https://ntrs.nasa.gov/search.jsp?R=20120009492 2019-08-30T20:36:28+00:00Z

Retrieving aerosol in a cloudy environment: Aerosol availability as a function of spatial and temporal resolution

Lorraine A. Remer[1], Shana Mattoo [1,2], Robert C. Levy [1,2], Andrew Heidinger[3], R. Bradley Pierce[3], Mian Chin[1]

[1] Earth Science Division, NASA Goddard Space Flight Center, Greenbelt MD 20771
[2] Science Systems and Applications, Inc., Lanhan MD 20709
[3] Center for Satellite Applications and Resarch, NOAA at the Cooperative Institute of Meteorological Satellite Studies (CIMSS), University of Wisconsin, Madison WI

Submitted to *Atmospheric Measurement Techniques*
27 December 2011

Corresponding author:
Shana Mattoo
Science Systems and Applications, Inc.
Code 613
NASA Goddard Space Flight Center
Greenbelt MD 20771
301-614-6214
shana.mattoo@nasa.gov

Abstract

The challenge of using satellite observations to retrieve aerosol properties in a cloudy environment is to prevent contamination of the aerosol signal from clouds, while maintaining sufficient aerosol product yield to satisfy specific applications. We investigate aerosol retrieval availability at different instrument pixel resolutions, using the standard MODIS aerosol cloud mask applied to MODIS data and a new GOES-R cloud mask applied to GOES data for a domain covering North America and surrounding oceans. Aerosol availability is not the same as the cloud free fraction and takes into account the technqiues used in the MODIS algorithm to avoid clouds, reduce noise and maintain sufficient numbers of aerosol retrievals. The inherent spatial resolution of each instrument, 0.5x0.5 km for MODIS and 1x1 km for GOES, is systematically degraded to 1x1 km, 2x2 km, 4x4 km and 8x8 km resolutions and then analyzed as to how that degradation would affect the availability of an aerosol retrieval, assuming an aerosol product resolution at 8x8 km. The results show that as pixel size increases, availability decreases until at 8x8 km 70% to 85% of the retrievals available at 0.5 km have been lost. The diurnal pattern of aerosol retrieval availability examined for one day in the summer suggests that coarse resolution sensors (i.e., 4x4 km or 8x8 km) may be able to retrieve aerosol early in the morning that would otherwise be missed at the time of current polar orbiting satellites, but not the diurnal aerosol properties due to cloud cover developed during the day. In contrast finer resolution sensors (i.e., 1x1 km or 2x2 km) have much better opportunity to retrieve aerosols in the partly cloudy scenes and better chance of returning the diurnal aerosol properties. Large differences in the results of the two cloud masks designed for MODIS aerosol and GOES cloud products strongly reinforce that cloud masks must be developed with specific purposes in mind and that a generic cloud mask applied to an independent aerosol retrieval will likely fail.

1.0 Introduction

Atmospheric aerosols are important short-lived climate forcing agents in Earth's atmosphere. These small, suspended liquid and solid particles play a role in Earth's energy balance by directly affecting the distribution of incoming sunlight and by indirectly changing clouds and weather patterns that in turn alter climate. However, unlike greenhouse gases, aerosols are highly variable and transitive, creating uncertainty in estimating their effect on climate (Kaufman et al., 2002). Aerosol forcing, either by direct or indirect pathways, remains one of the largest uncertainties in the climate system (IPCC, 2007), which must be reduced in order to estimate the magnitude of climate change with sufficient confidence. In addition, small aerosol particles can be inhaled into the lungs, creating adverse health effects (Krewski et al., 2000; Samet et al., 2000; Pope et al. 2002). Particulate matter, another term for aerosols, is one of the six harmful pollutants monitored by the U.S. Environmental Protection Agency as part of the national standards for air quality (EPA, 2007). Again, the transitory nature of aerosols creates difficulties for agencies and communities to mitigate and warn populations of potential dangers (Al Saadi et al., 2005).

Both climate and air quality applications require continual monitoring of aerosol loading over broad geographical regions. For climate, a global perspective is needed. For air quality, even if interest is more regional, there is need for a more complete coverage and higher density of spatial sampling than a network of ground-based in situ monitoring stations can provide (Chu et al., 2003; Prados et al., 2007; Gupta and Christopher, 2009). Both these applications are increasingly relying on satellite retrievals of aerosol information to provide the observational constraints on models, offer new insights on aerosol distributions, and provide day-to-day coverage and accumulated statistics of aerosol properties (Stier et al., 2005; Yu et al. 2006; van Donkelaar et al., 2006, 2011). Satellites make a unique contribution to climate and air quality studies by providing the global coverage needed for climate applications and the density of coverage needed by the air quality community.

Aerosol properties can be derived from space-based observations with well-defined uncertainties, and used successfully in a wide array of applications (Remer et al., 2005; Kahn et al., 2010; Torres et al., 2007; Tanré et al. 2011). However, making aerosol retrievals on an operational basis is challenging, and making aerosol retrievals in cloudy environments is especially challenging (Zhang et al., 2005; Wen et al., 2006; Marshak et al., 2008). Aerosol retrievals in a cloudy environment require that a "cloud mask" be developed that separates cloud scenes from cloud-free (Martins et al. 2002). Traditionally aerosol has only been derived in cloud-free scenes, although efforts are underway to derive aerosol above clouds using certain sensors (Jethva 2011; Waquet et al., 2010). Separating clouds and aerosols is inherently difficult because there exists no clearly defined separation between the two in any variable. This is an issue of measurement systems, but also an inherent physical continuum between aerosol particles, wet aerosol particles, activated cloud droplets and dissipated cloud fragments (Koren et al., 2007; Charlson et al., 2007). Remote sensing algorithms employ complicated schemes, using many variables (Ackerman et al., 1998; Frey et al., 2008), to make this separation as best they can, but no "cloud mask" is perfect. The reality is that different cloud masks are produced for different purposes.

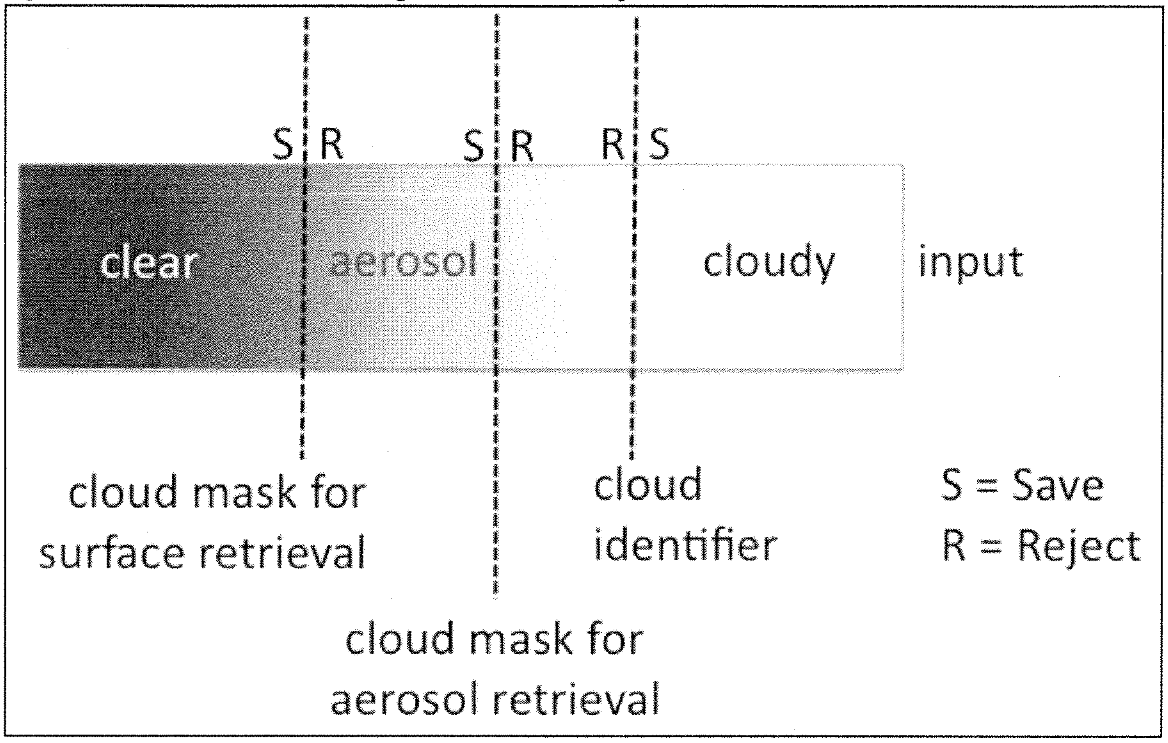
A cloud mask designed for an aerosol retrieval, ideally, must exclude all cloud and cloud remnants from a pixel designated as 'cloud-free'. On the other hand, extreme restriction that avoids any cloud contamination would prevent a sufficient number of aerosol retrievals from being made. Thus, there is a tradeoff between perfect protection of the aerosol product and *availability* of that product, as some pixels must be designated 'cloud-free' in order for an aerosol product to be obtained. The degree of the accuracy and availability of retrieved aerosol products critically depends on the cloud mask criteria and the instrument's pixel resolution.

Here we explore the availability of an aerosol retrieval in a cloudy environment under various criteria including sensor pixel spatial resolution, different cloud masks and polar orbiting versus geosynchronous satellite orbits. First, we demonstrate the concept that different cloud masks are defined for different purposes. Second, we provide details of the MODerate resolution Imaging Spectroradiometer (MODIS) aerosol cloud mask, and a second cloud mask developed for the Geostationary Operational Environmental Satellite - R (GOES -R) data, and explain the different purposes of the two cloud masks. Third, using the MODIS and GOES cloud masks applied to their respective satellite data, we explore the availability of an aerosol retrieval over North America and surrounding oceans under varying pixel spatial resolutions. Finally, we examine the capability of a geosynchronous satellite to resolve daytime variations of aerosols at different sensor pixel resolutions. In doing so we attempt an answer to the question of whether enhanced temporal resolution from a geosynchronous satellite offsets the decreasing availability presented by decreased sensor spatial resolution, compared to the availability from a polar orbiting satellite. For example, can a 4x4 km resolution instrument aboard a geosynchronous satellite with measurements every 30 to 60 minutes provide the same availability as a once-a-day polar orbiting sensor with finer spatial resolution? In the end we discuss the implications of these results to currently proposed satellite missions.

