CALIPSO OBSERVATIONS OF AEROSOL PROPERTIES NEAR CLOUDS

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ABSTRACT

Clouds are surrounded by a transition zone of rapidly changing aerosol properties. Characterizing this zone is important for better understanding aerosol-cloud interactions and aerosol radiative effects as well as for improving satellite measurements of aerosol properties. We present a statistical analysis of a global dataset of CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) lidar observations over oceans. The results show that the transition zone extends as far as 15 km away from clouds and it is ubiquitous over all oceans. The use of only high confidence level cloud-aerosol discrimination (CAD) data confirms the findings. However, the results underline the need for caution to avoid biases in studies of satellite aerosol products, aerosol-cloud interactions, and aerosol direct radiative effects.

1. INTRODUCTION

Several recent studies have indicated that clouds are surrounded by a transition zone of rapidly changing aerosol properties [1-4]. Characterizing this transition zone is important for better understanding two critical yet poorly understood aspects of anthropogenic climate change—aerosol-cloud interactions and aerosol radiative effects— and also for devising effective sampling strategies for satellite measurements of aerosol properties.

Satellites offer excellent opportunities to study the transition zone near clouds, though the separation between clouds and cloud-free areas is often uncertain and ambiguities can occur at all scales [5]. As was summed up in [6], "Multiple lines of evidence exist that call into question the degree to which clear and cloudy sky can be separated...". Consequently, improving our knowledge of the transition zone requires improvements in understanding and separating remote sensing uncertainties and physical phenomena such as aerosol swelling in humid air.

One reason why such improvements are important is that aerosol changes and remote sensing uncertainties near clouds create a dilemma: excluding the transition zone in order to avoid its remote sensing uncertainties can bias a study toward low aerosol loads and radiative effects, but including the transition zone despite the remote sensing uncertainties can bias the study toward too high aerosol loads and radiative effects.

Lidar instruments offer excellent opportunities for studying the transition zone, because their measurements are not affected by 3D cloud radiative effects [7-8]. Recently, paper [9] used the spaceborne CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) lidar for studying the transition zone. Following their results this study analyzes a large global dataset of CALIPSO measurements, which can reveal even the subtle changes that occur at the more distant portions of the transition zone.

2. DATA AND METHODOLOGY

We analyze a monthlong (Sept 15-Oct.14, 2008) global dataset of CALIPSO lidar data over all oceans free of sea ice. Our statistical analysis uses the operational 1 km-resolution CALIPSO cloud mask and 333 m-resolution attenuated backscatter profiles at both 532 nm and 1064 nm wavelengths. The results shown are for nighttime data simply because the weaker background illumination creates smaller noise and allows more reliable cloud detection.

Following [9], we characterize the transition zone by examining how median attenuated backscatter values vary with distance from the nearest cloud. Median values are well-suited for this purpose because they are less affected by uncertainties in cloud detection or by unobserved clouds right near the satellite track.

This study focuses on clear areas closest to low-level clouds (below 3 km), but we note that results for clear areas near any clouds were very similar to those presented here. One reason for the similarity is that 50% of all clear profiles analyzed here are closer than 4.4 km to a cloud below 3 km, and 75% is closer than 20 km. The remaining 25% of clear profiles includes both those clear profiles that are closest to a cloud higher than 3 km, and those clear profiles that are more than 20 km away from any cloud. We note that paper [4] found 66% of all clear areas over the Indian Ocean to be closer than 4 km to clouds.

Our results indicate that much more clear profiles lie close to clouds below 3 km than to higher clouds, even though the highest cloud top is more often above than below 3 km. This occurs because high clouds often form large continuous layers, and so only a few clear profiles can be close to high clouds—whereas low cloud layers often consist of numerous small clouds separated by clear gaps, which allows many clear profiles to be close to them. The CALIPSO cloud detection algorithm [10] may further emphasize this tendency, when it reduces the effects of observational noise by detecting faint clouds after averaging observed backscatter values over larger scales, which fills in any small gaps in thin high clouds.

