# High spatial resolution aerosol retrievals used for daily particulate matter monitoring over Po valley, northern Italy

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Dear Referee,
please find here below our replies (indented), and the improvements introduced in the paper, addressing all of the comments received. As requested by the referee, major revision has been updated in the manuscript.

Best regards,
The authors

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**Anonymous Referee #2**

*The approach, however, has a few holes.*
*First, the approach doesn't show how does Eq. (1) lead to the normalization of AOD by PBL height?*

> **REPLY**: How the Eq. (1) lead to the normalization of AOD by PBL height has been clearly presented in the revised manuscript, following the technique presented in literature by Tsai et al., 2011.
> The approach used has been addressed at point **1)** of "Major comments" section.

*Second, the approach does not take into account f(RH) effect when correlating ambient AOD with dried PM10 mass concentration.*

> **REPLY**: We agree that our analysis doesn't account for variations in f(RH) and acknowledge this in the revised manuscript. See point **2)** of "Major comments" section.

*Thirdly, these results lack the evaluation of uncertainties of estimated PM10 derived by AOD (MODIS vs. sun photometer).*

> **REPLY**: The goal of this manuscript is to study the PM10-AOD correlation and show that AOD normalized by PBL height is highly correlated with surface PM10 in the Po Valley. Our intention was not to estimate the PM10 mass concentration based on AOD.
> This has been more clearly stated in the revised manuscript. See point **4)** of "Major comments" section.

*Finally, the bin-averaged results would not represent daily variation.*

**<u>REPLY</u>**: We have acknowledged this in the revised manuscript. See point **6)** of “Major comments” section.

*In summary, the title of using monitoring is not accurate based upon the correlation resulted from MODIS. Evaluating AOD-PM10 relationship would be more appropriate than daily monitoring for the manuscript.*

**<u>REPLY</u>**: The **title** has been updated as:
“High spatial resolution aerosol retrievals used for seasonal monitoring of regional aerosol distributions over Po valley, northern Italy”
The title has been changed to better reflect the seasonal and regional results into the manuscript. Details are reported in the “Major comments”, in particular at point **3)**.

*In recent years, research on AOD-PM relationship has progressed significantly, including airborne and regional sunphotometer measurements. Spatial variability based upon satellite AOD products may be biased because of retrieval errors. As a result, the interpretation of correlation as function of distance is questionable.*

**<u>REPLY</u>**: The interpretation of correlation as a function of distance has been clarified in the revised manuscript. See point **4)** of “Major comments” section.

## Major comments

**--------------------------**

***1)*** *The interpretation of AOD normalized by boundary layer depth is not included. Eq. (1) only expressed the definition of AOD equal to integration of extinction with height. How does Eq. (1) lead to the normalization of AOD by boundary layer depth? Tsai et al. (2011) elaborated the derivation of haze layer height as constrained by AOD in the atmospheric column that normalizing AOD by haze layer height is equal to the normalization of AOD by boundary layer depth if no aerosols aloft above boundary layer. What are the aerosol vertical distributions in different conditions (e.g., seasons) in Po Valley?*

**<u>REPLY</u>**: This section has been re-written in the revised manuscript. The relationship between AOD and boundary layer extinction through the introduction of the mixing layer height as a normalizing factor has been introduced. New references have been added and the method of normalization following Tsai et al., 2011 has been clearly presented, including adding a schematic and more extensive discussion. Moreover, previous research has been cited to present different studies published on the comparison of simulated and measured mixing height. A discussion of the aerosol vertical distributions in different conditions in Po Valley could be included by conducting an analysis of the seasonal variation of CALIPSO extinction profiles but we feel that this is beyond the scope of this manuscript.

<u>Therefore part of the **Section 2.4** in the manuscript has been re-written as below</u>:

**“**$PM_{10}$ and AOD represent two different measurements of the atmospheric loading of aerosols. The $PM_{10}$ is the dry mass, measured at ground level, at a specific geographic location. On the other hand, the satellite AOD represents total column aerosol loading averaged over a specific spatial area and it depends on the environmental conditions. As suggested by the literature, the PM - AOD correlation may be improved by considering meteorological information such as the role of the relative humidity (RH), or vertical distribution of aerosols (Gupta et al., 2006, Wang and Martin, 2007, Tsai et al., 2011). In this work, variations in the vertical distribution of aerosols are considered by introducing information on the Planetary Boundary Layer (PBL) depth. The use of PBL depth as parameter to improve the correlation between surface PM and AOD measurements has utilized measurements (Boyouk et al., 2010, Barnaba et al., 2010, Tsai et al., 2011, Chu et al., 2013) and model simulations (Gupta and Christopher, 2009, Emili et al.,

