EMI R&D PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2026
Project Title:	Developments in observational operators for atmospheric lidars
Computer Project Account:	`spgramir`
Principal Investigator(s):	Dr. Vassilis Amiridis
Affiliation:	National Observatory of Athens
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr. Angella Benedetti
Start date of the project:	16 February 2026
Expected end date:	31 December 2026

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	0	0	6,000,000	2,982,317
Data storage capacity	(Gbytes)	0	0	0	0

Summary of project objectives (10 lines max)

The project aims to advance the assimilation of spaceborne lidar observations in numerical weather models, with emphasis on EarthCARE ATLID. Its first objective is the development of observational operators for lidar extinction, depolarisation ratio, and lidar ratio within the NCAR DART ensemble assimilation framework. Its second objective is to investigate the impact of advanced non-spherical optical models for desert dust on modelled dust loads, emissions, deposition, and the assimilation itself, compared to the spherical representations still assumed in most operational systems. The developed operators are verified through ensemble assimilation experiments over North Africa and the North Atlantic, targeting the period of the ORCESTRA/PERCUSION campaign of August and September 2024 and validated against its airborne observations. The work supports the EarthCARE DISC project (WP 7310) and the Horizon Europe CERTAINTY project, and ultimately aims to reduce the large current uncertainties in dust forecasting.

Summary of problems encountered (10 lines max)

We have not encountered any technical issues, as the codes and procedures were thoroughly tested during the predecessor project `spgramir (2023)`. Minor issues of a scientific nature were resolved without over-consumption of the allocated resources.

Summary of plans for the continuation of the project (10 lines max)

The results presented in this report concern only EarthCARE Lidar Extinction assimilation. We aim to continue our work to enable assimilation of more shape- and species- dependent variables (depolarization ratio, lidar ratio) and then continue to the joint experiment with both EarthCARE and polarimetric data.

List of publications/reports from the project with complete references

A detailed presentation regarding this work was given at the EarthCARE Science and Validation Workshop 2026:

- Georgiou T., Gialitaki A., Tsikerdekis A., Tsekeri A., Bantouna A., Spyrakos V., Marinou E., Melas D., Amiridis V.: Advances in dust optical modelling and EarthCARE dust data assimilation, EarthCARE Science and Validation workshop 2026, 8-12 June 2026, Oxford, UK, https://www.earthcare-science-validation-2026.org/

Additionally, the results were described in the Horizon Europe CERTAINTY project's deliverable D2.2 with title "Recommendations for improved aerosol assimilation" and a related journal article is under preparation.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

The project supports the development and validation of observational operators for spaceborne atmospheric lidars, with emphasis on EarthCARE ATLID, and the investigation of advanced non-spherical optical models for desert dust in ensemble data assimilation. During the reporting period, the allocated resources were used to deploy the ensemble assimilation system on the ECMWF HPC facility, to carry out the free-running preparatory ensembles needed to configure the system, and to complete a first set of assimilation experiments with ATLID extinction coefficient profiles. The work directly supported the CERTAINTY deliverable D2.2 "Recommendations for improved aerosol assimilation" (June 2026), where the results below are documented in full, and related peer-reviewed publications are in preparation.

Assimilation system. All experiments use the WRF-Chem regional model (version 4.7.0) coupled with the Ensemble Adjustment Kalman Filter implementation of NCAR DART, orchestrated by the wrf-ensembly tool. The configuration is a 30-member ensemble at 27 km horizontal resolution with 45 vertical levels, using the five-bin GOCART-AFWA desert dust scheme over a domain covering North Africa and the North Atlantic. The experiments target a Saharan Air Layer dust outbreak in August 2024, coinciding with the ORCESTRA/PERCUSION campaign whose airborne observations serve as independent validation data. The choice of 27 km resolution together with a 2-hour assimilation window was justified quantitatively through a cell-crossing time analysis. Transport winds in the dust layers, with a median of 8.5 m/s and a 90th percentile of 13.9 m/s, confine advective displacement within the window to a few grid cells, which keeps representativeness error bounded while the window still admits several thousand lidar super-observations per cycle. Two dust optical models are carried through every experiment in parallel, namely the conventional spherical representation and the new CERTAINTY "SphHex" model, a random mixture of spheroids and irregular hexahedra constrained by multi-wavelength polarisation lidar data from the ESA ASKOS campaign (developed under CERTAINTY Task 1.4).