2.0 Cloud masks

The term 'cloud mask' is a common term used by the satellite remote sensing community, but it has three separate connotations depending on its intended purpose. There are cloud masks developed to identify clouds, those to protect a retrieval of surface properties and finally those designed to protect an aerosol retrieval. All of them identify clouds, but each makes decisions in how to define a cloud or cloud-free scene that best suits the ultimate goal of the remote sensing algorithm.

Figure 1. Schematic illustrating thresholds of input used to differentiate clear from



cloudy for different purposes. For the purpose of a surface retrieval, only the clearest pixels are saved. For the purpose of a cloud identifier, only the cloudiest pixels are saved. For the purpose of an aerosol retrieval, a mid-range threshold must be determined.

For example, a cloud mask that selects pixels for retrieval of cloud properties is going to select the cases best suited for a retrieval of cloud properties. Marginal cloud edges, cloud fragments and pixels that are not overcast will be designated 'cloud free' by this type of cloud mask. On the other hand, a cloud mask whose purpose is to select cloud free pixels for retrievals of surface properties will take the entirely opposite approach. Those pixels containing marginal cloud edges and fragments designated by the first cloud mask as 'cloud free' will be assigned 'cloudy' in the surface retrieval algorithm. In addiition, the surface retrieval algorithm will also not take a chance when the scene is obscured by aerosol. If the scene is obscured by either cloud or by heavy aerosol, the pixel will be designated 'cloudy'. Clearly, both cloud masks are not suitable for aerosol retrieval, as the first one will introduce significant cloud contamination in aerosol products and the second one will prevent retrieving heavy aerosol loadings. Therefore an aerosol algorithm has to be designed that eliminates marginal cloud situations and still designates the heavy aerosol events as 'cloud free'. Figure 1 illustrates the criteria of positioning of potential thresholds along a gradient of satellite-measured inputs representing the deep blue ocean surface overlaid by a gradual increase of aerosol and then cloud particles.

Figure 2 shows an example of three different cloud masks applied to the same MODIS image in a situation where heavy aerosol coincides with a cloud field. The standard cloud mask (Ackerman et al., 1998; Frey et al., 2008) applied to the image and shown in the upper right panel does not take a chance when the heavy dust aerosol overlays the cumulus field. It designates almost the entire left third of the image as 'cloudy'. This cloud mask corresponds to the "cloud mask for surface retrieval" of Figure 1. Meanwhile the algorithm producing cloud optical thickness (Platnick et al., 2003) shown in the lower left panel, is much choosier, selecting much fewer pixels for a cloud retrieval than was designated 'cloudy' by the first cloud mask. The lower left panel is an example of the "cloud identifier" of Figure 1. The aerosol cloud mask (Martins et al., 2002) used to make an aerosol retrieval is also different than the first cloud mask. In the upper left corner of the image, the aerosol cloud mask avoids some of the pixels that the first cloud mask designated as 'cloud free', and yet finds holes in the cloud field on the left side of the image to make an aerosol retrieval. It also designates the area covered by dust as 'clear' to allow aerosol retrieval, in contrast with the standard cloud mask. The aerosol cloud mask is not created simply by drawing the threshold between the other two cloud masks, as is suggested by the one-dimensional schematic in Figure 1. There are several variables under consideration and the result is a cloud mask that is both more and less conservative than the mask designed for surface retrieval. Note also that the aerosol cloud mask is not the simple inverse of the cloud identifier for the cloud optical thickness retrieval.

The main point is that a cloud mask must be designed with a specific retrieval in mind. A one-size-fits-all cloud mask will not succeed.

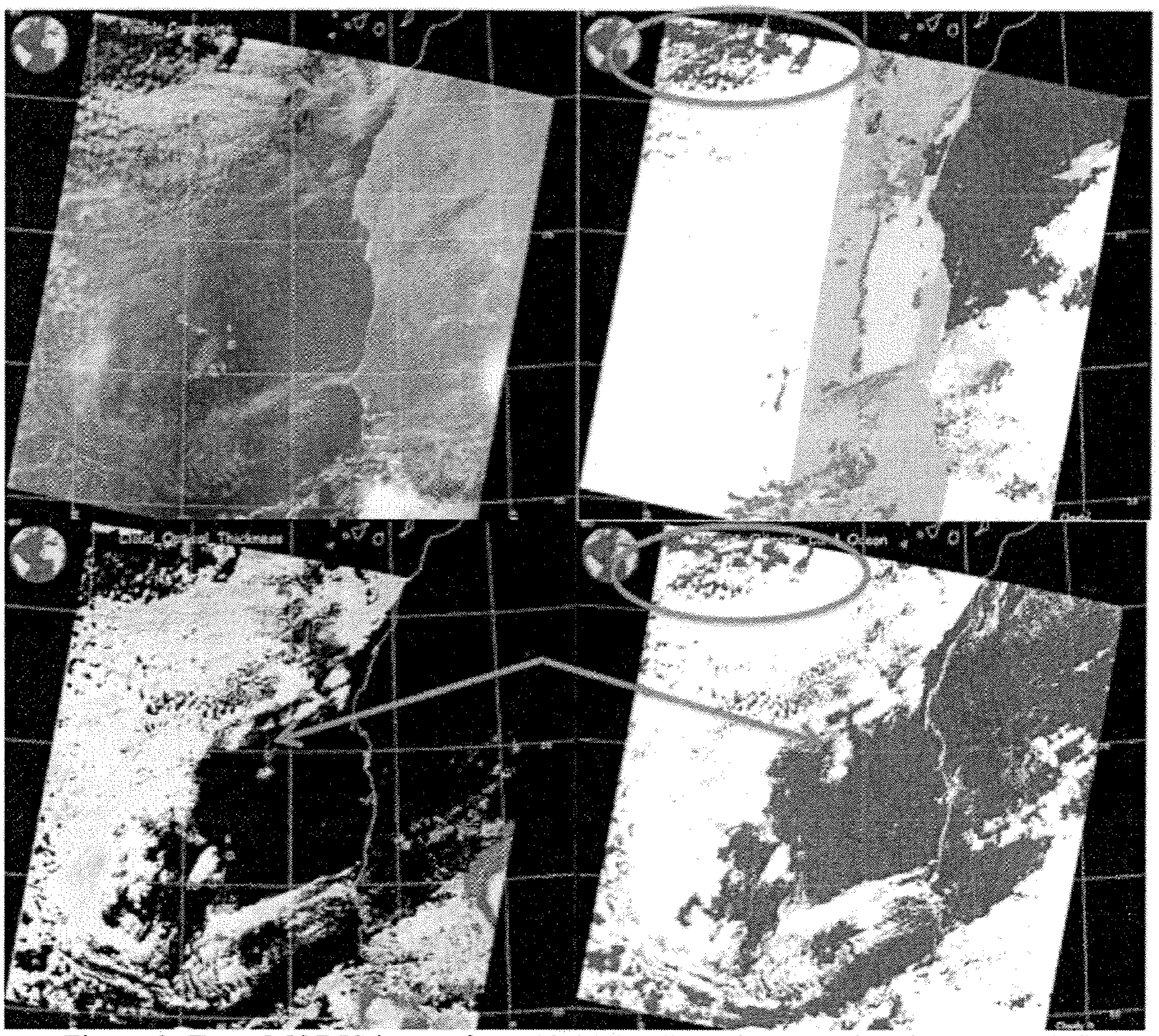


Figure 2. Terra MODIS image from 12:00 UTC 2 July 2010 showing (upper left) true color image of heavy dust spreading over the Atlantic from northern Africa. (upper right) standard MODIS cloud mask (MOD35) with white areas identified as cloudy, gray as sun glint, red as probably cloudy, blue probably clear and green as clear. (lower left) MODIS cloud optical thickness product (MOD06) (lower right) MODIS aerosol cloud mask (MOD04) with white designating cloudy and blue, cloud-free. This panel shows only the cloud mask, not the pixels chosen by the retrieval. Aerosol retrievals are not made in the sun glint region. Red oval identifies region where aerosol cloud mask finds more clouds than standard cloud mask. Red arrow identifies area that neither the cloud retrieval nor the aerosol retrieval chooses to use to derive cloud or aerosol properties, respectively.

3.0 MODIS and GOES-R cloud masks

In this study we use two different pixel selection processes. The first is the MODIS aerosol cloud mask (Martins et al., 2002) and data selection process (Remer et al., 2005). The second is the GOES-R Algorithm Working Group Cloud Mask (ACM) (Heidinger and Straka, 2010).

