Polar Multi-Sensor Aerosol Product: Validation Report

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Document Change Record

Issue / Revision	*Date*	*DCN. No*	*Changed Pages / Paragraphs*
V1	12 February 2014		Initial version for PVRB board.
V1A	17 February 2014		Update after PVRB board meeting • Added disclaimer in Limitations section 1.3 • Added tables with satellite ID spatial resolution and information on coverage • Added captions to figures • Updated AERONET geographical distribution plots • Added AERONET summary plots • Editorial changes and corrections
V2	18 December 2014		Version prepared following PVRB meeting and for operational status.
V3	02 March 2016		Initial version for PVRB board for PMAp version 2. This extends the AOD algorithm for footprints over ocean to footprints over land.
V3A	22 April 2016		Update after PVRB board and release of PMAp v2.
V4	23 January 2017		Updated and completely reworked version for the release of PMAP v2.1. Results from the external study by MPI Mainz have been summarized and added to this report together with results of other entities (CAMs) and of the internal validation efforts.
V4A	3 February 2017		• Section 2.4 and 2.4.1 Summary of the validation outcomes • Section 4.6 Aeronet comparison results from internal online monitoring added • Section 5 Conclusions and Recommendation added.
V4A	09 February 2017		Update after PVRB board meeting • Section 2.4 Summary of the validation outcomes update with RMS and over sea results • Section 4.6 updated with plots of RMS as a function of AOD values • Section 4.7 added with AERONET comparison results over sea surface from the Validation Report v3A
V5	17 June 2019		Update version for the PMAP-C version 2.1. for dissemination to restricted users.
V5B	27 July 2019		Update version for PMAp-C for full dissemination to all users

V5C	30 Sep 2019		Update after PVRB board meeting. Minor comments across document and improved figures.
V6	27 April 2021		Updated and completely reworked version for PVRB board for the release of PMAp version 2.2.4.

Contents

List of figures

List of tables

1 INTRODUCTION

1.1 Purpose

This document describes the validation of the Polar Multi-sensor Aerosol product (PMAp) for Metop A, B and C. It analyses the quality of the data produced in the ground segment and their consistency with the Metop-A, Metop-B, and Metop-C counterparts as a basis for an appropriate decision on the distribution of the operational product to end-users.

1.2 Scope

This document describes the current status of the product to inform the end-users about the quality of the data product including its strengths and known shortcomings.

- The analysis has the following general focus: it is limited to the AOD product. Additional products and parameters are not taken into account. For details, see Section 3.
- The results presented herein are based on the outcome of an internal validation exercise set up for a reference data-set with the aim of monitoring the performance and quality of the PMAp product corresponding to different PMAp releases of PMAp-A and –B.
- PMAp-A and –B will be used as a proxy for the validation of PMAp-C.

1.3 Limitations

This report focuses on data collected and processed for a reference data-set composed by two so-called validation periods, i.e., June-September 2013 and February-May 2015. PMAp products for these periods have been processed in the offline technical computing environment (TCE) using PMAp version 2.2.4 over land and water surfaces. Since the PMAp-C was not available over these time periods, the validation of the product will be based on its comparison with the PMAp-A and –B products which, in turn, could be validated over these two periods.

The level 2 AOD product retrieved with PMAp version 2.2.4. for Metop-A and –B has been compared to AERONET observations. Since the number of AERONET measurement sites in oceanic areas is limited, the level 2 AOD AERONET comparison might be biased towards an almost only over land comparison. Furthermore, additional PMAp retrieved products (in particular cloud optical depth, cloud temperature, cloud fraction) are currently provided as auxiliary information and have not undergone validation yet, but they are considered useful for monitoring purposes and may be useful to the users within these restrictions.

1.4 Applicable Documents

Ref	*Title*	*Document ID*
AD 1	Polar Multi-Sensor Aerosol Product: User Guide	EUM/TSS/MAN/14/742654
AD 2	Polar Multi-Sensor Aerosol Product v2_2_4_ATBD	EUM/TSS/SPE/14/739904
AD 3	Polar Multi-Sensor Aerosol Product: User Requirements	EUM/TSS/REQ/13/688040

1.5 Reference Documents

Ref	*Title*	*Document ID*
RD 1	Review of Aerosol Optical Properties Retrieval Algorithms	EUM/MET/TEN/09/0797, v2
RD 2	EPS Product Development Plan	EUM/STG/60/12/DOC/19
RD 3	AVHRR Level 1b Product Guide	EUM/OPS-EPS/MAN/04/0029
RD 4	Polar Multi-Sensor Aerosol PPF 2.0 Software Release	EUM/TSS/DOC/14/688377
RD 5	O. Hasekamp, O. Tuinder and P. Stammes, *Final report of the O3M-SAF activity: Aerosol retrieval from GOME-2: Improving computational efficiency and first application*	EPS.MIS.SPE.97228
RD6	CAMS feedback on PMAp v2.2.2	EUM/RSP/DOC/21/1225050
RD7	CAMS feedback on PMAp v2.2.4	EUM/RSP/DOC/21/1225051

1.6 Document Structure

This document contains the following sections:

Section 1	This introduction
Section 2	An overview of the retrieval concept with its known anomalies and a short summary of the validation outcome, a brief product overview, including input data and output products.
Section 3	Complete description of the verification and validation, including the process followed, known limitations, and results.
Section 4	Contains conclusions and recommendations based on the validation.

1.7 Abbreviations and Acronyms Used in this Document

Acronym	*Full Name*
AER	Aerosol Product
AERONET	**AE**rosol **RO**botic **NET**work
AOD	Aerosol Optical Depth
ARA	Aerosol Retrieval Algorithm
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
BT	Brightness Temperature
BTD	Brightness Temperature Difference
CFR	Cloud fraction ratio
CMa	Cloud Mask
CyI	Cyprus Institute
COD	Cloud optical depth
ECHAM5	The fifth-generation atmospheric general circulation model
EMAC	ECHAM5/MESSy2 Atmospheric Chemistry General Circulation Model
GOME	Global Ozone Monitoring Experiment
GS3	Ground segment of EUMETSAT 3 (for VERification)
GS2	Ground segment of EUMETSAT 2 (copy of GS1 for VALidation)
GS1	Ground segment of EUMETSAT 1 (for OPErational platforms)
ITT	Invitation to tender
IASI	Infrared Atmospheric Sounding Interferometer
IR	Infrared
LER	Lambertian Equivalent Reflectance
LUT	Look-Up Table
MAN	Marine Aerosol Network
MESSy	Modular Earth Subsystem Model
MPIC	Max Planck Institute for Chemistry
METOP	Meterological Operational Satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
MPIC	Max-Planck Institute for Chemistry, Germany
NIR	Near Infrared
PMD	Polarization Monitoring Device
PMAp	Polar Multi-sensor Aerosol Product
PPF	Product Processing Facility
RAL	Rutherford Appleton Laboratory, Great Britain
RAZI	Relative Azimuth Angle
RTM	Radiative Transfer Model
SAF	Satellite Application Facility
SZA	Solar Zenith Angle
TIR	Thermal Infrared
TOA	Top Of Atmosphere
UV	Ultraviolett
VIS	Visible (solar)
VZA	Viewing Zenith Angle

2 EXECUTIVE SUMMARY

2.1 Instrumental Description and Target Resolution

The PMAp algorithm is configured as a multi-instrument, but single-platform aerosol retrieval algorithm. PMAp currently uses AVHRR/3, GOME-2 and IASI on Metop-A, Metop-B and Metop-C.

The AVHRR/3 is a six-channel scanning radiometer providing three solar channels in the visible/near-infrared region and three thermal infrared channels with spatial resolutions up to 1.1 km. GOME-2 is a medium-resolution double UV-VIS spectrometer, fed by a scan mirror which enables across-track scanning in nadir, as well as sideways viewing for polar coverage and instrument characterisation measurements using the moon. The PMAp algorithm uses the so-called Polarization Monitoring Devices (PMD) which provides reflectances and stokes fraction in 16 different bands ranging from the UV to the red edge (311 nm to 805 nm). IASI is an Interferometer with 8461 channels, plus an embedded imager. In the PMAp algorithm use is made of 3 IASI TIR channels in the band 8.26 µm to 15.50 µm, for which collocations to the GOME PMD are calculated, to provide a better classification of volcanic ash aerosol.

The PMAp product is produced as GOME-2 product with the spatial resolution of the GOME-2 PMD footprint:

Satellite Platform	*Spatial resolution (GOME-2 PMD spatial resolution)*	*Swath*
Metop-A	5 km × 40 km[1]	960 km
Metop-B	10 km × 40 km	1920 km
Metop-C	10 km × 40 km	1920 km

Note on the use of tandem operations: Due to the different swath dimension reported above, when using only Metop-A data, we get global coverage for the chosen latitudes (from +70 to –70) approximately for three days. When using only Metop-B data, we get global coverage at these latitudes approximately for 1.5 days. Using the two instruments in tandem, or all of the three Metops, we get good daily global coverage with some product-inherent gaps. These gaps are due to thick clouds and problematic observation geometries (sun-glint conditions), depending on the conditions of the measurements. The combination of the three platforms allows for full daily global coverage.

2.2 Summary of the Algorithm

The algorithm consists of three steps:

- Step 1: A pre-classification is applied based on AVHRR, IASI and the GOME-2 UV index. This includes the detection of clouds, calculation of cloud correction factors, detection of dust and ash events as well as a pre-classification of possible aerosol types.
- Step 2: A set of AODs is retrieved assuming different aerosol types and microphysical properties using one band only. Over land, the band (8 or 7) is selected dependent on values taken from a surface climatology to minimize the impact of the surface to the retrieval but taking other uncertainties into account as well. Over ocean, a PMD band (12) with appropriate overlap to

[1] Since 15 June 2013. Before this date, the spatial resolution of GOME-2 PMDs on Metop-A was 10 km × 40 km with a 1920 km swath.

AVHRR/3 band 1 is selected to get most accurate cloud corrections and taking into account the low surface reflectance for non-glint conditions in the red/NIR spectral region. For clear sky pixels over ocean, a set of chlorophyll corrections are fitted in addition to the AOD simultaneously using two additional bands. Each of these AODs is retrieved with respect to different aerosol types. At this point of the retrieval it is unknown which aerosol type is the best representation of the given scene. The procedure is simplified for partly cloudy pixels and specific observation geometries.

- Step 3: One of the AODs retrieved within step 2 is selected–this is the one which best fits the satellite measurements (using a lot of bands in reflectance and stokes fraction in the visual spectral range from the blue to red edge or near infrared).

A more detailed introduction to the algorithm can be found in [AD 1]. The full description of the scientific algorithm is available in [AD 2].

2.3 Known anomalies and Updates of the PMAp Processor since the introduction of version 1

This section describes bug fixes / updates of the PMAp processor after the start of test disseminations. Technical details are described in [RD 4].

2.3.1 Release 1.0.6 in February 2014

The cloud optical depth product showed unexpected gaps which were not present in the prototype retrieval. The gaps are only found when processing on AIX machines–not Linux-based systems. This anomaly has no effect on the aerosol products. A fix has been implemented and the gaps are removed on GS1 after installation of the update.

2.3.2 Release 1.0.7 in March 2014

- Bug fix in the AVHRR collocator to avoid uncertainties in the collocation at higher latitudes.
- Switch from PMD-S bands to PMD-P bands because PMDP reflectances are expected to have a smaller error in absolute radiance calibration.

2.3.3 Release 1.0.8 in May 2014

- Bug fixes in PMAp error calculation.
- Bug fixes in the PMAp output (GIADR section).

2.3.4 Release 1.0.9 in November 2014

- Within the validation report, a set of mismatches in the volcanic ash flags are found in particular for Metop-B. This problem is correlated with wrong brightness temperatures in AVHRR CH4 and CH5. We apply a calibration correction for the thermal AVHRR channels [RSP/JA, personal communication]. In addition, a priori values for regression coefficients were used instead of the values from the Level-1 product due to a bug in the PPF. This is corrected in release 1.0.9. The preliminary bias correction for Metop-B has been removed.
- A corrected / improved cloud correction scheme is included in this release.

2.3.5 Release 1.0.10 in January 2015

- Correction of bug fixes in release 1.0.9 removing some problematic routines in the detection of thick aerosol events.

2.3.6 Release 1.0.11 in August 2015

- Technical corrections

- Full usage of the AVHRR snow mask.

2.3.7 Release 2.0.0 – 2.0.1

- Intermediate releases; not used for in this analysis.

2.3.8 Release 2.0.2

- Implementation of the PMAp retrieval over land surfaces.
- New EPS native output data format v.11.0.
- *Quality flags* are renamed *retrieval flags*. This reflects their function better as they should not generally be used as a filter to identify suitable pixels.
- A set of new quality flags is added.
- Some experimental and auxiliary parameters are replaced (e.g. ash temperature by ash flag), new output parameters added (e.g. snow/ice coverage).

2.3.9 Release 2.1.0 (February 2017)

- Surface reflectance homogeneity test
- Rayleigh scattering calculations improved by adding a surface elevation correction function.
- Use is made of a surface reflectance database (namely Lambertian Equivalent Reflectance, LER, database v.1.6) statically masked for a better partition of land/water areas.
- Aerosol class identification upgrade: added volcanic Ash/SO_2 flag as determined by using IASI measurements in the thermal IR range.

2.3.10 Release 2.1.2.-2.1.3

- Over land surfaces, use is made of a surface reflectance database (namely Minimum LER angular database v.2.12) taking into account the dependence of the reflectance on the GOME-2 viewing angle.
- New auxiliary file with correct AVHRR radiometric calibration for PMAp-C.
- Correction of the orbit number for Metop-A.

2.3.11 Release 2.2.4 (6 May 2021)

- A dust detection scheme has been added in the PMAp pre-classification step exploiting IASI measurements.
- To solve hotspot issue in retrieved AOD (serious issue for assimilation of AOD by CAMS), cloud filtering is revisited in the algorithm flowchart and led to improved detection of aerosol contaminated clouds besides upgrade of flags e.g. Aerosol contaminated cloud, volcanic ash contaminated cloud.
- Over land surfaces, the use of a surface reflectance database (namely Minimum LER angular database) has been updated to v.3.0 to be compatible with the database derived from both Metop-A and Metop-B.
- The LER viewing angle dependency is implemented in PMAp. Later, its implementation was reviewed and corrected for anomalies.
- A degradation correction procedure to GOME2 Level 1b data has been integrated for Metop A, B and C with the possibility to:
  (i) update the correction coefficients used in the calculation and;
  (ii) switch off the correction.
- Degradation correction coefficients have been updated to be in line with the latest version derived from re-processed GOME-2 L1b data.

- The need for a radiometric adjustment of GOME-2 PMD-P radiances was recognized without which significant number of pixels with AOD=0 would exist over land; methodology has been developed and applied for Metop-A, B and C.
- The differences between AOD retrieved from Metop-A and B and C have been reduced to have a consistent AOD product from all platforms. This was a consequent of all above-mentioned updates but the key role is played by radiometric adjustment of GOME-2 PMD radiances.

2.4 Summary of the PMAp AOD validation outcome

Aerosol optical depth at 550 nm has been retrieved globally over ocean and land with PMAp v.2.2.4, together with the corresponding aerosol class and several associated output products for Metop-A and Metop-B in these two time periods:

- validation period 1: June – September 2013
- validation period 2: February – May 2015

PMAp AOD values have been globally validated against corresponding AERONET level 2 data. Main outcome of the validation is reported in Table 1 and Table 2 in both validation periods for corresponding AOD over land and over ocean case, respectively.
These results provide a statistical validation of the aerosol product. A wider analysis is needed to conclude on the performance or its improvement, especially for the spatial and temporal consistency, or the consistency with other references. This is planned to be conducted after the release of PMAp 2.2.4. These statistics provide a robust evaluation of the averaged performance but cannot describe every aspects of the performance more detailed in section 3.

2.4.1 Validation over land.

In Table 1. the summary of the validation vs AERONET over land surfaces is presented. The performance of the PMAp retrieval is indicated in terms of gain, offset, Pearson correlation coefficient (R) and number of retrievals (N). The gain and offset refers to the slope and offset of the line of best fit in the scatterplot of PMAp and Aeronet AOD. The Pearson correlation coefficient is a measure of linear correlation between PMAp and Aeronet AOD. It is the covariance of two variables, divided by the product of their standard deviations. More details and further statistics (e.g. a measure of bias and its distribution per AOD) can be found in Sect. 3.

In the following summary tables, we provide two sets of statistics for each Metop:

i) for all data i.e. all available ~120 Aeronet stations for land and 23 stations for ocean;
ii) filtered data i.e. the AOD retrieval cases over partially cloudy pixels or over bright land are excluded from validation routine and the statistics are representative of normal and dark land.

Since Aerosol retrieval over cloudy pixels and bright land is a challenging case in which many aerosol products have unresolved issues, providing two sets of statistics as explained above, will create the opportunity to have a better understanding of PMAp performance in the case of AOD retrieval over cloud-free normal/dark land.
As reported in Table 1, for the two validation periods considered in this analysis, the R is mostly higher than 0.7 in cloud-free conditions in which retrieval is done over normal or dark land. The range of R changes to 0.4 to 0.58 when we consider all retrieval cases including retrievals in partially cloudy and bright land scenes.
The gain is - in most part of the cases - higher than 0.6, indicating that the aerosol optical properties used in the retrieval are fairly mimicking the aerosol suspended in the atmosphere.
The offset values range between 0.03 and 0.08 for cloud-free normal/dark land retrieval while this range is larger when we include partially cloudy retrieval and bright land: 0.08 - 0.14.

This comparison provides satisfactory values for all the parameters confirming the overall reliability of the PMAp retrievals over land. To have a measure of the bias value between PMAp retrievals and AERONET, we use Symmetric mean absolute percentage error (SMAPE) and analyse its distribution as a function of AOD values. SMAPE is an accuracy measure based on percentage (or relative) errors and is defined as following:

$$SMAPE = \frac{100\%}{n}\sum_{i=1}^{n}\frac{|x_i - y_i|}{(|x_i| + |y_i|)/2}$$

where x is observation (here PMAp AOD) and y is the forecast value (here Aeronet AOD) and the range of SMAPE is 0-200%. For more details see section 3. The performance of PMAp over land are overall around 50%, slightly higher than the threshold requirements of 40%. But in some of AOD bins (in bias per AOD distribution), the bias is less than 40% (See specifications in [AD 3]). These cases with bias smaller than requirement increase when we validate PMAp retrieval over cloud-free normal/dark land.

Table 1. Summary of the PMAp 2.2.4 retrieval validation against AERONET over land only. All data refers to using all available Aeronet stations ~ 120. Filtered data means we exclude pixels at which AOD is retrieved in partially cloudy conditions or we have underlying bright surface.

	PMAp v. 2.2.4							
	June - Sept 2013				***Feb – May 2015***			
	Metop-B		***Metop-A***		***Metop-B***		***Metop-A***	
	All data	***Filtered data***	***All data***	***Filtered data***	***All data***	***Filtered data***	***All data***	***Filtered data***
gain	0.87	0.64	1.3	1.0	0.84	0.63	0.78	0.53
offset	0.08	0.03	0.12	-0.03	0.10	0.07	0.14	0.08
R	0.40	0.72	0.51	0.71	0.58	0.67	0.52	0.75
N	1082	142	956	165	1821	371	1303	412

2.4.2 Validation over ocean

In Table2. the summary of the AERONET comparison over ocean surfaces is presented. Similarly to the over land surfaces the performances of the PMAp v2.2.4 over water are evaluated in terms of gain, offset, Pearson correlation coefficient (R) and number of measurements (N).
The Pearson's correlation coefficients (R) ranges between 0.543 and 0.87 which turn out to be in good agreement with the range of values presented by the same parameter of the aerosol CCI retrieval methods (0.58 - 0.89; Popp et al., 2016). At the same time the offset ranges between 0.0 and 0.09. Overall, the validation statistics are comparable with that of land.
From the analysis of the bias (SMAPE) values between PMAp retrievals and AERONET as a function of AOD values, the performances of PMAp over ocean are around or below ~40%, with values lower than the threshold requirements of 30 % .

Table 2: Summary of the PMAp 2.2.4 retrieval comparison to AERONET over ocean only ~ 23 stations (all data)

	PMAp v. 2.2.4			
	June - Sept 2013		***Feb – May 2015***	
	Metop-B	***Metop-A***	***Metop-B***	***Metop-A***
gain	0.51	0.94	0.96	1.3
offset	0.09	0.03	-0.005	-0.02
R	0.55	0.71	0.68	0.87
N	117	99	105	62

2.5 Improvements achieved by upgrading from v.2.1.0 to v2.2.4

As introduced in section 2.3.10, PMAp v 2.2.4 is characterized by some innovations with respect to operational PMAp v.2.1 (e.g. dust detection scheme). For this reason, a simple comparison between the two versions is not possible because many of new added retrieval cases in v2.2.4 are over challenging case of bright land which were missed in v2.1. The increase in number of retrievals in v2.2.4 is about 15 to 50 % depending on the period and used satellite which is a significant increase. This is an important point when comparing the statistics. Since, a higher number of retrieval, which includes many cases over bright land, makes it difficult to have a fair comparable statistics between the two versions.
However, using two periods as a benchmark, the performances of PMAp v2.1 and v.2.2.4 can be inter-compared in terms of overall results they provided. The improvements over land can be recognized in the increase of gain and decrease of offset value for PMAp v2.2.4 retrieval reported in Table 3. compared to Table 3. by which the summary of the PMAp v 2.1 retrieval validation over land is reported.
The Pearson correlation coefficients (R) values are quite close for the two versions, in some cases increase or decreases. However, as discussed this can be a result of significant increase in the number of retrievals in PMAp v2.2.4 and also having retrieval of dust over bright land which was missing in PMAp v 2.1.
Additionally, considering the number of involved changes when passing from v2.1 to v2.2.4 (e.g. applying a degradation correction, dust retrieval etc.), keeping more or less the same statistics along having improvements is of great importance for all the periods and platforms.
Similarly to the results in Table 2 for the PMAp v2.2.4 retrieval, in Table 4 we present the summary of the PMAp v 2.1 retrieval validation over ocean.

Table 3: Summary of the PMAp 2.1 retrieval comparison to AERONET over land only (all data)

	PMAp v. 2.1			
	June - Sept 2013		***Feb – May 2015***	
	Metop-B	***Metop-A***	***Metop-B***	***Metop-A***
gain	0.597	0.752	0.540	0.503
offset	0.113	0.081	0.168	0.158
R	0.589	0.636	0.552	0.612
N	906	830	1232	1000

Table 4: Summary of the PMAp 2.1 retrieval comparison to AERONET over ocean only (all data).

	PMAp v. 2.1			
	June - Sept 2013		***Feb – May 2015***	
	Metop-B	***Metop-A***	***Metop-B***	***Metop-A***
gain	0.838	0.783	0.493	0.535
offset	0.076	0.045	0.115	0.084
R	0.870	0.836	0.777	0.871
N	110	90	22	51

In the case of ocean, in most of the cases, gain increased and offset decreased in v2.2.4 compared to v2. But correlation coefficients in some cases remains the same or in some decreases which can be an effect of increase in number of retrievals.
The overall behaviour can indicate - as commented in the above section - that the aerosol optical properties used in the retrieval are reasonably simulating the aerosol suspended in the atmosphere. These findings can confirm the reliability of the whole retrieval scheme, making use – in the first phase - of

information coming from different sensors (AVHRR, IASI and GOME-2) for the clouds' detection and aerosol type discrimination. These information are then used in the following steps to constrain the proper retrieval at the GOME-2 wavelengths.

2.6 Brief highlights of anomaly fixes and improvements in v2.2.4.

In this section, we briefly explain anomaly fixes and improvements achieved during the upgrade from v.2.1.0 to v2.2.4:

2.6.1 A dust detection scheme

A dust detection scheme has been added in the PMAp pre-classification step exploiting IASI measurements in 100 channels throughout its whole spectrum (Clarisse et al., 2013). In case of positive detection the retrieval in step 2 is forced to use desert dust optical properties. Figure 1 shows one example of average AOD for five days and corresponding aerosol class map from all three Metops in September 2020 in which the California fire plume, Saharan dust outbreak and amazon fire plume is retrieved successfully. Dust is indicated by blue in the corresponding aerosol class map.

Figure 2 shows another example from the recent Saharan dust transport to Europe retrieved by all three Metops on 6th of February 2021 and the corresponding aerosol class map.

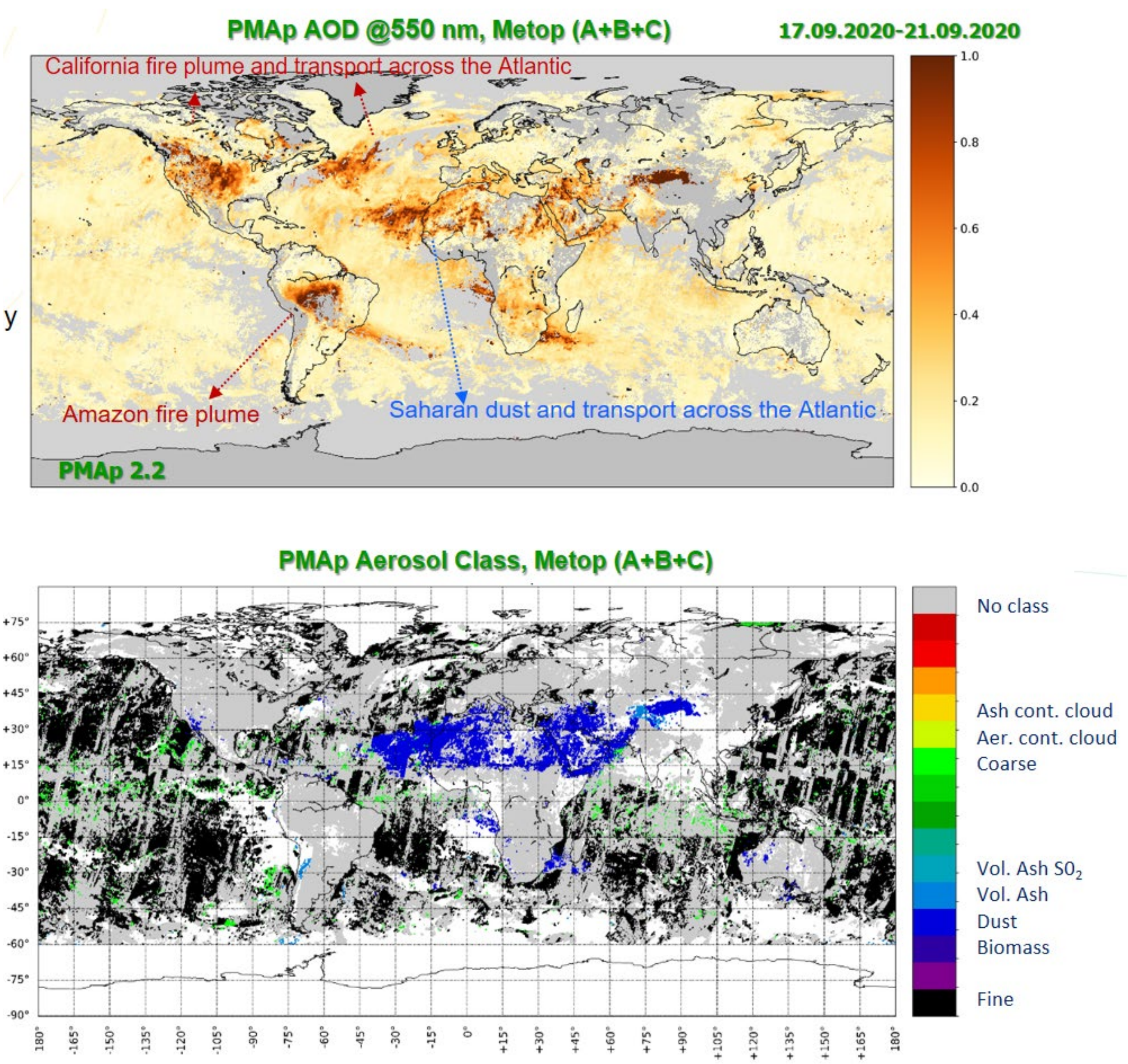


Figure 1. Upper panel: AOD and bottom panel: corresponding class map identification by PMAP v2.2.4 from Metop-A, B and C for 17.09.2020 to 21.09.2020, California and Amazon fire plume, Saharan dust (indicated by blue) outbreak.