Preparatory experiments. A substantial part of the consumed resources went into a free-running grid-search ensemble in which members sweep the GOCART dust emission tuning factor, which is a global linear coefficient for the model's emission fluxes. This single integration served every preparatory step of the assimilation design. First, it located the emission setting that renders the prior unbiased against ATLID extinction, approximately 0.50 for the spherical operator against 0.30 for SphHex. This reduction of roughly forty per cent mirrors the higher extinction efficiency of the non-spherical mixture and is corroborated independently by AERONET, VIIRS, and PACE/HARP2 references (Figure 1). Second, it revealed that around forty per cent of observed dust pixels lie where the model carries no dust at all. This placement error cannot be removed by any emission setting and must instead be expressed by ensemble spread. Third, it exposed how the CAMS-derived initial conditions relax toward the model equilibrium with a reshaped size distribution, motivating a per-bin rescaling of initial and boundary conditions (the giant-particle bin is reduced by roughly a factor of ten, while mid-coarse bins are scaled up). Fourth, the observation error was estimated empirically from the departure statistics through the spread-consistency relation, yielding a signal-dependent error model applied per observation. Finally, the lidar profiles were resampled into super-observations matched to the model grid (27 km along track by 310 m vertically), with an error treatment that accounts for the fully correlated within-bin retrieval errors. Ensemble spread itself was constructed from two complementary components, a zero-mean spatial offset of the aerosol initial and boundary fields that seeds placement uncertainty at plume edges, and persistent multiplicative perturbation fields that provide amplitude spread. The resulting free-running spread is sustained at roughly a quarter of the mean column AOD throughout the experiment.

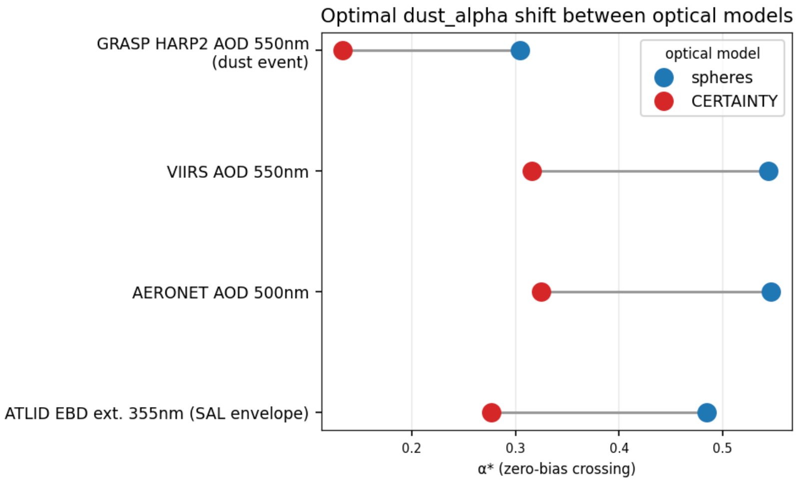

Figure 1*: Unbiased-mean emission tuning factor for each validation instrument under the spherical (blue) and SphHex (red) operators. All instruments indicate a consistently lower emission setting for the more extinction-efficient SphHex operator.*

Assimilation results. With the system prepared, four 30-member ensembles were integrated over the experiment period, a control and an assimilation run per optical model, sharing identical priors and perturbation fields. At the analysis enclosing the 14:45 UTC EarthCARE overpass of 12 August 2024, 5,033 super-observations were assimilated. The analysis reduces the departure root-mean-square from 57.1 to 46.6 1/Mm (18 per cent) for the spherical operator and from 54.4 to 46.1 1/Mm (15 per cent) for SphHex, with the observation-model correlation rising from 0.74 to 0.81 in both. Splitting the observations by regime shows that the improvement is concentrated where the background carries dust (33 to 36 per cent departure reduction), while pixels where the prior is empty barely move, quantifying the placement ceiling of the ensemble filter. In the vertical, the increment is two-signed, deepening the under-represented elevated Saharan Air Layer and trimming over-predicted dust in the lowest kilometres, so the posterior matches the observed layer depth more closely than the prior (Figure 2). Consistency diagnostics (Desroziers estimates and spread-skill ratios) indicate the assigned observation error is conservative, so the reported increments represent a lower bound on the achievable impact.