3.1 MODIS aerosol cloud mask

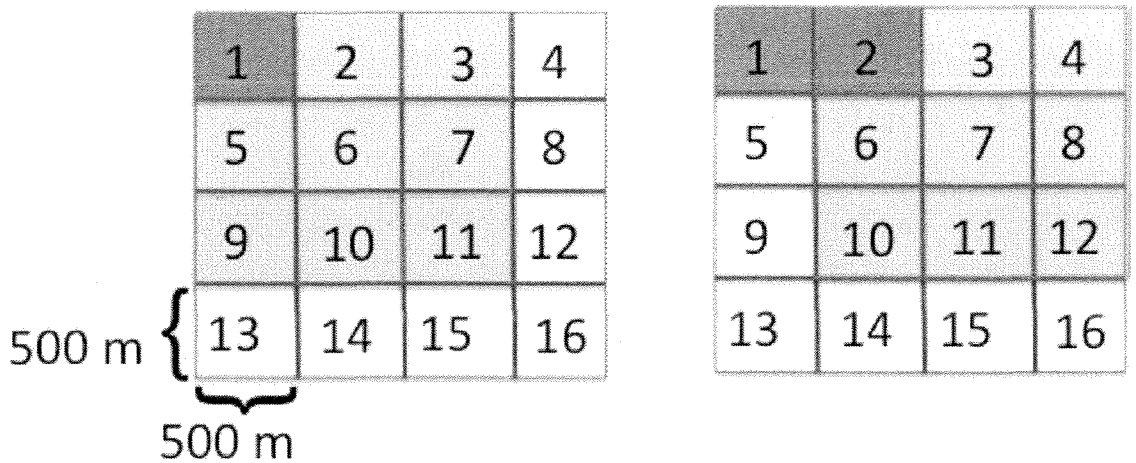


Figure 3. Illustration of MODIS aerosol cloud mask spatial variability test. The algorithm identifies a set of 3x3 0.5 km pixels and calculates standard deviation of the reflectance of those 9 pixels. If the standard deviation exceeds a designated value, the upper left hand pixel (pixel 1) is designated 'cloudy' (denoted by shaded red in the figure.) Then the algorithm tests the next set of 3x3 pixels to determine if pixel 2 is 'cloudy'.

The purpose of the MODIS aerosol cloud mask is to protect the products of the MODIS aerosol retrieval algorithm from cloud effects while maintaining adequate product availability at all levels of aerosol loading. The cloud mask must be able to separate heavy aerosol events from clouds. The basis of the retrieval is spatial variability. Sets of 3x3 0.5 km resolution reflectance values are examined and standard deviation is calculated from the 9 pixels. If the standard deviation of the reflectance exceeds a designated value, at least one of the pixels must be cloudy. The single 0.5 km pixel in the upper left corner is designated 'cloudy' and the window of 3x3 pixels moves one pixel over. The standard deviation test is repeated along the entire span of the image, then advanced by one 0.5 km pixel in the along track image and continued. The procedure is repeated until all pixels in the image have been tested. Figure 3 illustrates this technique. The advancing 3x3 window will over estimate cloudiness to some degree, because if the cloudy pixel in the Figure 3 example is pixel 6, the spatial variability test will also mask out pixels 1, 2 and 5. The goal is to be sufficiently conservative to remove some of the pixels contiguous to the actual cloudy pixel.

In the MODIS over ocean retrieval, the spatial variability test is applied using reflectance at 0.66 μm to avoid ocean color variability. In the over land retrieval, the algorithm applies the spatial variability test to the 0.47 μm channel because the land is darker and more homogeneous at this wavelength. The algorthims also apply a similar spatial variability test to the 1.38 μm channel using 1 km pixels, because this channel is particularly sensitive to thin cirrus. Over ocean, additional tests using absolute reflectance at 1.38 μm and the ratio of the reflectances of 1.38 μm and the 1.24 μm channels attempts to remove further effects of thin cirrus (Gao et al., 2002). Finally there are three cloud mask tests using the longwave channels at 1 km that are adapted from the standard MODIS cloud mask (MOD/MYD35). These are the infrared thin cirrus test (Bit 11), the 6.7 μm test for high cloud (Bit 15) and the split window test (Bit 18) . All of these tests must return a 'cloud free' designation for the 0.5 km pixel to be further considered for an aerosol retrieval. In the case of a test applied to 1 km reflectances, a 'cloudy' designation at 1 km will be passed to all 4 of the 0.5 km pixels affected. The binary, 'cloudy'/'cloud free', designations at 0.5 km are reported in the MODIS Collection 6 product as Aerosol_Cldmask_Land_Ocean.

Creation of the 0.5 km binary 'cloudy/cloud free' mask is the first step in choosing pixels from which to derive aerosol products. The next step continues the deselection process. The 0.5 km pixels are now grouped into retrieval boxes of 20x20 pixels to generate a 10 x 10 km product. Figure 4 illustrates two hypothetical retrieval boxes, one over ocean and one over land. The over ocean example is straightforward. White boxes are pixels identified as 'cloudy' by the tests described above. In this box of 400 pixels, 225 pixels have been identified as 'cloudy', leaving 175 'cloud free' pixels of various shades of blue. Now the brightest 25% and darkest 25 % of the 'cloud free' blue pixels are arbitrarily discarded, leaving 87 pixels representative of the reflectance over the ocean in this box. The average reflectance in each channel is calculated from these remaining 87 pixels, which are then used to make the aerosol retrieval. Over land, not only are cloudy pixels discarded, but also inland water, snow and bright land surfaces. In this case, the algorithm arbitrarily discards the brightest 50% and the darkest 20% of all pixels escaping the masking tests. In the example of Figure 4, 44 pixels remain after masking and deselecting the brightest and darkest pixels. The arbitrary discarding of bright and dark pixels removes residual cloud and surface features and cloud shadows that are not otherwise addressed. The ocean algorithm requires a minimum of 10 remaining pixels to make a retrieval for a 10x10 km aerosol product. The land algorithm requires 12.

Figure 4 also illustrates the point that the instrument pixel resolution (0.5 km) is not necessarily the same as the aerosol product resolution (10 km), and that product resolution boxes do not need to be entirely cloud free in order to retrieve an uncontaminated aerosol product. Creating a product resolution coarser than the resolution of the input pixel reflectance allows much discretion in selecting pixels for retrieval while maintaining high levels of product availability.

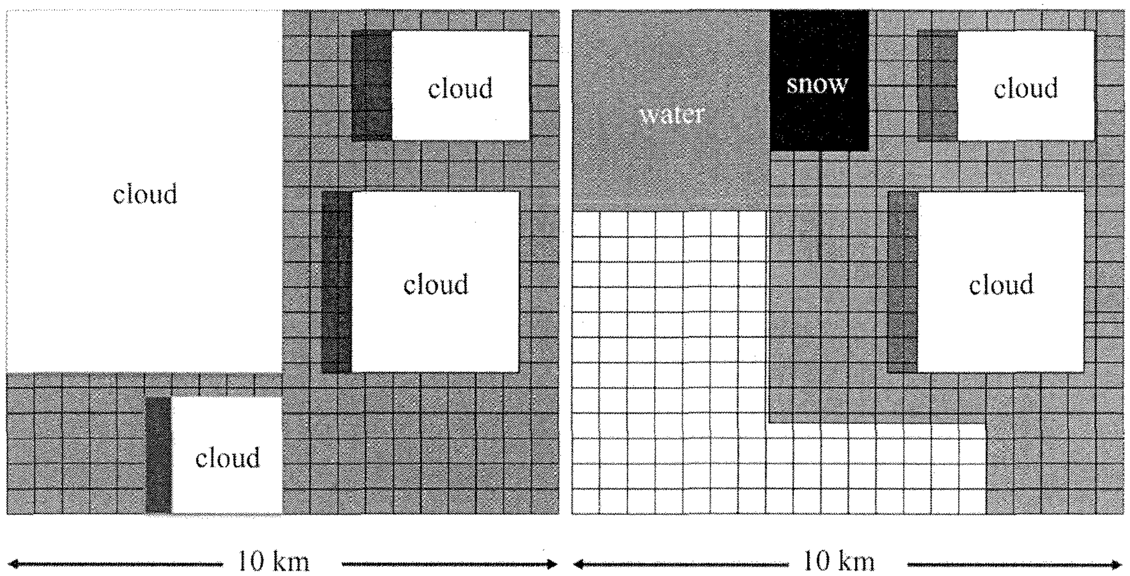


Figure 4. Schematic of a MODIS aerosol algorithm 10 km retrieval box over ocean, left, and land, right. In any given 10 km box there could be both cloudy and cloud-free pixels identified, and over land a variety of surface features, as well. Starting from 400 pixels at 0.5 km resolution, represented by the small grid squares, 225 are identified as cloudy over ocean and 55 over land. The land algorithm also eliminates an additional 196 pixels due to inappropriate surface features. This leaves 175 "good" pixels over ocean and 149 over land. From these the darkest and brightest pixels are arbitrarily eliminated, as described in the text, leaving 87 pixels from which to derive aerosol in the ocean 10 km box and 44 pixels in the land box.

3.2 GOES-R cloud mask

The GOES-R Algorithm Working Group Cloud Mask (ACM) is a cloud identification algorithm as defined in Figure 1. It was developed for the Advanced Baseline Imager (ABI), which will provide 16 spectral observations with a spatial resolution of 2 km for the IR channels and 0.5 km for the visible (0.65 micron) channel. The ACM uses 15 tests to detect the presence of cloud. Of these 15 tests, 11 use IR channels and 4 use solar reflectance channels. Four of the ACM tests exploit spatial heterogeneity to detect cloud and two exploit temporal information. The ACM returns 4 levels of cloudiness (clear, probably-clear, probably-cloudy and cloudy). Any positive test for cloud results in a cloudy classification. Cloud pixels that border a non-cloudy pixel are reclassified as probably-cloudy. Clear pixels that fail one or both of two spatial uniformity tests are classified as probably-clear. The ACM provides the results of each test. The goal of the ACM was to provide other GOES-R AWG algorithms useful information on cloudiness and the flexibility to optimize the cloud mask for their application.

The thresholds for the ACM tests were computed using 4 months of collocated CALIPSO/CALIOP and MSG/SEVIRI data. The thresholds were set so that the false alarm rates from each test were under 2%. A false alarm is when a pixel is identified as a cloud, but is not. The overall goal of the ACM was to minimize false alarm rates at the risk of increased rates of missing cloud. The guidance from other AWG algorithms was that they preferred to add additional cloud identification techniques rather than implement techniques to detect the presence of false cloud. This process is described in Heidinger and Straka (2010). More description of these individual tests and the processing using CALIPSO/CALIOP to determine thresholds is given by Heidinger et al. (2011).

In this paper, the ACM is applied to GOES data where the IR channels have a resolution of 4 km and the visible channel has a resolution of 1 km. For the 1 km results, the IR channels were oversampled to match the resolution of the visible channel. The GOES data allowed for operation of 12 out of the 15 ACM cloud tests.

