Ocean surface and subsurface studies from space-based lidar measurements

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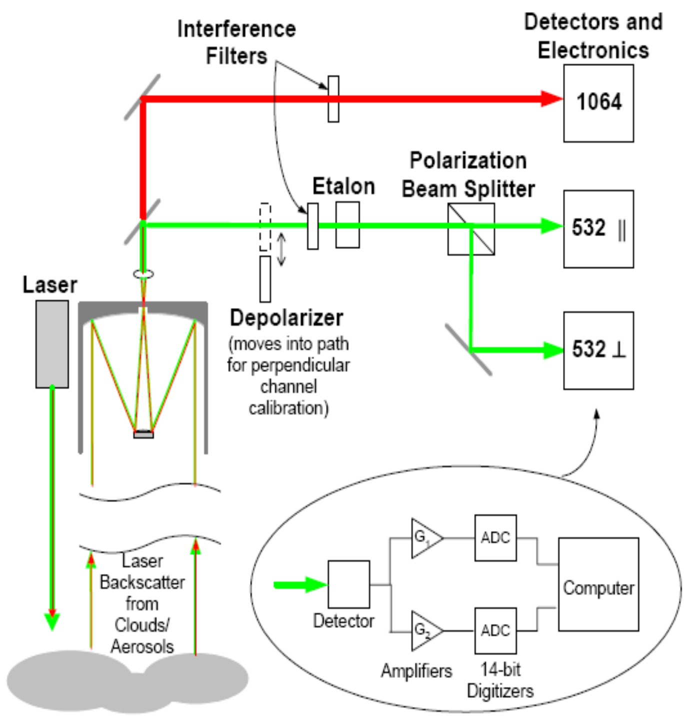
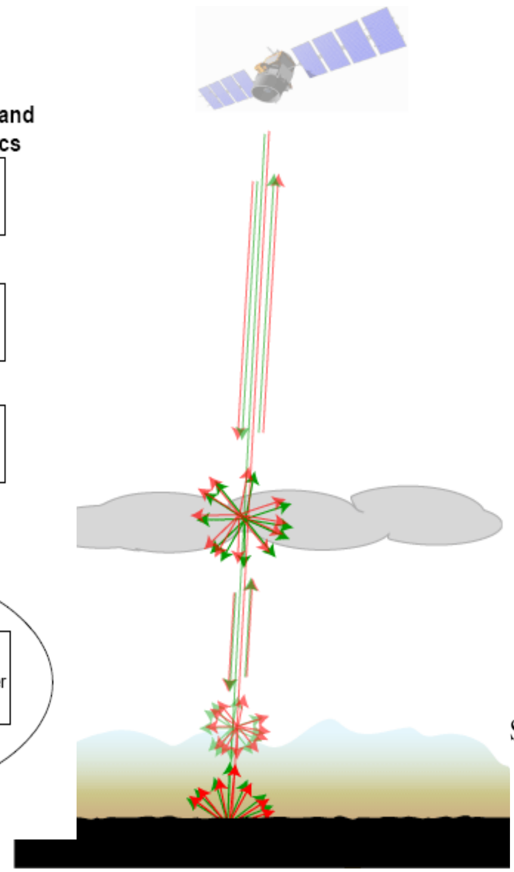
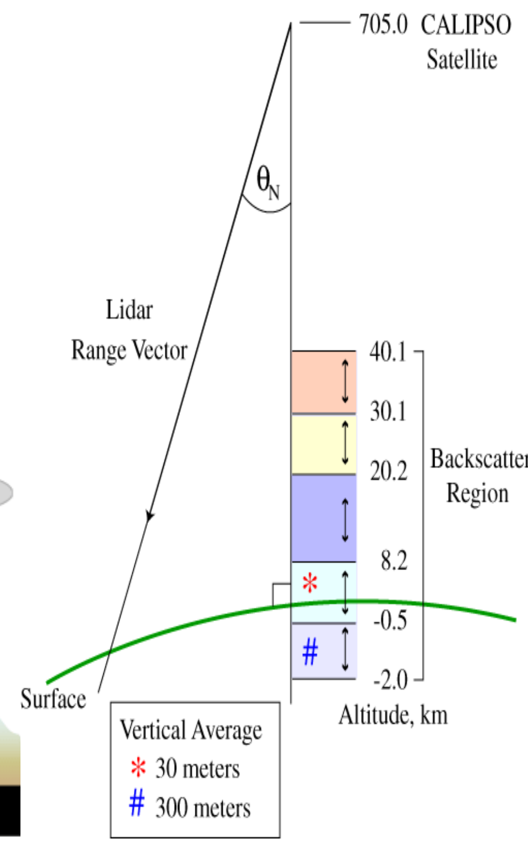
➢ CALIPSO Lidar—Atmosphere measurements

