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MODIS Cloud screening for remote sensing of aerosols over oceans using spatial variability

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[1] A cloud masking algorithm based on the spatial variability of reflectances at the top of the atmosphere in visible wavelengths was developed for the retrieval of aerosol properties by MODIS. It is shown that the spatial pattern of cloud reflectance as observed from space, is very different from that of aerosols. Clouds show a very high spatial variability in the scale of hundred meters to few kilometers, whereas aerosols in general are very homogeneous. The concept of spatial variability of reflectances at the top of the atmosphere is mainly applicable over the ocean where the surface background is sufficiently homogeneous for the separation between aerosols and clouds. Aerosol retrievals require a particular cloud masking approach since a conservative mask will screen out strong aerosol episodes and a less conservative mask could allow for cloud contamination that tremendously affect the retrieved aerosol optical properties (e.g. aerosol optical depth and effective radii). A detailed study on the effect of cloud contamination on aerosol retrievals is performed and parameters are established determining the threshold value for the MODIS aerosol cloud mask (3X3-STD) over the ocean. The 3X3-STD algorithm discussed in this paper is the operational cloud mask used for MODIS aerosol retrievals over the ocean. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 3360 Meteorology and Atmospheric Dynamics: Remote sensing

1. Introduction

[2] The problem of cloud screening is a major challenge for the remote sensing of aerosols from space. *Ackerman et al.* [1998] develop a cloud mask for MODIS using the combination of 14 wavelengths in more than 40 tests that discriminate clear sky cases from clouds, attesting to the challenge of efficient cloud masking algorithms. Recent approaches also include polarized light [*Breon and Colzy*, 1999]. Several MODIS algorithms are dedicated to the retrieval of aerosol parameters over land and ocean [*Chu et al.*, 2001; *Kaufman et al.*, 1997; *Remer et al.*, 2001; *Tanré et al.*, 1997, 1999]. In general, all aerosol retrievals depend on the identification of cloud free pathways by cloud masking algorithms. Most cloud masking algorithms are based on visible and infrared (IR) spectral reflectance thresholds or in combinations of different wavelengths [*Ackerman et al.*, 1998]. These algorithms may have difficulties separating between clouds and heavy aerosol loading due to similarities between the spectral reflectance of large aerosol particles (e.g.: dust) and clouds. Aerosols above cloud layers, and large droplet clouds (darker in the near IR) can also mislead tests based on spectral reflectance thresholds, even confusing clouds with smaller aerosol particles. Also, spectral and reflectance thresholds are very sensitive to calibration errors and physical changes in the system. A cloud mask specifically developed for cloud studies or towards clear sky identification may not be suitable for aerosol retrievals. A very conservative mask suitable to identify clear sky areas would likely misinterpret thick aerosol plumes as clouds. On the other hand, a less conservative cloud mask, optimized to identify cloud scenes and suitable for cloud studies could fail identifying thin and sub-pixel clouds.

2. Spatial Variability of Aerosols and Clouds

[3] Distinguishing between aerosol and clouds using spatial pattern analysis is based on the basic physical differences between

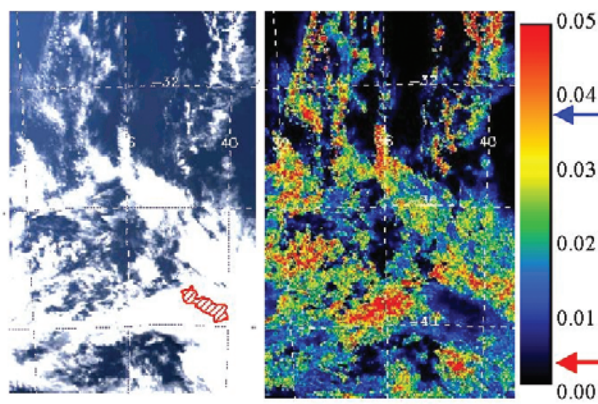

Figure 1. (Left) True color composite of clouds and smoke over the ocean from MODIS data at 500 m resolution on August 21, 2000 at 7:45 UTC. The red dashed area shows an example of a very homogeneous cloud identified on the right figure. (Right) Absolute standard deviation of every 3 × 3 pixels. The color bar indicates the standard deviation scale for each pixel. The red arrow indicates the threshold used in the MODIS operational aerosol algorithm (0.0025). The blue arrow indicates a higher threshold allowing for extensive cloud contamination (0.038).