2010). Recently, Chu et al., 2015, have published a new result for mapping vertical and horizontal distribution of aerosols over Baltimore - Washington Corridor.
As mentioned previously, the Aerosol Optical Depth is an integration of the aerosol extinction, from the surface to the top of the atmosphere:

$$AOD = \int_{0}^{TOA} \sigma_{0.55\mu m}^{ext}(z)\,dz \qquad (1)$$

In Tsai et al., 2011, two types of aerosol vertical distributions are considered. The first assumes that the aerosols are well-mixed and confined in the PBL; the second one is characterized by two layers of aerosols, the first layer where the aerosols are well-mixed and a second layer with an exponential decay of aerosol extinction coefficient with height above the top of the first layer. The first type of vertical distribution is assumed in the current study. Mathematically this can be expressed as follows:

$$AOD^{*} = \sigma_{0.55\mu m}^{ZPBL} ZPBL \qquad (2)$$

which is schematically represented in Fig. ??. Under the hypothesis that most of the aerosols are confined and mixed homogeneously within the planetary boundary layer, the values of AOD normalized by PBL depth may be regarded as mean PBL extinction in $km^{-1}$ ($\sigma_{0.55\mu m}^{ZPBL}$). It may be more representative of the surface $PM_{10}$ concentration since variations in the depth of the PBL are accounted for. The normalization was applied both for MYD04 and MAIAC AOD retrievals.

The seasonal trend of PBL heights over Po Valley shows low values during the winter and high values during the summer (Fig. 5). This seasonality is reflected in the AOD monthly mean values normalized by PBL depth and results in higher values in the winter and fall period (Fig. 7, panel (c)). The normalized MYD04 and MAIAC mean AOD values follow the PM trend throughout the whole year and shows the strong seasonal correlation between PM and PBL depths within the Po valley.

To verify the GDAS PBL depth estimates we compare them to PBL depths obtained from CALIPSO measurements (Winker et al., 2003, Winker et al., 2009). The CALIPSO PBL depths are derived using a Haar wavelet analysis to detect boundaries in scattering ratio (i.e. a normalized backscatter) in Lidar observations that include the atmospheric boundary layer. The CALIPSO PBL heights are taken as altitude where the maximum amplitude average wavelet occurs computed over a range of Haar filter widths ranging from 0.9 to 1.65 km (Kuehn, R.E., 2013, personal communication). Figure 5 shows the monthly mean of the 6 hourly gridded GDAS PBL depths (green), as well as the mean of the GDAS PBL interpolated to the CALIPSO track (blue), and the CALIPSO PBL depths (red) over the Po Valley. The blue trend and the red one follow almost the same seasonal trend. The CALIPSO sampled GDAS PBL heights are comparable to the seasonal trend of the gridded GDAS PBL heights over Po Valley, except in January, where the CALIPSO sampling introduces a high bias. Comparison between the coincident CALIPSO and GDAS PBL depths shows very similar seasonal trends but CALIPSO PBL depths are systematically higher than the GDAS analysis. The bias between the two trends could be due to the two approaches used to determine the PBL height, the first from a Lidar measurement, which is a really measure of the mixing layer depth, and the second from a model implementation."

The revised manuscript includes the following **figure** to illustrate the relationship between aerosol extinction and AOD for aerosols that are confined to a well mixed boundary layer:

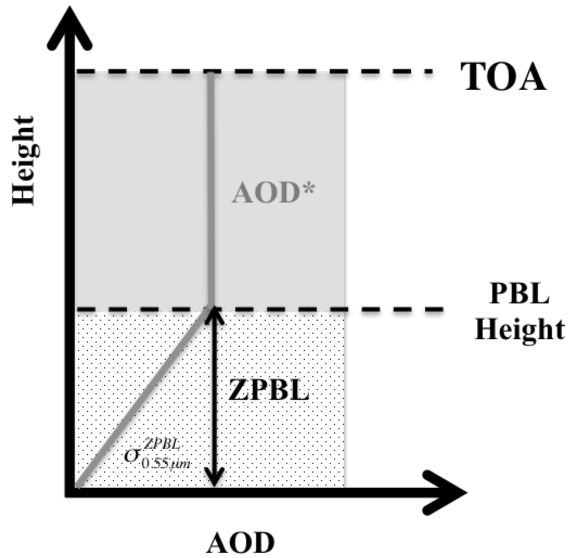


Figure ??. (The correct number of the figure will be define when it introduce in the manuscript) Schematic aerosol vertical profile where the aerosols are considered well-mixed and confined in the PBL height.

<u>In the manuscript, the following **references** have been added:</u>

Wang, J., & Martin, S. T. (2007). Satellite characterization of urban aerosols: Importance of including hygroscopicity and mixing state in the retrieval algorithms. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *112*(D17).

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

Barnaba F., Putaud, J.P.,Gruening C., dell'Acqua A., Dos Santos S., 2010. Annual cycle in collocated in situ, total-column, and height-resolved aerosol observations in the Po Valley (Italy): implications for ground-level particulate matter mass concentration estimation from remote sensing, J. Geophys. Res., 115, D19209, doi:10.1029/2009JD013002.

Boyouk, N., J. F. Léon, H. Delbarre, T. Podvin, and C. Deroo, 2010. Impact of themixing boundary layer on the relationship between PM2.5 and aerosol optical thickness, Atmos. Environ., 44, 271-277.

Emili, E., Popp, C., Petitta, M., Riffler, M., Wunderle, S., & Zebisch, M. (2010). PM 10 remote sensing from geostationary SEVIRI and polar-orbiting MODIS sensors over the complex terrain of the European Alpine region. *Remote sensing of environment*, *114*(11), 2485-2499.

