Improvement of optical depth relations to PM2.5 concentrations using lidar derived PBL Heights

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ABSTRACT

To provide reasonable forcasts of near surface PM2.5 levels, it necessary that satellite measurments provide a reasonable estimator of PM2.5 which can be coupled to a transport model Unfortunately this requires that the aerosol be homogeneously mixed and that the extent of the PBL be sufficiently accurate. For example, the IDEA product (Infusing satellite Data into Environmental Applications) used by the EPA relies on a static relationship connecting PM2.5 to MODIS aerosol optical depth (AOD) which relies on a static model of the PBL aerosol height. In this paper, we show that the PBL height is far from static and by taking the variable PBL into account, a better prediction of PM2.5 from the MODIS (AOD) measurements is obtained. In addition, seasonal variations in the microphysical properties are also demonstrated and accounting for the additional variability further improves the PM25/AOD slope predictor.

1. INTRODUCTION

NOAA has been directed by congressional mandate to implement an operational air quality forecast system which will provide 24-48hr forcasts of ozone and fine particulate matter (PM2.5) to benefit public health. In order to perform this obligation, NOAA and EPA formed a partnership to transfer scientific advances in air quality monitoring and forecasting into the National Center for Environmental Prediction (NCEP) . In support of this effort, the IDEA[1] (Infusing satellite Data into Environmental Applications) product was developed through a Joint collaboration from NASA, EPA and NOAA which couples a satellite estimate of AOD[2] using the MODIS sensor into a NOAA lagrangian transport model. The Air-Quality forcast is then assessed through the use of the EPA PM2.5 surface monitoring network.

It is clear that the minimum requirements needed so that the IDEA product provides a useful estimate of PM2.5 are as follows:

1. The MODIS satellite should produce an accurate measure of the AOD. In general MODIS performs the best retrieval in dark vegative regions which may not be available in urban environments.
2. The vertical profile of the aerosol should be well mixed without any aloft layers
3. The scene where comparisons are made should be spatially and temporally stable.

4. The PBL height and the aerosol model used in converting AOD to surface PM2.5 should be representative of the actual state of the atmosphere.

It is the purpose of the paper to examine and decouple the different mechanisms that might account for the significant errors observed between the PM2.5 and the IDEA prediction and show the importance of providing an accurate estimate of the PBL height

2. ASSESSMENT OF MODIS AOD FOR NYC

Since urban areas are particularly relevant due to the health hazards involved in excessivce PM2.5, it is particularly important to be able to examine the accuracy of the IDEA product for these scenes. The most obvious problem observed when examining the time series data such as the example in Figure 1 is that the MODIS AOD estimate of PM2.5 very often overestimates the PM2.5 values.

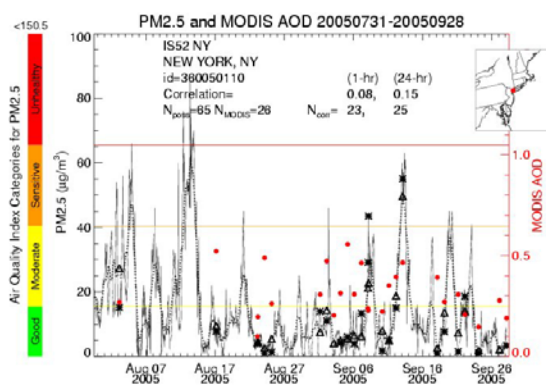

Fig. 1 IDEA matchup between measured PM2.5 and the MODIS estimator based on a static aerosol PBL model.

To begin, it is important to assess the accuracacy of the MODIS AOD product over the urban NYC area. In particular, urban areas provide a particular challenge for

MODIS since the ground albedo is more complex than for dark surfaces such as vegetation. Therefore, it is useful to understand how MODIS AOT is obtained operationally.

