CAMS Service Evolution

D4.2 Demonstration of a future operational deposition validation

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1 Executive Summary

Representing the deposition of atmospheric constituents is an arduous task, as it combines the uncertainties in both the simulated concentrations and of the meteorological parameters that provoke the deposition (wind speed mostly for dry deposition, precipitations for wet deposition). Recently, the global CAMS system has been moving towards an operationalization of deposition products. However, the CAMS deposition products can't be considered operational yet as they are not included in the routine evaluation of CAMS forecasts, which covers more and more aspects of the global CAMS production. In this deliverable, we explore possibilities on how to implement a partial routine evaluation of CAMS dust and sulphur/nitrogen wet deposition products. For sulphur and nitrogen wet deposition fluxes, most of the effort focused on the acquisition and processing of observational datasets. The evaluation of sulphur/nitrogen wet deposition fluxes is done routinely by many institutions and requires less. We focused more on establishing a validation protocol for desert dust deposition.

The limiting factor for the routine evaluation of global CAMS products is the availability the observational datasets. For dust deposition, most of the data is climatological or dating from many years in the past. Given the strong yearly variability of desert dust, comparing a single quarter or year against climatological values can be misleading. In order to remedy this, we investigated the use of novel dust deposition products which combine remote sensing observations and meteorological simulated data into mass balance algorithms to provide estimated dust deposition over non-source areas. Several such products have been retrieved and inter-compared, and used for a test evaluation of CAMS dust deposition products. Despite limitations and uncertainties, it was found that these products could be fit for purpose for a qualitative routine assessment of CAMS dust deposition.

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2 Introduction

2.1 Background

Monitoring the composition of the atmosphere is a key objective of the European Union's flagship Space programme Copernicus, with the Copernicus Atmosphere Monitoring Service (CAMS) providing free and continuous data and information on atmospheric composition.

The CAMS Service Evolution (CAMEO) project will enhance the quality and efficiency of the CAMS service and help CAMS to better respond to policy needs such as air pollution and greenhouse gases monitoring, the fulfilment of sustainable development goals, and sustainable and clean energy.

CAMEO will help prepare CAMS for the uptake of forthcoming satellite data, including Sentinel-4, -5 and 3MI, and advance the aerosol and trace gas data assimilation methods and inversion capacity of the global and regional CAMS production systems.

CAMEO will develop methods to provide uncertainty information about CAMS products, in particular for emissions, policy, solar radiation and deposition products in response to prominent requests from current CAMS users.

CAMEO will contribute to the medium- to long-term evolution of the CAMS production systems and products.

The transfer of developments from CAMEO into subsequent improvements of CAMS operational service elements is a main driver for the project and is the main pathway to impact for CAMEO.

The CAMEO consortium, led by ECMWF, the entity entrusted to operate CAMS, includes several CAMS partners thus allowing CAMEO developments to be carried out directly within the CAMS production systems and facilitating the transition of CAMEO results to future upgrades of the CAMS service.

This will maximise the impact and outcomes of CAMEO as it can make full use of the existing CAMS infrastructure for data sharing, data delivery and communication, thus supporting policymakers, business and citizens with enhanced atmospheric environmental information.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

This deliverable aims to provide a pathway towards the routine evaluation of CAMS deposition products. In particular, we focus on dust deposition and evaluate how applicable are fusion products from mass balance algorithms for a possible use in the routine evaluation of dust deposition.

2.2.2 Work performed in this deliverable

In this deliverable, a wide panel of observational datasets of deposition of sulphur, nitrogen and dust has been collected and analysed.

2.2.3 Deviations and counter measures

No deviations have been encountered.

2.2.4 CAMEO Project Partners:

ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
Met Norway	METEOROLOGISK INSTITUTT
BSC	BARCELONA SUPERCOMPUTING CENTER-CENTRO NACIONAL DE SUPERCOMPUTACION
KNMI	KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT-KNMi
SMHI	SVERIGES METEOROLOGISKA OCH HYDROLOGISKA INSTITUT
BIRA-IASB	INSTITUT ROYAL D'AERONOMIE SPATIALEDE BELGIQUE
HYGEOS	HYGEOS SARL
FMI	ILMATIETEEN LAITOS
DLR	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV
ARMINES	ASSOCIATION POUR LA RECHERCHE ET LE DEVELOPPEMENT DES METHODES ET PROCESSUS INDUSTRIELS
CNRS	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
GRASP-SAS	GENERALIZED RETRIEVAL OF ATMOSPHERE AND SURFACE PROPERTIES EN ABREGE GRASP
CU	UNIVERZITA KARLOVA
CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
MF	METEO-FRANCE
TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO
INERIS	INSTITUT NATIONAL DE L ENVIRONNEMENT INDUSTRIEL ET DES RISQUES - INERIS
IOS-PIB	INSTYTUT OCHRONY SRODOWISKA - PANSTWOWY INSTYTUT BADAWCZY
FZJ	FORSCHUNGSZENTRUM JULICH GMBH
AU	AARHUS UNIVERSITET
ENEA	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

3 Deposition fluxes: why do they matter?

Atmospheric nutrient deposition plays a critical role in both terrestrial (Fernández-Martínez et al., 2017; MMF-GTAD: https://community.wmo.int/en/activity-areas/gaw/science-for-services/mmf-gtad) and marine ecosystems (GESAMP; 2022), enhancing productivity in high-nutrient, low-chlorophyll (HNLC) oceanic regions and impacting Earth's carbon cycle. Conversely, excessive deposition can lead to risks such as eutrophication, soil acidification, and biodiversity loss. Nitrogen (N), sulphur (S), iron (Fe), and phosphorus (P) are among the most crucial atmospheric species (Mahowald et al., 2017) that serve as nutrients for these ecosystems upon deposition (Hedin, 2000). Nitrogen compounds are primarily emitted from fossil fuel combustion, contributing oxidized nitrogen forms (NO, NO_2, HNO_3), while agricultural activities release reduced nitrogen forms (NH_3) from livestock waste and fertilizers (Kanakidou et al., 2016). Sulphur dioxide (SO_2) is mainly emitted from industrial processes, leading to acid rain that can leach essential nutrients from soils and negatively affect plant health. Additionally, iron and phosphorus are key components of dust aerosols, with wildfires accounting for a significant fraction of their total emitted flux (e.g. Myriokefalitakis et al., 2018).

Atmospheric removal processes are governed by wet scavenging and dry deposition. Precipitation removes atmospheric species, including critical water-soluble nutrients like ammonium (NH_4^+) and nitrate (NO_3^-), as well as dissolved iron forms (ferrous and ferric organic ligands), all of which can impact productivity. Gases and particles can settle onto surfaces, including reactive nitrogen gases like ammonia (NH_3) and nitrogen oxides (NO_x), which can also interact with vegetation and soils. Nutrient-containing aerosols, such as Fe and P-containing mineral dust aerosols, are also significantly influenced by sedimentation, which affects their lifetime during long-range transport. However, compared to wet deposition, dry deposition is often more variable and is frequently affected by nearby activities, such as agricultural or urban emissions. Various efforts have been made to better understand and quantify the deposition of bioavailable aerosols from natural and anthropogenic dust, and their contribution relative to biomass burning and anthropogenic aerosols, such as the ESA DOMOS project (https://eo4society.esa.int/projects/4datlantic-domos/). Overall, accurately simulating these dynamics is essential for managing environmental impacts and preserving ecosystem integrity, both on land and in the oceans.

Desert dust deposition poses a significant challenge to the efficiency of solar panels, particularly in arid and semi-arid regions. As fine dust particles settle on the surface of photovoltaic modules, they scatter and absorb incoming sunlight, drastically reducing the amount of solar radiation that reaches the solar cells. This phenomenon, known as "soiling," can diminish energy output by as much as 20–50% in some extreme cases, depending on dust composition, climate conditions, and the frequency of cleaning. Over time, this not only reduces the overall energy yield but also increases operational and maintenance costs, as regular cleaning is required to restore performance. The impact is especially pronounced during dry seasons or dust storm events, making soiling one of the key performance-limiting factors for solar installations in desert environments.

In recent years efforts have been made to improve and validate the realism of the nitrate, sulphur and dust cycles in IFS-COMPO (Metzger et al., 2024; Rémy et al., 2024; Williams et al., 2024). Together with ECMWF's composition data assimilation capabilities this puts CAMS into the position to provide critical, long term and quality-controlled information on various deposition aspects as described above.

Forecasting deposition is fraught with uncertainties, as it combines uncertainties on the simulated concentration of the relevant aerosol and trace gases as well as uncertainties of the meteorological parameters that lead to dry or wet deposition: wind fields and in particular precipitations, which is one of the most uncertain parameter on the NWP side. Global and regional CAMS deposition products have been evaluated in several CAMS deliverables, such as the relevant CAMS2_35 deliverables focusing on the global dust, nitrogen and sulphur deposition fluxes, and the task 4041 intercomparison of the CAMS2_40 project, which compared regional and global (CAMS reanalysis and more recent global model versions) to EMEP observations of wet deposition fluxes. However, routine evaluation of deposition fluxes is not implemented yet; this deliverable aims to be one step in the direction of operational routine evaluation of deposition fluxes.

4 Deposition observations usable for routine evaluation purposes

In this section, we'll present the datasets of wet and dry deposition that have been fetched and can be used for routine evaluation purposes, as well as the available dust deposition datasets together with recently developed dust total deposition (dry and wet) datasets.

4.1 Datasets of wet/dry deposition of sulphur and nitrogen species

The U.S. National Atmospheric Deposition Program (NADP) has operated the National Trends Network (NTN) sinc e 1978 an d the Atmospheric Integrated Research Monitoring Network (AIRMoN) since 1992. Both networks measure concentrations of anions and cations in precipitation and use precipitation amounts to calculate wet deposition. NTN currently features more than 250 sites measuring weekly concentrations and AIRMoN has seven sites measuring event-based concentrations .In 2007 , NADP added the Ammonia Monitoring Network (AMoN) to measure ambient concentrations of ammonia.

The Clean Air Status and Trends Network (CASTNET) was established in 198 7 to assess trends in ambient air quality and deposition of acidic pollutants due to emission reduction programs . CASTNET currently operates more than 90 sites . CASTNET uses a filter pack and active flow system to measure weekly integrated ambient air samples of species similar to those measured by NADP. CASTNET methodology includes combining concentrations with estimated modeled deposition velocities to calculate dry deposition of gases and particles. Numerous methods have been employed using NADP and CASTNET data to estimate total deposition . Ideally , the two networks act as sister networks , each providing part of the total deposition .