Chu, D. A., Tsai, T. C., Chen, J. P., Chang, S. C., Jeng, Y. J., Chiang, W. L., & Lin, N. H. (2013). Interpreting aerosol lidar profiles to better estimate surface PM 2.5 for columnar AOD measurements. *Atmospheric Environment*, *79*, 172-187.

Chu, D. A., Ferrare, R., Szykman, J., Lewis, J., Scarino, A., Hains, J., Burton, S., Chen, G., Tsai, T., Hostetler, C., Hair, J., Holben, B., Crawford, J., (2015). Regional characteristics of the relationship between columnar AOD and surface PM 2.5: Application of lidar aerosol extinction profiles over Baltimore–Washington Corridor during DISCOVER-AQ. *Atmospheric Environment*, *101*, 338-349.

***2)*** *The authors didn't address the role f(RH) in the analysis. AOD is ambient measurements while PM10 mass concentration data are dehumidified, which is important.*

**REPLY**: The revised manuscript includes an acknowledgement of the role of the relative humidity on AOD retrievals. A discussion of the effect of the relative humidity in the PM-AOD correlation has been included in Section 3.2 of the revised manuscript (see reply to comment 4) of this document – "Minor comments"). It is intention of the authors to investigate the role of the relative humidity on the PM-AOD relationship in an upcoming manuscript, where the main focus will to improve the PM-AOD correlation (see also reply to comment 4) of this document – "Major comments").

***3)*** *Multiple data sets of 2012 were used in the analysis. However, it cannot stop me thinking about associated seasonal characteristics. Mostly importantly the Po valley would reveal unique seasonal characteristics compared to other regions.*

**REPLY**: In the second part of the Section 3.2 of the revised manuscript we now include an analysis considering the entire 126 available ground-based available sites in the Po Valley divided into subsets. The subsets have been chosen by following the administration divisions (Italian region) mentioned in the Section 2.1. The analysis has been conduct following a seasonality approach. The entire year of data has been divided into four seasons, Winter (JFD), Spring (MAM), Summer (JJA) and Fall (SON), for each region of the Po Valley domain and compared together. The results have been reported using the standard deviation analysis on a bar plot graph.

Therefore part of the **Section 3.2** in the manuscript has been re-written as below:
"[…]. In addition, we divided the entire 126 ground-based available sites over the Po Valley into four subsets, following the criteria of the administration divisions (Italian region) mentioned in the Section 2.1. For this study, the subset of MYD04 and MAIAC data for days when both products are available for a given ground-based site was considered. Since MAIAC retrieval provides more data, the limiting factor is the availability of MYD04 product. Again, a standard deviation approach was used and the results are reported as percentage standard deviations in Fig. 8 (1, 2 and 3). Although there are some variations among the four regions in topography and climate conditions (e.g. near the seacoast or the mountain chains or high level of urbanization or land use), and differences in the technique and instruments used to measure the daily particulate matter, the standard deviation analysis does not highlight significant variation in PM10 between the different districts. For winter and fall seasons the percentage standard deviation has the higher values. The higher percentage standard deviations occur in January and October/November months, where the number of satellite retrieval is less. This increase in percentage standard deviation is also evident for the satellite retrievals if the PBL depth normalization is considered."

and it has been introduced the following **figures**:

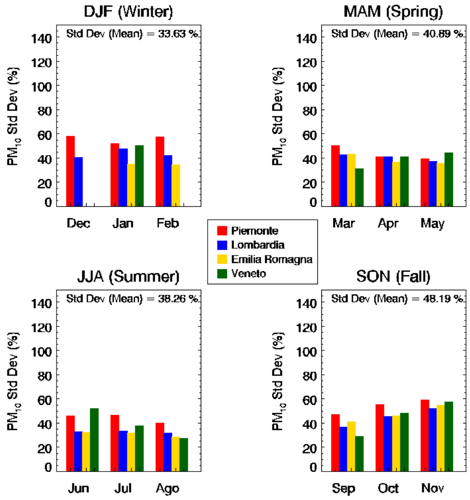


Figure 8 (1). $PM_{10}$ data analysis.

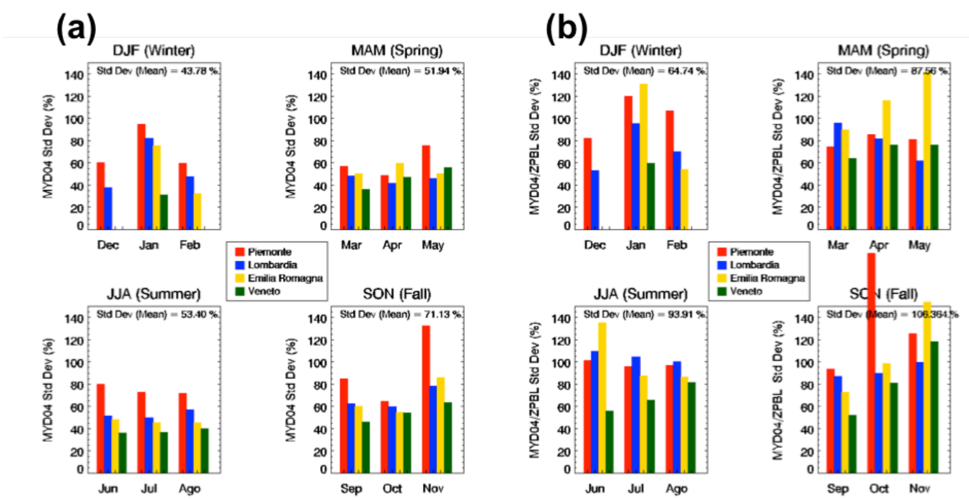


Figure 8 (2). MYD04 data analysis.