4.0 Aerosol availability from a polar orbiting satellite with different instrument resolution

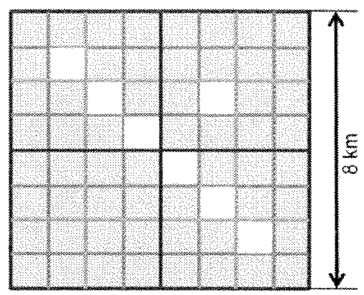
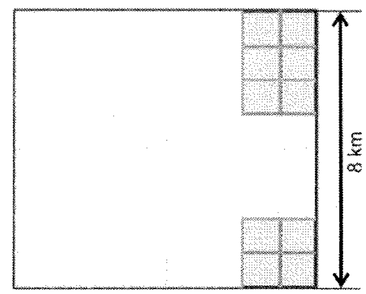
4.1 Methodology and Data

The MODIS aerosol cloud mask identifies clouds at 0.5 km resolution, but retrieves aerosol at 10 km resolution. Because of the relative fine resolution of the sensor's pixel size, aerosols can be derived even in partly cloudy situations when there are clouds within the 10 km retrieval box (Figure 4). If the MODIS sensor spatial resolution were degraded to 5 km in the above ocean example, no retrieval could be made because there is no 5 km area within the 10 km box that is cloud-free.

In this section we use the MODIS aerosol cloud mask derived from Terra-MODIS Level 1B reflectances to investigate the consequence to aerosol retrieval availability as sensor pixel size degrades from 0.5 km to 1, 2, 4 and 8 km. The Level 1B reflectances are read in at 0.5 km resolution and the MODIS aerosol cloud mask is calculated at this resolution. Coarser resolution masks are made by degrading the resolution of this original mask. If a 0.5 km pixel is designated 'cloudy' by the original mask, then all coarser masks that include that pixel are designated as 'cloudy' as well. It takes only one single 0.5 km pixel to be cloudy to designate an entire degraded coarse resolution pixel to be cloudy. In this way we are assuming a perfect cloud mask that never makes mistakes as resolution becomes coarser. For this exercise we define the aerosol product retrieval box to be 8x8 km instead of the MODIS operational algorithm box size of 10x10 km. This makes degradation to coarser resolution easier.

The MODIS aerosol algorithm makes a retrieval if more than ~10% of the pixels in the product box are cloud-free. Table 1 shows examples of opportunities to produce an 8x8 km product under two different cloudiness conditions with 1, 2, 4, and 8 km pixel resolutions. As those examples demonstrate, the higher the pixel resolution, the more opportunity to retrieve aerosols in a partially cloudy scene. Note that the retrieval opportunity is not the same as cloud-free fraction. For instance, in example #2 with 1 km pixel resolution, the cloud-free fraction is only 16% but the aerosol retrieval opportunity is 100%. Also, the retrieval opportunity in the examples of Table 1 is an upper bound; in an operational retrieval, it could be far less because other criteria, such as finding appropriate surface reflectance, etc., will have to be considered as well.

Table 1. Examples of different cloud configurations affecting retrieval opportunities in an 8x8 km product box.

	Example 1				Example 2			
Cloudy pixels (white) within a 8-km product box								
Pixel size (km)	1	2	4	8	1	2	4	8
Total pixel in 8-km box	64	16	4	1	64	16	4	1
# cloudy pixel	7	5	3	1	54	14	4	1
# clear pixel	57	11	1	0	10	2	0	0
8-km product	Yes	Yes	Yes	No	Yes	Yes	No	No

Therefore, using actual MODIS observations of real scenes, we will ask how availability of aerosol retrieval varies as a function of pixel size. Availability is defined as the number of 8 km product boxes available for aerosol retrieval divided by the total number of 8 km boxes in the region or time period of interest. In this study, our general area of interest is the northern hemisphere of the Americas and adjoining oceans, as shown in Figure 5. We have also defined five large subdomains including four quadrants of continental United States and a large region of midlatitude Atlantic Ocean (AO). The full domain, as designated in Figure 5, encompasses a larger area than the sum of the five subdomains, and therefore cannot be expected to represent the mean or median of the individual subdomains.

In the following analysis, level 1B MODIS reflectances, the first week of every month from March 2009 through February 2010 are analyzed to provide a representative sample of annual conditions. Seasonal statistics are calculated from three weeks of data, the first weeks of each of the three months that define each of the four seasons.

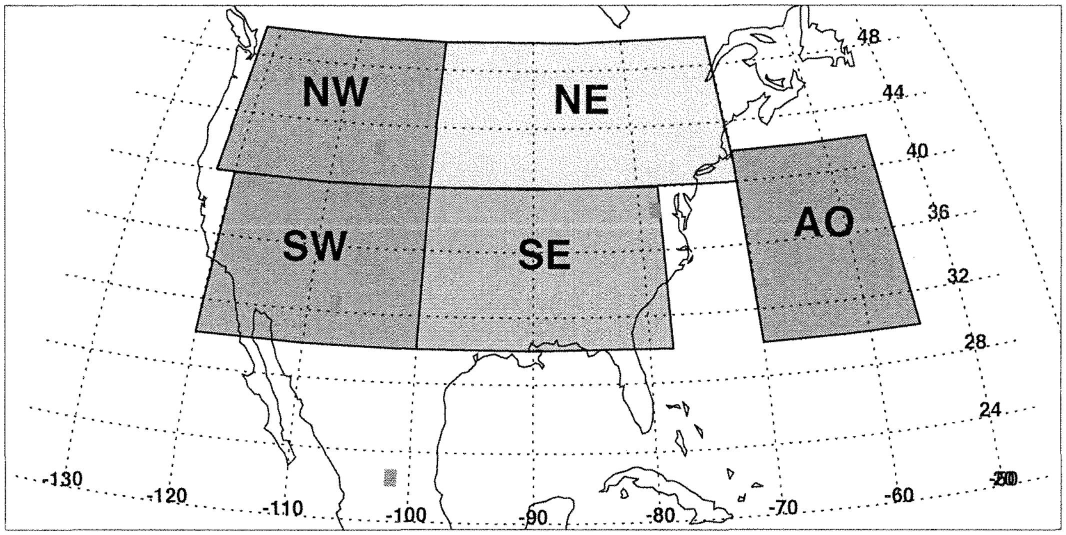


Figure 5. The full study domain extends from the equator to 55° N and from -139° to -13° W longitude. The full domain is divided into 5 subdomains: NW, NE, SW, SE and AO. The small red squares denote specific locations at 1°x1° of more intense analysis: Wyoming (WY) in NW, New Mexico (NM) in SW, Virginia (VA) in SE, and Mexico (ME) south of SW.

4.2 Regional and seasonal availability

The calculated availability using the data and methodology described in Section 4.1 is displayed in Figure 6 for the full domain and each regional subdomain as a function of instrument pixel size for each season. In every case, the coarser the resolution the fewer the number of 8 km boxes available for an aerosol retrieval. For example, in summer, at a spatial resolution of 0.5 km, availability ranges between 40% and 65%. This decreases to 33 – 58% by degrading to 1 km pixel resolution. By a 4 km pixel resolution availability has decreased further to 16-20%.

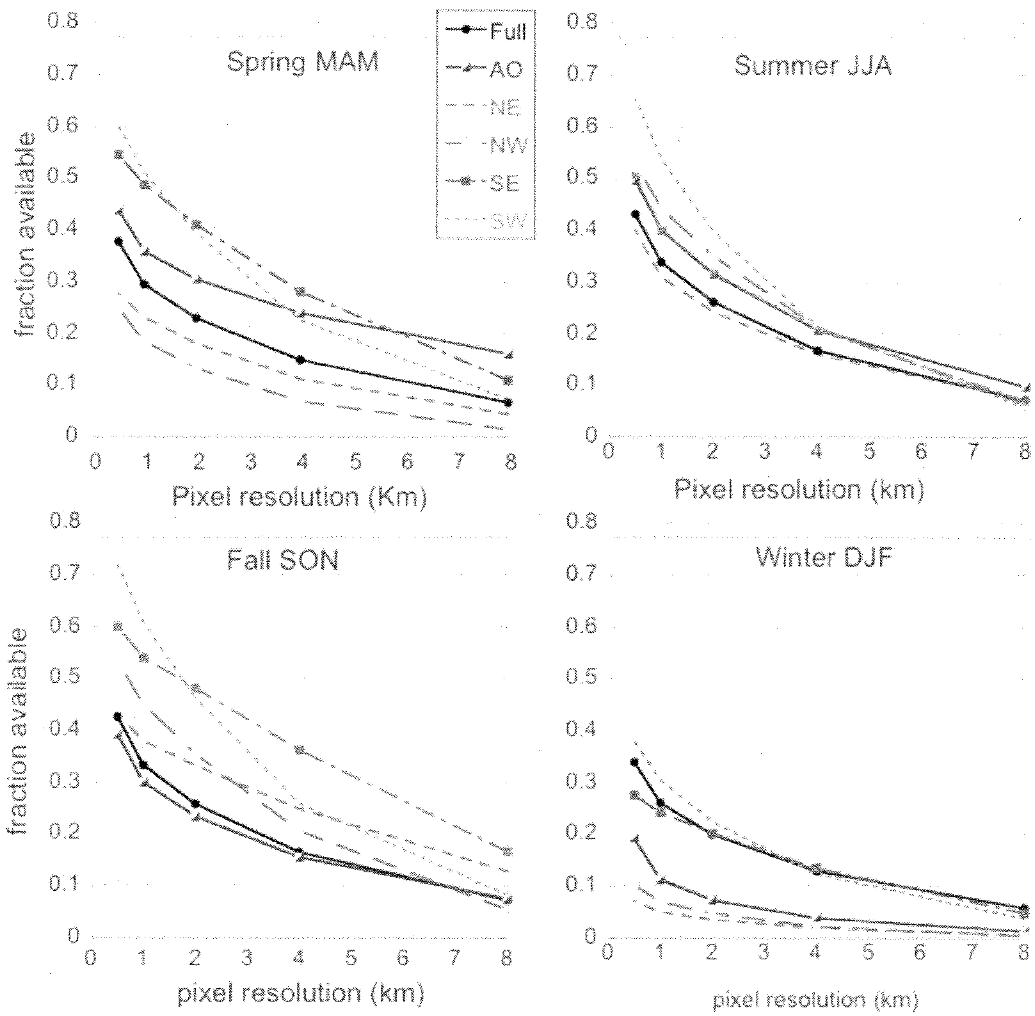


Figure 6. Calculated availability of an aerosol retrieval as a function of instrument pixel size for the full domain and subdomains defined in Fig. 5, for the four seasons.