Nitrogen and sulphur wet deposition measurements and dry deposition estimates throughout Canada are recorded by the Canadian Air and Precipitation Monitoring Network (CAPMoN; Canadian Air and Precipitation Monitoring Network, 2021) and are available through the National Atmospheric Chemistry (NAtChem) database (https://donnees.ec.gc.ca/data/air/monitor/). Dry deposition estimates from CAPMoN are calculated by multiplying the atmospheric concentration by the deposition velocity.

EBAS is a European database infrastructure developed and operated by NILU (Norwegian Institute for Air Research). Measurement data from, inter alia, the EMEP, OSPAR, and HELCOM networks are collected there and made publicly available. All these measurements are carried out at open field sites.

In EMEP the reference method for sampling atmospheric wet deposition is "wet-only" samplers, which open automatically during the precipitation event and close again after the event, avoiding the collection of particulate and gaseous deposition during dry periods. Bulk collectors (which are permanently open) are also used in areas where the dry deposition is low compared to wet deposition. Sampling is generally performed on a daily basis, but weekly, fortnightly and monthly samples are also performed for both sampler types.

The EBAS distinguishes between EBAS-m (about 80 sites), where sampling is done in daily, weekly or monthly intervals and used in monthly intervals and EBAS-d (about 48 sites), where sampling and analyses are done daily.

An extensive measurement network, dedicated to forests, has been in operation since 1986, that of the International Co-operative Programme on Assessment and Monitoring of Air

Pollution Effects on Forests (ICP Forests, http: //www.icp-forests.org). ICP forests was started in 1985, under the Convention on Long-Range Transboundary Air Pollution. ICP Forests is responsible for the level I and the more detailed level II monitoring system of forest sites, which have been in operation since 1986 (level I) and 1994 (level II). Level I includes ~6000 monitoring sites in Europe, and evaluates crown condition (defoliation, crown transparency and discolouration), soil condition, and the foliar nutrient status. Level II includes 620 monitoring sites as off 2018.

In the ICP Forests network, atmospheric deposition is continuously collected at Level II plots with weekly to monthly sampling periods using permanently open Bulk and Throughfall collectors. Bulk collectors are located in the open field to estimate depositions that are not affected by exchange with canopies. In this report, the measured deposition is assumed to be representative of wet deposition, although it can contain small fractions of dry deposition (as gases and particles can dry deposit on the surface during dry periods). Data from a few wet-only collectors (referred to as 'ICP-Forests-Wet') is also available, typically about 5 to 20. Throughfall collectors are located under the forest canopy. Sampling was carried out with national methods in accordance with the ICP Forests Manual Part XIV (Clarke et al. 2020). Quality Assurance measures include regular laboratory intercomparison exercises (Fürst & Kowalska, 2022). Throughfall deposition accounts for both wet deposition and dry deposition, because particles deposited on the tree canopies during dry periods are later washed down together with precipitation. However, canopy exchange includes uptake of nitrogen compounds and leaching of base cations from tissues, as well as uptake of gaseous compounds through stomata. Hence, throughfall depositions do not fully reflect the total depositions for oxidized and reduced nitrogen, as some nitrogen species are taken up or leached by the forest canopy. For sulphur and sea salt, however, throughfall deposition is in general a good estimate of total deposition. At the ICP-Forests network, the sampling frequency typically is weekly, fortnightly or monthly.

In China, a multiyear nationwide field study, including some Nationwide Nitrogen Deposition Monitoring Network (NNDMN) data, was compiled by Xu et al. (2019). For a wider Asian region, EANET (Acid Deposition Monitoring Network in East Asia (EANET), 2021, https://www.eanet.asia/) wet and dry deposition and precipitation data were available at 47 sites.

National measurements of nitrogen deposition did not exist in China until the instigation in 2004 of the Nationwide Nitrogen Deposition Monitoring Network (NNDMN) operated by China Agricultural University. Initially this network comprised only measurements of bulk (wet) N deposition. In 2010, simultaneous measurements of air concentrations and associated dry deposition fluxes of five major nitrogen species (i.e., gaseous NH_3, NO_2 and HNO_3, and particulate NH_4^+ and NO_3^-), were added. The data is compiled and used for analysis in Xu et al (2019).

The Acid Deposition Monitoring Network in East Asia (EANET) started its preparatory phase in 1998, and subsequently its regular phase in 2001, to respond to the concern of acid deposition and air pollution issues. The EANET covers the monitoring network of wet and dry deposition, soil and vegetation, inland aquatic environment, and catchment scale. Data report and periodic report have been published to evaluate the state of acid deposition and its effects on ecosystems based on the monitoring data. Through implementing the following activities for 20 years: (1) acid deposition and air pollution–related substances monitoring; (2) compilation, evaluation, storage, analysis, and provision of monitoring data; and (3) data quality assurance and quality control (QA/QC), EANET has significantly contributed to promoting cooperation among participating countries in East Asia to address acid deposition and air pollution problems. As of 2019, wet/dry deposition, soil/vegetation, and inland aquatic environment monitoring were performed in 59 sites, 22 sites, 13 lakes/reservoirs, and 6 rivers/streams, respectively. Those samples have been analyzed in the laboratories whose quality has been evaluated through interlaboratory comparison (ILC) projects by using artificial samples.

The International Global Atmospheric Chemistry (IGAC) Deposition of Biogeochemically Important Trace Species (DEBITS) Africa (IDAF) program measures precipitation concentrations of nitrogen and sulphur compounds on the International Network to Study Deposition and Atmospheric Chemistry in Africa (INDAAF, INDAAF – International Network to study Deposition and Atmospheric chemistry in AFrica, 2021a) website (https://indaaf.obs-mip.fr/) for 7 sites in Western Sahel

Table 1 lists the datasets that have been fetched within the CAMEO project for the evaluation of CAMS forecasts. With the exception of the NTN/CASTNET data, little data is available close to near real time. For the ICP forest dataset, access to the data has been asked and granted, but the data itself is being prepared, so it has not been acquired yet.

Table 1: Datasets of dry and wet deposition of sulphur/nitrogen species that can be used for the evaluation of CAMS forecasts.

Dataset	Region	Specifics	Availability as of 1/6/2025
NTN/CASTNET	U.S.	Sulphur wet and dry deposition/Nitrogen wet and dry deposition/Base cations wet and dry deposition	1985-2024
CAPMON	Canada	Sulphur wet and dry deposition/Nitrogen wet and dry deposition/Base cations wet and dry deposition	2002-2019
NNDMN	China	Surface concentration and wet/dry deposition of N and S over China. 2016-2018 data is not puclic and restricted to CAMEO.	2010-2018
EMEP	Europe	Sulphur wet and dry deposition/Nitrogen wet and dry deposition/Base cations wet and dry deposition	2000-2023 (2023 available for few stations only)
ICP-Forest	Europe	Sulphur wet and dry deposition/Nitrogen wet and dry deposition/Base cations wet and dry deposition	1985-2023
EANET	Asia	Sulphur wet and dry deposition/Nitrogen wet and dry deposition/Base cations wet and dry deposition	2000-2022
INDAAF	West Africa	Sulphur wet and dry deposition/Nitrogen wet and dry deposition	1996-2021 (not all years)

Figure 1 shows the use of the NTN/CASTNET dataset to evaluate simulated wet deposition of SO_2+SO_4 by two long IFS-COMPO experiments meant to prepare next reanalysis. This is an approach close to the trend analysis carried out in several papers, lastly in Aas et al (2024)

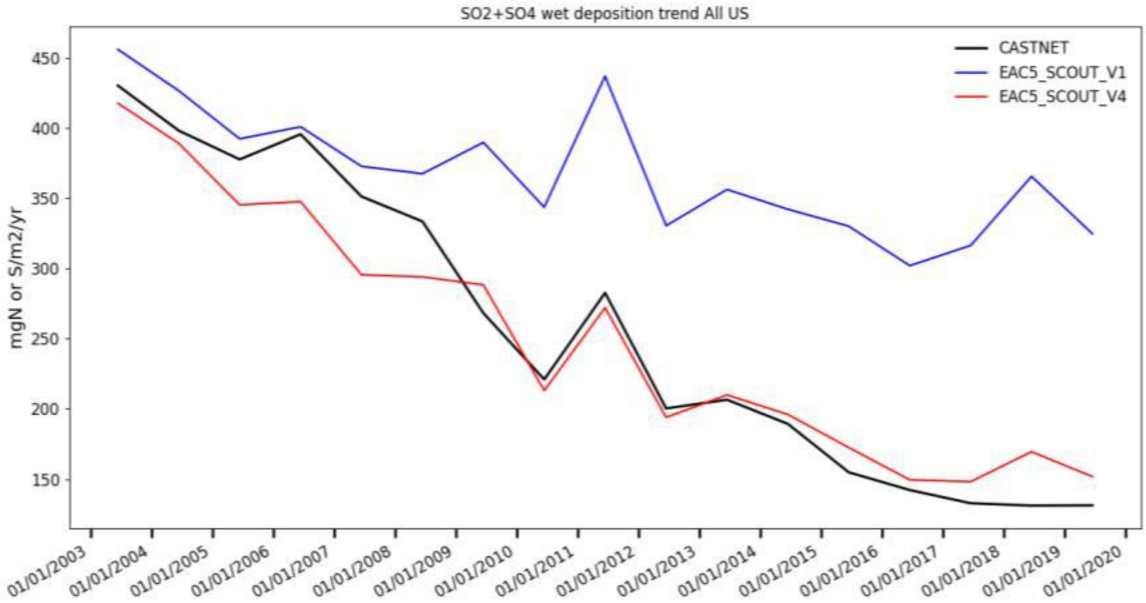


Figure 1: Yearly average of simulated and observed wet deposition of SO_2+SO_4, averaged over 93 NTN/CASTNET stations with full data over the 2003-2019 period.

4.2 Dust deposition ground observations

Table 2 lists datasets of ground observations of dust deposition. Unlike sulphur/nitrogen deposition, the validation data is very sparse and far from near real time. This is why we investigated the potential use of dust deposition rate from remote sensing to evaluate CAMS forecasts.

Table 2: Datasets of dust deposition that can be used for the evaluation of CAMS forecasts.

