A 3-D Evaluation of the MACC Reanalysis Dust Product Over Europe Using CALIOP/CALIPSO Satellite Observations

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Abstract This work focuses on the evaluation of the MACC (Monitoring atmospheric composition and climate) reanalysis dust product over Europe. Europe receives significant amounts of dust on an annual basis primarily from the large neighboring area sources (Sahara Desert, Arabian Peninsula) and from smaller local sources. Dust affects a number of processes in the atmosphere modulating weather and climate and exerts an impact on human health and the economy. Hence, the ability of simulating adequately the amount of dust and its optical properties is essential. For the evaluation of the MACC reanalysis, pure dust satellite-based retrievals from CALIOP/CALIPSO are utilized for the period 2007–2012. Specifically, the CALIOP/CALIPSO data used here come from an optimized retrieval scheme that was originally developed within the framework of the LIVAS (Lidar Climatology of Vertical Aerosol Structure for Space-Based LIDAR Simulation Studies) project. The natural aerosol extinction coefficients from MACC and the dust optical depth patterns at 550 nm are validated against dust extinction coefficients and dust optical depth patterns at 532 nm from CALIOP/CALIPSO.

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Our results highlight the important role that space-based lidars may play in the improvement of the MACC aerosol product.

1 Introduction

Europe receives significant amounts of dust on an annual basis from the Sahara Desert, the Arabian Peninsula and from smaller local sources. Dust affects climate and the biogeochemical cycles of various ecosystems (Stocker et al. 2013). The direct and indirect effects of dust modulate the radiative budget in the Earth-Atmosphere system. Cloud microphysical and macrophysical properties and precipitation rate can be changed since dust particles act as cloud condensation nuclei and ice nuclei. Mineral dust also affects human health in various ways (e.g. causing allergies, respiratory problems, eye infections, cardiopulmonary diseases, lung cancer) in some cases causing premature death (Giannadaki et al. 2014). In addition, dust deposition reduces crop yields and leads to livestock losses (Sivakumar 2005). Strong dust events hamper visibility affecting transportation while the deposition of dust on solar panels affects their energy production efficiency (Beattie et al. 2012). It becomes obvious that simulating adequately the amount of dust and its optical properties is essential. It was recently shown that dust optical depth is fairly well simulated and dust vertical variability is well captured within MACC reanalysis over the regions of Northern Africa and Middle East (Cuevas et al. 2015). In this work, we use a 3D (latitude-longitude-altitude) pure dust optical depth and extinction coefficient profile product which is based on CALIOP/CALIPSO satellite observations in order to evaluate the representation of dust within the MACC reanalysis product over the greater European region.

2 Data and Methodology

2.1 Data

In this work, dust columnar optical depth data at 550 nm (DOD_{550}) and natural aerosol (dust and sea salt) AOD_{550} vertical profiles and geopotential values from the MACC reanalysis are utilized. The data are available on a 3-h basis, at a horizontal spatial resolution of $\sim$79 km (60 vertical levels from the surface up to 0.1 hPa) and span from 2007 to 2012. The MACC data come from ECMWF's aerosol analysis and forecast system which consists of a forward model (Morcrette et al. 2009) and a data-assimilation module (Benedetti et al. 2009). AOD_{550} satellite retrievals from MODIS TERRA and AQUA are assimilated by the MACC forecasting system through a 4D-Var assimilation algorithm producing the aerosol analysis. The assimilation of satellite observations leads to improved AOD fields (see Benedetti et al. 2009; Mangold et al. 2011). MACC accounts for five aerosol types (mineral dust, sea salt, sulfates, black carbon, organic matter). Specifically for mineral dust and sea salt particles three different size bins are used.

The MACC reanalysis product is evaluated using CALIOP/CALIPSO DOD_{532} and dust extinction coefficient at 532 nm (in km^{-1}) satellite data from a Sahara dust optimized retrieval scheme that was developed within the framework of the LIVAS (Lidar Climatology of Vertical Aerosol Structure for Space-Based LIDAR Simulation Studies) project (Amiridis et al. 2015). More specifically the pure dust LIVAS product is used (Amiridis et al. 2013).

The LIVAS dust product exhibits better agreement with observations from MODIS and AERONET and simulations from the BSC-DREAM8b dust model over North Africa and Europe than the standard CALIPSO product hence being an ideal tool for the evaluation of other satellite-based products (Amiridis et al. 2013). The improvements are related to the use of a lidar ratio of 58 sr instead of 40 sr for the Saharan dust, the use of a new method to calculate pure dust extinction from dust mixtures and the application of an averaging scheme that includes zero extinction values for the non-dust aerosol types detected.

2.2 *Methodology*

Contrary to the MACC DOD_{550} and LIVAS DOD_{532} data which are directly comparable after being brought to a common $1° \times 1°$ grid, the MACC natural AOD_{550} profiles (pure dust profiles are not available from MACC) and the LIVAS extinction coefficients at 532 nm have to be processed properly prior to their comparison. Sea salt particles are mostly accumulated within the marine boundary layer; hence, sea salt is expected to have an impact only at the lower levels of the natural aerosol profiles. Therefore, in this work we mostly focus on layers higher than 1 km.

To convert the AOD_{550} profiles to extinction coefficients at 550 nm we first divided the given MACC geopotential fields with the gravity acceleration to obtain the physical layer heights and finally the physical depth of each MACC layer was calculated. Then, the AOD_{550} profiles were divided by the layers' physical depths in order to calculate the natural aerosol extinction coefficients in km^{-1}. The extinction coefficients from MACC were brought to the $1° \times 1°$ LIVAS grid using bi-linear interpolation and then they were temporally collocated to the LIVAS data (the MACC values which were closer to the overpass time of CALIPSO were selected). While the MACC data are available on a 3 h basis, the LIVAS data are available ~ 2 times per month as the ground track of CALIOP/CALIPSO has a 16 day repetition time.