There are seasonal and regional variations in availability. Fall, defined for the months of September, October and November (SON), offers the highest percentage of availability and winter, defined as December, January and February (DJF) offers the least availability. The MODIS aerosol cloud mask may conservatively label some cloud-free snow covered pixels as 'cloudy'. This would not produce adverse effects in the operational MODIS aerosol retrieval because snow pixels have to be eliminated from the retrieval also. Here, this factor may be contributing to the very low availability numbers of the northern tier subdomains in winter.

Regionally, the southwest subdomain (SW) offers the highest availability of any of the domains at 0.5 km pixel resolution, but does not necessarily provide the highest availability as spatial resolution degrades. For example, in Fall, by 8 km spatial resolution the SE and NE domains offer higher availability than does the SW. Differences in cloud type and morphology from region to region explain how this happens.

Table 2 lists all calculated availabilities for each domain, season and spatial resolution. The seasonal and regional analysis shows that an instrument with 4 km resolution can make less than half of the retrievals that a 0.5 km resolution instrument can make, over the course of a season.

Table 2. Calculated availabilities using MODIS aerosol cloud mask with MODIS input radiances for five spatial resolutions, four seasons, and six domains including the full domain described in Section 4.1.

	0.5 km	1 km	2 km	4 km	8 km
			Winter (DJF)		
Full	0.34	0.26	0.20	0.13	0.06
AO	0.19	0.11	0.07	0.04	0.01
NE	0.07	0.05	0.04	0.02	0.01
NW	0.10	0.07	0.05	0.02	0.01
SE	0.28	0.24	0.20	0.14	0.05
SW	0.38	0.31	0.23	0.12	0.04
			Spring (MAM)		
Full	0.38	0.30	0.23	0.15	0.07
AO	0.44	0.36	0.31	0.24	0.16
NE	0.28	0.23	0.18	0.11	0.04
NW	0.25	0.19	0.13	0.07	0.02
SE	0.55	0.49	0.41	0.28	0.11
SW	0.60	0.51	0.39	0.23	0.07
			Summer (JJA)		
Full	0.43	0.34	0.26	0.17	0.07
AO	0.50	0.40	0.32	0.21	0.10
NE	0.40	0.31	0.24	0.16	0.07
NW	0.53	0.44	0.35	0.21	0.06
SE	0.51	0.40	0.32	0.21	0.07
SW	0.65	0.54	0.40	0.21	0.06
			Fall (SON)		
Full	0.43	0.33	0.26	0.17	0.07
AO	0.39	0.30	0.24	0.16	0.08
NE	0.43	0.38	0.33	0.25	0.13
NW	0.53	0.45	0.36	0.21	0.06
SE	0.60	0.54	0.48	0.36	0.17
SW	0.72	0.61	0.46	0.26	0.08

Numbers are fractions. AO= Atlatic Ocean NE = Northeast NW = Northwest SE = Southeast SW = Southwest

4.3 Regional availability on a single day

Not all applications will be satisfied in obtaining aerosol statistics on a seasonal basis only. Some applications will require aerosol retrievals to be available within the region on a single day. Air quality forecasting and aerosol assimilation are such examples. To explore the availability in the five subdomains and the full domain of Figure 5, we calculate the availability for a randomly selected day, 12 August 2010. The left panel of Figure 7 shows the results.

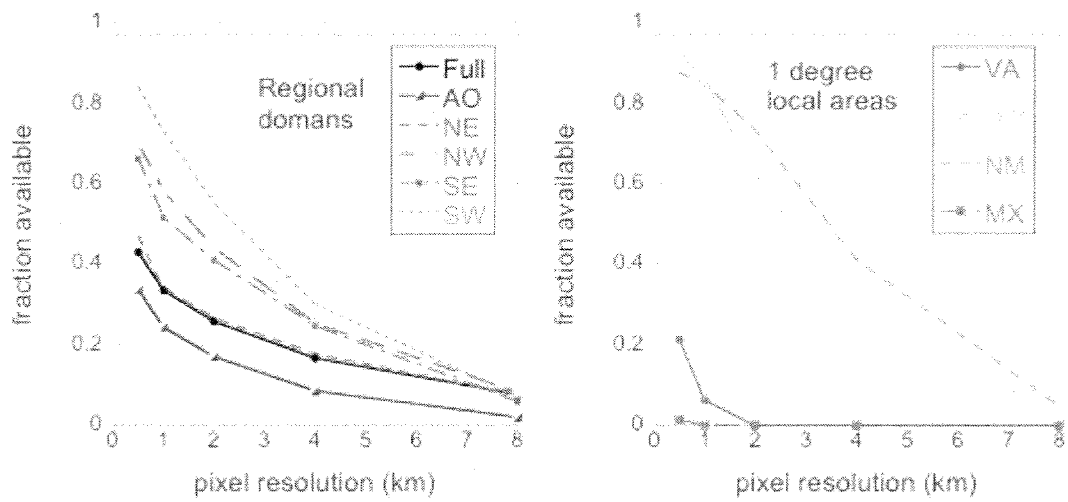


Figure 7. (left) Aerosol retrieval availability for 12 August 2010 for the full domain and five subdomains defined by Fig. 5, and (right) for the four 1-degree squares representing local areas, as defined in Figure 8.

There is greater spread of results from subdomain to subdomain for one day in August, as compared with the summer panel of Figure 6. Other differences include the low availability for the Atlantic Ocean domain for the one day, as compared with the season. On 12 August 2010, the ocean subdomain offers the least number of aerosol retrievals, at best approximately 35% at 0.5 km resolution, falling to less than 10% by 4 km resolution. The southwest subdomain (SW) offers the highest aerosol retrieval availability, over 80% at 0.5 km resolution and still 30% at 4 km resolution. Note, the availability calculation considers only cloudiness in its decision. The actual MODIS algorithm must also consider surface brightness, causing there to be far fewer retrievals in the SW from the operational MODIS algorithm than is suggested by Figure 7. Overall, degrading resolution from 0.5 km to 4 km causes a greater loss in the possible retrievals in almost every subdomain on that particular day than was evident in the seasonal analysis. In some cases, like the ocean, this leaves very few opportunities for retrieval. In other domains, the availability at 4 km remains above 25%. However, at 8 km resolution, almost all domains are reduced to 10% of their potential retrievals on this day.

4.4 Local availability on a single day

Calculations of aerosol retrieval availability over broad domains may be insufficient for applications that focus on a particular local area. To investigate local availability on a single day we again choose 12 August 2010 as a random day of interest and focus on four local regions indicated by the red dots in Figure 5. Each dot represents a 1-degree square chosen for a variety of cloud conditions on this particular day. The four regions are shown using Terra-MODIS imagery in Figure 8.

The availability was calculated for these local 1 degree squares on 12 August 2010 using the MODIS Level 1B data much the same as was done for the larger domains. The right panel of Figure 7 shows the results. The very cloudy local areas of Virginia (VA) and Mexico (MX) barely offer any opportunity for retrieval. However, it is surprising that at 0.5 km the availability at VA is still 20%. This opportunity for retrieval is closely tied to the 0.5 km resolution and essentially disappears even at 1 km. The Wyoming (WY) and New Mexico (NM) local areas are seen with a minimal amount of scattered small clouds. This situation permits over 80% availability at 0.5 km and 1 km resolution. However, even though many clouds are not seen by eye in the images, there are sufficient, randomly distributed clouds identified by the MODIS aerosol cloud mask to decrease retrieval availability as spatial resolution degrades. Remember, it only takes one cloudy 0.5 km pixel out of 64 to label a 4 km pixel as 'cloudy'. By 4 km the availability at WY and NM are 25% and 40%, respectively. At 8 km resolution, all four local areas offer less than 10% availability. Even though WY and NM appear 'cloud-free', the MODIS aerosol cloud mask is labeling pixels as 'cloudy'.

