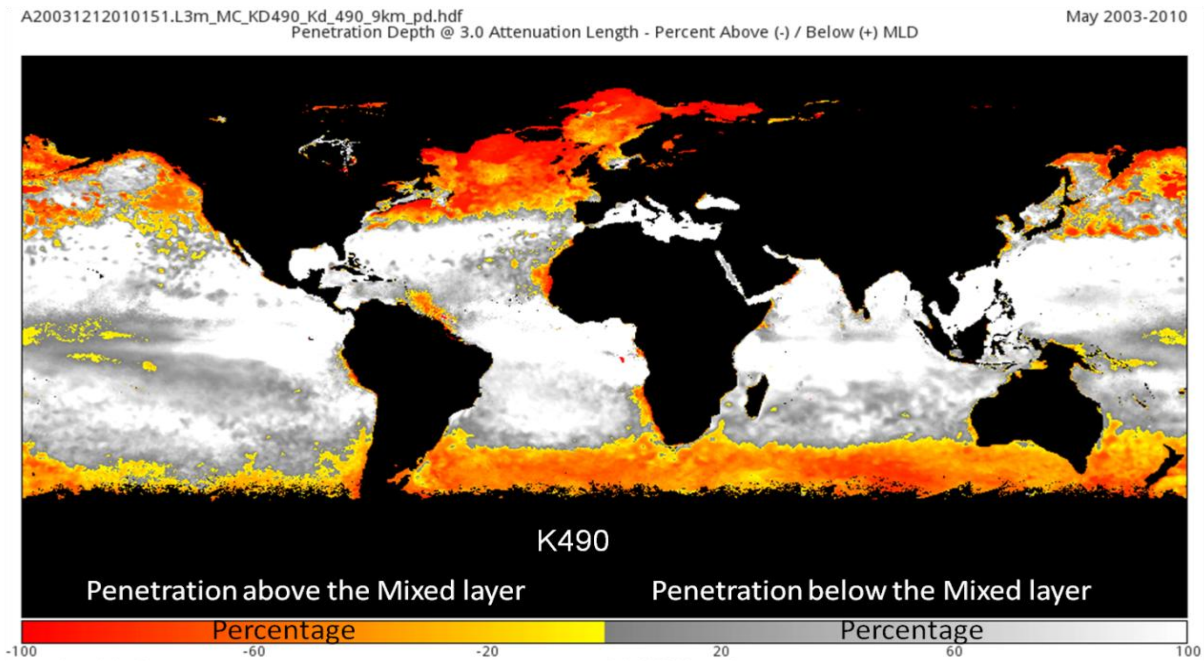



**Figure 4 – Percentage of depth to the MLD of 3 optical depths at 490 nm for May.**

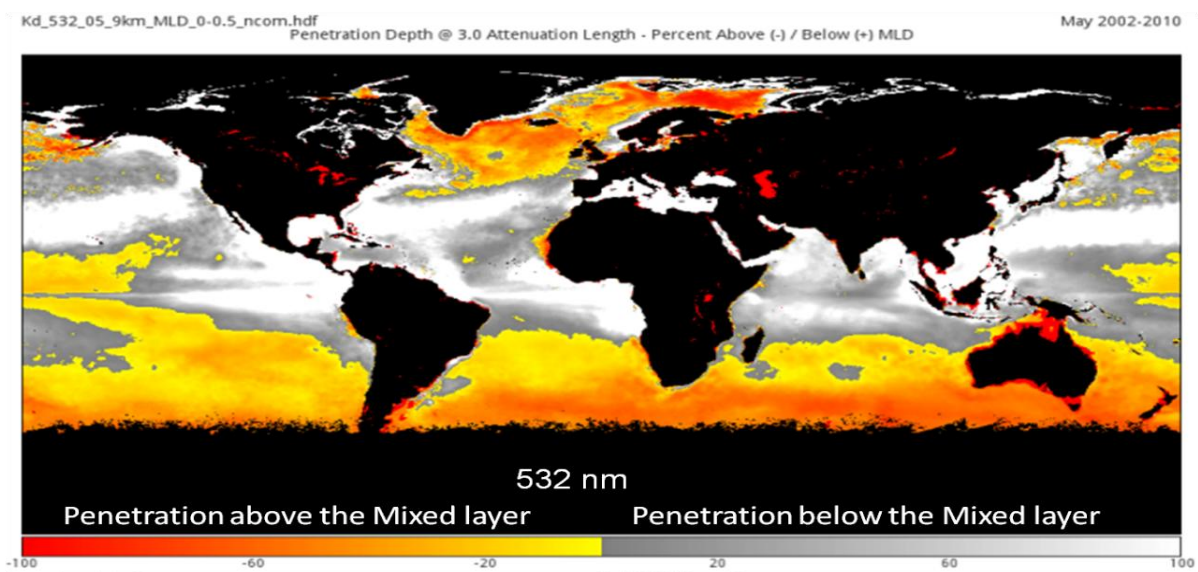



**Figure 5 - Percentage of depth to the MLD of 3 optical depths at 532 nm for May**

## 4. SEASONAL VARIBILITY OF THE PENETRATION

The seasonal changes of the mixed layer depth and the changes on the surface water transparency impact the depth of LIDAR penetration. Figure 6 illustrates the depth of penetration for 532 nm at three optical depths to reach the mixed layer for January, April, July and October. Note that in North Atlantic region, in January the MLD is deep and this may result in the LIDAR not reaching the depth. In April (spring), the shallowing of the mixed layer results in a phytoplankton bloom and decreased transparency and higher K532. The LIDAR penetration is similarly reduced. In July, with a shallow mixed layer, oligotrophic conditions result in LIDAR penetration below the mixed layer depth. These conditions persist into October for the North Atlantic where fall phytoplankton bloom and the decreased water transparency impacts the penetration depth. These figures show the interaction of the physical processes (mixed layer depth) and the water transparency (K532). The coupling and feedback of how water transparency impacts the deployment and location of the MLD and dependency of absorption and subsurface heating is not clearly observed. These monthly climatologies illustrate the spatial distribution of LIDAR penetration and depth of penetration to the mixed layer.