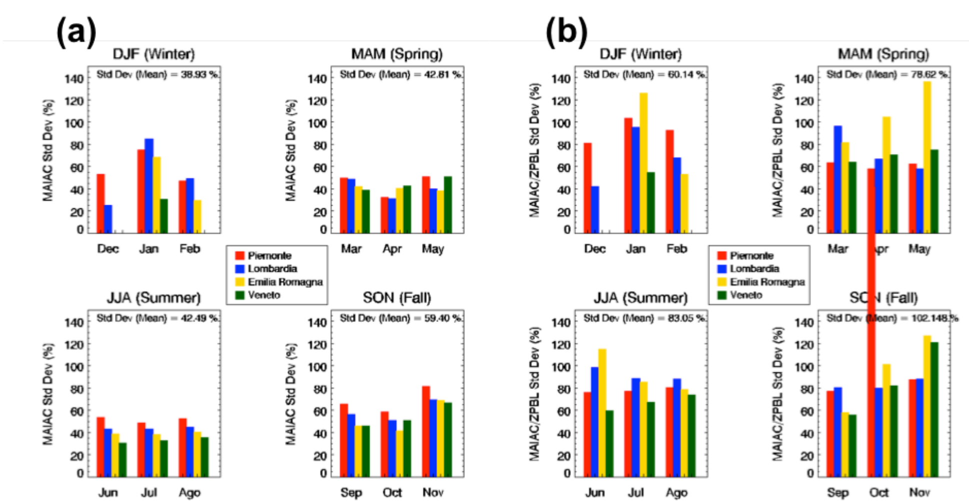


Figure 8 (3). MAIAC data analysis.

Figure 8. Seasonal Standard Deviation (SD) - in % - analysis using $PM_{10}$, MYD04 and MAIAC data. The total 126 ground-based stations was divided following the administration criteria, obtaining four regions: Piemonte, Lombardia, Emilia Romagna and Veneto. In the panels (b) of Figure 8 (2) - (3) the AOD data were considered normalized by the PBL depth.

***4)*** *Satellite AOD retrievals inherited uncertainties including instrument calibration, look- up table, and surface albedo estimation. Therefore, any results based upon satellite retrievals would be questionable. The argument of best results from distance ~12 km is doubtful. Spatial variability of AOD can be derived by sunphotometer network measurements (Chu et al., 2015). In other words, higher correlation will only be shown with smaller distance. The sunphotometer stations at Ispra, Modena, and Venice could at least verify the results obtained by MODIS.*

**REPLY**: The best results are obtained when the radius of coincidence is ~12km, which increases the number of retrievals averaged for each ground station and reduces the influence of random errors in the retrievals. As stated in the abstract of the manuscript, the main goal of the manuscript is to assess the use of a finer scale satellite AOD retrieval to see if they can better characterize the spatial-distribution of aerosols within urban areas. This point is important since if a small urban domain is considered, the MODIS standard aerosol product may not be appropriate for application due to the coarser resolution. It is intention of the authors to investigate the spatial variability within an intra-urban domain in future work, as pointed out in the conclusions of the updated manuscript. The Po Valley domain is characterized by more than one extremely polluted urban area. One of the most significant is the urban area of Milan. Due to high-pollution levels, the ARPA environmental agency has increased the number of ground-based PM stations in this area. A focused analysis of PM-AOD correlation within intra-urban domains could help to improve our understanding of fine-scale PM/AOD correlations. .
We are working on an oncoming manuscript where we focus on finer-scale analyses.

Therefore part of the **conclusions** in the manuscript has been re-written as below:
"[…]. The results reported in this work were obtained but considering just one factor that may affect the relationship between the ground-based and the satellite remote-sensing measurements.