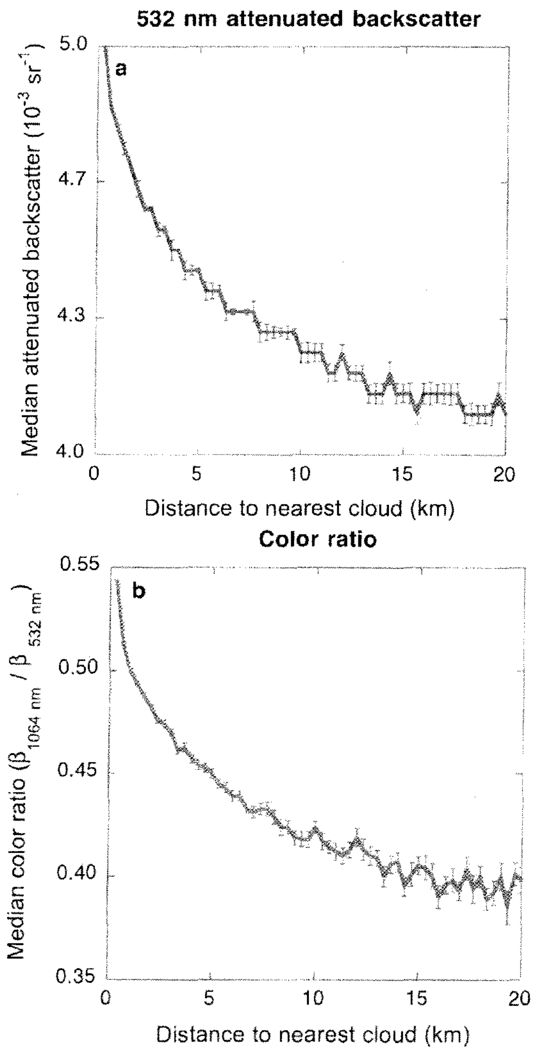

Figure 1. (a) Median vertically integrated attenuated backscatter for all nighttime CALIPSO observations over ice-free oceans. (b) Median color ratio.

Finally, we note that results shown in Fig. 1 are the attenuated backscatter values integrated up to 3 km altitude, but the results of integrating to 15 km altitude behaved very similarly. We chose to present the results for low-level backscatter because this is where the bulk of near-cloud aerosol changes occur.

3. RESULTS ON PARTICLES NEAR CLOUD

Figure 1a confirms the overall tendency in earlier papers that attenuated backscatter increases systematically toward clouds. This tendency is sufficiently ubiquitous to appear in global statistics, and the transition zone extends well beyond the ~4 km range of earlier studies, typically to about 15 km.

Figure 1b shows that the spectral behavior of attenuated backscatter (β) also changes near clouds: the median "color ratio" β_{1064}/β_{532} increases systematically near clouds. Because backscatter decreases with wavelength faster for smaller particles than for larger particles (i.e., smaller particles have larger Angstrom exponents), the color ratio increase in Fig. 1b indicates that particle size increases near clouds. This increase is consistent with the effects of both aerosol humidification and cloud detrainment, but establishing the relative importance of these two processes as in [9] will require a more detailed study. The increase near clouds in Fig. 1 is a global phenomenon and the overall trend is neither caused by a single dominant region nor is it an artifact of combining observations from vastly different regions of the Earth. While undoubtedly there are regional variations, much of the variations likely come from sampling issues.

4. RESULTS ON REMOTE SENSING EFFECTS NEAR CLOUDS

While aerosol particles are responsible for a large part of the near-cloud enhancements discussed above, misidentified or undetected cloud particles are also likely to contribute. Undetected cloud particles can contribute to clear-sky statistics because the separation of cloudy and cloud-free areas is sometimes ambiguous due to uncertainties both in detecting layers of scattering particles and in distinguishing clouds from aerosols [10-11]. Identifying cloud particles is especially difficult when small clouds cover only a portion of the lidar field-of-view—a situation that often occurs in sparse cumulus fields, where paper [5] found very small clouds to be fairly abundant.

As an example of remote sensing issues, Fig. 2 shows that lidar backscatter increases near clouds even in pristine atmospheric columns where the operational CALIPSO product did not detect any aerosol layers. The increase is most pronounced within 4-5 km from the clouds identified by CALIPSO. These results indicate that aerosol or cloud particles are often present even in these pristine profiles.

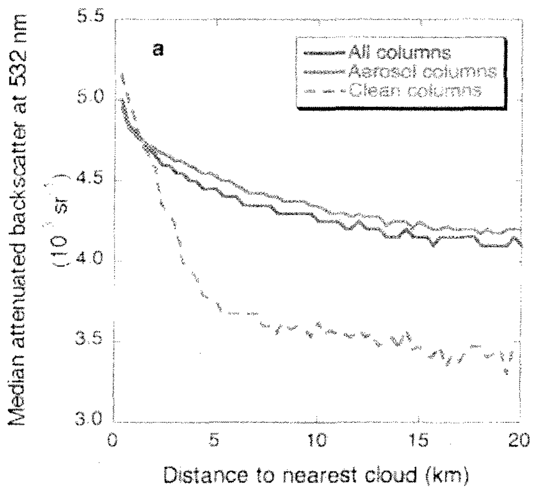

Figure 2. Median vertically integrated 532 nm attenuated backscatter for nighttime CALIPSO observations over ice-free oceans. This panel considers separately the atmospheric columns that are free of both cloud and aerosol layers and the columns that contain an aerosol layer, as specified by the operational CALIPSO.color ratio.

