Global high resolution wind speed statistics from satellite lidar measurement

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Abstract— The lidar on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission provides accurate ocean surface backscatter intensity at 1064nm wavelength. The measurements can be used for estimating ocean surface wind speed at CALIPSO's 70 m lidar footprint. We are developing the high spatial resolution ocean surface wind speed data product for all the CALIPSO measurements, starting from June 2006 and ending at the end of CALIPSO mission (likely 2012). Wind Speed probability distributions will be studied based on the high spatial resolution data and compared with QuikScat. Scale and shape parameters of the Weibull wind distributions are derived from the wind speed product, and their global and regional statistics, together with the CALIPSO wind speed product, will be made available to the research community. ***(Abstract)***

Keywords-component; formatting; style; styling; insert (key words)

1. *CALIPSO lidar measurements*

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission is a satellite mission being developed within the framework of collaboration between NASA and the French space agency, CNES. The CALIPSO mission provides unique measurements to improve our understanding of the role of aerosols and clouds in the Earth's climate system.

One of the CALIPSO mission's payload is a two-wavelength polarization-sensitive lidar. A diode-pumped Nd:YAG laser produces linearly-polarized pulses of light at 1064 nm and 532 nm. The atmospheric return is collected by a 1-meter telescope which feeds a three channel receiver measuring the backscattered intensity at 1064 nm and the two orthogonal polarization components at 532 nm (parallel and perpendicular to the polarization plane of the transmitted beam). Each laser produces 110 mJ of energy at each of the two wavelengths at a pulse repetition rate of 20.2 Hz. Only one laser is operated at a time. Beam expanders reduce the angular divergence of the laser beam to produce a beam diameter of 70 meters at the Earth's surface. The fundamental sampling resolution of the lidar is 30 meters vertical and 333 meters horizontal, determined by the receiver electrical bandwidth and the laser pulse repetition rate. Backscatter data are acquired from 0.5 km below the surface to 8 km above with 30 m vertical resolution. Backscatter data at coarser resolution are collected below and above that vertical altitude range (Figure 1).

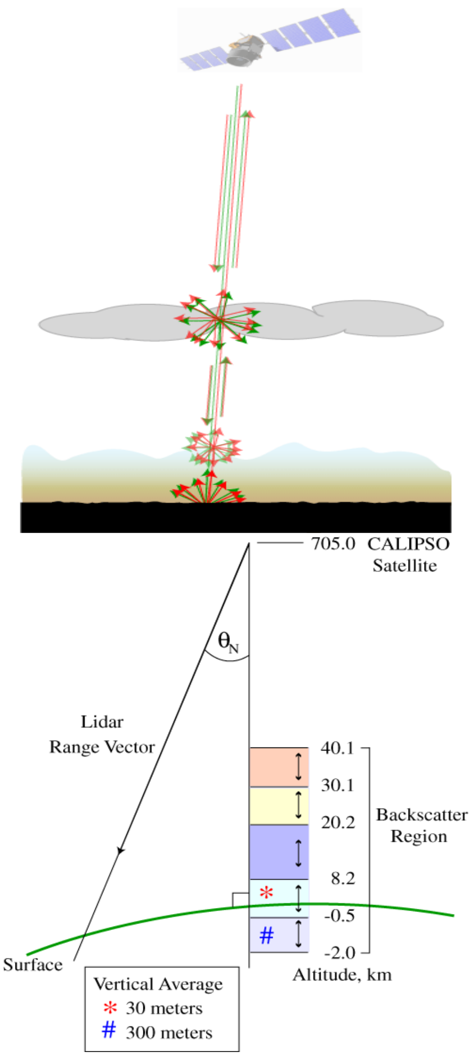

Figure 1 CALIPSO lidar measurements and vertical range resolution. The laser beam size is 70 m.

