Improvement of Aerosol Retrieval and Resolution using a refined Surface Albedo Model based on Simultaneous MODIS and Sunphotometer Measurements

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ABSTRACT

In this paper, we focus on the use of simultaneous MODIS and AERONET sky radiometer data to regionally refine the surface albedo models and improve on the current MODIS aerosol optical depth (AOD) over land operational product. In particular, we show that for urban scenes, the correlation coefficient assumption between the VIS and MIR channels used in the MODIS Collection (5) model for surface reflection parameterization are underestimated thereby leading to an underestimate in the VIS ground albedos and explaining the subsequent overestimate of the VIS optical depth. These results are consistent with ground albedo retrievals using high spatial imagery data from Hyperion, Furthermore, we find that the VIS/MIR ratios depend only weakly on the scattering geometry allowing us to generate in a simple manner a regional VIS/MIR surface reflectance correlation coefficient map at spatial resolutions down to 1.5km. When applying the new VIS/MIR surface reflectance ratio model, we show the agreement between MODIS and AERONET derived optical depth is significantly improved for the operational 10km resolution product. Furthermore, we show the high resolution surface model allows us to improve the resolution of the retrieved AOD to 1.5km.

Keywords: Urban Ground Albedo, Aerosol Retrieval over Land, Satellite Remote Sensing

I. INTRODUCTION

It is well known that accurate global estimation of AOD is essential to improve on accurate energy balance and climate change studies [1]. For these purposes, the development of retrieval algorithms which use global parameterizations and models are essential. On the other hand, there is growing interest in using satellite retrievals of AOD as a means to improve Air Quality Forecasts of PM2.5 (fine particles with 2.5 micrometer in diameter or smaller) and PM10 measurements [2-4]. In particular, it has been well documented that adverse health effects from breathing air with a high PM2.5 concentration include premature death, increased respiratory symptoms and disease, chronic bronchitis, and decreased lung function particularly for individuals with asthma [5]. Systems such as IDEA (Infusing satellite Data into Environmental Applications) [6] routinely use MODIS AOD retrievals along with lagrangian models to provide 24 hour predictions of PM2.5. This system works by using static estimators which attempt to connect AOD remote sensing measurements directly to surface PM2.5 concentrations [2-4]. Further systems at research level are already endeavoring to assimilate AOD from satellites into air transport models [4]

As urbanization continues to grow, retrieval of aerosols within these megacities becomes more important. However, retrieval of Aerosol Optical Depth (AOD) by satellite remote sensing measurements over land is complicated by the fact that the Top of Atmosphere (TOA) reflectance is a combination of the desired atmospheric path reflectance as well as the ground reflectance. To avoid this problem, AOD retrieval with the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument as described in the Collection (4) algorithm documentation [7] was focused on using "dark" pixels such as dense dark vegetation in an image as a way of isolating the aerosol contribution[8-9]. In fact, the correlation coefficients that connect the VIS ground albedos to the MIR albedo were set to values that were suitable mainly for vegetation. Clearly, these conditions are not realistically met over large urban areas such as the New York City megalopolis as well as other surfaces. In addition, the requirement of dark pixels is a prime reason for the low resolution AOD retrieval (at 10km) since the bright pixels are removed prior to processing. Therefore, loosening the restriction can ultimately improve the spatial resolution of the AOD product and is especially relevant for urban regions.

Clearly, building improved surface models were required and was the major focus for the revisions undertaken in the MODIS AOD over land algorithm (i.e. Collection (5)) [10] In this algorithm, special interest was paid to developing surface models based on global matchups of AERONET sky radiometer data and MODIS TOA reflectances. In performing these comparisons, it was found helpful to obtain global aerosol models based on cluster analysis techniques. Once these models were obtained and their climatology examined, selected aerosol models (for the fine mode aerosols) were chosen which were best linked to specific regions. From this analysis, in a comparison of sunphotometer and MODIS AOD, an empirical relationship was constructed to describe the surface VIS-MIR correlations which were shown to be functions of surface type (as defined by a SWIR vegetation index which is not sensitive to atmospheric uncertainty) and to a lesser extent on scattering angle. More over, in Collection (5) algorithm, LUT include polarization within the atmospheric parameters to reduce errors in derived AOD [11] .These modifications have recently been implemented in the Collection (5) retrieval algorithm. However, we find that by considering the full global data set in trying to build a universal model connecting VIS-MIR correlations to a modified vegetation parameter MVI, significant errors were obtained when this model is applied to regional urban areas.

The realization that urban regions requires new consideration is becoming more appreciated. In particular, there has been recent interest in modifying the surface model for urban areas using simultaneous measurements from sunphotometers and MODIS TOA reflectances on a regional scale. For example, in Mexico City, such an effort was carried out using a set of distributed hand-held sunphotometers as a means to explore different regions of the metropolitan area. In particular, when the data from the MILAGRO (Megacity Initiative: Local and Global Research Observation) [12] project was analyzed for AOD retrieval at 10×10 km^2 spatial resolution, the VIS-MIR surface relfectence ratio between 660nm and 2130nm value was found to be best described by a numerical value of (0.73). However, when examined at higher resolutions (i.e.1.5x1.5 km^2), a high variability of the surface reflectance ratio of VIS (660nm)/MIR (2120nm) was found which is significant enough to increase the uncertainties in the AOD values retrieved from satellite at the higher spatial resolution. These values are clearly not in agreement with the Collection (5) models which result in a maximum peak of approximately 0.59 for the VIS (660nm)/MIR (2120nm) surface reflectance ratio.

Our efforts for the New York City area are quite similar in spirit to the approach used in the MILAGRO project [12]. However, there are several differences in the methodology. To begin, we use only a CIMEL sky radiometer (part of the NASA GSFC AERONET network) as opposed to a network of hand-held MicroTop radiometers used in Milargo. To extend the surface retrievals a large geographic area, we filter our measurements so that the AOD observations (and aerosol type) were sufficiently homogeneous over the entire day. This homogeneity filter (discussed in detail in section IV) allows us to develop full contiguous surface correlation ratio maps for the entire scene.

The validity of this approach is demonstrated by observing the agreement of our VIS/MIR maps with high vegetation scene as calculated from the global surface models. In addition, unlike the MILAGRO study, we explore the variability of the correlation coefficients as a function of angle over a long time period. We come to a conclusion that any trends in the variability in correlation as a function of angle are less than the fluctuations in the surface variability around the trend line for all spatial resolutions. Therefore, it is sufficient to assume isotropic correlation coefficients. On the other hand, the individual reflectances are not lambertian [9]. However, sensitivity studies (not shown here) illustrate that the errors due to the lambertian approximation are on the sam order or smaller than the errors due to the variability of VIS-MIR correlation ratio.

The purpose of this paper is to demonstrate that the assumption used by the MODIS algorithm to estimate the ground reflectance is not appropriate for urban areas and to show that using the correct values improves both accuracy and spatial resolution. In section II, a comparison of the AERONET and MODIS retrievals is given for both the traditional Collection (4) algorithm which used a simple static surface correlation model and Collection (5) retrieval using the modified surface albedo models which dynamically input the geometrical angles as well as the surface type via a Modified Vegetation Index. In particular, we show the AOD bias of MODIS persists even for Collection (5).

In section III, before analyzing the results using MODIS and Aeronet measurements, we first explore surface reflection correlations using Hyperion Imagery taken under very clear sky conditions [13]. In analyzing the Hyperion data, a spatial regression approach based on the path radiance method [14] between the VIS and MIR channels is used which does not require an a-priori assumption of the aerosol model. The resulting calculations clearly illustrate the difference between urban pixels and vegetation pixels and are in good quantitative agreement with MODIS / Aeronet approach. In section IV, we describe the calculation of VIS/MIR (surface reflectance ratio) correlation coefficients for MODIS using simultaneous matchups with AERONET derived aerosol optical thickness including the preprocessing steps and filters used. In particular, we find significant changes in the correlation coefficient from the standard algorithms for urban areas. Furthermore, we note significant differences in the correlation coefficient values for different spatial averaging which we show to be due to the different levels of water contamination from the nearby bodies of water resulting in an apparent modification of the surface model with length scale. On the other hand, removing the water pixels directly results in VIS/MIR correlation values which are not very sensitive to scale. In section V, the modified surface models are applied to MODIS data at different resolution scales. We find that even for 3x3km resolution, AOD retrieval is significantly improved. Furthermore, in section VI, we verify the method and processing stream to data from Mexico City. In section VII, we summarize our results.

We also note that several recent publications are drawing attention to refine a surface albedos to account for errors in aerosol optical depth. For example, the technique use in reference [15] uses a regression approach which plots the TOA nadir corrected reflectances in the VIS channels against the TOA nadir corrected reflectances for cases within a comparatively short observation time where the surface is assumed constant. The idea is to identify the lower bound on the envelope as belonging to clean conditions and the slope of the curve than determines the VIS-MIR correlation coefficient. However, we find that resulting regressions obtained for high resolution does not yield a sufficiently clean linear plot in which to identify the clean molecular signal. In addition, on theoretical ground, even small deviations in the observation geometry can prevent the lowest bound from being due only to molecular scattering.

