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(Article begins on next page)

1 Seasonal monitoring and estimation of regional aerosol 2 distribution over Po Valley, northern Italy, using high- 3 resolution MAIAC product

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13

14 **Abstract**

15 In this work, the new 1-km-resolved Multi-Angle Implementation of Atmospheric Correction
16 (MAIAC) algorithm is employed to characterize seasonal AOD-PM₁₀ correlations over
17 northern Italy. The accuracy of the new dataset is assessed versus the widely used Moderate
18 Resolution Imaging Spectroradiometer (MODIS) Collection 5.1 Aerosol Optical Depth (AOD)
19 data, retrieved at 0.55 μm with spatial resolution of 10 km (MYD04). We focused on evaluating
20 the ability of these two products to characterize both temporal and spatial distributions of
21 aerosols within urban and suburban areas. Ground PM₁₀ measurements were obtained from 73
22 of the Italian Regional Agency for Environmental Protection (ARPA) monitoring stations,
23 spread across northern Italy, for a three-year period from 2010 to 2012. The Po Valley area
24 (northern Italy) was chosen as the study domain because of severe urban air pollution, resulting
25 from the highest population and industrial manufacturing density in the country, being located
26 in a valley where two surrounding mountain chains favor the stagnation of pollutants. We found
27 that the global correlations between PM₁₀ and AOD are $R^2 = 0.83$ and $R^2 = 0.44$ for MYD04_L2
28 and for MAIAC, respectively, suggesting for a greater sensitiveness of the high-resolution
29 product to small-scale deviations. However, the introduction of Relative Humidity (RH) and

1 Planetary Boundary Layer (PBL) depth corrections gave a significant improvement to the PM
2 – AOD correlation, which led to similar performance: $R^2 = 0.96$ for MODIS and $R^2 = 0.95$ for
3 MAIAC. Furthermore, the introduction of the PBL information in the corrected AOD values
4 was found to be crucial in order to capture the clear seasonal cycle shown by measured PM_{10}
5 values. The study allowed us to define four seasonal linear correlations that estimate PM_{10}
6 concentrations satisfactorily from the remotely sensed MAIAC AOD retrieval. Overall, the
7 results show that the high resolution provided by MAIAC retrieval data is much more relevant
8 than 10km MODIS data to characterize PM_{10} in this region of Italy which has a pretty limited
9 geographical domain, but a broad variety of land usages and consequent particulate
10 concentrations.

11

12 **1 Introduction**

13 Particulate matter (PM), also defined as atmospheric aerosol, is one of the major pollutants
14 studied and monitored since it affects air quality in urban and rural areas worldwide. PM is the
15 general term used to define a complex mixture of solid and liquid particles. These particles vary
16 in size and composition, and remain suspended in the air for different periods of time. The
17 sources of the atmospheric aerosols include both natural activity, such as fire, sea salt, volcanic
18 eruptions and windblown dust, and anthropogenic activity, such as combustion, traffic and
19 industrial emissions. PM with aerodynamic diameter of $10\mu\text{m}$ or less (PM_{10}) leads to serious
20 human health effects. They can be inhaled into the respiratory system and so cause respiratory
21 lung diseases and even premature death (Pope et al., 2004, Forastiere et al., 2005, Brunekreef
22 and Forsberg, 2005). At local scale, urban pollution plays a significant role on issues related to
23 health due to high urban population densities. Prior to the twentieth century, most urban air
24 pollution problems arose from the burning of wood, coal and other raw materials without any
25 emission controls. Such burning resulted in significant increases in health issues related to
26 urban pollution (Jacobson, 2012).

27 The Po Valley, in the northern part of Italy, is the area with the most severe air pollution
28 problems in the country and Europe as it is the largest industrial, trading and agricultural area
29 with a high population density (Mélin and Zibordi, 2005, Bigi et al., 2012, Bigi and Ghermandi,
30 2014, Putaud et al., 2014). The pollution problems that affect the Po Valley are not only related
31 to the presence of highly urbanized and industrial centers. In fact, the presence of the Alpine
32 mountain chain at the North and West sides of the valley, and the Apennines to the South, act

1 as a barrier to winds blowing from Northern Europe and the Mediterranean, favoring stagnation
2 conditions and accumulation of pollutants (Putaud et al., 2004, Mazzola et al., 2010, Putaud et
3 al., 2010). Because of this, monitoring in this area requires data with high spatial resolution to
4 better characterize the spatial variability of pollution within the Po Valley.

5 Due to health problems associated with urban air pollution, many environmental protection
6 agencies have been developing capabilities for continuous monitoring and assessment of air
7 pollution from ground-based stations and for improving sampling techniques. These ground-
8 based measurements are necessary to guide studies of possible ways to reduce the air pollution
9 problems. Yet, ground-based observations represent point measurements and do not have the
10 necessary coverage to characterize the regional distribution of aerosols in the atmosphere.
11 Moreover, the PM ground-based stations only provide information at the surface. The
12 development of satellite remote sensing aerosol products since the launch of the Moderate
13 resolution Imaging Spectroradiometer (MODIS) onboard the NASA Terra and Aqua satellites
14 has permitted the exploration of new research techniques for monitoring global air quality
15 (Gupta et al., 2006, Fishman et al., 2008). This alternative approach for air quality monitoring
16 provides air quality data where the ground-based measurements are not available. The potential
17 for using space-based sensors for the air quality monitoring was demonstrated using Aerosol
18 Optical Depth (AOD) data in combination with the PM ground-based stations, as the literature
19 suggest (Chu et al., 2003, Wang and Christopher, 2003). The use of MODIS aerosol products
20 to investigate air pollution was demonstrated both in research fields (van Donkelaar et al., 2006,
21 Gupta and Christopher, 2008b, Tian and Chen, 2010) and for operational applications (Al-Saadi
22 et al., 2005). But, satellite AOD quantifies the presence of aerosols in an atmospheric column,
23 while the surface PM mass concentration is needed for the assessment of air quality health
24 impacts: it is not obvious what the relationship between these two quantities is for a particular
25 region. Hoff and Christopher (2009) provide a detailed review of the literature on how satellite
26 remote sensing provides an alternative way to monitor surface PM mass concentrations. As
27 they point out, correlations between ground measurements and optical thickness are actively
28 used and investigated.

29 In previous works, the Po Valley domain was studied, where the air quality monitoring from
30 satellite measurements was applied (Di Nicolantonio et al., 2007, Di Nicolantonio et al., 2009,
31 Barnaba et al., 2010). These studies pointed to the use of satellite remote sensing observations
32 for monitoring the air pollution over industrialized and urban areas, such as the Po Valley.

1 However, their correlation is often not high enough for AOD retrievals to be operationally
2 incorporated in air quality monitoring procedures. The MODIS standard aerosol product spatial
3 resolution is appropriate for application on regional to global scale. However, its nominal
4 resolution at nadir (10 km) may be too coarse to resolve urban scale processes. Therefore,
5 alternative aerosol retrieval algorithms have been developed using the MODIS data in order to
6 produce a finer high-spatial resolution product. The MODIS NASA research team recently
7 released a new MODIS product: MODIS Collection 6, which includes a global aerosol product
8 at nominal 3 km, in addition to the standard MYD04 at 10 km (Remer et al., 2013, Munchak et
9 al., 2013, Livingston et al., 2014). Recently, the Multi-Angle Implementation of Atmospheric
10 Correction (MAIAC) algorithm was developed for MODIS (Lyapustin et al., 2011a, Lyapustin
11 et al., 2011b, Lyapustin et al., 2011c, Lyapustin et al., 2012). The MAIAC algorithm performs
12 a simultaneous retrieval of surface Bidirectional Reflection Distribution Function (BRDF) and
13 aerosol properties at a resolution of 1 km, and represents an interesting alternative for
14 characterizing spatial variability of aerosol within polluted and industrial urban areas (Emili et
15 al., 2011, Chudnovsky et al., 2013a, Chudnovsky et al., 2013b, Hu et al., 2014). Due to the
16 availability of high-spatial resolution products, recently, a series of studies have demonstrated
17 how the satellite remote sensing products can provide a potentially cost effective way to predict
18 PM (PM_{10} and $PM_{2.5}$) concentrations by using AOD in areas where ground monitoring is either
19 not available or too sparse (Chudnovsky et al., 2014, Hu et al., 2014a, Hu et al., 2014b, Kloog
20 et al., 2014, Kloog et al., 2015, Just et al., 2015).

21 In the current study, we extend the preliminary analysis of Arvani et al. (2013b) by using the
22 MAIAC 1 km resolution retrievals to analyze the relationship between PM_{10} mass concentration
23 and remotely sensed AOD within the Po Valley, for an extended period of three years, from
24 2010 to 2012. We started with a direct comparison between both MYD04_L2 and MAIAC
25 AOD retrievals and the surface PM_{10} measurements. Then, with the introduction of additional
26 meteorological information, as the role of the planetary boundary layer and relative humidity,
27 we analyzed the seasonal temporal and spatial variability of PM_{10} compared to AOD, for the
28 same days and locations. Finally, starting from a monthly sweep of linear correlation
29 coefficients, carried out on the 36 months where both datasets were available, we defined four
30 unique correlations to estimate the PM_{10} concentrations on a seasonal level. The coefficients
31 were obtained for both the coarse 10 km MYD04 and the finer high spatial resolution 1 km
32 MAIAC satellite products.

1 **2 Data and methods**

2 **2.1 Region of interest**

3 The region of interest, Po Valley in northern Italy, shown in Fig. 1, covers an area of
4 approximately 40° - 50° N and 5° - 15° E. In this paper, we considered three of its
5 administrative regions, west to east: Piemonte, Lombardia and Emilia Romagna. Piemonte is
6 characterized by major urban centers and is heavily industrialized. Most of the Italian Regional
7 Agency for Environmental Protection (ARPA) network stations within the Piemonte region is
8 located near the Alps. Lombardia is the most populated region, and it has the highest density of
9 industrial sites. The Emilia Romagna region, similar to Piemonte, is characterized by major
10 urban centers. Some of the ARPA sites within this region are located close to the Apennine
11 mountain chain to the south, and near the coast of the Adriatic Sea to the east.

