CALIPSO Lidar Measurements for Ocean Sub-Surface Studies

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Abstract - Since launching in April 2006 the primary objective of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission has been studying the climate impact of clouds and aerosols in the atmosphere. However, recent studies have demonstrated that both daytime and nighttime CALIPSO lidar measurements can also be used to estimate certain ocean subsurface properties such as sub-surface particulate backscatter at 532 nm. These sub-surface particulate measurements may help improve estimates of primary productivity and particulate inorganic carbon (PIC) throughout the coastal and open oceans of the world, thus improving our understanding of the ocean carbon cycle. This study introduces the ocean profiling measurement concept and its potential scientific applications.

KEYWORDS: atmosphere, lidar, oceans, oceanography, and space

1. INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) spacecraft was launched by a Boeing Delta-II rocket from Vandenberg Air Force Base, California on April 28, 2006. Its primary instrument, CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), is a three-channel lidar that uses a Nd:YAG laser emitting linearly polarized pulses of light at 1064 nm and 532 nm. The receiver uses a 1-meter diameter telescope and photomultipliers in the two 532 nm channels: one for parallel-polarized backscatter, and the other for perpendicular-polarized backscatter. The 1064 nm channel uses an avalanche photodiode (APD) for measuring the total backscatter at this wavelength. CALIPSO is in a near-circular sun-synchronous polar orbit, at a nominal altitude of 705-km and a 1:30 PM ascending node. CALIPSO is an integral part of the A-Train constellation of satellites, flying 75 seconds behind Aqua and in formation with CloudSat, Aura and PARASOL. CALIPSO has acquired nearly continuous measurements since June 2006, and is expected to continue operating well beyond 2011.

The goal of the CALIPSO mission is to provide vertically resolved measurements of the spatial and optical properties of clouds and aerosols in the Earth's atmosphere. The CALIOP vertical profile data extends from 40 km above mean sea level down to 2 km below the ocean's surface, with a vertical resolution of 30 meters in the atmosphere between 0 km to ~8.2 km AMSL, and about ~23 meters in the water between 0 km and ~0.5 km below the ocean surface (Hunt et al., 2009). As the lidar is pointed only slightly off-nadir, at an angle of either 0.3° or 3°, the backscatter from ocean surface can be orders of magnitude higher than backscatter from subsurface regions.

The space based atmospheric profiling lidar makes unique ocean measurements as well. The unique features of CALIPSO ocean observations include: (1) mean square wave slopes of all wave spectra; (Hu et al., 2008) (2) high resolution bubble detection and characterization (Hu et al., 2010); (3) nighttime as well as daytime ocean subsurface particulate backscatter; (4) vertical distribution of sub-surface backscatter; (5) unambiguous separation of atmosphere, ocean surface and ocean sub-surface. This paper will provide an overview of the methodology for calculating the lidar ocean subsurface particulate backscatter.

2. LIDAR BACKSCATTER PARTICULATES FROM OCEAN SUBSURFACE

The limitations of collecting oceanic in-situ measurements to study the ocean carbon cycle and measure primary productivity lead us to investigate other means to reach this goal. Primary productivity is highly correlated to optical properties of the ocean such as particulate beam attenuation and backscatter coefficients (Behrenfeld and Falkowski, 1997; Behrenfeld et al., 2005). With the suite of A-Train instruments, and specifically with the CALIPSO lidar, the ability to obtain high spatial and temporal resolution subsurface data is now available. The 532 nm subsurface signal from CALIOP can provide ocean sub-surface backscatter for ~3 optical depths (a few meters in turbid coastal waters, and up to 100 m for clearest parts of open-ocean with diffuse attenuation as low as 0.03 m^{-1}).

