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MODIS observations of enhanced clear sky reflectance near clouds

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[1] Several recent studies have found that the brightness of clear sky systematically increases near clouds. Understanding this increase is important both for a correct interpretation of observations and for improving our knowledge of aerosol-cloud interactions. However, while the studies suggested several processes to explain the increase, the significance of each process is yet to be determined. This study examines one of the suggested processes—three-dimensional (3-D) radiative interactions between clouds and their surroundings—by analyzing a large dataset of MODIS (Moderate Resolution Imaging Spectroradiometer) observations over the Northeast Atlantic Ocean. The results indicate that 3-D effects are responsible for a large portion of the observed increase, which extends to about 15 km away from clouds and is stronger (*i*) at shorter wavelengths (*ii*) near optically thicker clouds and (*iii*) near illuminated cloud sides. This implies that it is important to account for 3-D radiative effects in the interpretation of solar reflectance measurements over clear regions in the vicinity of clouds. **Citation:** Várnai, T., and A. Marshak (2009), MODIS observations of enhanced clear sky reflectance near clouds, *Geophys. Res. Lett.*, *36*, L06807, doi:10.1029/2008GL037089.

1. Introduction

[2] Aerosol effects on clouds constitute one of the most important yet least known aspects of anthropogenic climate change. Satellite observations revealed complex relationships between nearby cloud and aerosol properties, and provided many important insights into aerosol-cloud interactions [*Ignatov et al.*, 2005; *Kaufman et al.*, 2005; *Loeb and Manalo-Smith*, 2005; *Matheson et al.*, 2005; *Loeb and Schuster*, 2008]. An important recent finding was the presence of a transitional zone around clouds [*Koren et al.*, 2007]. Observing this transitional zone from the ground [*Chiu et al.*, 2009] or from satellites [*Koren et al.*, 2007], researchers found that the brightness of cloud-free areas systematically increases near clouds.

[3] Several factors were proposed to explain the enhanced brightness values, including (*i*) Swelling of aerosol particles in the humid environment near clouds; (*ii*) Increased number of aerosol particles due to aerosol-generating processes associated with clouds; (*iii*) Undetected cloud particles, due to detrainment or thin subpixel-size clouds; (*iv*) Instrument limitations such as a slight blurring of satellite images; (*v*) Three-dimensional (3-D) radiative interactions between clouds and surrounding clear areas. As discussed in earlier studies [e.g., *Marshak et al.*, 2008; *Wen et al.*, 2008], 3-D effects enhance clear sky reflectances when light reflected from clouds moves to nearby clear areas where it gets scattered toward the satellite, mostly by air molecules. (The dominance of molecular scattering is true at shorter wavelengths for cases of low-level clouds over dark surfaces, with aerosol below cloud top.) While all the factors mentioned above are likely to contribute to the enhanced brightness, their relative importance has not yet been established.

[4] Our main concern here is whether 3-D effects contribute significantly to the observed increases: Current aerosol retrieval algorithms rely on 1-D theory, and could misinterpret 3-D-related brightness enhancements as a sign of increased aerosol concentration. Moreover, 3-D related overestimations of aerosol content would be stronger near thicker clouds because they reflect more sunlight toward nearby clear areas, and this could create a spurious correlation between retrieved values of aerosol and cloud optical thickness. However, while theoretical simulations suggested strong 3-D effects [*Cahalan et al.*, 2001; *Wen et al.*, 2006, 2007], observations could not yet confirm this unequivocally: Some remote sensing studies found a stronger reflectance enhancement at shorter wavelengths [*Loeb and Schuster*, 2008] in a way consistent with 3-D effects called "apparent aerosol bluing" by *Marshak et al.* [2008], but other observations did not support such "bluing" and instead found some of the other proposed factors significant [*Kaufman and Koren*, 2006; *Koren et al.*, 2008; *Redemann et al.*, 2009]. Recently, *Su et al.* [2008] found only a relatively small increase (10–15%) in aerosol optical thickness near clouds using airborne lidar measurements not affected by 3-D radiative processes.

[5] This paper examines the importance of 3-D radiative effects through a statistical analysis of a large dataset of MODIS (Moderate Resolution Imaging Spectroradiometer) observations. Specifically, it examines whether reflectance increases near clouds display statistical behaviors that can undoubtedly be attributed to 3-D radiative effects.