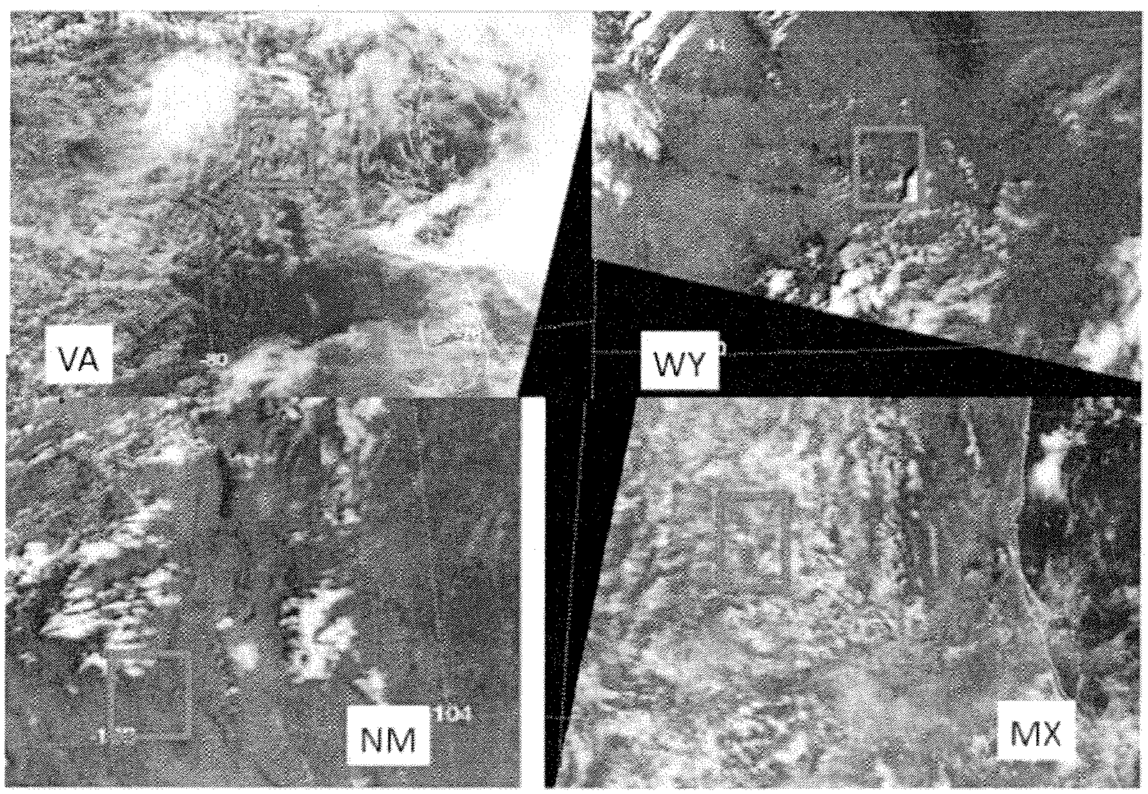


Figure 8. Terra MODIS true color imagery of four local areas on 12 August 2010. The red box in each image represents a 1 degree square used to define a local region in the

analysis. The four regions are Virginia (VA), Wyoming (WY), New Mexico (NM) and Mexico (MX).

5.0 Aerosol availability of a geosynchronous satellite

A polar orbiting satellite such as Terra or Aqua passes over each location on Earth only once per day during daylight hours. This permits MODIS only one chance to retrieve aerosol at a particular location, per satellite, per day. A geosynchronous satellite like GOES or the proposed Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission can observe each location multiple times per day, providing information on day time variation of aerosols. Even if a situation is too cloudy for an aerosol retrieval at the time of a polar orbiter's overpass, perhaps opportunity will open at other times during the day and the geosynchronous instrument will be able to retrieve. Thus, it may be able to trade high temporal frequency over a region for high spatial resolution over the globe and increase the availability of making at least one retrieval on a single day within the domain of measurement.

We explore the availability of aerosol retrievals from a geosynchronous satellite using the GOES-R cloud mask described in Section 3.2 and applied to one day of GOES data. The GOES-R cloud mask algorithm was applied to a special collection of GOES radiances obtained and stored every 5 minutes at 1 km resolution in the visible and at 4 km in the IR for 12 August 2010. The IR channels were oversampled to provide a nominal 1 km data set. As described above in Section 3.2, the philosophy of the GOES-R cloud mask is to err on the side of fewer clouds, because potential users have indicated that they prefer to add additional cloud detection schemes rather than attempt to unmask pixels falsely classified as 'cloudy'. In this way the GOES-R cloud mask is a cloud identification scheme, as illustrated in Fig. 1 and similar to the lower left panel of Fig. 2.

Availability was calculated in a similar procedure to what was described above for the MODIS aerosol cloud mask, but this time the GOES-R cloud product was used instead. As before, availability is not the same as the 'cloud-free' fraction. The input radiances are organized into 8 km retrieval boxes, and the number of 'cloud-free' pixels are calculated within each box. A retrieval box is designated as 'available' if the number of cloud-free pixels exceeds the specific criterion for the resolution as defined in Section 4.1. Availability for the region and time period of interest is the number of retrieval squares available for retrieval divided by the total number of 8 km retrieval squares. In the geosynchronous analysis, the finest spatial resolution is 1 km, which in turn is degraded to 2, 4 and 8 km pixel sizes.

Figure 9 shows the diurnal patterns of availability for four of the five subdomains defined in Figure 5 for the one day of analysis using the GOES-R cloud identification data set. The NE subdomain is not shown because it mimics the diurnal pattern of the AO subdomain. In all subdomains the diurnal pattern offers the greatest aerosol retrieval availability in the morning and the least in the afternoon. The coarser the pixel spatial resolution, the less the availability, and the greater is the amplitude of the diurnal availability signal. This is consistent with the growth of boundary layer clouds and general increase of cloudiness expected in the afternoon over land. However, the AO subdomain also shows a strong decrease of availability in the afternoon at 4 km and especially 8 km pixel resolution. In the western subdomains we see a kink in the availability at 1300 UTC at all spatial resolutions. In the west, it is still dark at 1200 UTC (5:00 to 6:00 am) over much of these subdomains. The kink is an artifact in the GOES-R cloud identification routine as it transitions from an all-infrared (IR) algorithm at night to a combined visible and IR algorithm during the day.

The overall availability is higher using the GOES-R data set than using the MODIS aerosol cloud mask, but some of the trends are similar. For example, the SW offers the highest availability on this day, while the AO offers the lowest. However, during the morning hours the loss of retrieval availability with degradation of spatial resolution is not as severe as seen in Figure 7, but increases severely in the afternoons. Still, the GOES-R cloud identifier permits at least 20% availability at 8 km over all subdomains, while the MODIS aerosol cloud mask allows only less than 10% at the same pixel resolution for that day.

Figure 10 shows the diurnal pattern availability for the four local 1-degree areas defined in Figure 8. The most interesting diurnal pattern occurs in NM. During the morning, including Terra overpass time of 1825 UTC (1025 local time) shown in Figure 8, the area is relatively cloud-free, resulting in high availabilities across all spatial resolutions. Then shortly after Terra overpass, availability decreases sharply. With a geosynchronous satellite making aerosol retrievals, the local NM area would have access to aerosol retrievals on that day, although an afternoon polar orbiter might make no retrievals due to clouds. In the two very cloudy areas, VA and MX, the afternoon cloudiness prevents any aerosol retrieval at 8 km at that time of the day, but a coarse resolution satellite with high temporal frequency might report aerosol retrievals either early or late in the day to compensate. Will those early and late retrievals properly represent aerosol conditions for that day when the scene was very cloudy for the majority of the day? The answer to that question lies outside the scope of this study.

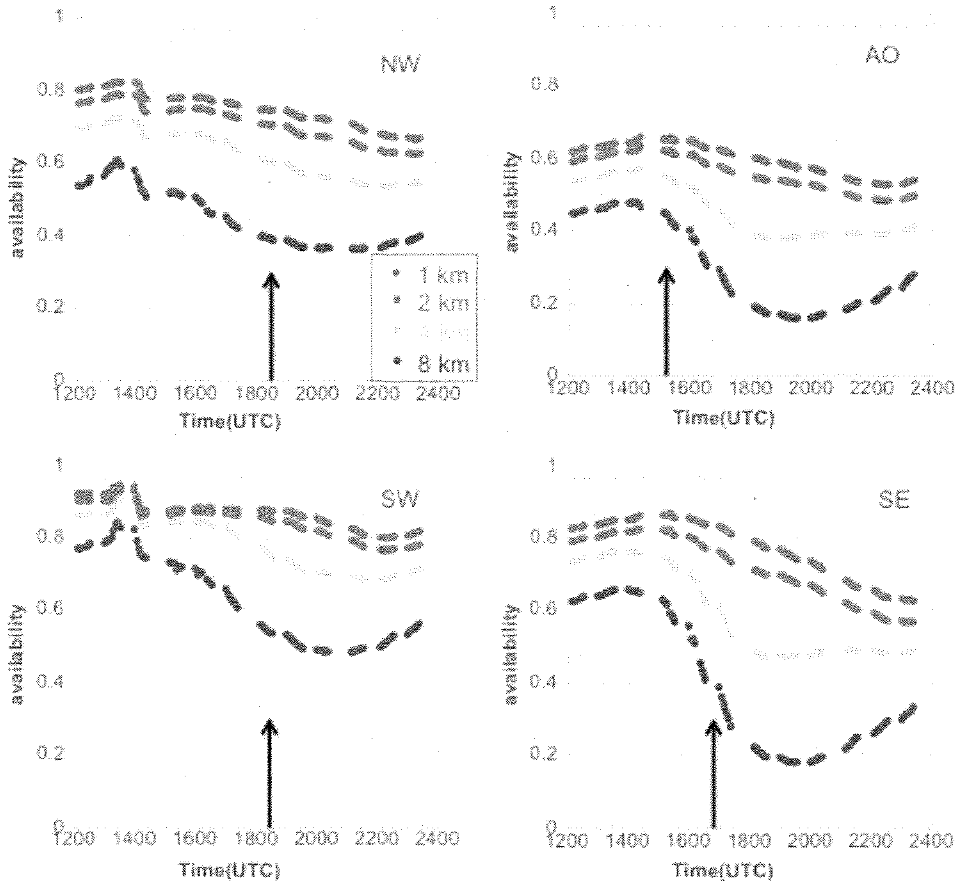


Figure 9. Diurnal patterns of aerosol retrieval availability on 12 August 2010 for four different spatial resolutions for four subdomains, Northwest (NW), Atlantic Ocean (AO), Southwest (SW) and Southeast (SE) defined in Figure 5. The availability was calculated using the GOES-R cloud mask applied to one day of GOES radiances archived at 5-minute temporal resolution. The black arrows indicate time of Terra overpass.

