Climate Modelling User Group

Deliverable D3.1e v2

Final report OWP5.5: Cloud and Aerosol Analysis Study

Centres providing input: ECMWF, BSC, DLR

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2.1	30th March 2026	First draft of OWP5.5
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CMUG CCI+ Deliverable D3.1e v2

Final report in OWP5.5

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Final report on progress achieved in OWP5.5

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1. Purpose and scope of this report

This document is the final report on activities carried on in the OWP5.5 Clouds and Aerosol study CMUG-CCI+. The aim of the study was to exploit ESA CCI and CCI+ data of aerosols and clouds for assimilation in Earth System Models (ESM), and in the optional phase of the project Earth System Model Evaluation Tool (ESMValTool) is used to evaluate the impact. For this purpose, we have used two CCI Essential Climate Variables (ECVs), clouds and aerosols, and two different models and approaches for the assimilation.

ECMWF assimilates operationally aerosol optical depth (AOD) in the Copernicus Atmosphere Monitoring Service (CAMS) for atmospheric composition forecasts, while limited cloud information is assimilated for Numerical Weather Prediction and reanalyses. In this study, we have assimilated both, aerosols and cloud information from AEROSOL_CCI and CLOUD_CCI datasets synergistically in the 4D-Var system.

BSC produces operationally daily forecasts of dust in the WMO Barcelona Dust Regional Centre. It produces dust forecasts with satellite data assimilation employing an ensemble LETKF assimilation scheme since July 2025. Dedicated dust observations are essential for this application, as well as for the constraint of the dust cycle in the Earth system. Using satellite dust optical depth, the MONARCH model at BSC has produced a 10-years dust reanalysis (Di Tomaso et al. 2022), which has been recently extended for two more years. This work assessed the potential benefit of using most recent developments on CCI aerosol retrievals for dust data assimilation, with perspectives of being used for assimilation in future dust reanalysis, and for verification of past operational forecasts.

In this final report the focus is on evaluating the ECMWF and BSC experiments with the ESMValTool.

2. Summary of cloud and aerosol analysis with the ECMWF system

This section presents a short summary of the ECMWF experimentation in the first phase of the project. All details can be found from the final report (Escribano et al., 2024).

The ECMWF IFS-COMPO system was technically prepared to assimilate the Climate Change Initiative (CCI) products for aerosol optical depth (AOD) and cloud optical depth (COD) from the Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel 3 satellites. AOD data is provided by the Swansea University, v1.14 (personal communication P. North and K. Pearson) and COD data by Science and Technology Facilities (STFC) and Deutscher Wetterdienst (DWD). The COD v3.3 dataset is not part of the official CCI data sets, but the same algorithms are being used to cover the test periods June 2020 and September 2021 (personal communication M. Stengel and G. Thomas, 2023). In OWP5.5 June 2020 was selected to be evaluated with ESMValTool as it is the shared period with the BSC experiments.

The AOD and COD observation quality has been evaluated in the ECMWF system with passive monitoring experiments. Passive monitoring means that the model counterpart for the observation is calculated with the corresponding observation operator but the observation has no impact in the analysis or resulting forecasts, i.e. it is passive. The monitoring experiments are a powerful way to design quality control for the new observations as well as to design realistic observation errors to be used in the active assimilation. Based on the monitoring statistics it was decided to focus on assimilating data over sea only as the data quality is more homogeneous.

Both AOD and COD products come with an uncertainty estimate for each observation. Sensitivity testing revealed that for AODs the uncertainty estimates can be used as scene-dependent observation errors in the assimilation, but it requires some inflation in order to obtain best results. An inflation factor of 1.4 was used in the final assimilation experiments. This is consistent with independent assessments of the product made by the AEROSOL_CCI using independent observations (Thomas Popp, personal communication). For COD, the provided uncertainty estimates were unrealistically low to be used as observation errors in the assimilation, an inflation factor of 6-10 would have been required depending on other screening decisions, such as tightness of the model first guess check where observations are compared to the model counterparts and if they deviate more than a predefined limit, the observation gets rejected. Thus, it was decided to use in the first assimilation experiments 0.75 x observed COD as observation error. This matches on average very well the magnitude of the average observation minus model background (OmB) standard deviation statistics, which is typically a good first estimate of the observation error.