On the other hand, more rigorous but highly complex approaches in determining the details of the surface (including BRDF) under more general conditions have been developed. For example, an algorithm called MAIAC (multi angle implementation of atmospheric correction) has been developed and is being considered for operational processing,[16] This approach in analogy to our method attempts to solve for the regression parameters but attempts to simultaneously pull out the AOD together with the surface properties. However, unlike our approach which utilizes existing ground assets, and relies on simple estimates of the surface correlation which are assumed stable over time, this method is extremely complex. Furthermore, to provide stability based on the small number of angular observations used, the resolution of the surface products is 25km Clearly, it will be useful in future to compare the reflection output of MAIAC to our regional surface maps.

II. INTERCOMPARISONS BETWEEN MODIS AND AERONET

In order to validate MODIS retrieval by intercomparisons of MODIS and AERONET data, it is imperative that only spatially homogeneous datasets are used to ensure that the AERONET retrievals can be used for a larger distributed area. Since the MODIS retrieval is often cloud contaminated, and the surface albedo itself is spatially variable, the spatial homogeneity of the AERONET (CIMEL) dataset was determined by using the criterion that a 4 hour interval surrounding the MODIS observation is stable to within 10%.

When we performed the comparison, we looked at two optical depth retrievals from MODIS (year 2001). The first value is the aerosol optical depth obtained closest to the sky radiometer position, which is most sensitive to the MODIS algorithm bias because the AERONET site is located deep within the urban region while the second value is the minimum AOD measured by MODIS in a 80x80km box around the sky radiometer which should be less sensitive to algorithm bias. This is due to the fact that the minimum aerosol retrieved is highly correlated to regions of dark surface albedo and MODIS operational algorithm is most suitable for these pixels. The results of this comparison are illustrated in Fig. 1.

Apparently the MODIS retrieval for the nearest pixel measurements is significicantly overestimated. On the other hand, the MODIS minimum AOD measurements are much better correlated to the AERONET measurements. The reason for this becomes clear by considering the spatial locations within the 80x80km box where the minimum AOD is measured. The locations marked, in Fig. 2, shows the minimum AOD is most likely to occur in highly vegetated scenes showing that for vegetative surfaces, the retrieval is reasonable. Of course, this approach would not be helpful in examining aerosol spatial variability which requires higher spatial resolution.

In an effort to improve the retrieval, Collection (5) from MODIS attempts to use a dynamic surface model based on surface classification dependant on a modified vegetation index. However, as shown in Fig. 3a, the Collection (5) algorithm still has significant overestimating biases. To get some insight into why the Collection (5) algorithm does not provide significant improvement, we plot in Fig. 3b the correlation coefficient for both vegetative and urban scenes. In particular, we see that the Collection (5) algorithm does not improve the static relationship used in the Collection (4) algorithm for urban retrieval. As we show in section IV, the true correlation values are notably larger, particularly in heavily urban scenes.

III. SURFACE ALBEDO RETRIEVAL PROCEDURE

A. Path reflectance method with statistical approach

The path reflectance method is quite simple when applied to low optical depth conditions. Using equation (1) and assuming a linear correlation between the VIS and MIR channels, simple algebra relates the TOA reflectances as $R_{vis}^{TOA} \approx kR_{MIR}^{TOA} + R_{vis}^{Atm}$ and in the limit of zero MIR reflectance $R_{MIR}^{TOA} \approx 0 \Rightarrow R_{vis}^{TOA} = R_{vis}^{Atm}$. It must be pointed out that it is clearly unnecessary to know the particular surface correlation but simply extrapolate the regression line to zero. The slope of the regression line is the correlation coefficient $k = cT_d(\mu)T_u(\mu')$. This approach is applied to complex urban ground terrain using Hyperion data that was taken over NYC (Sept 12, 2001). For more details, see [13]. It is useful for surface modeling due to the very low AOD observed for that day ($\tau_{0.5\mu m} \le 0.05$). Fig. 4 is the histogram of several regions of the Hyperion image surface reflectance ratio of 660nm /2120nm. These regions include vegetation (Central Park in Manhattan, NY), light urban (Hoboken, NJ) and high urban scenery (Downtown Manhattan, NY). It can be observed that in Central Park (vegetation), the correlation for the 660-2160nm bands is unbiased around a value of 0.5. However, when considering light or heavy urban scenes, the value for the correlation coefficient is significantly higher, peaking to 0.72 for heavy urban scenes in good agreement with the MILARGO results [12].

As a consistency check, we were also able to accurately reconstruct the TOA reflectance as a function of wavelength based on the surface reflectance. This is possible since simultaneous AERONET measurements were available showing the atmosphere was dominated with fine mode aerosol with an AOD ~0.05. The details of this matchup with Hyperion image data can be found in [13]. The resultant surface reflectance ratio (660nm/2120nm) from this technique agrees well with Collection (5) ratio over vegetation areas with a value ~ 0.5 but the ratio is significantly higher over urban area pixels, with a mean of approximately 0.73 . As we will see, these results are consistent with the second approach combining MODIS and Aeronet measurements.

B. Path reflectance method with MODIS operational LUT (Look Up Table)

Spatial statistical approaches are difficult with MODIS L2 data due to its low spatial resolution. Therefore we need to generate a per-pixel estimate of the surface VIS/MIR ratio from higher spatial resolution MODIS L1B data in combination with a-priori knowledge of the aerosol properties obtained from AERONET retrievals. During the surface albedo retrieval, it is important to use simultaneous comparisons which ensure low aerosol loading and aerosol homogeneity. Details of our filters are given in section III B (2).

1) Cloud Masking Procedure

To begin, we must first locate cloud free pixels to get TOA reflectance. The MODIS cloud mask algorithm identifies several conceptual domains according to surface type and solar illumination including land, water, snow/ice, desert, and coast for both day and night [17]. Once a pixel is assigned to a particular domain, a series of threshold tests attempts to detect the presence of clouds in the instrument field-of view. The approach we consider relies heavily on the existing cloud masks except that we significantly lower the restriction of the magnitude of the TOA reflectance. This is necessary if we are to accommodate higher surface albedos in urban scenes. Since we plan to explore retrievals at higher resolution, we analyze cloud clearing approaches at 3 resolutions (10km x 10km, 3km x 3km and 1.5 km x1.5km).

We use the MODIS L1B 500m resolution data in bands 3(0.47µm), and 7(2.12µm), as well as 1km resolution data in band 26 (1.38µm) to eliminate the cloud covered pixels. The cloud masking procedure is very similar to the MODIS procedure [10]. In this process, we compute the standard deviation of spatial variability of band 3 (0.47µm) and band 26 (1.38µm) for each group of 3x3 pixel and discarded the group if any pixel in the group of 3x3 has a standard deviation in band 3 (0.47µm) >0.01 or a standard deviation in band 26 (1.38µm) >0.003. In addition, we perform reflectance threshold test to reject the pixel if band 26 (1.38µm) >0.025 or band 3 (0.47µm) > 0.4 to avoid cloud contamination to the aerosol retrieval. After masking the cloud covered pixels, we select only the pixels where band 7 (2.12µm) reflectance is greater than 0.01 and less than 0.25. The processing of the TOA reflectance of selected pixels is completed by the solar zenith angle correction and the gas correction of L1 B data reflectance, for details see [10]. Due to our less conservative criteria (than the standard procedure), it may be possible that cloud contamination may be more frequent. However, since cloud optical properties (i.e. angstrom coefficient) are quite different from the fine mode aerosol dominated events (used in this work), an analysis of the fine /coarse mode mixing ratio should be sufficient to identify and eliminate any remaining cloud contamination effects.

2) Aerosol Model selection for New York metro region

Once the cloud clearing at a particular resolution is performed, an inversion to obtain surface properties can be carried out. Although the MODIS defined LUT has 4 fine aerosol models (Continental, Generic, Smoke, Urban) and a Dust aerosol, the Collection (5) ATBD document shows that for the North East, nearly all aerosol events are catalogued within the urban aerosol model category[10]. Therefore, in obtaining the surface model, we assume the aerosols are of urban type. The physical and optical properties of the 5 aerosol models are defined in ATBD document [10].

During the comparison, we only use atmospheres which we could verify a-priori as fine mode so we can approximate the surface reflectance at 2130 nm as the TOA reflectance, because SWIR is transparent to the fine mode aerosol and reflectance at the top of atmosphere is directly coming due to the ground.