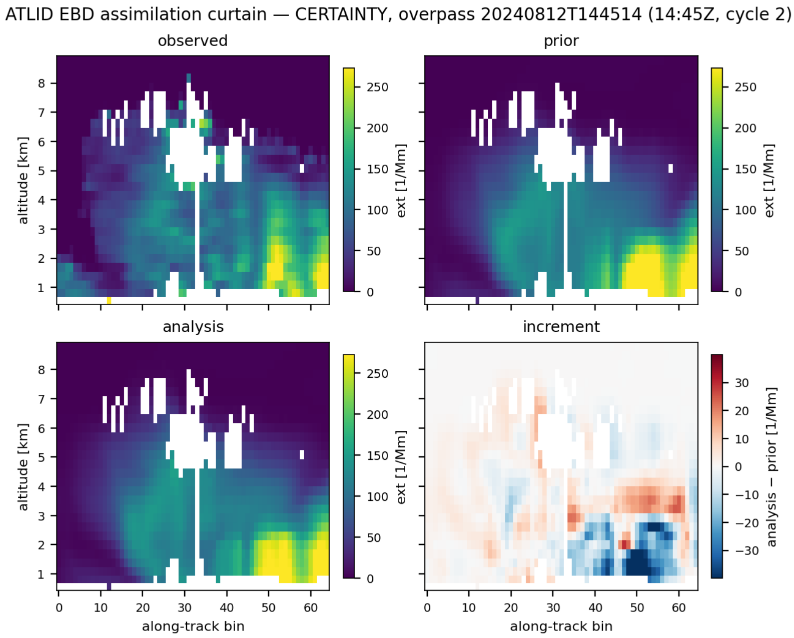

Figure 2*: ATLID EBD assimilation curtain along the assimilated 14:45 UTC overpass for the SphHex operator, showing the observed extinction, the prior, the analysis, and the analysis increment. The analysis raises the under-represented elevated Saharan Air Layer and trims the overestimated dust in the lowest levels.*

Forecast impact. The cycle following the analysis was integrated as a free forecast and verified against two independent EarthCARE overpasses roughly twelve hours later, which were never assimilated. The analysis increment persists and improves the forecast against both crossings and under both optical models, with departure reductions of two to six per cent relative to the corresponding control runs (Figure 3). The SphHex forecast is also the closest to the observations in absolute terms at every crossing, carrying its better-equilibrated prior forward.

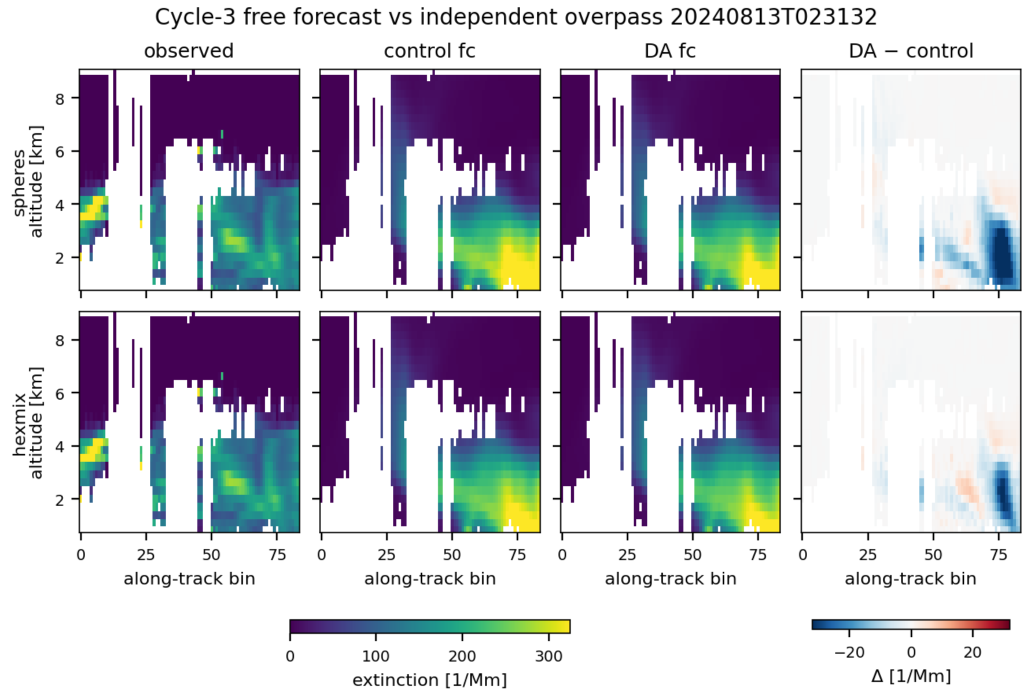

Figure 3: Free-forecast extinction curtain along the independent 02:38 UTC overpass for each optical model, showing the observed field, the control forecast, the assimilation forecast, and their difference. The persisted analysis increment is concentrated in the plume core.