Dataset	Temporal resolution	Region	Specifics
Dust deposition over the Atlantic	climatological	North Atlantic	23 observation points in the North Atlantic
Dust deposition over the Mediterranean	climatological	Mediterranean	15 observation points in the Mediterranean
Dust deposition over West Mediterranean (ChArMEx)	Weekly	West Mediterranean	4 sites, 2011-2013 (not all years for all sites)
Dust deposition over the Sahel (SDT)	Weekly	Sahel	4 sites in the Western Sahel, 2006-2021 (not all years)

4.3 Total dust deposition from mass balance algorithms

Dust deposition from mass balance algorithms are computed using backscatter from remote sensing and simulated wind fields over non-source regions. The last part is essential in order to explain the mass changes by deposition (and not emission) processes. Our objective is to assess whether we can exploit dust deposition rate (DDR) data from an independent source to perform near-real-time quality control on CAMS dust deposition products.

4.3.1 Data sources and methodology

We selected two independent sources for the DDR over the tropical Atlantic Ocean, both based on mass balance algorithms. The first consists of four NASA products [Yu et al. 2015; Yu et al., 2019], derived from four sensors: CALIOP, MODIS, IASI, and MISR. The second source is a single product developed by the DOMOS team [Proestakis et al., 2025].

The mass balance method can be summarized in four main steps shown in Figure 2: The first step involves deriving 3D extinction coefficient maps from vertical backscatter profiles, using CALIOP. This part involves using lidar ratio estimates for dust, which are highly uncertain. For the NASA products, an additional normalization step is performed using dust optical thickness for the other sensors (MODIS, IASI, MISR). The second step reconstructs the 3D mass concentration profiles from the extinction coefficients, using the mass extinction efficiency (MEE). The extinction coefficient is simply the product of the dust mass concentration and the MEE. In the third step, meteorological wind vector data are used (MERRA-2 for the NASA products and ERA5 for DOMOS) to compute the zonal (east-west) and meridional (north-south) dust mass flux profiles. Finally, in the fourth step the DDR is calculated by computing the divergence of the zonal and meridional dust mass fluxes. In other words, the excess of the incoming flux compared to the outgoing flux is interpreted as deposition. Figure 1 provides a schematic representation of all the steps described above for the NASA products (a supplementary fifth step is visible for the additional normalization step).

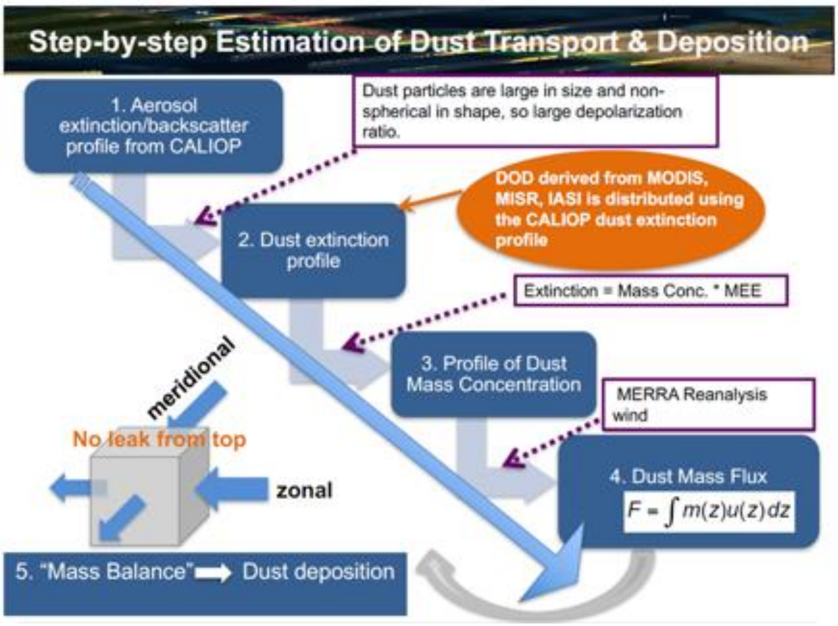


Figure 2: The NASA products steps to derive the dust deposition from remote sensing observations [Yu et al., 2015].

4.3.2 Characteristics of the NASA and DOMOS products

Regarding the NASA products, we have 10 years of DDR data, covering the period from 2007 to 2016. The data are provided as seasonal averages for the following periods: December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). The DDR data cover latitudes from -5° to 31° with a 2° resolution, and longitudes from -8.5° to 22.5° with a 5° resolution. This spatial domain corresponds to the area outlined in blue in Figure 3.

Concerning the DOMOS product, we have access to 16 years of data, extending from 2007 to 2022. It shares the same characteristics as the NASA data in terms of seasonal averaging and spatial resolution, with the exception that the geographical coverage is larger: latitudes from -61° to 41° and longitudes from -122.5° to 22.5°.

The key advantage of the NASA data lies in the availability of four independent sensors. While all share the same underlying assumptions, they differ in their use of the dust optical depth (DOD), which allows for uncertainty estimation in the DDR values. On the other hand, the strength of the DOMOS product is its potential for continuous improvement (three versions have already been released: V1 in 2022, V2 in 2023, and V4 in December 2024), as well as its availability in near-real-time.

The differences between the NASA and DOMOS products are summarised in table 3.

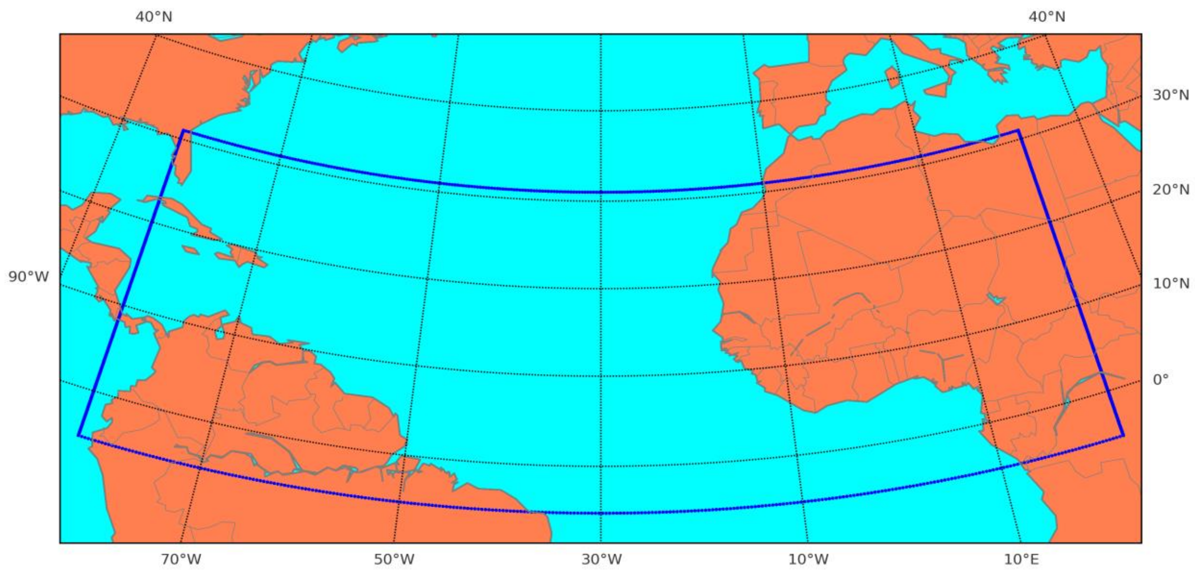


Figure 3: The spatial coverage of the NASA dust deposition products (inside the blue perimeter)

Table 3: Key differences between the NASA and DOMOS dust deposition products

	NASA Products	DOMOS Product
Number of products	4	1
Sensors used	CALIOP, MODIS, IASI, MISR	CALIOP
Extinction method	Extinction from CALIOP profiles + DOD normalization for MODIS, IASI and MISR	Extinction from CALIOP profiles
Meteorological data used	MERRA-2	ERA5
Temporal coverage	2007 – 2016 (10 years)	2007 – 2022 (16 years)
Spatial coverage	Lat: -5° to 31°, Lon: -8.5° to 22.5	Lat: -61° to 41°, Lon: -122.5° to 22.5°
Uncertainty estimation	Possible thanks to the 4 products	Not possible with only 1 product
Update and improvement	Static	Continuously improved
Near-real-time availability	No	Yes

4.3.3 Uncertainty analysis

In the remainder of the study, we chose to restrict our analysis to the geographical domain covered by the NASA products in order to enable consistent comparisons with the other products (DOMOS and CAMS).

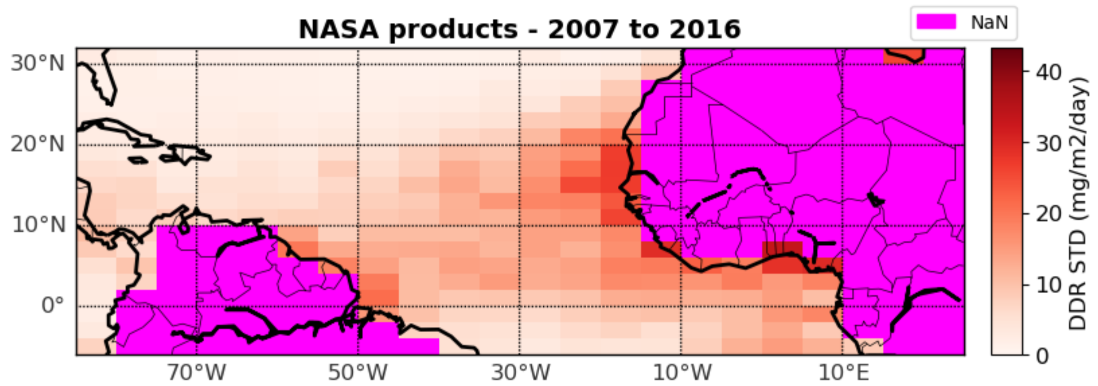
To quantify the standard deviation of the DDR, we employ the following equation:

$$DDR\_STD = \sqrt{\frac{\sum_i |DDR_i - \overline{DDR}|^2}{N}}$$

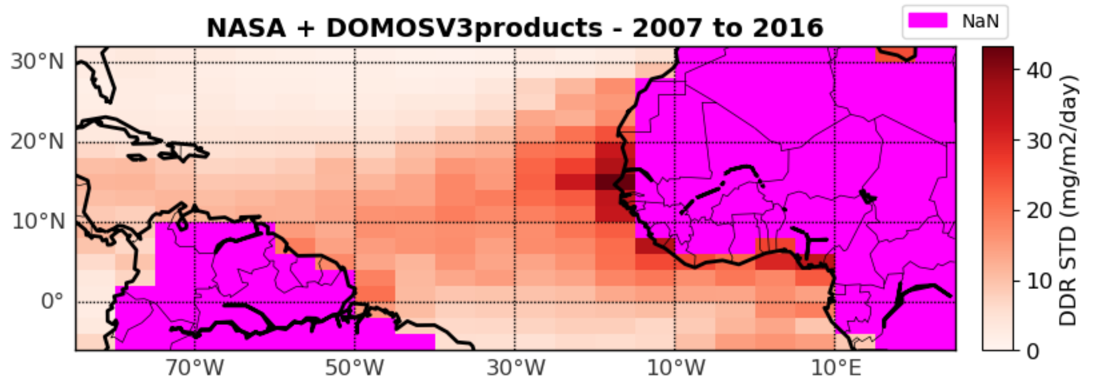
where DDR_i denotes the value from the ith DDR product (either one of the NASA products or the DOMOS product), $\overline{DDR}$ is the mean DDR across all selected products, and N is the total number of products considered.