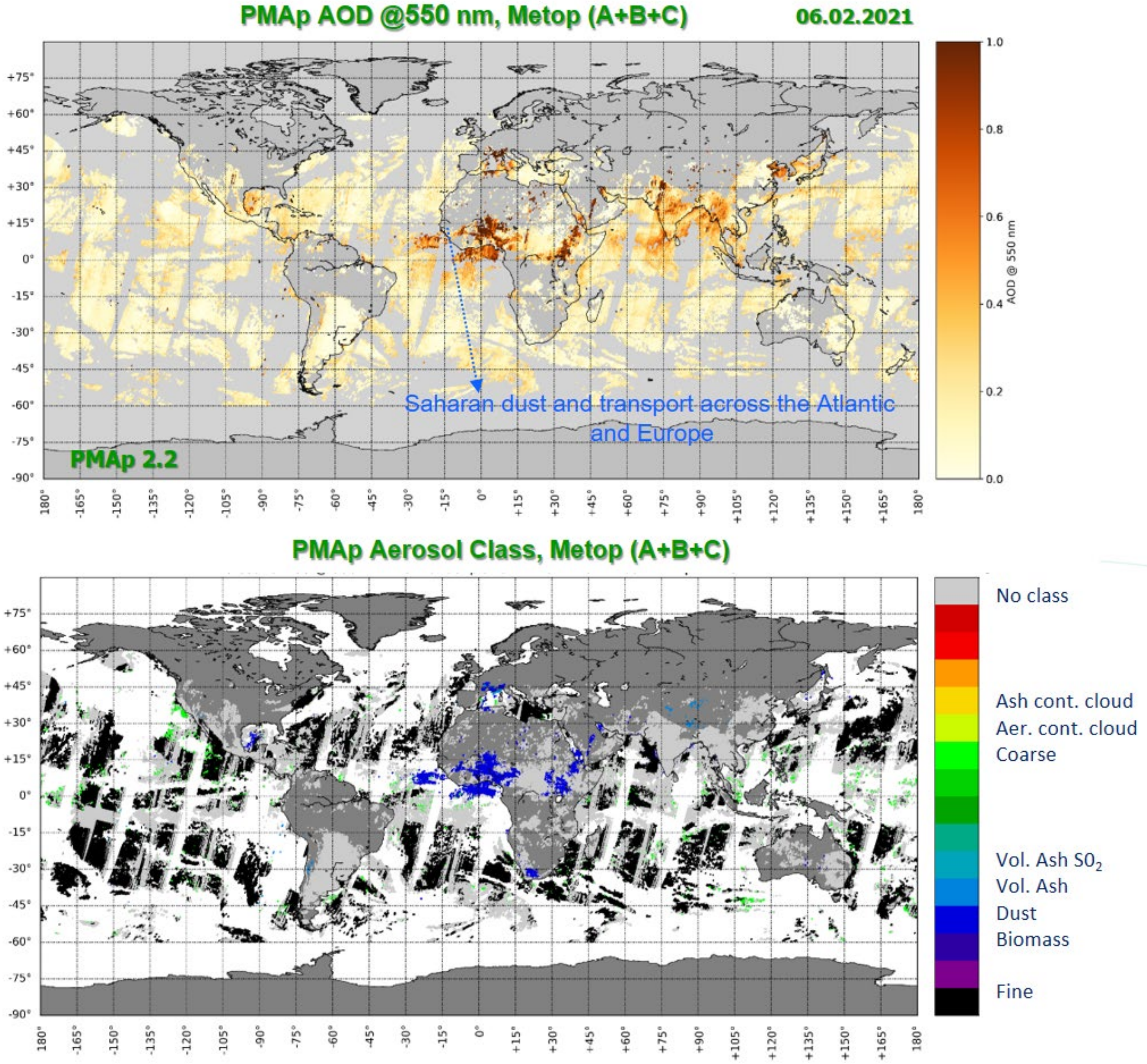


Figure 2. AOD and corresponding class identification by PMAP v2.2.4 from Metop-A, B and C on 06.02.2021, Saharan dust (indicated by blue) transport to Europe.

2.6.2 Hot spots

CAMS reported a hot spot issue in retrieved AOD which was solved by revisiting the cloud filtering and improved detection of aerosol contaminated clouds and the consequent upgrading flags e.g. Aerosol contaminated cloud, volcanic ash contaminated cloud. The anomaly was due to clouds mis-identified as aerosol.
Figure 3 shows one example of the issue in left panel which is solved in the right panel.

2.6.3 Minimizing the difference between PMAp of Metop-A and Metop-B

CAMS reported on a difference between AOD retrieved from Metop-A and B over ocean. This difference between AOD retrieved from Metop-A and B have been minimized by applying an offset correction on GOME2 PMD L1B radiances inside PMAp (see Figure 4 and Figure 5). To calculate the offset value, initially, the difference in global mean AOD between Metop-A and B was converted to an offset on L1B radiance. This offset correction was calculated and applied on all channels. Recently, we compared the old offset value at channel 12 (mainly used for AOD retrieval over ocean) with the value we calculated as radiometric adjustment at Ch12 using 6S simulation (more details in section 2.6.6.). The radiometric adjustment result agrees with previously calculated offset value.

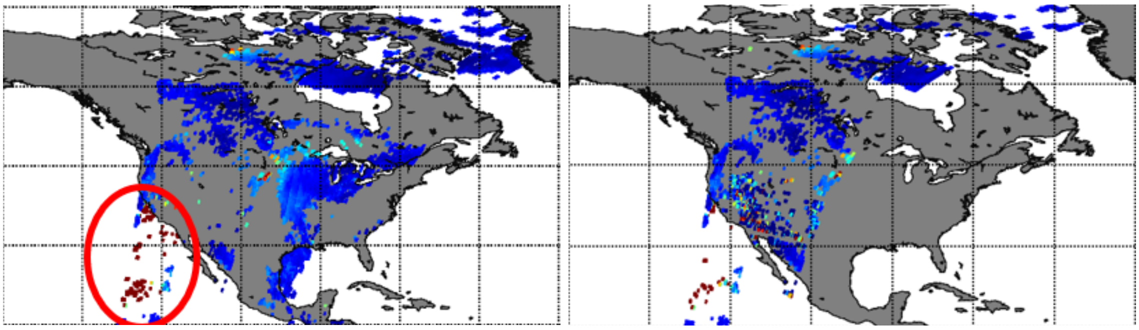


Figure 3 Left panel: hot spot issue in the retrieved AOD by PMAp, right panel: the same scene after correcting for hot spot.

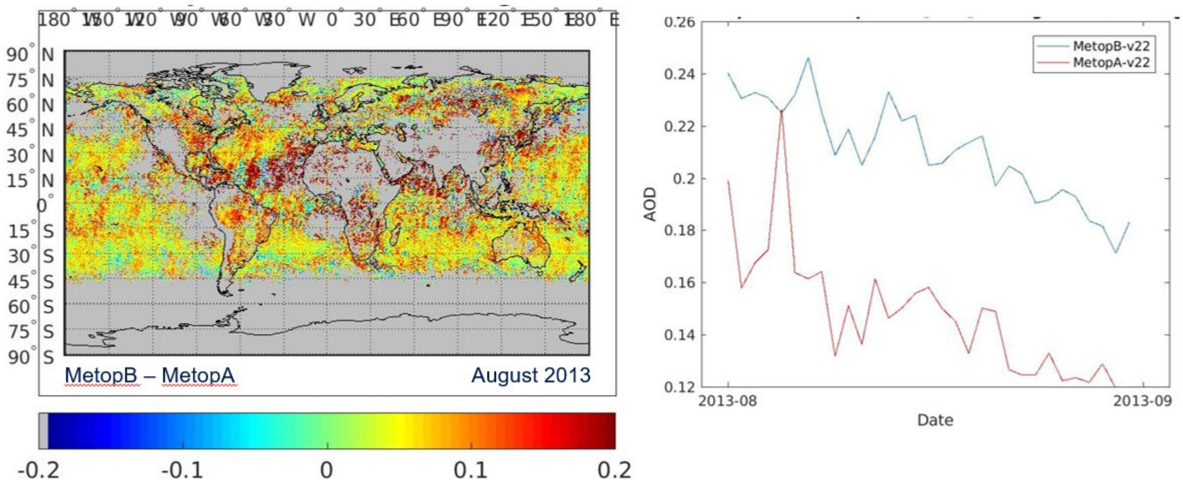


Figure 4 left panel: Difference between AOD of Metop-B and Metop-A, right panel: daily mean AOD from Metop-A and B.

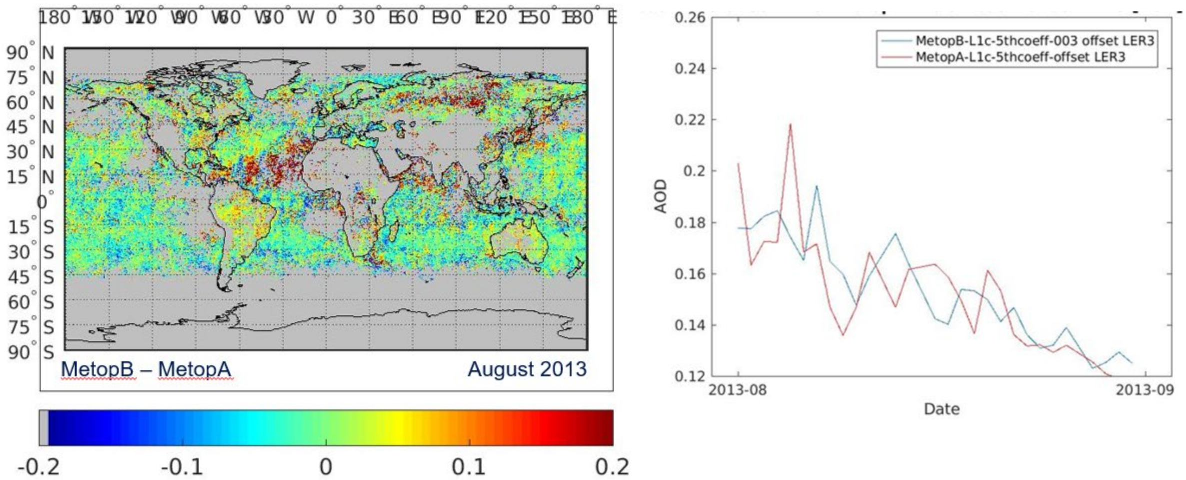


Figure 5. Same as Figure 4, but after minimizing the difference between Metop-B and Metop-A AOD

2.6.4 Correction of the LER viewing angle dependency.

One of the AOD retrieval issues over land, was the excessive variation of AOD along swath with very low AOD values at the east and high AOD values at the west of swath. The reason found to be an issue in the implementation of viewing angle dependency of LER. Figure 6 shows one example of this issue over south-Africa in the left panel and the same scene after solving the issue in the right panel. As indicated, the excessive variation along swath disappeared and we achieve a smooth transition of AOD along swath as expected. In addition, number of retrieval increases.

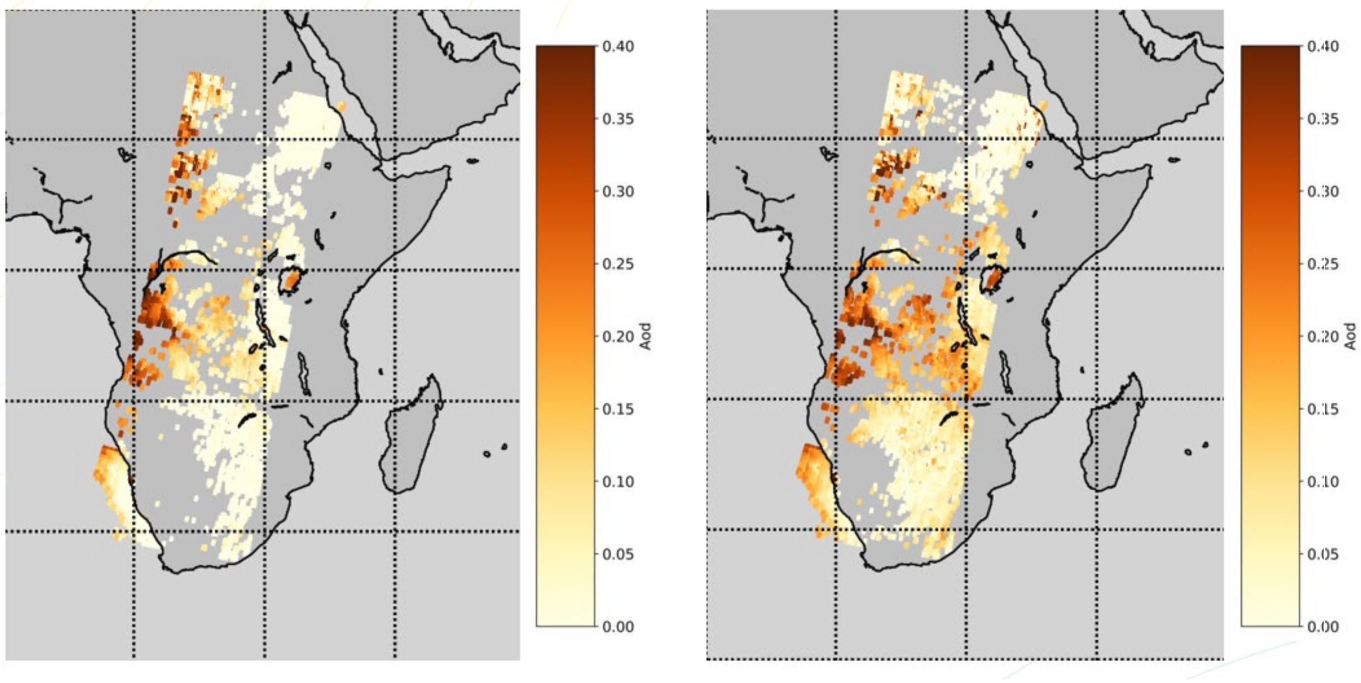


Figure 6. Left panel AOD of PMAp 2.2.3 over South Africa, with problematic implementation of LER angle dependency, right: the same scene after correcting LER angle dependency.

2.6.5 A degradation correction procedure for GOME2 PMD –P Level 1b

A degradation correction was required to correct GOME-2 L1b data for the ageing of the sensor and therefore has been integrated for Metop A, B and C (for more details see [AD 2]). The necessity comes from a list of contributors to the observed signal degradation of GOME-2 Metop-A/B/C identified over the years:

1) Thermal instability of the optical bench (spectral stability)
2) Internal contamination of the optical path
3) Degradation of the scan mirror with viewing angle dependent response
4) Solar optical path degradation
5) Straylight in channel 1.

The degradation model for GOME-2 is addressing all of the above issues (except the change in spectral resolution due to optical bench temperature changes) in a physical or in an empirical way

The performance of the degradation model will be very much wavelength dependent and it is the largest in blue spectrum meaning that the largest effect is reflected in the AOD retrieval over land which mostly relies on the blue spectrum for retrieval.

After integrating and applying GOME2 PMD-P L1b degradation correction coefficients in PMAp, reflectance and so the resultant AOD are decreasing significantly. Figure 7 shows two examples of the effect of degradation correction in retrieved AOD over land in PMAp.
Despite the necessity to apply degradation correction because of the mentioned reasons, an excessive low level of reflectance is still observed after degradation correction, and as a result a remaining too large number of pixels with AOD=0 (over land) This led us to recognize the need for a radiometric adjustment after degradation correction of GOME2 L1b as explained in following section.

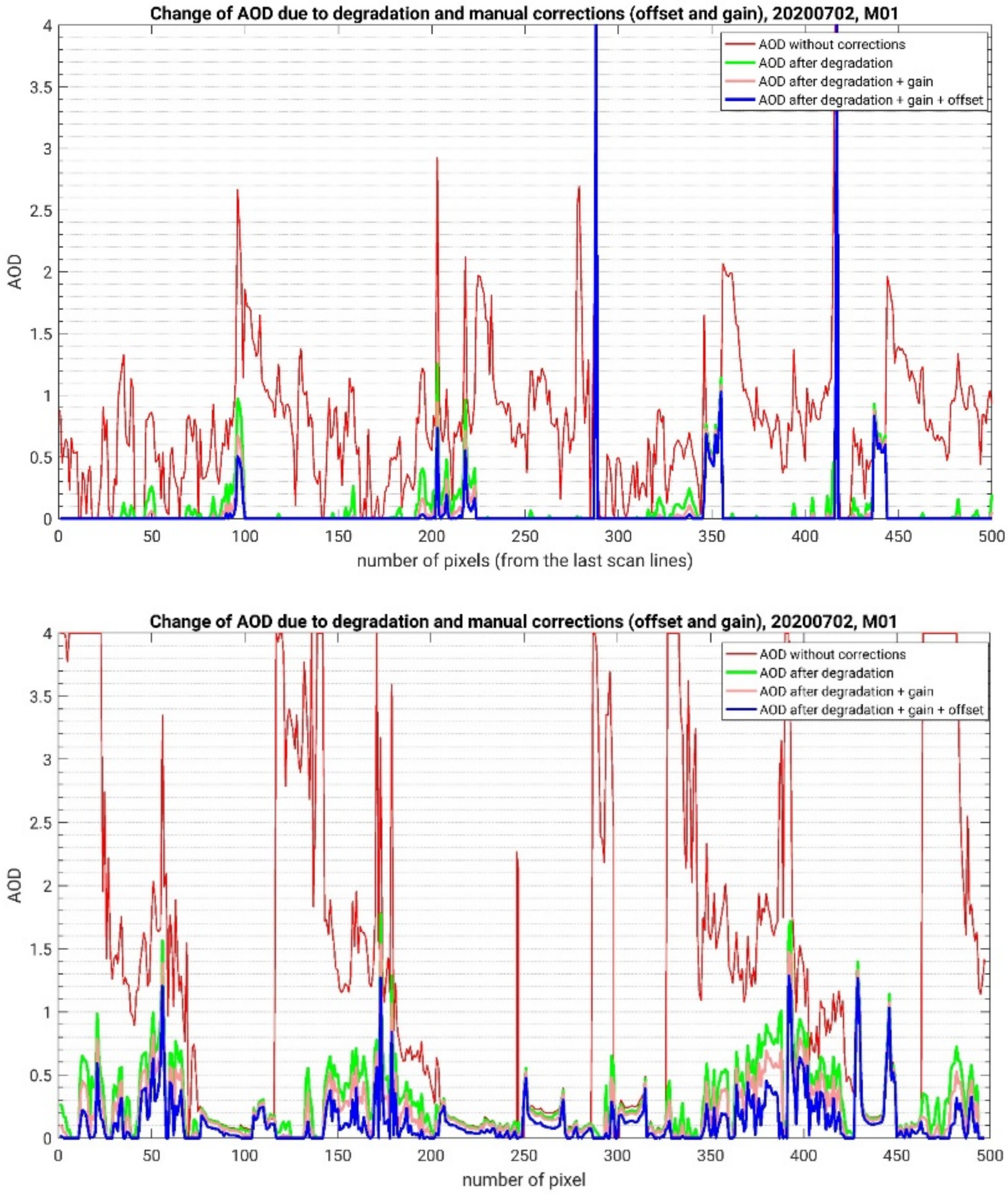


Figure 7. Two examples to show the cross track profiles of AOD in a scene over Sahara before and after applying degradation correction on 20200702.

2.6.6 Radiometric adjustment

The need for a radiometric adjustment of GOME2 PMD-P L1b data was recognized when significant number of pixels with AOD=0 was found in PMAp over land, andit was confirmed by some anomalies (low reflectance) on the TOA reflectance before the aerosol retrieval itself.
These pixels are in fact having negative AOD values which is stored as 0 in PMAp output. The number of null pixels were large over land ~ more than 50% of pixels, and therefore this issue was not negligible. The underestimation of AOD over land was also recognized by CAMS (see Sect. 3.3 for details).
Figure 8 shows one example of the issue for Metop-A and Metop-B. In the right panel, yellowish pixels are representing AOD=0 which is a significant amount of pixels over land as mentioned.
The analysis first tried to check if anomalies could be detected on the L1b reflectance before the aerosol retrieval. A methodology based on Rayleigh calibration has been developed to create a reference signal to be compared to Metop-A, B and C. A discrepancy was found between L1b and the Rayleigh reference highlighting the need for a radiometric adjustment. We convert the observed difference between reflectance of GOME2 and the reference to an adjustment on GOME2 PMD-P radiance at channel 7 and 8 used for land retrieval in PMAp (for more details see [AD 2]). We show one example in Figure 9 for the comparison of GOME2 reflectance with that of simulation from 6S and the need for a positive offset on GOME2 L1b. Figure 10 shows PMAp AOD retrieval for Metop-B after applying the radiometric adjustment. As we could expect, the number of pixels with AOD=0 decreased significantly.

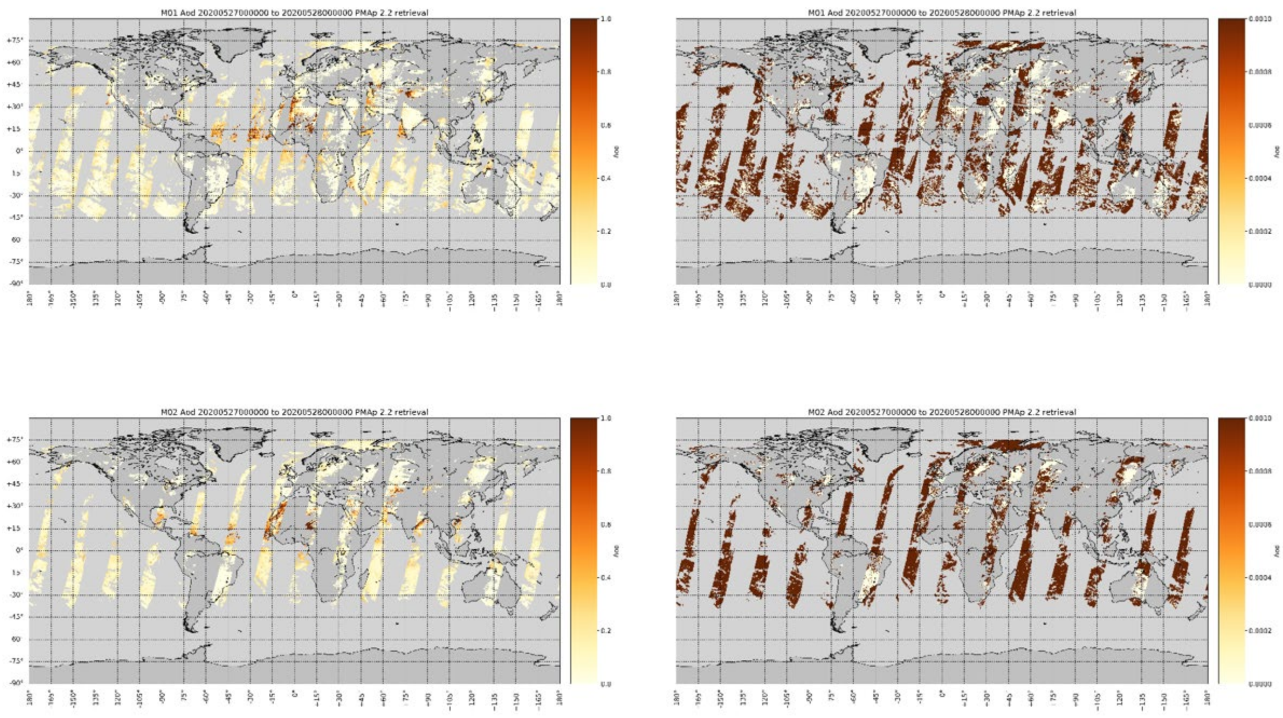


Figure 8: Upper left panel: Metop-B PMAp AOD for 20200527 and upper right: similar map with limited color scale to highlight pixels with AOD=0, lower left: Metop-A PMAp AOD FOR 20200527 and lower right: similar map with limited color scale to highlight pixels with AOD=0 in yellow..

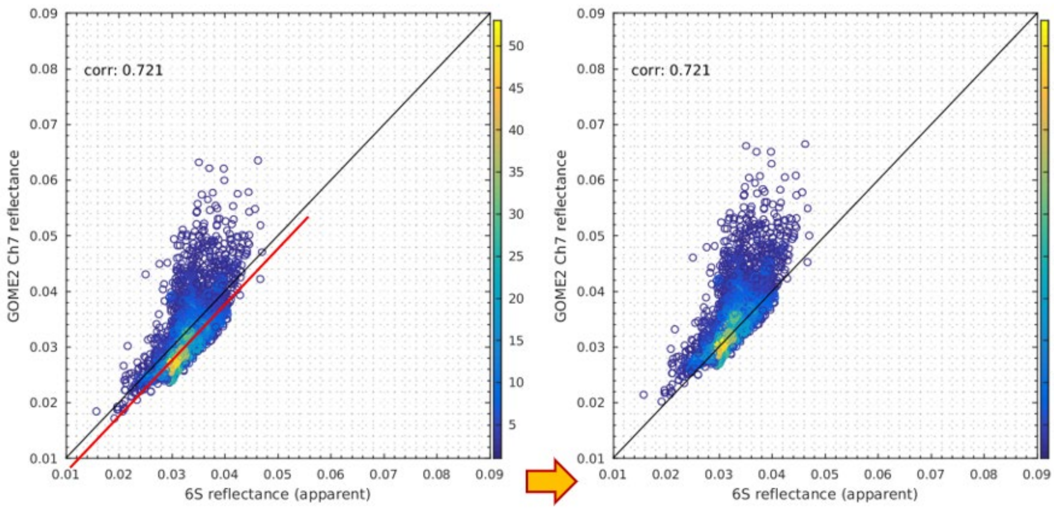


Figure 9. One example of the comparison of GOME2 reflectance with 6S simulation and the need for positive offset known as radiometric adjustment.

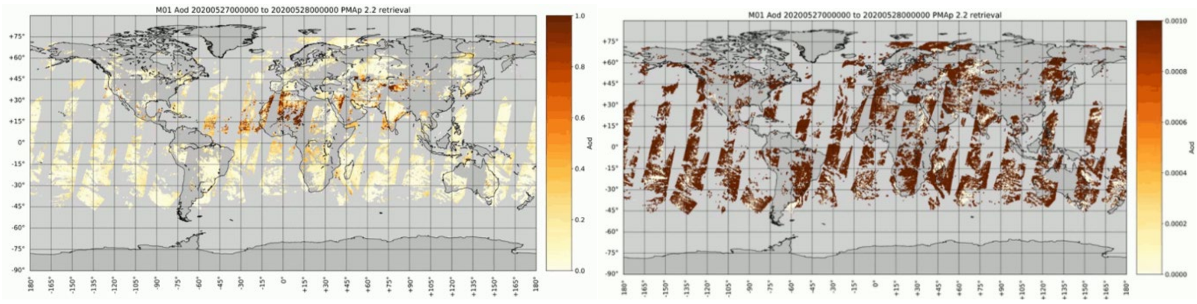


Figure 10: Similar to Figure 8 but after radiometric adjustment. One example to show the effect of radiometric adjustment in decreasing number of pixels with AOD=0

2.7 Product overview

2.7.1 Input Data

This section contains a list of required input data for PMAp.