12 **2.2 Ground-level mass concentration**

13 Twenty-four hour averaged PM₁₀ mass concentrations in μgm^{-3} , were obtained for 73 air quality
14 monitoring ground-based stations within the ARPA network over a time span of 3 years, from
15 2010 to 2012: Piemonte (18 stations), Lombardia (19 stations), Emilia Romagna (36 stations).
16 The spatial distribution of the ground-based stations almost uniformly covers most of the valley,
17 as highlighted in Fig. 1. Each regional ARPA network has a unique set of measurements,
18 carried out with different hardware and according to different daily averaging rules, thus
19 leading to regionally different uncertainties. This non-uniformity may affect the correlations.
20 In particular, in ARPA Piemonte PM₁₀ is measured using a Beta Attenuation Monitor (BAM)
21 with an accuracy of 2%. In ARPA Lombardia TEOM, TEOM-FDMS (Tapered Element
22 Oscillating Micro-balance - Filter Dynamics Measurement System), or BAM are used, with an
23 accuracy of $\pm 2.5 \mu\text{gm}^{-3}$. In ARPA Emilia Romagna, PM₁₀ data have been collected by the beta
24 attenuator SWAM 5A RL by FAI Instruments with an uncertainty lower than $\pm 10\%$. All
25 information related to the ARPA's stations and instrumentation are available at the ARPA web
26 sites of their respective regions, mentioned above. Yet all the instruments used are equivalent
27 to the gravimetric technique, inserted within the framework of the EC Directive on ambient air
28 quality and cleaner air for Europe (2008/50/EC).

1 **2.3 Remotely sensed data**

2 In the present work, we compare plain, standard MODIS Aqua Collection 5.1 (MYD04) aerosol
3 product data with a first application of the high-resolution MAIAC algorithm over the Po valley.
4 MYD04 data have a nominal spatial resolution of 10 km at nadir, which increases by roughly
5 four-fold at the edges of the swath. The MODIS AOD algorithm uses multispectral observed
6 radiance and pre-computed look-up tables to retrieve AOD over ocean and land (Remer et al.,
7 2005, Remer et al., 2009). The recently developed MAIAC aerosol retrieval algorithm
8 (Lyapustin et al., 2011a, Lyapustin et al., 2011b) employs MODIS Aqua Land retrieval data
9 and is thus provided over the land only. AOD is retrieved at a finer spatial resolution (1 km),
10 making simultaneous use of BRDF parameters. This is accomplished by using the time series
11 of MODIS measurements and simultaneous processing of groups of pixels. The MAIAC
12 algorithm guarantees that the number of measurements exceeds the number of unknowns, a
13 necessary condition for solving an inverse problem without empirical assumptions, which are
14 commonly used in current operational algorithms. The MAIAC time series approach also
15 provides coverage at multiple (15) view angles for every surface grid cell, which is required for
16 the BRDF retrievals from MODIS data. Moreover, MAIAC incorporates a Cloud Mask (CM)
17 algorithm based on spatio-temporal analysis, which augments traditional pixel-level cloud
18 detection techniques (Lyapustin et al., 2008). Fig. 2 shows three example days of MYD04
19 compared to MAIAC AOD retrieval, one day per each year of analysis (from 2010 to 2012).
20 Since the study domain of the Po Valley has limited geographical extents, assessing 1 km
21 MAIAC AOD retrievals which can achieve much greater detail than the standard MODIS
22 product is extremely promising for future applications of the satellite measurements as part of
23 predictive tools. The 10 km resolution of MODIS AOD does not allow local details of the AOD
24 field to be detected. On the contrary, 1 km AOD retrievals allow areas of intense air pollution
25 to be detected on the urban scale, such as Fig. 2 shows for June 5th, 2010 and March 16th, 2012.
26 Furthermore, the high spatial resolution MAIAC retrieval often provides data where MODIS
27 has reduced data coverage; for instance, the east coast of the Po Valley (marshland area), on
28 April 19th, 2011. This is allowed by the time-series-based analysis and angle-based interpolation
29 the MAIAC algorithm incorporates. A good review of this phenomenon is thoroughly explained
30 in Emili et al., 2011, where five different days over the Alpine chain are considered and
31 compared.

1 The MODIS Collection 5.1 retrieval has already been cloud filtered and is used without
2 additional quality control. On the contrary, the new aerosol retrieval algorithm MAIAC
3 includes masks of cloud and terrain, incorporated into the AOD Quality Assurance (QA)
4 parameter definition. The MAIAC Cloud Mask (CM) and the Land-Water-Snow (LWS) mask
5 fields have been considered during the MAIAC run in order to avoid pixels where clouds, water
6 or snow are detected. As a matter of fact, one of the fundamental limitations of satellite data is
7 the unavailability of air pollution observations both when clouds obstruct the satellite sensors
8 field of view and over domains with high reflectivity surfaces such as urban areas or when snow
9 and ice conditions predominate (Gupta and Christopher, 2008b, Emili et al., 2011). In Fig. 2,
10 March 16th 2012, lack of AOD retrieval close to the important industrialized centers of Milan
11 and Turin appears to be due to an intense pollution haze, which causes a total backscattering
12 (gas and aerosol scattering) of the radiance to the sensor and seems to be misinterpreted as a
13 cloud.

14 **2.4 Meteorological data**

15 The vertical span of the aerosol distribution defines the most relevant weighting parameter for
16 the AOD datum. This was introduced by considering Planetary Boundary Layer (PBL) depth
17 information. Relative Humidity (RH) was also introduced as a correction to dried PM₁₀ mass
18 concentration measurements. These parameters were obtained from 6 hourly analysis files from
19 the NOAA National Center for Environmental Prediction (NCEP) Global Data Assimilation
20 System (GDAS), downloaded from nomads.ncdc.noaa.gov, with a spatial grid resolution of
21 0.5°x0.5°. For each day, four analysis files are available, one per each synoptic hour (00, 06,
22 12 and 18 UTC). Therefore, 6 hourly meteorological files were interpolated on a time basis to
23 the time of satellite overpass over the Po Valley domain. The PBL height is diagnostically
24 determined and uses the bulk-Richardson (Troen and Mahrt, 1986) approach to iteratively
25 estimate a PBL depth starting from the ground upward (Hong and Pan, 1996). Relative
26 humidity in the GFS is computed according to the standard NCEP procedure:

- 27 • at $T < -20$ C, w.r.t. ice
- 28 • at $T > 0$ C, w.r.t. water
- 29 • $-20 < T < 0$, mix phased.

1 **2.5 Spatial co-location of satellite data and ground measurements**

2 The MODIS Collection 5.1 aerosol product, MAIAC retrievals and surface PM₁₀ were co-
3 located in space for the period from 2010 to 2012, for each ARPA station considered in the
4 study domain. The spatial co-location of MODIS and MAIAC pixels with PM₁₀ ground-based
5 stations was accomplished using the average approach as suggested in Gupta et al. (2006) with
6 a tolerance radius equal to 0.20° (about 20 - 25 km at the latitude of the Po Valley) for
7 MYD04_L2 product, and 0.02° (about 2 - 2.5 km at the latitude of the Po Valley) for MAIAC,
8 using the same scale factor as their spatial resolutions. To determine the coincidences, we
9 considered that if there is at least one missing pixel within the tolerance area we set the mean
10 AOD value equal to a missing data. This is a conservative approach since it automatically
11 excludes all the retrievals in the neighborhood of pixels identified by the terrain and cloud
12 masks within a fixed tolerance area. We find that the impact of neighboring missing values is
13 less of an issue for the standard MODIS retrieval, possibly due to a more conservative cloud
14 mask (Arvani et al., 2015).

15 **2.6 Normalization of the AOD parameter**

16 PM₁₀ and AOD represent two different measurements of the atmospheric loading of aerosols.
17 The PM₁₀ is a dry mass concentration ($\mu\text{g}/\text{m}^3$), measured mostly ground level, at a specific
18 geographic location. On the other hand, satellite AOD represents total column aerosol loading
19 averaged over a specific spatial area (unitless) and it depends on the environmental conditions.
20 As suggested by the literature, the PM - AOD correlation may be improved by considering
21 meteorological information such as the role of the Relative Humidity (RH) (Li et al., 2005,
22 Wang and Martin, 2007, Altaratz et al., 2013), or vertical distribution of aerosols (Gupta et al.,
23 2006, Wang and Martin, 2007, Tsai et al., 2011). In this work, both the variations in the vertical
24 distribution of aerosols and the role of the hygroscopic information are considered. For the first,
25 the information on the Planetary Boundary Layer (PBL) depth is introduced. The use of PBL
26 depth as parameter to improve the correlation between surface PM and satellite AOD
27 measurements has utilized both as measurements (Boyouk et al., 2010, Barnaba et al., 2010,
28 Tsai et al., 2011, Chu et al., 2013), and as model simulations (Gupta and Christopher, 2009,
29 Emili et al., 2010), and is still widely used at present, such as in Chu et al., 2015, where vertical
30 and horizontal distribution of aerosols over Baltimore - Washington Corridor are studied.

1 The Aerosol Optical Depth is defined as a vertical integral of aerosol extinction, from the
2 surface to the top of the atmosphere (TOA):

$$3 \quad AOD = \int_0^{TOA} \sigma_{0.55 \mu m}^{ext}(z) dz \quad (1)$$

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

$$10 \quad AOD^* = \sigma_{0.55 \mu m}^{ZPBL} * ZPBL \quad (2)$$

11 where ZPBL represent the height of the PBL, schematically represented in Fig. 3. Under the
12 hypothesis that most of the aerosols are confined and mixed homogeneously within the PBL,
13 the values of AOD normalized by PBL height may be regarded as mean PBL extinction in km^{-1}
14 $(\sigma_{0.55 \mu m}^{ZPBL})$. It may be more representative of the surface PM_{10} concentration since variations
15 in the depth of the PBL are accounted for. In this work, the normalization was applied both for
16 MYD04 and MAIAC AOD retrievals.

17 In Fig. 4 panel (a) the monthly trend of PBL height is reported, for the entire period (2010-
18 2012) and locations over the Po Valley domain. The box and whisker box graph was realized
19 considering all the equal months in the period (3 years). The highest mean and median values
20 were obtained during the summer, with the highest dispersion of data evaluated in terms of the
21 different between the 10th and 90th percentiles, with a maximum for the month of July. On the
22 contrary, the lowest mean and median values were obtained during the winter, with the lowest
23 dispersion of data, with a minimum for the month of December. The statistical parameters
24 obtained for the four seasons are shown in Fig. 5 panel (a). The highest mean and median values
25 were obtained in summer (June, July, August), and the lowest in winter (December, January,
26 February), which also presents the most limited dispersion features in contrary to the summer
27 season. In spring (March, April, May) pretty high values were obtained, with a significant
28 dispersion of data. In fall (September, October, November), instead, pretty low values were
29 obtained, but slightly higher than the winter ones. It is important to mention that such seasonal
30 changes were found under a complex and complete climatology study developed in Seidel et
31 al. (2012) work. The paper states that, as a cross climatology overview, daytime values over

1 Europe occasionally reach 2 km in summer, and during spring and summer the PBL heights are
2 higher than fall and winter. This confirms that the seasonal variations described above
3 characterize the mixed layer values over the Po Valley domain.