Spatial variability

Figure 4 shows the absolute standard deviation of DDR averaged over the period 2007–2016. Panel (a) presents results with solely the NASA products, while panel (b) includes all available products, i.e., both NASA and DOMOS. Figure 5 presents the same results but expressed as relative standard deviations. The findings highlight a substantial degree of uncertainty associated with DDR estimates, with relative standard deviations generally ranging from 40% to 60% across much of the tropical Atlantic Ocean. This level of variability persists even when considering only the NASA products, even though they are derived using similar methodological assumptions. The inclusion of the DOMOS product leads to a slight increase in uncertainty, but not significantly.

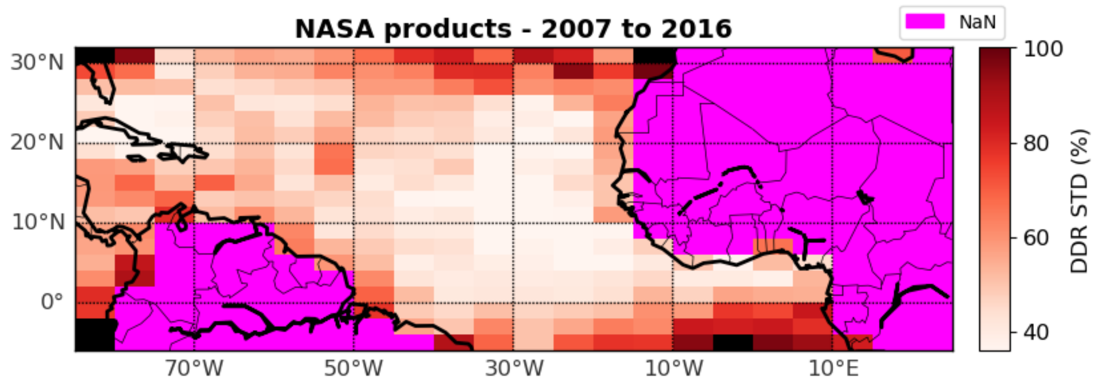


(a) Only the NASA products

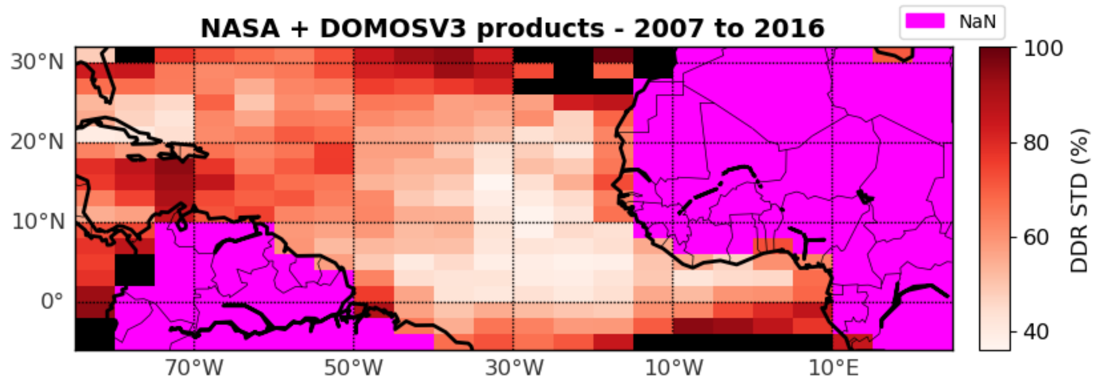


(b) The NASA and DOMOS products

Figure 4: Absolute standard deviation of the DDR averaged over the period 2007 to 2016



(a) Only the NASA products



(b) The NASA and DOMOS products

Figure 5: Relative standard deviation of the DDR averaged over the period 2007 to 2016

Temporal variability

Figure 6 further illustrates the temporal evolution of spatially average DDR values and their associated standard deviations. High standard deviations are observed during spring and summer, which can primarily be attributed to higher DDR values during these seasons. This seasonal pattern is corroborated by Figure 5, which presents the corresponding relative standard deviations.

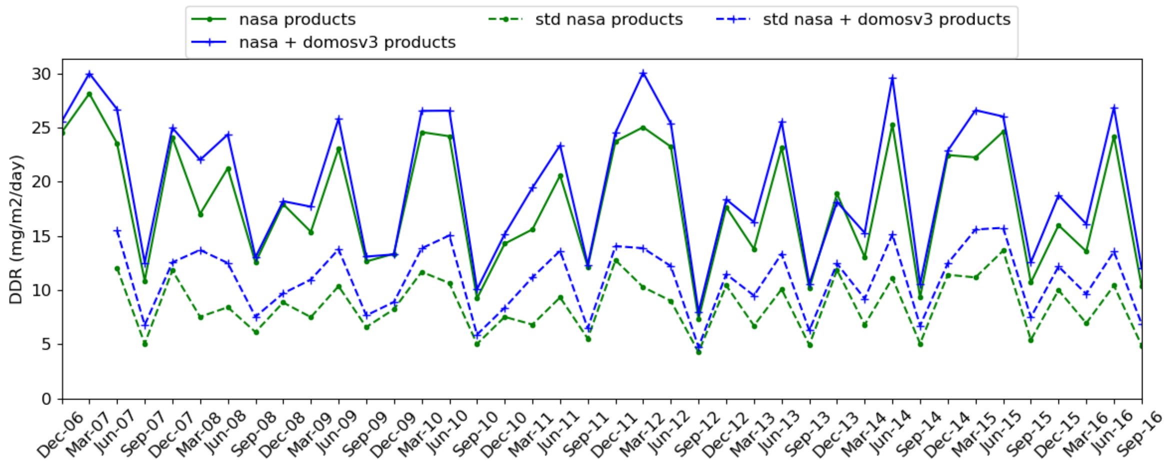


Figure 6: Temporal variability of spatial average DDR (all the NASA spatial coverage) and its absolute standard deviation. In green only NASA products and in blue all the products (NASA and DOMOS).

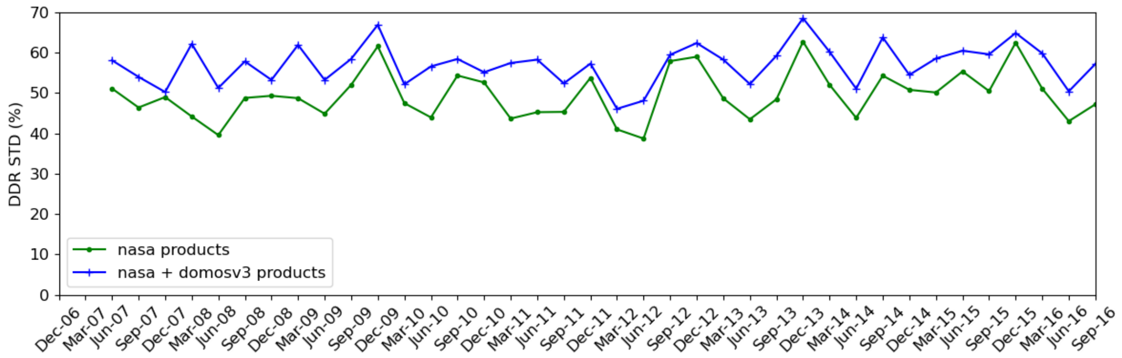
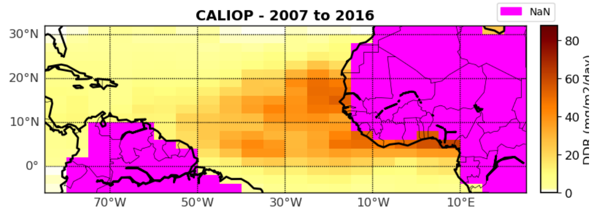


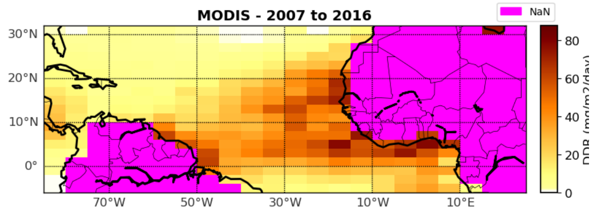
Figure 7: Same as Figure 6 but with only relative standard deviation

Inter-Product Spatial Patterns

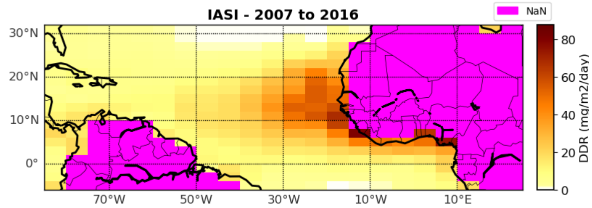
Finally, Figure 8 presents the DDR spatial distribution from the five products (NASA and DOMOS) over the tropical Atlantic Ocean, averaged over the period 2007–2016. A substantial degree of spatial variability is visible, even among NASA products, despite their reliance on shared methodological assumptions. Nevertheless, a consistent overall pattern emerges, with high DDR values originating from the Sahara and extending toward northern Brazil.