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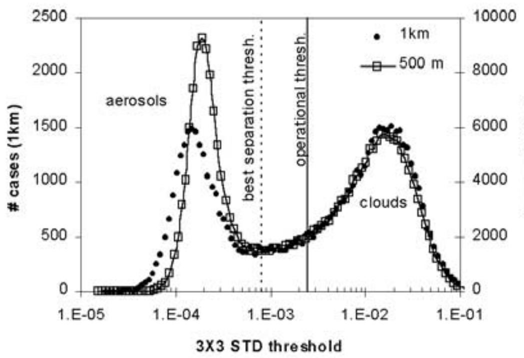

Figure 2. Histogram of 3 × 3-STD at 0.55 μm showing the basic separation between aerosols and clouds at two spatial resolutions.

clouds and aerosol. A cloud is an aerosol that through dynamic processes was exposed for a limited time to humidities larger than 100% and condensed large amount of water. Due to this highly unstable process, clouds show a more complex spatial behavior than aerosols. On a scale of a few kms, aerosols distant from its sources, show a highly homogeneous spatial structure that can be easily separated from most clouds. Spatial coherence tests (hereafter called spatial variability tests) in the infrared were first introduced as a cloud masking procedure by *Coakley and Bretherton* [1982]. *Jankowiak and Tanré* [1992] used similar procedure to separate clear sky, dust and clouds for the retrieval of aerosol optical thickness using Meteosat. In this paper, taking advantage of MODIS accuracy, spatial and spectral resolution, we develop an algorithm based on a spatial variability test applied to the isotropic reflectance in a single visible channel as a cloud mask devoted to the retrieval of aerosol properties over the oceans. The MODIS operational algorithm uses a land sea U.S. Geological Survey (USGS) to determine the use of the land or ocean aerosol algorithms. As part of the aerosol algorithm there are also reflectance tests performed in order to double check the surface properties, confirming if it is land or water. The 3 × 3-STD cloud mask algorithm is performed whenever the aerosol algorithm is used to retrieve aerosol properties over water. Aerosol retrievals can be made in any body of water larger than 10 × 10 km, being more effective for larger areas. Aerosol retrievals and applications of this cloud mask are limited to solar zenith angles smaller than 70 degrees and regions not subject to sun glint. The operational algorithm has a 40 degrees glint mask.

[4] Figure 1 (left) shows a true color RGB image as an example of clouds, aerosols and clear sky in the same scene. As it will be discussed later, this figure contains smoke aerosols from Africa with optical depth up to 0.6, and oceanic background aerosols with optical depth about 0.05. Figure 1 (right) shows the standard deviation of every 3 × 3 pixels (3 × 3-STD) in the image. This figure shows a large range of STD values between clouds and aerosols, with high STD values associated with clouds and low STD with aerosol or clear cases. There are few circumstances when clouds can be extremely homogeneous providing low enough variability to be confused with aerosols (eg. some thin cirrus, deep areas in the middle of very high and bright convective clouds, fog, etc.). The image in Figure 1 was selected in order to provide such example. The red dashed area exemplified in the RGB image (Figure 1 left) indicates a portion of the cloud with very low spatial variability, as it can be observed in Figure 1 (right). This cloud mask in particular does not treat fog independently. Although fog is a potential cause of contamination, spectral reflectance thresholds were avoided due to similarities between the reflectance of droplets and certain aerosol types. All the results discussed in this work refer to the 3 × 3-STD cloud mask that has been used as the operational cloud mask for aerosol retrievals with MODIS over the ocean.

[5] Figure 2 show a histogram of the 3 × 3-STD showing the statistical separation between aerosols and clouds. The histogram was made in logarithm scale due to the large range of standard deviation values. The histogram shows also the effect of the spatial resolution (from 500 m to 1 km) in aerosols variability but not in clouds. The figure also shows a best separation threshold to minimize cloud contamination, and the selected operational threshold that allow for some cloud contamination to be eliminated by other procedures.