2. Data and Methodology

[6] In this study we analyze 1 km resolution MODIS reflectances at several visible and near infrared wavelengths, as well as brightness temperatures at 11 μm. We also consider the 1 km and 250 m resolution MODIS cloud masks, the 1 km resolution cloud optical thickness product, and the 5 km resolution cloud top pressure product.

[7] The study area lies Southwest of the United Kingdom in the North Atlantic Ocean, between 45°–50°North and 5°–25°West. In the analysis we combine all daytime MODIS Terra observations for this area for the two week long period of September 14–29 in eight consecutive years,

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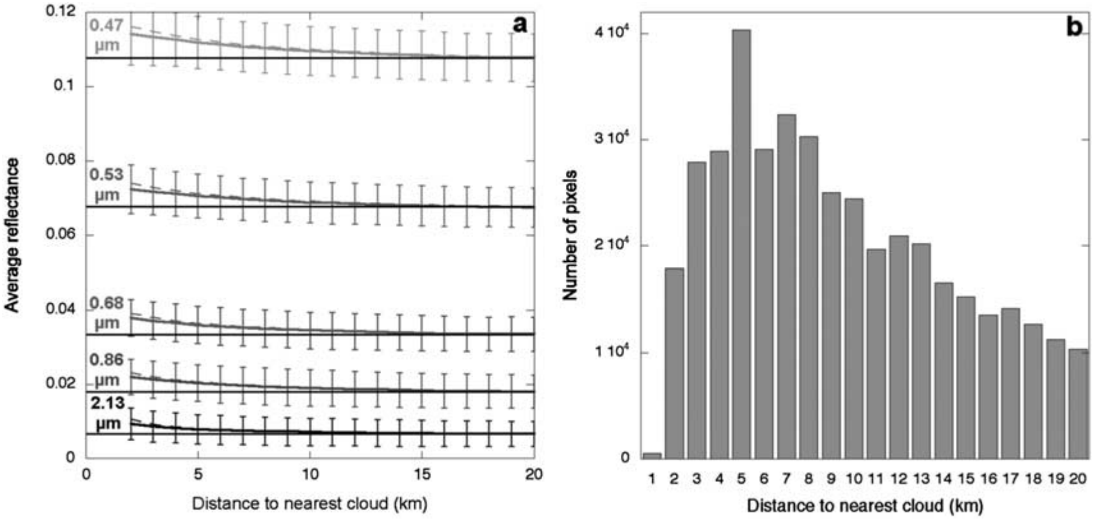

Figure 1. (a) Average clear-sky reflectances at several MODIS wavelengths. Dashed lines represent mean values of all clear pixels, whereas solid lines represent mean values of only the clear pixels whose nearest cloudy neighbor lies in downscan direction. To visualize reflectance enhancements, horizontal lines mark average reflectances at 20 km distance from the nearest clouds. Error bars indicate the standard deviation of data values. (b) Number of downscan pixels used.

from 2000 to 2007. To eliminate the possibility of sunglint and to ensure fairly constant sun-view geometry, we consider only the center of MODIS swaths where the viewing zenith angle remains below 10°. Because of the sun-synchronous orbit of the Terra satellite, this limits the solar zenith angle to 48° ± 2°.

[8] To help detect the influence of 3-D interactions between cloudy and clear areas, we make three precautions to minimize the influence of cloud detection uncertainties. First, we consider clear-sky reflectances only for pixels where the 1 km cloud mask value is "confident clear" and where the 250 m cloud mask value is "clear" for all 16 subpixels. Second, we reduce the influence of difficult cirrus detection decisions by considering only cloud-free pixels that have low-level clouds (cloud top pressure > 700 hPa) within their 20 by 20 km surroundings. Third, we calculate a cloud-free pixel's distance to the nearest cloud as the distance to the nearest pixel where clouds were not only detected but were even suitable for optical thickness retrievals in the operational MODIS cloud algorithm [*Platnick et al.*, 2003] (http://modis-atmos.gsfc.nasa.gov/C005_Changes/C005_CloudOpticalProperties_ver311.pdf).

3. Results

[9] A quick test of the dataset described above reveals that over two thirds of all cloud-free pixels are within 20 km of clouds and that the histogram of clear pixels peaks about 5 km away from the nearest clouds. Figure 1 shows that, as expected from earlier studies [*Koren et al.*, 2007], clear-sky reflectances systematically increase near clouds. As mentioned in the introduction, reflectance enhancements near clouds may arise from a combination of factors—and so in examining the influence of 3-D effects we need to consider other possible contributions as well.