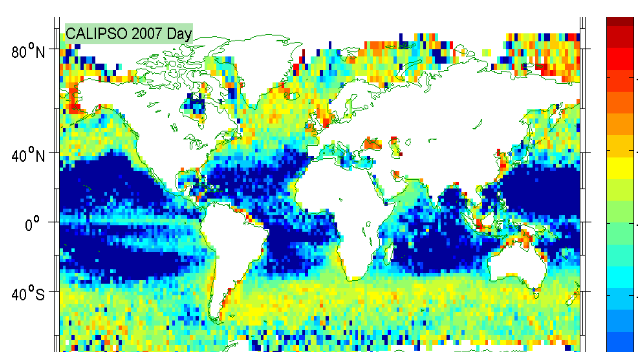

Figure 1a. Global distribution of CALIPSO daytime subsurface

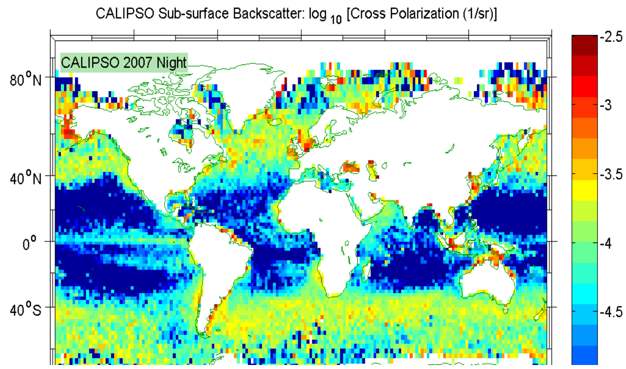

Figure 1b. Global distribution of CALIPSO daytime sub-surface backscatter at 532 nm. The differences seen in high latitudes between Figure 1a. and Figure1b. are mostly due to the fact that days and nights are in different season.

The ocean sub-surface profiles in the 532 nm parallel polarization channel typically include the strongest sub-surface backscatter signal. Unfortunately, for CALIOP these profiles are difficult to interpret since they are contaminated by time-delayed ocean surface reflection due to the low-pass filter in the receiver electronics and the non-ideal transient response of the PMT detector.

The most useful ocean sub-surface backscatter signal from CALIPSO is the backscatter profile from the 532 nm perpendicular channel. This value is calculated from integrating the 532nm perpendicular attenuated backscatter between 0.0582 km and -0.2716 km after cloud clearing has been performed. The measurements are available at nighttime (Figure 1b) as well as during daytime (Figure 1a). Comparing both panels of Figure 1, there is very little difference in the perpendicular 532 nm channel sub-surface liar backscatter in middle and low latitude regions. The differences seen in the polar region between Figure 1a, and Figure 1b, are mostly due to seasonal differences between summer and winter.

Using the collocated AMSR-E wind speed measurements (V) and the empirical relation between ocean surface lidar reflectance and wind speed (Hu et al. 2008), we can estimate the ocean sub-surface backscatter profile (γ) from the ratio of the uncalibrated sub-surface lidar signal γunc(subsurface) and the uncalibrated surface lidar signal γunc(surface) directly:

$$\gamma(\text{subsurface}) = \gamma_{unc}(\text{subsurface})\frac{\gamma_{theory}(\text{surface})}{\gamma_{unc}(\text{surface})} = f(V)\frac{\gamma_{unc}(\text{subsurface})}{\gamma_{unc}(\text{surface})}. \quad (1)$$

The CALIPSO lidar backscatter from the ocean sub-surface is thus self-calibrated, resulting in ocean sub-surface backscatter data that are insensitive to overlying aerosols and thin ice clouds. The CALIPSO sub-surface backscatter is thus highly accurate in both coastal and open waters. As seen in Figures 2a-d, CALIPSO is capable of identifying seasonal changes and inter-annual variations of the sub-surface lidar backscatter.

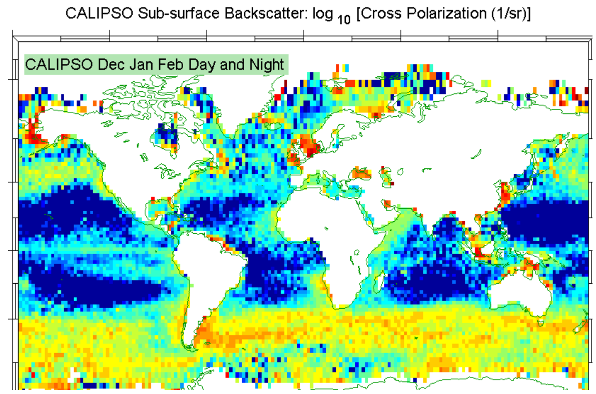

Figure 2a. Seasonal distributions of CALIPSO ocean sub-surface backscatter for Dec/Jan/Feb

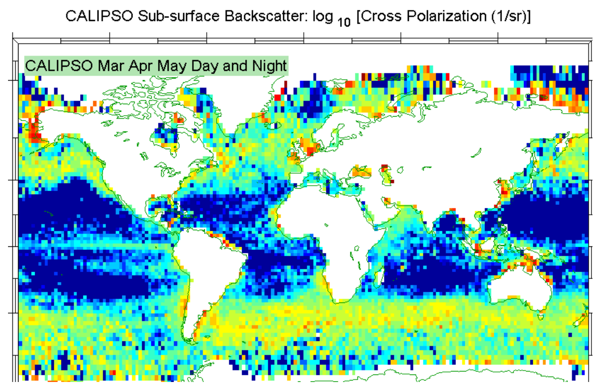

Figure 2b. Seasonal distributions of CALIPSO ocean sub-surface backscatter for Mar/Apr/May