[6] The operational threshold was defined based on the analysis of several cases including different types of clouds, aerosols, geographical locations, and geometries. Several pre-selected areas visually identified as cloudy or clean on images containing clouds, dust, smoke and background aerosols were selected for statistical

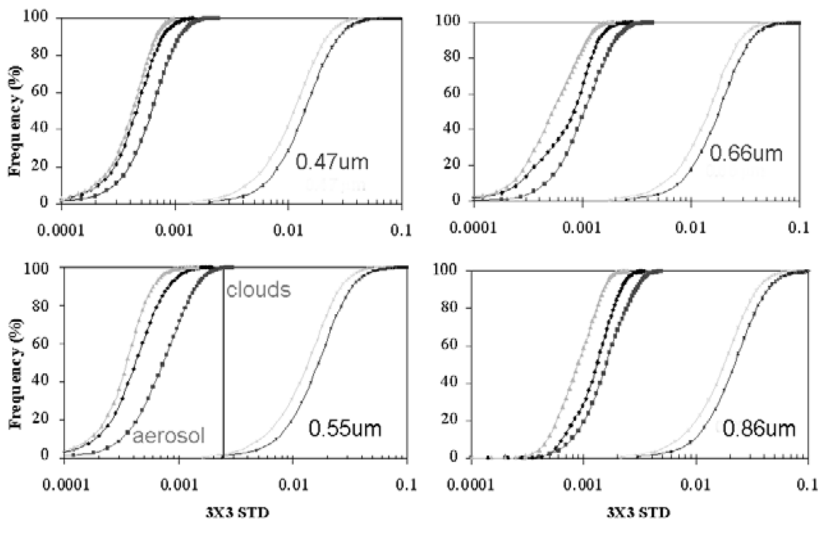

Figure 3. Cumulative histograms of 3 × 3-STD in several wavelengths on areas containing clouds, dust, smoke, and oceanic background aerosols separately. Each area corresponds to several thousands of pixels in which the standard deviation was calculated for every 3 × 3 pixels. The vertical line indicates the selected threshold separating aerosols and clouds.

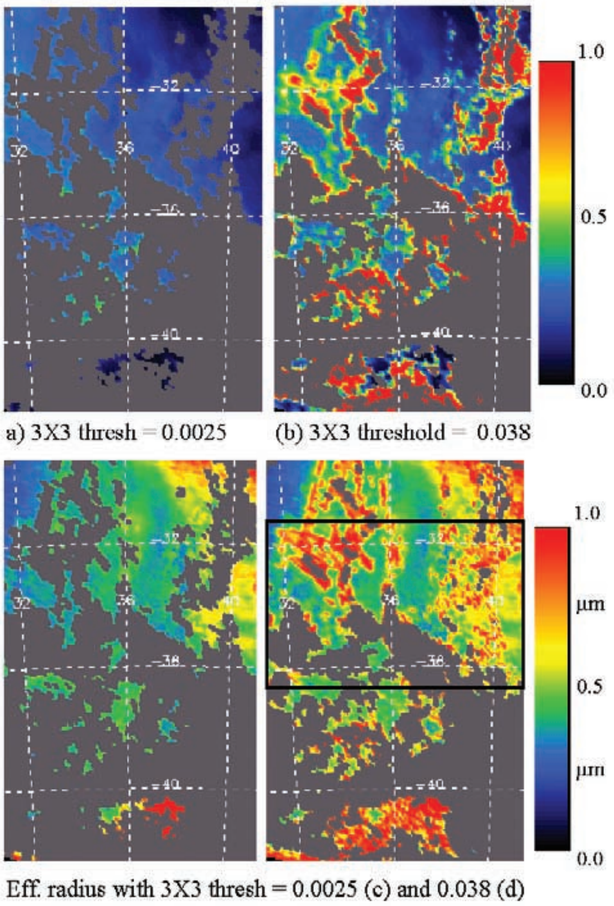

Figure 4. (a) Aerosol optical thickness retrievals using the operational MODIS aerosol algorithm and 3 × 3-STD cloud mask (August 21, 2000 at 7:45 UTC). (b) shows AOD retrievals using the 3 × 3-STD cloud mask with a higher threshold (0.038) allowing for cloud contamination. Figures 4c and 4d show Effective radius retrievals for operational (0.0025) and higher threshold (0.038). The color bars indicate the scale of the retrievals and the gray color corresponds to clouds identified in each case, including the IR tests.