- **Setup required at the start of the algorithm (one time):**
  - LUT database for reflectance and stokes fraction over ocean (PMD6-15).
  - LUT database for one PMD band describing reflectances dependent on solar zenith angle, zenith viewing angle, relative azimuth angle, Lambertian surface albedo and cloud optical depth.
  - LUT database for reflectances and stokes fractions over land (PMD6-15).
  - LUT database for the Aerosol Absorbing Index (AAI)
  - MERIS Surface albedo database
  - GOME-2 LER angular surface albedo database
  - Land-sea mask (used as a backup only, if AVHRR information is not available).
  - Surface elevation database.
  - Data base of spectral coefficients – over water and land surface - for IASI dust index calculation.
  - Coefficients for the Lev1b to Lev1c correction
  - Configuration parameter file.
- **Inputs required from the GOME-2 level-1 data:**
  - Reflectance of 15 PMD bands (currently only a subset (7-15) is in use, but the input of 15 values is foreseen in the device)
  - Solar reference of 15 PMD bands
  - Stokes fractions of 15 PMD bands
  - Solar zenith angle (SZA)
  - Viewing zenith angle (VZA) as defined in GOME-2 Level 1 product
  - Satellite azimuth angle as defined in GOME-2 Level 1 product
  - Solar azimuth angle as defined in GOME-2 Level 1 product
- **Inputs required for the collocation algorithm**

These parameters are required as input to the collocation algorithm to provide co-located data as described below:

- Land/sea flags (from AVHRR Level-1)
- 10 m wind speed for the given scene taken from ECMWF forecast
- Surface pressure for the given scene taken for ECMWF forecast
- AVHRR cloud flags (2 x 4 tests from AVHRR Level 1b per AVHRR pixel)
- AVHRR reflectance channel 1, 2, 3A
- AVHRR brightness temperature channel 4 and 5
- IASI Level 1C input collocated
- ETOPO5 surface elevation database.

2.7.2 User Requirements for the Main Aerosol Optical Depth Product

<table>
<tr><th>*PMAp-01*</th><th colspan="2">*Aerosol Optical Depth*</th></tr>
<tr><td>Type</td><td colspan="2">Product</td></tr>
<tr><td>Applications and users</td><td colspan="2">Air quality, traffic, climate</td></tr>
<tr><td>Characteristics and Methods</td><td colspan="2">Multi-wavelength measurements of reflectances and stokes fractions, Radiative transfer modelling</td></tr>
<tr><td>Comments</td><td colspan="2">Aerosol and cloud products refer to different footprints. This product is retrieved for the aerosol footprint.</td></tr>
<tr><td>Generation Frequency</td><td colspan="2">Metop GOME-2 PDU dissemination frequency:
every 3 minutes on daylight side of orbit</td></tr>
<tr><td>Input satellite data</td><td colspan="2">GOME-2, AVHRR, IASI</td></tr>
<tr><td colspan="3">Dissemination</td></tr>
<tr><td>Format</td><td>Means</td><td>Type</td></tr>
<tr><td>EPS native</td><td>EUMETCast, Internet</td><td>NRT, offline</td></tr>
<tr><td colspan="3">Accuracy</td></tr>
<tr><td>Threshold</td><td>Target</td><td>Optimal</td></tr>
<tr><td>0.2 (abs. threshold) or 30% (rel. Threshold) over sea

0.3 (abs threshold) or 40% (rel. Threshold) over land</td><td>10% or 0.05 (cloud free, ocean)
20% or 0.1 (cloudy, ocean and cloud free, land)
30% or 0.15 (cloudy, land)</td><td>0.05 or
5% (cloud free ocean)
10% (cloudy ocean and cloud free land)
20% (cloudy, land)</td></tr>
<tr><td>Verification method</td><td colspan="2">comparison to MODIS, GOME-2 UV index, AERONET</td></tr>
<tr><td colspan="3">Coverage, Resolution and Timeliness</td></tr>
<tr><td>Spatial coverage</td><td>Spatial resolution</td><td>Timeliness</td></tr>
<tr><td>Global</td><td>GOME-2 PMD resolution
10 km x 40km Metop-B
10 km x 40 km Metop-C
5 km x 40km Metop-A</td><td>≤ 3 hours</td></tr>
</table>

See also specifications in [AD 3].

2.7.3 Output Products

The output is provided in EPS native and netcdf4 format. For the validation described here, only native products are used. This section summarizes the most important parameters obtained from the retrieval or from co-located auxiliary data. Aerosol optical depth was used for the validation described in this document. Other parameters are either provided in support or are not included in the scope of the validation.

Parameter	*Description*
aerosol_optical depth	Aerosol optical depth at 550 nm retrieved for the GOME-2 PMD ground pixel.

Other parameters such as cloud mask or aerosol type are either provided in support or are not included in the scope of the validation.

Parameter	*Description*
error_aerosol_optical_depth	Error of the AOD retrieved
aerosol_class	0: no dust / fine mode (ocean) 1: coarse mode (ocean) 2: thick Biomass burning 3: desert dust 4: volcanic ash/thick dust 5: volcanic ash with SO_2 10: Aerosol contaminated cloud 11: Ash contaminated cloud 15: no classification
flag_ash	0: no ash 1: ash 15: no classification
pmap_geometeric_cloud_fraction	Cloud fraction co-located with PMD pixel (corners corrected according to the time shift of the reference PMD band used for aerosol properties retrieval) as used for AOD PMAp for cloud-screening [0-1].
chlorophyll_pigment_concentration	Chlorophyll pigment concentration in mg/m^3 (ocean, clear sky)

Parameter	*Description*
retrieval_flags_aerosol	Quality flags of the aerosol product (1=problem found, 0=no problem detected). We provide the following flags: 1 Large cloud contribution to the signal (correction factor low) over sea 2 Observation geometry with typically enhanced errors in the retrieval over sea and land. 3 Measured signal exceeds upper or lower limits over sea and land 4 Limitation in aerosol type pre-classification over sea, in particular fine/coarse mode classification. 5 Signal has an enhanced dependence on the actual wind speed 6 Bad fit 7 Thick aerosols
retrieval_algorithm	Retrieval algorithm used by the AOD retrieval 0 ocean, main retrieval for clear-sky pixels 1 ocean, simplified retrieval for partly cloudy pixels 2 ocean, alternate retrieval, AOD from reflectance 3 ocean, alternate retrieval, AOD from stokes fraction *any value less than 3: land, not implemented* 4 land, dark surfaces, cloud free 5 land, normal mode, cloud free 6 land, bright surfaces, cloud free 7 land, dark surfaces, partly cloudy 8 land, normal mode, partly cloudy 9 land, bright surfaces, partly cloudy 15 no retrieval
avhrr_geometric_cloud_fraction	Geometric cloud fraction retrieved from AVHRR pixels inside the GOME-2 pixel [0-1].
flag_sun_glint	Flag indicating cases of sun glint. This is calculated in the same way as the ‘probably sun glint’ flag in the GOME Level-1 product. For pixels over land, the flag is always set to 0--a priori.
flag_snow_ice	Flag indicating if a pixel is partly or completely covered by snow or ice. The flag derived from the AVHRR cloud product.
split_window_btd	Average brightness temperature of AVHRR channel 4 and AVHRR channel 5
wind_speed	10 meter wind speed from ECMWF forecast [m/s]
land_fraction	Fractional coverage of land surfaces within the PMD

Parameter	Description
reflectance_inhomogeneity	Variance of the reflectances in AVHRR channel 1 within the GOME-2 PMD pixel.

Table 3. Output aerosol products. Other parameters are either provided in support or are not included in the scope of the validation.

3 VERIFICATION AND VALIDATION OF THE AEROSOL PRODUCT

3.1 Verification of the aerosol optical properties retrieval

The whole set of introduced aerosol level 2 products, has been retrieved for the two selected validation periods historically chosen to quantify the improvements:

validation period 1	June – September 2013
validation period 2	February – May 2015

These two periods provide a valid number of observations for the spatio-temporal collocations matched with ground-based and other satellite-based aerosol optical properties. Moreover, they allow the comparison analysis to be carried out in different seasons and under representative atmospheric conditions for the full seasonal cycle.

3.1.1 Comparison of PMAp v2.2.4 to v2.1

Figure 11 shows a global map of Aerosol Optical Depth (AOD) at 550 nm retrieved by PMAp v2.2.4 and AOD product from v2.1 using Metop-A, B and C observations on 6th of February 2021. The corresponding aerosol class is shown in Figure 11 as well. The comparison between the two products show that the overall spatial pattern of AOD is consistent between two versions but there are differences as well:

1) For this specific event of Saharan dust transport, the newly added dust scheme is performing well and leads to higher number of retrieved pixels and AOD. The difference also can be seen in aerosol class map with higher number of dust scenes in v2.2.4. The improved capabilities of

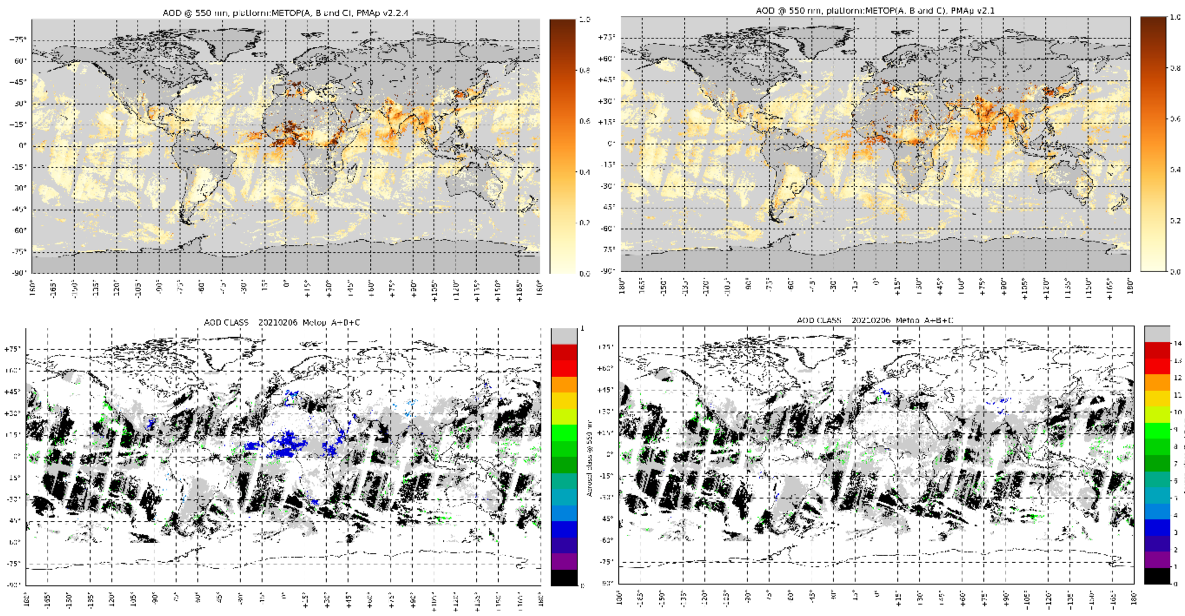


Figure 11: PMAp, left column AOD v2.2.4 and corresponding aerosol class, right column: AOD PMAp v2.1 and corresponding aerosol class

PMAp v.2.2.4 in detecting dust aerosol type (see Table 4. for aerosol type classification) is clearly recognizable for all platforms.

2) In v2.2.4, AOD over ocean is lower than v2.1, which is expected because in line with the applied modifications, and also meet the request from CAMS (see section 3.3 for details).
3) It can also be seen that AOD (non dust) over land in v2.2.4 is lower than v2.1. The main reason for this is the application of degradation correction (reducing the reflectance). However, this reduction is balanced by the radiometric adjustment (which increases slightly the reflectance).

Aerosol type	*Class Number*
Fine mode	0
Coarse mode	1
Biomass Burning	2
Volcanic Ash / Dust	3
Volcanic Ash – SO2	4
Unclassified	15

Table 4: Aerosol types to class numbers correspondence in PMAp.

3.1.2 Comparison of PMAp from all Metop(s)

One way to verify AOD product of PMAp is to compare retrieved AOD from all three Metop(s).
Despite the existing differences between the three Metops(s) and therefore the expected differences in retrieved AOD, e.g. swath width, spatial resolution, degradation effect and correction, it is of great importance to have consistent AOD values from Metop-A, B and C. It gets more important for the operational use of the data for CAMS assimilation, or for studies such as analysis of Climate Data Record (CDR).
For this reason, we compared the three AOD products from all Metop(s) by analysing average of AOD per latitude. To mitigate the differences originating from different swath width, we limit the viewing angle of Metop-B and C to the viewing angle of Metop-A. This is not the ideal way to select the comparable pixels from all Metop(s), but it is a straightforward solution to derive a simple first comparison. To have a better understanding of PMAp performance over land and ocean, we separated the analysis for land and ocean.
Figure 12 and Figure 13 are one example of this comparison for land and ocean respectively. The case study is selected from 31th of March 2021, when we had a significant dust outbreak and transport from Sahara to Europe. For this reason, we expect to have differences in Saharan belt. However, as one can see from the comparison over land (Figure 12), Metop-A and B and C are in great agreement especially out of Sahara Belt in low latitudes. But in high latitudes, Metop-C shows higher AOD compared to A and B.
For Metop-C land, we have known existing anomalies especially over bright land where AOD increases at the east of swath. Neither Metop-A nor Metop-B does not show similar values there. This can be partly the reason for higher AOD values for Metop-C at high latitudes. This issue could be related to degradation correction of Metop-C and is currently under investigation.
Over ocean, all 3 Metops agree very well in southern and high latitudes out of Sahara belt. This is very important for the use of combined assimilation of the 3 Metops by CAMS.

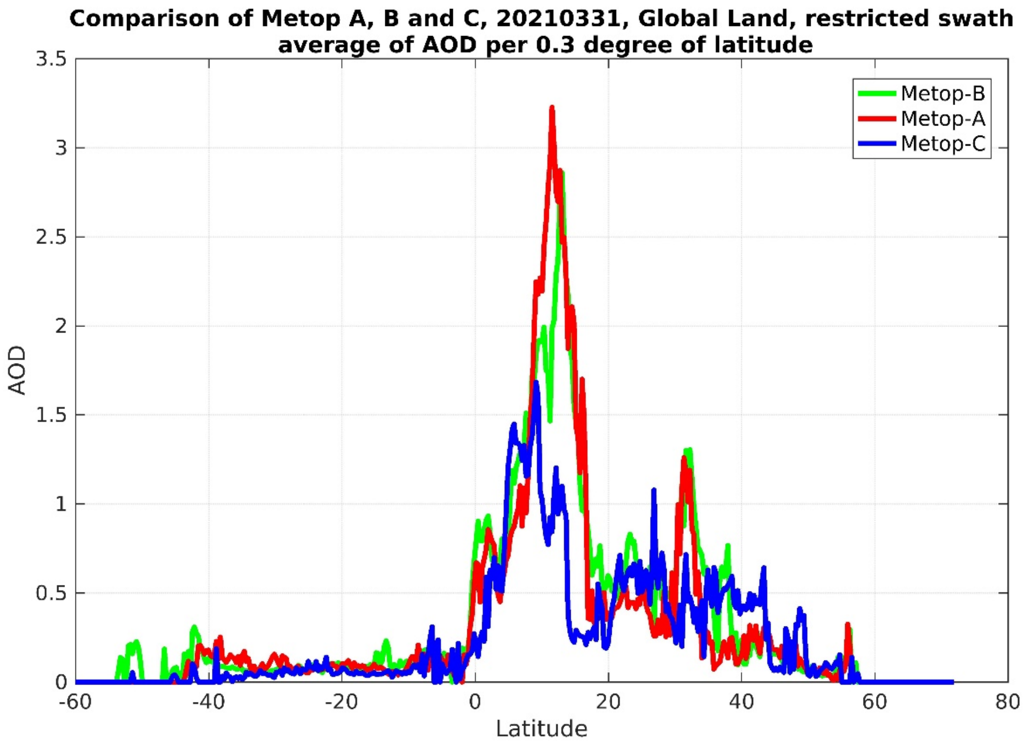


Figure 12, AOD and latitude dependency, comparison of Maetop-A, B and C over land, restricted swath, 20210331.

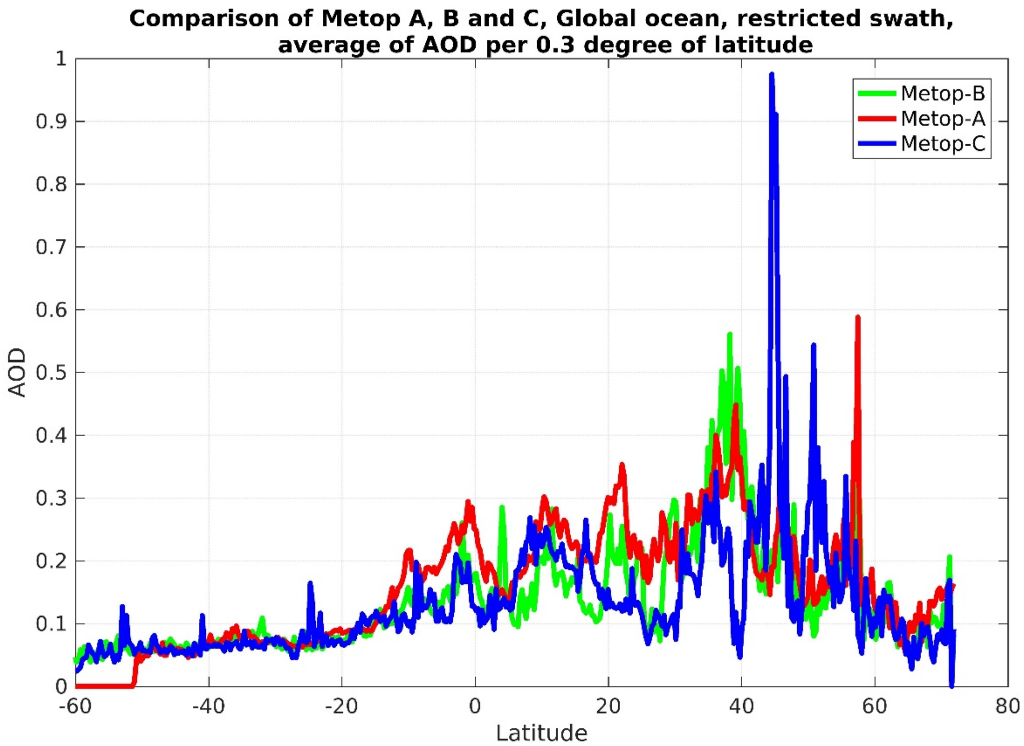


Figure 13. AOD and latitude dependency, comparison of Maetop-A, B and C over ocean, restricted swath, 20210331.

3.1.3 Comparison of PMAp with MODIS and VIIRS

Qualitative comparison of PMAp AOD to that of Moderate Resolution Imaging Spectroradiometer (MODIS) retrieved by the combined dark target / deep blue algorithm is another way of verifying PMAp AOD. Though, MODIS AOD product has its own known issues and anomalies, it has been historically used in many studies as a reference to verify AOD products.
The MODIS AOD product monitors the ambient aerosol optical thickness over the oceans globally and over a portion of the continents. Daily Level-2 data are produced at the spatial resolution of a 10x10 1-km pixel array (at nadir). Here we use MODIS Collection 6.1.
Another AOD product we used for qualitative verification of PMAp AOD is the Suomi National Polar-orbiting Partnership (SNPP) Visible Infrared Imaging Radiometer Suite (VIIRS) NASA standard Level-2 (L2) deep blue aerosol product which provides satellite-derived measurements of AOD and their properties over land and ocean, every 6 minutes, globally. The Deep Blue algorithm draws its heritage from previous applications to retrieve AOT from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS measurements over land. This orbit-level has an at-nadir resolution of 6 km x 6 km, and progressively increases away from nadir given the sensor's scanning geometry and Earth's curvature. Viewed differently, this product's resolution accommodates 8 x 8 native VIIRS moderate-resolution (M-band) pixels that nominally have ~750 m horizontal pixel size. The L2 Deep Blue AOT data products, at 550 nm reference wavelengths, are derived from particular VIIRS bands using two primary AOT retrieval algorithms: Deep Blue algorithm over land, and the Satellite Ocean Aerosol Retrieval (SOAR) algorithm over ocean. Although this product is called Deep Blue based on retrievals for the land algorithm, the data includes over-water retrievals as well.

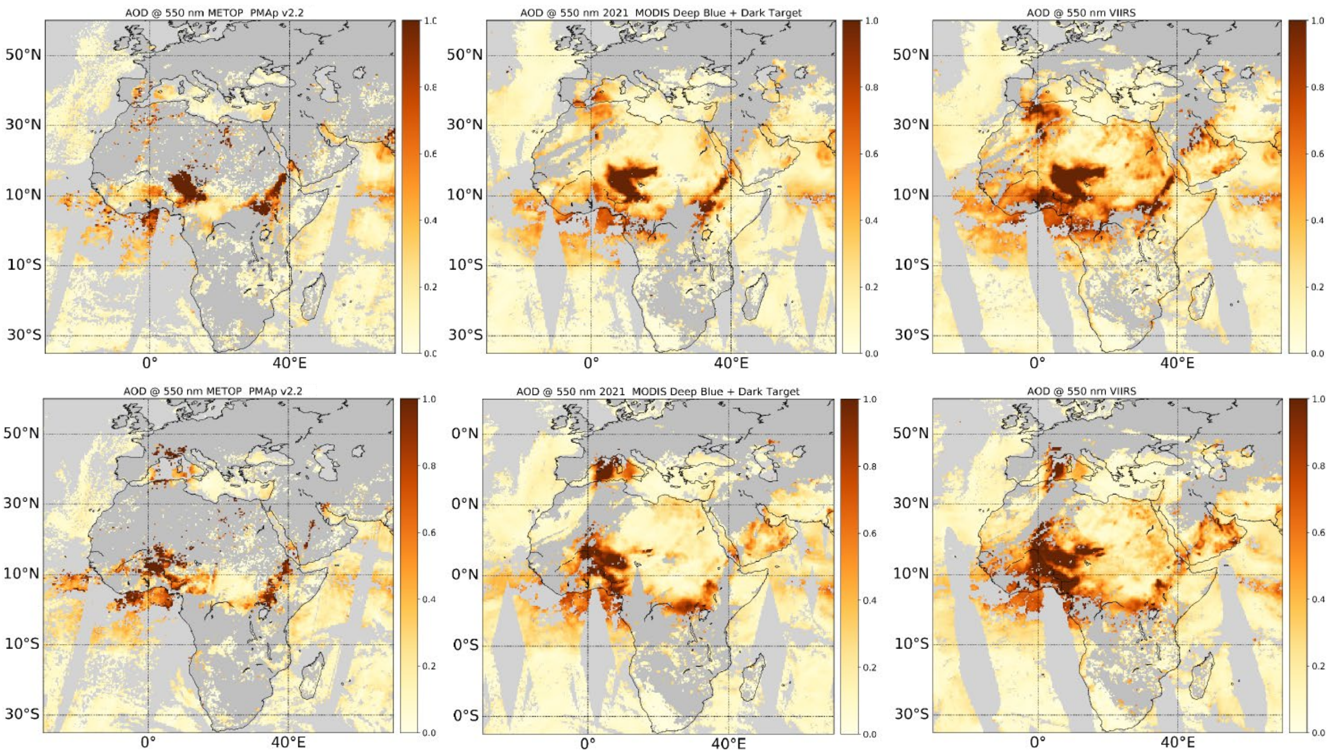


Figure 14: One example for the verification of PMAp AOD (left column) against MODIS (middle column) and VIIRS (right column). Case study: transport of Saharan dust to Europe, 5th (upper panel) and 6th (bottom panel) of February 2021.

Figure 14 is one example of a qualitative comparison between MODIS, PMAp and VIIRS AOD products. Despite the over screening of PMAp over Sahara, a promising agreement can be seen in the rest of retrieval scenes between the three product. The agreement is higher between MODIS and PMAp.

3.2 Validation of PMAp AOD using the operational PMAp/AERONET monitoring

Validation of the PMAp AOD is based on the comparison against other corresponding independent data sets to ensure an unbiased validation. In this view, the ground-based reference is represented by the AERONET level-2 data which comes from a widespread network of sites; this allows for a thorough comparison of the PMAp output against a well-documented and quality-controlled ground-based network.

AOD measured throughout the two validation periods by sun photometer instruments in about 685 AERONET sites (AErosol RObotic NETwork, http://aeronet.gsfc.nasa.gov) have been employed as a reference ground-based data set. AERONET (Holben et al., 1998) provides the AOD at different wavelengths (340, 380, 440, 500, 670, 870, 940, 1020 nm).

AOD retrieved for the two validation periods have been compared with the AERONET data set using the operational PMAp/AERONET monitoring internal tool.

In the following the results of the comparison over land (3.2.2) and water surfaces (3.2.3) for each reference validation period and for each platform are presented.

3.2.1 Method

The validation exercise is carried out using the following method and criteria:

1. Collect AERONET measurements (level 1.5) within a 30-minute span of a Metop overpass.
2. Identify corresponding GOME-2 measurements in a 30 km circle around the station.
3. Calculate the average AOD and plot the minimum and maximum value around the station using a solid line.
4. If AERONET measurement at 550 nm wavelength is not available, the AERONET value is interpolated at 550 nm from the neighbouring spectral measurements.
5. Plot the PMAp AOD against the AERONET AOD.

In this section 3.2, we present respectively :

- the matchups with Aeronet
- the statistics for the Symmetric mean absolute percentage error (SMAPE)
- the timeseries of AOD compared to Aeronet

This threefold set of results is presented for 8 datasets:

Retrieval over land	***section 3.2.2***
• Metop-B for June-September 2013	section 3.2.2.1
• Metop-A for June-September 2013	section 3.2.2.1
• Metop-B for February-May 2015	section 3.2.2.2
• Metop-A for February-May 2015	section 3.2.2.2
Retrieval over ocean	***section 3.2.3***
• Metop-B for June-September 2013	section 3.2.3.1
• Metop-A for June-September 2013	section 3.2.3.1
• Metop-B for February-May 2015	section 3.2.3.2
• Metop-A for February-May 2015	section 3.2.3.2

3.2.2 Comparison results over land surface

3.2.2.1 *PMAp versus AERONET for June - September 2013*

AOD values from PMAp/Metop-B for June-September 2013 are validated against corresponding AERONET AOD data and the results are reported in the scatter plots in Figure 15 and Figure 16.

Overall, there are 1082 available retrieval cases for validation. A significant number of sites show a good agreement between PMAp and AERONET which can be seen in the density scatter plot with the highest population around 1:1 line.

PMAp/Metop-B data are plotted against the ground-based data provided by all the previous AERONET sites in linear (Figure 15) and logarithmic scale (Figure 16) for both cases of all data and filtered ones (cloud-free and non-bright surface).

The parameters of the linear regression fit are as following: gain equal to 0.40 (all cases) and 0.72 (filtered cases) and offset equal to 0.08 (all cases), and 0.03 (filtered cases). This indicate a trend in a slight overestimation AOD when PMAp retrieves in partially cloudy scene or over bright surface.

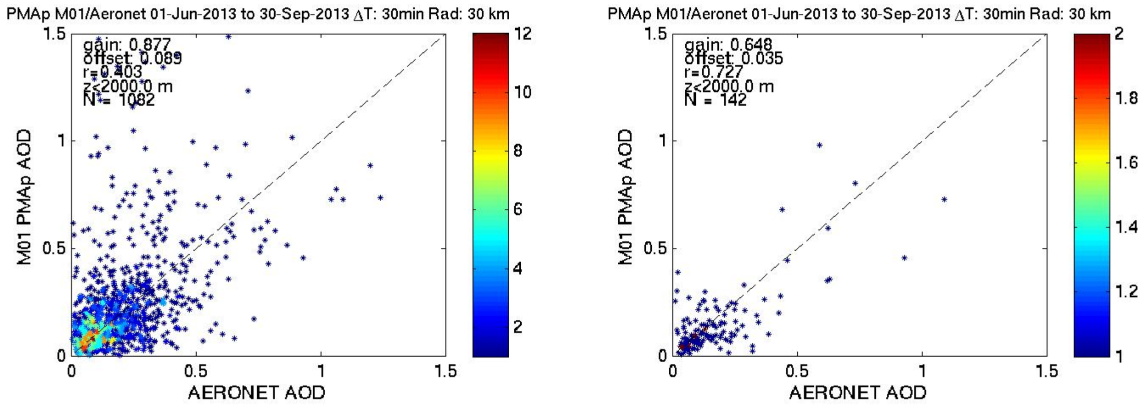


Figure 15. Scatter plot – linear scale –: AOD at 550 nm from PMAp/Metop-B is plotted versus corresponding AERONET measurements in June-September 2013; left panel: for the overall AERONET sites, right panel: retrieval in partially cloudy scene or over bright land is excluded.