2. *Mean square slope estimates from CALIPSO ocean surface lidar backscatter*

The parallel polarization component of the CALIPSO lidar backscatter from ocean surfaces is primarily a result of specular reflection. When a laser beam hits a water surface at near normal incidence, about 2% of the laser energy is reflected and the rest of the energy goes into the water. For weak winds, the water surface is smooth and specular reflection is a narrow beam with little divergence. As wind speed increases, the surface roughens and the divergence angle of the same 2% of specularly reflected energy increases. Thus, lidar backscatter intensity from the ocean surface decreases as wind speeds increase. Simple relations [e.g., Cox and Munk, 1954; Wu, 1990; Hu et al., 2008] between wind speed and ocean surface roughness (wave slope variance) can be applied to estimate ocean surface wind speed from 1064nm lidar clear sky ocean measurements.

It has been over half a century since Cox and Munk (1954) introduced the Gaussian distribution relation between sea surface wind and the slopes of wind driven waves. A Gaussian distribution has maximum information entropy [P(si)logP(si), where P(si) is the probability of slope si] and thus is the most probable state if we can consider the wind driven slopes (si) as many independent and identicallydistributed random variables [central limit theorem]. In the same study, Cox and Munk (1954) also suggested a linear relationship between wind speed at 12.5m above sea surface and the mean square slope, based on measurements of the bi-directional sea surface reflectance pattern of reflected sunlight. Using laboratory measurements, Wu (1990) revised the relation between wind speed and slope variance to two log-linear relations. When the wind speed is less than 7 m/s, capillary waves, resulting from a balance between atmospheric wind friction and water surface tension, is the predominant component of wind driven waves. For wind speed exceeding 7 m/s, the surface becomes rougher and the predominant wavelengths grow to centimeter scale while surface tension weakens and gravity becomes more important in terms of restoring surface smoothness (i.e., gravity-capillary waves). The wind speed – wave slope variance relation also varies with sea surface state and meteorological conditions (Shaw and Churnside, 1997).

Using collocated TRMM sea surface radar cross sections and wind speeds from microwave radiometer, Freilich and Vanhoff (2003) analyzed the wind speed – mean square slope relations on a global scale and demonstrated that at lower wind speed ($U<10$ m/s), a log-linear relation agrees well with the observations, while at larger wind speed (5 m/s$<U<$19 m/s), both the linear Cox-Munk relation and log-linear Wu relation are within the uncertainty of observation. The wave slope variances derived from microwave data are slightly different from those derived from visible and infrared measurements since they cover different wave-number ranges of wind-generated waves (Liu et al., 2000). A global analysis of wind speed – mean square slope relation for waves that fall within the lidar backscatter sensitivity range can be performed by comparing sea surface backscatter of the CALIPSO lidar with the collocated wind speed measurements of AMSR-E on the Aqua spacecraft. As the space-based lidar onboard the CALIPSO satellite only measures sea surface backscatter at a 0.3 degree off-nadir angle, directional properties, such as skewness and peakedness, can be ignored. The independent absolute calibration of CALIPSO lidar measurements enables an accurate assessment of the relations by comparing the AMSR-E wind speeds with the variance information derived from lidar backscatter (Figure 3).

By definition, the CALIPSO lidar sea surface backscatter, γ, is

$$\gamma = \frac{\rho}{4\pi < s^2 > \cos^4\theta} \exp\left(-\frac{\tan^2\theta}{2 < s^2 >}\right).$$

For near-normal incidence, the Fresnel reflectance, ρ, is 0.0209 for sea water at 532 nm and 0.0193 at 1064nm. For 0.3 degree off-nadir lidar pointing, $\tan^2\theta$ is very close to 0 and $\cos^2\theta$ is very close to 0. Thus, at 1064nm wavelength,

$$\gamma \approx \frac{0.0193}{4\pi < s^2 >}.$$

So, the ocean surface lidar backscatter from CALIPSO, γ, is a direct measurement of mean square slope, $<s^2>$ (Figure 2).