4 **2.7 Relative humidity correction**

5 While the remotely sensed AOD value is the columnar aerosol abundance in ambient
6 environment, the mass concentration of PM is a dry measure at a fixed RH. Therefore, as the
7 literature suggests, introducing hygroscopic information on measured ground PM mass
8 concentrations by means of a scaling function may be relevant.

9 Hence, we chose the relationship by Tsai et al. (2011), which was successfully applied to rather
10 moist environments. This function expresses an aerosol growth factor $f(RH)$ due to relative
11 humidity as

$$12 \quad f(RH) = \frac{1}{\left(1 - \frac{RH}{100}\right)}, \quad (3)$$

13 where RH is the relative humidity value expressed in percentage.

14 In Fig. 4 panel (b) the monthly mean trend of RH for the Po Valley is reported. The highest
15 mean and median values were seen during September, with a mean relative humidity of 35%
16 and the highest dispersion of data evaluated in terms of the different between the 10th and 90th
17 percentiles for the months of October and November leading to the formation of typical humid
18 morning and occurrence of mild to heavy fog. The seasonal trend of relative humidity is shown
19 in Fig. 5 panel (b). The highest mean and median values were obtained during the fall, and in
20 summer. However, while dispersion is maximum during the fall, it is minimum in the summer.
21 The lowest mean and median values were obtained during the winter.

22 In the section below, we consider the simple expression defined in (3) to test how the RH affects
23 the PM₁₀ – AOD correlation, AOD being normalized by PBL depth.

24 **3 Results and discussion**

25 **3.1 PM₁₀ vs. AOD correlation: binned scatter plot analysis**

26 First of all, a direct comparison between daily PM₁₀ mass concentrations and remotely sensed
27 AOD values with no meteorological corrections was done. A non-corrected linear correlation

1 was obtained from both MYD04 and MAIAC, at all ground stations and for the whole 2010 to
2 2012 period.

3 Because of the evidently large spread of AOD and PM values (not reported in this paper, but
4 shown in Arvani et al., 2013a for a limited period of time and domain of analysis), and not
5 promising values of R^2 (see Table 1), we divided the AOD into 20 bins of 0.05 intervals for the
6 range [0-1], and we compared them with the mean PM_{10} within each bin. So, the final PM-
7 AOD correlation value is determined by using the average value of PM in each AOD bin. This
8 set of twenty points is reported on the scatter plot as black dots in Fig. 6, panels (a). The solid
9 red line shows the linear regression line for these two data sets. White dots refer to median
10 values of AOD at fixed value of PM_{10} . Gray symbols represent the 25th and 75th percentile (first
11 and third quartiles) respectively in PM_{10} for a particular AOD bin. N , on the top of each plot,
12 represents the number of coincidence calculated from the full scatter plots, before binning,
13 where by coincidence we mean a (station, date) case where both PM measurement and the AOD
14 value are available. This simple statistical approach gives a robust estimate of the linear
15 regression between the PM_{10} and satellite data (Gupta et al., 2006). Using this regression
16 relation, obtained from the bin-averaged PM_{10} and AOD correlation, surface PM_{10} mass
17 concentration can be quantified when the remotely sensed AOD is available and an estimate of
18 the air quality index could be obtained. The correlation between bin-averaged AOD and PM_{10}
19 concentration is highest for MYD04, with $R^2 = 0.83$. The higher resolution MAIAC retrieval
20 algorithm has a significantly lower R^2 of 0.44. Looking at the result in Fig. 6 lower panels (a)
21 this worst result may be due to the last bins, especially the last two ones that have values of
22 mean, median and 75th percentile completely out of range. A possible explanation of this would
23 be correlated to the fact that we are looking to maximum edge of the possible values of AOD,
24 therefore fewer values available for solid statistics. In agreement of this, both MYD04 and
25 MAIAC correlation show a strange behavior for the last six bins, for the range [0.8-1].

26 As mentioned in the previous subsection, the PM_{10} – AOD correlation is not enough to estimate
27 a mass concentration value from a remotely sensed measured. Therefore, the introduction of
28 meteorological variables is necessary. Firstly, we introduced the PBL depth values, for the same
29 period and locations of analysis. This led to consider the AOD/ZPBL vs. PM_{10} correlation,
30 and we used the same procedure describe above. The results are summarized in Fig. 6, panels
31 (b), for both MYD04_L2 and MAIAC retrievals. They show a significant improvements after
32 the normalization, with an R^2 of 0.96 and 0.95 for MYD04_L2 and MAIAC, respectively. This

1 indicates that the introduction of well-mixed PBL information is mandatory for both remotely
2 sensed measurements. Secondly, we introduced the RH correction on the mass concentration
3 measurements. However, it did not produce improvements in the correlations, as reported in
4 Fig. 6 panels (c).

5 This analysis suggested that the introduction of the hygroscopic factor on the PM mass
6 concentration measurements seems produce a much less significant improvement in the PM –
7 AOD correlation, and could hence be discarded for the current study, while the introduction of
8 vertical distribution information cannot be avoided as it leads to a huge improvement.

9 **3.2 Temporal trends of AOD and PM₁₀ mass concentration**

10 As second step of our study, we introduced time-series analysis to quantitatively examine the
11 temporal trends of PM₁₀ levels, as well as their AOD correlations.

12 In Fig. 7 upper panels, the monthly trend of the PM₁₀ (a), the MODIS (b) and MAIAC (c) AOD
13 are reported respectively, for the entire period (2010-2012) and locations over the Po Valley.
14 PM₁₀ and AOD monthly trends have opposite behavior for both retrievals. The PM₁₀ monthly
15 mean trend over a year is characterized by low mean and median values as well as limited
16 dispersion during the summer months, and high mean and median values - with large dispersion
17 - during the winter period. This is summarized by the corresponding seasonal statistics reported
18 in Fig. 8 upper panel (a), which have been derived from the same data set for all locations and
19 dates. During the spring and fall seasons, intermediate values smoothly follow the summer vs.
20 winter behavior, the fall values being slightly higher than the spring ones.

21 On the other hand, the AOD monthly mean trends of Fig. 7, upper panels (b) and (c), for
22 MYD04_L2 and MAIAC products, respectively, are characterized by high mean and median
23 values with significant dispersion during the spring/summer period and low mean and median
24 values with limited dispersion during the winter. Both retrievals show similar monthly trends,
25 as also enforced by the seasonal statistics of Fig. 8 upper panels (b) and (c). The fact that
26 seasonal statistics for both retrieval methods tend to converge to the same values suggests that
27 MAIAC produces a reliable higher-resolution prediction, which fits the same averaged data as
28 the coarser product. Seasonal high values of PM during the fall and winter can be partly related
29 to the meteorological conditions that characterize the Po Valley. During these periods, in fact,
30 events of strong temperature inversion, which favor the buildup of near-ground pollutants and
31 lead to the formation of fog events, are frequent. When the pollutants are trapped within the

1 stable layer, they may stay with a residence time of the order of hours. Furthermore, intense
2 human activities which characterize the area, with the largest presence of agriculture and
3 industry levels of activities in Italy (Fuzzi et al., 1992, Di Nicolantonio et al., 2009, Mazzola et
4 al., 2010), should also be regarded as responsible for this phenomenon. As far as the AOD trend
5 is concerned, instead, high values of AOD (detected both by MODIS and MAIAC monthly
6 mean trends) during the spring/summer period appear to be correlated in part to meteorological
7 factors, like desert dust intrusions from northern Africa, transport of fire particles at the low
8 latitude, and anthropogenic factors, like a long-range transport of aerosol produced by human
9 activities from Central Europe (Mazzola et al., 2010). Yet, the limited dispersion of data
10 recorded during the fall/winter period, which has a minimum in December, is correlated to often
11 prohibitive conditions for the satellite to remotely sense the columnar abundance over the
12 domain, due to intense and frequent formation of a layer of clouds, presence of snow or intense
13 haze over the urban areas with high reflectivity (Gupta and Christopher, 2008a). In Table 2 the
14 total number of dataset points, both for PM_{10} and AOD measurements, are reported.
15 Considering all 73 locations and the whole 2010-2012 period (1096 days), the largest possible
16 dataset would contain 80.008 measurements. While PM_{10} measurements are available for most
17 days and locations (no data being provided only when instrumentation issues at the ground-
18 based stations happened), the remotely sensed AOD values are only available at the 32% and
19 28% of the cases, for MYD04_L2 and MAIAC respectively.

20 In the lower row of Figure 7, panels (a), (b) and (c), instead, the monthly trend of PM_{10} mass
21 concentration is corrected by the RH function of Eqn. (3), and the MODIS and MAIAC AOD
22 values are both normalized by the PBL depth. In agreement to what verified in Section 3.1, the
23 introduction of the hygroscopic factor, may not produce a significant alteration, but it appears
24 to noticeably reduce data dispersion during the winter season. The seasonal statistics are again
25 shown in Fig. 8, lower panel (a) confirm what observed above. On the other hand, the
26 normalization of AOD by PBL depth produces significant changes in both the MODIS and
27 MAIAC AOD trends. AOD/ZPBL monthly trends are now characterized by an opposite
28 behavior than non-normalized AOD: low mean and median values, with limited dispersion, are
29 seen during the summer months, and high mean and median values during the winter, with
30 more intense dispersion. Seasonal statistics for AOD/ZPBL in Fig. 8 lower panels (b) and (c),
31 for both retrievals, now show trends clearly mimic the behavior of RH-corrected measured
32 PM_{10} . This significant improvement on the AOD side is caused by the PBL height – whose

1 monthly mean trend is presented in Section 2.6 - which reaches the highest value during the
2 spring/summer period.

3 **3.3 Spatial trends of AOD and PM₁₀ mass concentration**

4 Fig. 9 upper panel (a) shows the mean spatial distribution of ground PM₁₀ measurements from
5 ARPA sites, compared with the mean spatial distribution of AOD values for both MODIS and
6 MAIAC retrievals (upper panels (b) and (c)), across all years (2010-2012) and locations.
7 MAIAC AOD seems to replicate the major spatial pattern of ground measurements of PM₁₀ in
8 the east side of the valley and near the coast. On the other hand, high values of PM₁₀ measured
9 close the major urban and industrialized sites of Milan and Turin is not well detected by both
10 the non-corrected AOD retrievals. The second row of Fig. 9 compares instead global time
11 averages of relative-humidity-corrected measured PM₁₀ measurements – panel (a) – with PBL-
12 normalized AOD for both MODIS and MAIAC (panels (b) and (c)), at each monitoring site.
13 PBL information has a significant impact on MODIS retrievals in the southeast of the valley
14 and on the southern edge (near-mountain stations), where normalized AOD have significantly
15 smaller values. MAIAC AOD spatial distribution is instead less affected in those regions –
16 fewer coincidences being invalid because of cloud cover or snow-related reflectance (different
17 cloud mask). This led MAIAC to better replicating the major spatial pattern shown by PM₁₀
18 ground measurements, also near the major northwestern urban and industrialized sites, where a
19 consistent increase of normalized AOD's was seen versus the non-normalized ones. The RH
20 correction impact on the PM₁₀ measurements was of increasing the PM values anywhere. The
21 effect was however particularly evident at the sites that exhibited the largest PM₁₀ averages,
22 i.e., the urban and industrialized sites of Milan and Turin.