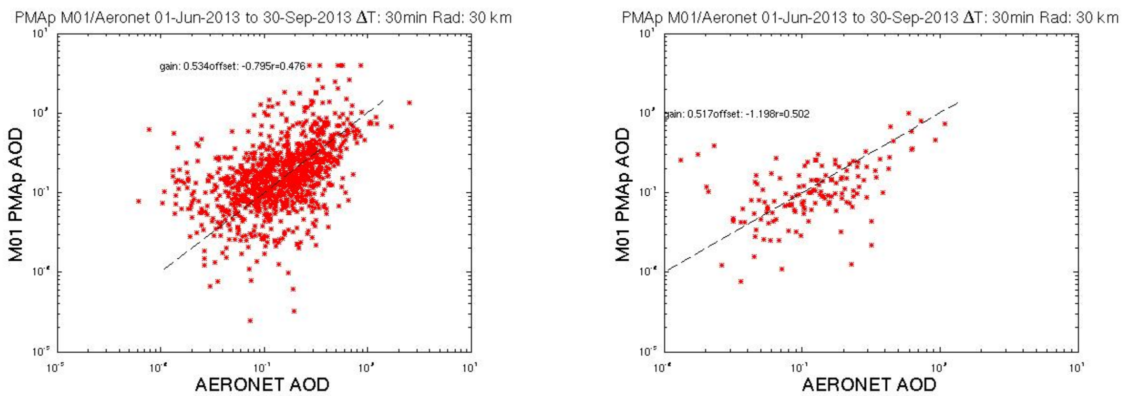


Figure 16. Scatter plot – logarithmic scale - for the overall AERONET sites June-September 2013: AOD at 550 nm from PMAp/Metop-B is plotted versus corresponding AERONET measurements.

In Figure 17, the Symmetric mean absolute percentage error (SMAPE) values, corresponding to the data in Figure 15 are plotted as a function of AOD.

Data were binned with 0.05 bin-width in the 0–0.5 AOD range. For AOD greater than 0.5, the bin-width employed has been set to 0.1. SMAPE average values over all bins have also been calculated for all available measurements (the blue dashed line) and for cases with a number of measurements greater than 3 (the red dashed line). AOD values lower than 0.05 (grey bar) were not included in the calculation, as 0.05 is the PMAp lower detection limit below which no sensitivity has been shown by PMAp .
The SMAPE average is at the ~55% and 50% level for all data and filtered data respectively in this validation period, with higher number of bins having SMAPE values even lower than 40% (which is at the level of the requirement for land).

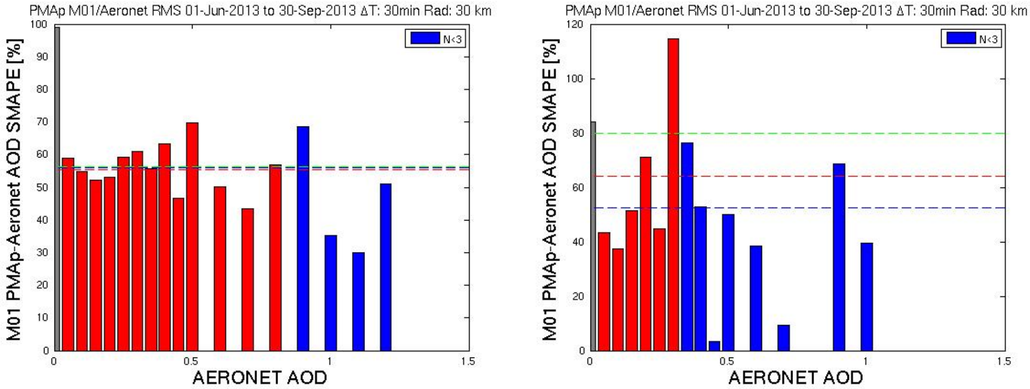


Figure 17: SMAPE values corresponding to the data presented in Figure 15, plotted as a function of AOD for June-September 2013 validation period, Metop-B. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

The comparison is completed with the AOD time series reported in Figure 18 to Figure 26 for Metop-B. AERONET AOD measurements (blue line) are compared to the corresponding PMAp (red line) retrieved values from Metop.

The presented sites are characterized by different environmental conditions from significantly polluted urban area (e.g. Beijing CAMS and XiangHe) to important dust source region such as Gobi desert (e.g. BSRN Bad Boulder, Bozeman stations) or relatively cleaner urban areas (e.g. Madrid and Valladolid). In most of the cases PMAp retrievals nicely follows the AERONET measurements. In all cases, the dynamics are well captured by PMAp. But for bright surface cases such as BSRN Bad Boulder in Gobi desert or relatively bright such as Fresno, positive bias of AOD can be seen in time series which is significantly less in the retrieval cases over darker surface types in Europe such as Madrid and Valladolid.

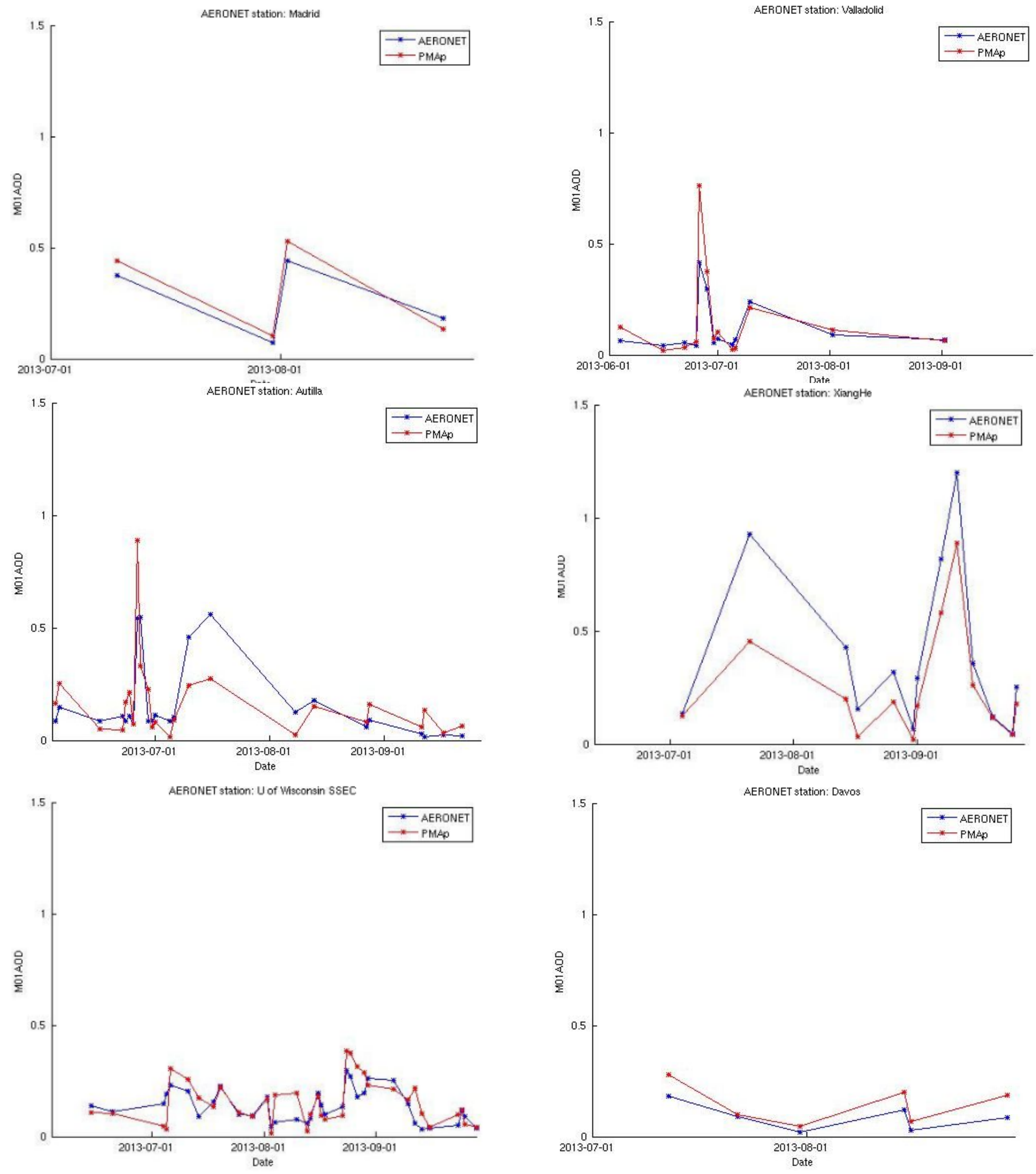


Figure 18. Time series of the AOD at 550 nm for June-September 2013 measured at different stations, compared to the AOD retrieved from Metop-B.

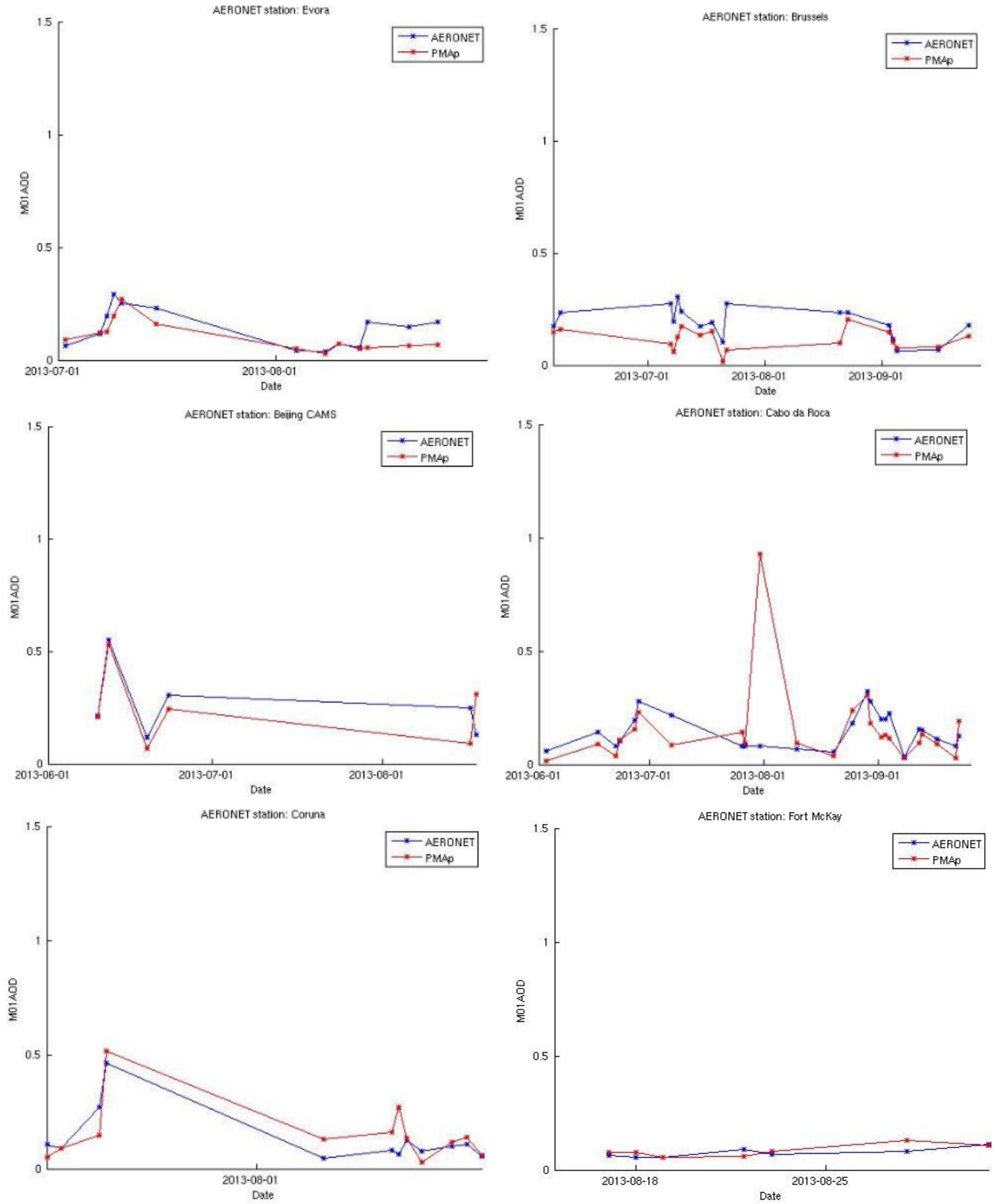


Figure 19. Time series of the AOD at 550 nm for June-September 2013 measured at different stations, compared to the AOD retrieved from Metop-B.

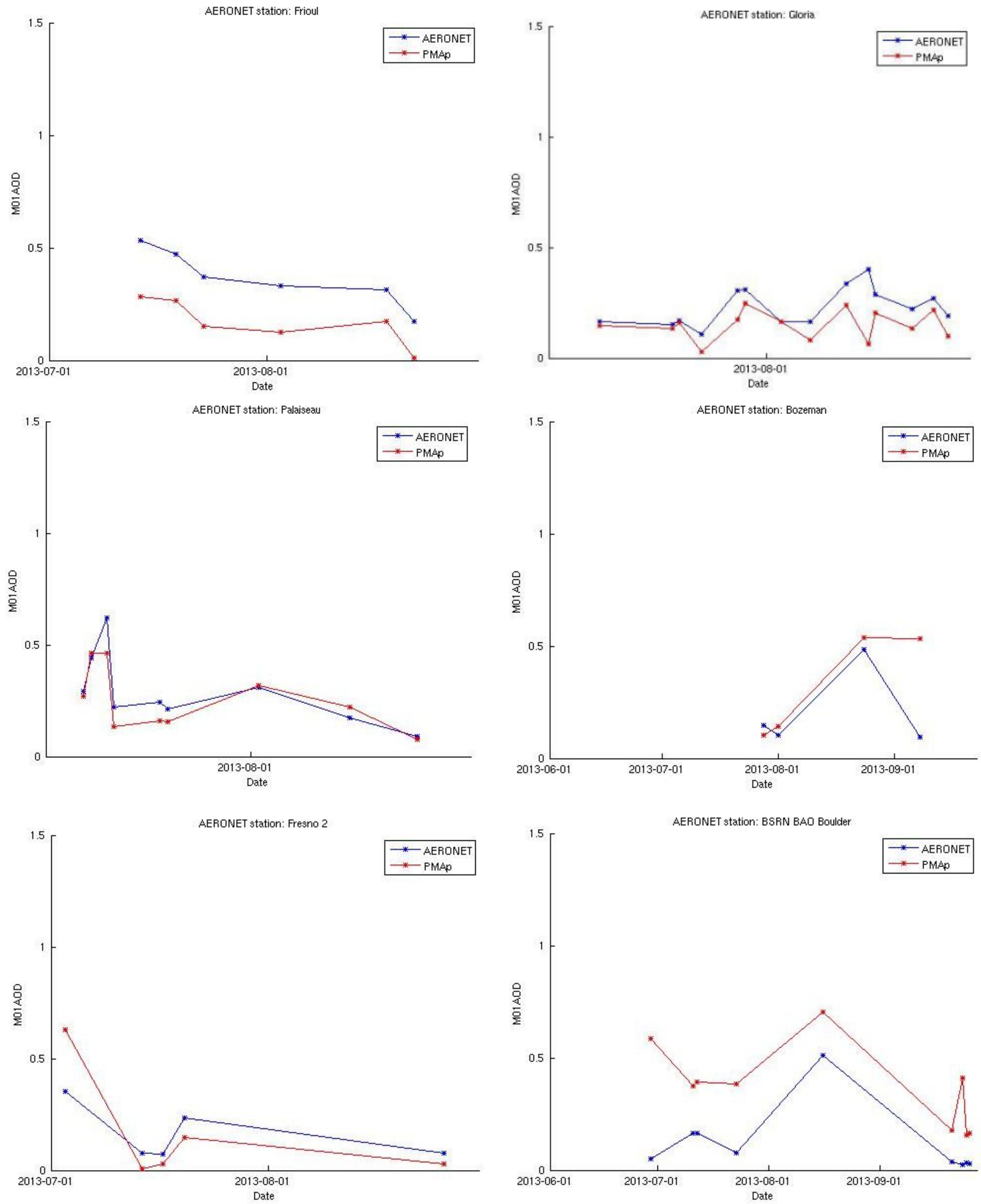


Figure 20. Time series of the AOD at 550 nm for June-September 2013 measured at different stations, compared to the AOD retrieved from Metop-B.

Figure 21 and Figure 22 show the plots relative to the PMAp/Metop-A retrieval for the same period. For this platform, the overall number of retrieval cases providing measurement for the comparison is 956.

The scatter plots for all the available co-located measurements between PMAp/Metop-A and AERONET for July 2013 are presented in linear and logarithmic scale, respectively (see Figure 21 and Figure 22).

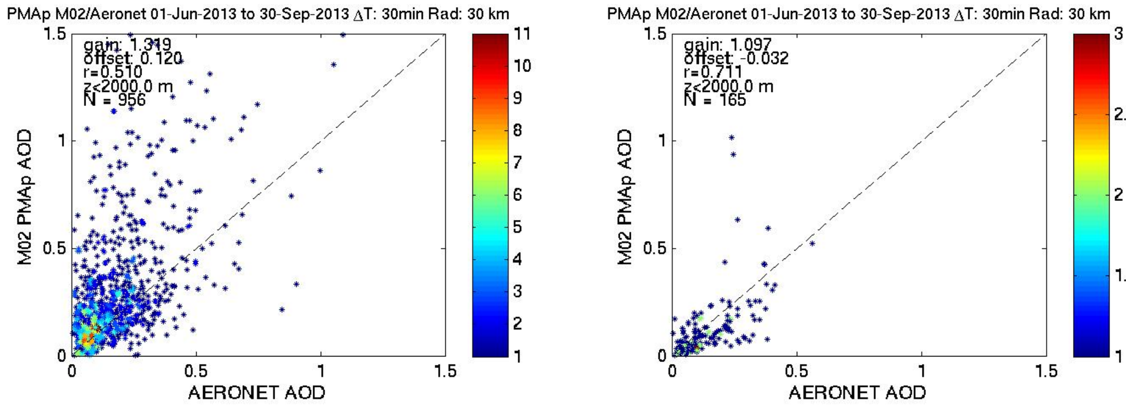


Figure 21: Scatter plot – linear scale – left panel: for the overall AERONET sites, right panel: cases retrieved partially cloudy scene or bright land is excluded; in June-September 2013: AOD at 550 nm from PMAp/Metop-A is plotted versus corresponding AERONET measurements.

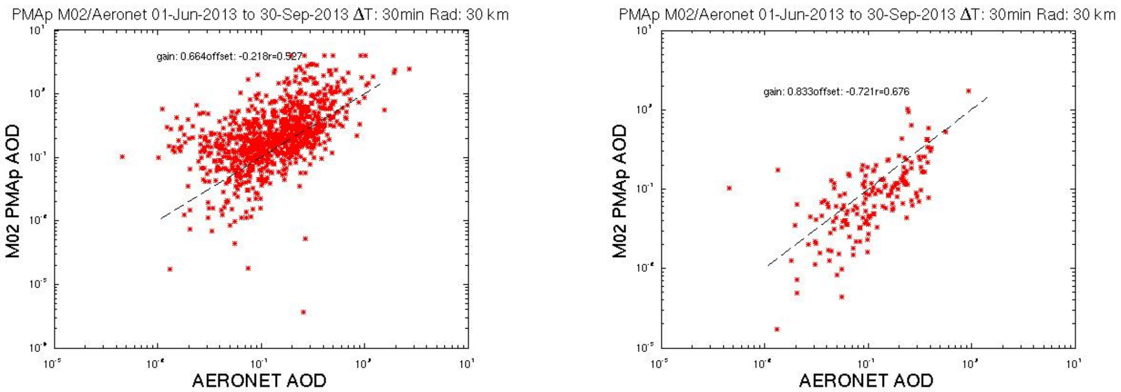


Figure 22: Scatter plot – logarithmic scale - for the overall AERONET sites June-September 2013: AOD at 550 nm from PMAp/Metop-A is plotted versus corresponding AERONET measurements.

This retrieval provides a relatively good agreement, in terms of linear fit parameters gain ~ 0.51 and offset ~0.12, which changes to 0.71 and -0.03 respectively for filtered data, indicating that reliable AOD values are retrieved over land for different surface and atmospheric conditions.

Figure 23 shows the SMAPE values, corresponding to the data presented in Figure 21, plotted as a function of AOD, for PMAp/Metop-A retrieval. The major part of the bin values lies around 50% for cloud free normal/dark land, the average SMAPE increases to 60% when we involve retrieval in partially cloudy pixels and bright surface. The average SMAPE value calculated is slightly higher with respect to the PMAp/Metop-B retrieval.

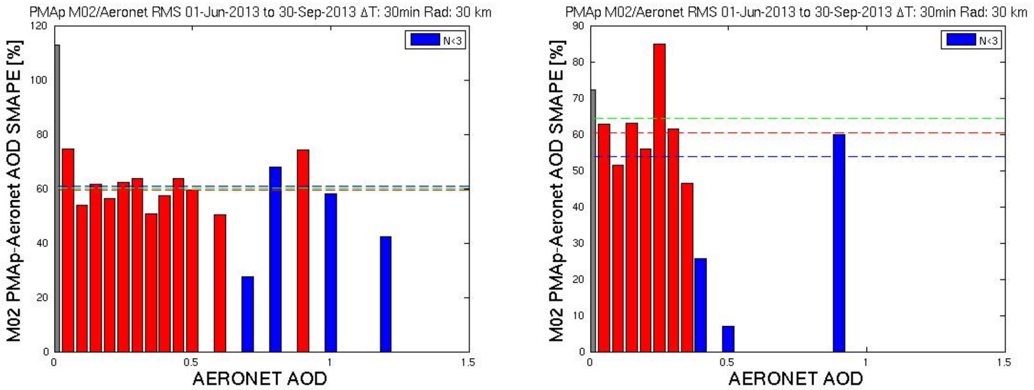


Figure 23: SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for June-September 2013 validation period, Metop-A. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

The comparison is completed with the AOD time series in Figure 24 to Figure 26:

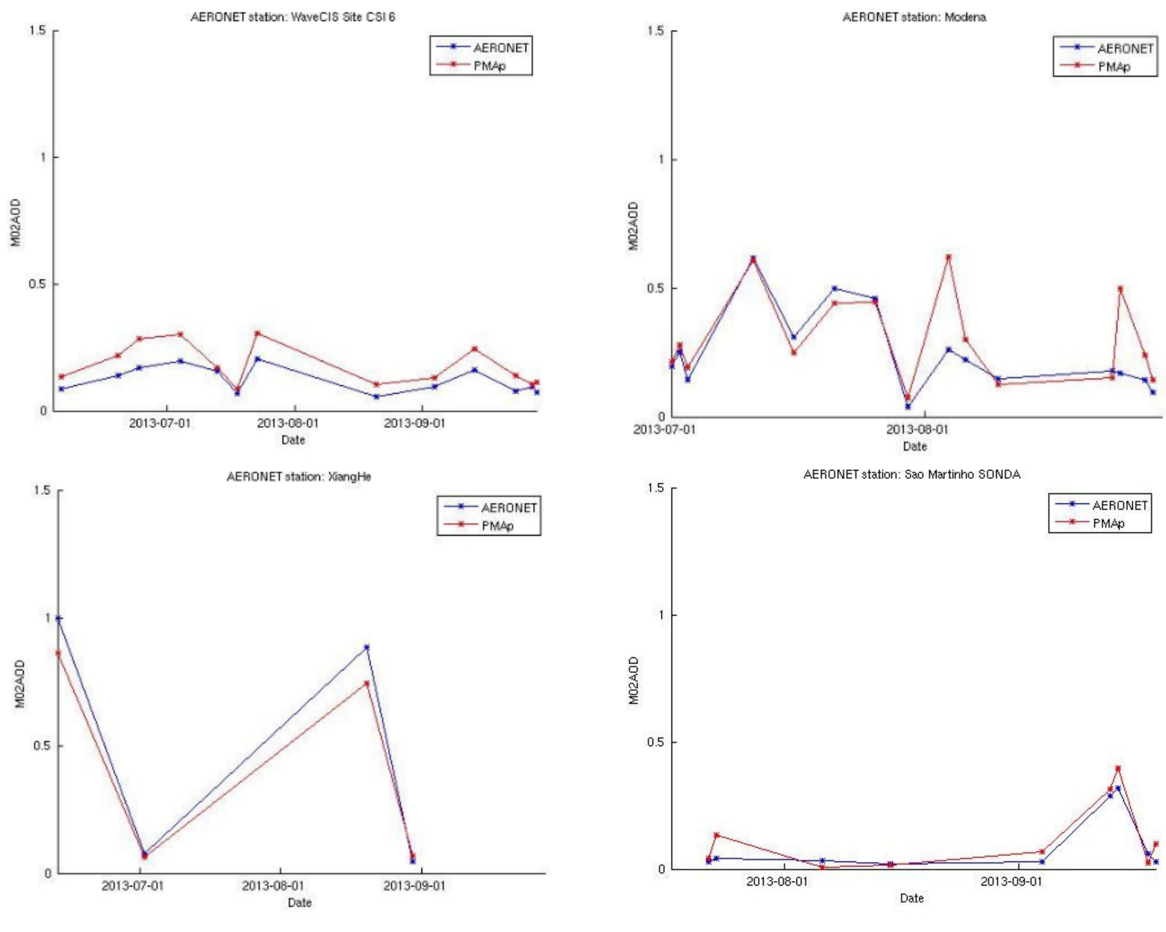


Figure 24. Time series of the AOD at 550 nm for June-September 2013 measured at different stations, compared to the AOD retrieved from Metop-A.

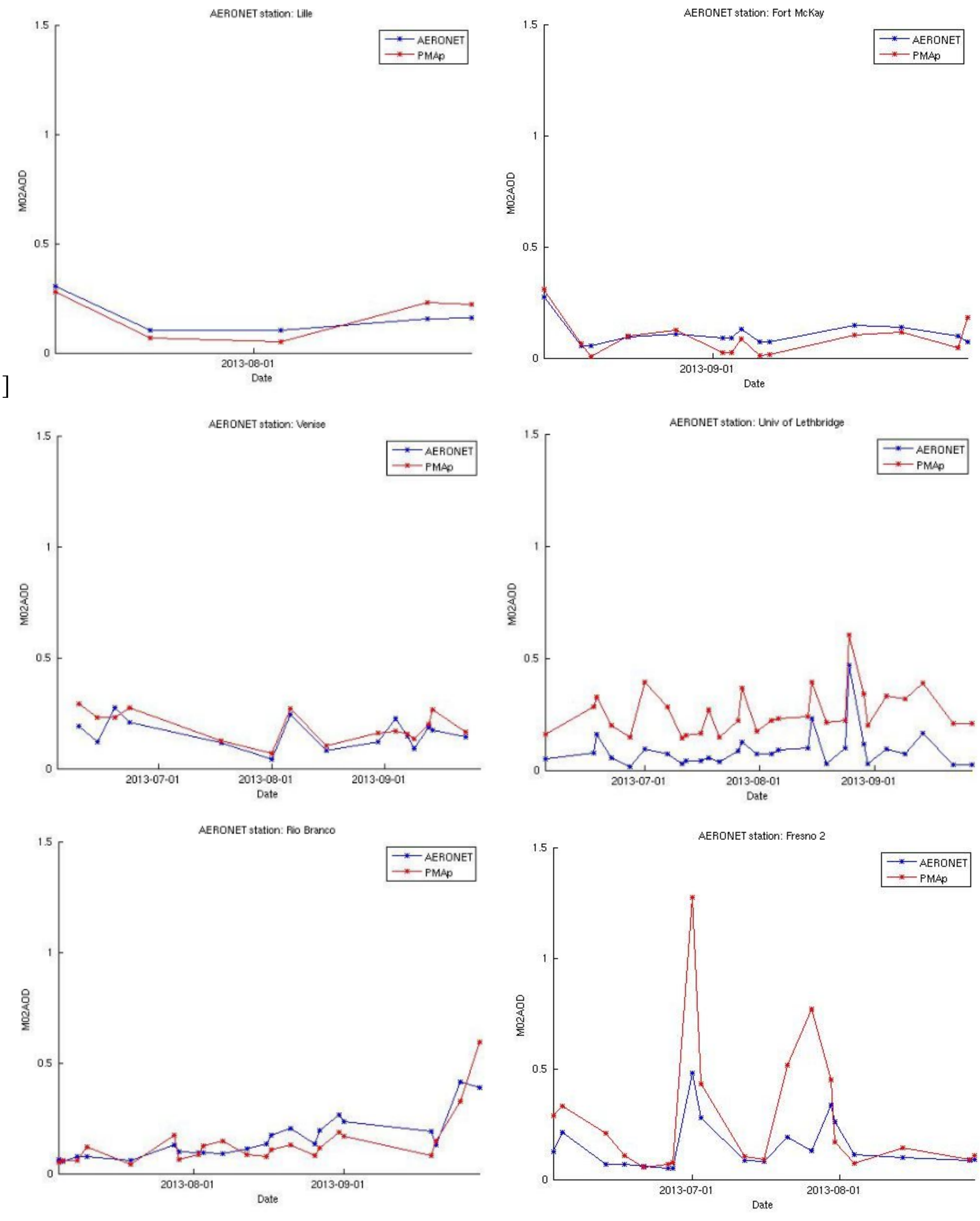


Figure 25. Time series of the AOD at 550 nm for June-September 2013 measured at different stations, compared to the AOD retrieved from Metop-A.