Quality assessment of COD observations also indicated that there are large biases (in magnitude and in geographical coverage) over the Tropics. In the assimilation trials performed, no variational bias correction was implemented for COD. In the joint testing of AOD and COD impact the COD values were limited to the range 0.5 – 10 in order to exclude thick convective clouds where the observed and model COD can differ from each other notably.

The impact of AOD and COD assimilation was verified against several temperature and humidity sensitive observations, including for example Advanced Technology Microwave Sounder (ATMS) and Advanced Microwave Sounding Unit-A (AMSU-A) as well as conventional radiosonde observations. The impact on aerosol optical depth was evaluated against Aeronet AOD observations. The conclusions were that joint assimilation of AOD and COD data has positive impact for aerosols, similar in magnitude to those seen for the operationally assimilated AOD observations in the CAMS system. The impact on the model performance for temperature and humidity was negative, and the result was consistent throughout verification of different observations. However, there was clear positive impact for short-range wind forecasts. This can be a result of the tracer advection effect of the 4D-Var assimilation, e.g. wind fields can be changed to advect humidity to and from other areas.

3. Summary of dust assimilation experiments with the BSC system

This section presents a short summary of the BSC experimentation in the first phase of the project. All details can be found from the final report (Escribano et al., 2024).

The assimilation of SLSTR aerosol optical depth (AOD) v1.14, produced by Swansea University, was implemented into the MONARCH global dust model coupled to a 20-member Local Ensemble Kalman Filter (LETKF). The case of study was the extreme "Godzilla" dust event of June 2020, the same case used by ESA's DOMOS project, so that results could be benchmarked against the DOMOS VIIRS and LIVAS assimilation experiments.

In the first part SLSTR Dust AOD and Coarse AOD products were found to underestimate the dust plume, so total AOD was assimilated instead. Two configurations were tested: a linear model of the observational uncertainty (LIN_UNC) and the pixel-wise uncertainty provided in the SLSTR retrieval (PIX_UNC1). Both improved forecasts and analyses with respect to the free-running control (FR) when compared against AERONET, with skills comparable to the DOMOS VIIRS/LIVAS experiments. PIX_UNC1 produced the best scores but also showed a noisy small-scale pattern over ocean, suggesting that the pixel-wise SLSTR uncertainties were underestimated there and that the analysis overfit the observations.

The second part addressed this overfitting. Desroziers et al. (2005) diagnostics in observation space were applied to the LETKF output and indicated that the R covariance over ocean should be inflated by a factor of 2 to 3 for AOD > 0.4. Three new sensitivity experiments were run on MareNostrum5 with a re-calibrated dust emission factor and inflation factors of 2, 3 and 4 over ocean (PIX_UNC2–PIX_UNC4), in addition to FR, LIN_UNC and PIX_UNC1. Verification against AERONET coarse AOD and AERONET AOD filtered by Ångström exponent showed that all pixel-level experiments outperformed the linear-uncertainty one, that inflation of 2–3 gave the best trade-off between bias, error and correlation, and that the inflated analyses were visibly less noisy. Re-computed diagnostics for the inflation-3 experiment confirmed a more consistent error balance over ocean.

The section concluded with recommendations to CCI data providers: a dedicated dust AOD product from SLSTR with reliable pixel-level uncertainties would directly benefit operational dust data assimilation, and ocean uncertainties should be treated with an inflation factor to account for the representation error inherent to the assimilation system.

4. ESMValTool and the data sets used in evaluation

Numerical models are important tools to improve our understanding of present-day weather and climate and to project climate change under different plausible future scenarios. For this, models are continuously improved and extended resulting in more complex and higher-resolution models. Particularly during the model development phase or when changing the model configuration (e.g. assimilation of new observational products), it is important to continuously monitor how well the model reproduces the observed atmospheric state and to systematically analyze, evaluate, understand, and document possible shortcomings. To effectively evaluate the complex state-of-the-art models, new tools for comprehensive analysis are essential. The opensource community-driven Earth System Model Evaluation Tool (ESMValTool) addresses this critical need by providing a software package for scientists to assess the model performance using common diagnostics and metrics (Righi et al., 2020). In this study, ESMValTool has been extended to allow for processing the output of the ECMWF and MONARCH models directly for comparison with observational data. For this, daily data of AOD at 0.44 and 0.55 µm, dust AOD at 0.55 µm and daily values of cloud liquid and ice water path (LWP, IWP) have been implemented into ESMValTool.