In essence, the algorithm assumes that there are processes (true for vegetation) which correlate the ground albedos between the VIS 470nm, 660nm channels to the 2160nm channel. Using correlations based on a-priori estimates of land cover type, the 0.47 and 0.66 μm ground reflectances can be estimated thereby allowing an improved estimate of atmospheric reflectance[4]. Based on these principles, the basic approach for an operational and unsupervised aerosol remote sensing algorithm for the MODIS sensor is :

1. Determination of the presence of the dark pixels in the blue (0.47 μm) and red (0.66 μm) channels using their remotely sensed reflectance in the mid- IR channels (2.1 μm).
2. Estimation of the surface reflectance of the dark pixels in the red and blue channels using the measurements in the mid-IR and information on surface type when possible.
3. Determination of the aerosol type using information on the global aerosol distribution and the ratio between the aerosol path radiance in the red and blue channels.
4. Inversion of the measured radiance at TOA into the aerosol optical thickness, volume (or mass) concentration and spectral radiative forcing using radiative transfer look-up tables.

Therfore, if the correlation coefficients are incorrect, the VIS channel ground albedos will be incorrecxt and significant errors will result in the AOD estimate. To explore this issue, we applied the path radianxce method [5]to decouple the aerosol and land features in a high spatial resolution satellite image of NYC using the Hyperion sensor.

We see that in urban scenes, these coefficients are too low as seen in figure 2. While the vegetatation (park) is seen to follow the MODIS correlation presecription, the MODIS correlation values is underestimated for both light urban and heavy urban scenes. It is clear that this error will lead to a MODIS underestimate of the optical depth. This is indeed the case when simultaneous MODIS and an Aeroent Sunphotometer AOD are compared. To insure sufficient homogeneity, a strict matchup procedure was utilized. In particular,

- CIMEL Optical Depth taken between NYC and Brookhaven (5 hour mean to agree within 10%)
- MODIS 10km products. 3 x 3 cells to have std < 20% mean

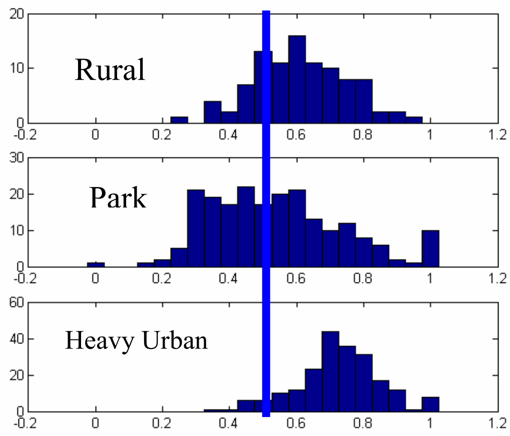

Figure 2. VIS-MIR Ground correlations statistics as compared to MODIS reference

As a test of the matchup procdure (for the sunphotometer), the AOD's at two different sites (~80km apart) are compared in figure 3.

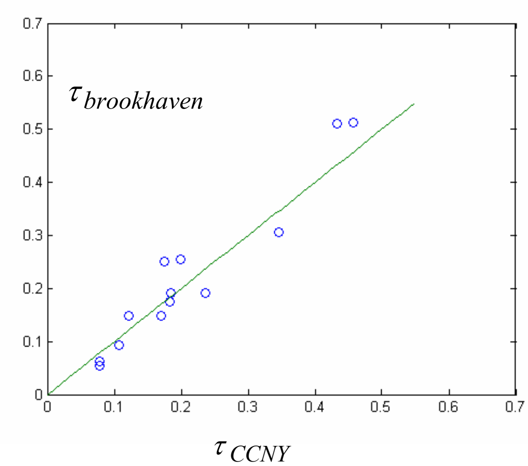

Figure 3. Spatial correlation of temporally stable CCNY Aeroent data sets.

The matchups are presented in Figure 4 above. The results are presented for two different choices of the MODIS pixel in the intercomparison. In the first scenario given by the red pixels, we choose the 3x3 box to be centered at the nearest pixel to the sunphotometer (i.e. Manhattan) and observe how MODIS greatly overestimates AOD relative to the sunphotometer. The dashed line is used as reference to show the magnitude of correction due to the underestimate of the ground albedo for urban pixels (taken as 20%). In this case, the actual viewing geometry was not taken into account (so the correction is uniform).