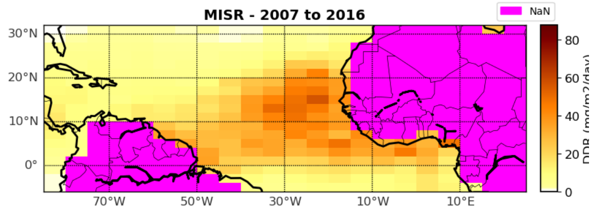
(a) CALIOP NASA product



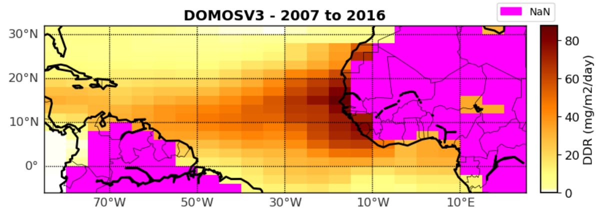
(b) MODIS NASA product



(c) IASI NASA product



(d) MISR NASA product



(e) DOMOS product

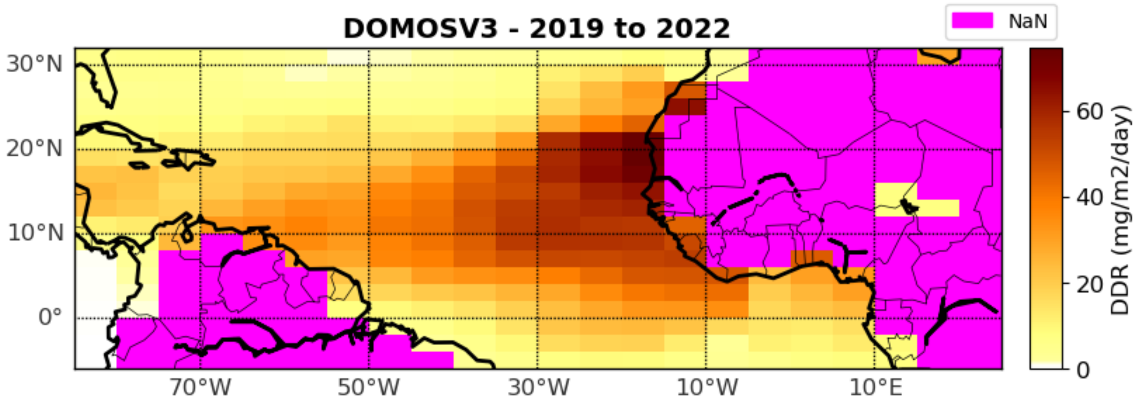
Figure 8: Dust Deposition Rate (DDR) over the tropical Atlantic Ocean from the NASA and DOMOS products for the period 2006 – 2016.

4.4 Use of dust deposition from mass balance to evaluate CAMS products

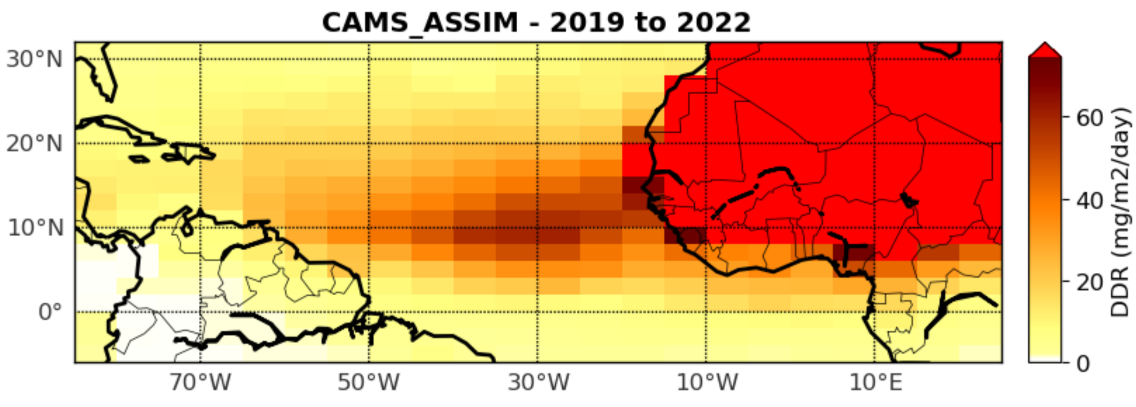
4.4.1 CAMS NRT and DOMOS over the period 2019 – 2022

Yearly analysis

Figure 9 presents a comparison between the DOMOS product and the operational CAMS Near Real Time total dust deposition between 0-24h forecast time product (with data assimilation) over the period 2019–2022. The simulated dust deposition is likely impacted by several upgrades of the CAMS NRT system, such as the implementation of a new dust emission scheme in cycle 46R1 (July 2019), and the upgrade the dust source function in cycle 47R1 (October 2020). However the observations assimilated and the configuration of the data assimilation system remained the same in this period, which reduces the impact of model changes. The use of CAMS reanalysis data for this evaluation is more complicated, as the deposition fluxes of aerosol species are not officially archived in CAMSRA. The results are broadly comparable, although DOMOS DDR values tend to be systematically higher. Notable differences in spatial patterns are observed, particularly a pronounced DDR peak in the DOMOS product over the ocean off the coast of Mauritania, which is not captured by CAMS.



(a) DOMOS



(b) CAMS NRT

Figure 9: Dust Deposition Rate (DDR) over the tropical Atlantic Ocean from CAMS NRT (operational) and DOMOS products for the period 2019 – 2022.

Seasonal analysis

Figure 10 displays the same comparison as in Figure 9 but disaggregated by season. Except for autumn, substantial differences in spatial patterns are observed across all seasons. The prominent DDR peak off the Mauritanian coast appears in summer, possibly linked to the extreme dust event of June 2020.

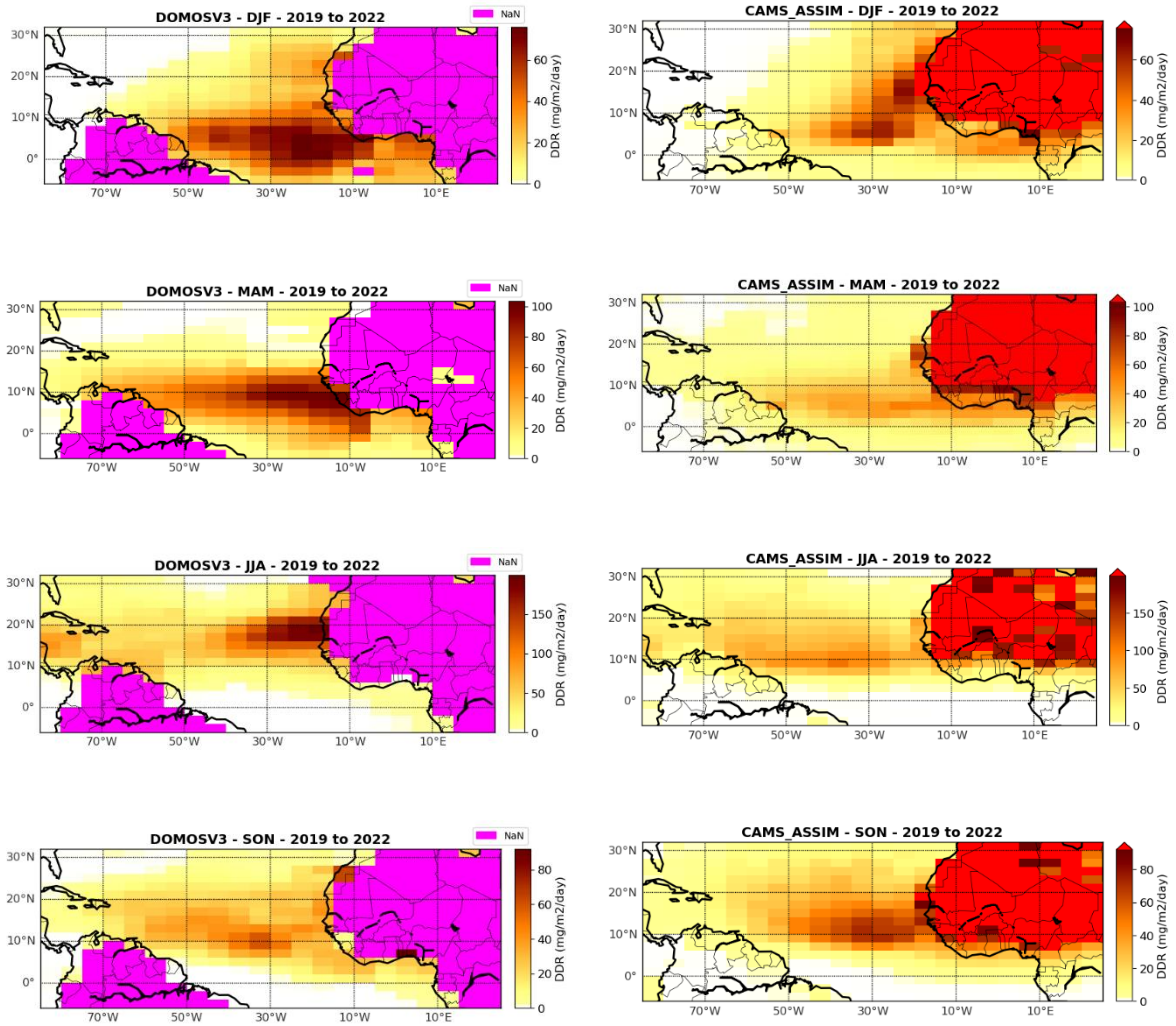


Figure 10: Same as Figure 9 but for each season.

4.4.2 CAMS forecast only and DOMOS over the period 2007 – 2016

Figure 11 is similar to Figure 6 but includes the CAMS forecast only product (cycle 49R1). Among all products, the CAMS forecast-only dataset appears to be more consistent with DOMOS, especially when compared to the NASA-derived products.