CALIPSO uses the lidar cloud and aerosol discrimination (CAD) algorithm [11] to identify aerosol and cloud features. Figure 3 illustrates the median of vertically integrated 532 nm backscatter as a function of the distance to nearest clouds for all aerosol data and only for data with the best 5% CAD score (between -95 and -100). This corresponds to the highest confidence level of aerosol cloud discrimination. As expected, for the highest confidence data, the increase in backscatter towards clouds is smaller but still statistically significant. Also as expected, the fraction of high confidence level observations decreases towards clouds from 70% to 35% (Fig. 3c). Therefore, while we can confidently state that particle backscatter and size certainly increase near the clouds detected by CALIPSO, both the nature of these particles (cloud vs. aerosol) and the processes creating them (e.g., aerosol swelling in humid air) need to be clarified waiting them with the appropriate CAD score.

5. CONCLUSIVE THOUGHTS

This paper presents a statistical analysis of a monthlong global dataset of CALIPSO lidar observations over oceans. The results show that clouds are surrounded by a transition zone of enhanced particle backscatter and size that is ubiquitous over all oceans. The transition zone is much wider (~15 km) than the ranges examined in earlier studies. In addition, the results also provide information on uncertainties in aerosol remote sensing near clouds comparing all aerosol data with the highest confidence data. They confirm that the observed increase in attenuated backscatter is statistically robust.

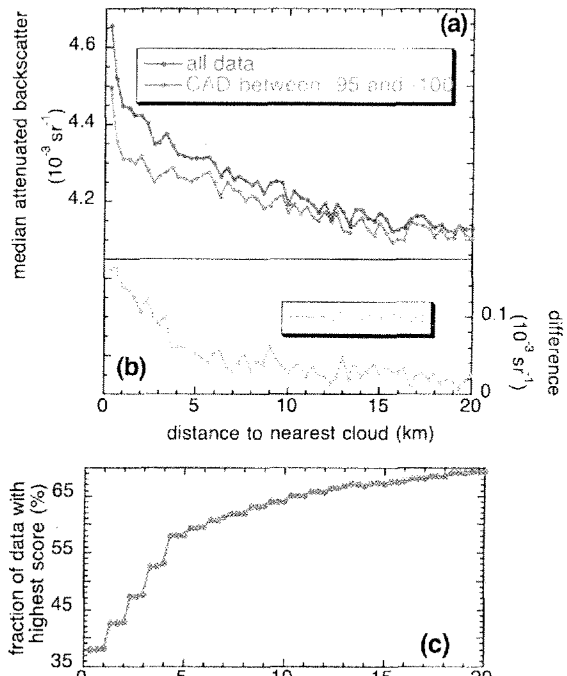

Figure 3. (a) Median vertically integrated 532 nm attenuated backscatter for nighttime CALIPSO observations over ice-free oceans. The upper curve corresponds to all aerosol data while the lower one to only data with the CAR score between -95 and -100. (b) The difference between the two curves from panel (a). (c) Fraction of data with the CAD score between -95 and -100.

The width and ubiquity of the transition zone near clouds imply that studies of aerosol-cloud interactions and aerosol direct radiative effects need to account for aerosol changes near clouds. For example, these changes can cause systematic biases toward smaller aerosol radiative forcing if areas near clouds are not included in order to avoid aerosol retrievals ambiguities that arise near clouds (e.g., 3D radiative effects, instrument blurring, cloud contamination). On the other hand, including aerosol products near clouds despite these ambiguities may overestimate aerosol radiative forcing. As a result, there is an urgent need for developing methods that can assess and account for remote sensing challenges [12-13] and thus allow for including the transition zone into the study. Alternatively, one may remove biases by seeking a balanced sampling strategy that may compensate for excluding both near-cloud and far-from-cloud areas to a similar degree [14]. Finally, statistical adjustments of results limited to areas far from clouds may also be possible if the statistical behavior of the transition zones becomes well understood. More detailed future analysis of transition zones is expected to provide further insights into their origins and influence on the atmosphere, radiative processes, and satellite data products.

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