To ensure the fine mode aerosol dominant days, we select only days when the angstrom coefficient $\alpha > 1$ (as defined in equation (2)), and to reduce errors due to misclassification of aerosols, we limit the AOD to $\tau_{0.55\mu m} < 0.2$

$$\alpha = \frac{\log(\tau_{675nm} / \tau_{1020nm})}{\log(1020/675)} \tag{2}$$

Moreover, to ensure horizontal homogeneity in the aerosol during the surface retrieval, we require at least 10 cloud cleared points exist in AERONET measurement in the 4 hour interval (approximately 2 hours before and 2 hours after MODIS/Terra passing time) surrounding the MODIS observations and the full daily relative standard deviation in the AOD to be less than 20%. These filters on the allowed days for comparison help to reduce possible errors in our assumption that the aerosols are of the urban type and to ensure that regions in the vicinity of the AERONET site are described approximately by the same aerosol model.

3) Radiative transfer model

To use the AERONET AOD data, we must be able to feed this information directly into the radiative transfer code. Assuming a lambertian surface albedo, the surface reflectance can be written as

$$\rho_\lambda^{surf}(\theta_0,\theta,\Delta\phi,\tau)=\frac{\rho_\lambda^{TOA}(\theta_0,\theta,\Delta\phi,\tau)-\rho_\lambda^{path}(\theta_0,\theta,\Delta\phi,\tau)}{\bar{s}(\theta_0,\tau)(\rho_\lambda^{TOA}(\theta_0,\theta,\Delta\phi,\tau)-\rho_\lambda^{path}(\theta_0,\theta,\Delta\phi,\tau))+T_\lambda^{up}(\theta_0,\theta,\tau)F_\lambda^{dn}(\theta_0,\tau)} \quad (3)$$

In equation (3), P_λ^{TOA} is the measured top of atmosphere reflectance form MODIS L1 B cloud free data, P_λ^{Path} is the atmospheric path reflectance, s is the atmospheric albedo,F_λ^{dn} is the downward transmission, and T_λ^{up} is the upward transmission, θ_0, θ, $\Delta\varphi$ are the solar zenith angle, senor (satellite) zenith angle and relative solar sensor azimuth angle respectively[10]. Ingesting the AERONET AOD and MODIS urban aerosol phase function is sufficient to obtain the surface reflections for both visible channels independently. Furthermore, since the aerosols are fine mode dominated, the ground reflectance at 2130*nm* is directly obtained allowing us a measure of the VIS-MIR correlation coefficients.

IV. VIS/SWIR surface reflectance ratio calculation

Following the procedure in Section III, the surface reflectances can be calculated. The results of these calculations as a function of the scattering angle are shown in Fig. 5 for 3 spatial resolutions (10x10km, 3x3km and 1.5x1.5km boxes) surrounding the City College of New York (AERONET site in Manhattan, NY). We first note that the calculated VIS/SWIR reflectance ratios are higher than those implemented from MODIS operational algorithm defined VIS/SWIR reflectance ratios and these ratios are in good agreement with Hyperion results]. Furthermore, we do not detect any meaningful trend behavior as a function of angle. In fact, any trend observed is significantly smaller than the fluctuations around the trend line. However, we also note a serious anomaly in which the correlation coefficient increases significantly as the spatial resolution is increased from 10x10km to 1.5x1.5 km, see Fig. 5 (e) and (f). This is not expected for normal homogenous surface types.

However, this anomaly can be explained when we consider the water contamination due to the nearby Hudson river. In fact, when the spatial resolution is low (10x10km box), only a small portion of the region is contaminated by water. The effect of water in the pixel is to drive the value of the correlation up since for any water body, no reflection at 2120nm occurs while a small but non zero value is present due to highly turbid water condition. In effect, this leads to an anomalously high VIS/MIR reflectance ratio which distorts the correlation values for the surface pixels.

This explanation can be tested if we re-analyze the results but mask all water pixels shown using a 2120nm filter directly (i.e. $\rho_{TOA} > 0.05$). The results are shown in Fig. 6. We note in particular that the correlation values are much more independent of the scene resolution as expected.

To see how the urban pixel compares with a vegetation pixel, we explore north of New York City which is dominated by vegetation pixels. The results are shown in Fig. 7(a-b), showing good agreement with the values used in MODIS Collection (4) surface VIS/MIR correlation coefficients.

Note also that the fractional error in the retrieval is higher than in urban pixels. This is due to the fact that not only is the ground reflection ratio smaller than for urban scenes but the total reflection is lower over vegetation. Therefore, the retrieval of the surface properties is expected to have a larger fractional error.

The above results were obtained for a single illustrate that the angular dependence of the correlation coefficient is not significant. Therefore, we can determine VIS/SWIR surface reflectance ratio as the mean correlation coefficients of each pixel within a reasonable distance from the CCNY site independent of scattering angle. The results map of the VIS/SWIR surface reflectance ratios are shown in Fig. 8 and clearly illustrate the need for a regional surface correlation model to account for the significant differences in surface type The regional map extends from 40.61N latitude to 41.4N Latitude, 74.2 W longitudes to 73.71 W longitudes. Basically the VIS/MIR ratios are significantly higher in the urban area compared to the vegetated areas. In the northern vegetated areas, the VIS/MIR 460*nm*/2120*nm* ratio is ~ 0.25 and the 660*nm*/2120*nm* ratio is ~0.5 which agrees with the MODIS Collection (5) model but the VIS/MIR ratio in the urban area is much higher. This is particularly clear in urban scenes on both sides of the Hudson River (i.e., New Jersey and Manhattan).

$$MVI = \frac{\rho_{1240}^{TOA} - \rho_{2120}^{TOA}}{\rho_{1240}^{TOA} + \rho_{2120}^{TOA}} \qquad (4)$$

To further illustrate the unique features of the urban pixels, we also calculate the mean MVI of the New York City area (NYC) as shown in Fig. 9. In the area north of the NYC where MVI is higher the VIS/MIR surface reflectance ratios are significantly lower. In figure 10, the correlation coefficients are shown as a function of MVI and compared to the operational model. As we observe, our result is not only quantitatively different from the current Global Collect 5 Model but is actually opposite when comparing urban and vegetation correlation coefficients.

V. AOD retrieval results

As previously emphasized, the correlation coefficient ratios results from Fig. 5 and Fig. 6 are significantly higher than the MODIS Collection (5) version. When this surface reflection in VIS wavelengths are approximated as a linear relationship with SWIR and fed back into the AOD retrieval processing stream, a significant improvement as seen in Fig. 11 is obtained. Note however that the fluctuations increase dramatically with higher resolution which is clearly due to the large uncertainties in the correlation coefficient due to water contamination. When the water body is masked and the procedure is repeated, the uncertainty even at higher resolution is quite small as seen in Fig 12. To help in the comparison, the standard deviation both before and after masking the inland water body is shown in Table 1. In particular, we find that removing the water contamination greatly improves the STD error in the correlation coefficients and the results also become more independent of the spatial resolution scale. This is reasonable since the water contamination is due to a narrow river which is most prominent when considering observations on the 1.5km scale. The increase in these correlation coefficients in the absence of a suitable mask are due to the fact that the SWIR signal is negligible while the VIS signals are not resulting in an anomalously high correlation coefficient.

In our approach, we recall that due to the insensitivity of the correlation coefficients to angle, we made the simplifying assumption that the best value is simply averaged over all observations. Clearly, the accuracy in this approximation is limited to the std error seen in these correlation coefficients. Therefore, in assessing AOD retrieval accuracy, we must include the uncertainty in the correlation coefficients. The results of this sensitivity exercise are shown in Fig 13 where the uncertainty in aerosol retrieval is determined by reprocessing the MODIS data using the full variability of the correlation coefficients. In particular, defining $C_j = R_g(\lambda_j)/R_g(2120)$, we reprocess the retrievals using $\overline{C}_j \pm \sigma(C_j)$keeping in mind that due to the high correlation between the two correlation coefficients, we can consider both regressions coefficients as covarying In particular, we find that the retrieved AOD is obtained within reasonable limits. However, it should be noted that a constant correlation coefficient does not imply a lambertian surface albedo in general. Preliminary efforts to assess the errors when using the BRDF [16] seem to indicate that the errors due to this source are no bigger than the errors we observe due to the simple variation in the correlation coefficient magnitude and will not be considered further in this paper.

Once the surface correlation map is generated, we can attempt to retrieve an AOD map for the entire New York City area within the operational algorithm at higher resolution where the only change is in the correlation surface models. As an example, we take a relatively cloud free day (seen by (AERONET) CIMEL radiometer data, Fig. 14) and explore the retrieved AOD using both the operational and regional surface models. The results are shown in Fig. 15. The right panel (Fig 15 b) is processed with the Collection (5) algorithm while the left panel (Fig 15 a) uses the modified regional model. Clearly, a significant improvement can be observed as artificial hot spots in the AOD map are reduced. Although we cannot directly validate the spatial distribution, we can indirectly probe the result by examining the histogram of data over the region. In Fig. 16, the regional correlation map results are in much better agreement to the statistics seen in the AERONET time series retrieval of Fig. 14.