Specifically, the ECMWF experiments testing the assimilation of AOD and COD observations are evaluated against Aeronet v3.0 level 2.0 AOD observations, AEROSOL_CCI AOD observations from Sentinel 3 SLSTR v1.12 provided by Swansea University, liquid and ice water path observations from v3.0 CLARA AVHRR (CM SAF).

5. Impact assessment of the ECMWF experiments

Figure 1 shows the monthly mean aerosol optical depth at 0.44 µm for June 2020, the left panel is for the CTL experiment and the right panel for the AOD+COD experiment. The shading indicates the model fields and the circles are the AOD observations from the Aeronet network. Assimilating the AOD and COD observations into the ECMWF IFS-COMPO system improves the root mean square error (RMSE) for AOD, which decreases from 0.093 to 0.074. Overall, the model fields are in good agreement with the Aeronet AOD observations.

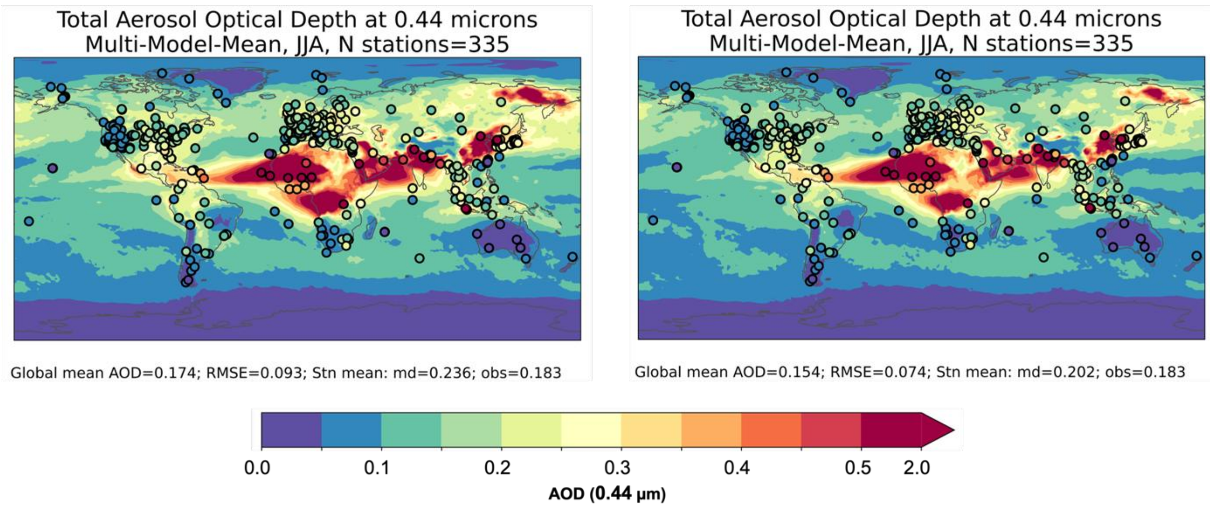

Figure 1: Monthly mean aerosol optical depth at 0.44 µm, the left panel is for the CTL experiment and the right panel for the AOD+COD experiment. The shading indicates the model fields and the circles are the AOD observations from the Aeronet network. Considered period is June 2020.

Figure 2 shows the scatter plots for Aeronet AOD observations on x-axis and model AOD at 0.44 µm on y-axis. The coefficient of determination, R^2, is the proportion of the variation in the dependent variable that is predictable from the independent variable(s). In these experiments it increases from 0.75 to 0.79 when AOD and COD observations are included in the assimilation, indicating improvements in the model AOD fields.