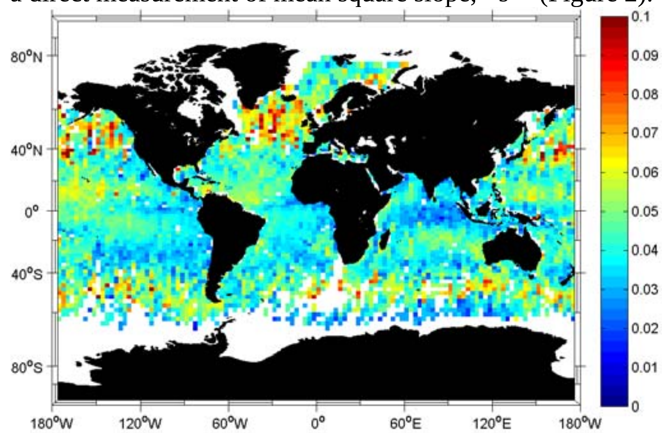

Figure 2. Mean square slope estimated from CALIPSO 1064nm ocean surface backscatter (January 2008).

On average, the signal-noise-ratio (SNR) for a single lidar shot ocean surface backscatter measurement (70 m laser spot) is around 100 at nighttime (better at lower wind speed and worse at higher wind speed). After accounting for uncertainties such as aerosol optical depth calculations and calibration, the instantaneous error of the mean square slope estimates at 70 m lidar footprint from CALIPSO measurements is around 5-10% (which translates to instantaneous wind speed uncertainty of around 1 m/s).

3. *How can these high spatial resolution measurements compliment QuickScat*

Due to the limitation of coverage (nadir viewing only), the use of the global CALIPSO wind speed observations is limited, comparing with QuikScat data. But the high spatial resolution (70 m) wind speed statistics from the lidar measurements do bring important information that can compliment QuikScat.

With the70 m spatial sampling of the wind speed, CALIPSO captures more wind gusts and provide global statistics of that. As a result, the wind speed distribution is broader than measurements with larger footprint sizes (e.g., QuikScat and AMSR-E). As demonstrated in Figure 4, the CALIPSO wind speed (70 m)distribution has more low and high winds than AMSR-E (40 km), while the mean wind speeds of CALIPSO and AMSR-E are very close (Hu et al., 2008).

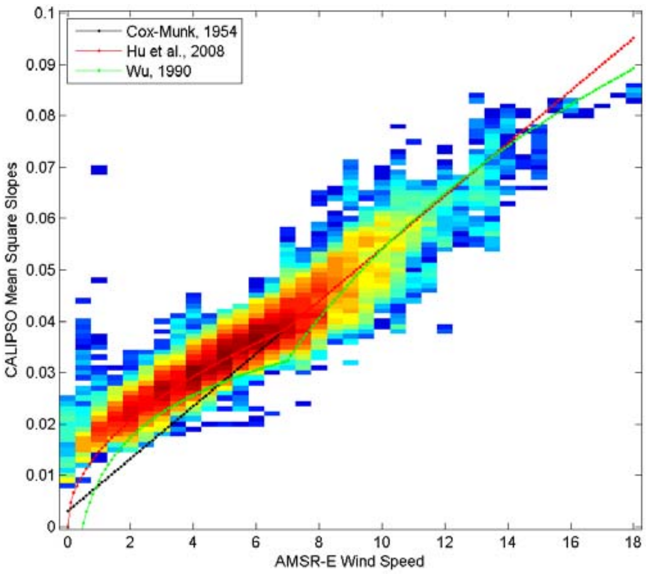

Figure 3. Frequency of occurrence (color bar: log scale) of the AMSR-E wind speed – CALIPSO mean square wave slope relation.

Using The wind speed – wave slope relations derived from the collocated CALIPSO and AMSR-E measurements as illustrated in figure 3, wind speed at CALIPSO laser sot size (70 m) resolution can be derived (Hu et al., 2008).