Finally, we illustrate an improved performance at Medger Evers College where we have set up a MFRSR shadowband radiometer. In particular, we show that even for locations with significant separation from CCNY (16km), the use of the surface results obtained from CCNY can be used with success. In figure 16, we show the results at 1.5km resolution for the matchups over Medger Evers college (and their locations) . This data set is not extensive with only 2 months available in Sept. Oct 2007 but large improvement is seen. The reason for residual over bias is difficult to determine at present but can possibly be due to errors in MFRSR processing (not as accurate as aeronet).

VI. VALIDATION OVER MEXICO CITY

In this section, we explore another heavy urban region in a different location to confirm that the processing method is robust and the results of NYC are more justified. For this purpose, the Mexico City region is selected. Unlike New York City area, Mexico City is located approximately more than 2 Km above the sea level and most of the fine mode aerosols are within Smoke Aerosol model category (in MODIS LUT). We use the Mexico City AERONET station data acquired during 2000-2007.The procedures of the surface reflectance retrieval are the same as before in NYC region. In addition, due to the height of Mexico City, a pressure correction was implemented. [10] The resultant VIS/MIR surface ratios are very similar to NY City urban area’s outcome. The averages of 460/2120 nm and 660/2120nm surface reflectance ratios are approximately 0.43 and 0.70 in

10x10km resolution and 0.44 and 0.71 in 3x3km resolution. Using these refined regional VIS/MIR surface reflectance ratios, the significant improvement in AOD retrieval can be observed in Fig. 18. It should be pointed out however that Mexico City aerosol climatology has a smaller percentage of fine-mode aerosol cases. Therefore, the number of training measurements when compared to New York is much smaller. At 1.5km resolution, too few cases of fine mode clear sky cases were available so analysis was limited to 3x3km.

VII. CONCLUSIONS

The need for a regionally based surface model has been demonstrated based on significant overestimation with respect to AERONET in the AOD retrieval using the current Collection (5) algorithm. This is due to the fact that, the globally based model cannot retrieve the high VIS-MIR correlation coefficients observed when regionally processing urban areas. In inverting the TOA reflectance data, simultaneous AOD measurements from MODIS and an AERONET CIMEL sky radiometer were used to retrieve regional surface properties where suitable filters on the aerosol loading and stability was used in building the analysis data set. These filters were put in place to ensure that the aerosol optical depth was small, and fine mode dominated and that the aerosol is fairly stable over the day. This ensured that good surface reflection data can be obtained at 470nm, 660nm and 2120nm allowing us to retrieve accurate surface reflection VIS-MIR correlation functions.

The resultant correlations were significantly higher than Collection (5) results and were shown to be in good agreement with surface reflectance ratio from Hyperion results [13]. In addition, we find significant differences between the Collection 5 relation between the correlation coefficients and MVI parameters including the fact that the urban correlations are signficiantly higher than vegetation. On the other hand, we did not detect any meaningful trend behavior as a function of scattering angle allowing us to use a Lambertian approximation of the surface. However, we found that water contamination is a serious problem, artificially increasing the surface correlation values for scenes in close proximity to water. To eliminate this problem, we used a simple water body mask on the 2120nm channel and eliminated these pixels allowing for a much more homogeneous result. In validating our procedure, we show that the correlation map over vegetation areas is consistent with values appropriate for vegetation dominated regions.

Intercomparisons of AOD between AERONET and MODIS processed using the regional surface model clearly show that the bias has been removed and if the water contamination is dealt with, there is only slight degradation in the retrieval even for spatial resolutions as high as 1.5km. As a demonstration, we were able to retrieve high spatial resolution AOD maps for a case where the AOD is higher than the data used to derive the new VIS/MIR ratios but small enough so that errors in the ground model are significant. In this case, the spatial distribution of aerosols were shown to be well approximated by a Gaussian distribution with much more accurate mean value then if the processing was done operationally. Most important, anomalously high AOD retrievals (i.e. hotspots) obtained using the collect 5 algorithm due to significant underestimation of surface albedo were drastically reduced allowing for a much more accurate of aerosol loading within the city and thereby eliminating false EPA non attainment predictions.

In addition, complementary results for Mexico City urban area were obtained showing that the surface model obtained from NYC is quite similar. This is also in good agreement with surface albedo modeling obtained during the MILARGO campaign. Ultimately, more urban cases should be explored to assess whether the VIS-MIR albedo correlations and their relationship to the MVI parameters are more universal.

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Table caption

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Fig. 2. Location of AOD Minimum relative to NYC

Fig. 3. (a)Collection (5) retrievals versus AERONET (Year 2001-2007) showing positive bias and (b) Collection (5) surface albedo ratio

Fig. 4. Statistical correlation for 660-2160nm reflectance ratio (i) vegetation, (ii) light urban and (iii) urban pixels

Fig. 5. Surface reflectance ratio of 0.46 / 2.1 μm and 0.66 /2.1 μm with respect to (x axis) scattering angle. Mean reflectance ratio for different spatial resolution: 10x10-km (a-b), 3x3km (c-d) and 1.5x1.5km (e-f) surrounded to the nearest pixel to AERONET site at CCNY from 2001 to 2006 with fine mode aerosol dominant atmosphere (not masked for inland water bodies)

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Fig. 8. VIS/MIR correlation coefficient ratios of 460nm/2120nm (left panel) and 660nm/2120nm (right panel) in nearby New York City area

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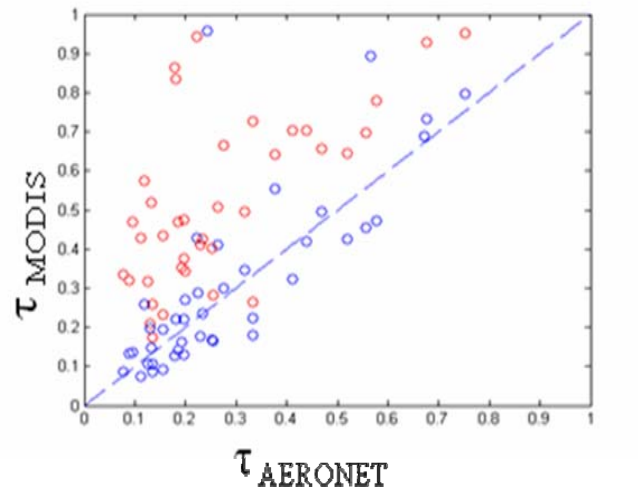
Figures



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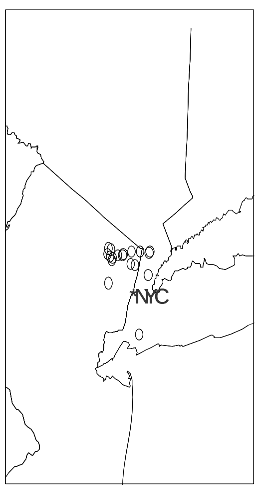

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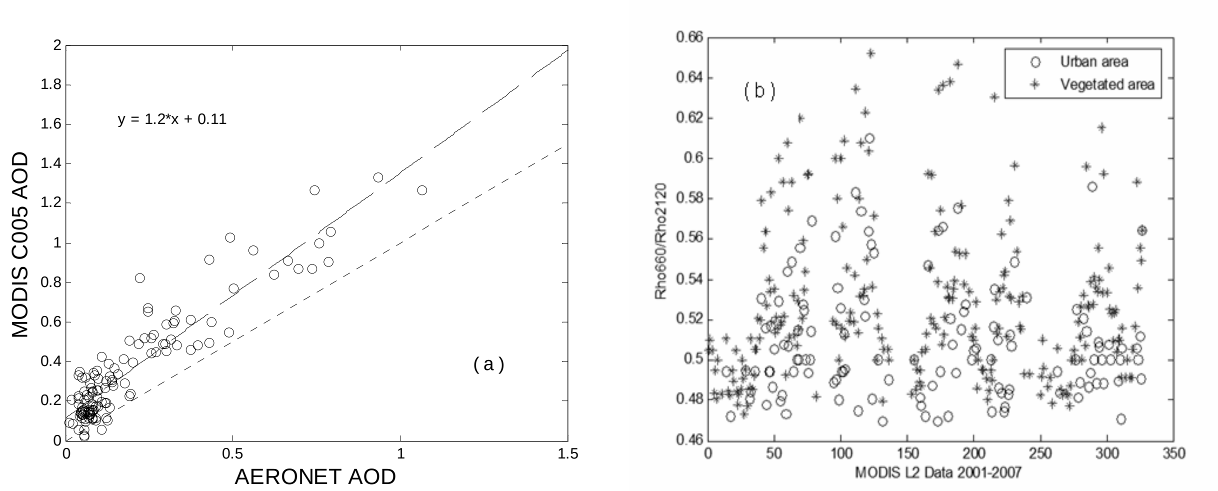