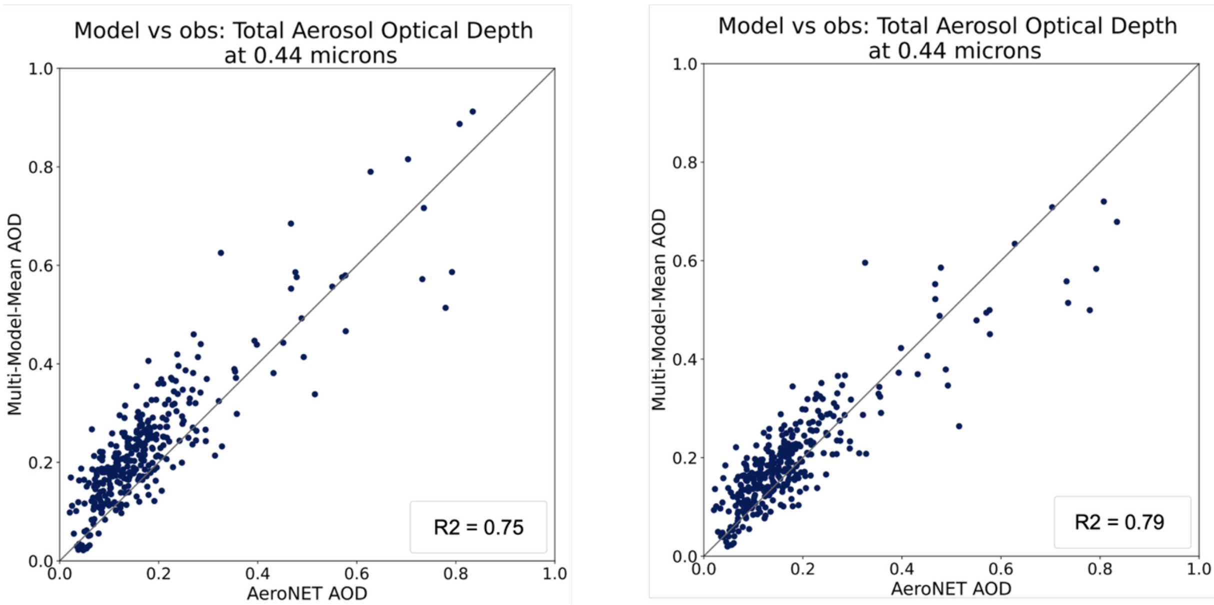

Figure 2: Scatter plots for Aeronet AOD observations on x-axis and model AOD at 0.44 µm on y-axis, left panel is for the CTL experiment and right panel for the AOD+COD experiment. Considered period is June 2020.

Evaluation against AEROSOL_CCI AOD observations is consistent with the Aeronet evaluation results. Figure 3 shows the difference maps between the model monthly mean AOD at 0.55 µm and the ESA AEROSOL_CCI AOD observations, left panel is for the CTL experiment and right panel for the AOD+COD experiment. The RMSE values decrease from 0.0785 in CTL to 0.0713 in AOD-COD and correlation increases from 0.88 to 0.89 indicating improvements from assimilation of the AOD and COD data. It is good to keep in mind though that the ESA AEROSOL_CCI AOD data assimilated (v1.14) is improved version of the data set used in the evaluation (v1.12). Thus, the data used in evaluation is not completely independent and could somewhat exaggerate the improvements.