[10] First of all, instrument imperfections may cause apparent reflectance increases near clouds because of both blurring and detector inertia. Blurring is usually characterized through the point-spread function, which unfortunately is not available for most MODIS bands. However, our initial tests using published data for the 531 nm band [*Qiu et al.*, 2000, Figure 2] suggest that blurring makes only a minor contribution to the observed reflectance increases. We will quantify this contribution for several MODIS bands in a future study. Detector inertia contributes to the observed reflectance increases through the so-called latency effect: MODIS detectors need a little time to fully respond to sharp brightness drops at cloud edges, and so they register slightly too high reflectance values over cloud-free areas that are observed right after scanning through bright clouds. To alleviate this problem, our detailed analysis uses only those clear pixels that are observed before the cloud closest to them. In other words, we use only the half of clear pixels whose closest cloudy neighbor lies in a downscan (and not upscan) direction. Figure 1 reveals that while the latency effect makes reflectance enhancements near clouds stronger, the enhancements remain strong even when the latency effect is removed.

[11] Additional notable features in Figure 1 include reflectance enhancements extending to about 15 km away from clouds, and the enhancements being stronger at shorter wavelengths. This wavelength dependence (also apparent in subsequent figures) is consistent with enhanced aerosol concentrations near clouds (aerosol particles scatter more light at shorter wavelengths) and also with 3-D radiative effects: Rayleigh scattering in clear areas is more effective at shorter wavelengths in redirecting the light coming from clouds toward a satellite above [*Marshak et al.*, 2008; *Wen et al.*, 2008]. In contrast, undetected cloud particles scatter light fairly similarly at all wavelengths, and so they could not explain the wavelength dependence of cloud enhancement in Figure 1. Still, undetected clouds (and instrument blurring) are likely to contribute and to be especially important at 2.1 μm, where aerosol scattering effects are weak and Rayleigh scattering is negligible.

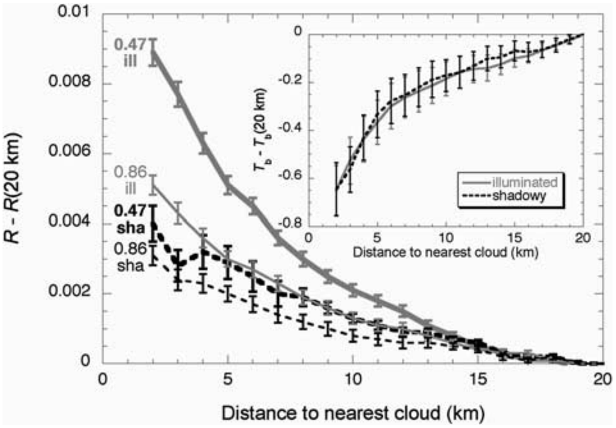

Figure 2. Asymmetry of clear sky reflectance enhancements near illuminated and shadowy cloud sides at 0.47 μm and 0.86 μm. The inset shows that the asymmetry is minimal for 11 μm brightness temperatures (T_b). Error bars indicate standard errors based on the spread of results for each individual year (= standard deviation of annual results divided by $\sqrt{\text{number of years}}$). Because each year includes a different number of pixels, the error bars provide an upper limit to statistical uncertainties.

[12] As *Várnai and Marshak* [2002] demonstrated, asymmetries in reflectances with respect to the sun can provide clear signatures of 3-D radiative effects. We examine the presence of asymmetries by comparing reflectance increases in two subsets of our dataset. The "illuminated" subset includes clear pixels whose closest cloudy neighbor is to the Northeast—which implies that the clear pixel is closest to an illuminated, Southwestern cloud side. In contrast, the shadowy subset includes clear pixels whose nearest cloudy neighbor lies to the South—implying that the clear pixel is closest to a shadowy, Northern cloud side. To avoid latency effects, both subsets include only the clear pixels whose nearest cloudy neighbor lies on the downscan side.

[13] Figure 2 shows that reflectance enhancements are much stronger near illuminated than shadowy cloud sides, which is fully consistent with the presence of 3-D effects [*Wen et al.*, 2007]. Moreover, the asymmetry is larger at 0.47 μm than 0.86 μm, which is consistent with 3-D effects being stronger at shorter wavelengths.