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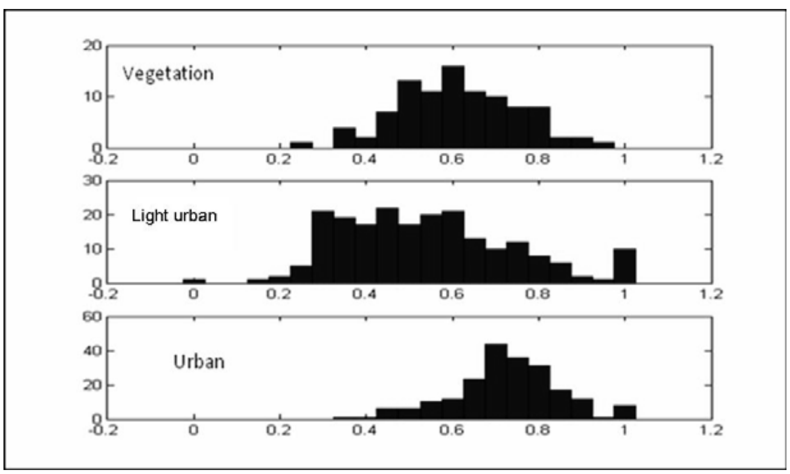

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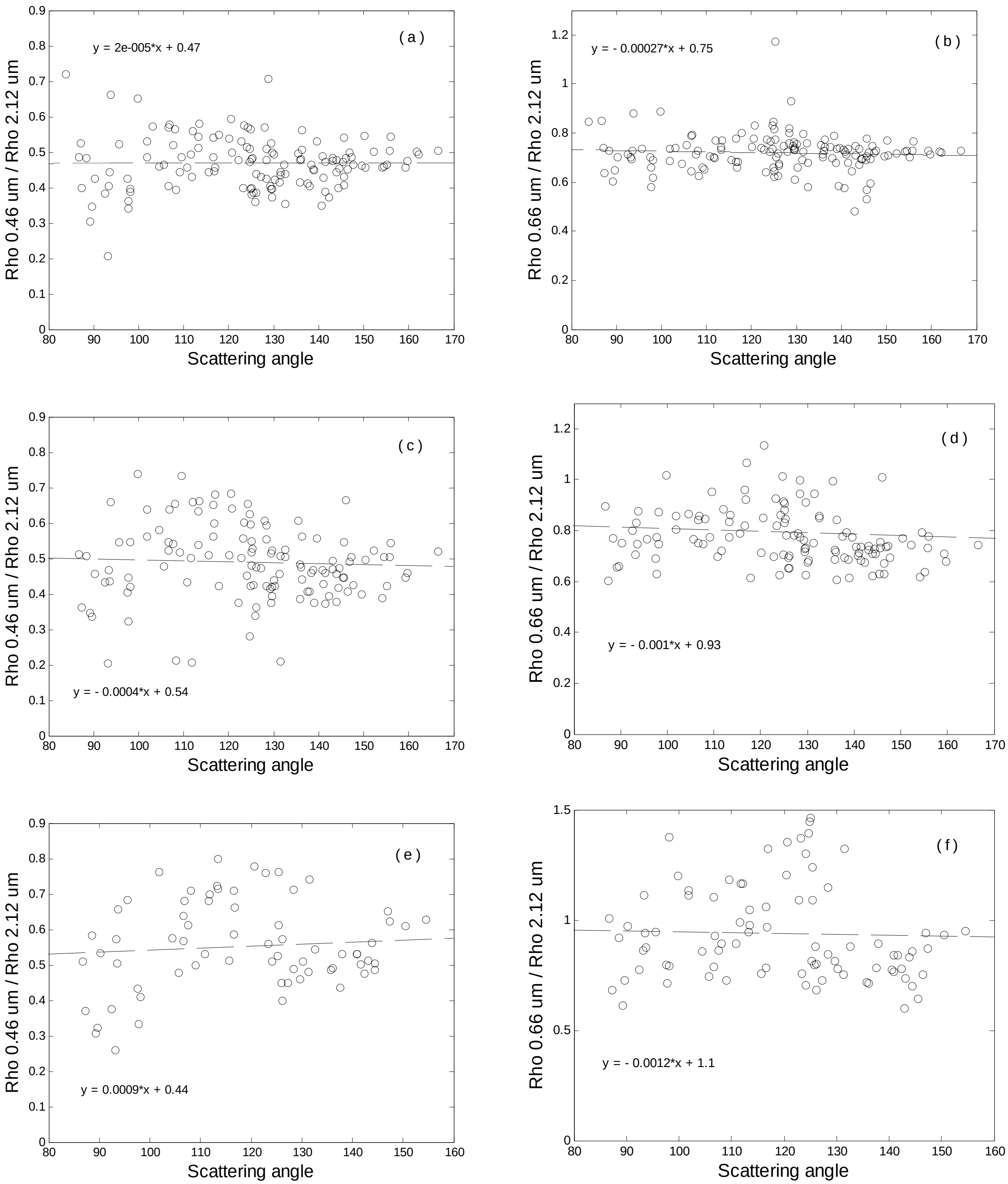

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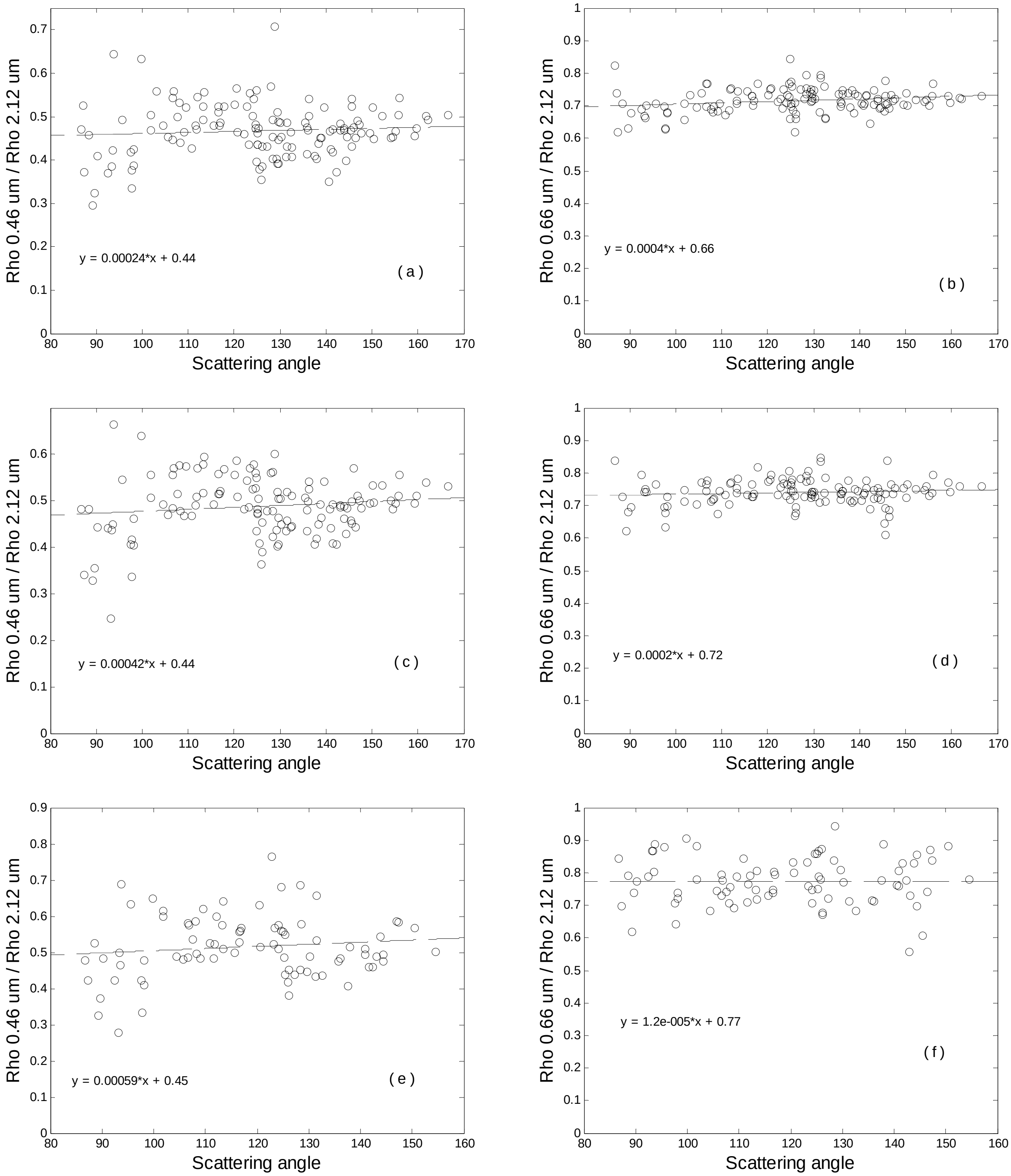