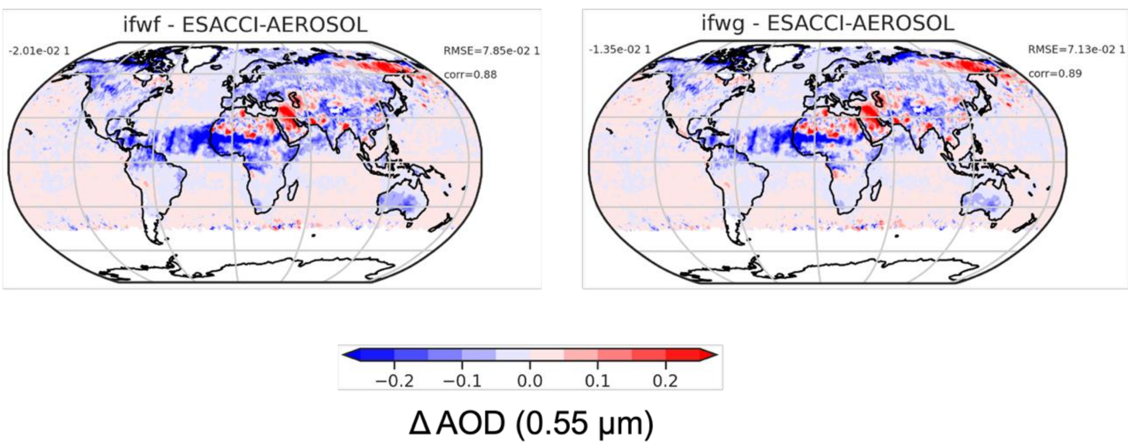

Figure 3: Difference maps between the monthly mean model AOD at 0.55 µm and the ESA AEROSOL_CCI AOD observations, left panel is for the CTL experiment and right panel for the AOD+COD experiment. Considered period is June 2020.

Figure 4 shows monthly mean difference maps (similar to Fig. 3, but for cloud liquid water path (LWP, upper panels) and cloud ice water path (IWP, lower panels) compared with CLARA AHVRR data). The left panels show the CTL, the right panels the AOD+COD experiment. For LWP the RMSE is decreased from 0.0292 kg m^{-2} to 0.0267 kg m^{-2} while for IWP RMSE is increased from 0.0308 kg m^{-2} to 0.0316 kg m^{-2}. I.e. for LWP the results are slightly improved while for IWP there is a small degradation. Maps for the LWP differences show significant negative differences in typical marine stratocumulus areas which are related to known model deficiencies over those regions.

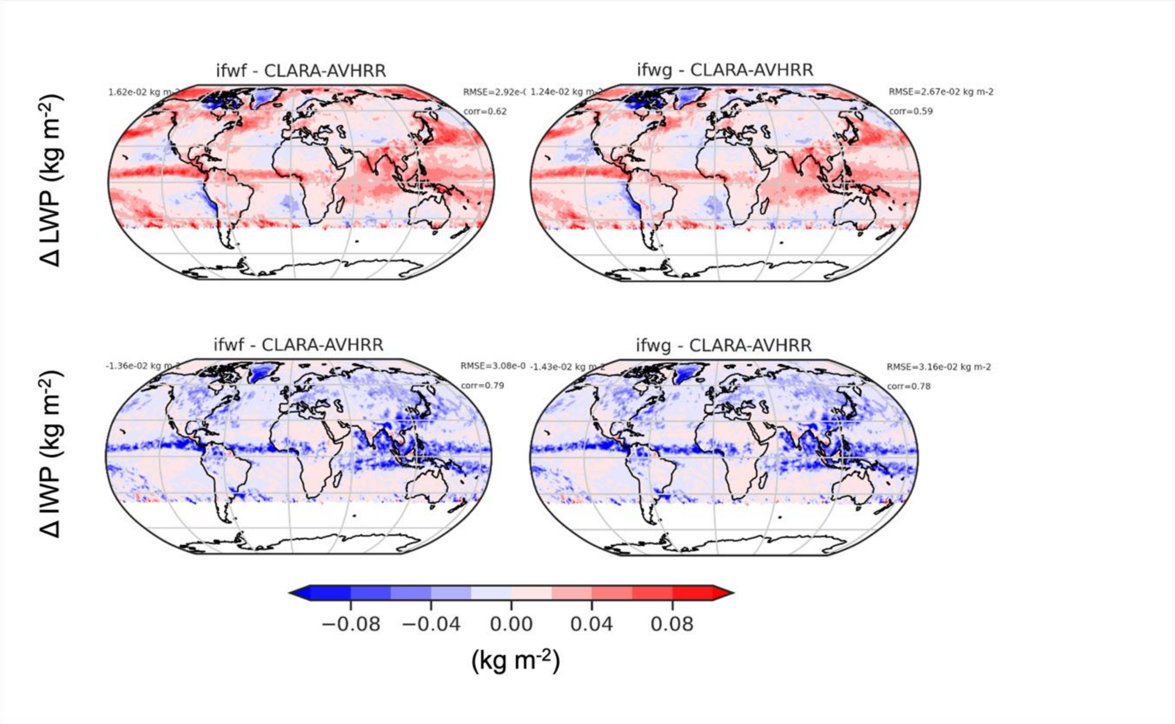

Figure 4: Monthly mean difference maps between the model LWP (top row) and IWP (bottom row) and CLARA-AVHRR v3.0 data, left panel is for the CTL experiment and right panel for the AOD+COD experiment. Considered period is June 2020.