In future studies, we will focus on three aspects to better improve the understanding of the correlation between satellite-retrieved AOD and surface $PM_{10}$. First, we will investigate the role of environmental conditions on the PM10 – AOD relationship the by dividing the Po Valley into different geographic areas. . Our goal will be to demonstrate the performance of MAIAC AOD over brighter urban areas and the benefit of its high spatial resolution over urban domains (Lyapustin et al., 2011b). Secondly, we will investigate the extent of spatial variability of AOD in relation to PM10 mass concentration (Chudnovsky et al., 2013b) by considering the intra-urban domain of Milan, the most polluted area in the middle of the Po Valley. As third focus, we will study how the relationship of AOD retrieved in ambient condition and dehumidified surface PM is affected by relative humidity (RH). We suspect that seasonal standard deviations in AOD are more larger compared to seasonal standard deviations in PM10 mass concentration due to sensitivity of urban aerosols to relative humidity. AOD increases in summer time due to particle growth under high humid conditions (Wang and Martin, 2007, Altaratz et al., 2013). Finally, as third focus, we will investigate the use of higher resolution PBL estimates obtained from regional NWP over Italy (Kukkonen et al., 2012, Baldauf et al., 2011, Barthlott et al., 2010) and explore the relationship for each administrative district over Po valley separately. The aim will be to investigate whether the use of finer PBL depth and satellite-retrieved AOD (MAIAC) helps to characterize the spatial variability of aerosol pollution within the Po Valley and study the impact of industrialized regions on PM vs. AOD relationships. […]. "

In the manuscript, the following **references** have been added:

Wang, J., & Martin, S. T. (2007). Satellite characterization of urban aerosols: Importance of including hygroscopicity and mixing state in the retrieval algorithms. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *112*(D17).

Altaratz, O., Bar-Or, R. Z., Wollner, U., & Koren, I. (2013). Relative humidity and its effect on aerosol optical depth in the vicinity of convective clouds. *Environmental Research Letters*, *8*(3), 034025.

***5)*** *The sole use of Aqua MODIS data in corresponding to daily mean PM10 could be biased. What is the reason excluding Terra MODIS in the analysis? Both MODIS standard and high-resolution (MAIAC) AOD are produced according to Terra and Aqua daily overpasses. The comparison of mean MODIS AOD (Terra and Aqua) with daytime mean sunphotometer AOD is more important to understand the potential uncertainties attributed to MODIS retrievals and subsequently introduced in the analysis of AOD- PM10 relationship.*

**REPLY**: MAIAC provides separate datasets from Terra and from Aqua. We agree with the referee, but at the period of our work we just had the data for Aqua since MAIAC was not publically available at the time of the research study. As future work, it is the intention of the authors to conduct a new and more complete analysis over the Po Valley using a new release of the MAIAC dataset where and issue with seasonality has been corrected. The seasonality issue has been found to be responsible for lower correlations with AERONET due to the introduction of a high bias during the late fall-winter.

We agree with the referee, the comparison of mean MODIS AOD (Terra and Aqua) with daytime mean sunphotometer AOD has not been fully explored in the manuscript. However, we consider it beyond the scope of this manuscript due to limited Aeronet data available during the period considered.

***6)*** *The authors used 10 bins of PM10 in the analysis of AOD-PM10 relationship. Although the correlations derived are very high, the results of bin averages would not represent daily variation of both AOD and PM10 since the bin averages are most likely involving both monthly and seasonal variations. What is the meaning of the relationship between bin-averaged PM10 and AOD? Is this approach suitable for daily monitoring as the authors tried to do?*

**REPLY**: the direct comparison between PM10 and AOD from MODIS AOD results in a large spread of PM10 and AOD values and poor correlations (not shown in the manuscript). For this reason, we decided to use the technique presented in Gupta et al., 2006 (explained in the manuscript. For this, see the Sec. 3.3). Using the regression relation, obtained from the relationship between bin-averaged PM10 and AOD, the surface PM10 mass concentration can be estimated from remotely sensed AOD and an estimate of the air quality index can be obtained. As suggested by Gupta et al., 2006, the main point of the analysis is to be able to infer the air quality category from satellite data. The analysis presented in this manuscript currently only demonstrates predictive skill at an annual time-scale. Therefore, this approach may not be suitable for daily monitoring. . As we specify in the conclusion paragraph, our future goal will be to have a retrieval suitable for a daily monitoring, but we realize that in this manuscript we did not demonstrate enough accuracy for daily monitoring, as written in the title.

Therefore part of the **Section 3.3** in the manuscript has been re-written as below:
"[…]. This simple statistical approach gives a robust estimate of the linear regression between the $PM_{10}$ and satellite data (Gupta et al., 2006). Using the regression relation, obtained from the

relationship between bin-averaged PM10 and AOD, surface PM10 mass concentration can be quantified from remotely sensed AOD and an estimate of the air quality index could be obtained. If applied to one day of data, this technique may be a good estimate for a daily monitoring. […].”

## Minor comments

**------------------------**

***1)** GDAS boundary layer data should be described in the data section*

**REPLY**: In Section 2.0, a new sub-section has been introduced (“2.3 Meteorological data” in the updated version of the manuscript). The GDAS boundary layer data paragraph has been re-written and integrated into the revised manuscript. It is also been introduced how the PBL depth from the GDAS analysis files is determined.

Therefore **Section Meteorological data** in the manuscript has been re-written as below:
“For the analysis, the variations of the vertical distribution of aerosols are considered by introducing information on the Planetary Boundary Layer (PBL) depth. This parameter is provided by 6 hourly analysis files from the NOAA National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS), downloaded from *nomads.ncdc.noaa.gov*, with a spatial grid resolution of 0.5°x0.5°. For each day, four analysis files are available, one per each synoptic hour (00, 06, 12 and 18 UTC). Therefore, these 6 hourly meteorological files were interpolated in time to the satellite overpass hour over the Po Valley domain. The PBL height is diagnostically determined and uses the bulk-Richardson (Troen and Mahrt, 1986) approach to iteratively estimate a PBL height starting from the ground upward (Hong and Pan, 1996).”