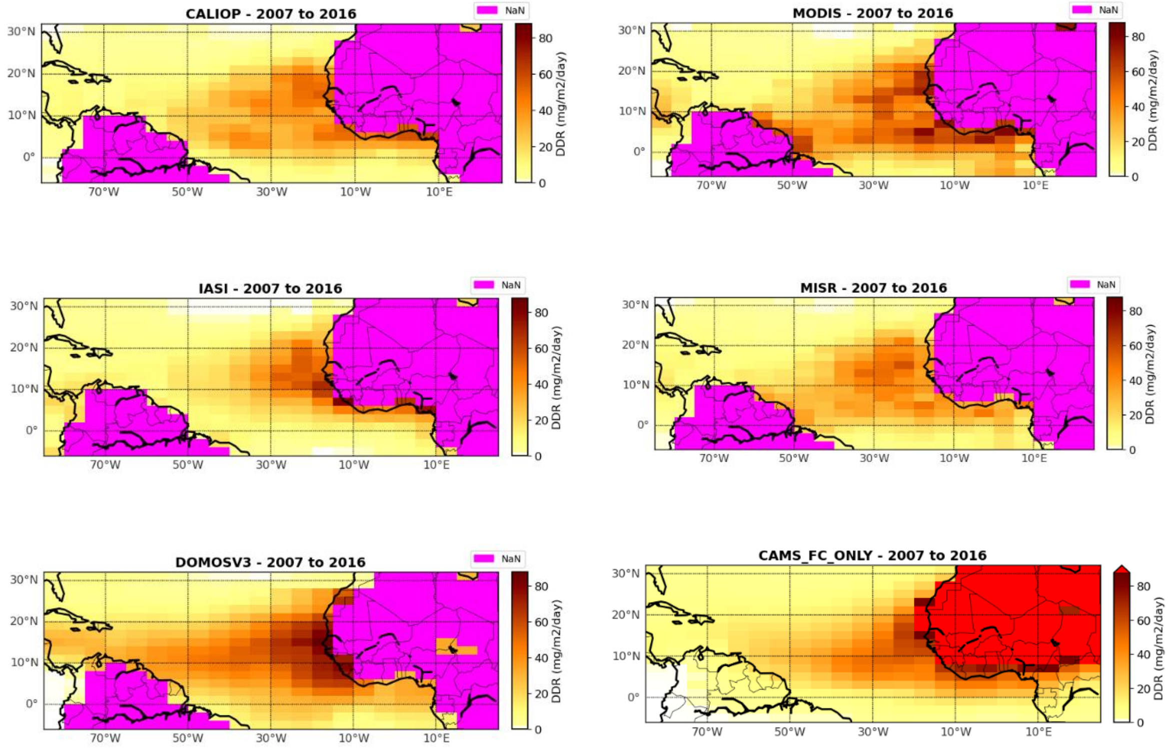
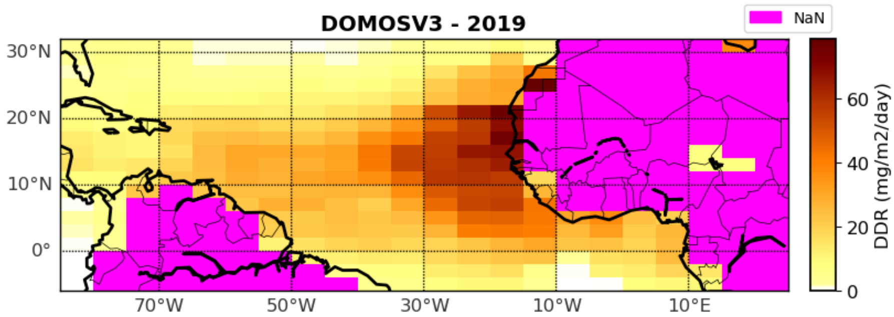


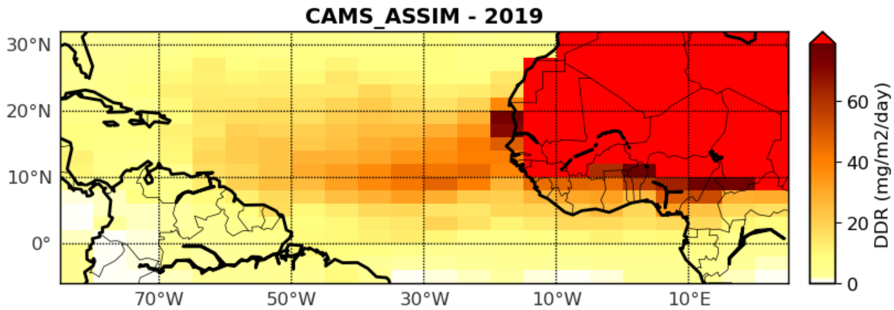
Figure 11: Same as Figure 8 but with the addition of the CAMS forecast only product.

4.4.3 CAMS NRT, CAMS forecast only and DOMOS for the year 2019

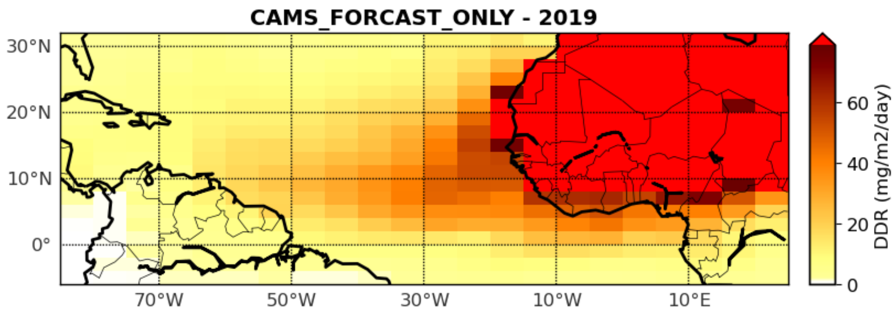
Figure 12 presents a comparison between the DOMOS product, CAMS NRT, and CAMS forecast only for the year 2019. A clear discrepancy is observed between the two CAMS products, which can be attributed to model differences between assimilation cycles 46R1 (used in NRT) and 49R1 (used in forecast only). When comparing either CAMS product to DOMOS, no obvious improvement or degradation is observed in terms of consistency or pattern reproduction.



(a) DOMOS product



(b) CAMS NRT product



(c) CAMS forecast only product

Figure 12: Dust Deposition Rate (DDR) over the tropical Atlantic Ocean from the DOMOS, CAMS NRT and CAMS forecast only for the year 2019.

4.5 Proposed deposition evaluation protocol

We propose to differentiate between dust deposition and nitrogen/sulphur wet deposition evaluation, as the datasets involved are not the same. For dust deposition evaluation in Near-Real-Time, our recommendation is to rely on products from mass balance algorithms such as the DOMOS one. While DOMOS is built on the LIVAS product which uses CALIOP (for which data is available up to the end of 2023), the use of other remote sensing lidar products, and in particular the use of data from the ATLID instrument onboard Earthcare is envisaged. The team who developed DOMOS at the National Observatory of Athens is already working on such a project.These can be produced at relatively little cost and close to the current date. However, because of the numerous assumptions and sources of uncertainties of these products, we suggest to carry out yearly instead of quarterly evaluation. Additionally, we propose that these products should be used qualitatively, ie for an eyeball comparison of values and patterns, and that no systematic skill scores be computed from them, at least until further research improves their robustness and reduces their uncertainty.

For nitrogen and sulphur deposition, the main observational networks provide data with a delay of 6 months (NTN/CASTNET) to 1.5 years (EMEP/ICP-forest) and more than two years and half for EANET and INDAAF. This delay imposes a validation of operational products that are quite far way from Near-Real time. For the global CAMS, at each model update, a test dataset of one year of data with the new model version and using data assimilation is generated for test purposes, and for dissemination to the regional CAMS models. This dataset could be used for the evaluation of deposition fluxes. For the evaluation of the global CAMS control run (without data assimilation), there is more flexibility as these runs are much less costly and time consuming to produce. This constrain suggest a reporting period that is aligned with the upgrades of the operational systems (global or regional). If possible, the comparison should be made using two model versions: the operational and the future operational versions.

The global system produces fluxes of dry and wet deposition, which should be compared to the closest analog from the observational datasets. For wet deposition, this means using accumulated wet deposition, and not concentration in precipitation as the reference. This approach is preferable, as it provides an evaluation of the errors of the final product that is accessible to users. However, this means that the evaluation will provide information on the skill of precipitation forecasting in addition to the skill of deposition forecasts. Dry deposition data is often indirect or fusion product, which limits somewhat the added value of the evaluation. Still, despite these caveats, an evaluation of dry deposition should be provided, but clearly explicating its limitations and qualitative rather than quantitative nature. For both dry and wet deposition, quality control of the observational dataset should be either verified or carried out so as to remove outliers or unphysical values. The EMEP and CASTNET/NTN datasets have been used widely by many groups an were found to be in general devoid of unphysical values.

The evaluation should focus on two aspects: the ability of the model to represent daily variability, and deposition events, and the ability of the model to represent the average deposition fluxes. For the first aspect, we suggest to use the smallest temporal accumulation possible, ie daily for EMEP-d and weekly for NTN/CASTNET and ICP forest, if available. For the second aspect, we suggest to use monthly averages, which should reduce double penalty effects associated with badly simulated precipitation events.

The results of the evaluation should use common metrics (bias and normalized bias, root mean square error – RMSE and normalized RMSE, and Pearson correlation coefficient). The normalized skill scores are important so that the large values don’t hide the signal for the smaller values in terms of bias and errors. The results should be presented in aggregated skill scores over continental areas such as Europe and U.S., and also for sub-regions defined by meteorological regimes, such as Western and Eastern U.S. 2D maps should also be provided in order to appreciate the geographical aspect of the skill of the deposition products. Density scatterplots can also be provided, which provide another angle on the skill of the products. Finally, a few station plots for locations deemed representative of a specific areas could be provided.

5 Comparison of in-situ observations of soiling loss with CAMS products

This section presents a preliminary study of correlation between CAMS aerosol parameters and in-situ measurements of solar panel soling loss. The study presented here is focused on one site in Ivory Coast.

5.1 The measurement campaign

The soiling data here presented comes from a ground-based solar radiation measurement campaign conducted by Yandalux Solar GmbH and CSP Services GmbH as part of the World Bank Project “Solar Development in Sub-Saharan Africa—Phase 1 (Sahel)” for the West African Power Pool (WAPP), an agency of the Economic Community of West African States (ECOWAS) (Norde Santos et al, 2024; . The WAPP stations consist of 33 measurement locations distributed across 14 countries in West Africa, as shown in Figure 13. The measurement campaign began in summer 2021 and lasted for two consecutive years. The first observations were conducted during July 2021, but the exact start date depends on each station. At the moment, only data from the first measurement year is freely available.