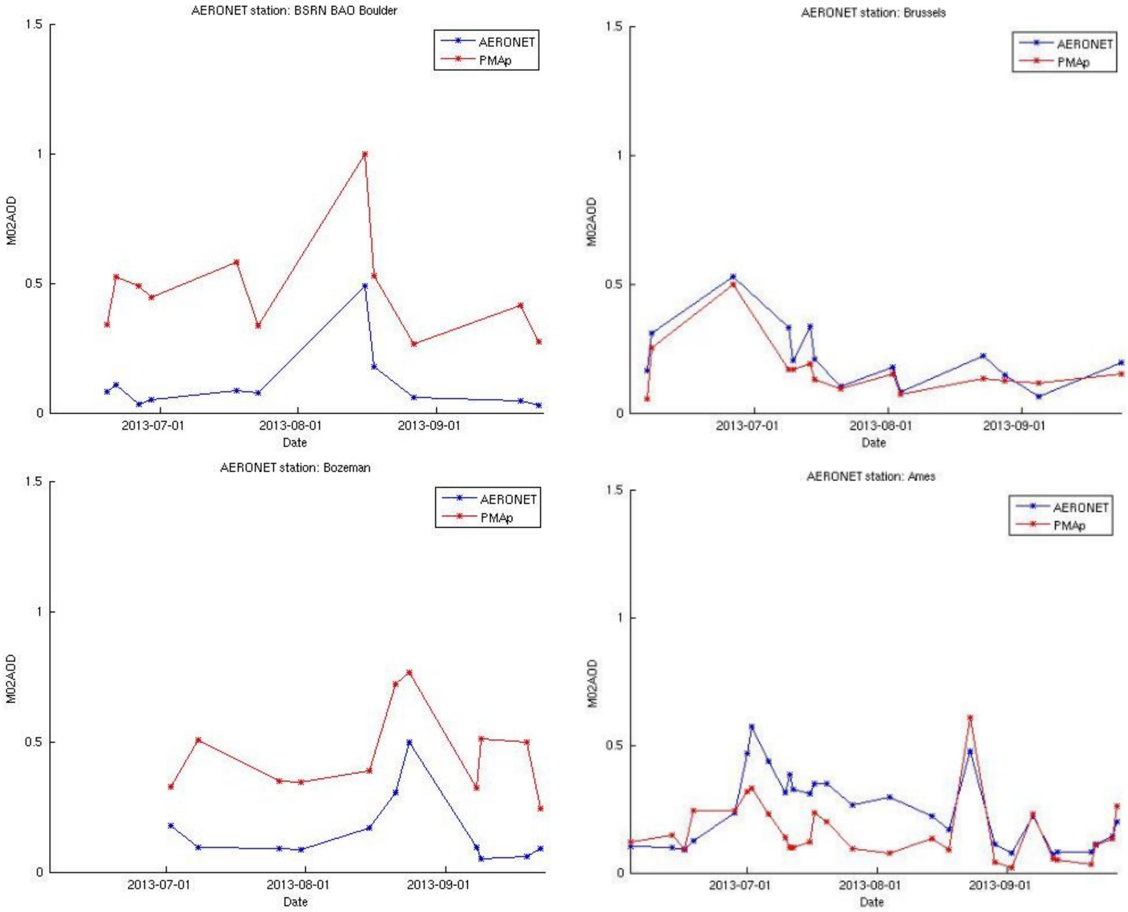


Figure 26: Time series of the AOD at 550 nm for June-September 2013 measured at different stations, compared to the AOD retrieved from Metop-A.

3.2.2.2 PMAp versus AERONET for February May 2015

Similarly to the June-September 2013 period, in this section we present the scatter plots and the time patterns of the AOD values from PMAp/Metop-B for February–May against corresponding AERONET AOD. All of these data are represented and plotted in linear and logarithmic scale in Figure 27 and Figure 28, respectively.

The linear regression fit provides gain equal to 0.84 and offset equal to 0.10 which changes to 0.63 and 0.07 if we exclude partially cloudy scenes and bright land. The results show an improvement in the gain values with respect to the former v2.1 in gain ~ 0.54 and also offset ~ 0.16. The offset values is still large but smaller than v2.1. The correlation value also increased in PMAp 2.2.4 ~ 0.58 (all data) and 0.68 (filtered data) compared PMAp 2.1 in which we had ~ 0.55 for all data.

SMAPE values, corresponding to the data in Figure 27 is presented in Figure 29. The SMAPE average for cases with N >3 is around 55% (all data) and 50 (filtered data) % level in this validation period.

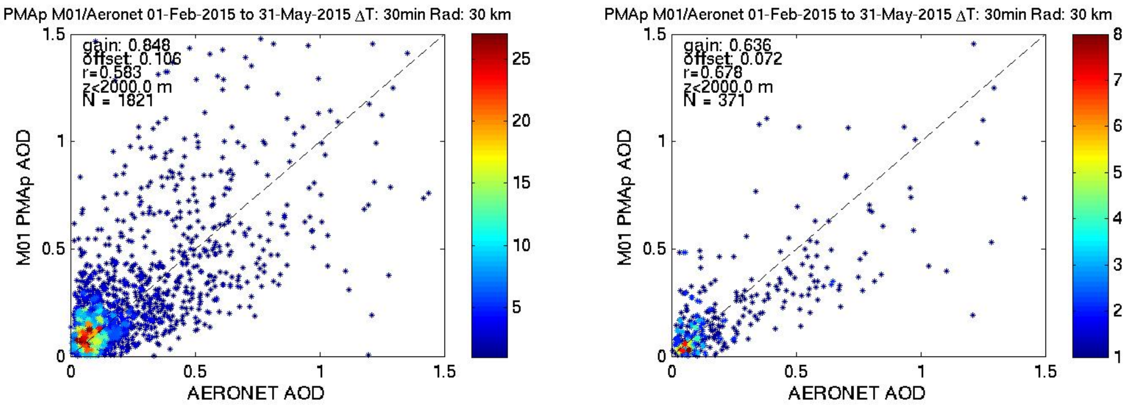


Figure 27. Scatter plot – linear scale – left panel: for the overall AERONET sites, right panel: cases retrieved partially cloudy scene or bright land is excluded; in February-May 2015: AOD at 550 nm from PMAp/Metop-B is plotted versus corresponding AERONET measurements.

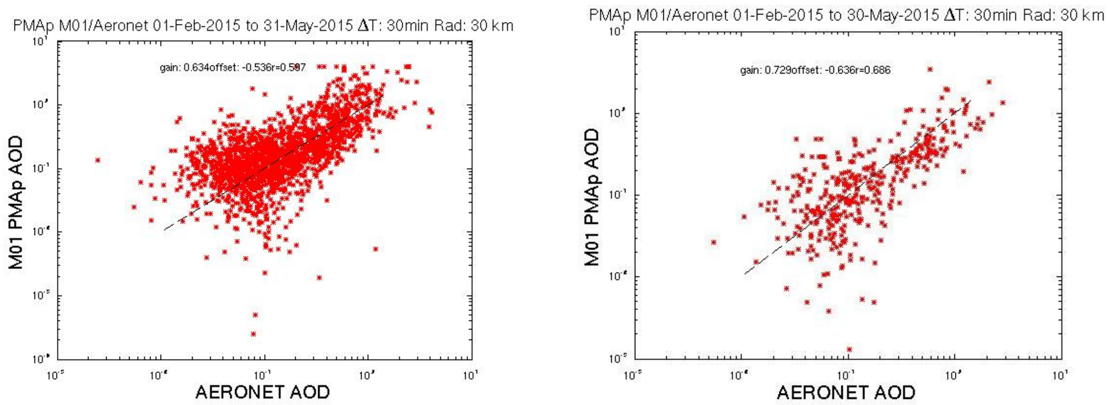


Figure 28. Scatter plot – logarithmic scale - for the overall AERONET sites February-May 2015: AOD at 550 nm from PMAp/Metop-B is plotted versus corresponding AERONET measurements.

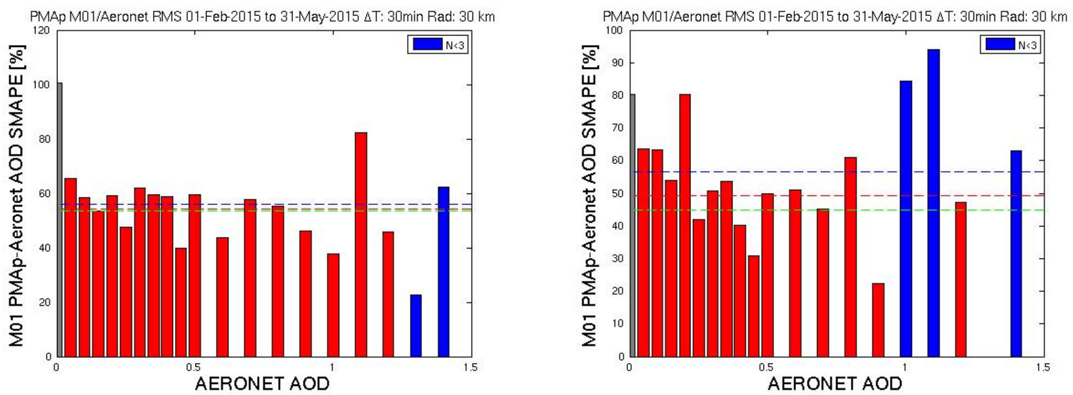


Figure 29. SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for February-May 2015 validation period, Metop-B. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

The comparison is completed with the AOD time series in Figure 30 to Figure 32:

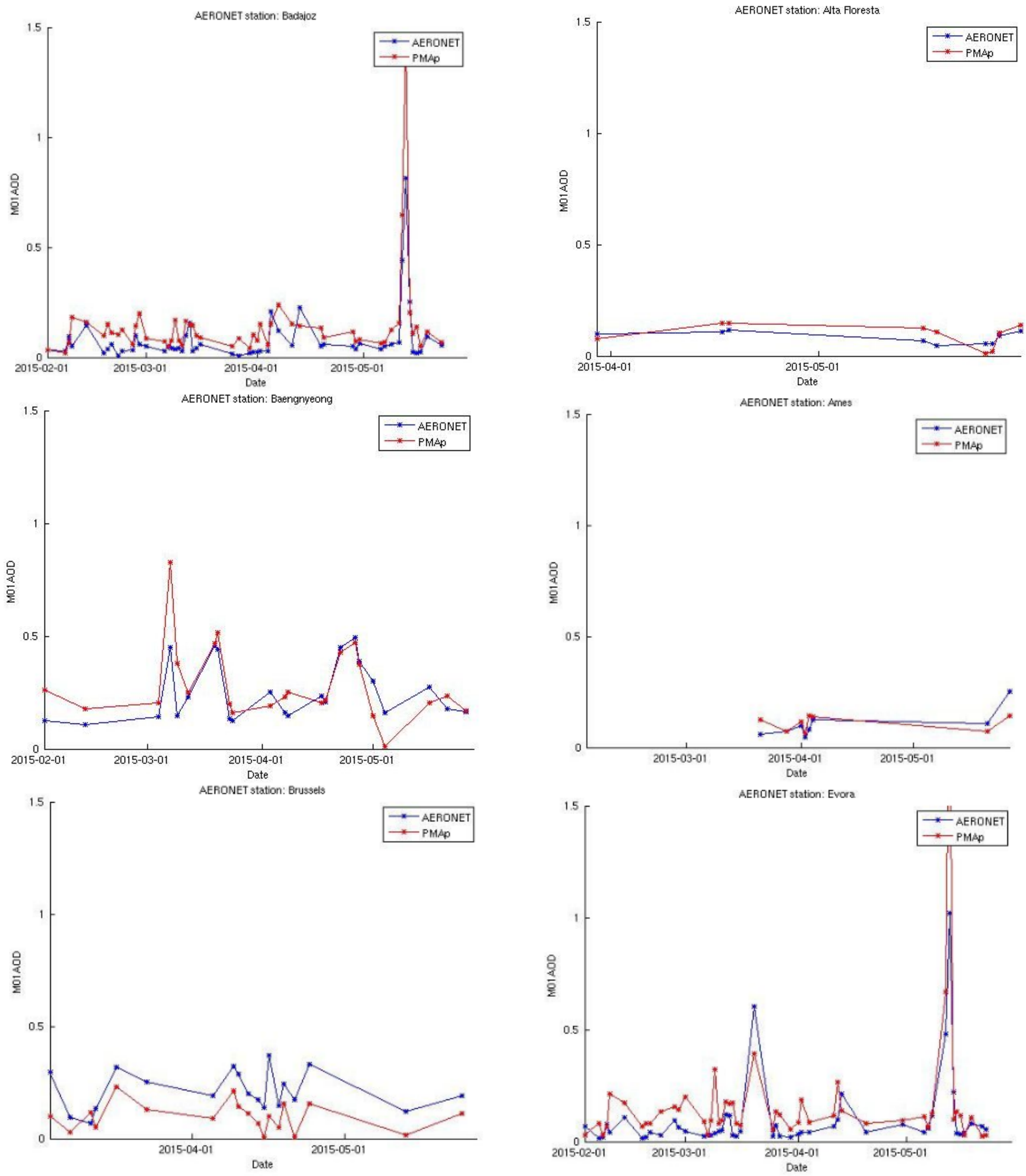


Figure 30. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop- B.

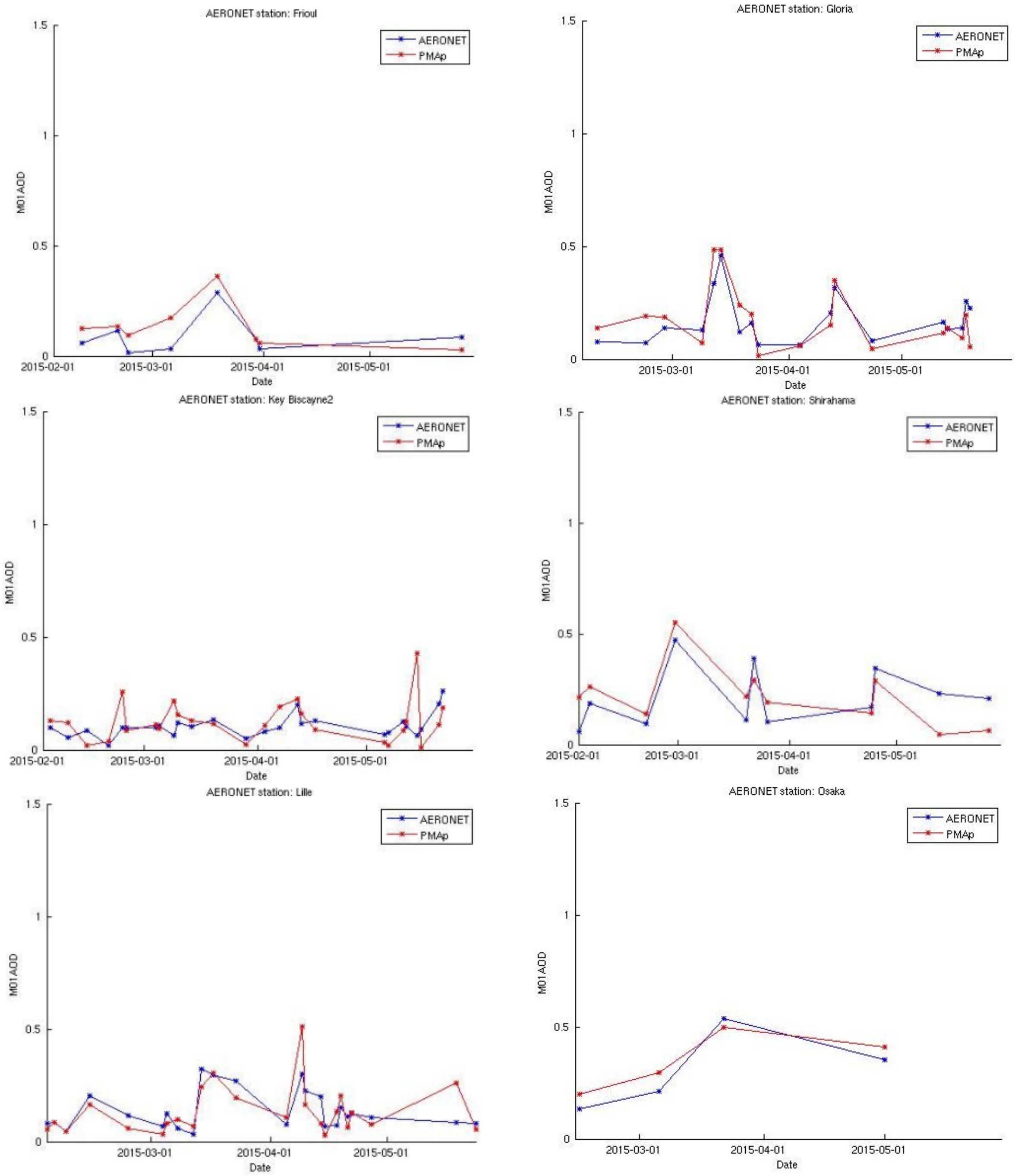


Figure 31. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop- B.

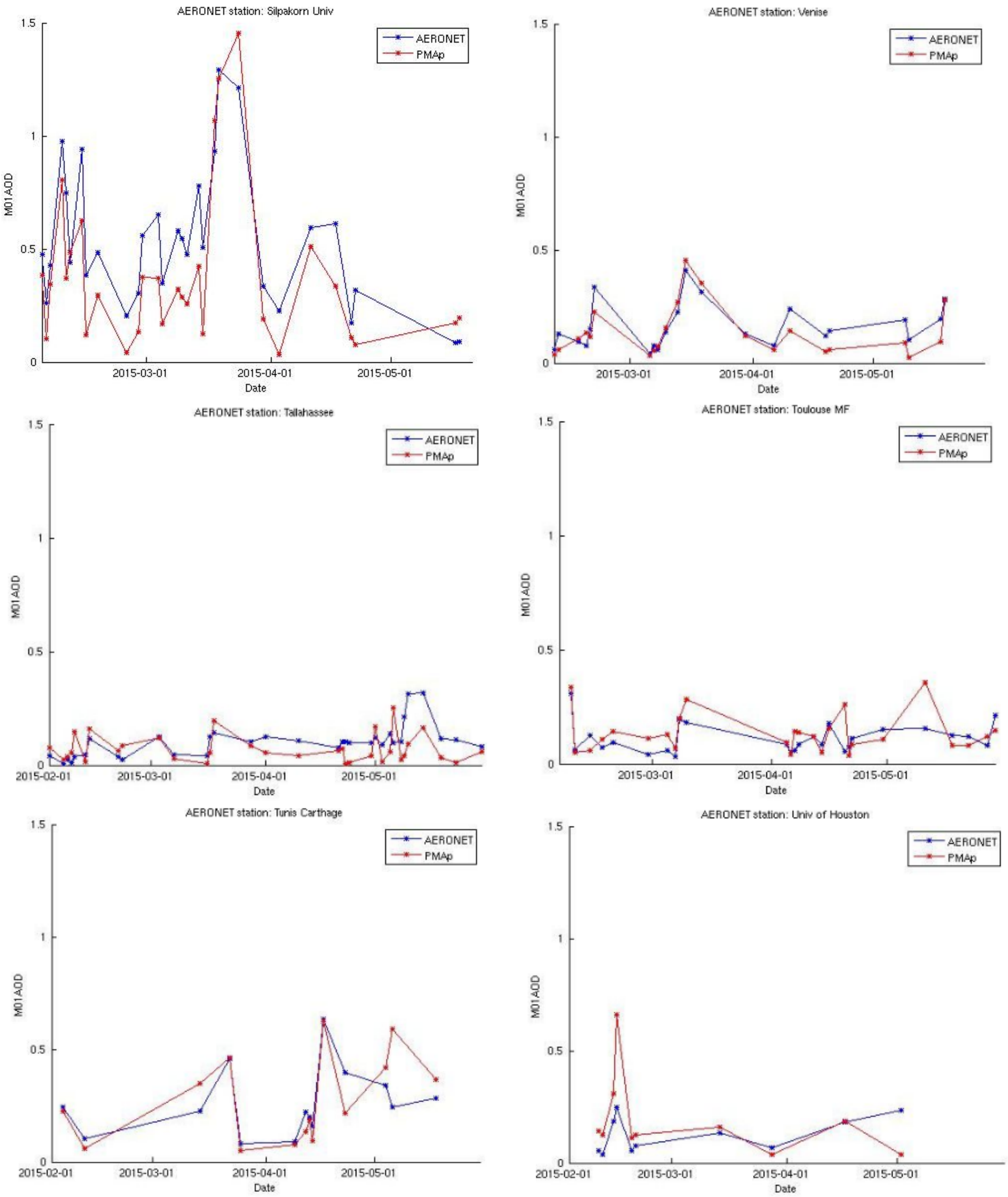


Figure 32. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop- B.

Figure 33 and Figure 34 show the plots relative to the PMAp/Metop-A retrieval for the same period for an overall number of cases equal to 1303. The scatter plots for all the available co-located measurements between PMAp/Metop-A and AERONET for the 2015 period are presented in linear and logarithmic scale, respectively.

The linear fit parameters provided by this retrieval are gain equal to 0.78 and offset equal to 0.14 which changes to gain of 0.53 and offset of 0.08 if we exclude retrievals over partially cloudy pixels or bright land. In this case, though the offset is still larger compared to previous cases, the gain and offset is being improved compared to the performances given by the PMAp v2.1 retrieval in which gain and offset were 0.50 and 0.15, respectively. Correlation value decreased slightly from 0.6 to 0.52, but this can be due to the fact that the number of retrieval increased in v2.2.4 about 15-50% to which dust detection scheme contributed the most. If we exclude retrieval over bright land and partially cloudy pixels, correlation increases to 0.75.

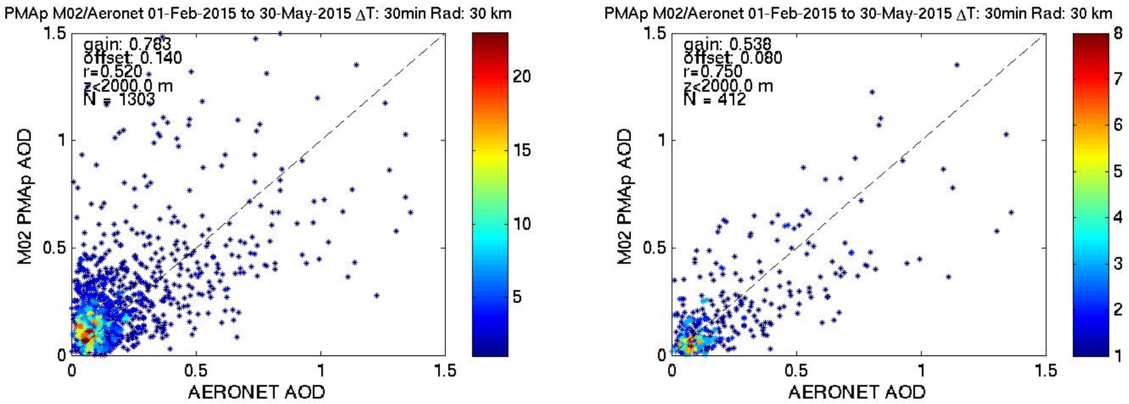


Figure 33. Scatter plot – linear scale – left panel: for the overall AERONET sites, right panel: cases retrieved partially cloudy scene or bright land is excluded; in February-May 2015: AOD at 550 nm from PMAp/Metop-A is plotted versus corresponding AERONET measurements.

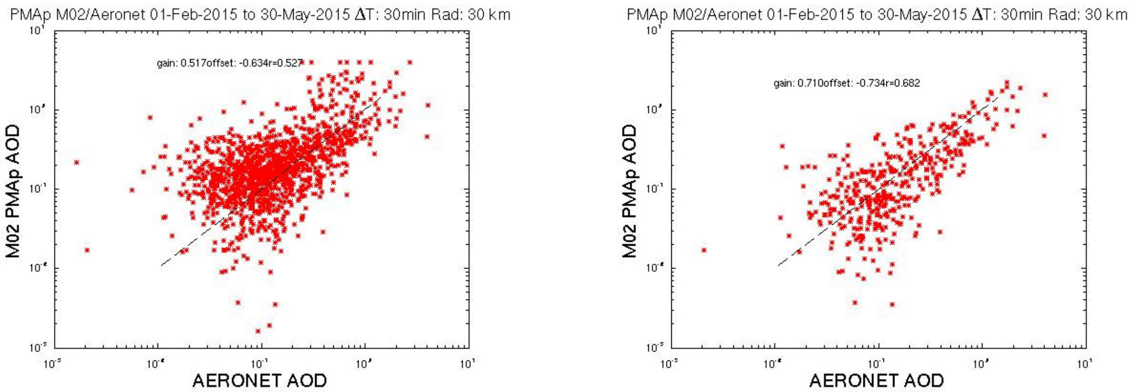


Figure 34. Scatter plot – logarithmic scale - for the overall AERONET sites February-May 2015: AOD at 550 nm from PMAp/Metop-A is plotted versus corresponding AERONET measurements.

Figure 35 shows the SMAPE values, corresponding to the data presented in Figure 33 plotted as a function of AOD, for PMAp/Metop-A retrieval. The SMAPE average value calculated for cases with a number of measurements greater than three (red dashed line) is around 60% as for the PMAp/Metop-B retrieval which decreases to 50% if we exclude bright land and partially cloudy pixels. In the latter case, we have more bins having SMAPE value smaller than the requirement ~ 40%.