[14] To test whether it is safe to attribute this asymmetry to 3-D effects, we checked the possibility of other explanations through two additional tests. First, we eliminated the remote possibility of asymmetric point spread functions by analyzing a smaller dataset of MODIS observations from the South Pacific Ocean (40°–45°South, 120°–140°West). The results (not shown) clearly indicated that the asymmetry is reversed when the sun lies to the North, even though the point spread function does not change when the satellite crosses the equator. Second, we examined 11 μm brightness temperatures and found a well pronounced, but symmetric cooling near clouds (see the inset in Figure 2), which is a clear indication that while undetected cloud particles and enhanced water vapor content cause some cooling, they do not cause the asymmetries in Figure 2. This also suggests that humidity fields are statistically symmetric and so aerosol swelling does not create the observed shortwave asymmetries.

[15] Next, let us examine if the enhancements in clear sky reflectance depend on the optical thickness of nearby clouds. For this, we separate clear pixels into four sub-categories based on the maximum cloud thickness of the 3 by 3 array centered on the nearest cloudy pixel. Because the results for each sub-category are based on fewer pixels than the overall results were, we reduce sampling noise by plotting results only up to 10 km away from clouds. Figure 3 shows that cloud optical thickness has a strong influence on reflectance enhancements at nearby clear areas. Near sunlit cloud sides the dominant feature is that thicker clouds reflect more light and hence cause stronger enhancements in nearby clear-sky reflectances. Near shadowy cloud sides this effect dominates only farther away from clouds, because shadowing dominates closer to clouds; thus the enhancement is smaller near thicker clouds and may even have a negative sign [*Wen et al.*, 2007]. The transition occurs at about 3–4 km away from clouds, which is comparable to the length of shadows expected for 48° solar zenith angle and 3 km cloud altitude (near our 700 hPa threshold). Note that Figure 3 also reveals that cloud thickness makes a larger difference at shorter wavelengths, which is consistent with 3-D effects being stronger at those wavelengths.

[16] Overall, the behaviors in Figures 1–3 are consistent with the influence of 3-D radiative effects. However, while other factors discussed in earlier studies, such as instrument limitations, undetected cloud particles, enhanced aerosol concentration, and aerosol swelling in humid environment are likely to contribute to the observed enhancements, they are unable to explain some well-pronounced features of the observations (e.g., enhancements being larger near illuminated than shadowy cloud sides). Thus MODIS observations confirm the theoretical predictions that 3-D radiative processes are an important factor in the reflectance enhancements at shorter wavelengths.

[17] This finding is consistent with the results of *Su et al.* [2008], where lidar measurements not affected by 3-D processes indicated much smaller increases in aerosol optical thickness near clouds than the possible 3-D radiative influences reported by *Wen et al.* [2007].

[18] Finally, the enhancements observed in this study are comparable to the 3-D enhancements simulated by *Wen et al.* [2007, 2008] for cumulus clouds over Brazil. Because those simulated enhancements caused 1-D retrievals to overestimate aerosol optical thickness by 50%–140%, the enhancements observed here are also likely to have substantial effects on aerosol retrievals. However, as the complexities of MODIS operational algorithms make the task of translating reflectance enhancements into aerosol retrieval errors fairly elaborate, we will assess the influence of 3-D effects on aerosol retrievals in a separate study.

4. Summary

[19] This study examines the reasons behind recent observations of systematically enhanced clear sky reflectances near clouds. Specifically, it examines whether 3-D radiative processes play a significant role in the enhanced reflectance of clear areas in the vicinity of clouds. We address this question through a statistical analysis of all daytime