The CALIPSO satellite, launched successfully on April 28, 2006, can provide two-wavelength elastic backscattered signals on a nearly global scale.







Outline of the talk

The primary objective of the CALIPSO mission has been studying the climate impact of clouds and aerosols in the atmosphere. However, recent studies have demonstrated that CALIPSO also collects information about ocean subsurface. The objective of this study is to,

1. Remove the effects of lidar receiver's transient response on the attenuated backscatter

2. Estimate the theoretical ocean surface backscatter from the empirical relation between sea surface lidar backscatter and wind speed

3. Estimate the Ocean sub-surface lidar backscatter

1. The effects of lidar receiver's transient response

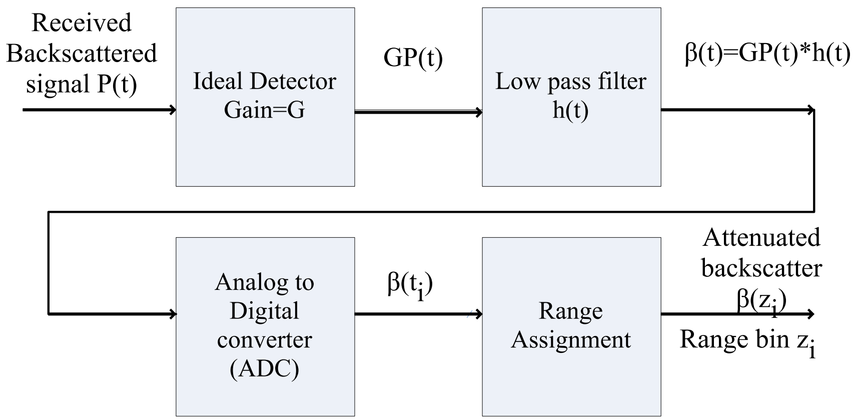


Fig. 1. Receiver subsystem for the atmospheric profiling lidar.

For a profiling lidar on a spacecraft platform (e.g., CALIOP), the receiver subsystem is illustrated in Fig.1. The lidar backscattered pulse P(z), which is a function of time t or altitude z (z=ct/2, c the speed of light), is collected by the telescope and focused onto a detector. The detector is modeled as an ideal detector with its gain of G, followed by a low-pass filter with an impulse response given by h(z).

The output of low-pass filter is sampled and quantized by an analog-to-digital converter (ADC) or a digitizer. Data is generally sampled sequentially with equal space interval corresponding to the vertical resolution of the lidar. $\beta(z_i)$ is the sampled signal, where z_i is altitude corresponding to the i^{th} range bin and i is a positive integer.