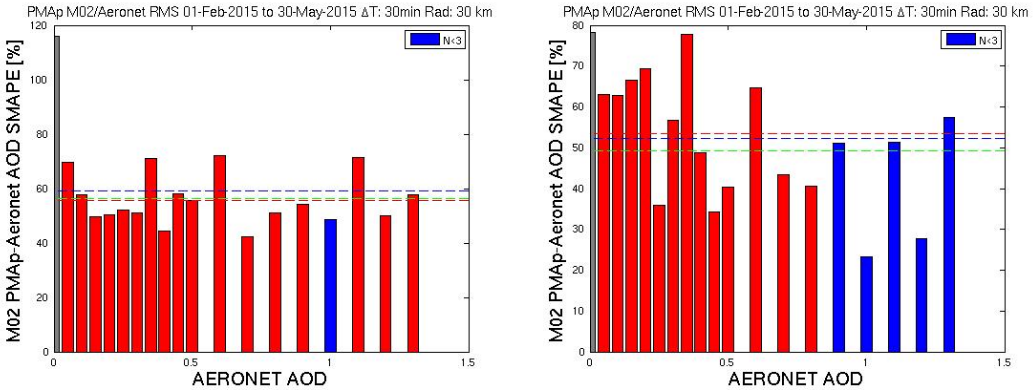


Figure 35. SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for February-May 2015 validation period, Metop-A. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

The comparison is completed with some examples of AOD time series (Figure 36 to Figure 39) from PMAp/Metop-A for the case of all data (no filter on the data). AERONET AOD measurements (blue line) are compared to the corresponding PMAp (red line).

Overall PMAp follows Aeronet measurements nicely. Pokhara station in Nepal is located in an area with highly variant topography with 800 m height above mean sea level. Pokhara is a suburban site in Nepal region with local contribution from Pokhara City and significant rural biomass burning, and downwind of the IndoGangetic Plains, which are often covered in haze during winter and spring. Pokhara monthly averaged AOD measured at the AERONET site at 550nm shows a strong seasonal cycle with the highest peak in April around 0.8 (Xu et al., 2014). This can be one reason for the deficiency in surface estimation and overall underestimation in this station. The same applies for Son la station in Laos. Silpakorn station is located on coastline in Thailand, Chiang M. M. S. in north Thailand and Bac Lieu in Vietnam, all shows underestimation of AOD in this area. However, PMAp follows the dynamics very well. Rio Branco station located in Amazon forest and Sao M. SONDA and Ji Parana stations in south America represent a very good agreement for this location. Shirahama station in Japan and Yonsei Uni. Station in south Korea represent promising results. Hung Chun station shows very good performance over Taiwan. Kellog LTER and Univ of Houston are examples over US. Quarzazate: North Africa; Pretoria_CSIR-DPSS: south Africa.

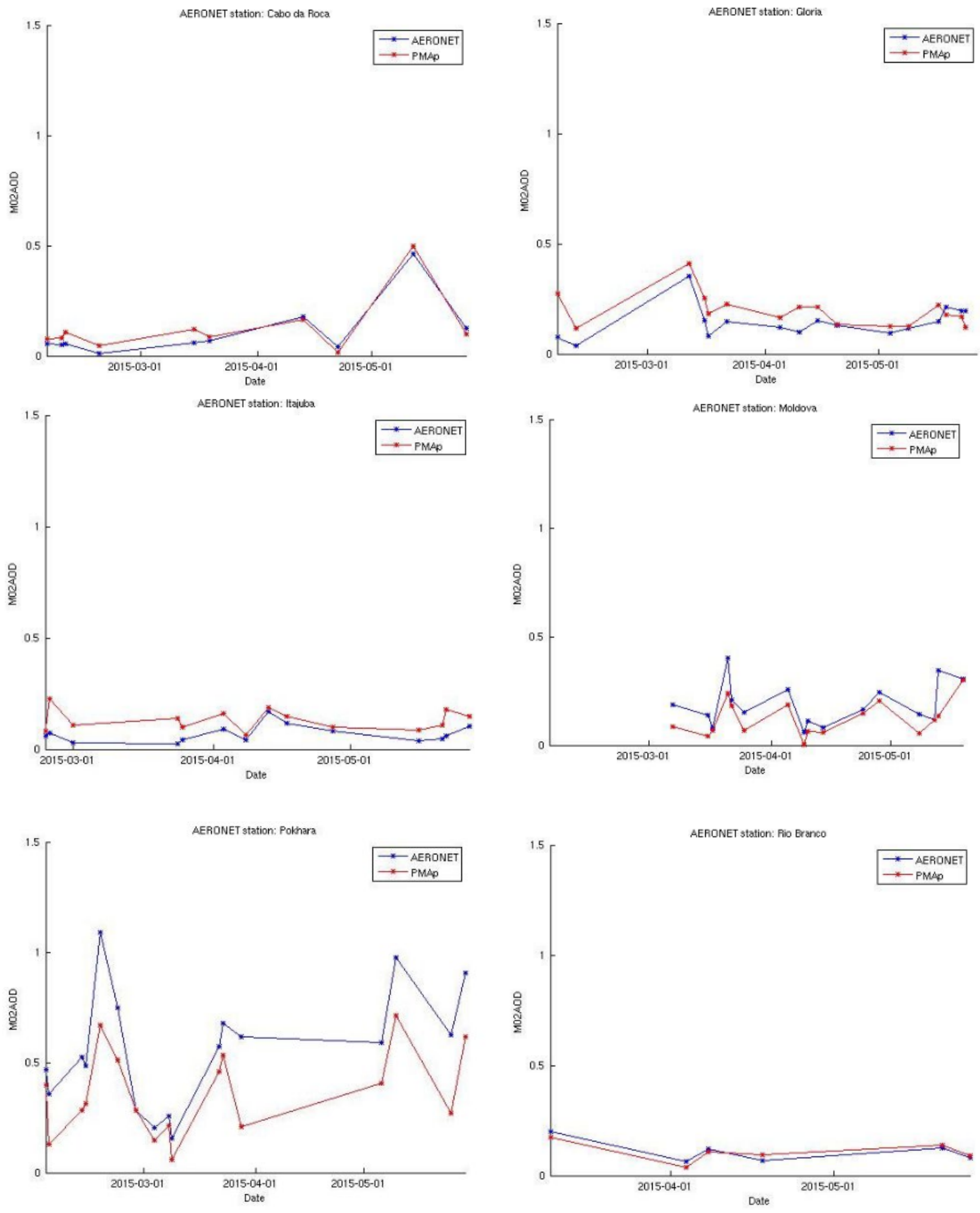


Figure 36. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop-A.

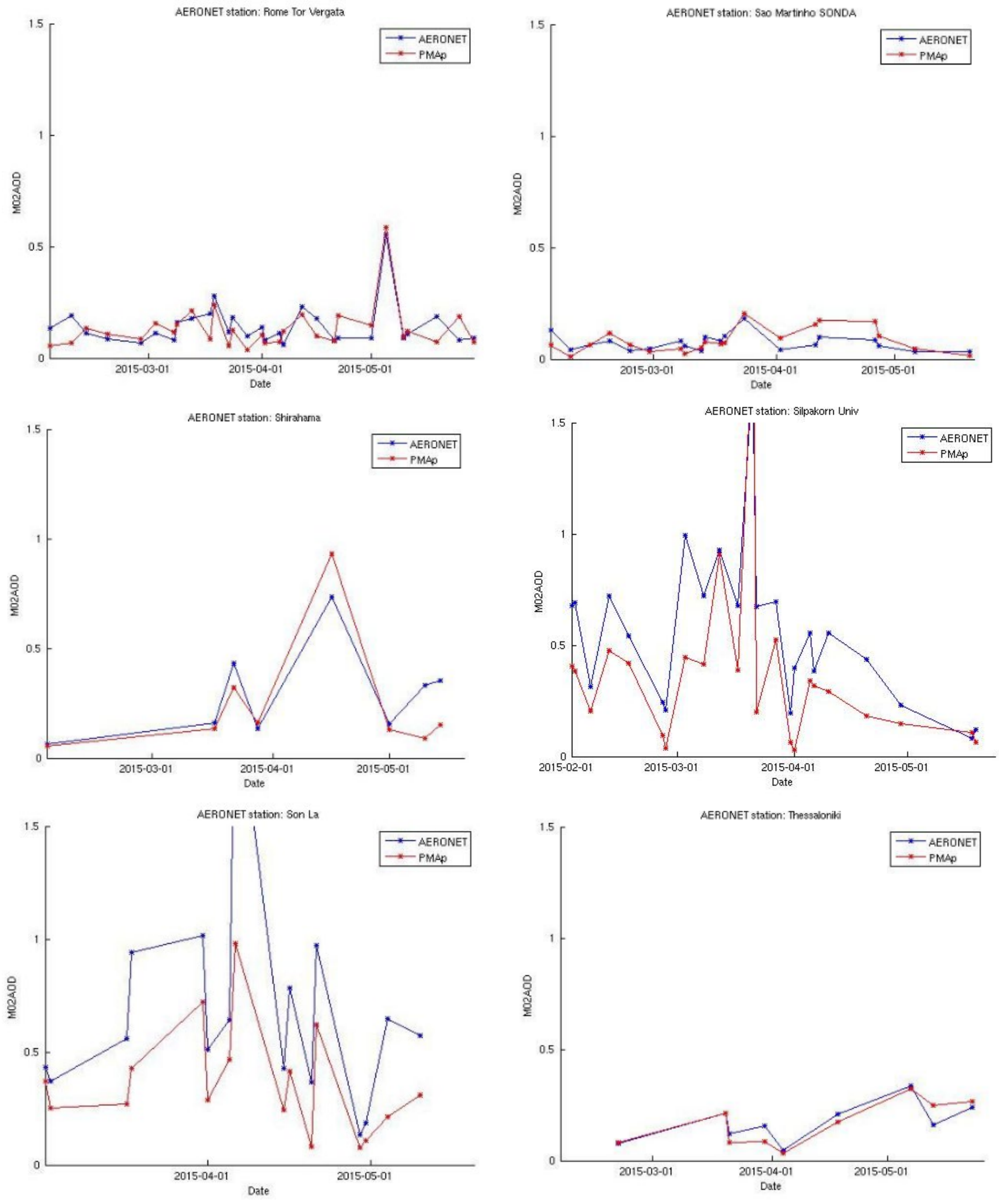


Figure 37. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop-A.

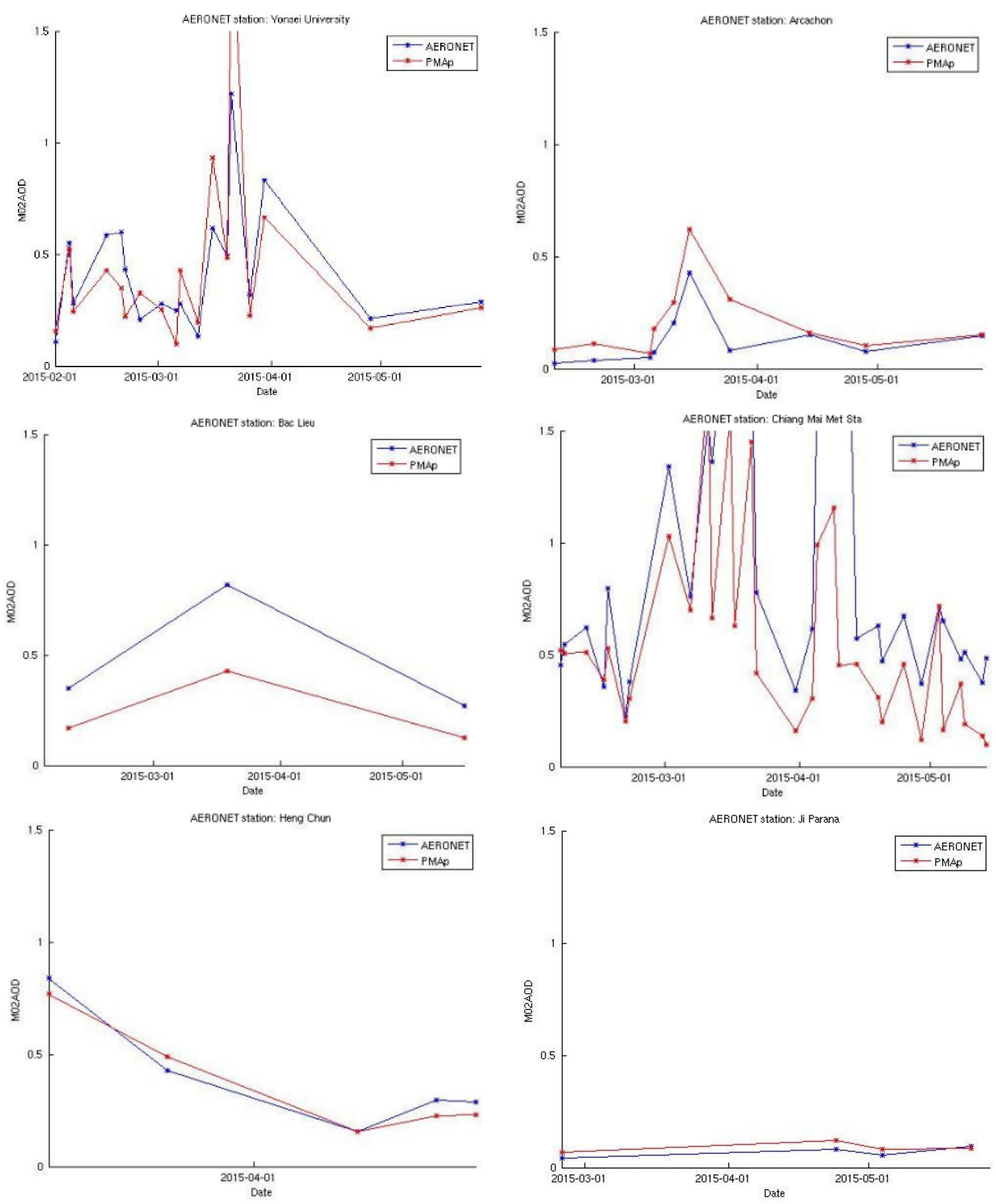


Figure 38. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop-A.

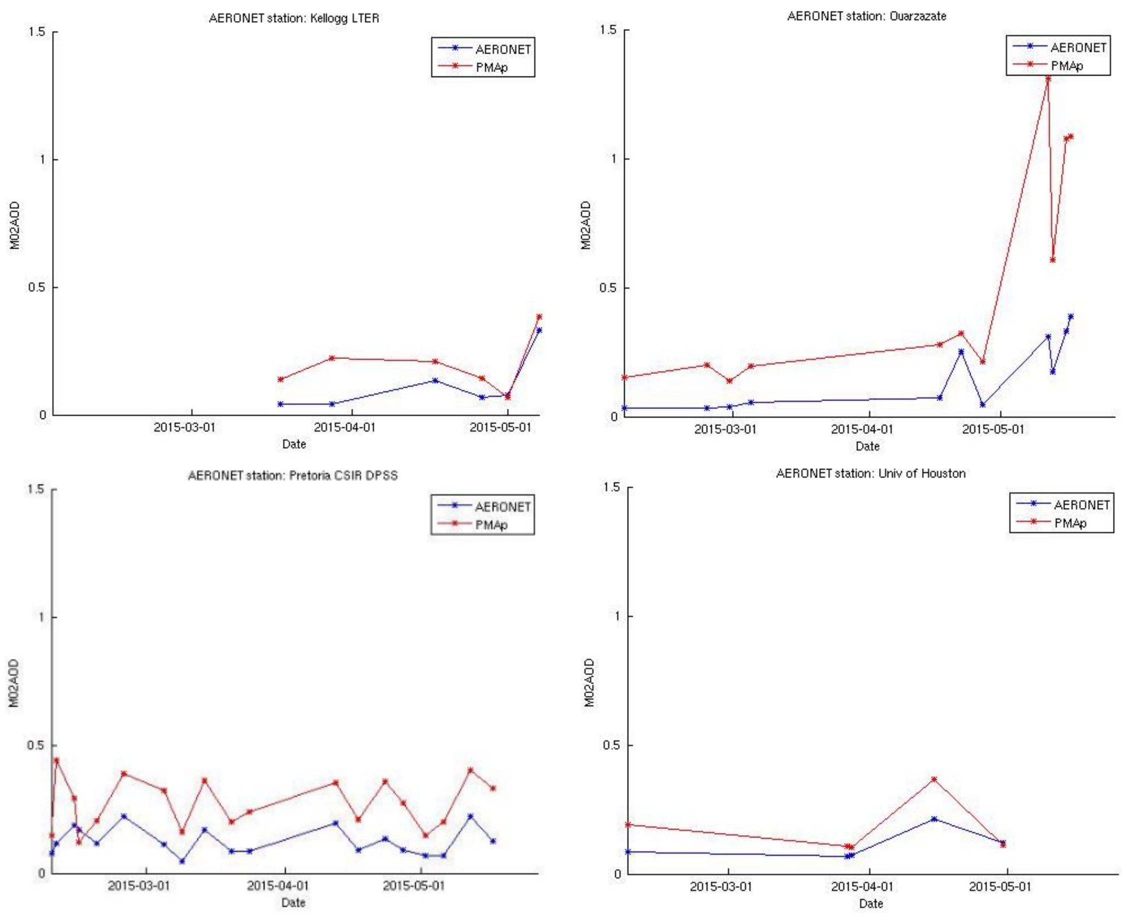


Figure 39. Time series of the AOD at 550 nm for February-May 2015 measured at different stations, compared to the AOD retrieved from Metop-A.

3.2.3 Comparison results over water surface

In the following two sections the results of the validation over sea surface are presented for the two validation periods and for each Metop platform separately.

3.2.3.1 *PMAp versus AERONET for June - September 2013*

AOD values from PMAp/Metop-B for June-September 2013 set against corresponding AERONET AOD data for sites located in small islands are reported in the scatter plots of Figure 40 for an overall numbers of retrievals equal to 117. This data includes retrieval cases in both cloud-free and partially cloudy scenes.

The data are reported in single scatter plot in linear and logarithmic scale showing a good overall agreement between PMAp and AERONET collocated data. The regression parameters of the linear scale scatter plot are equal to 0.51 for the gain and 0.098 for the offset.

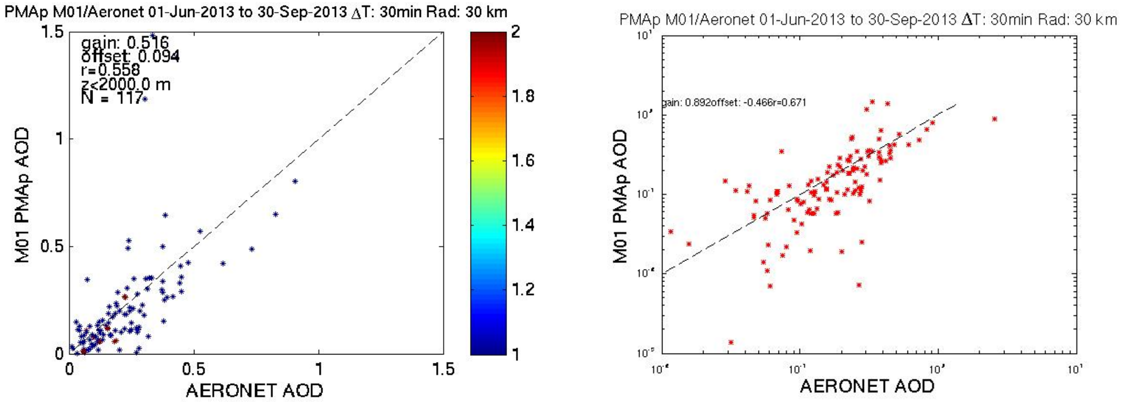


Figure 40 Scatter plot – left: linear, right: logarithmic scale - for the overall AERONET sites in June – September 2013 : AOD at 550 nm from PMAp/Metop-B is plotted versus corresponding AERONET measurements.

In Figure 41, the SMAPE values corresponding to the data presented in Figure 40, are plotted as a function of AOD. The major part of the bin values has values ≤ 40% and the SMAPE average value calculated for cases with a number of measurements greater than three (red dashed line) is ~ 50%. The binned values are decreasing with increasing AOD, even for bins with N> 3, still in this trend two spikes for AOD around 0.3 and 0.7 are present.

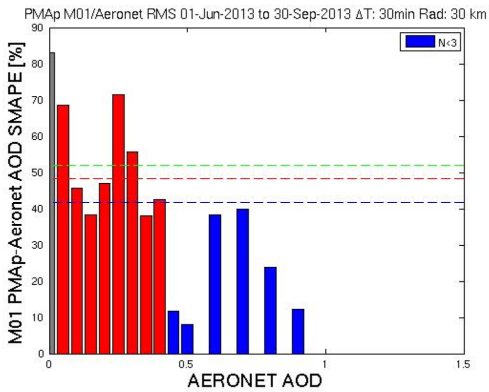


Figure 41 SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for June-September 2013 validation period, Metop-B. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

The time-series plots are presented in Figure 42. In general, all sites present a good agreement. A noticeable exception is Mauna Loa (about 3400 m amsl). For this site, a very small AOD is given by AERONET, this level being close or below the detection limit of PMAp, already determined for the v.2.1. In addition, considering the GOME2 pixel size, the land/ocean heterogeneity of Hawaii, and the altitude of the Aeronet site, the satellite to ground-based comparison a good comparison remains challenging.

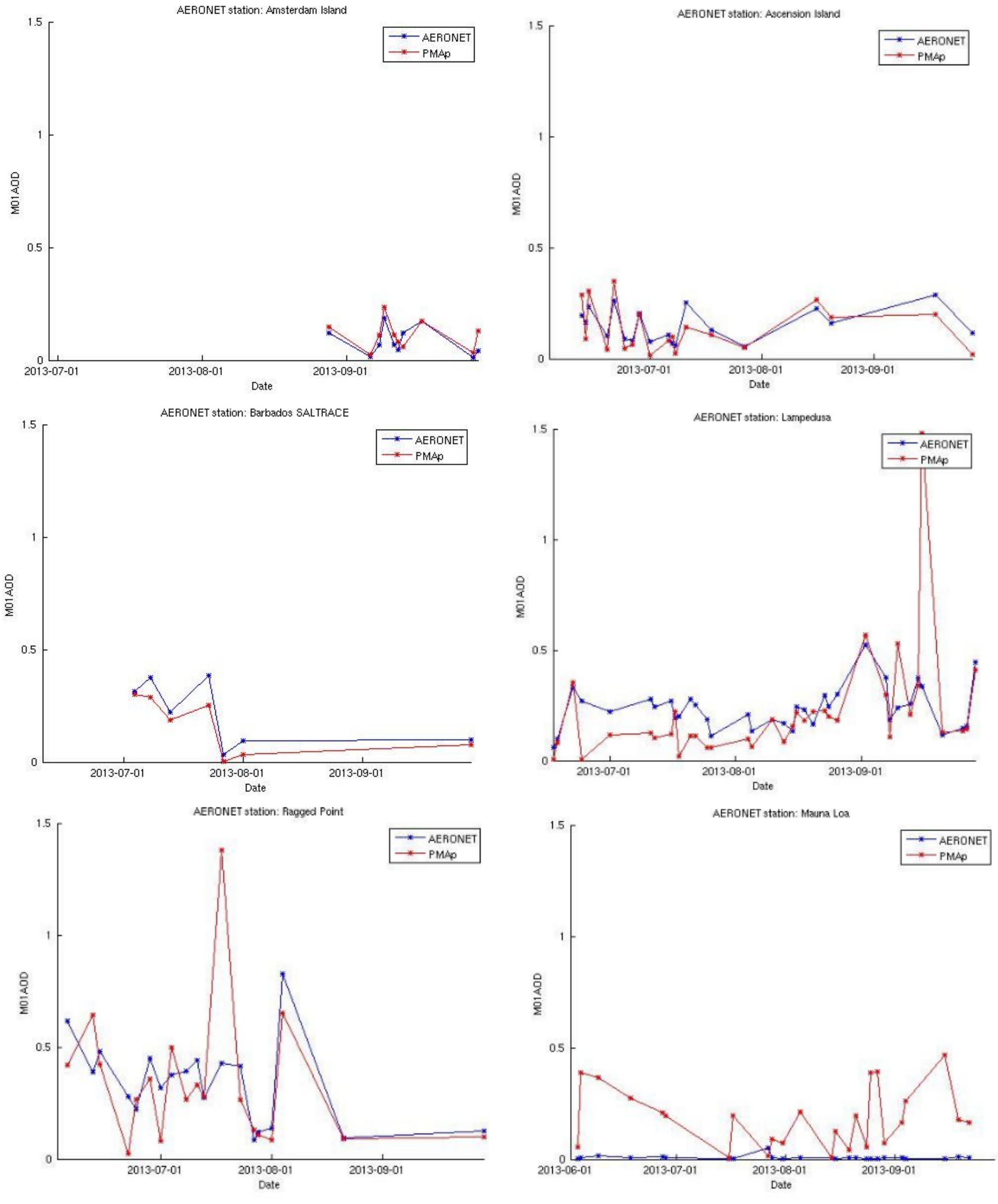


Figure 42. Time series of the AOD at 550 nm for June_September 2013 measured at different stations, compared to the AOD retrieved from Metop-B.

In Figure 43, are reported all the scatter plots for each AEROENT site having AOD measurements co-located in correspondence with PMAp/Metop-A retrieval in the period June-September 2013.

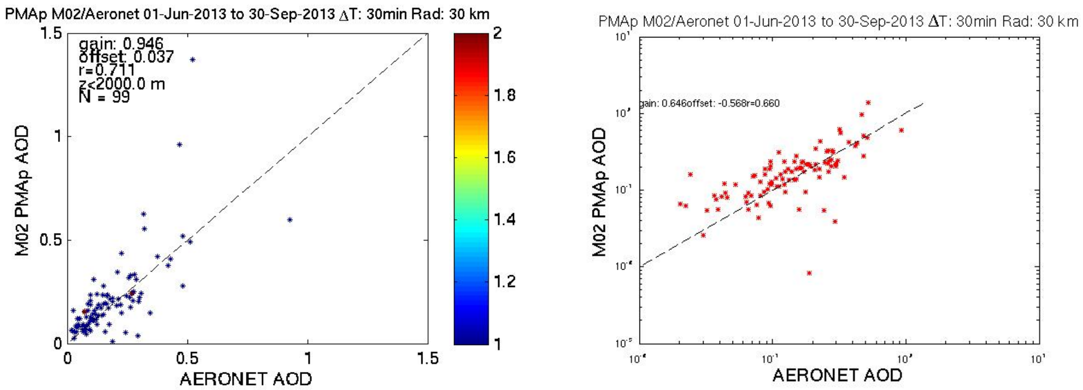


Figure 43. Scatter plot – left: linear, right: logarithmic scale - for the overall AERONET sites in June – September 2013 : AOD at 550 nm from PMAp/Metop-A is plotted versus corresponding AERONET measurements.

The general behaviour is similar to those of PMAp/Metop-B with an overall good agreement for all sites with the exception of the peculiar values shown by the Mauna Loa site.

This good agreement is confirmed by the linear and log-scale logarithm relative to all the available co-located measurement of the period. The linear regression fit is providing slope value equal to 0.94 and offset equal to 0.03. SMAPE values corresponding to these data are plotted against AOD values in Figure 44. Two peaks around 0.3 and 0.5 AOD values are observed.