In the manuscript, the following **references** have been added:

Troen, I. and L. Mahrt, 1986. "A Simple Model of the Atmospheric Boundary Layer: Sensitivity to Surface Evaporation." Boundary Layer Meteorology. Vol. 37, pp. 129-148.

Hong, S.-Y. and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev., 124, 2322-2339

***2)** The MODIS standard 10-km AOD image is clearly smoothed but the MAIAC 1-km AOD image is not in Figure 3. What is the reason for the authors to state substantial spatial variability shown in MAIAC image? Also, what is the reason for areas without AOD retrievals in both 10-km and 1-km images of Figure 3?*

**REPLY**: The study domain, Po Valley, is a limited area. Therefore, the fact that the 1-km MAIAC AOD retrieval is much more detailed than the MODIS one is absolutely fundamental. The 10-km resolution of MODIS AOD does not allow the local details of the AOD field to be detected. With higher resolution AOD retrievals (e.g. 1-km) it is possible to distinguish areas of intense air pollution (e.g. urban area) from other regions where the AOD is less. Considering the AOD retrieval presented in Figure 3, the MAIAC AOD retrieval is able to better define the east cost of the Po Valley (marshland area). Regarding to this, an interesting example is presented in Emili et al., 2011, where five different days over the Alpine chain are considered.
First, it is important to highlight that the MAIAC data set considered during the analysis covers just a part of a MODIS standard land tiles. Therefore, the MAIAC AOD retrieval does not cover the entire Po Valley domain plotted in Figure 3.
The reasons for areas without AOD retrieval in both the AOD retrievals presented are:

- Presence of snow over the Alpine chain and (N and N-W)

- Presence of clouds over the Tyrrhenian Sea (south-west area)

These areas are well represented by the MAIAC Cloud Mask and Land-Water-Snow mask field in Figure 4. On the other hand, if we consider the Milan industrial area (most polluted area in the west side of the Po Valley), the lack of AOD retrieval is due to an intense pollution haze, which causes a total backscattering (gas and aerosol scattering) of the radiance to the sensor and may be mis-interpreted as a cloud.

Therefore **Section 2.2** in the manuscript has been re-written as below:

"[…] In Fig. 3, a comparison between MODIS standard and MAIAC aerosol retrieval results between is shown. As immediately evident, the higher resolution MAIAC retrieval shows substantial spatial variability, which is not captured by the standard 10 km retrieval. Using a AOD retrieval with an higher resolution (e.g. 1 km like MAIAC retrieval is) it is possible to better distinguish area of intense air pollution (e.g. urban area) from other where the AOD value is less. Considering the AOD retrieval presented in Fig. 3, the MAIAC retrieval is able to better define the east cost of the Po Valley (marshland area). Regarding to this, an interesting example is presented in Emili et al., 2011, where five different days over the Alpine chain are considered. […] The MAIAC Cloud Mask (CM) and the Land-Water-Snow (LWS) mask fields have been considered during the MAIAC run in order to avoid pixels where clouds, water or snow are detected. One of the fundamental limitations of satellite data is the unavailability of air pollution observations both when clouds obstruct the satellite sensors field of view and over domains with high reflectivity surfaces such as urban areas or when snow and ice conditions predominate (Gupta and Christopher, 2008, Emili et al., 2011)."

In the manuscript, the following **references** have been added:

Gupta, P., & Christopher, S. A. (2008). An evaluation of Terra-MODIS sampling for monthly and annual particulate matter air quality assessment over the Southeastern United States. *Atmospheric Environment*, *42*(26), 6465-6471.

***3)** Figure 5 x-axis is Julian day but ZPBL monthly mean was plotted. The actual data points are 12. Therefore "Month" is better used for x-axis. Figure caption should also change to "Monthly PBL height trend. . .. . ."*

**REPLY**: In the manuscript, the Figure 5 and its caption have been updated (see new updated figure below). The x-axis tag has been replaced with "Month" instead of "Julian Day", the Standard Deviation to the ZPBL Monthly Mean trend and number of samples (for the PBL depth value, considering the total number of stations available over the Po Valley domain) has been added on the plot.

Therefore the **Figure 5** has been updated and caption in the manuscript has been re-written as below:

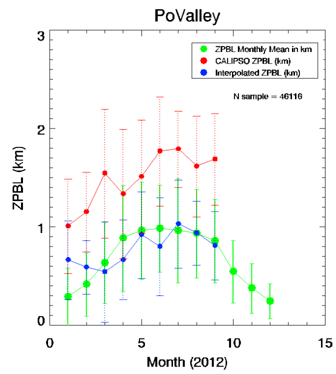


Figure 5. Monthly PBL height trend, calculated over Po Valley domain, compared to both CALIPSO and Interpolated ZPBL one.