studies separating the standard deviation of aerosol and clouds. Histograms of the standard deviation were constructed for aerosols and clouds for each one of these areas. Figures 3a, 3b, 3c, and 3d, show cumulative histograms of the 3 × 3-STD for λ = 0.47, 0.55, 0.66, and 0.87 μm, respectively. These figures show that clouds and aerosols are completely separated in the histograms with very distinct 3 × 3-STD in all wavelengths. Even though the 0.47 μm channel was considered one of the best MODIS visible channel for the 3 × 3-STD it was avoided in the ocean mask because of the higher ocean reflectance in the blue and the larger variability in ocean properties due to chlorophyll. Based on these histograms, a threshold value of 3 × 3-STD = 0.0025 was defined as the separator between aerosols and clouds for λ = 0.55 μm. Based on Figures 2 and 3 one can see that this threshold allows for a small fraction of cloud contamination (1–5 % of the studied cases), but generally it did not deselect aerosol cases, even for very large dust or smoke optical thickness.

[7] As seen in Figure 3, a threshold similar to the one selected for 0.55 μm can also be applied to all other tested wavelengths with similar results showing that this technique can be applied to other satellite sensors with different wavelengths, and likely broadband sensors in similar spectral range. Tests with 250, 500 and 1000 m resolution images showed approximately the same values for the 3 × 3-STD threshold.

3. Cloud Masking Strategy

[8] In the 3 × 3-STD operational algorithm, the 0.55 μm channel is used over the ocean in MODIS images with 500 meters resolution. Every 3 × 3 pixels are grouped together for the determination of its absolute standard deviation. Since pixels adjacent to clouds are usually inadequate for aerosol retrievals, the mask is moved by 3 pixels at a time screening out the whole 3 × 3 box for high STD values, producing a final mask resolution of 1.5 Km. An alternative approach would be to move the mask by a single pixel in the horizontal and in the vertical. This approach is more important in retrievals dealing with coarser spatial resolution ($\gg$1 km), and is not currently used in the MODIS operational aerosol cloud mask.

[9] In addition to the 3 × 3-STD the MODIS operational algorithm uses additional IR tests for helping the identification of homogeneous thin cirrus and high clouds. These additional tests are the CO_2 test (using 13.9 μm band, sensitive mainly to high clouds in cold regions of the atmosphere), the 6.7 μm test (sensitive to high clouds in cold regions of the atmosphere using an H_2O absorption band), the IR cirrus (mainly sensitive to thin cirrus clouds), and the Delta-IR test, all described in details by *Ackerman et al.* [1998]. An alternative complementary mask for homogeneous thin cirrus and other high clouds was tested based on the unique 1.38 μm channel from MODIS [*Gao et al.*, 1993]. The 1.38 μm channel is mainly sensitive to high clouds once the strong H2O absorption band reduces significantly the amount of radiation reaching the surface, also making it attractive for 3 × 3-STD tests over land, although it is not in use in the current MODIS 3 × 3-STD algorithm.

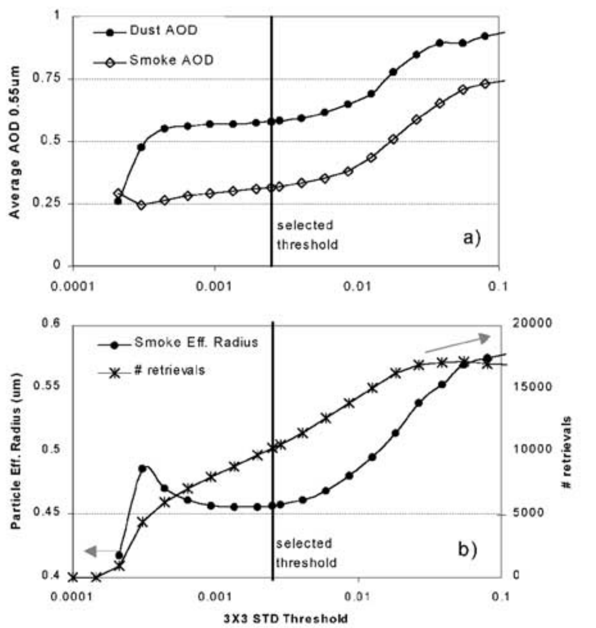

Figure 5. (a) Average retrieval of aerosol optical depth (0.55 μm) in selected areas containing clouds, dust, smoke and oceanic background aerosols as a function of the 3 × 3-STD cloud mask threshold. (b) Average particle effective radius and number of retrievals.