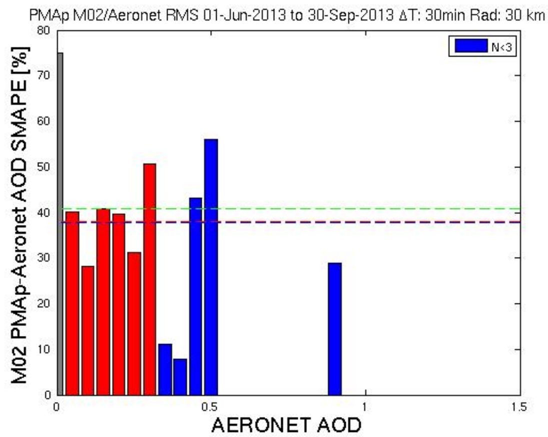
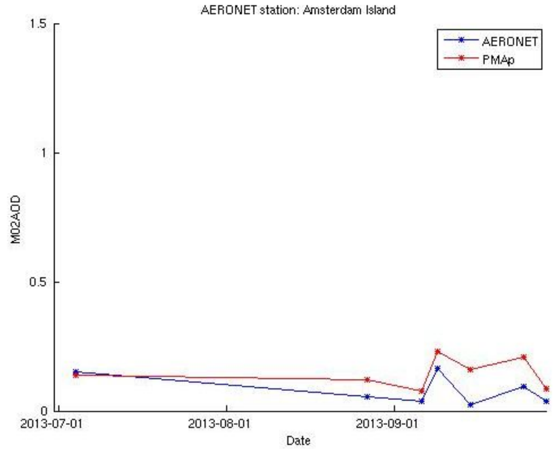
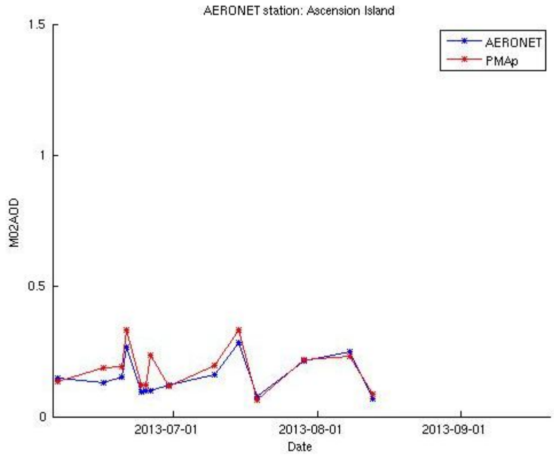
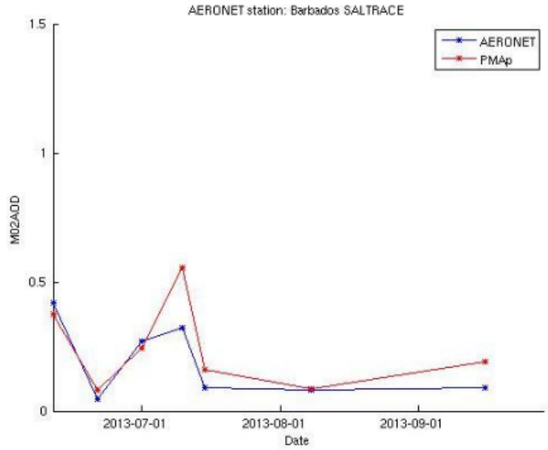
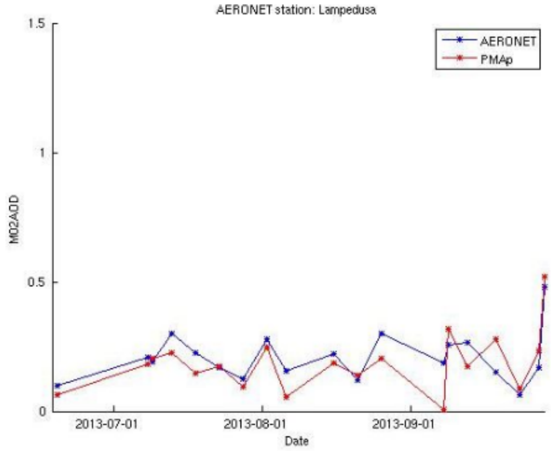


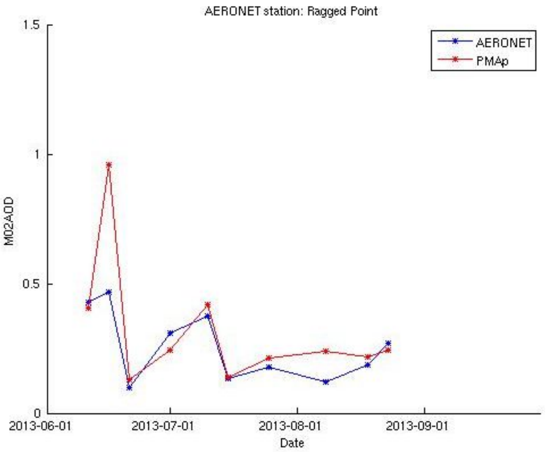
Figure 44. SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for June-September 2013 validation period, Metop-A. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

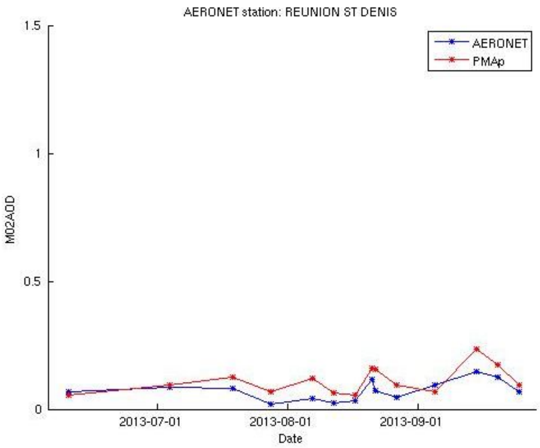

AERONET station: Amsterdam Island
AERONET
PMAp
M02AOD
Date
1.5
1
0.5
0
2013-07-01
2013-08-01
2013-09-01


AERONET station: Ascension Island
AERONET
PMAp
M02AOD
Date
1.5
1
0.5
0
2013-07-01
2013-08-01
2013-09-01


AERONET station: Barbados SALTRACE
AERONET
PMAp
M02AOD
Date
1.5
1
0.5
0
2013-07-01
2013-08-01
2013-09-01


AERONET station: Lampedusa
AERONET
PMAp
M02AOD
Date
1.5
1
0.5
0
2013-07-01
2013-08-01
2013-09-01


AERONET station: Ragged Point
AERONET
PMAp
M02AOD
Date
1.5
1
0.5
0
2013-06-01
2013-07-01
2013-08-01
2013-09-01


AERONET station: REUNION ST DENIS
AERONET
PMAp
M02AOD
Date
1.5
1
0.5
0
2013-07-01
2013-08-01
2013-09-01

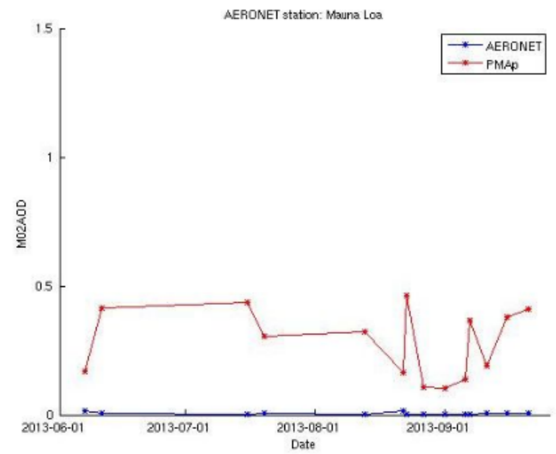


Figure 45. Time series of the AOD at 550 nm for June_September 2013 measured at different stations, compared to the AOD retrieved from Metop-A.

3.2.3.2 *PMAp versus AERONET for February May 2015*

AOD values from PMAp/Metop-B for February – May 2015 set against corresponding AERONET AOD data for sites located in small islands are reported in the scatter plots of Figure 46. The available sites present a fair agreement which provides overall linear regression parameters equal to 0.96 for the slope and 0.00 for the offset. The SMAPE values are presented in Figure 47.

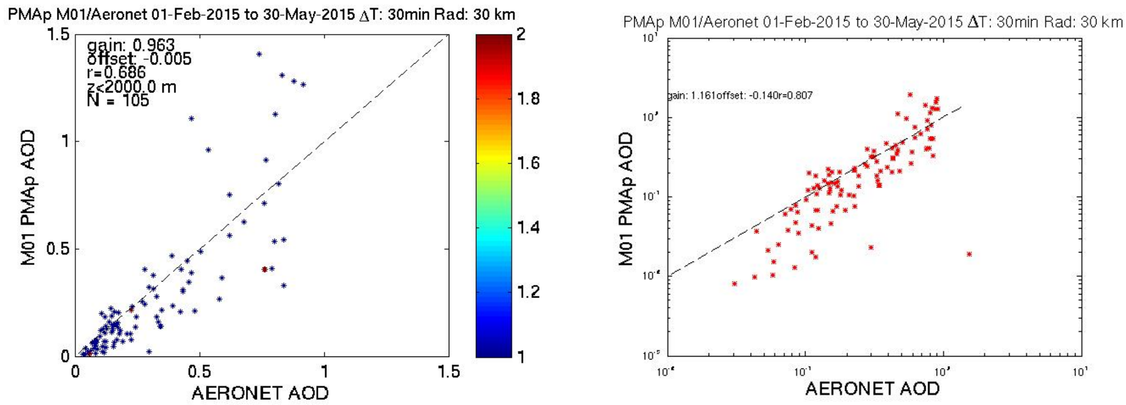


Figure 46 Scatter plot – left: linear, right: logarithmic scale - for the overall AERONET sites in February – May 2015 : AOD at 550 nm from PMAp/Metop-B is plotted versus corresponding AERONET measurements.

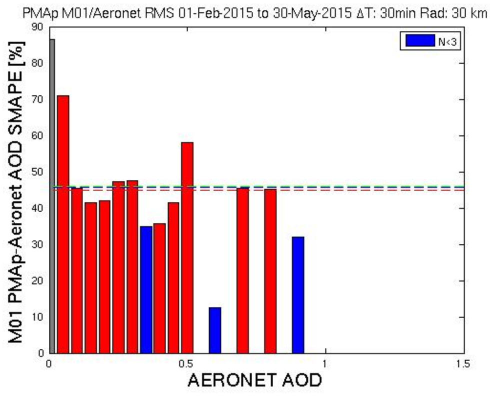


Figure 47. SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for June-September 2013 validation period, Metop-A. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

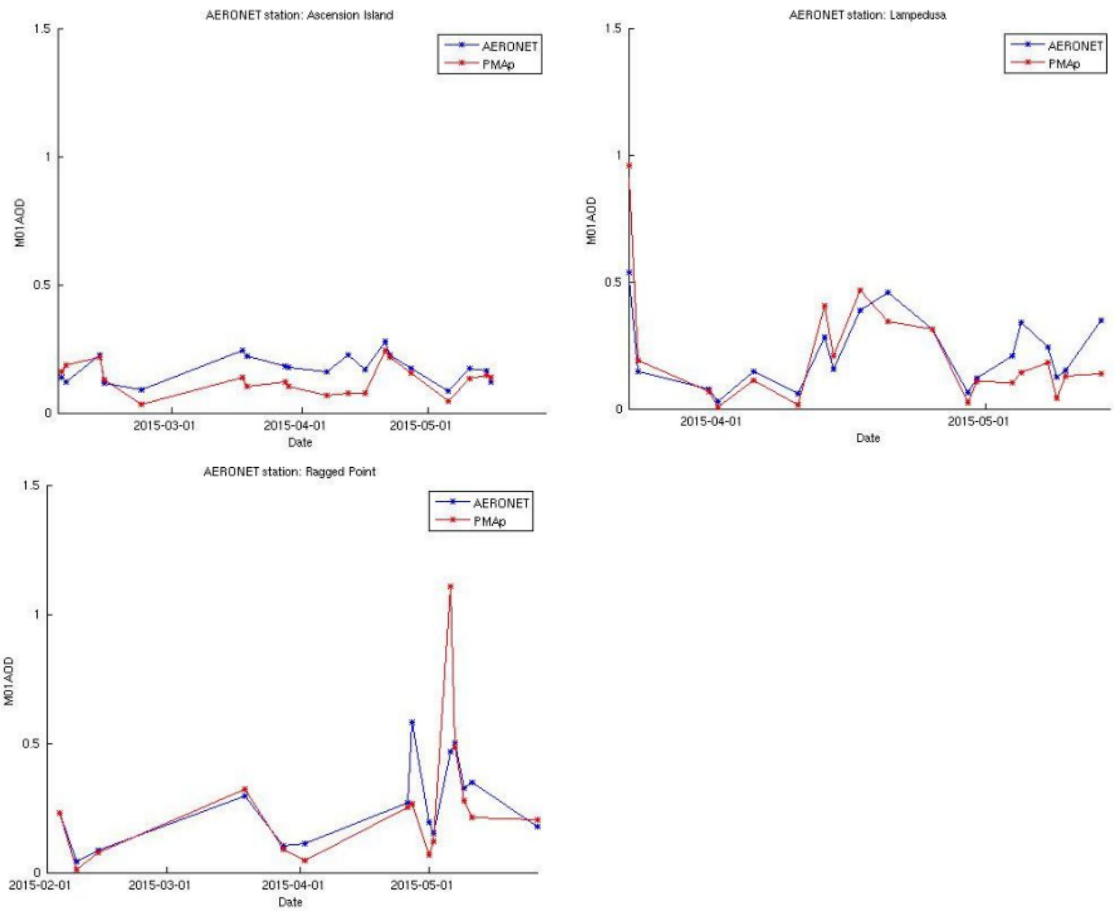


Figure 48. Time series of the AOD at 550 nm for February_May 2015 measured at different stations, compared to the AOD retrieved from Metop-B.

AOD values from PMAp/Metop-A for February – May 2015 set against corresponding AERONET AOD data are reported in the scatter plots of Figure 49.

The general agreement is fair and no significant outlier are present for these sites. The overall scatter plots collecting all the data are reported in linear and logarithmic scale. The linear regression fit is giving 1.3 as slope and -0.02 as offset. For this platform the SMAPE values against AOD values is plotted in Figure 50.

The comparison is completed with the time-patterns presented in Figure 51. In the top panel the AOD from Metop-A (red line) is plotted together with the corresponding AERONET values (blue line) for Ascension Island. PMAp is following the AERONET values throughout the summer 2013 period.

In the bottom panel of Figure 50 PMAp / Metop-A for the same period is plotted for Lampedusa site confirming the capabilities of the retrieval of detecting and reproducing the daily variability even in presence of moderate and/or low aerosol loading conditions.

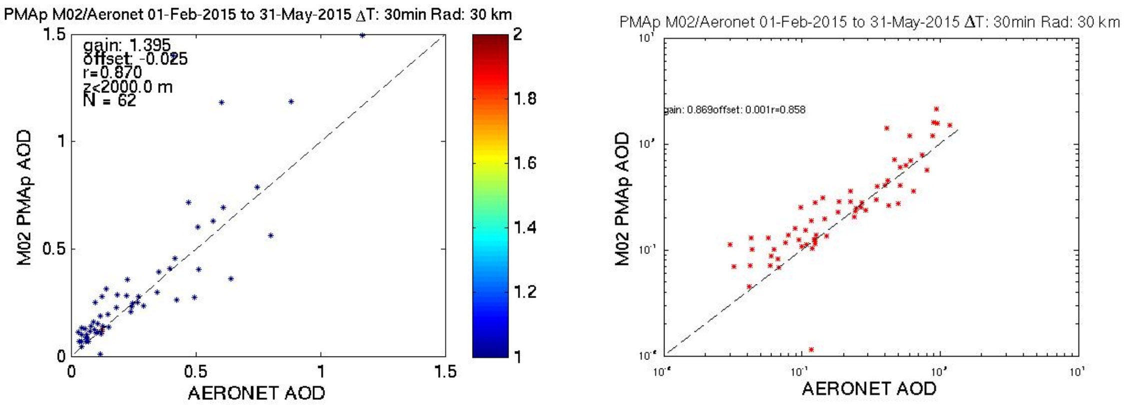


Figure 49. Scatter plot – left: linear, right: logarithmic scale - for the overall AERONET sites in February – May 2015 : AOD at 550 nm from PMAp/Metop-A is plotted versus corresponding AERONET measurements.

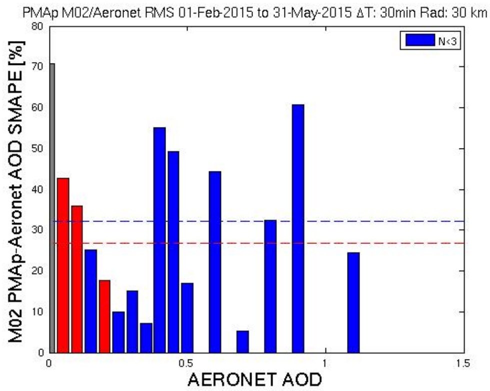


Figure 50. SMAPE values, corresponding to the data presented in Figure 20Figure 13, plotted as a function of AOD for June-September 2013 validation period, Metop-A. SMAPE values are binned with 0.05 bin-width in the 0 to 0.5 AOD range, for AOD values greater than 0.5 bin width is equal to 0.1. Bars with number of co-located measurements less than three are shown in blue. SMAPE average values are also reported for all available measurements (blue dashed line) and for cases with a number of measurements greater than 3 (red dashed line).

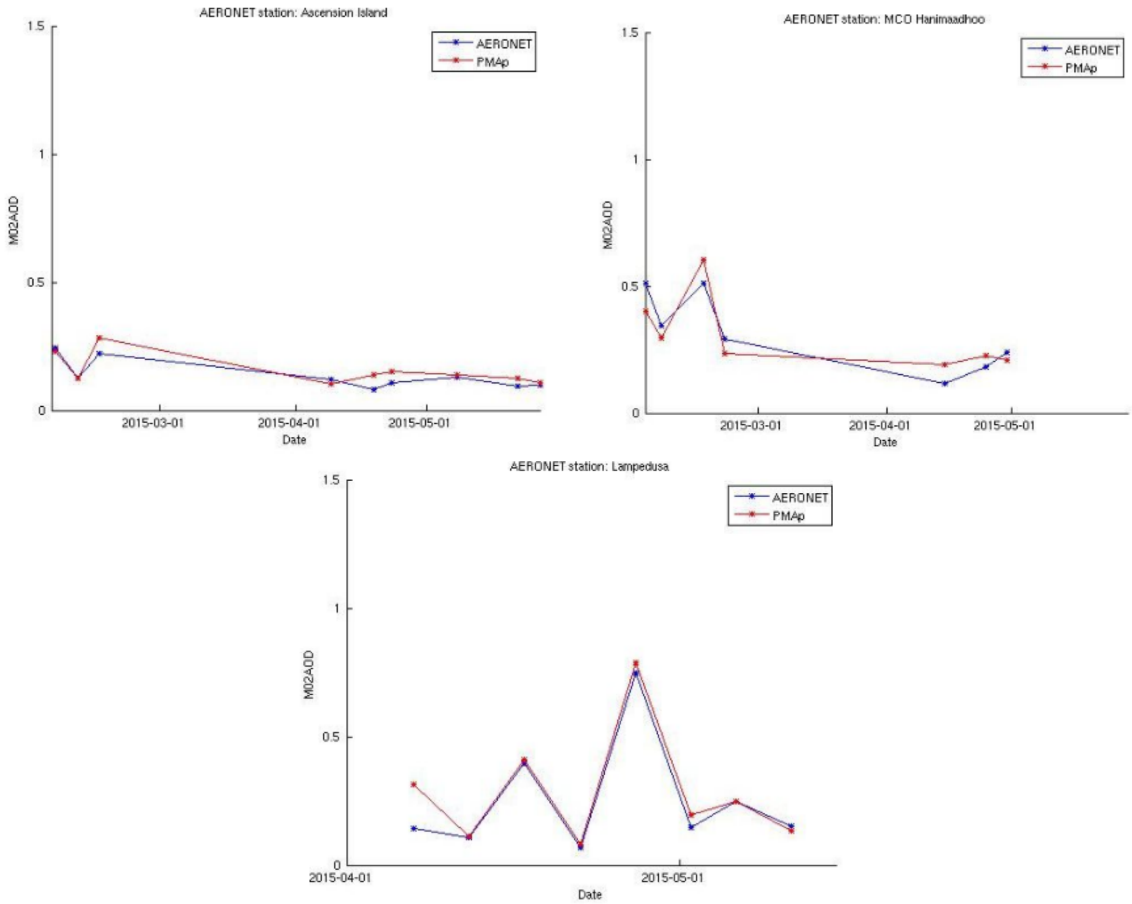


Figure 51. Time series of the AOD at 550 nm for February_May 2015 measured at different stations, compared to the AOD retrieved from Metop-A.

3.3 Monitoring and Assimilation test of PMAp AOD version 2.2 by ECMWF

Currently, ECMWF is assimilating into Copernicus Atmospheric Monitoring Service (CAMS) several atmospheric composition data provided by EUMETSAT – O3, CO, SO2. As for aerosols, at this moment MODIS AOD assimilation is active. PMAp AOD products from Metop-A, Metop-B and C are currently monitored operationally by CAMS. Some of the latest results on the use of atmospheric composition data from EUMETSAT in the CAMS data assimilation system were presented by ECMWF in 2020 AerosatAerocom conference.

CAMS analysed v2.2. during its progress and provided two reports of their work:

- Feedback 1: a comparison of version **2.2b** (2.2.2) PMAp AOD data at 550nm to version 2.1
- Feedback 2: An evaluation of the version **2.2c** (2.2.3) of the PMAp dataset

The first one is dedicated to the evaluation of the version 2.2.2 of PMAp dataset against the version 2.1 which is being used in the current CAMS operational suite (Ades, M 2019). The second report is for evaluating PMAp v2.2.3 (over ocean similar to v2.2.4) compared to v2.2.2.

However, both of reports and included analysis were prepared prior to finalising the improvements over land in PMAp 2.2.4. Since PMAp 2.2.4 had no change over ocean in Metop-A and B compared to v2.2.3, both reports are valid for v2.2.4 over ocean, but not over land.

But for Metop-C, we have updates in v2.2.4 over ocean besides land.

The reports cover two periods: the 1st to the 31st August 2013 and the 1st to the 31st March 2015.

3.3.1 CAMS feedback over ocean comparing v2.2 and 2.1:

3.3.1.1 Metop-B Ocean:

Feedback 1 to evaluate v2.2.2. compared to v2.1:

The new offset in version 2.2.2 leads to it being lower than version 2.1 as both a global average and geographically over the majority of the oceans.

The exceptions are the hotspots on the West Coast of Africa and North and South America and the North Pacific Ocean between 30° and 60°N. Where both version 2.1 PMAp-B data was higher than MODIS Terra, the version 2.2.2 is predominantly lower, although again the hotspots still stand out as being higher.

The decrease brings the version 2.2.2 retrieval in line with the model as a global average, in contrast to version 2.1 (see Figure 52 and Figure 53).

Feedback 2 to compare v2.2.3 with v2.2.2:

In version 2.2c (2.2.3 and therefore 2.2.4 over ocean), PMAp derived from Metop-B shows no major changes over most sea areas except a decrease over the hot spots of West Africa coast, Salomon island areas and the North Pacific Ocean between 30°N and 60°N that corrects the issue found in v2.2.2.

This results in reduced departure between PMAp and the model over these regions.

3.3.1.2 Metop-A Ocean:

Feedback1 to evaluate v2.2.2. compared to v2.1:

Over ocean, as a global average, PMAp-A version 2.2.2 is an increase compared to version 2.1. This brings it more in line with both the model (see Figure 52 and Figure 53) and MODIS Terra than the version 2.1 retrieval.

However, there are a few specific places where the increase is too high and the AOD stands out as erroneous, notably on the West coast of Africa and between 30° and 60° N over the Pacific Ocean. CAMS will continue investigation in this area because as mentioned by CAMS, MODIS in known to have underestimation of dust in this area. Therefore, the higher AOD in this region can be interpreted as improvement of PMAp because of dust detection scheme. These areas aside, the version 2.2.2 data represents an improvement on the retrieval algorithm compared to version 2.1.

Feedback2 to compare v2.2.3 with v2.2.2:

New version 2.2.3 shows no major changes over sea except a decrease over the western coast of Africa and within 30°N and 60°N over the Pacific Ocean (China, Russia and Alaska coastal areas) where better consistency was found with both MODIS and the modelled AOD.

The increase in AOD related to Saharan desert dust outflow over the central Atlantic area, that was seemed to be too large in version 2.2.2, is slightly lower for Metop-A in v2.2.3 and shows smaller deviation with both the MODIS and the modelled AOD.

Overall for Metop-A, v2.2.3 shows smaller deviation between observation and analysis over sea compared to v2.2.2. But PMAp 2.2.2 values are still much higher than both model and MODIS AOD for coarse aerosols. The conclusion is not consolidated yet to say whether this is an improvement of PMAp, a limitation of MODIS, or both PMAp and MODIS. Investigation by CAMS will continue. PMAp v2.2.2 overestimates MODIS in few places in the Atlantic and the North Pacific

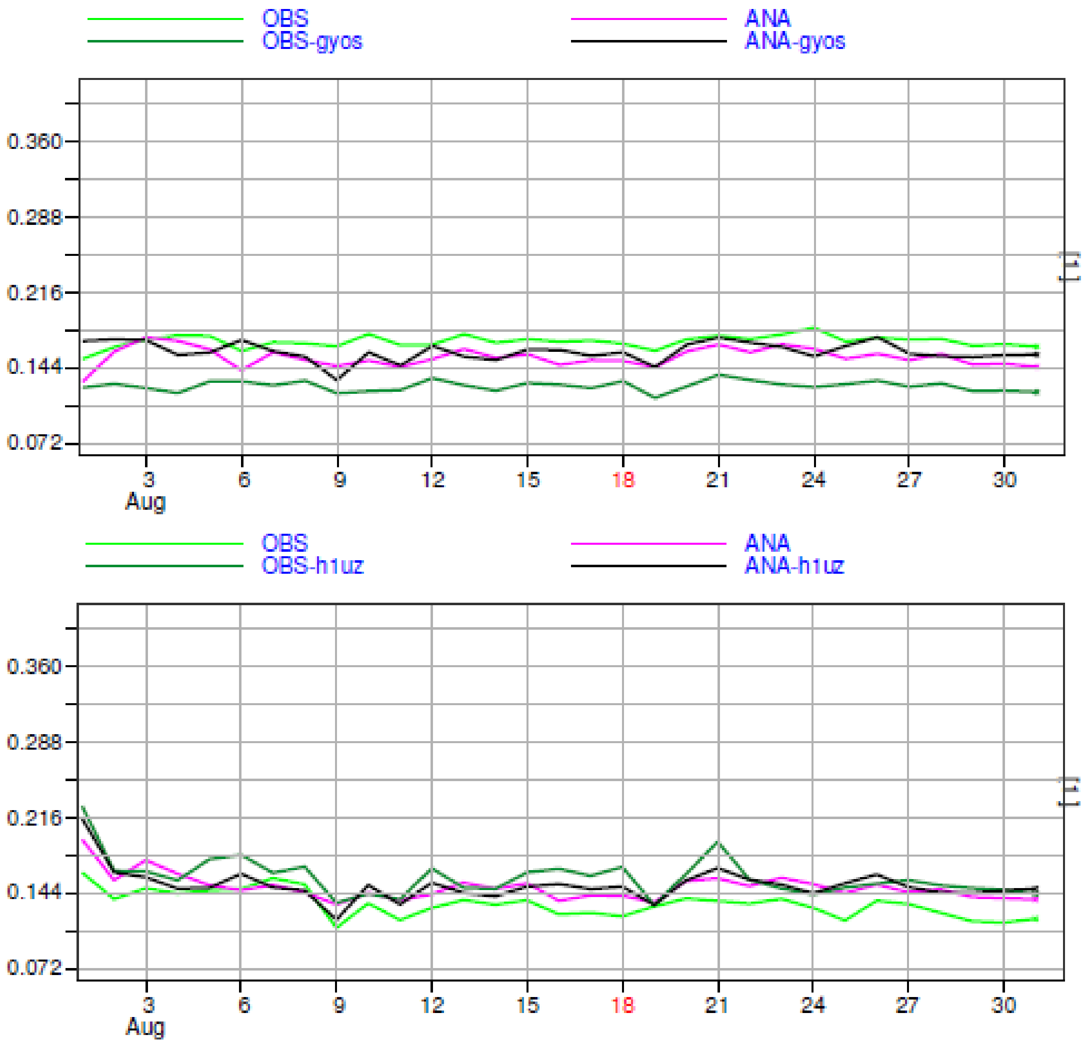


Figure 52. The global mean AOD over ocean for the period 1st to the 31st August 2013 for version 2.1 (upper panel) and 2.2.2 (bottom panel)PMAp data, PMAp observations are indicated by: PMAp-A - dark green, PMAp-B - light green) compared to the model equivalent (PMAp-A equivalent - black, PMAp-B equivalent - magenta).