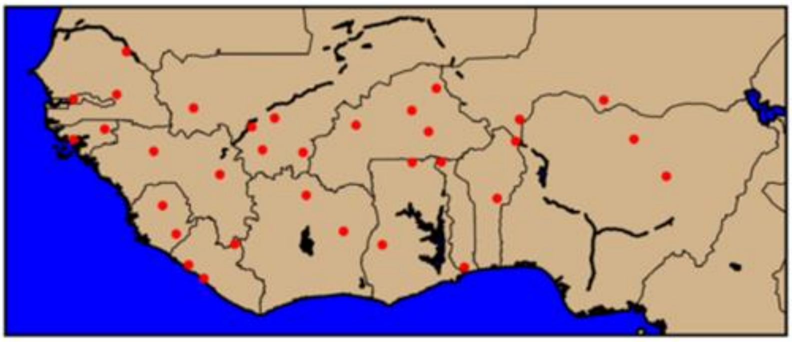


Figure 13. Location of the 33 WAPP stations location on West Africa

Observations of standard meteorological parameters (solar radiation, temperature, relative humidity, wind speed and direction, barometric pressure, and precipitation) were performed at each station at 1-minute resolution. Additionally, each station contained two reference PV modules in order to quantify the effect of soiling on the PV production. While one module was cleaned on a daily basis, and hence kept as the clean reference, the second one was only cleaned once a month, allowing in this way the accumulation of dirt over the module. This configuration is shown in Figure 14 for the Serebou station (Côte d’Ivoire) where the modules are installed with a 10° tilt angle and southwards oriented.

Figure 14. Clean and soiled PV modules at Serebou (Côte d'Ivoire)

5.2 The measured soiling ratio and soiling rate

Soiling ratio in a minutely resolution (SR_{1min}) is calculated based on the temperature-corrected short-circuit current (I_{sc}) of the PV modules, after conversion to plane-of-array irradiance (G_{POA}), following:

$$SR_{1min} = \frac{G_{POA,soiled}}{G_{POA,clean}} = \frac{c_{I-G,soiled}\, I_{sc,soiled}}{c_{I-G,clean}\, I_{sc,clean}},$$

With G_{POA} the plane-of-array irradiance and $c_{I\text{-}G}$ a panel-specific calibration factor to convert I_{sc} to G_{POA}. In order to estimate daily soiling ratio (SR_{daily}) values, the procedure presented in [3] was followed and only SR_{1min} values acquired within 2 hours around the solar noon were considered. The daily soiling loss is then defined as:

$$SL_{daily} = 1 – SR_{daily}$$

Soiling ratio is averaged during the two hours, and the daily soiling rate is computed as the difference between two successive averaged soiling ratios:

$$S_{rate} = SR_{daily}(\text{previous day}) - SR_{daily}(\text{current day})$$

5.3 In-situ observations at Serebou, Côte d’Ivoire

Daily soilng rate

Measurements are acquired at Serebou between April 2022 and April 2023. The mean soiling ratio is 0.989+-0.012, with a median of 0.992. The minimum is 0.930, observed at the end of February.

The daily soiling rate S_{rate} is close to zero, with a negative median of -0.002 day^{-1}. The soiling rate is rather variable, between a minimum of -0.007 day^{-1} and a maximum of 0.042 day^{-1}, observed in January 2023, and a standard deviation of 0.007 day^{-1} (Table 1). By distinguishing the cleaning days to the regular soiling phenomenon, the average is -0.003+-0.002 day^{-1} for $S_{rate} < 0$ and it is 0.008+-0.012 day^{-1} for $S_{rate} > 0$.

Table 4. Mean values of the daily soiling rate at Serebou in 2022-2023 for different filters

filter	Number of days	Mean+-std dev (day^{-1})
all	353	0+-0.007
Manual cleaning	12	0.014+-0.013
No cleaning	341	0+-0.006
No cleaning, Precip > 1 mm	63	0.003+-0.006
No cleaning, Precip=0	136	-0.001+-0.003

Positive S_{rate} indicates cleaning either by precipitations either manually. Table 5 gives the 12 manual cleaning dates at Serebou and the corresponding S_{rate}, which are indeed all positive, even if it is 0 on 2022/09/01. The mean S_{rate} during the manual cleaning dates is 0.014+-0.013 day^{-1} (Table 4).

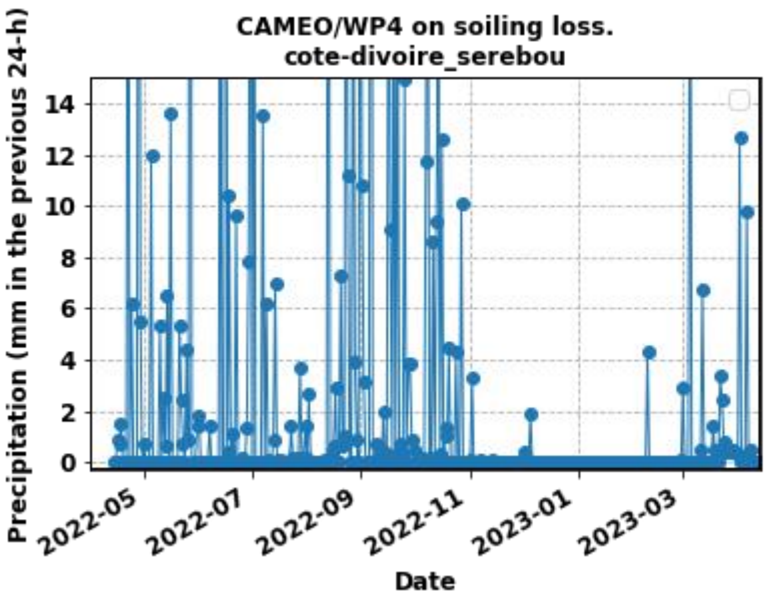
Table 5. Manual cleaning dates at Serebou, with corresponding observed soiling rate and mean relative humidity.

Cleaning date	S_{rate} (day^{-1})	Relative humidity (%)
2022/04/30	0.004	82.6
2022/06/01	0.003	85.1
2022/07/03	0.007	88.5
2022/09/01	0.000	93.8
2022/10/01	0.005	85.5
2022/11/01	0.012	82.8
2022/12/02	0.012	82.1
2022/12/19	0.014	77.2
2023/01/09	0.042	59.3
2023/01/18	0.017	51.9
2023/02/01	0.031	46.3
2023/03/01	0.025	65.3

Precipitation

Accumulated precipitation (Precip) is computed from noon on the previous date to noon on the current date, and recorded on the current date. Other weather parameters are averaged on the same time window, as relative humidity (RH).

Figure 15 shows the time series of both daily accumulated precipitation and relative humidity at Serebou, which clearly indicate a rather dry time period in January-February. The last rain of the humid season occurs on 2022/11/02 with 3.3 mm/day of fallen water within 24 h, even if 2 mm/day of rain also occurs on 2022/12/05. Relative humidity gives another indication of change of season, with daily mean value decreasing below 70% around 2022/12/20. Strong rain of 2023/03/05, with Precip > 20 mm/day, triggers the 2023 wet season, and a few days later on 2025/03/23, RH reaches 82%. The significant decrease of precipitation in December-February explains why the cleaning is then more effective with Srate > 0.012 day^{-1} after 2022/11/01 (Table 5).



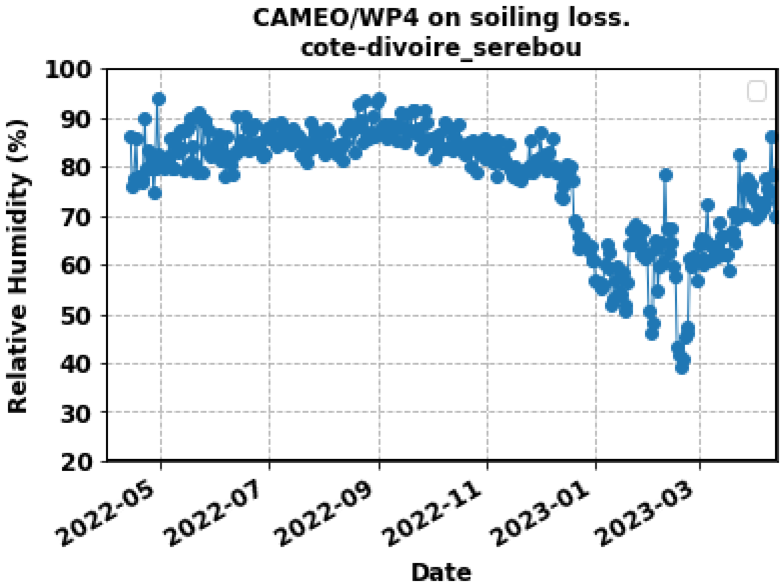


Figure 15. Time series of precipitation (top) and relative humidity (bottom) observed in-situ at Serebou in 2022-2023. Precipitation is accumulated over 24 hours from previous noon to current day noon, and relative humidity is averaged on the same time window.

When rain occurs (Precip > 0), the mean S_{rate} is 0.001+-0.008 day^{-1}, or 0.003+-0.006 day^{-1} for Precip > 1 mm (63 events), indicating a cleaning impact of rains, while it is -0.001+-0.003 day^{-1} when no rain occurs (136 events) (Table 1), indicating soiling.

Some outliers are observed, as soiling occurring despite rain as on 2022/07/02 and 2022/08/20 with Srate = -0.005 day^{-1}, and significant cleaning with S_{rate} =0.018 day^{-1} despite no rain and no manual cleaning, on 2022/12/25, as well as on both 2022/11/23 and 24 with Srate = 0.005 day^{-1}. Red rain events may cause soiling, and wind may partly clean the panels.

5.4 Aerosols at Serebou according to CAMS

Several aerosol parameters are extracted from the CAMS-NRT data set, for the pixel including Serebou: PM2.5 and PM10, speciated and spectral aerosol optical depth (AOD), speciated dry and wet aerosol deposition fluxes ("aerddp"), and speciated aerosol sedimentation fluxes ("aersdm"). Species are for example black carbon (BC), desert dust (DD), organic matter (OM) etc.