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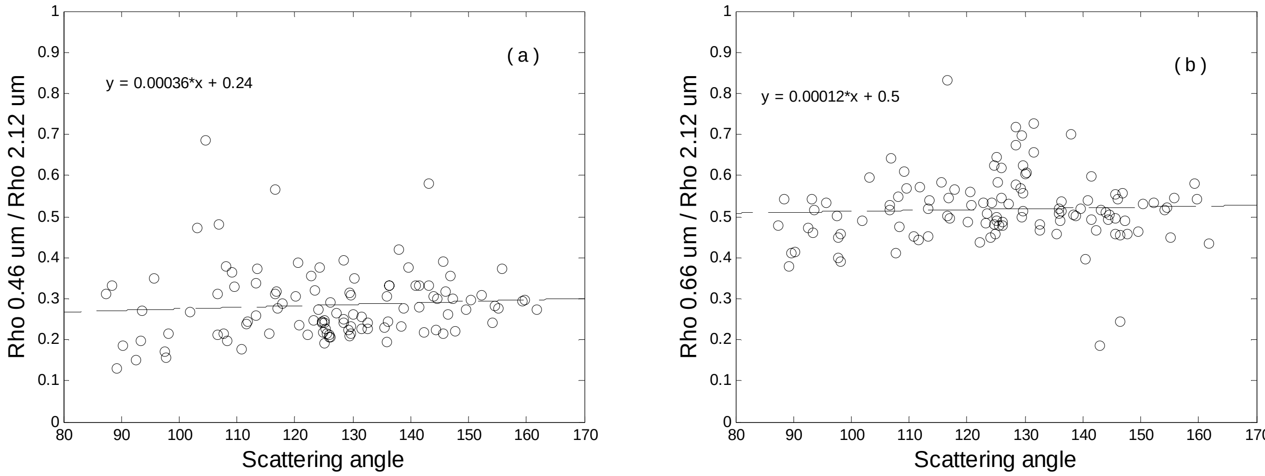

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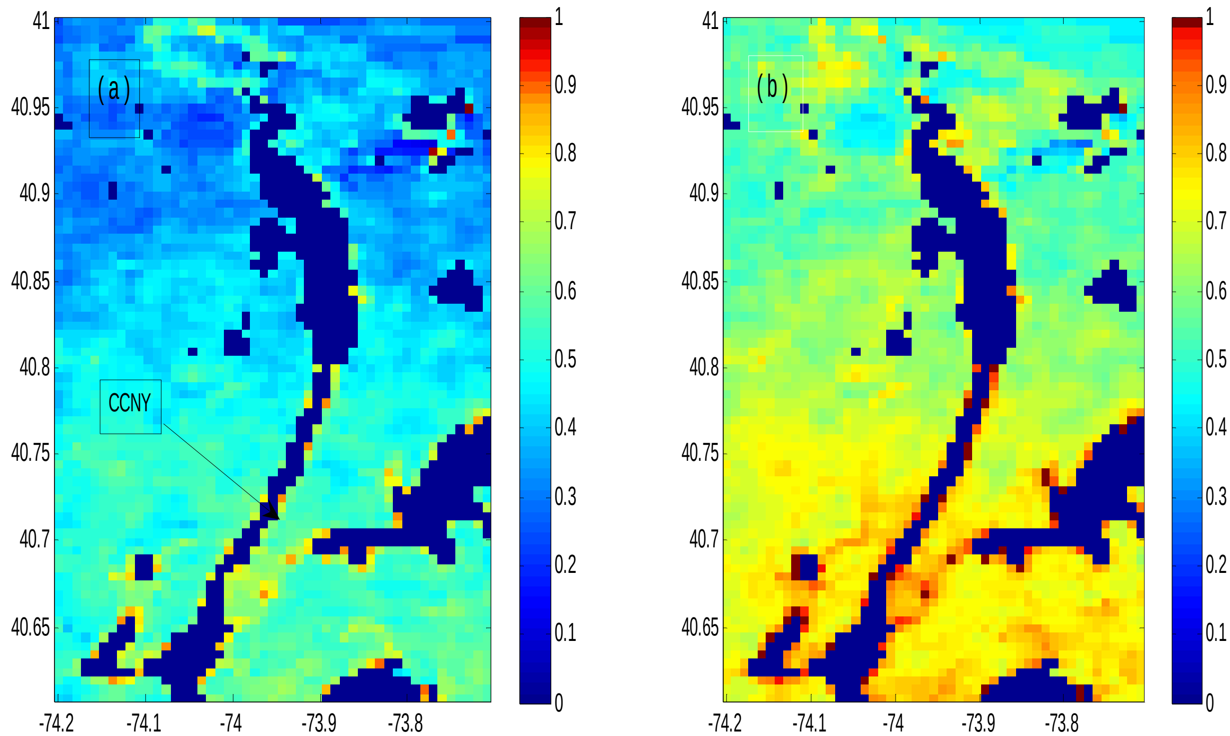

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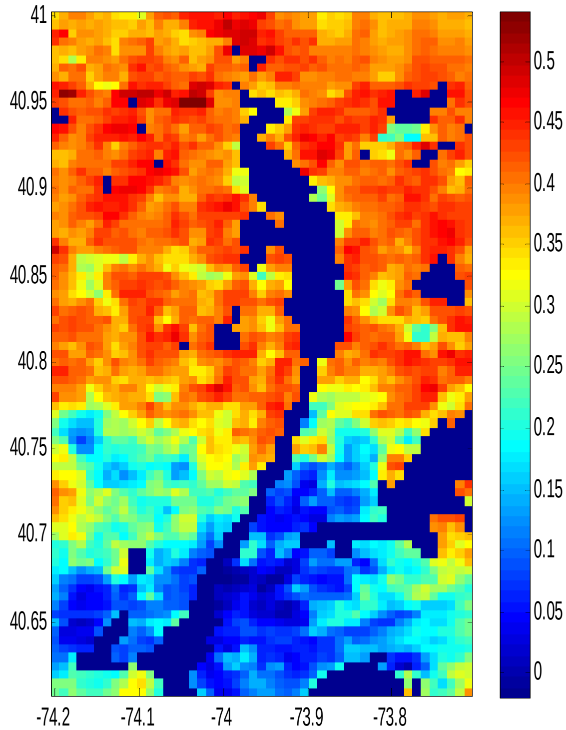

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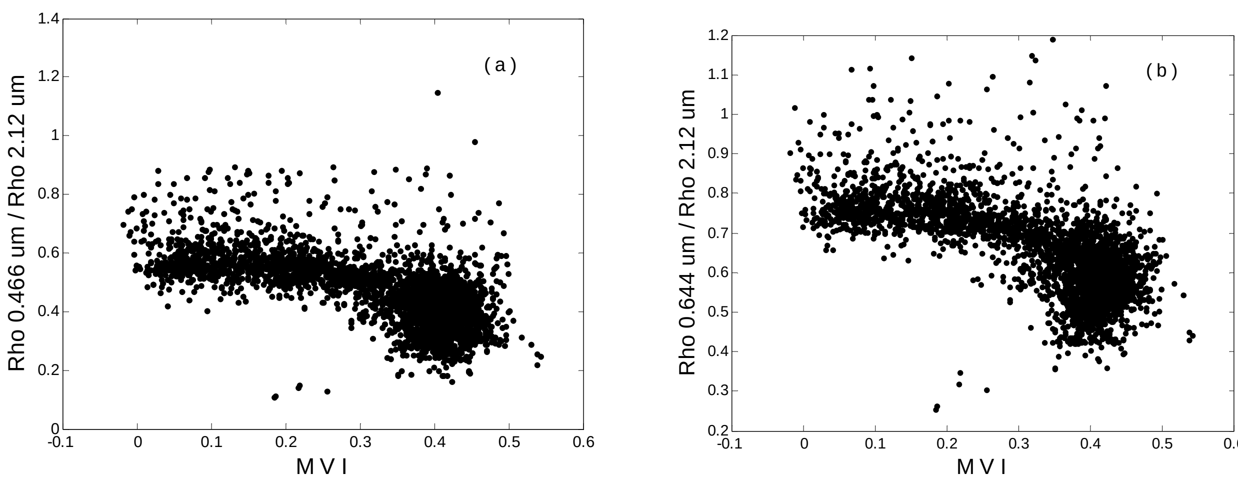