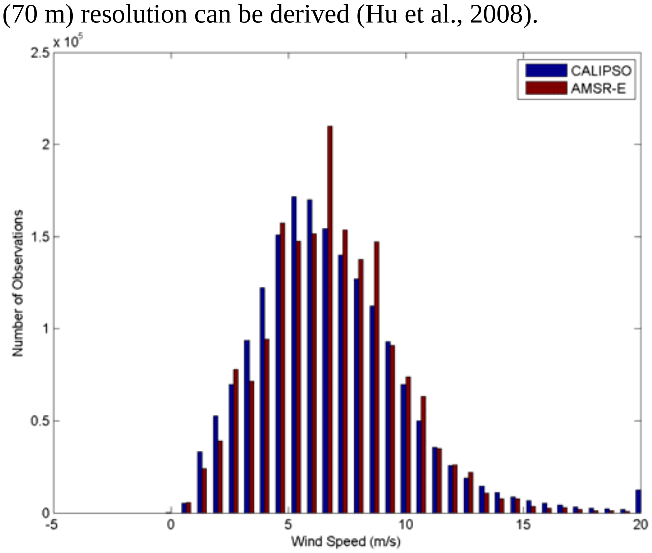

Figure 4 Global ocean surface wind speed distribution of Jan. 2008 from CALIPSO (blue) and AMSR-E (red) collocated measurements.

Figure 5 shows that nearly almost everywhere, the standard deviations of the monthly mean winds from CALIPSO measurements are much higher than the standard deviation of AMSR-E winds.

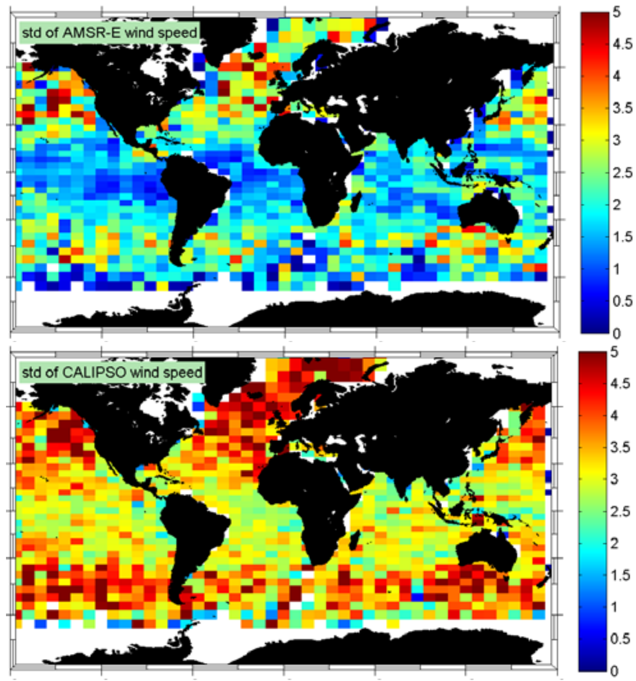

Figure 5 Standard deviations (m/s) of Jan 2008 wind speed from AMSR-E (upper) and CALIPSO (lower).

The vertical turbulent transport velocities of heat and gases are sensitive not only to the mean surface wind speed, but also the detailed wind speed probability distributions (e.g., Winninkhof et al., 1992).

Wind speed probability distribution is normally represented by Weibull distribution (e.g., Justus et al., 1978; Monahan, 2006),

$$P(x) = \frac{b}{a}(\frac{x}{a})^{b-1}\exp[-(\frac{x}{a})^{b}].$$

The parameters a and b denote the scale and shape parameters of the distribution (Justus et al., 1978),

$$b = [\frac{mean(x)}{std(x)}]^{1.086}, and$$

$$a = \frac{mean(x)}{\Gamma(1+1/b)}.$$

The scale parameters, a, for both AMSR-E and CALIPSO are similar (upper panel of Fig 6). But the shape parameters, b, are very different (lower panels of Fig 6). Due to AMSR-E's narrower wind speed distribution, the b values of AMSR-E are much higher than the CALIPSO b values.