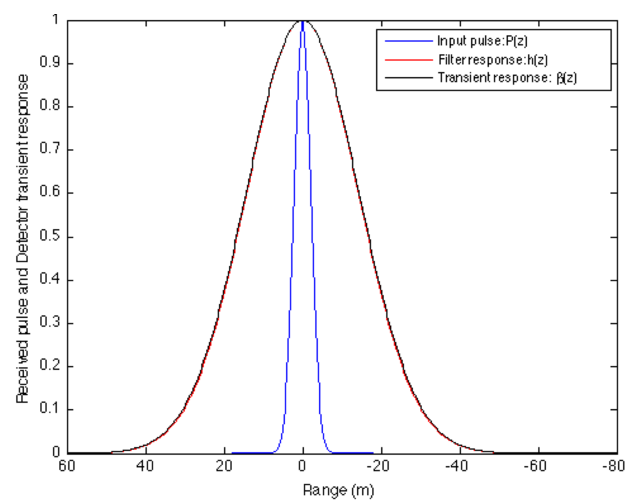


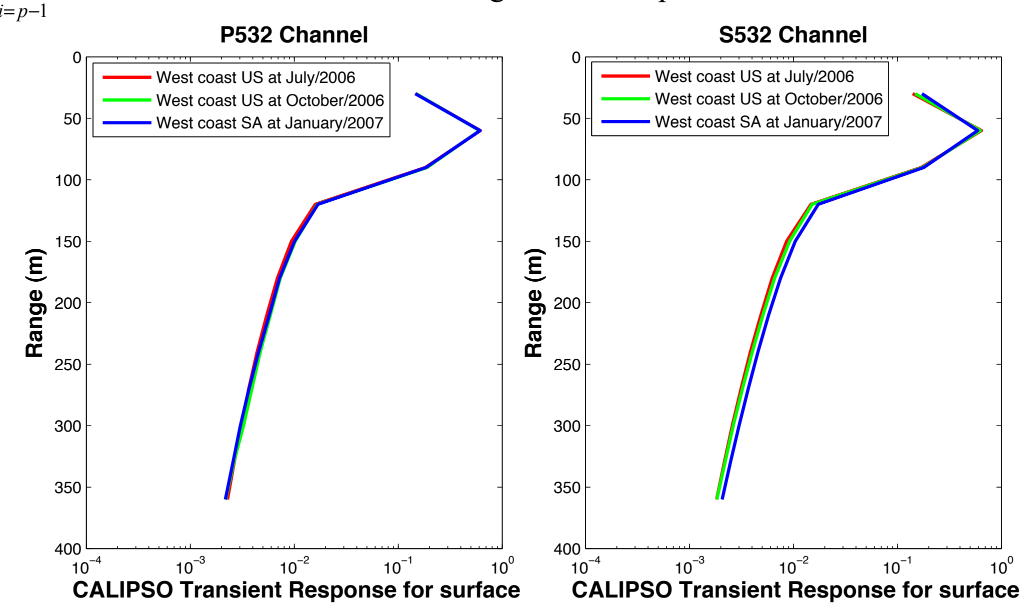
Figure 2. The input pulse P(z) (blue line), the impulse response of low-pass filter h(z) (red line) and the detector's transient response β(z) (black line); the curves are scaled to their peak values.

Because the CALIOP 532 nm laser pulse cannot easily penetrate the land surface, the lidar backscatter signal from a land surface goes quickly from a small value to a very large value and then quickly back to zero under ideal conditions, and should be distributed in single vertical range bin (30 m). However, due to the PMT's noise tail effect and low-pass filter's broadening effect , the strong land surface return was spread by the CALIOP instrument transient response over several adjacent range bins. Therefore, a hard land surface should be a good target for studies of the CALIOP receiver transient response function.

The CALIOP's transient response function F can be obtained from land surface in twelve adjacent range bins as fellows:

$$F(z_j) = \frac{\beta'(z_j)}{\sum_{i=p-1}^{i=p+10} \beta'(z_i)} \quad (j = 1,2,3,\ldots,12)$$

where the twelve range bins starting from the one range bin before the peak to the tenth range bin after the peak surface return, and $\beta'(z_i)$ is the attenuated backscatter of each bin, i is the range bin number and p is the range bin of the peak surface return.



Actually, the current observed attenuated backscatter signal $\beta'_m(z)$ is a result from a convolution between the correct attenuated backscatter $\beta'_c(z)$ and the CALIOP transient response function F. This convolution process can be described mathematically as follows,

$$\begin{bmatrix} F(z_2), F(z_1), 0, \cdots\cdots\cdots\cdots, 0 \\ F(z_3), F(z_2), F(z_1), \cdots\cdots\cdots, 0 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ F(z_{n+1}), F(z_n), F(z_{n-1}), \cdots, F(z_2) \end{bmatrix} \cdot \begin{bmatrix} \beta'_c(z_1) \\ \beta'_c(z_2) \\ \vdots \\ \beta'_c(z_n) \end{bmatrix} = \begin{bmatrix} \beta'_m(z_1) \\ \beta'_m(z_2) \\ \vdots \\ \beta'_m(z_n) \end{bmatrix}$$