Impact of the dust optical model. The central scientific result concerns the role of the optical model. The two assimilation experiments, identical in everything except the particle shape treatment, converge on analyses that are nearly indistinguishable in observation space, with their analysed column extinction at the assimilated 355 nm wavelength agreeing to within one per cent. Yet the spherical analysis carries approximately 46 per cent more column dust mass than the SphHex analysis (1.52 against 1.04 g/m2 over the Saharan Air Layer plume), because the non-spherical mixture is about 1.45 times more extinction-efficient per unit mass. The difference is not a uniform rescaling. The mass ratio grows from 1.34 in the fine bin to 1.55 in the coarse bins, so the inferred size distribution is reshaped as well, with direct consequences for deposition, dust-borne nutrient transport, and radiative effects (Figure 4a). Expressed spectrally, the two analysed states agree at the assimilated wavelength but diverge away from it, their column optical depth ratio growing from 1.01 at 355 nm to 1.35 at 1064 nm (Figure 4b). This demonstrates that assimilation constrains the observable rather than the underlying mass, that diagnostics computed in observation space alone cannot detect the discrepancy, and that a consistent non-spherical optical model is required when combining lidar profiles with passive AOD observations at other wavelengths.

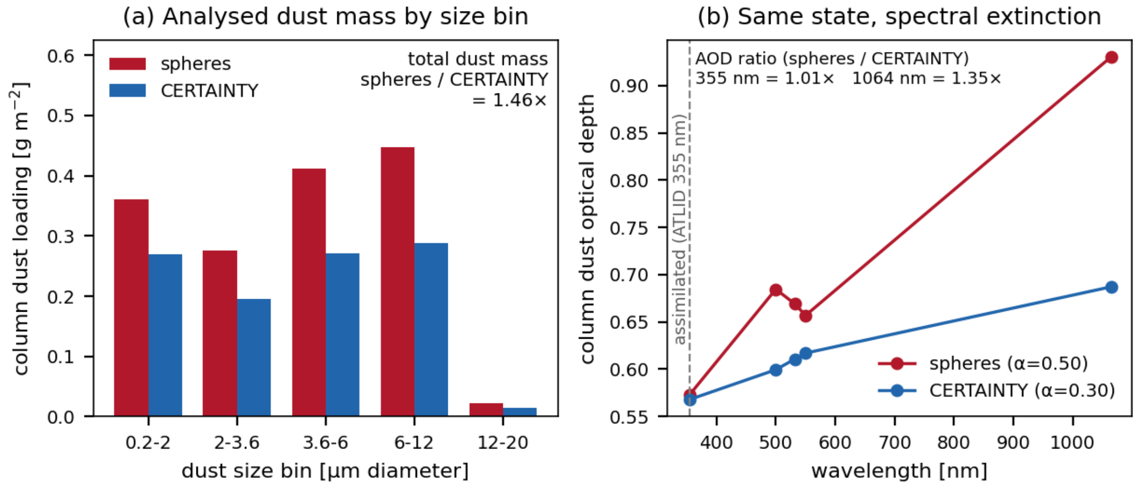

Figure 4*: The same extinction sustained by different mass, at the analysis and averaged over the Saharan Air Layer plume. (a) Analysed column dust mass per size bin for the two optical models. (b) The same analysed dust fields expressed as spectral column optical depth, with agreement at the assimilated 355 nm and divergence toward longer wavelengths.*

Resource usage and outlook. The consumed resources correspond to the preparatory grid-search ensemble, the four cycling experiments described above, and the associated post-processing, in line with the cost estimates of the proposal. The developed configuration, operators, and preparatory methodology are in place for the extended multi-cycle experiments and the depolarisation and lidar ratio operator developments planned for the remainder of the project.