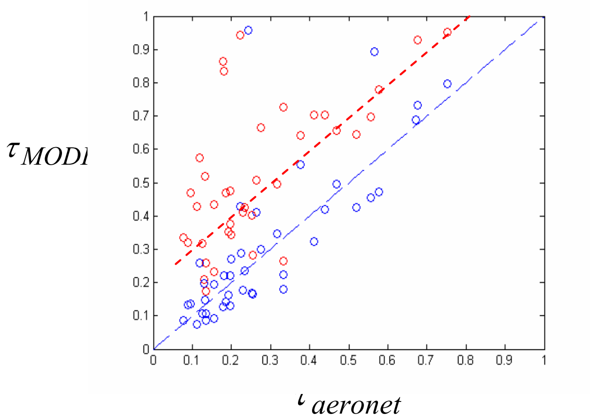

Figure 4. MODIS-Aeroent AOD comparison matchup.

In the second scenario, the 3 x 3 MODIS box is chosen to be centered around the AOD minimum over a 40km x 40km search space. Such minima were easy to find and were always located north of the City about 15-20km in a very vegetated area. It is clear that the MODIS results taken at an AOD minimum results in a very good correlation. This is clearly due to the fact that AOD minimum is almost always associated with the darkest ground signature which provides the purest atmospheric signal. In addition, the fact that the correlations are good and the bias removed even though the geographic matchup was not exact validates our procedure for maintaining homogeneity. From this result, we see that in order to perform a correct assessment of the IDEA product, it is necessary to choose the MODIS pixels which result in the lowest AOD to ensure that the surface is as dark as possible resulting in the most accurate value.

3. PM2.5 VS AEROENT OPTICAL DEPTH SLOPE .

To begin, we explore the linear relationship between the PM2.5 and Aeroent CIMEL (Sky Radiometer) AOD with the particular purpose of testing the static IDEA relationship which assumes $60\mu g/m^3 \sim 1.0\ AOD$. In order to carry out the comparison, it is necessary to exclude cases where smoke or aerosol high altitude plumes occur. To ensure this, we have filtered all cases with the 1064nm channel of the lidar which is particularly sensitive to high altitude plumes. In Figure 5a, we plot the intercomparoson between PM2.5 obtained from the EPA site used in the particular IDEA product versus the Aeronet AOD for June 2005. To

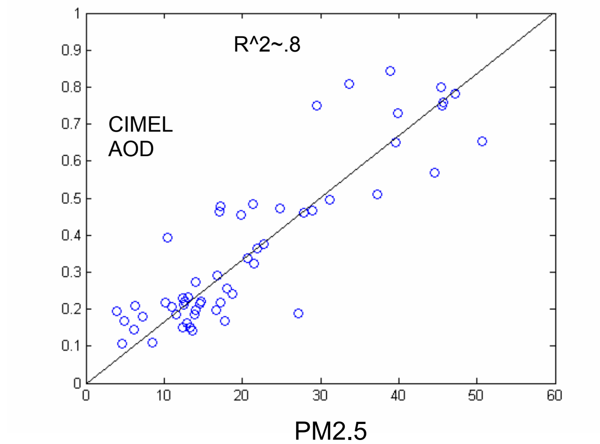

Fig 5a. Intercomparison PM2.5 vs aeroent (June 2005)

optimize the matchups, they are performed as hourly averages and care is made to ensure that the mean PM2.5 value obtained from all sites in the area vary by no more than 25%. In particular, we note that an excellent linear relationship results and that the static IDEA slope is quite accurate. However, the situation is quite different in the humid as the humidity increases such as August as seen in figure 5b

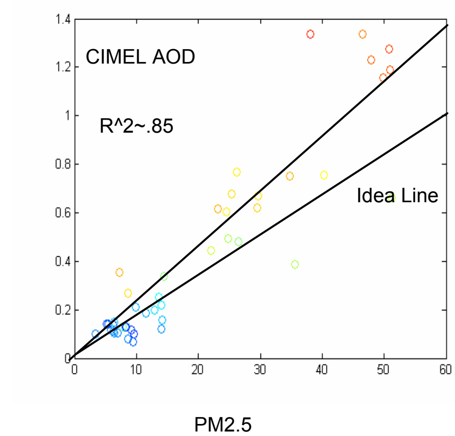

Fig 5b. Intercomparison of PM2.5 vs aeroent (August 2005)

This result is not surprising since the combination of temperature and humidity results in an extended PBLas seen in ref 7. In figure 5c, we present November results which shows a decrease in the slope line. As we see in the next section, the PBL variations will only partially improve the AOD PM2.5 slope