23 The seasonal spatial trends are reported in Fig. 10. The largest impact of a correction is seen
24 for AOD normalization during the winter. Here (lower panels (b) and (c)), both MODIS and
25 MAIAC retrievals show significantly higher values when PBL-normalized, for all sites in the
26 valley. RH correction is again less relevant. However, it has a positive effect across all seasons
27 in terms of better “distinguishing”, or increasing the local gradients of PM₁₀, between the urban
28 versus the mountain areas. While before the correction PM₁₀ presents an almost flat spatial
29 trend on the valley, the RH-corrected spatial trend provides much more comparable data to the
30 PBL-normalized AOD values of lower panel (c). Again, MAIAC provides a better comparison
31 with measured data than MODIS, where the spatial results are much more scattered. Looking

1 at the other three seasons (Spring, Summer and Fall), they have lower values than in winter
2 because of the larger PBL heights. However, the improvement in local gradient distribution is
3 still evident, even if up to a smaller extent.

4 The seasonal spatial trends analysis presented in this section suggests that normalized AOD
5 spatial trends present a comparable pattern to the PM_{10} measured one for MAIAC, while the
6 MODIS spatial trend, as an effect of its much coarser spatial resolution, suffers from more data
7 dispersion especially during the winter season where the retrievals are fewer and less reliable.

8 **3.4 Estimation of PM_{10} using the coarse MYD04 and the fine MAIAC products**

9 As last step of our study in this paper, we introduced linear relationship to estimate PM_{10}
10 concentrations, using both the coarse 10 km MYD04 and the high-resolution 1 km MAIAC
11 products.

12 We started to examine the linear correlation coefficients monthly trends, reported in Fig. 11,
13 for both the AOD retrievals (MODIS 10 km in upper and lower panels (a) and MAIAC 1 km
14 in upper and lower panels (b)), and for entire period of analysis. In order to assess the effect of
15 the AOD correction, linear correlation coefficients were obtained by correlating monthly PM_{10}
16 measurements with MYD04 and MAIAC, both with (Fig. 11, second row) and without (first
17 row) PBL depth normalization. The intercepts, which provide a ‘ground’ or ‘noise’ PM value
18 to be applied when AOD is zero, are not influenced by the correction of meteorological
19 variables. Slope trends show instead much different behaviors. The annual trend tends to
20 disappear into a flat line when AOD is PBL-normalized; for both retrievals, the slopes are
21 similar, and fluctuate around the global average of 17.9 for MODIS and 21.7 for MAIAC.

22 The seasonal coefficients were directly obtained from this analysis, and are listed in Table 3.
23 For each season, a slope and an intercept value were found as the means of their corresponding
24 monthly mean values. For the $PM_{10} - AOD$ correlation type, MAIAC shows a tendency towards
25 lower intercepts than MYD04, and correspondingly higher slopes; both retrievals showing
26 similar correlation coefficients, R^2 . For the normalized $PM_{10} - AOD/ZPBL$ relationship, while
27 the intercepts remain lower for MAIAC, the slopes now show similar results as the MODIS
28 ones. This suggests that the PBL normalization brings a more stable, closer-to-linear
29 relationship between the ground measurement and the satellite datum for both retrievals.
30 Therefore, we used the four intercepts and slopes for the normalized AOD datum to define four
31 corresponding seasonal correlations (4a – 4b – 4c – 4d):

$$1 \quad Y_{MAM} = m_{MAM} * X + q_{MAM} \quad (4a)$$

$$2 \quad Y_{JJA} = m_{JJA} * X + q_{JJA} \quad (4b)$$

$$3 \quad Y_{SON} = m_{SON} * X + q_{SON} \quad (4c)$$

$$4 \quad Y_{DJF} = m_{DJF} * X + q_{DJF} \quad (4d)$$

5 where Y represents estimated PM_{10} map concentrations and X the corresponding map of
6 normalized AOD/ZPBL values for both the coarse MODIS AOD product and the finer high-
7 resolution MAIAC. Fig. 12 and Fig. 13 show twelve one-day examples of estimated (map) and
8 measured (dots) PM_{10} concentrations, one for each month. The estimate was made using
9 MYD04 at 10 km spatial resolution (Fig. 12) and MAIAC AOD retrieval at 1 km spatial
10 resolution (Fig. 13), respectively. The available PM_{10} in-situ measurements are displayed on
11 top of the PM_{10} estimated map of concentrations, with the same concentration scale. The
12 patterns of PM_{10} concentrations predicted by both MYD04 and MAIAC retrievals are similar
13 in spring and summer, when the pollutant levels remain moderate. During the fall and winter
14 seasons, when the pollutant levels reach the highest values, MAIAC is able to better capture
15 the major spatial gradients shown by measured PM_{10} . The coarse 10 km MYD04 product does
16 not allow the PM_{10} concentrations to be well detected on a local scale, and it is also affected by
17 reduced data coverage. The dates of November 16th, December 5th and January 26th, show
18 regions where it is possible to estimate the PM_{10} concentrations using MAIAC, but where
19 MODIS data at 10 km is not available. This suggest MAIAC's better potential to serve PM_{10}
20 studies in the Po Valley, which is characterized by high cloud cover values for many days
21 during a year, especially during the fall and winter seasons where PM values are maximum.

22 To assess the goodness of fit of the estimated values, two statistical indicators such as the Root
23 Mean Square Error (RMSE) and the coefficient of determination (R^2) were calculated between
24 the predicted PM_{10} concentrations and the observations. The seasonal results of the used
25 statistical indicators are listed in Table 4. The RMSE ranges from 6.91 in summer to 8.58 $\mu\text{g}/\text{m}^3$
26 in spring for MYD04, and from 6.63 in summer to 15.10 $\mu\text{g}/\text{m}^3$ in winter for MAIAC. Overall,
27 the results indicate a good fit between predicted PM_{10} concentration values and the
28 observations. In particular, looking at MAIAC RMSE values, the high-spatial resolution
29 product provides slightly better RMSE values on spring and summer, and worst for the fall and
30 winter seasons. For instance, in winter MAIAC has a RMSE which is 50% higher than the
31 MODIS result. For both the retrievals, the lowest error was obtained in summer, where the

1 pollutant concentrations reach the lowest levels and the meteorological condition of cloudless
2 permits the highest number of available remotely sensed data. After the normalization by the
3 ZPBL on both MYD04 and MAIAC AOD retrievals, the RMSE range changes as from 5.33 in
4 winter to 8.33 $\mu\text{g}/\text{m}^3$ in spring and from 6.45 in summer to 11.45 $\mu\text{g}/\text{m}^3$ in winter, respectively.
5 The introduction of the meteorological variable on the AOD retrieval, not only increments the
6 PM – AOD correlation and improves the temporal and spatial trends, but also reduces the
7 existing error between predicted and measured PM_{10} concentrations. This is true for both
8 retrievals. Also in this case, MAIAC is slightly better in spring and summer, but worse in fall
9 and winter where the AOD retrieval rate is less. The discrepancy between the winter RMSE for
10 MODIS and the winter RMSE for MAIAC is still around 47%, also after the normalization.
11 While MAIAC obtained the lowest error in summer, MODIS did it in winter, apparently in
12 contradiction to what stated before. Regarding the coefficient of determination, the results show
13 that R^2 is relatively low – ranging from 0.46 down to 0.04 for MODIS, and from 0.26 to 0.16
14 for MAIAC. Both retrievals show that the highest R^2 was obtained in the summer, with a
15 maximum number of AOD retrievals, whereas the lowest was obtained in winter, with a
16 minimum number of AOD retrievals. On average, MAIAC show slightly worse results in spring
17 and summer. Yet, an improvement was obtained for the fall and winter seasons. While the
18 normalization by the ZPBL variable seems to slightly improve the R^2 values for MODIS
19 retrievals (except in winter), on average in MAIAC the statistical indicator become worse, in
20 each season.

21 **4 Concluding Remarks**

22 Until recently, the MODIS satellite AOD data product, with 10 km resolution, was the main
23 source of global satellite aerosol data used by the air quality community. The new MAIAC
24 AOD product, at 1 km resolution, provides a significantly higher resolution that may be more
25 appropriate for urban air quality studies. This paper analyzed the effect of spatial resolution on
26 the correlation between remotely sensed AOD and ground-based PM_{10} concentration
27 measurements and the estimation of the PM_{10} concentrations from the high-spatial resolution
28 at 1 km product over the Po valley domain, in northern Italy. Three years, from 2010 to 2012,
29 of MODIS Aqua and MAIAC AOD retrievals were used. The study also focused on seasonal
30 trends in the Po valley, and their effect on the accuracy of the retrievals.

31 Based on this study, the following conclusions were drawn:

- 1 1. A direct comparison between coarse MYD04_L2 10 km AOD and high-resolution MAIAC
2 1 km AOD for all collocated PM vs. AOD pairs for the same period of analysis and sites
3 showed that both retrievals have pretty low correlation coefficients, if PM-AOD points are
4 not binned into a number of AOD ‘classes’;
- 5 2. The link between surface measurements and AOD data alone not suitable for quantitative
6 analysis. The normalization of the optical parameter AOD by the PBL depth significantly
7 improves the R^2 , and is also able to capture seasonal changes in the PBL height over the Po
8 Valley. Similar global correlation coefficients, $R^2 = 0.96$ and $R^2 = 0.95$, were obtained for
9 standard MODIS and MAIAC retrievals, respectively, when considering all the period and
10 locations.
- 11 3. The seasonal temporal analysis showed opposite trends for non-normalized monthly mean
12 AOD versus the PM_{10} mass concentrations. This strengthened the need to always apply the
13 mixing layer correction in order to achieve a suitable AOD monthly mean trend, resulting
14 proportional with the PM one.
- 15 4. The study of how the relationship of AOD and dehumidified PM at surface is affected by
16 relative humidity (RH) showed that seasonal changes in AOD are more prominent
17 compared to seasonal changes in PM_{10} mass concentrations, and that the RH correction on
18 the PM mass concentration measurement did not significantly improve the PM – AOD
19 correlation in this area, which is affected by a rather homogeneous relative humidity
20 concentration all year long (Fig. 4 b).
- 21 5. The seasonal spatial analysis showed acceptable agreement between the MAIAC AOD
22 retrieval after the PBL normalization and the PM_{10} measurements after the RH correction.
23 This agreement is even better during the winter season, when the pollutant values are
24 maximum, especially close to the major urban and industrialized sites.
- 25 6. The results obtained from the linearization procedure to estimate the PM_{10} concentrations
26 showed that – if averaged over the whole domain – the MAIAC predicted PM_{10}
27 concentrations at 1 km resolution are comparable with MODIS predicted PM_{10}
28 concentrations at 10 km resolution. However, local values, relevant in a limited
29 geographical domain such as the Po Valley, are substantially better when using the high
30 spatial resolution MAIAC AOD product than MODIS, as more spatial details near the major

1 urban and industrialized areas in the domain are captured both by the satellite retrieval and
2 by its seasonal PM₁₀ estimation function.