The GOES-R cloud identification produces a wide range of availability as a function of spatial resolution. With increasing of cloudiness, there is a large difference in availability between 1-2 km pixel size and 4-8 km. In VA and MX, the two very cloudy regions, there are times during the late morning when the 1 km resolution produces almost 100% availability simultaneous to the 8 km resolution producing 0% availability. This contrasts with the MODIS aerosol cloud mask results of Figure 7. Even at Terra overpass times of 1645 UTC and 1650 UTC when the MODIS aerosol cloud mask produced 10% and 0% availability at 1 km, for VA and MX, respectively, the GOES-R cloud identifier produced nearly 100% availability at 1 km. Figure 11 further demonstrates these differences for all domains and areas. The GOES-R cloud identifier always allows for greater availability than the MODIS aerosol cloud mask for all domains and local areas. In some situations, especially the relatively cloud free local areas, the two cloud products result in similar levels of availability, but the difference between the two increases as the cloudiness of the domain increases. This is because the two cloud products were developed for different purposes, which will be discussed below.

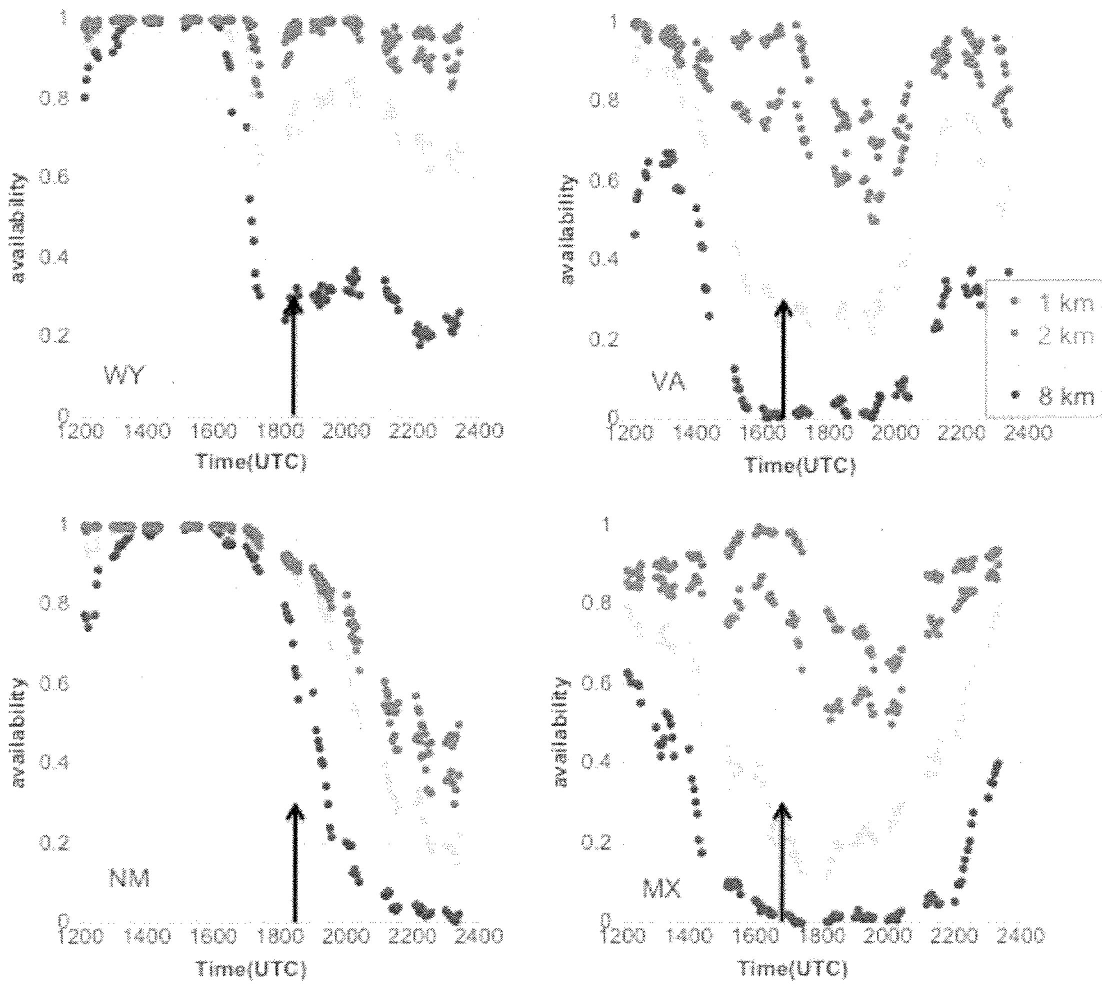


Figure 10. Diurnal patterns of aerosol retrieval availability on 12 August 2010 for four different spatial resolutions for the four 1-degree local areas defined in Figure 8. The availability was calculated using the GOES-R cloud mask applied to one day of GOES radiances archived at 5 minute temporal resolution. Black arrows point to times of Terra overpass.

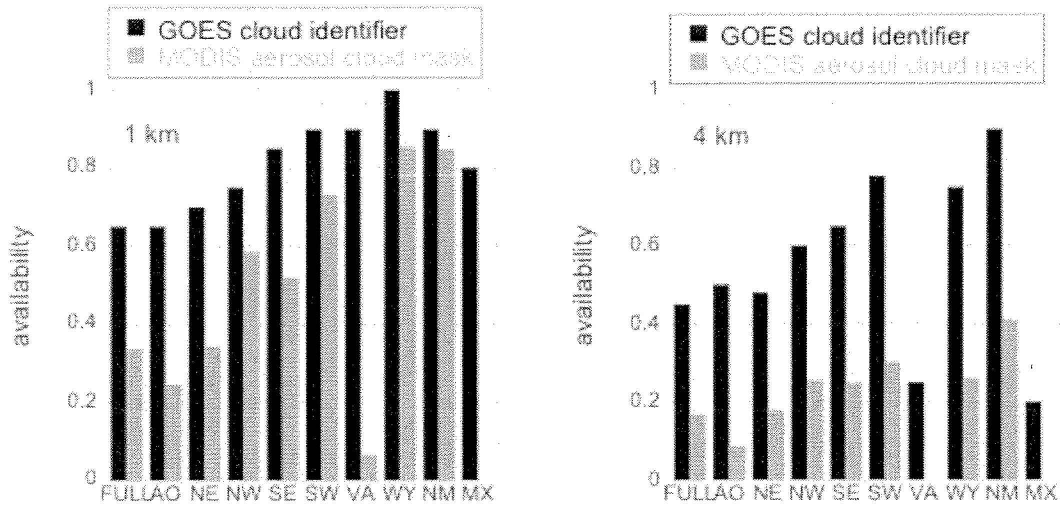


Figure 11. Aerosol retrieval availability for the Full domain and the five subdomains defined in Fig. 5, as well as for the four local 1-degree areas defined in Fig. 8 for 1 day, 12 August 2010. Shown are the results from using the GOES-R cloud identifier applied to GOES data and the MODIS aerosol cloud mask applied to MODIS data, for 1 km resolution (left) and 4 km resolution (right). The availabilities for the local areas (VA, WY, NM, MX) are calculated for the same time as MODIS overpass and are not diurnal averages.

6.0 Discussion and Conclusions

Using cloud masks applied to MODIS and GOES radiances we explore the availability of an aerosol retrieval in a cloudy environment. Availability is defined as the number of aerosol retrievals that could be made despite the clouds in a specific space and time domain, divided by the total number of possible retrievals in that domain if it were completely cloud free. Availability, as we define it, is not the same as cloud free fraction, because aerosol retrievals are made after selecting ideal pixels for retrieval within a larger box.

The cloud mask used for MODIS aerosol retrieval is designed to eliminate as many cloud problems as possible, even if the masking creates false positives for cloud. The other cloud mask developed for GOES-R and applied to one day of GOES data, takes a different approach that attempts to minimize false positives. These different approaches create striking differences in aerosol retrieval availability. In some situations the MODIS aerosol cloud mask coupled with the MODIS-like criteria resulted in essentially 0% availability, while the GOES-R cloud mask that avoids false positives for clouds found 80% availability. Clearly, a "one-sized" cloud mask cannot fit all. Imposing a cloud mask developed to identify clouds will cause the aerosol retrieval to fail.

Because of these striking differences between availability calculated from the two cloud masks for collocated scenes, we conclude that the GOES-R availabilities calculated here are overly optimistic for aerosol retrievals. These results can be used to learn about diurnal patterns, but should not be used for absolute availablity. The MODIS values, where the aerosol cloud mask is well-established, provide much better estimates of availability of different sensor resolutions for a variety of domains.

The results using MODIS show a decrease of availability as the sensor pixel size is made coarser. An instrument with a 4 km footprint will lose 60% to 70% of the retrievals that it would have made with a 0.5 km pixel instrument. An instrument with an 8 km footprint will lose 70% to 85% of its aerosol retrievals. We note that this study only considers clouds as it calculates availability. There are many other situations besides cloudiness that will prevent an aerosol retrieval, most likely inappropriate surface reflectances such as sun glint, snow, ice, inland water, bright deserts, etc.. Kahn et al., (2009) note that actual MODIS availability is close to 15% on a global basis. That is at 0.5 km resolution. This indicates that globally, a MODIS-like sensor and algorithm with 8 km pixel size will retrieve aerosol only over 3% to 5% of the Earth.

The analysis of the GOES-R cloud mask applied to geostationary satellite radiances from GOES reveal interesting diurnal patterns. These suggest that regions overcast with clouds at typical polar orbiting satellite overpass times may open up to aerosol retrievals either early or late in the day. The diurnal availability pattern is most significant at the coarser spatial resolutions, suggesting that an aerosol retrieval using 8 km radiance may be almost as available in the early morning as the 1 km retrieval is at midday. This diurnal pattern has some regional and seasonal variation. However, from a scientific perspective the early morning aerosol that can be retrieved may have very different properties than the aerosol that cannot be retrieved. We note that based on this analysis there is little possibility of resolving the diurnal cycle of aerosol properties from satellite if using an instrument with a 4 km or 8 km footprint. The availability at midday is too low. However, the diurnal analysis was limited to just one day, and may not be representative of other conditions.

