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Cloud adjacency effects on top-of-atmosphere radiance and ocean color data products: A statistical assessment

Lian Feng *, Chuanmin Hu

College of Marine Science, University of South Florida, 140 Seventh Avenue, South, St. Petersburg, FL 33701, USA

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ABSTRACT

Ocean color measurements taken near cloud boundaries suffer from cloud adjacency effects (AEs). As a result, ~50% of the cloud-free ocean data are flagged as low quality. Quantitative assessment of such effects, as well as the methodology required to minimize, or correct for them, is rarely available. The goal of this study is to quantify such effects on top-of-atmosphere (TOA) radiance and ocean color data products for MODIS/Terra, MODIS/Aqua, and SeaWiFS measurements. The AEs estimation was based on statistics and an objective method applied to carefully selected clear-water scenes (the number of cloud patches was >100,000 for each instrument) where ocean properties are relatively homogeneous, over both the North Atlantic and South Pacific. The AEs were quantified as the relative difference between the near-cloud pixels and pixels at least 20 km away from any cloud. Results show that the AEs on TOA radiance share similar patterns among the three missions. Specifically, the AEs decrease sharply as distance increases from cloud edges, and the AEs increase monotonically with increasing wavelengths because they were evaluated in relative rather than absolute terms. However, while discernable memory effects (MEs) are observed on cloud-adjacency pixels of both MODIS missions, they are insignificant on the SeaWiFS mission, and are found in measurements along the scan direction downstream of the clouds, representing >15% of the total AEs in TOA radiance. The AEs on the retrieved remote sensing reflectance (R_{rs}) data products are different among the three missions possibly due to their differences in vicarious calibration and uncertainties in atmospheric correction, leading to different patterns in the chlorophyll-a (Chl-a) and normalized Florescence Line Height (nFLH) data products. Large AEs (>50%) are observed in nFLH of both MODIS/Terra and MODIS/Aqua, likely due to the opposite AEs on R_{rs} between 667 and 678 nm. Finally, when the OCI Chl-a algorithm is used, the current MODIS stray-light masking window (7×5) used to mask the AE-contaminated pixels may be relaxed to 3×3 without sacrificing data quality, leading to >40% of the previously masked low-quality data being recovered for clear waters.

1. Introduction

The accuracy requirements of ocean color missions are 0.5% for the top-of-atmosphere (TOA) radiance in the blue bands, corresponding to ~5% of the atmospherically corrected remote sensing reflectance (R_{rs}, sr^{-1}) for blue bands or ~30% of the retrieved chlorophyll-a concentrations (Chl-a, mg m^{-3}) in the open ocean (Hooker, Esaias, Feldman, Gregg, & McClain, 1992). Recent validations using either in situ measurements or high quality R_{rs} (selected with a novel Chl-a algorithm (Hu, Lee, & Franz, 2012) suggest that both SeaWiFS and MODIS have met their mission goals of achieving R_{rs} and Chl-a accuracies (Hu, Feng, & Lee, 2013; Moore, Campbell, & Feng, 2014). However, these assessments were conducted using the "best" satellite observations, while uncertainties could be much larger for image pixels associated with the various quality control flags (namely the L2 flags). The stray-light flag reflects a pixel's adjacency to bright targets (e.g. clouds and land), accounting for more than 50% coverage of the cloud-free Level-2 data (Meister & McClain, 2010; Várnai & Marshak, 2014). Although these flagged pixels were not used in composing global data, understanding the stray-light effects on both the TOA radiance and the retrieved data products can help refine the criteria in flagging stray-light and, once proven, may also help "recover" some of the flagged pixels to increase data quantity without losing data quality.

The radiance from the nearby bright pixels may "leak" into the current field of view, resulting in "adjacency effects" (AEs) (Hooker, Firestone, & Acker, 1995). Such AEs (or stray-light) can be prominent in the vicinity of clouds or land, and can extend several kilometers from the source. Particularly, these effects degrade the accuracy of ocean color data products, as most atmospheric correction schemes treat each individual pixel independently from all other pixels. As demonstrated in Fig. 1, when compared to pixels away from the clouds, cloud-adjacent pixels show relatively lower or higher Chl-a and normalized Florescence Line Height (nFLH).

* Corresponding author.
E-mail address: lianfeng@mail.usf.edu (L. Feng).