That is, $M\beta_c^{'} = \beta_m^{'}$

With the values of the transient response functions, we can retrieve the correct attenuated backscatter signal by de-convolution process

$$\beta'_c = M^{-1} \cdot \beta'_m$$

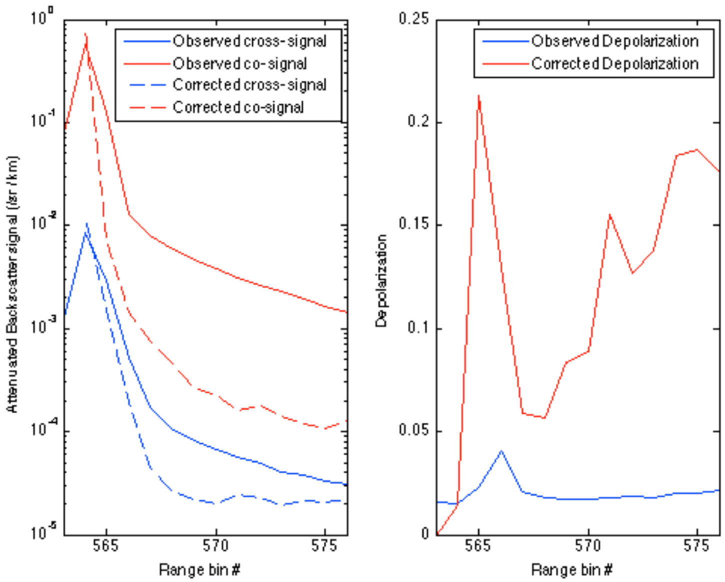
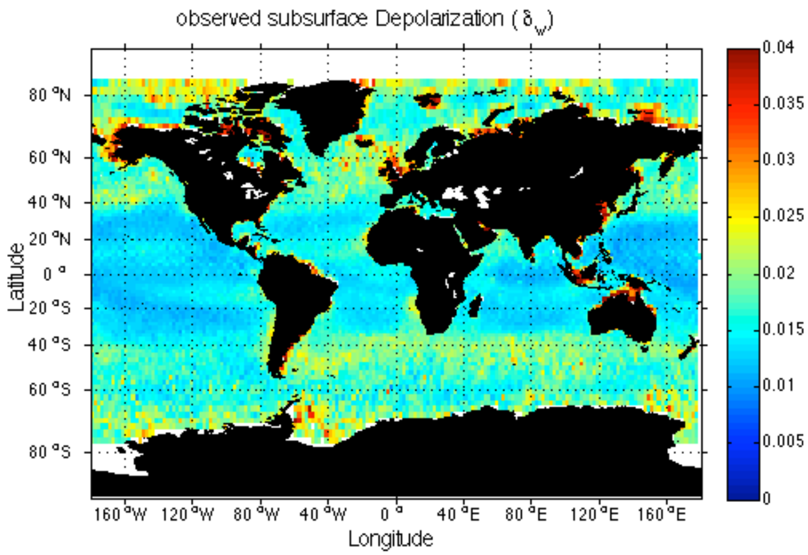


Fig. 2. Left panel: The depth profiles of the retrieved correct ocean attenuated backscatter (dashed line) and the observed ocean attenuated backscatter at CALIOP (solid line) 532 nm cross- (blue) and co-polarized (red) channels. Right panel: the depth profiles of depolarization calculated from observed signals (blue line) and correct signals (red line).