3 Therefore, the study suggested that MAIAC has a good potential to provide data for PM₁₀
4 concentration predictions and so it may be later be used to serve PM₁₀ health effects studies in
5 a narrow, populated, industrialized and urbanized domain, like the Po Valley in Italy.

6 In future studies, we will focus on two aspects. First, we will investigate further extensions of
7 the satellite-retrieved AOD and PM₁₀ relationships, such as by dividing the entire domain into
8 areas to study the effects of different levels of urbanization on surface brightness and thus
9 quality of the aerosol retrieval (cf. Lyapustin et al., 2011b). Second, the use of higher resolution
10 PBL estimates over Italy (Kukkonen et al., 2012, Baldauf et al., 2011, Barthlott et al., 2010)
11 will be used to explore the relationship for each administrative district over Po valley separately.
12 The aim is to understand if the use of finer PBL depth and satellite – retrieved AOD (MAIAC)
13 helps to better characterize the spatial variability of aerosol pollution within the Po Valley.

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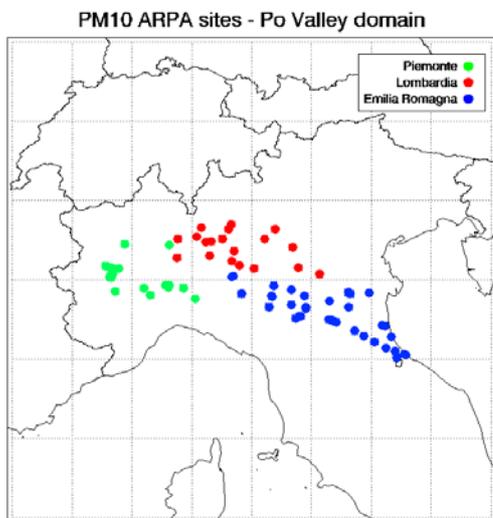
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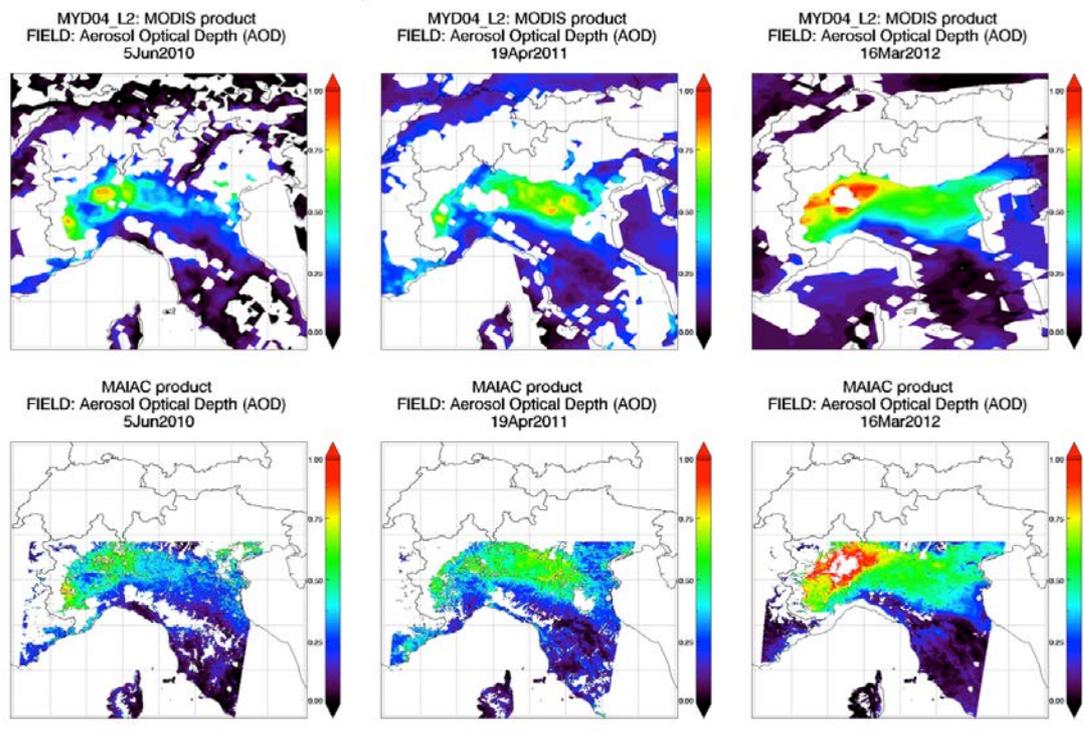
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3 Figure 1. In the figure, the geographic study domain. The colored dots mark locations of the
4 ARPA PM₁₀ ground-based stations; they are grouped into different color to respect the
5 administrative division of the sites (Piemonte in green, Lombardia in red and Emilia Romagna
6 in blue).

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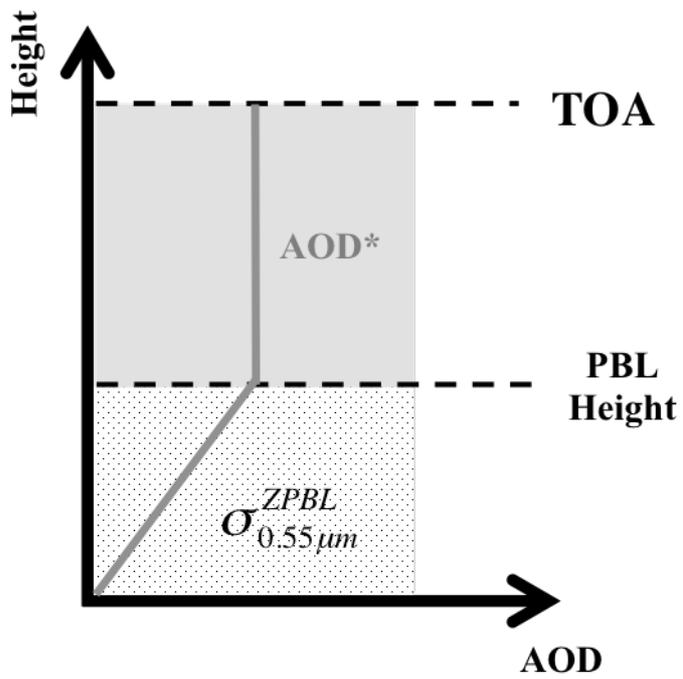
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Figure 2. MYD04 10 km (on the top) and MAIAC 1 km (on the bottom) AOD retrievals for three example days, one per each year of analysis (2010, 2011 and 2012). The higher resolution data reveals a substantial spatial variability of AOD, which is not as well captured using a coarse 10 km scale, especially near the urban areas, and near the sea coast.



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3 Figure 3. Schematic aerosol vertical profile where the aerosols are considered well-mixed and
 4 confined in the PBL height.

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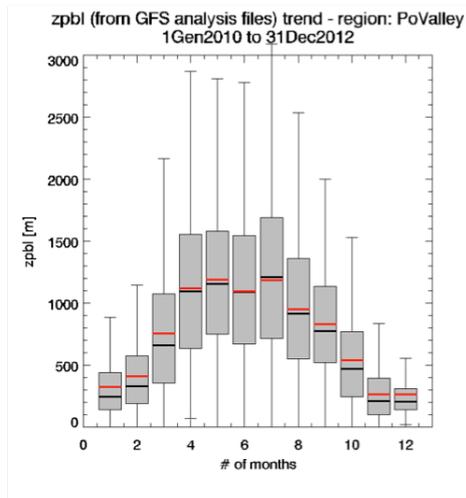
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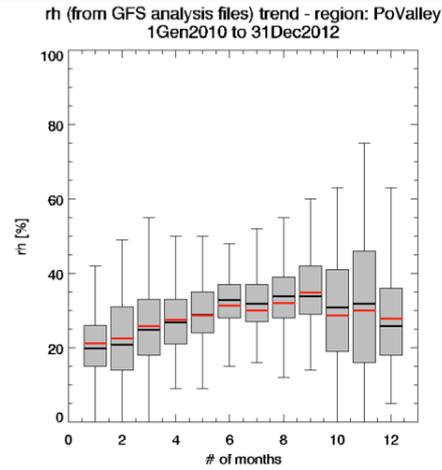
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(a)



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3 Figure 4. PBL depth and RH monthly trends, from 2010 and 2012. For each candlestick, the
4 10th, 25th, 50th (median, horizontal black thick line), 75th, 90th are shown as horizontal black
5 bars. The red thick line represents the monthly mean value. The graph was realized considering
6 all the equals months in the period of analysis.