New satellite sensors are being discussed with a variety of possible spatial resolutions. GEO-CAPE is a proposed geostationary mission with part of its objectives to characterize and monitor air pollution, including aerosols. The results here suggest that at 1 or 2 km resolution, GEO-CAPE will have sufficient aerosol availablity even on a day-to-day basis for a local area, and will be able to resolve the diurnal aerosol signal. The difference between 1 km and 2 km is not significant. However, by 4 km, the scarcity of aerosol retrievals will begin to hamper applications. Another potential satellite sensor for aerosol retrievals is the Aerosol Polarimeter Sensor (APS) that was launched as part of the Glory mission, but did not reach orbit. A reflight is possible. With its 6 km footprint at nadir and 20 km at far viewing angles, clouds will almost always be in APS's field of view. The results here reinforce the understanding that cloud mitigation efforts need to be developed for APS or substantial aerosol availability will be lost.

7.0 References

Ackerman, S. A., Strabala, K. I., Menzel, W. P., Frey, R. A., Moeller, C. C., and Gumley, L. E.: Discriminating clear-sky from clouds with MODIS, J. Geophys. Res., 103(D24), 32,141– 32,157, 1998.

Al-Saadi, J., et al.: Improving national air quality forecasts with satellite aerosol observations, Bull. Am. Meteorol. Soc., 86(9), 1249–1264, doi:10.1175/BAMS-86-9-1249, 2005.

Charlson R.J., Ackerman A. S.: Bender Frida A-M., et al.: On the climate forcing consequences of the albedo continuum between cloudy and clear air, TELLUS B, 59, 715-727, DOI: 10.1111/j.1600-0889.2007.00297.x , 2007.

Chu D. A., Kaufman, Y.J., Zibordi, G.: Chern, J.D., Mao, J., Li, C., and Holben ,B.N.: Global monitoring of air pollution over land from EOS- Terra MODIS, J. Geophys. Res., (D21), 4661, 108, 10.1029/2002JD003179, 2003.

EPA (United States Environmental Protection Agency): The plain English guide to the national Clean Air Act. Office of Air Quality Planning and Standards, Research Triangle Park NC, EPA-456/K-07-001. [Available on-line at http://www.epa.gov/airquality/peg_caa/pdfs/peg.pdf]

Frey, R.A., Ackerman, S. A., Liu,Y.: Strabala, K.I., Zhang, H., Key J., and Wang, X.: Cloud Detection with MODIS, Part I: Recent Improvements in the MODIS Cloud Mask , JTECH.25, 1057-1072, 2008.

Gao, B.C., Kaufman, Y.J., Tanre, D., et al.: Distinguishing tropospheric aerosols from thin cirrus clouds for improved aerosol retrievals using the ratio of 1.38-μm and 1.24-μm channels, Geophys. Res. Lett., 29, 18, 1890 DOI: 10.1029/2002GL015475, 2002.

Gupta, P., Christopher, S. A.: Particulate matter air quality assessment using integrated surface, satellite, and meteorological products: Multiple regression approach, J. Geophys. Res.-Atmos., 114, D14205, DOI: 10.1029/2008JD011496, 2009.

Heidinger A. K., Evan, A. T.: Foster M. J. and Walther, A.: A Naïve Bayesian Cloud Detection Scheme Derived from CALIPSO and Applied within PATMOS-x. in press to JAMC, 2011.

Heidinger A., and Straka III, W.C.: GOES-R ABI Cloud Mask Theoretical Basis Document, version 2.0. GOES-R Program Office., 2010.

IPCC (Intergovernmental Panel on Climate Changes): Changes in Atmospheric Constituents and in Radiative forcing, in Climate Change. Cambridge University Press, New York, 2007.

Jethva, H. and Torres, O.: Satellite-based evidence of wavelength-dependent aerosol absorption in biomass burning smoke inferred from ozone monitoring instrument, Atmos. Chem. Phys. Discuss, 11, 7291-7319, doi:10.5194/acpd-11-7291-2011, 2011.

Kahn R.A., Nelson, D. L., Garay, M., Levy, R.C., Bull, M.A., Martonchik, J.V., Diner, D. J., Paradise, S.R., Wu, D.L., Hansen, E.G. and Remer, L.A.: MISR Aerosol product attributes, and statistical comparisons with MODIS, IEEE Trans. Geosci. Rem. Sens., No. 12,, 47, 4095-4114, 2009.

Kahn, R.A., Gaitley, B.J., Garay, M.J., Diner, D.J., Eck, T., Smirnov, A., and Holben, B.N.: Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network. J. Geophys. Res. 115, D23209, doi: 10.1029/2010JD014601, 2010.

Kaufman Y.J., Tanre, D. , and Boucher, O.: A satellite view of aerosols in the climate system. Review Nature, 419, 215-223, 2002.

Koren, I., Remer, L. A., Kaufman,Y.J, Rudich, Y. and Martins, J. V.: On the twilight zone between clouds and aerosols, Geophys. Res. Lett., 34, L08805, doi:10.1029/2007GL029253, 2007.

Krewski, D., Burnett, R. T. , Goldberg, M. S., Hoover, K., Siemiatycki, J., Jerrett, M., Abrahamowicz, A., and White, W. H.: Reanalysis of the Harvard six cities study and the American Cancer Society study of particulate air pollution and mortality, A special report of the institute's particle epidemiology reanalysis project, 97 pp., Health Effects Inst., Cambridge, Mass, 2000.

Marshak, A., Wen, G., Coakley, J. A. Jr., et al.: A simple model for the cloud adjacency effect and the apparent bluing of aerosols near clouds, J. Geophys. Res., 113, D14, D14S17, DOI: 10.1029/2007JD009196, 2008.

Martins, J.V., Tanré, D., Remer, L., et al.: MODIS Cloud screening for remote sensing of aerosols over oceans using spatial variability, Geophys. Res. Lett., 29, 12, 1619, DOI: 10.1029/2001GL013252, 2002.

Platnick, S., King, M.D., Ackerman, S.A., et al.: The MODIS cloud products: Algorithms and examples from Terra, IEEE Trans. Geosci. Remote Sens.,41, 2, 459-473, DOI: 10.1109/TGRS.2002.808301, 2003.

Pope, C. A., III, Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurston, G. D.: Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution. J. Amer. Med. Assoc., 287, 1132–1141, 2002.

Prados A.I., Kondragunta S., Ciren P., et al.: GOES Aerosol/Smoke product (GASP) over North America: Comparisons to AERONET and MODIS observations, J. Geophys. Res.-Atmos. , 112, D15, D15201, 2007.

Remer, L.A., Kaufman, Y.J., Tanré, D., Mattoo, S., Chu, D.A., Martins, J.V., Li, R.R., Ichoku, C., Levy, R.C., Kleidman, R.G., Eck, T.F., Vermote, E., Holben, B.N.: The MODIS aerosol algorithm, products and validation, J. Atmos. Sci., 62, 947–973, 2005.

Samet, J. M., Dominici, M.D.F., Curriero, F.C., Coursac, I. and Zeger, S. L.: Fine particulate air pollution and mortality in 20 U.S. Cities, 1987–1994, New. Engl. J. Medicine, 343(24), 1742–1749, doi:10.1056/NEJM200012143432401, 2000.

Stier, P., Feichter, J., Kinne, S., Kloster, S., Vignati, E., Wilson, J., Ganzeveld, L., Tegen, I., Werner, M., Balkanski, Y., Schulz, M., Boucher, O., Minikin, A., and Petzold, A.: The aerosol-climate model ECHAM5-HAM., Atmos. Chem. Phys., 5, 1125-1156, 2005.

Tanré D., Bréon, F.M., Deuzé, J.L., Dubovik, O., Ducos, F., François, P., Goloub, P., Herman, M., Lifermann, A., Waquet, F.: Remote sensing of aerosols by using polarized, directionnal and spectral measurements within the A-Train: the PARASOL mission, Atmos. Meas. Tech., 4, 1383-1395, doi:10.5194/amt-4-1383-1395-2011, 2011.

Torres, O., Tanskanen, A., Veihelman, B., Ahn, C., Braak, R., Bhartia, P. K., Veefkind, P., and Levelt, P.: Aerosols and Surface UV Products from OMI Observations: An Overview, J. Geophys. Res., 112, D24S47:doi:10.1029/2007JD008809, 2007.

van Donkelaar, A., Martin, R.V., Park, R. J.: Estimating ground-level PM(2.5) using aerosol optical depth determined from satellite remote sensing, J. Geophys. Res.-Atmos., 111, D21, D21201, DOI: 10.1029/2005JD006996, 2006.

van Donkelaar, A., Martin, R.V., Levy, R. C., et al.: Satellite-based estimates of ground-level fine particulate matter during extreme events: A case study of the Moscow fires in 2010, Atmos. Environ., 45, 34, 6225-6232, DOI: 10.1016/j.atmosenv.2011.07.068, 2011.

Waquet, F., Riedi, J., Labonnotte, L., Thieuleux, F., Ducos, F., Goloub, Ph., and Tanré, D.: Aerosols remote sensing over clouds using the A-train observations, A-Train Symposium, New Orleans, USA, 25–28 October, 2010.

Wen, G.Y., Marshak A., Cahalan R.F.: Impact of 3-D clouds on clear-sky reflectance and aerosol retrieval in a biomass burning region of Brazil , IEEE Geosci. Remote Sens. Lett., 3, 1, 169-172, DOI: 10.1109/LGRS.2005.861386, 2006.

Yu, H., Kaufman, Y. J.: Chin, M., Feingold, G., Remer, L. A., Anderson, T. L., Balkanski, Y., Bellouin, N., Boucher, O., Christopher, S., DeCota, P., Kahn, R., Koch, D., Loeb, N., Reddy, M. S., Schulz, M., Takemura, T., and Zhou, M.: A review of measurement-based assessments of the aerosol direct radiative effect and forcing, Atmos. Chem. Phys., 6, 613–666, 2006.

Zhang, J.L., Reid, J.S., Holben, B.N.: An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products. Geophys. Res. Lett., 32, 15, L15803, DOI: 10.1029/2005GL023254, 2005.