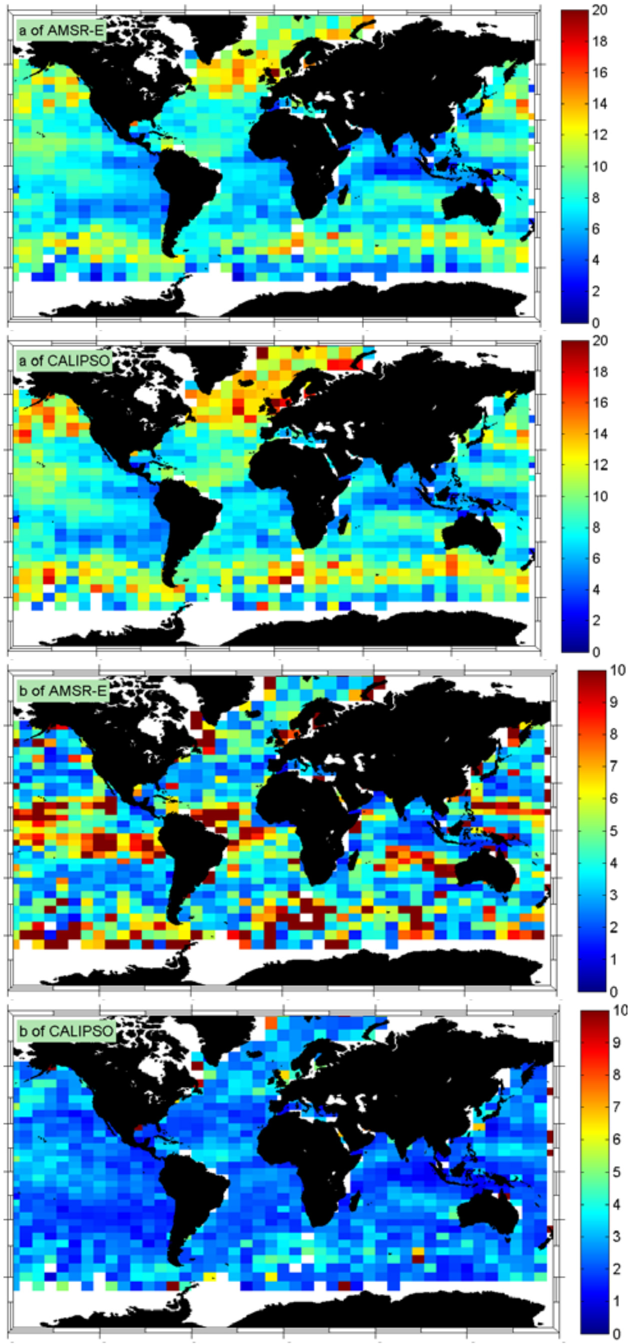

Figure 6 The statistics of a (upper) and b (lower) of Weibull distributions for AMSR-E (left) and CALIPSO (right). This is from Jan 2008 collocated AMSR-E and CALIPSO data.

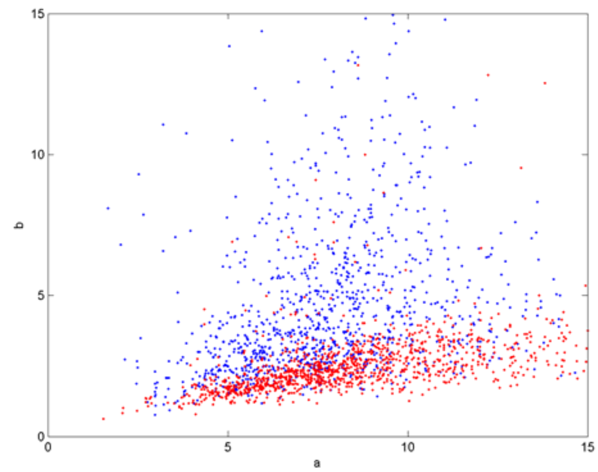

Figure 7. the relation between a and b of Weibull distributions from AMSR-E (blue) and CALIPSO (red). Rayleigh distribution (b=2) is a good approximation for wind speed around 7 m/s when CALIPSO high spatial resolution wind speed is used.

The shape parameters, b, derived from CALIPSO wind speed are mostly around 2 (lower right panel of Figure 6, and Fig 7). Figure 7 indicates that when using CALIPSO high resolution wind speed measurements, the shape parameter, b, are always around 2 and increases slightly with scale parameters. Thus Rayleigh distribution (b=2) is a good approximation.

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