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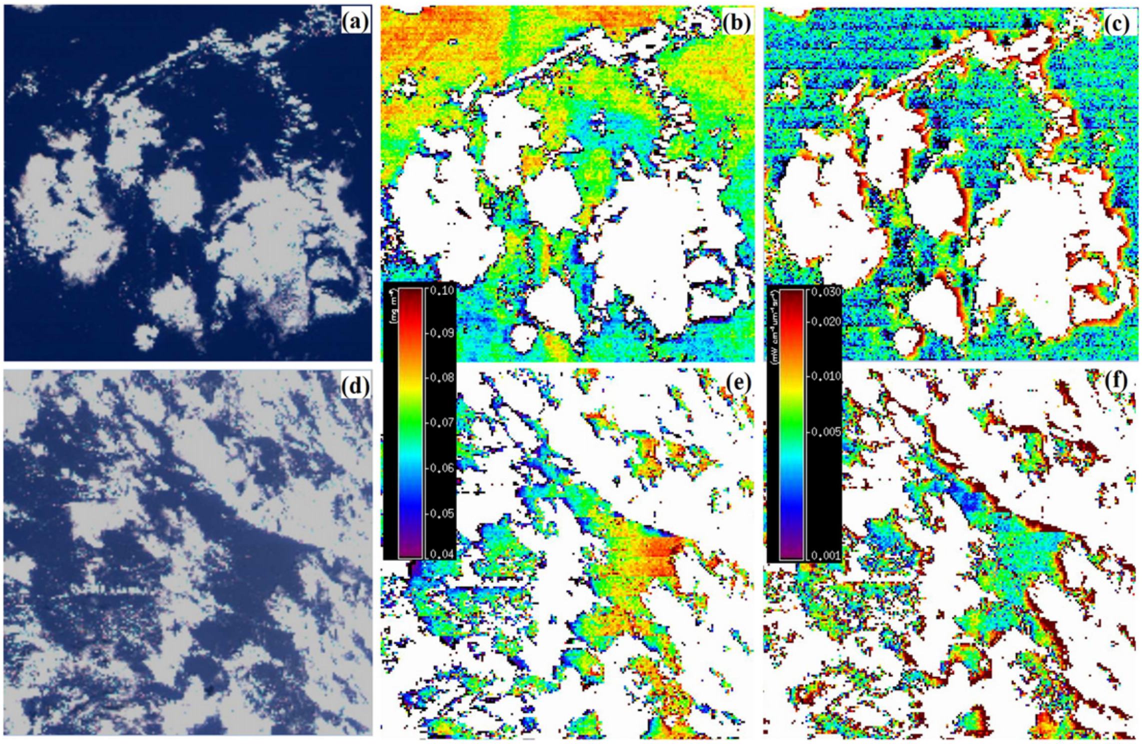

Fig. 1. An example showing the cloud adjacency effects (AEs) on MODISA (A2005008011000, [19–22°N, 175– W]) and MODIST (T2005008211000, [9.5–11.5°N, 157.5–159.5°W]) in Chl-a (derived with the SeaDAS default band-ratio algorithm) and nFLH. (a) and (d) are the Red–Green–Blue (RGB) true color images for MODISA and MODIST, (b) and (e) are the corresponding Chl-a, and (c) and (f) are the nFLH products, respectively. Compared with pixels further from clouds, Chl-a and nFLH show relatively lower or higher values, respectively, around the cloud edge for both sensors.

In addition to the cloud AEs, pixels adjacent to bright targets also suffer from memory effects (MEs) (also called bright target recovery) along the scan direction. The MEs are defined as when a scanning instrument (such as MODIS and SeaWiFS) scans first over a bright target (e.g., clouds) and then over a dark target (e.g., water), the memory of the bright target will be carried to the dark target, causing a false enhanced signal (Hooker et al., 1995). An example of the AEs and MEs are shown in Fig. 2, where pixels near the clouds have a discernably higher TOA radiance at 443 nm due to AEs, superimposed on which are the MEs along the scan direction downstream of the clouds (west of clouds for MODISA and east of clouds for MODIST), resulting in a more pronounced high signal. For clarity, in this context the AEs refer to those without presence of the MEs unless explicitly stated otherwise.

The problems of the AEs have been discussed by several researchers since the 1970s (Diner & Martonchik, 1984; Mekler & Kaufman, 1980,

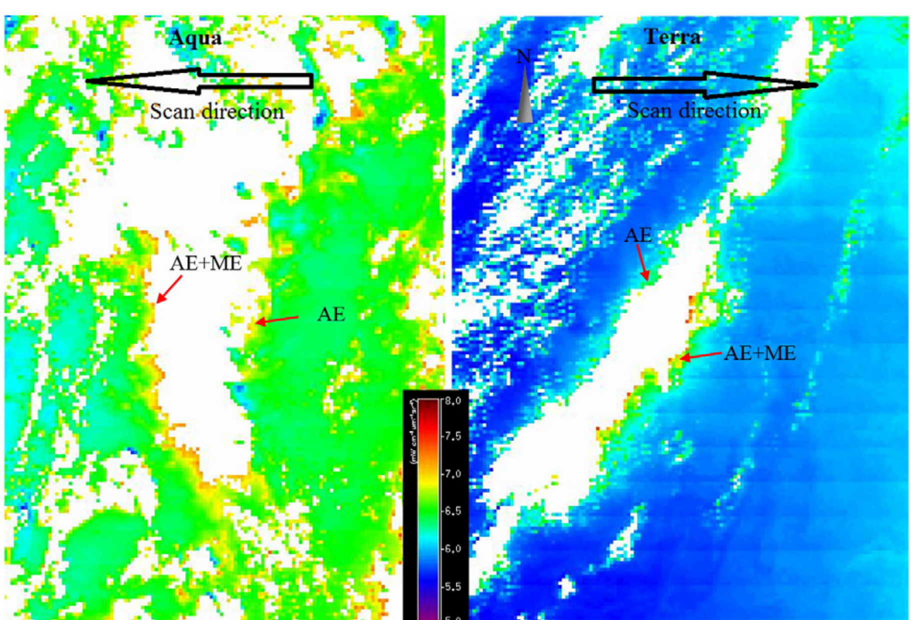

Fig. 2. Two examples showing the combined effects of AEs and MEs in $L_{t,443}$ following the scan directions of MODISA (west of the cloud edge) and MODIST (east of the cloud edge), where the AEs are also shown in the opposite sides of the clouds (i.e., east of the cloud edge for MODISA and west of the cloud edge for MODIST).