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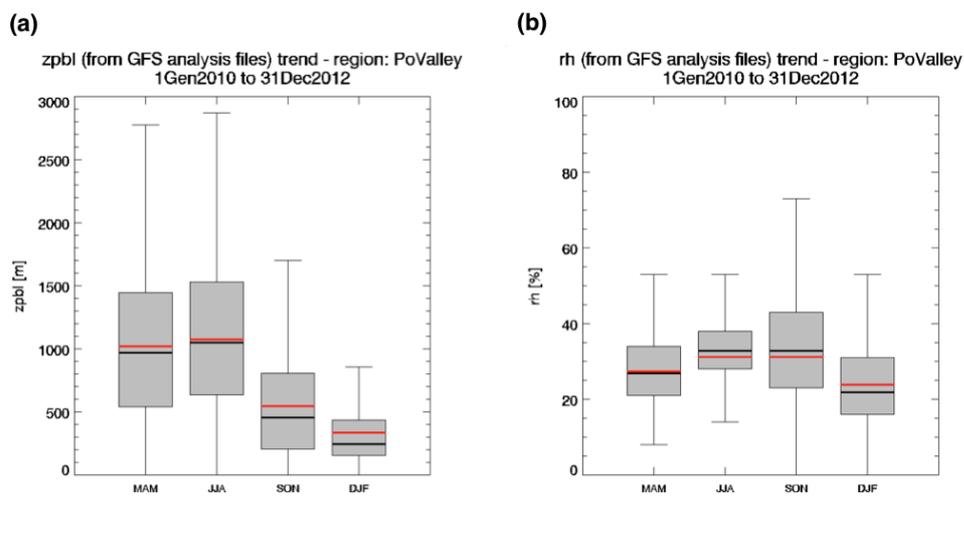
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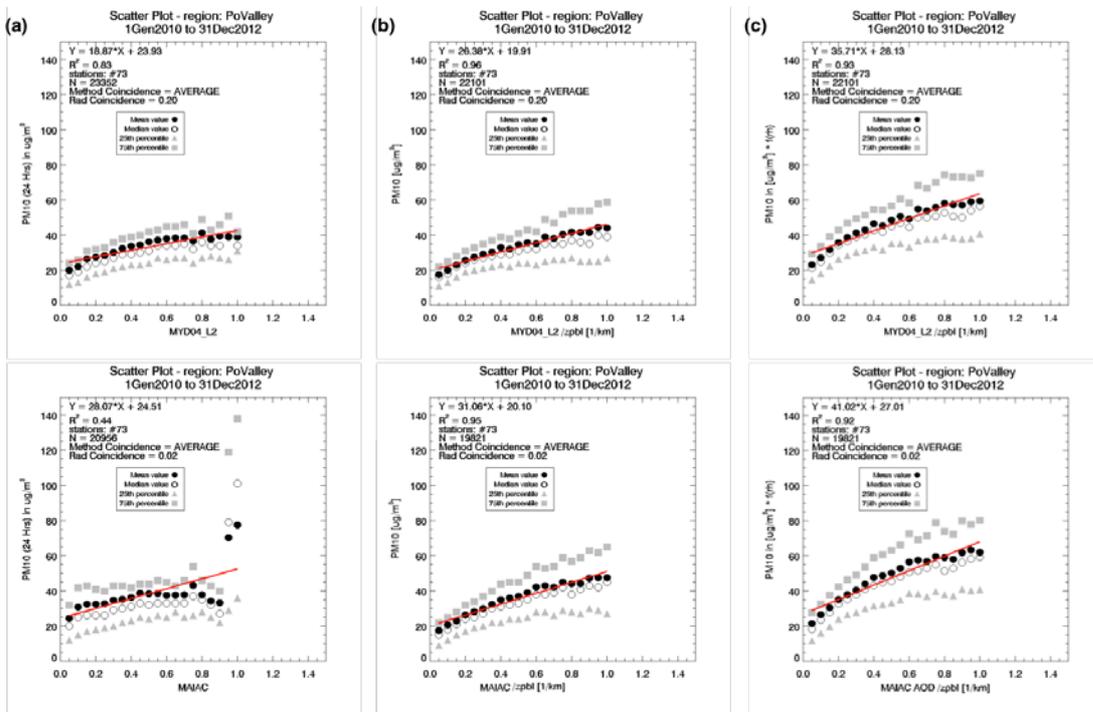
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Figure 5. PBL depth and RH seasonal trends, from 2010 and 2012. MAM (March, April, May) refers to the spring months; JJA (June, July, August) refers to the summer months; SON (September, October, November) refers to the fall month and DJF (December, January, February) refers to the winter months. For each candlestick, the 10th, 25th, 50th (median, horizontal black thick line), 75th, 90th are shown as horizontal black bars. The red thick line represents the seasonal mean value. The graph was realized considering all the equal months in the period of analysis (3 years) and then grouped into the four seasons.

1 Table 1. Global statistics values for the direct PM₁₀ – MYD04 and PM₁₀ – MAIAC AOD linear
 2 correlations, with and without ZPBL normalization and RH correction, for the period from 2010
 3 to 2012, for the same days and locations.

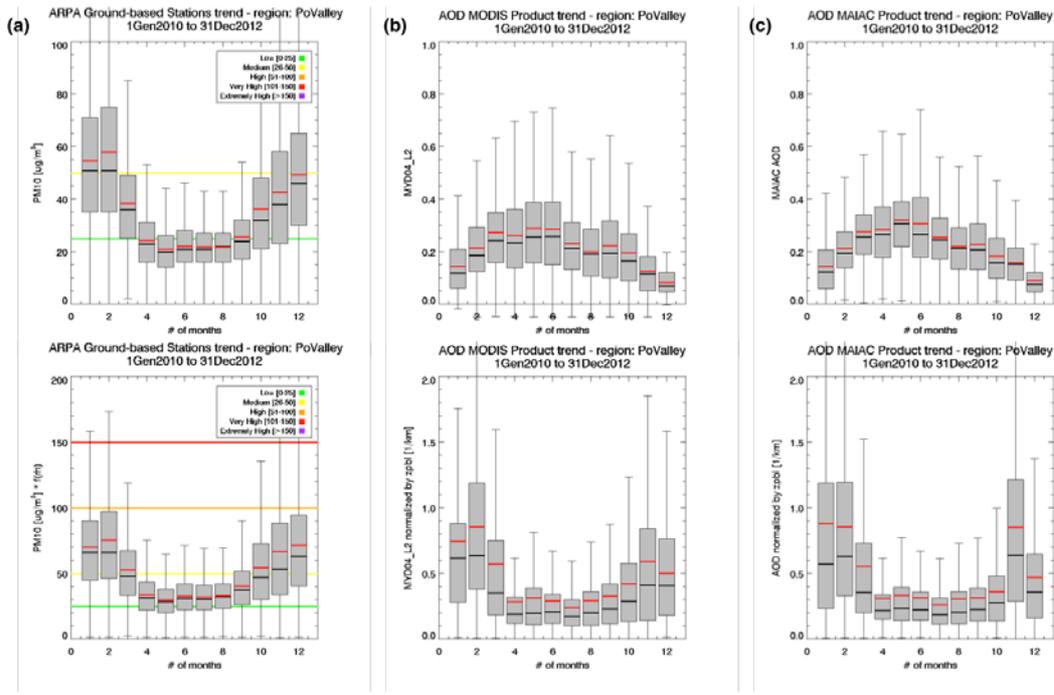
Correlation type			Statistics			
			Intercept	Slope	R ²	<i>p</i> -value
MYD04	2010-2012	PM ₁₀ ; AOD	21.35	30.23	0.09	<0.0001
		PM ₁₀ ; AOD _{ZPBL}	22.59	17.94	0.21	<0.0001
		PM ₁₀ *f(RH); AOD _{ZPBL}	31.63	23.98	0.22	<0.0001
MAIAC	2010-2012	PM ₁₀ ; AOD	28.49	20.81	0.02	<0.0001
		PM ₁₀ ; AOD _{ZPBL}	23.64	21.71	0.29	<0.0001
		PM ₁₀ *f(RH); AOD _{ZPBL}	31.96	27.53	0.29	<0.0001

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Figure 6. Correlation between PM₁₀ and MYD04_L2 and MAIAC AOD at Po Valley ground-based stations from 2010 to 2012. Bin scatter plot analysis presented for both retrievals (MYD04_L2 top panels, MAIAC bottom panels). Panels (a): simple correlation between PM₁₀ and AOD; panels (b) correlation between PM₁₀ and AOD normalized by ZPBL; panels (c) correlation between PM₁₀ corrected by RH and AOD normalized by ZPBL.



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Figure 7. PM₁₀ and AOD (both for MYD04_L2 and MAIAC retrievals) monthly trends, from 2010 and 2012. In panels (a), the PM₁₀ monthly trend (top) is compared to the PM₁₀ trend multiple by the RH correction (bottom). In panels (b) and (c) the AOD monthly trends, for MODIS and MAIAC AOD respectively, are compared with the AOD trend normalized by the PBL depth value. For each candlestick, the 10th, 25th, 50th (median, horizontal black thick line), 75th, 90th are shown as horizontal black bars. The red tick line represents the monthly mean value. The graph was realized considering all the equals months in the period of analysis.

1 Table 2. PM₁₀ and AOD total available data

Total presumed data (tpd)	N_{tot} = 73 (#stations) * 1096(days) = 80008
total PM ₁₀ retrieved data (trd_PM ₁₀)	N _{PM10} = 74357
(trd_PM ₁₀)/(tpd)	93%
total MYD04 retrieved data (trd_AOD)	N _{MYD04} = 25697
(trd_MYD04)/(tpd)	32%
total MAIAC retrieved data (trd_AOD)	N _{MAIAC} = 22547
(trd_MAIAC)/(tpd)	28%