4. Effects of Cloud Contamination

[10] In order to construct a cloud mask suitable for use in aerosol retrievals, one can decide for a more or less conservative approach allowing for some residual cloud contamination or considering losses in the number of aerosol retrievals. In this section we will discuss the effects of remaining cloud contamination in aerosol retrievals. Figure 4a show aerosol optical depth (AOD) retrievals performed with the MODIS operational algorithm over the ocean showing smooth aerosol retrievals with no cloud contamination. Figure 4c show results of the retrieved effective radius for the same scene. In this analysis it is important to consider the different aerosol types (mainly background sea salt and smoke from African biomass burning) present in the studied image. In low AODs (less than 0.1) sea salt aerosol prevails and therefore we see mainly the optical properties of sea salt (low AOD and large particle size). In this case, high AODs are associated with small particles originated from biomass burning emissions. As the smoke particles are transported away from their sources, they tend to increase in size due to heterogeneous chemistry, and the plume undergoes reduction in concentration increasing the relative participation of sea salt in the total column optical thickness and, therefore, increasing the average column particle effective radius. Thus, higher AODs in this image are associated with smaller particle size and vice versa. This effect can be observed in the comparison between Figures 4a and 4c. Similarly, since clouds are composed of relatively large droplets, in the presence of cloud contamination the retrieved effective radius is generally larger than that for smoke aerosols. The effect of cloud contamination on the AOD and particle effective radius can be observed in Figures 4b and 4d respectively, where the 3×3-STD threshold was relaxed to a significantly larger value (thresh = 0.038). The complementary IR mask discussed in section 3 flags in most of the gray areas showed in Figure 4b. Since the main purpose of this paper is to discuss the spatial variability cloud mask, the IR mask was kept constant like the operational algorithm for all the analyses performed hereafter.

[11] The box indicated in Figure 4d corresponds to a defined study area containing smoke, sea salt, and clouds. A similar sub-set was selected for a dust case study. Figure 5a shows the average AOD of the selected area for the dust and smoke cases. One can observe that above a certain very low threshold, the average AOD reaches a plateau-like behavior (mainly observed in the dust case) up to the selected operational threshold. Above the selected operational threshold, cloud contamination starts to significantly increase the average AODs. Similar behavior attributed to cloud contamination can be observed on the retrieval of aerosol effective radii. Figure 5b shows the retrieved effective radius for the smoke case as a function of the selected thresholds. For low thresholds we see the combination of effective radius of smoke and sea salt (lower spatial variability due to the more homogeneous area source for sea salt and larger distances from the coast for the smoke), up to the selected operational value. For thresholds larger than the selected value, the effects of cloud droplets contamination increase the average retrieved effective radius. The optimum threshold for cloud masking corresponds to a minimum value of the average effective radius before the increase in size due to cloud contamination. Figure 5b shows also the number of aerosol retrievals obtained as a function of the cloud mask threshold. The number of retrievals decreases fast as a function of reductions in the cloud mask threshold.

5. Discussion and Conclusion

[12] The spatial variability cloud mask at 0.55 μm, in combination with IR tests constitute the MODIS operational aerosol cloud mask used for the retrievals of aerosol properties over the ocean. This mask is producing satisfactory separation between clouds and aerosols for nearly all aerosols and cloud types. The 3×3-STD test resolves most of the cloud contamination in the retrievals without deselecting aerosol cases. Small remaining contaminations are resolved by applying the IR tests dedicated to identify high homogenous clouds. Tests performed on several types of aerosol particles and clouds, including soil dust and intense smoke showed very good results (e.g.: African dust episodes, smoke cases from biomass burning in Africa, etc.). Some of the main advantages of the 3×3-STD cloud mask are the simplicity of the procedure involving mainly 1 wavelength, and the weak dependence of the cloud mask with calibration errors, which strongly affect cloud masks based on reflectance and spectral tests. Also, since the 3×3-STD visible thresholds are not strongly dependent on wavelength, the same methodology can by applied to other satellite sensors, even with broadband channels.

[13] Final average global aerosol products derived over the ocean are shown and discussed in the paper by *Remer et al.* [2001]. This paper shows global composites of aerosol retrievals over the ocean after cloud screening with the 3×3-STD cloud mask and exemplify the performance of this cloud mask over the globe. Other global aerosol retrievals over the ocean showing minor or no cloud contamination can be found in the MODIS atmospheres homepage (http://modis-atmos.gsfc.nasa.gov/).

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