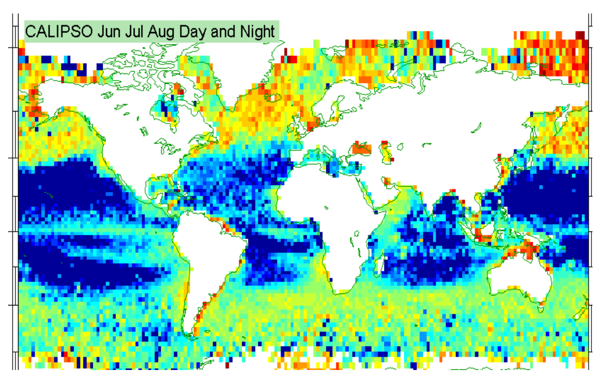

Figure 2c. Seasonal distributions of CALIPSO ocean sub-surface backscatter

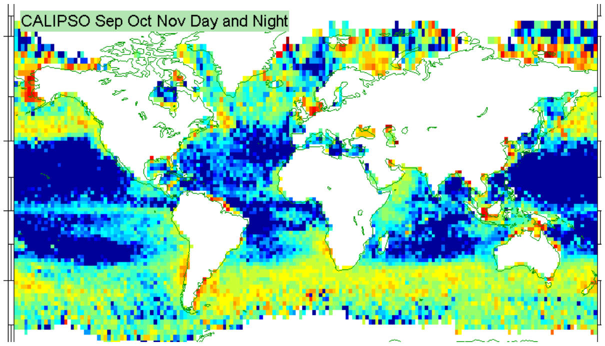

Figure 2d Seasonal distributions of CALIPSO ocean sub-surface backscatter for Sep/Oct/Nov

While we are currently able to extract the sub-surface backscatter signals from CALIPSO measurements, the next step is to interpret and validate these data. As we see in Figure 3a and Figure 3b the apparent correlation between the CALIPSO sub-surface backscatter and the MODIS chlorophyll is promising. The changes in chlorophyll concentrations appear to mimic corresponding changes in backscatter intensity.

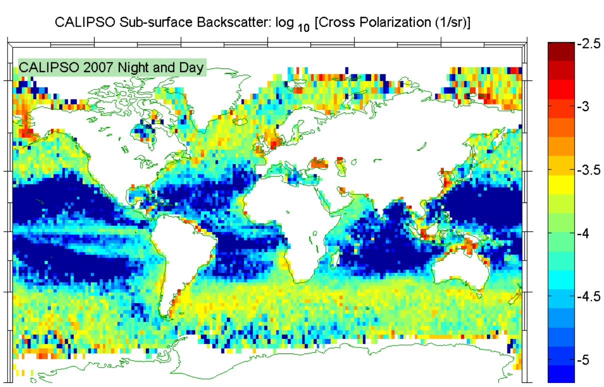

Figure 3a Yearly distributions of CALIPSO ocean sub-surface backscatter for 2007

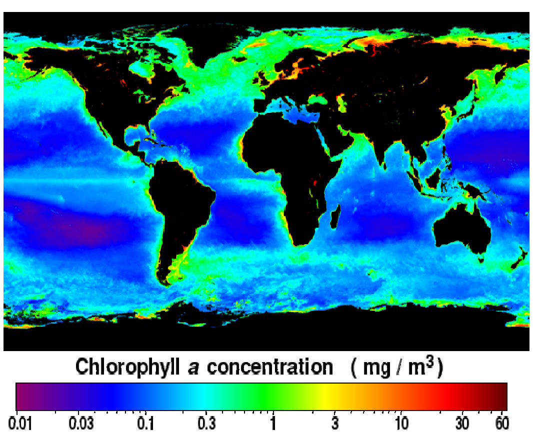

Figure 3b Yearly distributions of Chlorophyll for 2007

3. CONCULSIONS

The ocean surface and sub-surface measurements from space-based profiling lidars have the potential to enhance our understanding of ocean processes. In this paper we presented the methodology for calculating the lidar ocean subsurface particulate backscatter and it's potential correlation with the primary productivity. Additional work is needed to identify the components of the lidar subsurface signal and isolate the organic and inorganic oceanic particulate signature. Analysis of collocated MODIS ocean color data products and CALIPSO lidar data products will further this study.

4. REFERNCES

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