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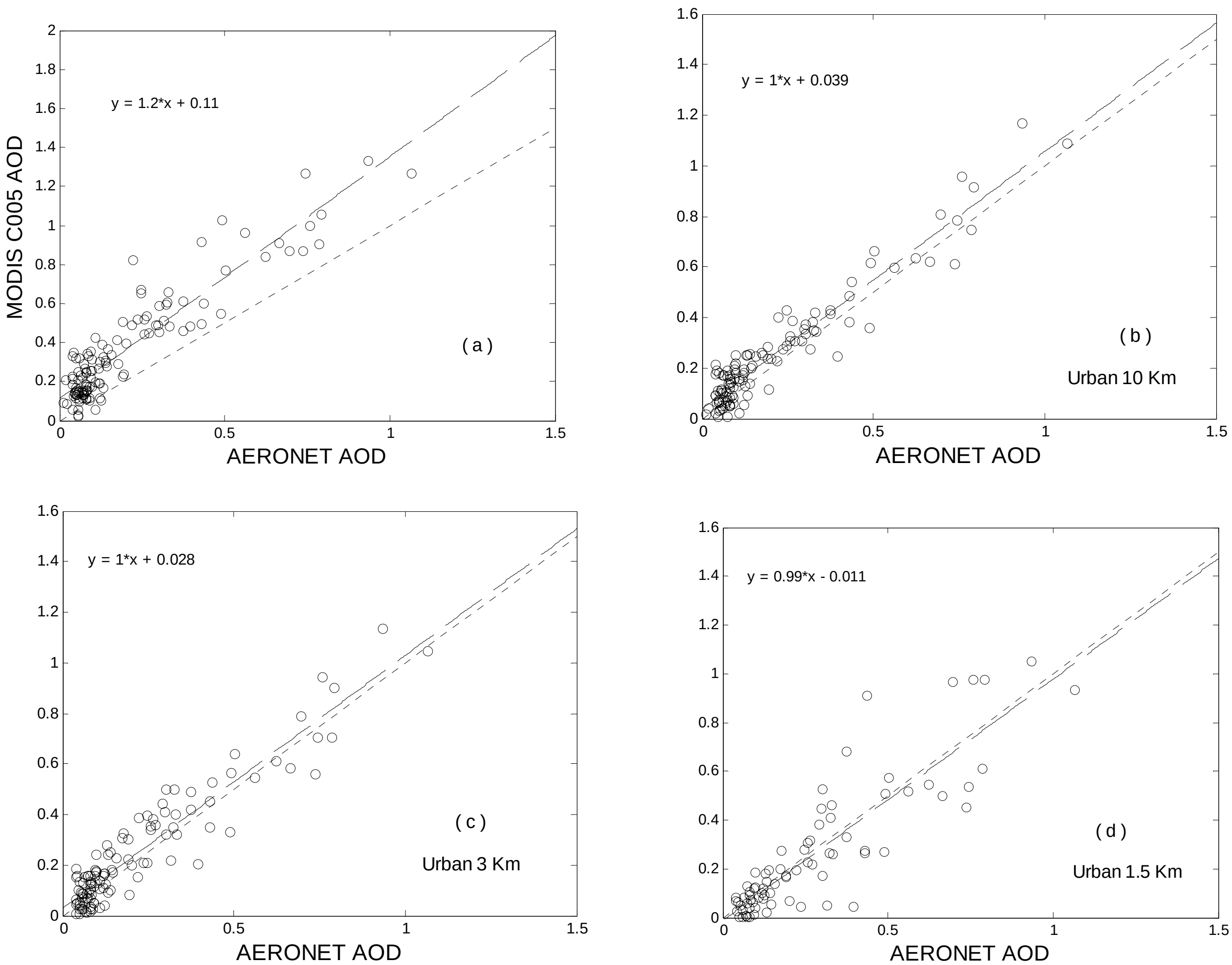

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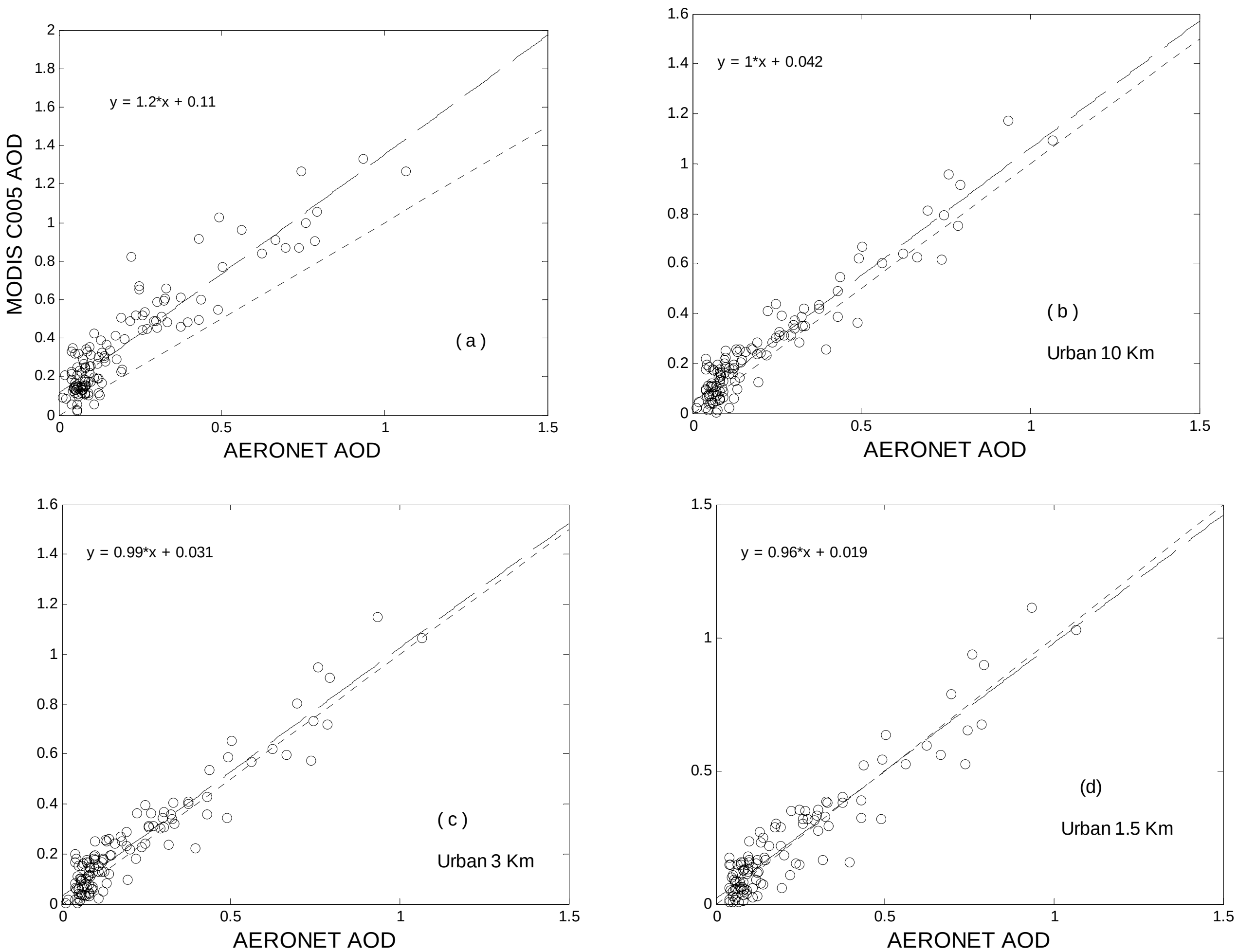

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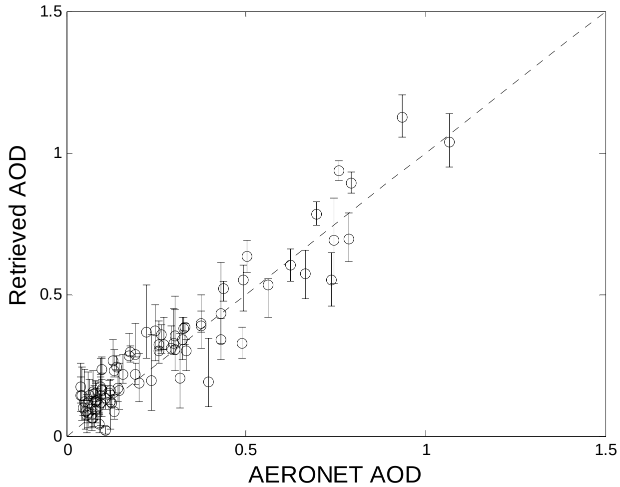

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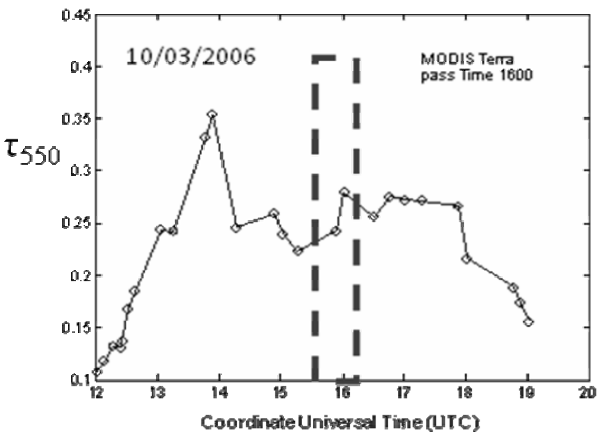