***4)*** *Please add N (number of samples) in deriving statistics in Figures 5, 7, 8.*

**REPLY**: In the manuscript, on Figure 5 the number of samples has been added on the plot (see new updated figure above).
Moreover, this section has been re-written. First, we have changed the title of the subsection 3.2 as "3.2 Seasonality in $PM_{10}$-AOD relationship". Second, the standard deviations values have been reported in the graphics (referring to Figure 7 in the manuscript), for the approaches considered. On specific, the plots have been updated as a box and whisker plot (see new updated figure below). Moreover a new Table (Table 1 see below) has been introduced, which summarizes the PM10 and AOD total available data. Then a complete discussion of the new analysis has been added, for both PM10 and AOD variables, highlighting how the seasonal variance compares.

**Figure 5**: updated. See above

**Figure 7**: updated. See below.

**Figure 8**: deleted.

Therefore the **Section 3.2** in the manuscript has been re-written as below:
"The AOD - $PM_{10}$ analysis begins with the study of the 2012 monthly mean trend of $PM_{10}$ versus AOD for both the spatial co-location approaches presented in Sec. 2.3. The results are reported in Fig. 7, with a box and whisker plot approach. The top graph of the figure shows the monthly mean value of $PM_{10}$ 24 hour mass concentration (red box), for all 126 ARPA stations. The AOD monthly mean values are represented on the graph by the blue and the green boxes, for MYD04 and MAIAC, respectively. As immediately evident, the trends in PM and AOD are different during the winter and fall periods for the *nearest-neighbor* coincidence approach. For the methods, a radius of coincidence equal to 0.20° was used to allow for a more direct comparison. The disagreement is particularly notable for the two last months of the year, where the PM monthly mean values increase, while AOD values decrease. The highest values of PM are recorded in this period of the year due to the meteorological conditions that favor the buildup of near-surface pollutants, and regional environmental protection agencies are actively trying reducing air pollution problems (Di Nicolantonio et al., 2009, Mazzola et al., 2010). In winter, a larger variation of PM10 is evident compared to summer. For the AOD datasets happen the opposite, with larger variations in the summer. This may be due to the influence of the relative humidity, where in summer it increases the particle size resulting in higher AOD.

Therefore, for the same amount of dry $PM_{10}$ mass concentration, the corresponding AOD measure is larger in summer than in winter (Wang and Christopher, 2003). The same analysis was conducted considering the second approach (*average*) and did not show significant differences (results not shown). Other important aspect, especially both in fall and winter periods, is the unavailability of satellite AOD retrievals due to increased clouds and over domains with high reflectivity surfaces, e.g. urban areas or snow, (Gupta and Christopher, 2008). This leads to a different number of data points, if PM or AOD data are considered, as reported in Table 1. The numbers of coincident AOD values represent just the 30% and 39% of the total possible $PM_{10}$ measurements, for MYD04 and MAIAC retrieval respectively. […]"