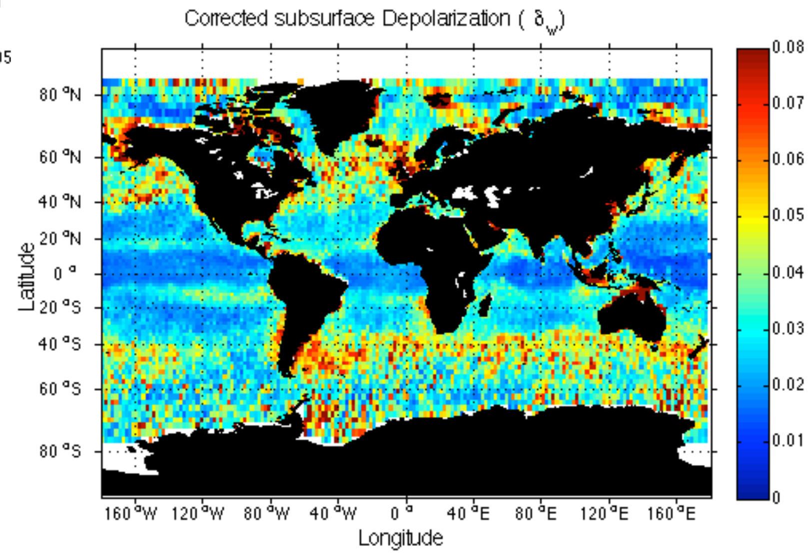
Ocean subsurface observed and corrected depolarization ratio



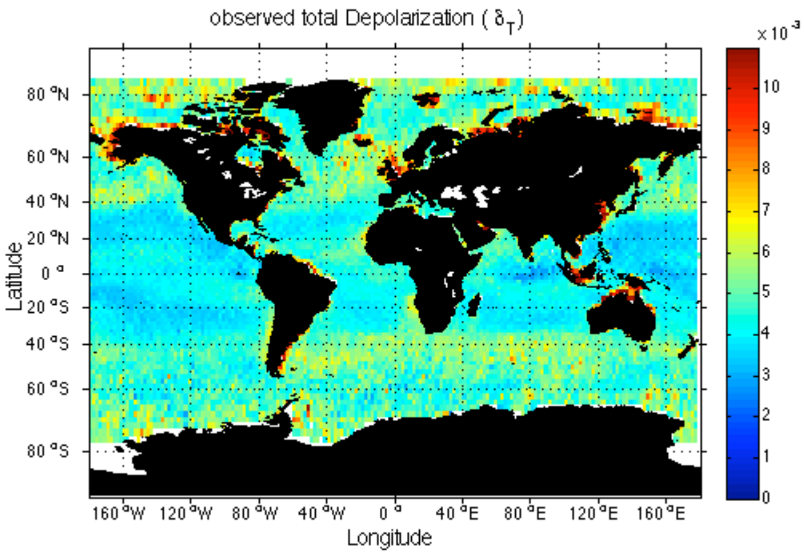
$$\delta_w = \sum_{i=1}^{10} \beta'_{\perp}(z_i) / \sum_{i=1}^{10} \beta'_{\parallel}(z_i)$$

The integrated ocean subsurface depolarization ratios δ_w, defined as the ratio of the cross-polarized signal to co-polarized signal integrated from the first range bin to the tenth range bin below the surface

Global distribution (2° by 2°) of CALIOP Ocean subsurface observed and corrected depolarization ratio δ_w. Color code is the value of δ_w.

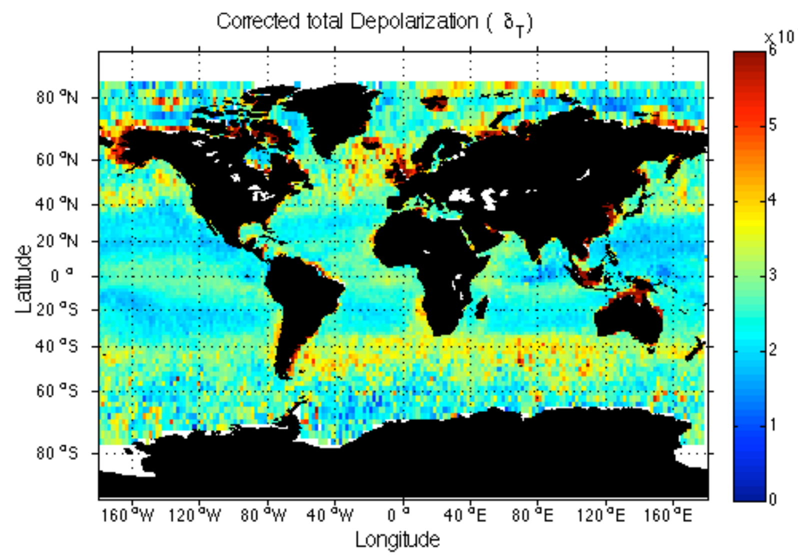


Ocean observed and corrected total depolarization ratio



The integrated total depolarization ratio δ_T that includes both surface and subsurface backscatter

Global distribution (2° by 2°) of CALIOP Ocean observed and corrected total depolarization ratio δ_T. Color code is the value of δ_T.