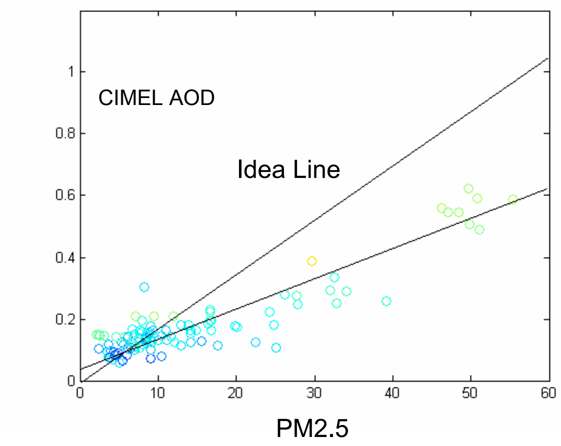

Fig 5c. Intercomparison (Sept. 2005)

4. REGRESSION SLOPE COMPARED TO PBL STATISTICS OBTAINED FROM LIDAR .

Performing these calculations over the course of the annual cycle, we see very significant changes occur in the montly regression slopes in Figure 6a which will adversely affect the final PM2.5 estimate. We see very clearly that the minimum slope appears in the summer and is consistent with the maximum PBL height since the larger the PBL height for the same AOD, the smnaller the PM25 concentration would be.

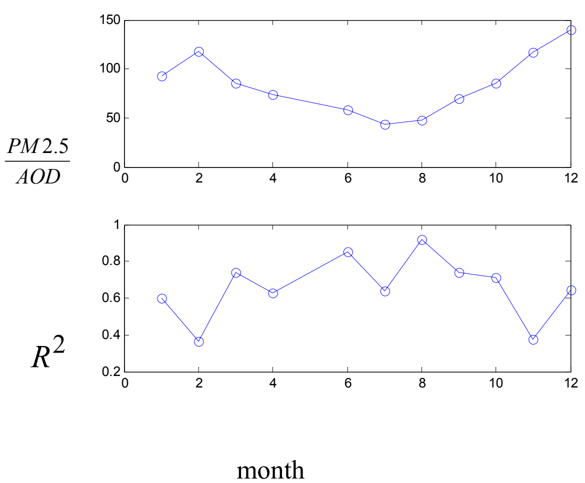

Fig 6 a) Monthly PBL/AOD dlope variation b) regression linear quality factor

To test this hypothesis, we plot in figure 7, the IDEA slope corrected for the PBL height variation. (i.e. $60*(2km/PBL)$) where the 2km value was chosen as a reasonable estimate of the urban PBL height.

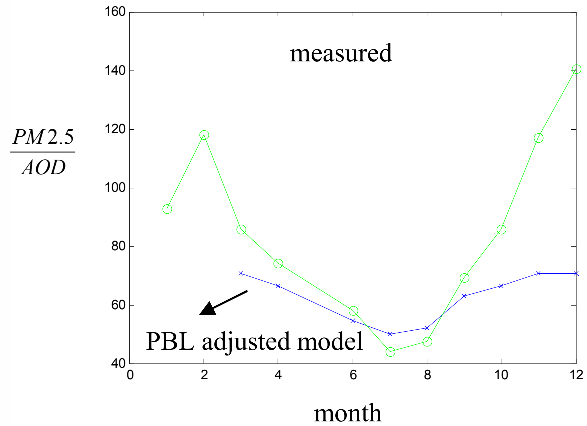

Fig. 7 Comparison of measured slope to IDEA model with PBL height correction.

5. CONNECTING AEROSOL MICROPHYSICS TRENDS TO THE PBL/AOD SLOPE TREND .

To see if the variability in the slope line can be attributed to the variability of the microphysical properties, we use the Aeroent PSD results to generate both PM2.5 and optical extinction as

$$\langle PM2.5\rangle \propto \int_{r_{\min}}^{r_0=1.25} \left[\frac{dV}{d\log(r)}\right] d(\log(r)) \qquad (1a)$$

$$\tau(\lambda) \approx \alpha L_{PBL} = \int_{r_{\min}}^{r_{\max}} \left(\frac{3}{4r}\right) Q_e\left(q=\frac{2\pi r}{\lambda}, m_r(\lambda), m_i(\lambda)\right)\left[\frac{dV}{d\log(r)}\right] d(\log(r)) \qquad (1b)$$