To show some consistency between the CAMS parameters and the in-situ observation, we compare times series during an intense soiling event occurring in February 2023. From 09 to 28/02, the soiling ratio decreases by 7% in 20 days, to reach the minimum of 0.930. S_{rate} decreases below -0.004 day^{-1} for 6 days between 2023/16/02 and 22, significantly below the 2022-2023 average of -0.001 day^{-1} (Figure 16). Consistently, the wind speed was larger than the average from 15 to 21/02, with concomitant change in the wind direction, and the relative humidity was smaller than the campaign average.

Figure 17 shows CAMS parameters in February 2023. The top figure shows AOD at 469 and 865 nm, and DD and OM AOD at 550 nm. According to CAMS, AOD increases from 17/02, until 27/02 included. AERONET data acquired at the nearby LAMTO station is also downloaded, and measured AOD at 550 nm is added in Figure 4. AERONET AOD also increases in the same time period. According to CAMS, AOD maximum occurs on 19-22/07 and on 19-20 according to AERONET.

PM at surface level also increases consistently to AOD, by a factor of 3 from before 16/02 to the monthly maximum on 20-22/02. There is also an increase in the dry deposition flux, but with a time shift, the maximum occurring on 15-17/02.

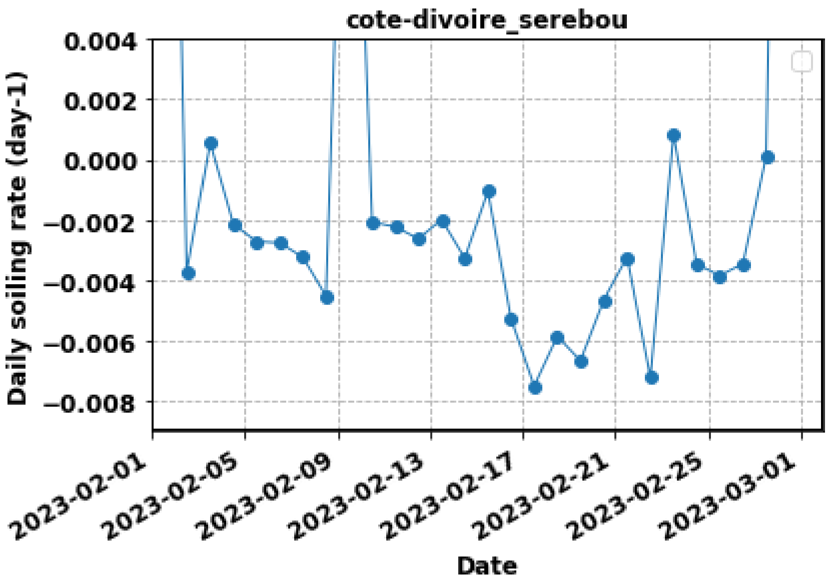


Figure 16. Time series of the daily soiling rate at Serebou in February 2023.

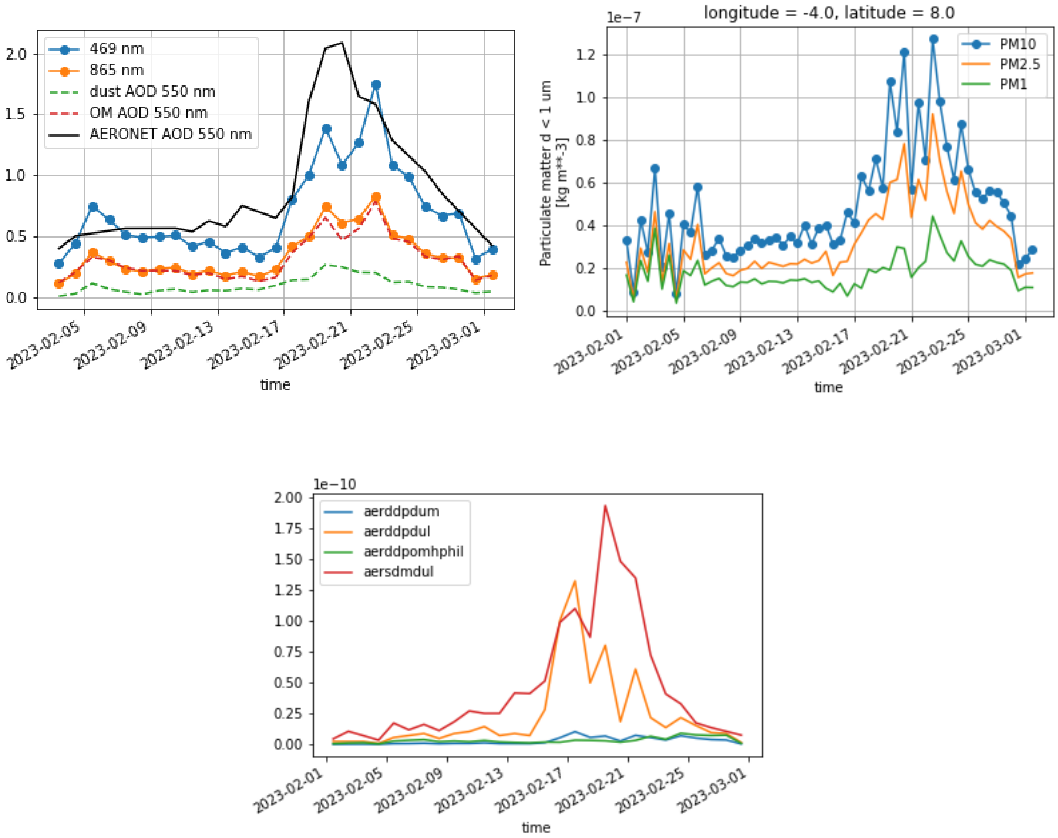


Figure 17. Several CAMS aerosol parameters at Serebou in February 2023: AOD (top), PM in kg/m^3 (middle) and aerosol dry deposition in kg/m^2/s (bottom). The top figure shows total AOD at 469 and 865 nm, DD and OM AOD at 550 nm, and AOD from the AERONET station of LAMTO is also added at 550 nm. The middle figure shows PM1, PM2.5 and PM10. The bottom figure shows the most contributing components to dry deposition at noon: middle bin desert dust dry deposition, large bin desert dust dry deposition, hydrophilic OM dry deposition, and large bin desert dust sedimentation.

5.5 Correlation coefficients between CAMS aerosol parameters and in-situ observation of soiling rate

Linear correlation was tested between S_{rate} and all the downloaded CAMS parameters, at 12:00. As the focus is on soiling, the data set excludes the manual cleaning dates as well as dates with Precip > 0.

Too small correlation coefficients are found over the 136 days without both rain and manual cleaning events. It was for example -0.25 with aod469, and -0.36 with dry deposition by hydrophobic BC. The correlation coefficients are increased (in absolute value) by selecting the wet season excluding 4 dates showing outliers. The wet season is defined either between 2022/12/21 and 2023/03/04 (45 days) or with RH < 70% (46 days). The correlation coefficients are -0.46 for BC dry deposition (and -0.44 for OM), -0.39 for aod469, -0.38 for PM10 (Figure 18). Sedimentation does not always occur, and only correlation with the large bin desert dust is provided, which is quite small -0.29, and consequently the correlation with summed sedimentation and dry deposition is also small.

It is interesting to note that the correlation coefficients are increased when adding the AERONET filter on clear-sky. Indeed AERONET Level 2.0 data is combined here, which screens out sky situations with cloud cover. The number of days fall to 27 but the correlation coefficient for BC dry deposition increases to -0.54, to -0.43 for aod469 (and -0.46 for DD aod550), to -0.52 for PM10, and to -0.45 for large-bin DD sedimentation.

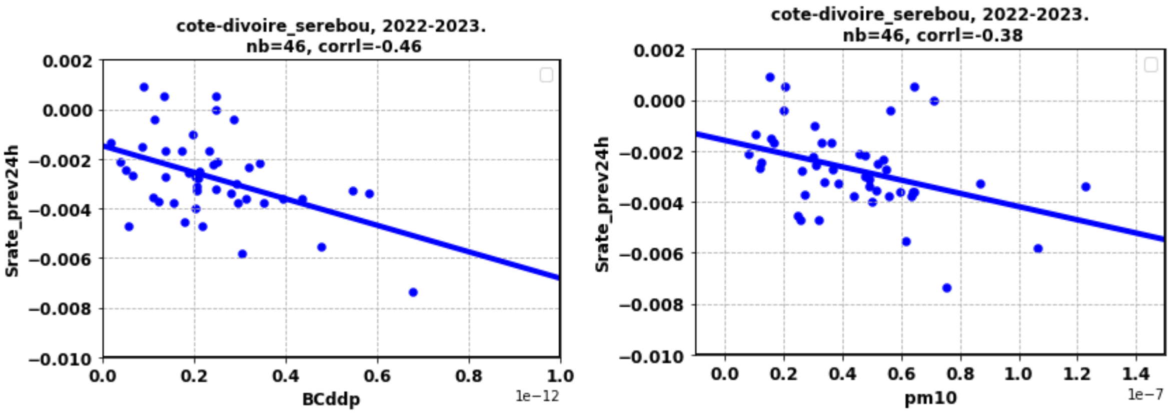


Figure 18. Correlation between the daily in-situ soiling rate and two CAMS aerosol parameters: BC dry deposition and PM10.

The correlations, although small, show the relationship between losses on PV production and different CAMS parameters. Extending the initial work here presented to different locations would be necessary to confirm these findings, and conclude about the feasibility of a potential validation of the CAMS considered parameters with soiling rate observations.

6 Conclusion

In this deliverable a tentative protocol for the evaluation of dust deposition as well as nitrogen and sulphur wet deposition has been laid out. For dust deposition, we propose to rely on novel fusion products that combine observations and simulated wind to provide dust deposition estimates using a mass balance algorithm. Several datasets using this approach have been retrieved, inter-compared, and used to evaluate simulated dust deposition from global CAMS products. Although the uncertainty of these products is significant, the comparison was found to be still informative on the skill of CAMS dust deposition.

Extensive wet deposition datasets have been retrieved covering the years 1985 to 2024, over North America, Europe, East Asia and West Africa. These datasets are being used for the evaluation of experimental CAMS products, and could be used for the evaluation of operational CAMS products. The critical factor here is the availability of the data : only over US is the observational data made available for the year before the current year.

Finally, the correlation between CAMS deposition data and observed soiling rates over a station in West Africa have been investigated, with promising results. This paves the way for a more thorough evaluation of the added value of global CAMS products to estimate the soiling rates.

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Document History

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