1. The effects of lidar receiver's transient response

As a result, the CALIOP transient response can

- Affect the vertical distribution (that is, the waveform) and magnitude of the lidar backscatter signal and the depolarization ratio.
- Affect the values of the integrated subsurface depolarization δ_w and total depolarization ratio δ_T

Thus, the effects of CALIOP receiver transient response on the attenuated backscatter should be removed first.

2. Estimate the theoretical ocean surface backscatter

When the effects of CALIOP detector's transient response on the attenuated backscatter profile were removed, the CALIOP correct attenuated backscatter signal from ocean surface and subsurface is

$$\beta'_{532} = \beta_{532} T^2_{532}$$

where T is the one-way atmospheric transmittance along the lidar look direction, β is the volume backscatter coefficient.

The theoretical ocean surface backscatter can be estimated as,

$$\beta^s_{532} = \frac{0.0209}{4\pi\sigma^2 \cos^4\theta} \exp[-\frac{\tan^2\theta}{2\sigma^2}]$$

Where θ is CALIOP's off nadir pointing angel (0.3 or 3 degree) and σ^2 is the wave slope variance, which is a function of AMSR-E wind speed [1].

Then, the transmittance of the overlying atmosphere can be estimated as the ratio between the CALIOP ocean surface backscatter and the theoretical one,

$$T^2_{532} = \frac{\beta^{s'}_{532}}{\beta^s_{532}}$$

Finally, the ocean subsurface backscatter can be obtained as,

$$\beta^u_{532} = \frac{\beta^{u'}_{532}}{T^2_{532}}$$

where $\beta^{u'}_{532}$ is the attenuated backscatter below ocean surface

Reference

1. Y. Hu, K. Stamnes, M. Vaughan, J. Pelon, C. Weimer, D. Wu, M. Cisewski, W. Sun, P. Yang, B. Lin, A. Omar, D. Flittner, C. Hostetler, C. Trepte, D. Winker, G. Gibson, and M. Santa-Maria, "Sea surface wind speed estimation from space-based lidar measurements," *Atmos. Chem. Phys.,* vol. 8, pp. 3593-3601, 2008

3. Estimate the Ocean sub-surface lidar backscatter

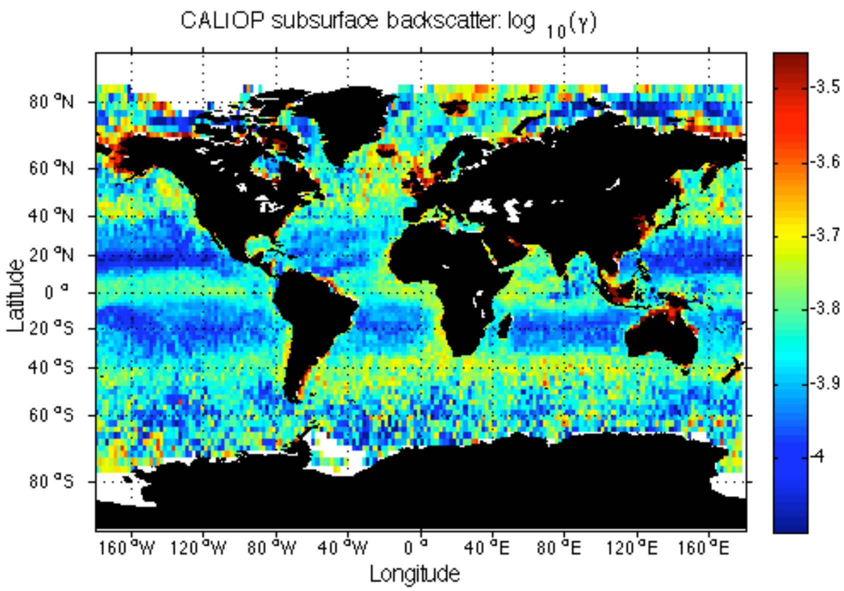
532nm Perpendicular: Subsurface Particulate Backscatter from 532nm Cross Polarization Signal