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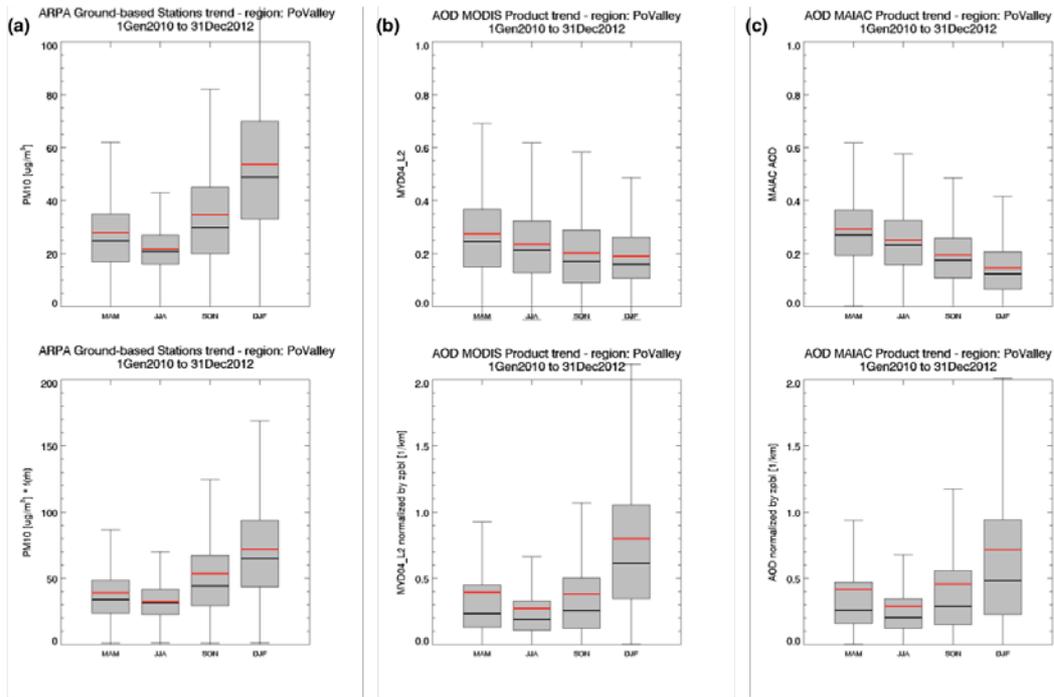
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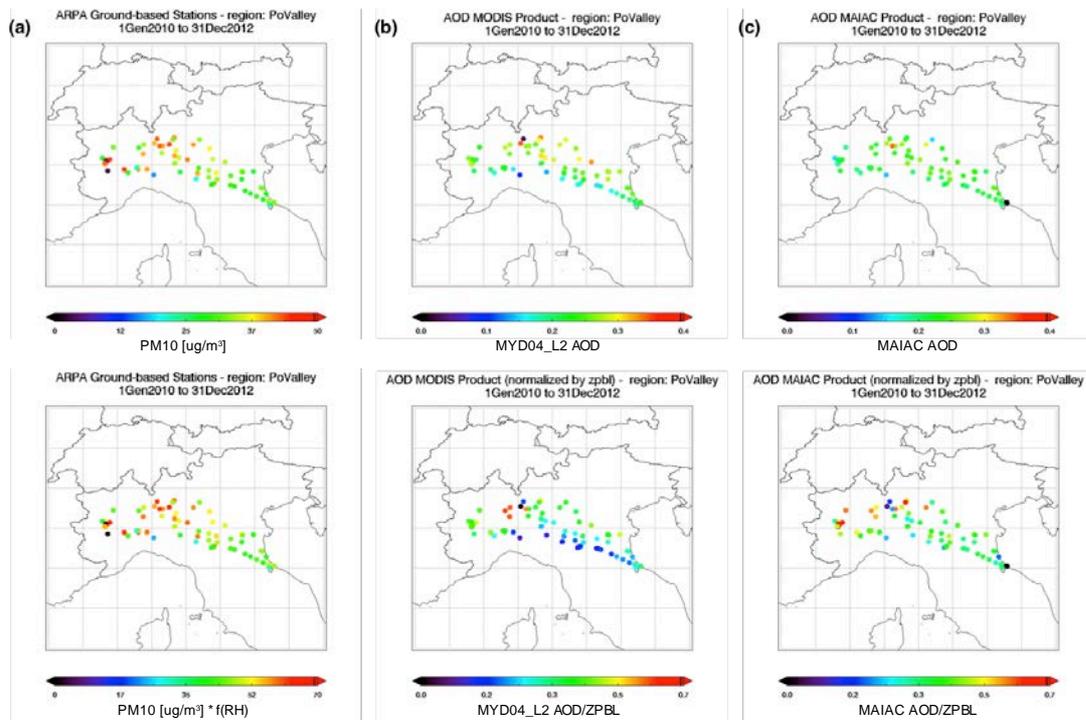
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Figure 8. PM_{10} and AOD (both for MYD04_L2 and MAIAC retrievals) seasonal trends, from 2010 and 2012. In panels (a), the PM_{10} seasonal trend (top) is compared to the PM_{10} trend multiple by the RH correction (bottom). In panels (b) and (c) the AOD monthly trends, for MODIS and MAIAC AOD respectively, are compared with the AOD trend normalized by the PBL depth value. MAM (March, April, May) refers to the spring months; JJA (June, July, August) refers to the summer months; SON (September, October, November) refers to the fall month and DJF (December, January, February) refers to the winter months. For each candlestick, the 10th, 25th, 50th (median, horizontal black thick line), 75th, 90th are shown as horizontal black bars. The red thick line represents the monthly mean value. The graph was realized considering all the equal months in the period of analysis (3 years) and then grouped into the four seasons.



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3 Figure 9. Panels (a): annual mean PM₁₀ concentration measured from ARPA ground-based
 4 stations, without (top) and with (bottom) the RH correction. Panels (b) and (c): annual mean
 5 MODIS and MAIAC AOD retrievals, respectively, without (top) and with (bottom) the
 6 normalization from the PBL depth. All the results refer to the entire period and locations of
 7 analysis.

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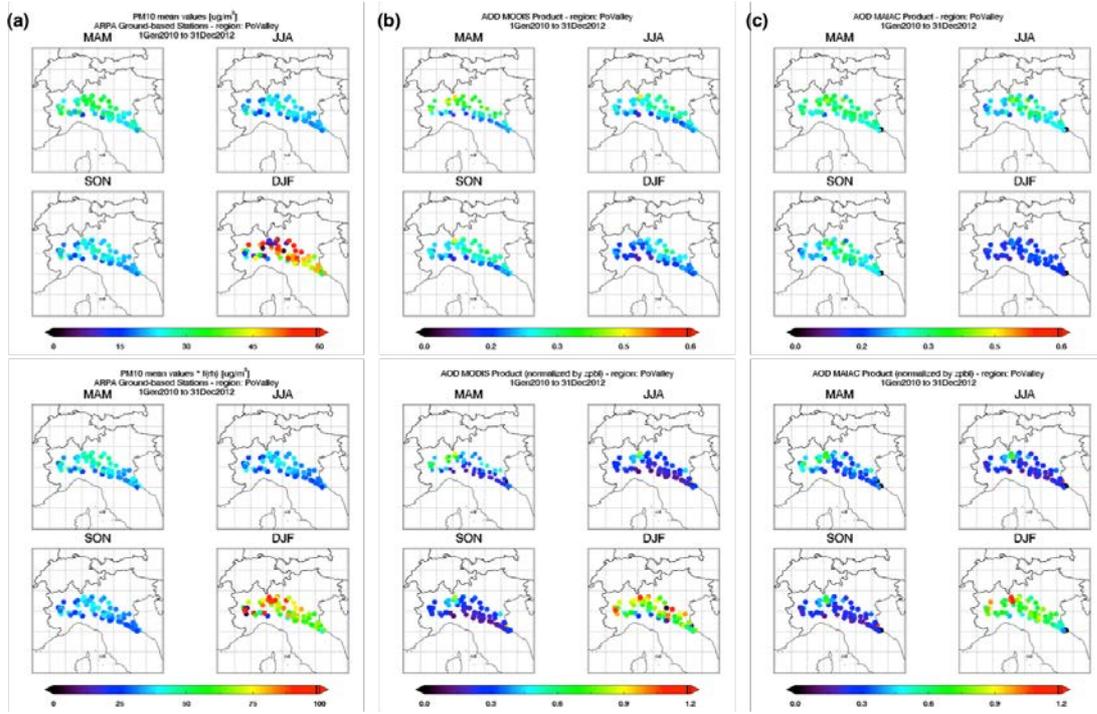
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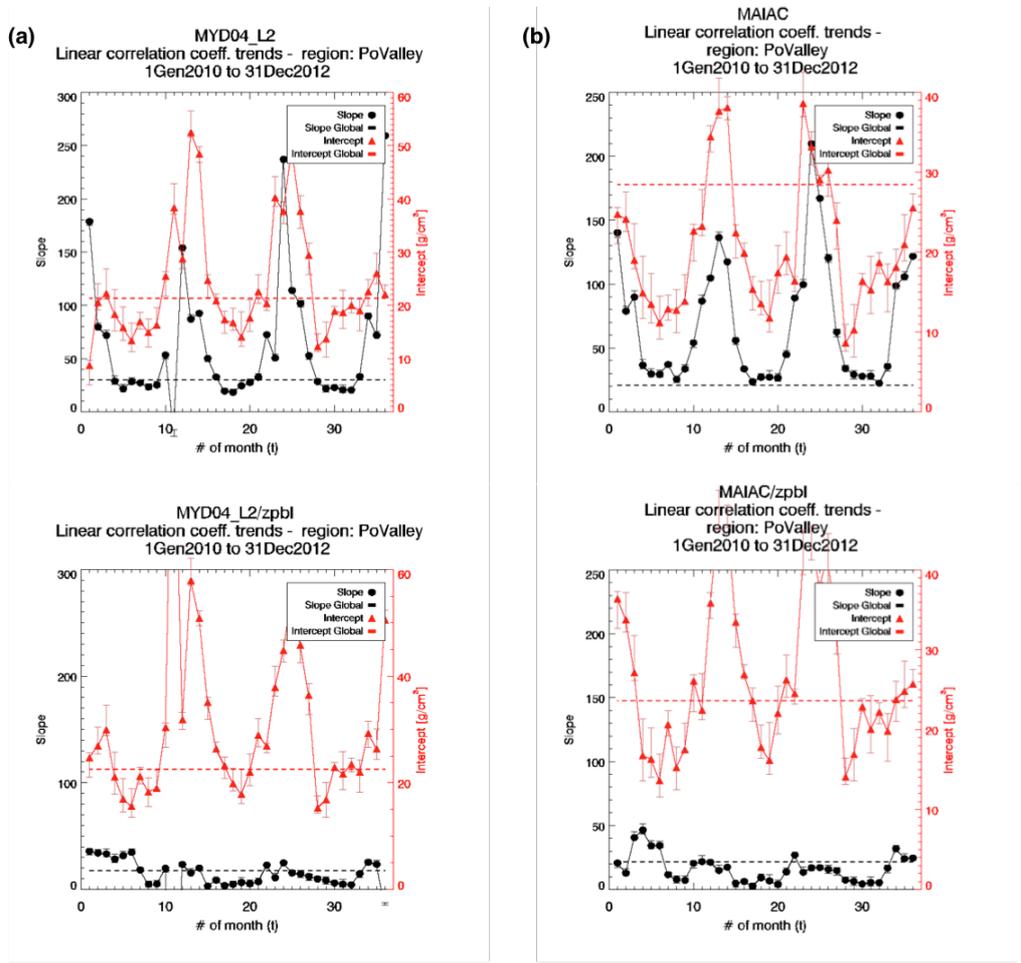
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3 Figure 10. Panels (a): seasonal mean PM_{10} concentration measured from ARPA ground-based
 4 stations, without (top) and with (bottom) the RH correction. Panels (b) and (c): seasonal mean
 5 MODIS and MAIAC AOD retrievals, respectively, without (top) and with (bottom) the
 6 normalization from the PBL depth. In each panels, the mean values are grouped into the four
 7 seasons: MAM (March, April, May) refers to the spring months; JJA (June, July, August) refers
 8 to the summer months; SON (September, October, November) refers to the fall month and DJF
 9 (December, January, February) refers to the winter months.