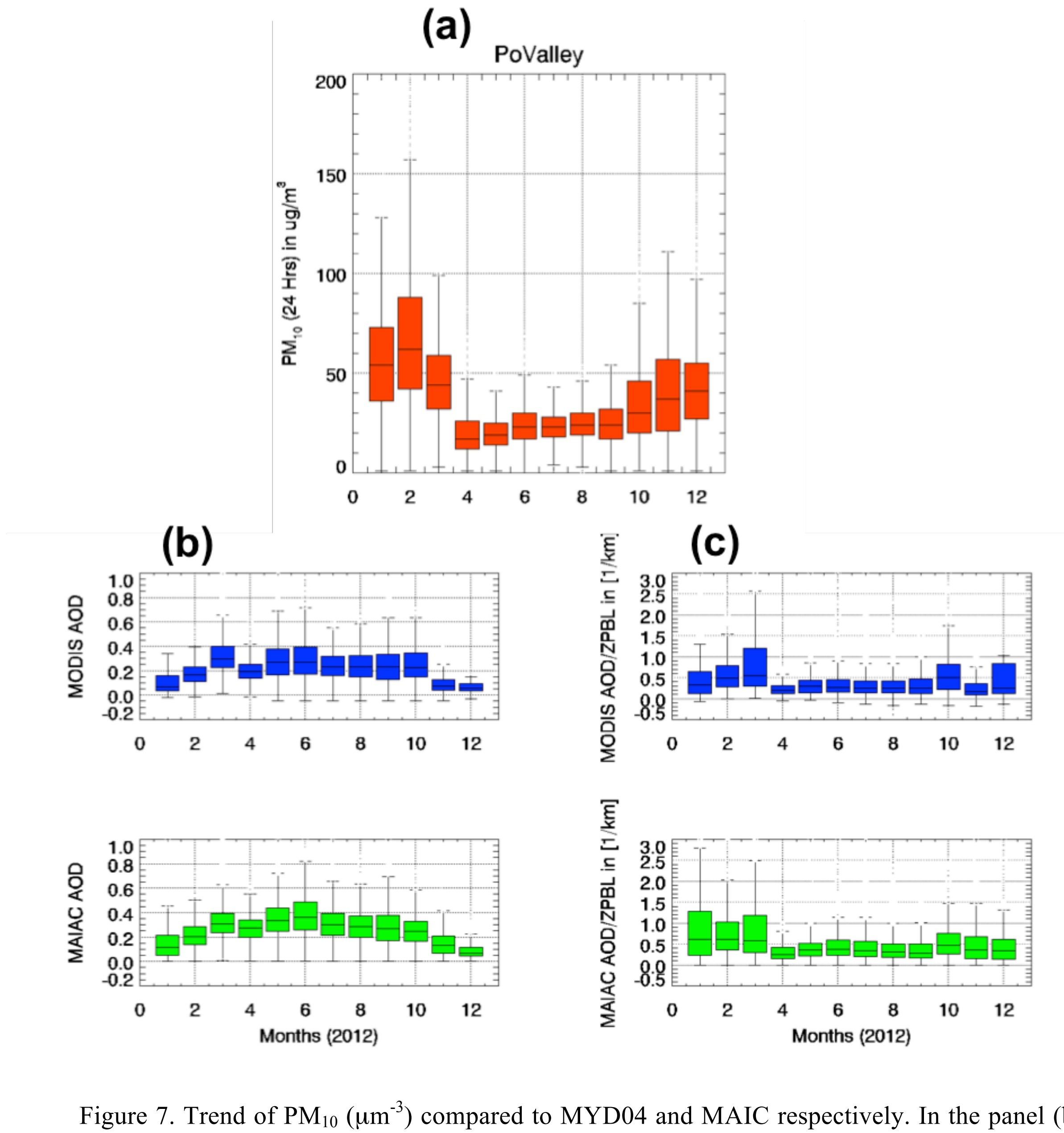


Figure 7. Trend of $PM_{10}$ ($\mu m^{-3}$) compared to MYD04 and MAIC respectively. In the panel (b) the relationship PM – AOD is considered, while in the panel (c) is reported the result for PM – AOD/ZPBL relationship. The black line in the box represents the median value, the edges of the box are the $25^{th}$ and $75^{th}$ percentiles, and the whiskers should extend out to largest and

smallest value within 1.5 times the interquartile range. It was considered a radius of coincidence equal to 0.20°.

and it has been introduced the following **table**:

Table 1. $PM_{10}$ and AOD total available data

| **Total presumed data (tpd)** | **$N_{tot}$ = 126 (#stations) * 366(days) = 46116** |
|---|---|
| total $PM_{10}$ retrieved data (trd_PM10) | $N_{PM_{10}}$ = 42798 |
| (trd_$PM_{10}$)/(tpd) | 93% |
| total MYD04 retrieved data (trd_AOD) | $N_{MYD04}$ = 13603 |
| (trd_MYD04)/(tpd) | 30% |
| total MAIAC retrieved data (trd_AOD) | $N_{MAIAC}$ = 18011 |
| (trd_MAIAC)/(tpd) | 39% |

In the manuscript, the following **references** have been added:

Gupta, P., & Christopher, S. A. (2008). An evaluation of Terra-MODIS sampling for monthly and annual particulate matter air quality assessment over the Southeastern United States. *Atmospheric Environment*, *42*(26), 6465-6471.

***5)*** *The N values in Figures 9 and 11 are not consistent with the data points plotted.*

**REPLY**: In the manuscript, the "N" value reported on top of Figures 9 and 11 refers to the number of coincidences. It was calculated as the number of points of PM and AOD that verify the condition of both no null values. The reported N value has been calculated from the full scatter plots, before binning. We decided to not change the values because it is important to highlight that we have more coincidences if we consider MAIAC retrieval instead of MODIS one. But we better explained what N parameter is in the 3.3 Section.

Therefore the **Section 3.3** in the manuscript has been re-written as below:
"[…] in Fig. 9, using the *nearest neighbor* approach. The solid red line shows the linear regression line for these two data sets. White dots refer to median values of AOD at fixed value of $PM_{10}$. Yellow symbols represent the $25^{th}$ and $75^{th}$ percentile (first and third quartiles) respectively in AOD for a particular $PM_{10}$ bin. N, on the top of each plot, represents the number of coincidence calculated from the full scatter plots, before binning. […]"

***6)*** *Why the authors did not include Modena sunphotometer in MODIS AOD validation (Figure 6)?*

**REPLY**: We decided to not include Modena sunphotometer in MODIS AOD validation because for the entire year of 2012 (except for January) the sunphotometer did not work. So, due to the lack of data for the period of study, we decided to consider just the other sunphotometer over the Po Valley domain, Ispra, as reported in Figure 6.

***7)*** *The behavior of coincidence of MAIAC in Figure 13 is strange for the "Average" results.*

**REPLY**: we re-run the simulation and we did not found any significant errors in code we used. We agree with the Referee on the fact that the behavior of coincidence of MAIAC in Figure 13 for the "average" results is strange, but we think that the explanation of this is correlated to definition of "Average approach" define in Section 3.3 of this manuscript.

***8)*** *Suggested citations regarding aerosol mixing height for PM estimation to include in the manuscript*

**REPLY**: the suggested citations have been introduced into the manuscript in Section 2.4 ("AOD normalization").