- For a linearly polarized incident lidar beam (e.g., CALIOP), spherical particles, Rayleigh scattering, and reflection at the ocean surface do not contribute significantly to cross polarization

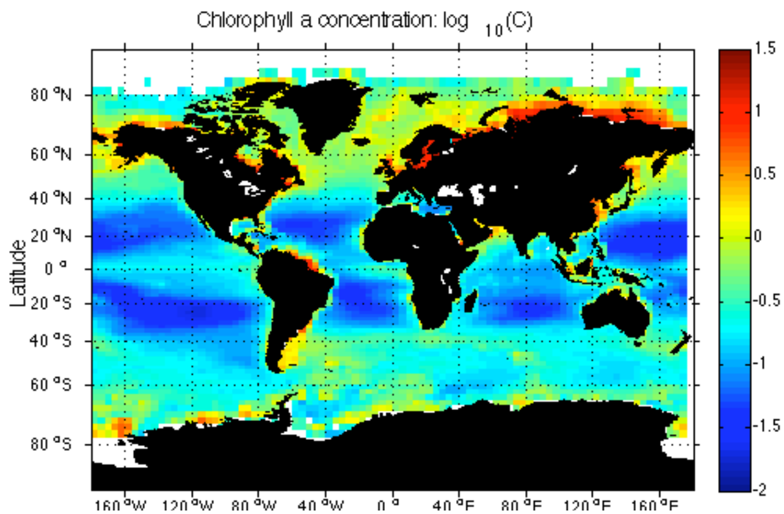
- Cross polarization (measured by the perpendicular channel) is dominated by backscattering of **non-spherical particles**

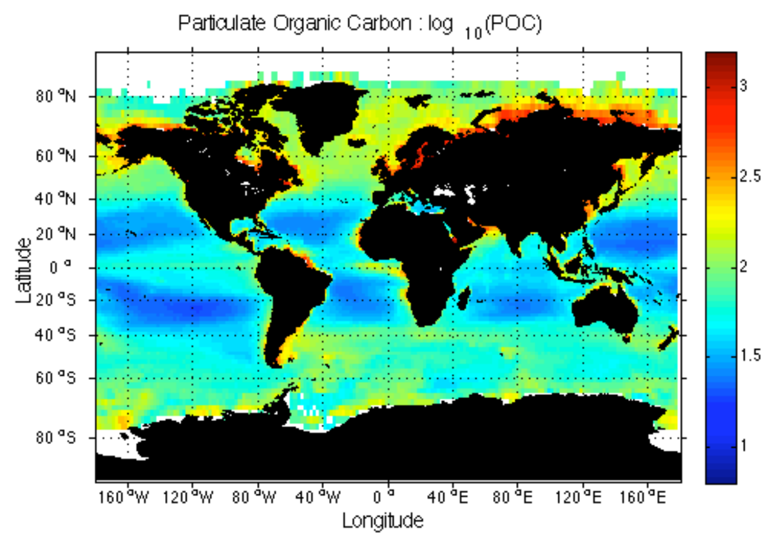
e.g., cloud ice crystals in atmosphere
plankton and other non-spherical particles in the water