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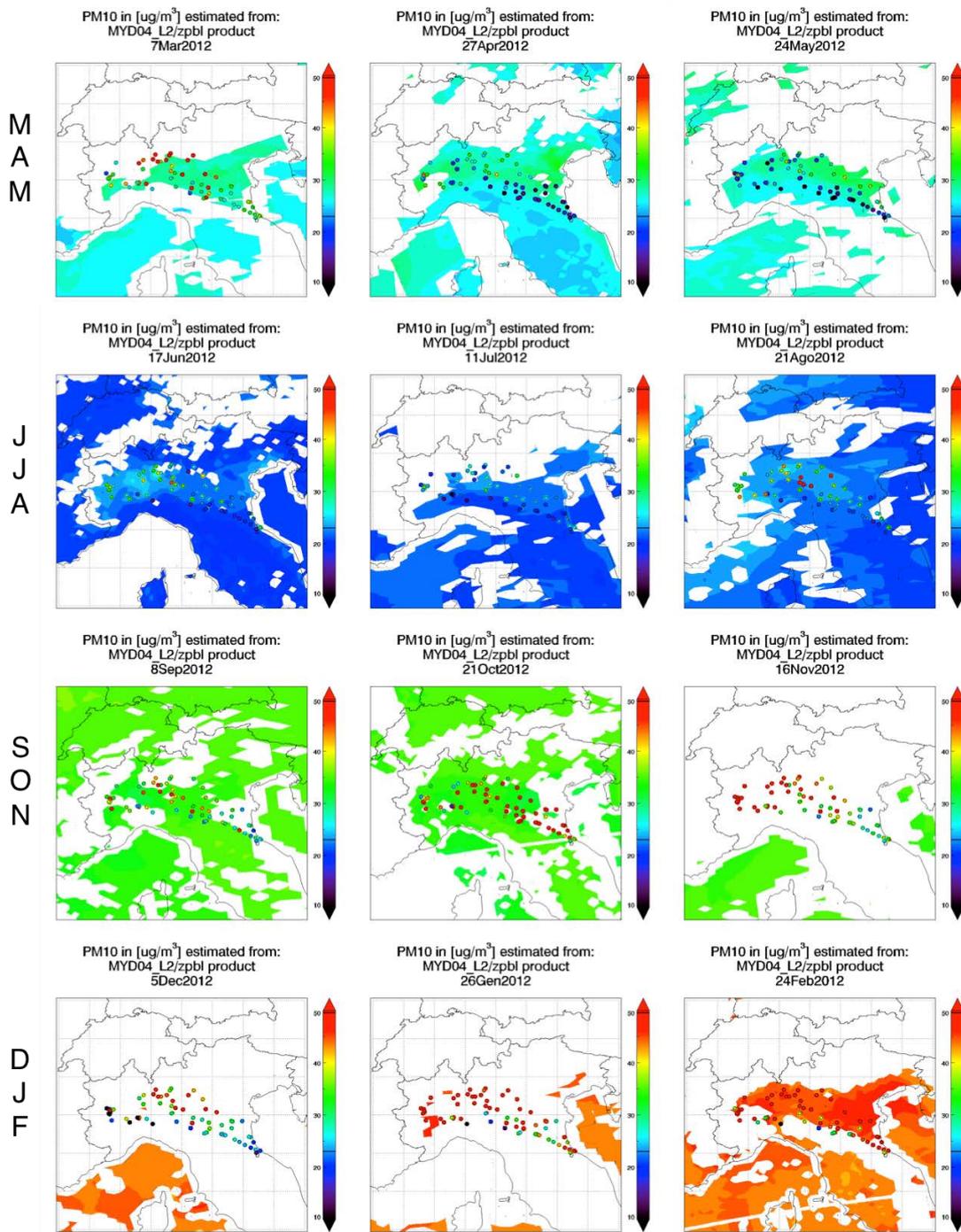
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Figure 11. Linear correlation coefficients monthly trends for the MYD04_L2 and MAIAC AOD dataset. Coefficient “slope” of the linear correlation in black; in red, the “intercept” coefficient, both for the period from 2010 to 2012. The dash lines on the graph refer to the intercept and slope values obtained from the entire dataset, for the entire period.

1 Table 3. Seasonal statistics coefficients obtained from the linear correlation PM_{10} –
 2 MYD04/MAIAC AOD datasets, with and without the ZPBL normalization, considering the
 3 total period of analysis from 2010 to 2012, and locations.

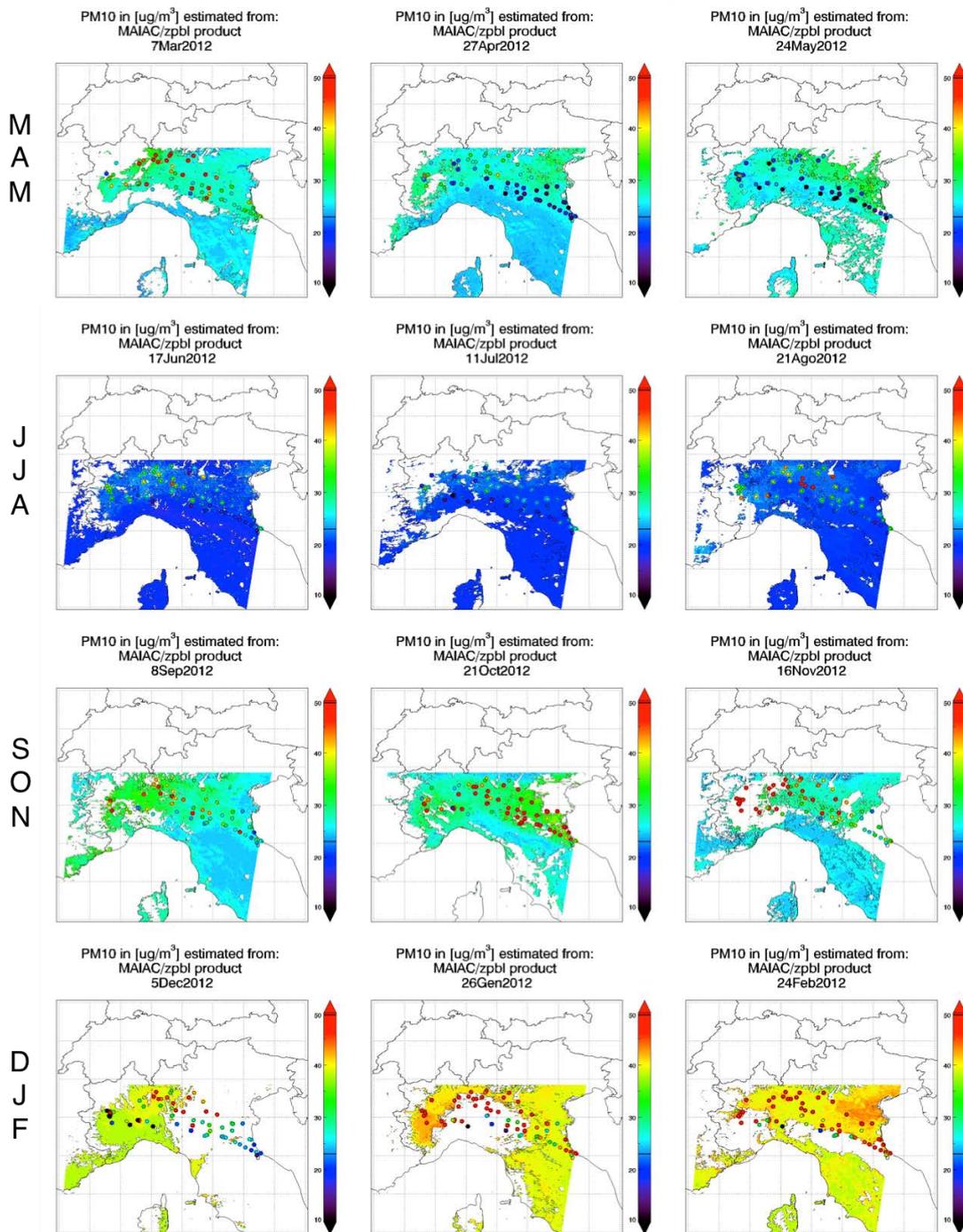
Correlation type		Statistics					
		Intercept (q)		Slope (m)		R ²	
		MYD04_L2	MAIAC	MYD04_L2	MAIAC	MYD04_L2	MAIAC
MAM	PM ₁₀ ; AOD	19.46	16.46	36.53	43.94	0.20	0.19
	PM ₁₀ ; AOD _{ZPBL}	24.63	23.18	15.63	18.36	0.13	0.12
JJA	PM ₁₀ ; AOD	16.85	14.47	23.82	27.93	0.19	0.21
	PM ₁₀ ; AOD _{ZPBL}	20.37	19.00	10.21	10.06	0.08	0.09
SON	PM ₁₀ ; AOD	25.70	21.10	45.43	72.08	0.19	0.20
	PM ₁₀ ; AOD _{ZPBL}	36.28	25.17	-8.04	19.79	0.21	0.19
DJF	PM ₁₀ ; AOD	34.03	30.83	145.08	133.08	0.31	0.18
	PM ₁₀ ; AOD _{ZPBL}	43.25	38.64	19.02	18.16	0.27	0.19

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Figure 12. Estimated pollutant PM_{10} values from the MYD04 AOD retrieval normalized by the PBL depth. On the basemap the PM_{10} ground-based sites measurements are overlapped. An example day per each month of the year (2012) is reported, dived into the four seasons.



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Figure 13. Estimated pollutant PM₁₀ values from the high-resolution MAIAC AOD retrieval normalized by the PBL depth. On the basemap the PM₁₀ ground-based sites measurements are overlapped. An example day per each month of the year (2012) is reported, divided into the four seasons.

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2 Table 4. RMSE seasonal values obtained between the measured and estimated PM₁₀
 3 concentrations. The pollutant was estimated by both MYD04_L2 and MAIAC AOD dataset,
 4 with and without the ZPBL normalization, considering the total period of analysis from 2010
 5 to 2012.

		RMSE [$\mu\text{g}/\text{m}^3$]		R ²	
Correlation type		MYD04_L2	MAIAC	MYD04_L2	MAIAC
MAM	PM ₁₀ ; AOD	8.58	8.06	0.29	0.23
	PM ₁₀ ; AOD _{ZPBL}	8.33	7.89	0.31	0.18
JJA	PM ₁₀ ; AOD	6.91	6.63	0.46	0.26
	PM ₁₀ ; AOD _{ZPBL}	6.78	6.45	0.46	0.20
SON	PM ₁₀ ; AOD	7.82	9.03	0.17	0.22
	PM ₁₀ ; AOD _{ZPBL}	6.44	7.22	0.18	0.16
DJF	PM ₁₀ ; AOD	7.54	15.10	0.04	0.16
	PM ₁₀ ; AOD _{ZPBL}	5.33	11.45	0.04	0.13

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