In the last formula, the column AOD for a static PBL assumption provides an estimate of ther extinction coefficient. In figure 8, we examine the the PM2.5

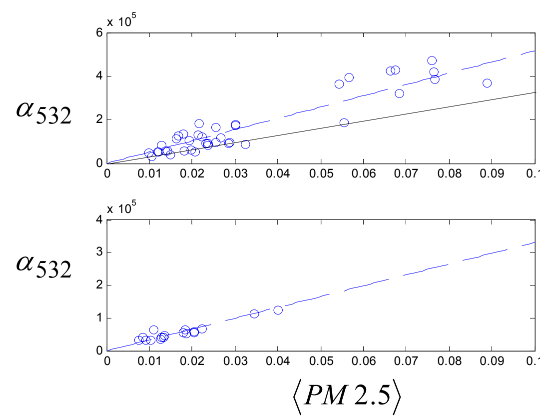

Fig. 8 Comparison of aeronet PSD derived slope over different months

AOD slope for differenty months. In particular, we note good linear behavior showing that monthly averages is suitable for our trend study. From the slopes, we see that in winter, the AOD/PM25 slope is much smaller than the summer value and may be attributed in the fundamental microphysical changes due to increased RH affecting the watrer solubale aerosols.

To see if this additional variability improves our slope predictor, we plot in figure 9, the slope variability from the aeroenet model variability as function of month scaled to the month of june since we are interested primarily in the trend. Note in particular, the increased slope in the summer months and the significant decrease in spring / autumn . This trend is in agreement with our measured trend.

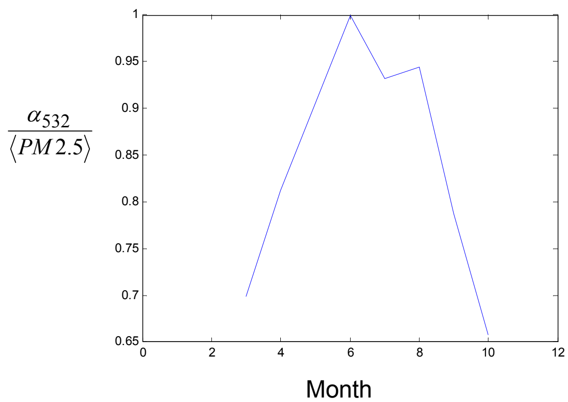

Fig. 9 Microphysical trend of slope line

In figure 10, we plot the effect of including both the PBL trend and microphysical trend. It is quite evident that by including both trends, we are better able to

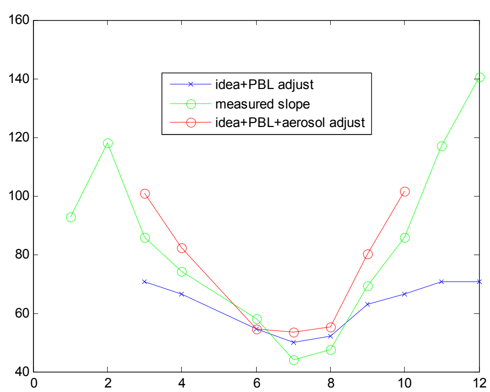

Fig. 10 Modifying slope predictor to include PBL as well as microphysical seasonal variability

explain the variability of the PM2.5/AOD slope line. It is crucial to observe that not including these seasonally based corrections will lead to a severe underestimate of PBL using AOD as indicator.

6. CONCLUSIONS

We have examined the possibility of achieving a workable relationship between PM2.5 and MODIS. Under the restrictions of sufficient homogeneity, it is shown that a reasonable estimate of PM2.5 can be achieved if the following procedures are implemented.

1. The MODIS AOD product must show sufficient homogeneity and must be evaluated in a non-urban arera.
2. A static relationship between AOD and PM2.5 must be corrected for the PBL seasonal variability
3. An additional variability in the microphysical properties of the aerosol model was detected and when added to the PBL variability, was able to better match the variability in the AOD / PM2.5 slope.

ACKNOWLEDGEMENTS

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