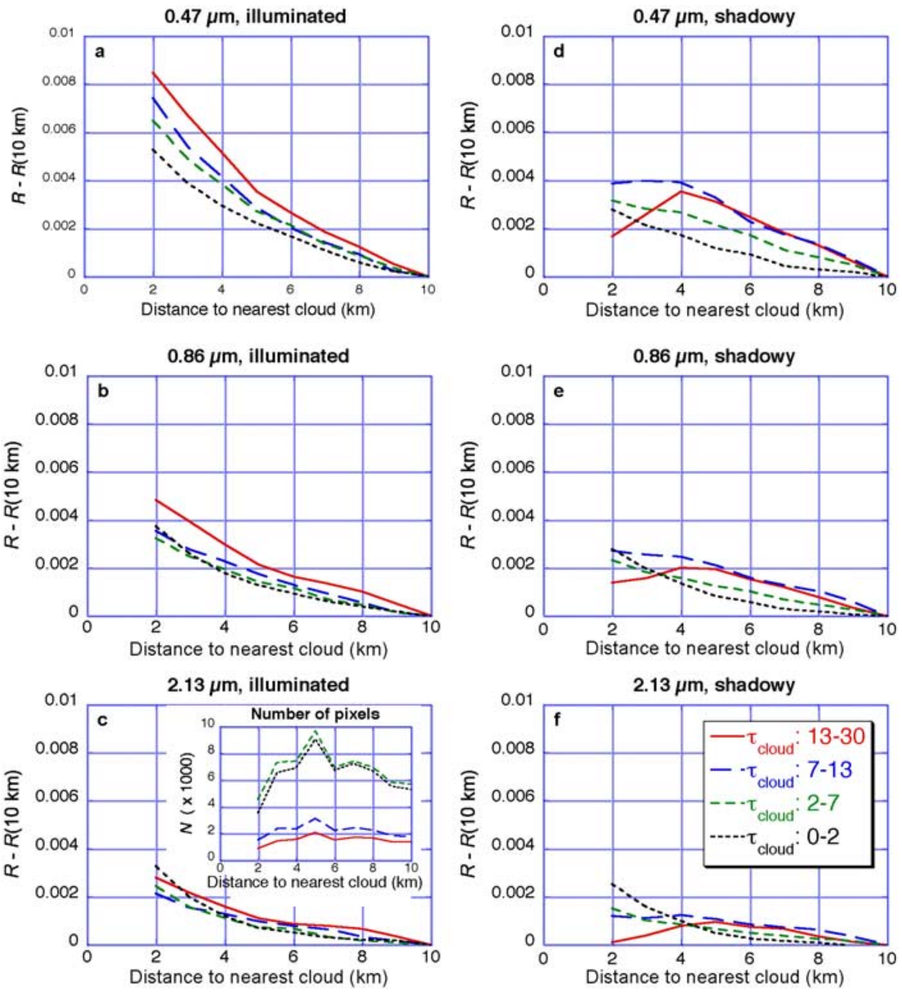

Figure 3. Dependence of clear-sky reflectance enhancements on cloud optical thickness (τ_{cloud}). The inset in Figure 3c shows the number of pixels used, which is very similar for all plots.

MODIS Terra observations from two week long periods in eight years over a roughly 1000 km by 500 km size area of the Northeast Atlantic Ocean.

[20] After removing the effects of detector inertia, we found the following key features for clear sky reflectance enhancements near clouds:

[21] 1. The enhancements extend up to about 15 km away from clouds and are stronger near illuminated cloud sides than near shadowy ones.

[22] 2. The enhancements are stronger at shorter wavelengths and near optically thicker clouds, which is consistent with the assumptions of the *Marshak et al.* [2008] simple model of 3-D radiative enhancement.

[23] As discussed in earlier studies, several factors may contribute to the observed enhancements, including undetected cloud particles, enhanced aerosol concentration and size, and instrument limitations. However, it appears highly unlikely that these factors alone would explain all features of the observed enhancements (e.g., larger enhancements near illuminated cloud sides and thicker clouds). Thus we conclude that 3-D radiative processes play an important role in creating clear sky reflectance enhancements observed at shorter wavelengths. Though the results do not provide an estimate of the contribution of 3-D effects to total clear sky reflectance enhancements near clouds, they can provide a lower limit if the difference between areas near sunlit and shadowy cloud sides is fully attributed to 3-D radiative effects.

[24] The main implication of our current results is that researchers using passive shortwave remote sensing need to consider 3-D radiative effects in interpreting clear sky reflectances in areas near clouds. If not considered, 3-D effects can introduce biases in estimated aerosol concentrations and skew perceptions of aerosol-cloud interactions. For example, optically thicker clouds causing stronger 3-D enhancements can result in spurious correlations between cloud optical thickness and (overestimated) aerosol concentration. 3-D effects should also be accounted in studies of surface properties and ultraviolet radiances near clouds.

[25] While selective sampling is likely to mitigate 3-D related problems in operational MODIS retrievals [*Remer et al.*, 2005], avoiding the most affected areas near clouds reduces data coverage and representativeness (especially if aerosol properties are different near clouds), and also makes it difficult to analyze aerosol-cloud interactions. This underlines the need for a better understanding of data limitations and for the development of new retrieval algorithms, either in the form of 1-D methods that are less sensitive to 3-D

effects [e.g., *Kassianov and Ovtchinnikov*, 2008], or in the form of new methods based on 3-D radiative transfer [e.g., *Marshak et al.*, 2008].

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