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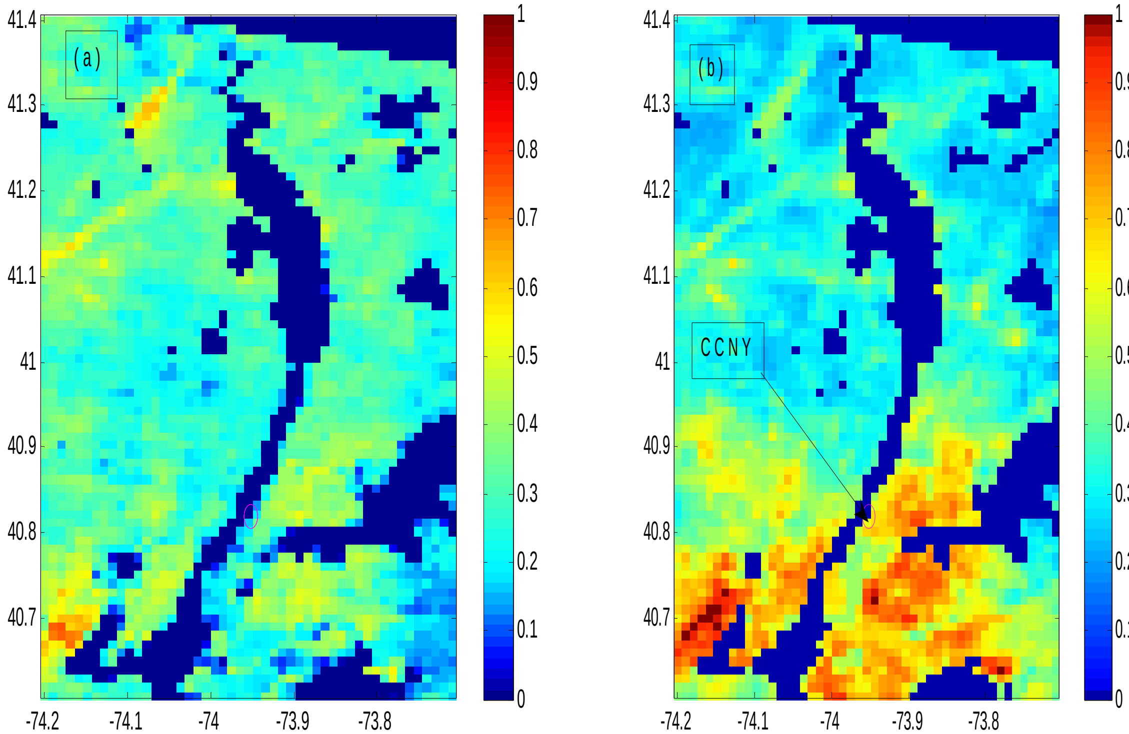

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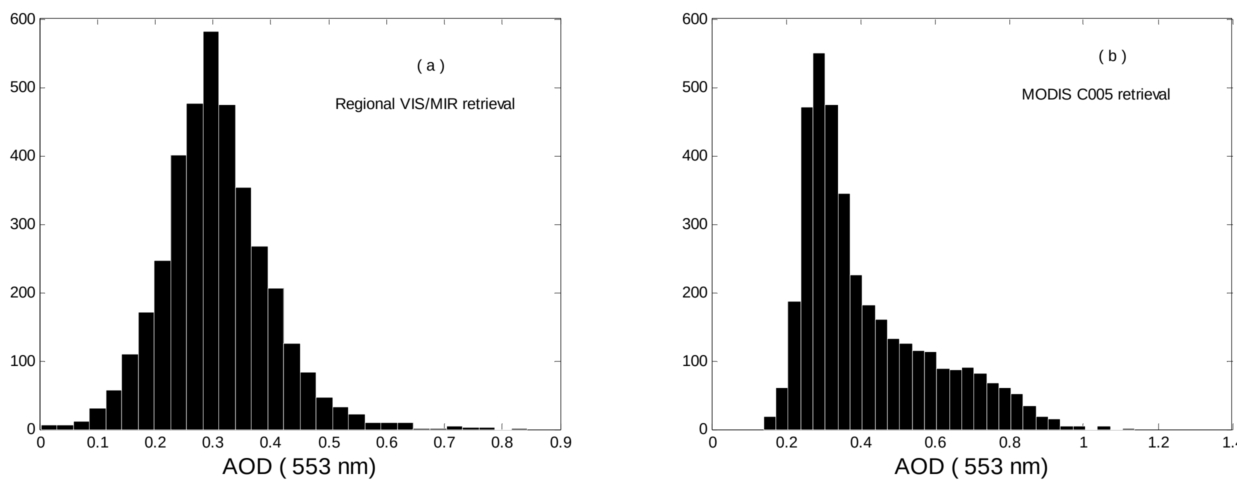

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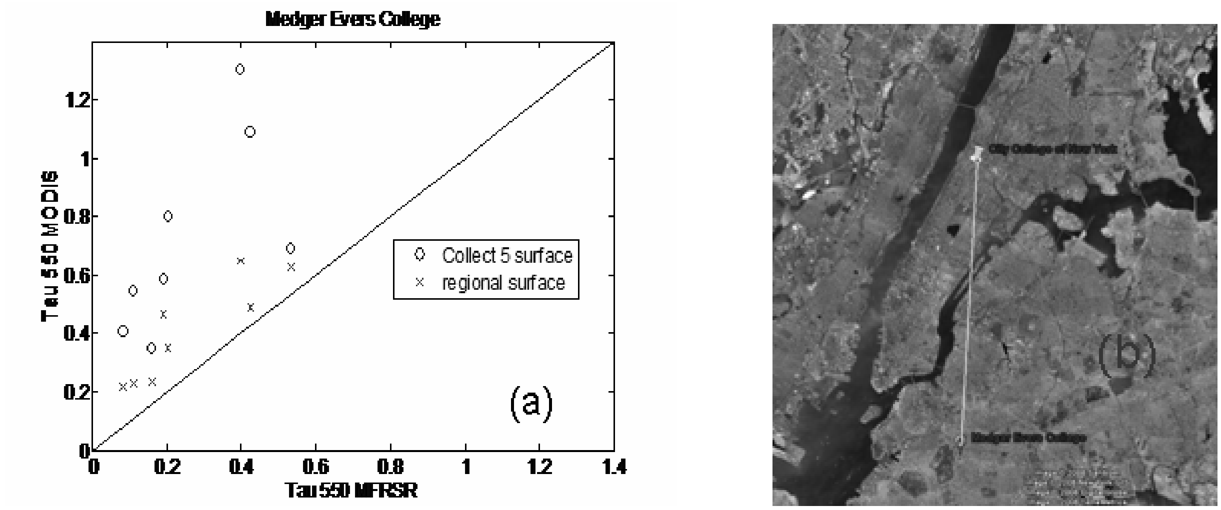

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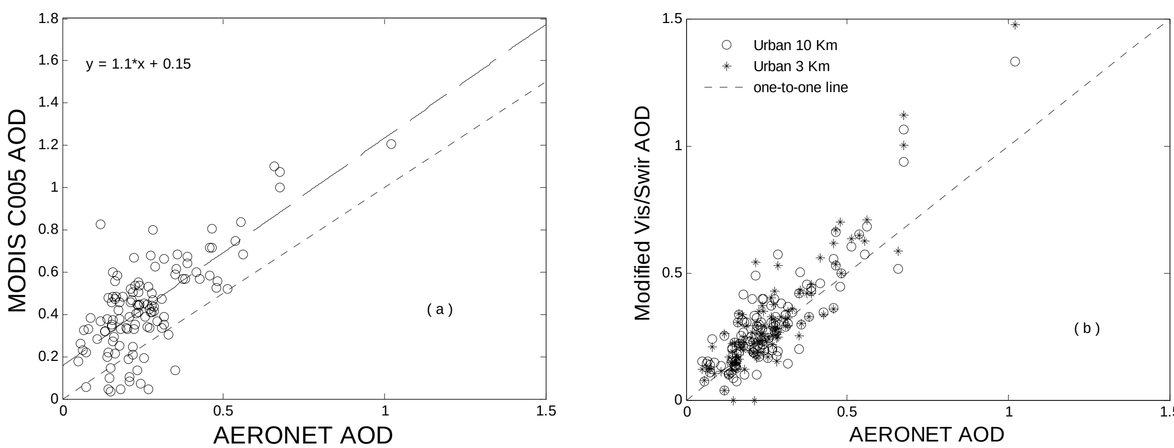

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	No Mask				Mask			
	460/2120 nm		660/2120 nm		460/2120 nm		660/2120 nm	
	Mean	std	Mean	std	mean	std	mean	std
10x10	0.4683	0.0746	0.7256	0.0565	0.4671	0.0619	0.7155	0.0378
3x3	0.4863	0.1052	0.7741	0.1075	0.4882	0.0636	0.7402	0.0404
1.5x1.5	0.5564	0.2153	0.9326	0.2761	0.5153	0.0858	0.7734	0.0729