Before proceeding with the evaluation, we had to make sure that both the datasets had the same vertical resolution. The LIVAS extinction coefficient retrievals are available at 399 predefined heights which characterize a layer of ~ 60 m for altitudes lower than ~ 20 km and ~ 180 m for higher altitudes. In this work, linear interpolation was applied on the calculated MACC extinction coefficients in order to have one MACC value for each one of the 399 LIVAS levels. Finally, the extinction coefficients from both the datasets were averaged within a set of selected layers each one having a depth of 300 m (see also Cuevas et al. 2015).

Maps and tables with the mean bias (MB) and the normalized mean bias (NMB) between the MACC and the LIVAS DOD datasets and profiles from the two extinction coefficient datasets at a 300 m vertical resolution are presented in the next section.

3 Results

The mean bias (MB) patterns between MACC DOD_{550} and LIVAS DOD_{532} are found in Fig. 1. Overall, it is shown that MACC overestimates DOD compared to LIVAS except for areas within Central-Western Sahara (CWSah) and Middle East (ME). For the whole domain (EU) MB is equal to 0.024 and NMB is ∼22 %. The corresponding values for the regions appearing in Fig. 1 are given in Table 1. The use of NMB returns large values for some regions (e.g. CE, EE) as the DOD levels from LIVAS are nearly zero. This metric is not appropriate for the evaluation of the MACC vertical profiles as it takes huge values for heights above 5–6 km.

The comparison of the 300 m resolution profiles for the whole domain reveals that MACC exhibits higher extinction coefficients than LIVAS for all the 29 levels extending from 450 to 8850 m (see Fig. 2). The MB between MACC and LIVAS extinction coefficients ranges from ∼0.0016 to 0.0063 being stronger for heights below ∼2 km while a second peak appears between 5 and 7 km.

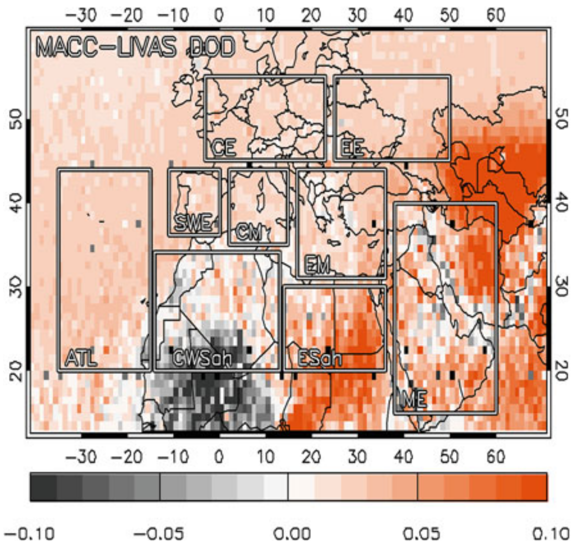

Fig. 1 Mean bias patterns between MACC DOD_{550} and LIVAS DOD_{532}

Table 1 MACC DOD_{550}, LIVAS DOD_{532}, MB and NMB for the regions appearing in Fig. 1

	EU[a]	CE	EE	SWE	CM	EM	ATL	CWSah	ESah	ME
MACC	0.132	0.033	0.043	0.049	0.068	0.071	0.071	0.178	0.173	0.248
LIVAS	0.108	0.012	0.016	0.026	0.051	0.050	0.047	0.186	0.123	0.215
MB	0.024	0.021	0.027	0.023	0.017	0.021	0.024	−0.008	0.050	0.033
NMB (%)	22	175	169	89	33	42	51	−4	41	15

[a]EU: whole European domain

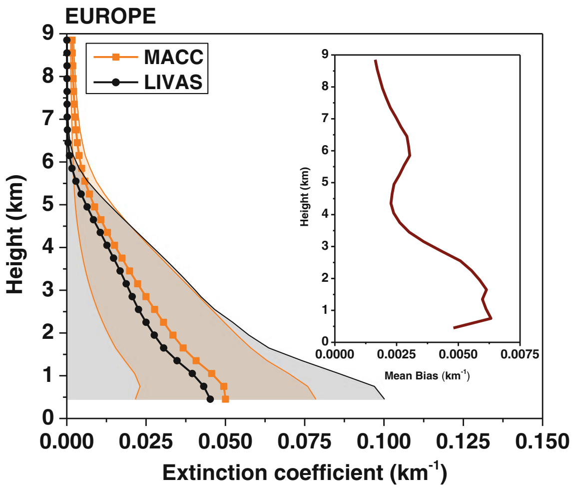

Fig. 2 Profiles of MACC (natural aerosol) and LIVAS (pure dust) extinction coefficients at 550 and 532 nm, correspondingly and the mean bias per level for the whole European domain

4 Conclusions

The main findings of this paper can be summarized in the following:

1. Generally, MACC overestimates DOD compared to LIVAS over the greater European region except for areas within CWSah and ME.
2. For the whole domain, the MB between the two products is 0.024 and the NMB is ~22 %.
3. MACC exhibits higher extinction coefficients than LIVAS for all the examined height levels.
4. For the whole domain, the MB between MACC and LIVAS extinction coefficients ranges from ~0.0016 to 0.0063 being stronger for heights below ~2 km. A second peak appears between 5 and 7 km.

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