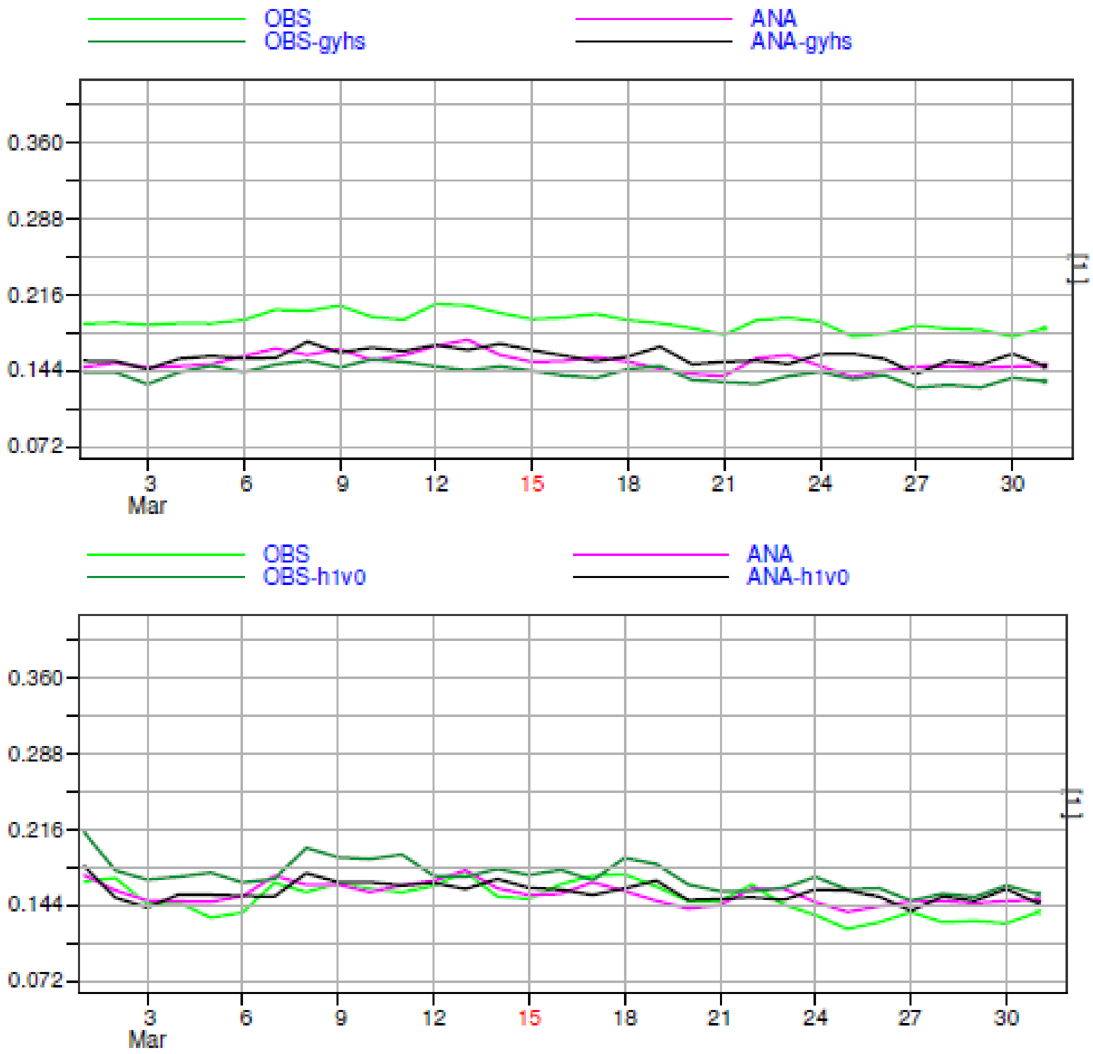


Figure 53. The global mean AOD over ocean for the period 1st to the 31st March 2015 for version 2.1 (upper panel) and 2.2.2 (bottom panel)PMAp data, PMAp observations are indicated by: PMAp-A - dark green, PMAp-B - light green) compared to the model equivalent (PMAp-A equivalent - black, PMAp-B equivalent - magenta).

3.3.1.3 Differences between Metop-A and B:

Feedback1 comparing v2.2.2 with 2.1:

- For version 2.1 the PMAp-B data was higher than PMAp-A over the sea and generally lower over the land.
- For version 2.2.2 the difference between PMAp-A and B has now changed, with PMAp-B being pre-dominantly lower than PMAp-A over the sea and much more balanced over land. There are still a few areas of high AOD values that stand out as being present in PMAp-B but not -A, such as the high values between 30 and 60°N over the Pac Ocean and the patches of the coast of North and South America in 2013.

Feedback2 comparing v2.2.3/2.2.4 with v2.2.2:

Over sea, the magnitude of the differences between PMAp-A and -B is reduced in v2.2.3 compared to 2.2.2 in the Atlantic of the West African coast and within 30°N and 60°N over the Pacific Ocean (China coast).
Over land, the spatial distribution of the discrepancies between PMAp-A and -B does not change from v2.2.2 to v2.2.3. The global mean difference between PMAp-A and -B substantially decreases in v2.2.2.

3.3.1.4 Comparison to MODIS:

Feedback1:
Metop-A:

- The slight increase in PMAp-A data over the sea, for the version 2.2.2 data compared to version 2.1, is reflected in a more balanced mix of positive and negative differences compared to MODIS Terra over sea.
- The areas over land where we see a significant change with the version 2.2.2 PMAp data (the west coast of North and South America and the band across Afghanistan, the Himalayas and the Tibetan plateau) are generally too low with the version 2.1 PMAp data when compared to MODIS.
- Similarly, the AOD values of the west coast of North Africa that are reduced (2015) or missing (2013) for the PMAp-A data with version 2.1 are now captured with version 2.2.2 but are an over-estimation in comparison to MODIS.
- The wildfire retrievals are noticeably missed in all versions of the PMAp-A data, but this has now been identified as being caused by PMAp retrievals not being made due to difficulties distinguishing cloud from aerosol, rather than a substantial mismatch in the retrievals.
- The over-estimation by the version 2.1 PMAp-A data over Australia now shows a much better match to the MODIS data with PMAp 2.2 data.

Metop-B

- A much more dramatic difference is seen between the match to MODIS Terra data with version 2.2.2 for PMAp-B. Version 2.1 of PMAp data was in general higher than MODIS Terra. This has now changed with version 2.2.2 PMAp data and the retrieval is in general lower than the MODIS Terra data.
- However, similar to PMAp-A, the areas over land that were lower than MODIS with version 2.1 are increased with PMAp-B version 2.2.2 and are often higher than the MODIS Terra data. This is particularly evident on the west coast of North and South America and over the Himalayas.

- There still appears to be some issues with the new version 2.2.2 retrieval between 30 and 60°N and the West Coast of North and South America. This may be quality fagged already in the retrieval and not being picked up by our system but if not it would be good to identify this data as erroneous.

Figure 54 and Figure 55 show the qualitative comparison of MODIS and PMAp AOD for both versions of 2.1 and 2.2.2. We observe the spatial coherency increased between PMAp and MODIS in v2.2.2. But there is high erroneous AOD in some regions e.g. west California, Alaska. This issue was reported by CAMS and was addressed in PMAp 2.2.3. CAMS reported on reduction of theses erroneous pixels in the next feedback.

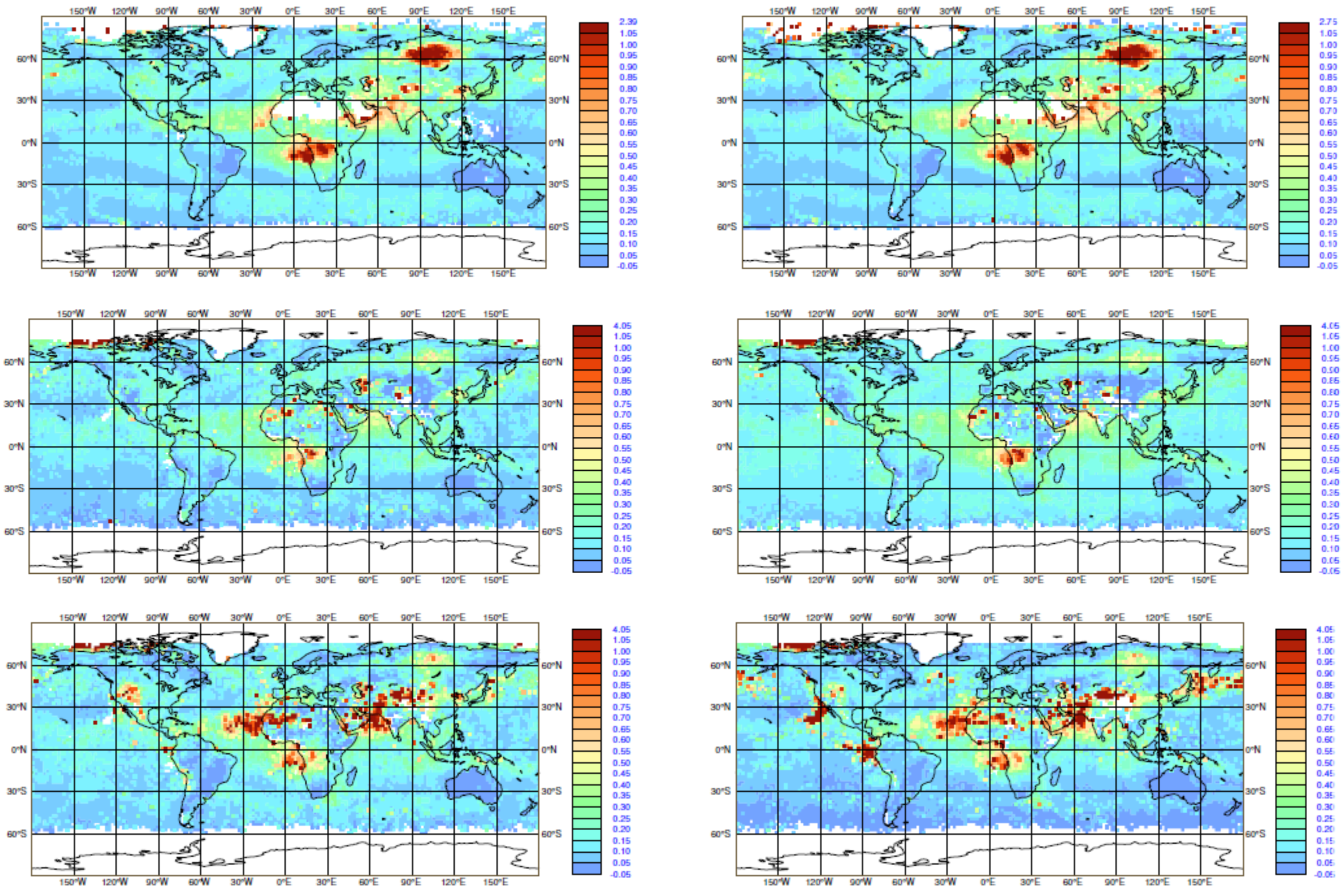


Figure 54. The mean AOD observation from MODIS Terra, MODIS Aqua (first raw left and right respectively), PMAp version 2.1 (Metop-A and B left and right respectively), and PMAp version 2.2.2 over the 2013 test period from the 1st to the 31st August 2013.

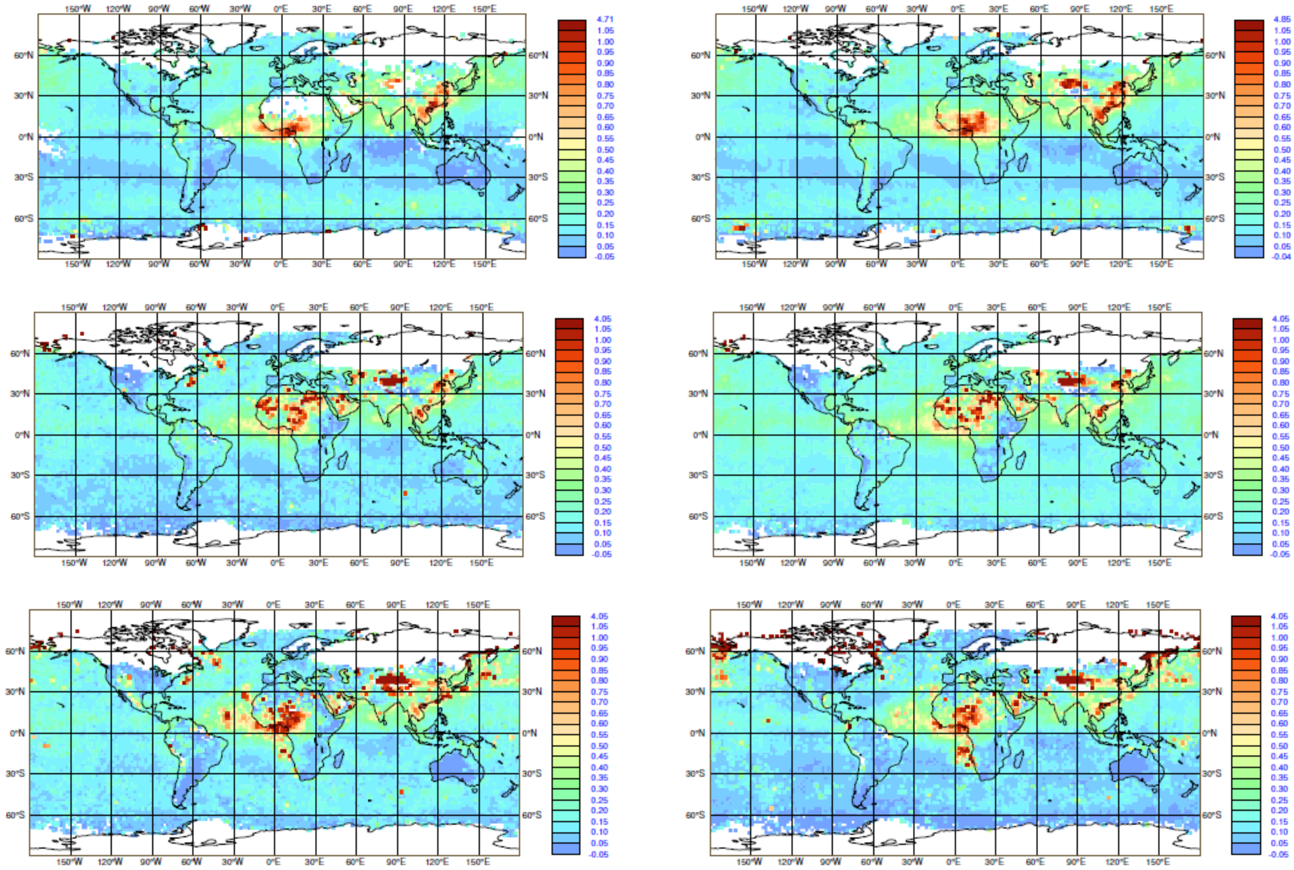


Figure 55. The mean AOD observation from MODIS Terra, MODIS Aqua (first raw left and right respectively), PMAp version 2.1 (Metop-A and B left and right respectively), and PMAp version 2.2.2 over the 2013 test period from the 1st to the 31st March 2015.

The difference maps between MODIS and PMAp are shown in Figure 56 and Figure 57 to present a quantitative comparison between the two products.

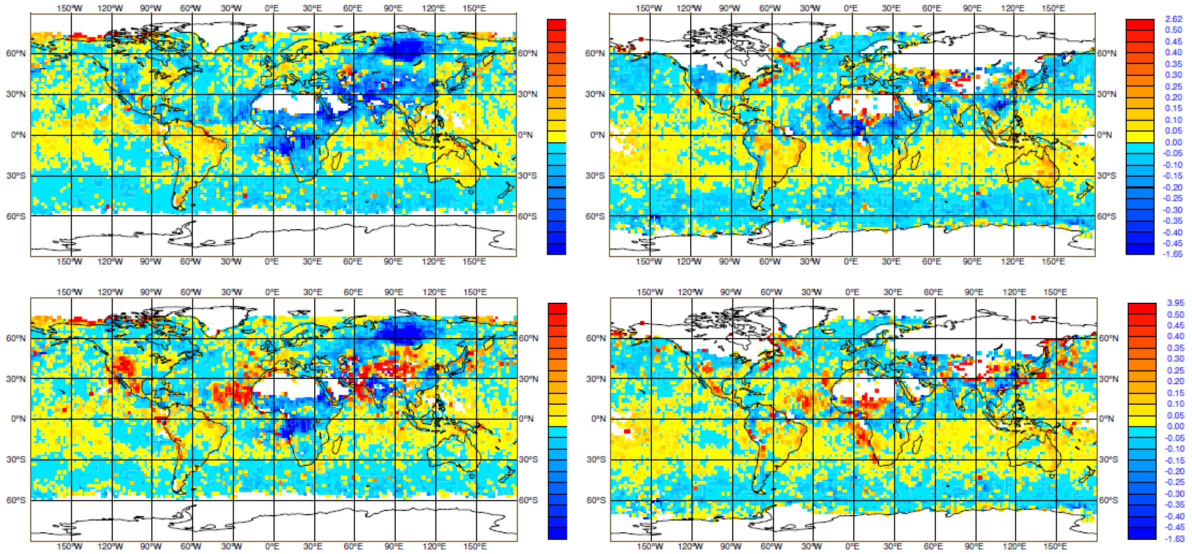


Figure 56. The difference between the mean AOD observation PMAp-A minus MODIS Terra in 2013 (left column) and 2015 (right column), first raw: PMAp 2.1, second raw: PMAp v2.2.2.MODIS Terra was chosen rather than Aqua since the overpass times are a closer match. Warm colours show that the PMAp observations are higher than MODIS Terra and cool colours that they are lower.

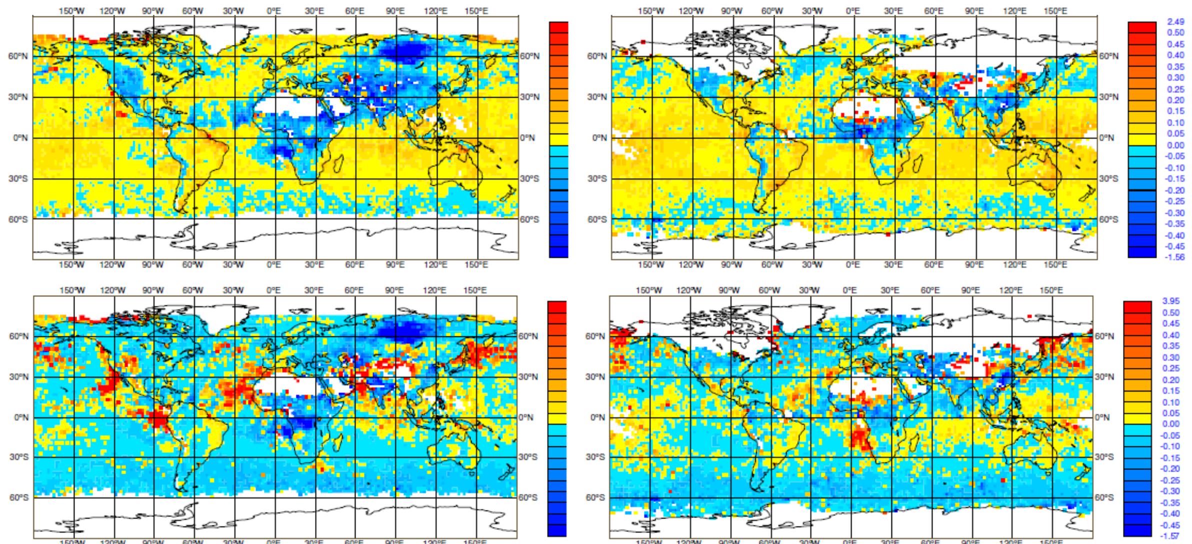


Figure 57. The difference between the mean AOD observation PMAp-B minus MODIS Terra in 2013 (left column) and 2015 (right column), first raw: PMAp 2.1, second raw: PMAp v2.2.2.MODIS Terra was chosen rather than Aqua since the overpass times are a closer match. Warm colours show that the PMAp observations are higher than MODIS Terra and cool colours that they are lower.

Feedback2 to compare PMAp v2.2.3 with v2.2.2.:

The spatial patterns of the differences between PMAp and MODIS remain unchanged. The mean global difference in AOD value between PMAp and MODIS is lower in v2.2.3 than in 2.2.2.
Over sea, v2.2.3 exhibits a better agreement with MODIS along the western coast of Africa and within 30°N and 60°N over the Pacific Ocean (China, Russia and Alaska coastal areas). Over land, the spatial discrepancies between PMAp and MODIS are unchanged in v2.2.3. PMAp-A v2.2.3 shows a slightly

better agreement with MODIS than PMAp-B v2.2.3. The increase in PMAp-B AOD over land leads to larger discrepancies with MODIS over Central Africa and India.

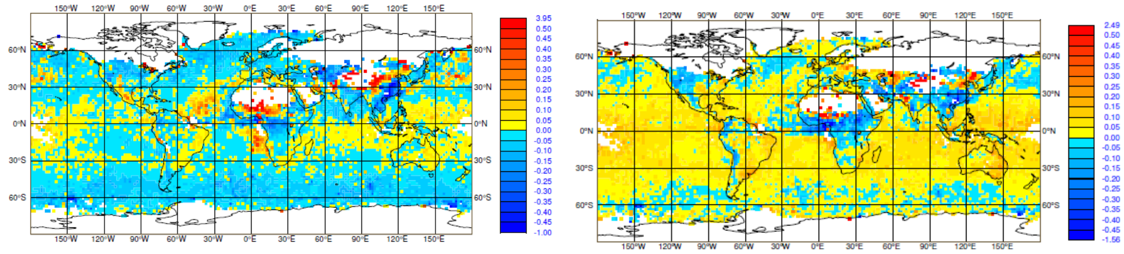


Figure 58 Left: PMAp-B v2.2c minus MODIS Terra 2015- all surfaces, 2015-02-28 21 - 2015-03-30, Right: PMAp-B v2.1 minus MODIS Terra 2015- all surfaces, 2015-02-28 21 - 2015-03-30

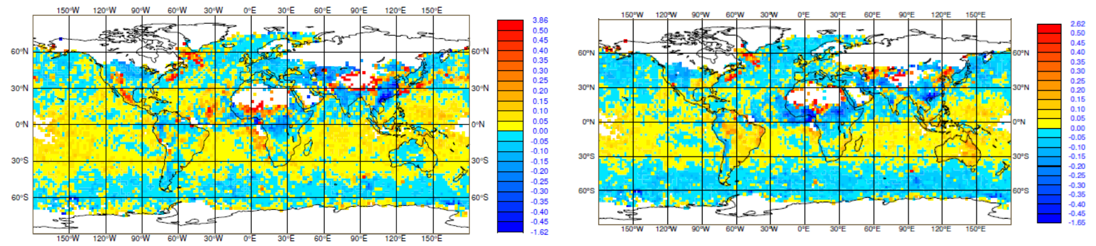


Figure 59 Left panel: PMAp-A v2.2c minus MODIS Terra 2015- all surfaces, 2015-02-28 21 - 2015-03-30, right panel: PMAp-A v2.1 minus MODIS Terra 2015- all surfaces, 2015-02-28 21 - 2015-03-30

3.3.1.5 Summary of CAMS feedback:

Over Ocean:

In summary, the new offset applied to PMAp-B brings the retrievals more in-line with each other and the model for Metop-A and B. This improves on version 2.2 PMAp data makes it more likely that the new version PMAp data will continue to be assimilated over the sea in the CAMS system.
The main improvement in v2.2.3 (and so 2.2.4) compared to v2.2.2 is the reduction of the unrealistic AOD hotspots off the western coast of Africa, within 30°N and 60°N over the Pacific Ocean (China, Russia and Alaska coastal areas) and over the Salomon sea area.
However compared to MODIS, the departure between PMAp and the analysis is still large off the west African coast over the North Pacific and the Central Pacific for PMAp-A only where PMAP tends to overestimate the modelled AOD. CAMS mentioned they need to do more investigation on this comment since it is known that MODIS underestimates AOD in that region.
For Metop-C, overestimation of AOD was reported as a remaining issue. This has been addressed in PMAp 2.2.4 and CAMS will re-evaluate Metop-C AOD over ocean.

Over Land:

The CAMS report is prior to new improvement over land in v2.2.4:
No major changes was found. PMAp underestimates the modelled AOD in v2.2.3 as it was reported for both v2.1 and 2.2.2. This concerns North and South America, most of Africa continent (except South Africa where departure is low and part of central Africa where PMAp overestimates the analysis), Middle-East and few locations in Asia. The large overestimatation of the modelled AOD over the Tibetan plateau identified in v2.2.2 persists with v2.2.3.

Over Ocean, the main findings from ECMWF are in good agreement with those reported by the present validation and analysis. In particular, PMAp provides reliable global maps capturing the main features of the aerosol global distribution. Improvements of v2.2.3 and so 2.2.4 compared to v2.1 have been

reported with no major unresolved issue. The overestimation of AOD on the west coast of Africa, is mentioned to be not a solid conclusion. Because MODIS underestimates dust in that region as mentioned by CAMS. More investigation is needed from CAMS on this comment. It is also mentioned investigation is needed more generally about MODIS, while an overestimation of AOD over the open ocean is now being acknowledge by the community (also under investigation with Sentinel-3).
Over land, as it has been mentioned also in the above paragraphs, some criticalities were reported which are addressed in new version of PMAp 2.2.4. We will provide new data to CAMS to re-evaluate the retrieval over land.
PMAp is assimilated by CAMS only over ocean. After additional evaluation of PMAp 2.2.4, the assimilated of AOD over land could be re-assessed.

4 CONLUSIONS AND RECOMMENDATION

4.1 Conclusions

As mentioned above:

Over ocean:

- According to reports from CAMS, the improvements in v2.2.4 over ocean brings PMAp more in line with the model and MODIS.
- PMAp has no unresolved remaining reported issue over ocean except the mentioned overestimation of dust on the west coast of Sahara which is not clear and consolidated to be true. Because the comparison is done with MODIS by CAMS and according to reports MODIS underestimates dust in this area (reference: CAMS). More investigation is needed.
- For Metop-C, the overestimation over ocean is addressed and solved.
- The consistency between the three Metop is well achieved and done.

Over land:

- The new improvements made in v2.2.4 addresses the “too much underestimation” issue reported by CAMS in many areas for all version of PMAp.
- The validation vs Aeronet indicates that over normal/dark land, PMAp A and B are within the threshold range (error either below 0.3 or less than 40%). But over bright land, we may have overestimation in some cases. However, temporal and spatial dynamics are well captured even over bright land.
- Metop-C has unresolved issues over bright land and shows significant variation along the swath in some areas which could be due to degradation correction (largest in blue spectrum used for retrieval over bright land). But this is not clear yet and more investigation is needed.
- The benchmarking periods against which the subsequent releases of the PMAp products are validated do not cover a period coincident with the Metop-C products. But the comparison to Metop-A and B shows a very good agreement and consistency between the three satellites. Discrepancies are observed in Sahara belt and higher latitudes which can be due to the remaining issue of Metop-C over bright land, or simply the fact the 3 satellites don’t sample exactly the same surface on the Earth.

4.2 Recommendations

Conclusion 1	Over ocean: • Aerosol Optical depth data over ocean retrieved by PMAp are reliable in terms of aerosol loading, spatial and temporal distribution. • Improvements compared to previous version 2.1, over ocean is indicated by internal validation and reports from CAMS.
Support	Internal Validation analysis for ocean and CAMS report for ocean.
Recommendation	Open to release.

Conclusion 2	Over land: • Aerosol Optical depth data over land retrieved by PMAp are reliable in terms of aerosol loading, spatial and temporal distribution. • Improvements compared to previous version 2.1, over land is indicated by internal validation and reports from CAMS. • High consistency between the three Metops.
Support	Internal Validation analysis and Verification.
Recommendation	Open to release.

Conclusion 3	Limitations: • PMAp-C AOD over bright land has unresolved issue: along swath variation. • Slight overestimation over bright land.
Support	Since the retrieval processing is the same for all Metops and the first issue is seen only in Metop-C bright land, this could be due to degradation correction and L1b issues but more investigation is needed.
Recommendation	Inform end-users.