3. Ocean subsurface results



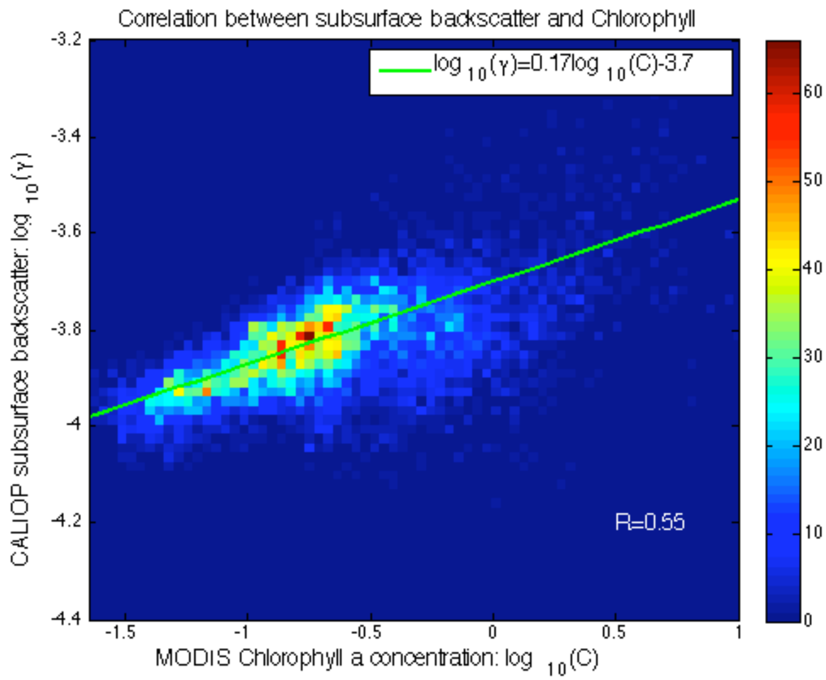
Global distribution (2º by 2º) of CALIOP Ocean subsurface backscatter

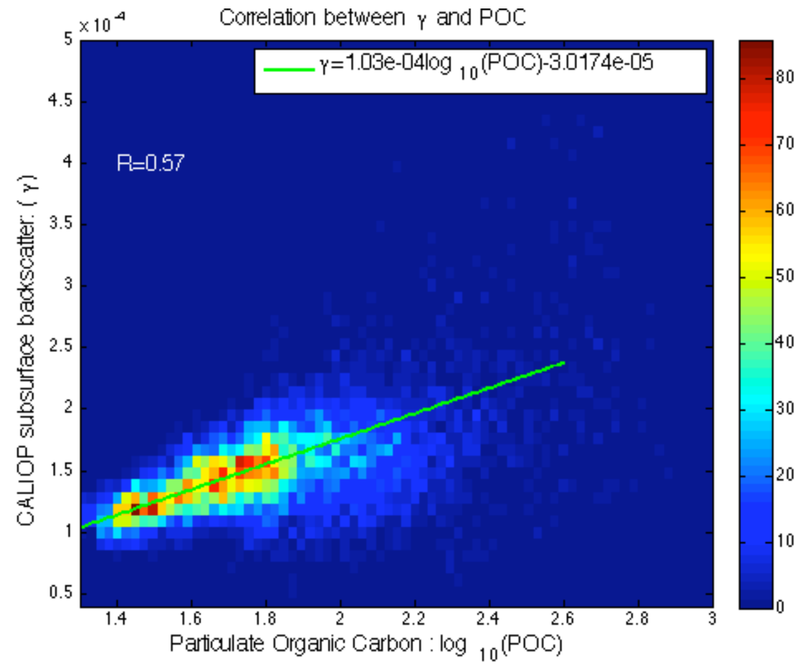




Global distributions (2º by 2º) of MODIS chlorophyll a concentration, C (mg/m^3) and Particulate Organic Carbon, POC (mg/m^3). Color code is the decimal logarithm of C and POC.

Relationship between the obtained CALIPSO subsurface backscatter γ and MODIS chlorophyll-a C and Particulate Organic Carbon, POC





We found an interesting relation between integrated ocean subsurface backscatter γ(/sr) and chlorophyll-a concentration C (mg/m^3), and relation between γ(/sr) and POC (mg/m^3) as,

$$\log_{10}\gamma = 0.17\log_{10} C - 3.7$$

$$\gamma = 1.35\times10^{-4}\log_{10} POC - 8.1\times10^{-5}$$

The relations indicate a potential of CALIOP lidar for quantifying global chlorophyll-a and POC concentrations, which will open up a new application for the space-based CALIOP lidar

Summary

Besides the primary cloud and aerosol data products such as cloud types, cloud physical properties, aerosol type and aerosol optical properties, **CALIOP profiling lidar measurements also provides a lot more information for ocean studies, e.g,**

- Ocean sub-surface particulate backscatter
- Ocean sub-surface depolarization ratio
- Estimate chlorophyll-a and POC concentrations

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Any question?
Thank you for your attention