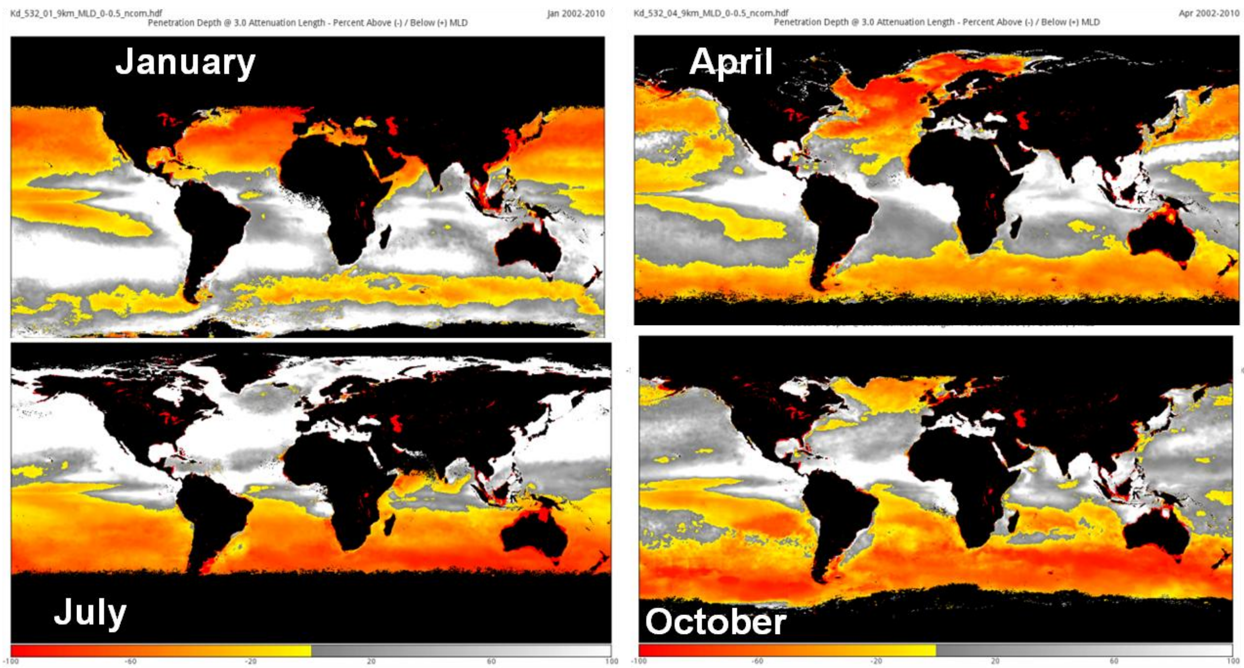



Figure 6. Monthly variability of the percentage of depth to the MLD of 3 optical depths at 532 nm

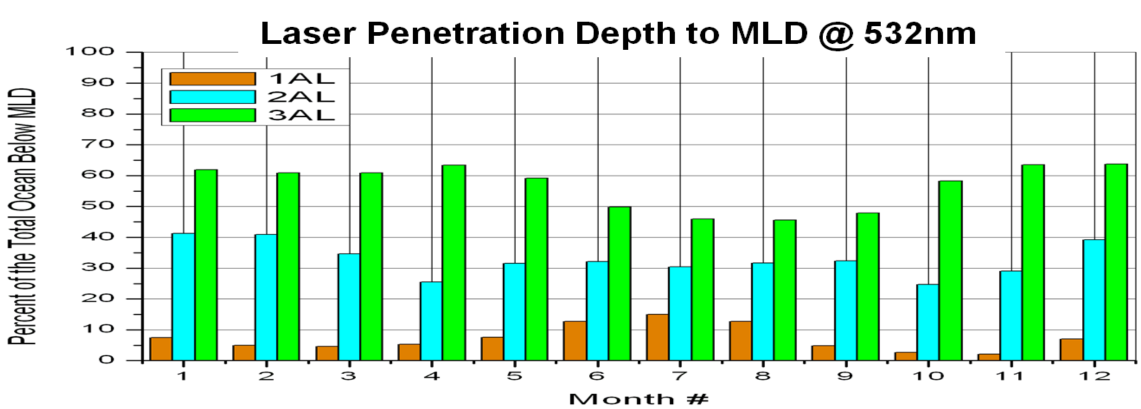



Figure 7 Monthly percentage of the Global waters that 1,2, and 3 optical depths extend to and below the mixed layer depth.

An estimate of the global percentage of the ocean regions that 1, 2 and 3 optical depths (OD) that reaches the mixed layer was determined for each month (Figure 7) by determining the total percentage of the ocean coverage. It is estimated that for approximately 58 % of ocean waters, 3 optical depths can reach to or below the mixed layer depth. This percentage changes from a high of ~ 64% in April / December to a low of ~48% in July / Aug.

## 5. SUMMARY

An estimate of the penetration depth of LIDAR was determined for ocean waters using the diffuse attenuation coefficient derived from SeaWIFS monthly climatology from 2002 to 2010. The estimate is based on using the diffuse attenuation coefficient K490 and converting to K532 which is standard for LIDAR sensors and assuming a penetration depth of three optical depths. We assumed that the attenuation coefficient derived from SeaWIFS was vertically homogenous and the first optical depth was consistent with depth.

The global NCOM ocean model was used to determine the monthly climatology of the vertical density field and the mixed layer depth from 2002 to 2010. The MLD climatology for the global ocean was mapped to the spatial and temporal resolution of the SeaWIFS diffuse attenuation coefficient climatology.

We determined the percentage of the MDL that three optical depths (OD) penetrated for the global ocean climatology. The percentage above and below the MLD was computed and was used to provide an estimate of the global coverage if a LIDAR can be used to sense to the mixed layer depth. A monthly estimate of the global coverage was determined on a monthly basis. Based on our assumptions we conclude that a LIDAR can penetrate to the mixed layer depth for approximately 58% of ocean waters.

The utility of the LIDAR to probe below the ocean surface and reach the MDL can provide a unique remote sensing capability to characterize subsurface processes. This extends well beyond present remote sensing system which only monitors the surface waters (ocean color and SST). This can provide an invaluable asset in sensing the inter-action of the physical and biology processes that occur below the surface layers in the ocean and can be applied for global ocean waters.

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