Figure 5 shows the joint distribution of global daily LWP and AOD at 0.55 µm from CLARA AVHRR and ESA AEROSOL_CCI (left panel) in comparison with results from the AOD+COD experiment (middle panel) and the CTL experiment (right panel). The distribution of LWP vs AOD values is closer to observations in the CTL experiment compared to the AOD+COD experiment.

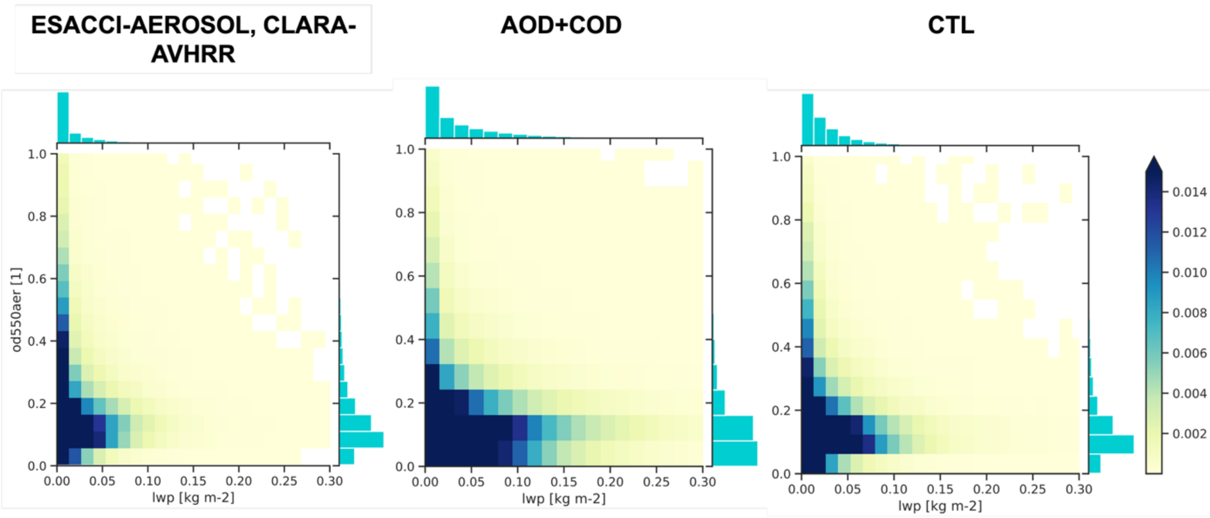

Figure 5: Joint distribution of LWP (x-axis) and AOD values (y-axis) of global daily values from CLARA AVHRR and ESA AEROSOL_CCI (left panel), the AOD+COD experiment (middle panel) and from the CTL experiment (right panel).

6. Impact assessment of the BSC experiments

During the optional phase of WP5.5 monthly averages of dust optical depth from MONARCH have been computed using ESMValTool (Righi et al. 2020). The tool has been extended during OWP5.5 to integrate MONARCH outputs and can now produce maps such as those shown in Figure 6. The original model outputs at 3-hourly frequency are averaged to match the target dataset, which is Dust Optical Depth (DOD) from the SLSTR SU v1.12 (ESA-CCI product) at daily frequency. Model grid points with corresponding missing satellite values are discarded before computing monthly averages. While this is not a fully independent evaluation (SLSTR SU v1.14 total AOD has been assimilated in MONARCH), it provides a view on DA outcome from a different angle (average fields) and it showcases the new possibilities offered by ESMValTool. Figure 6 depicts an average reduction in MONARCH DOD due to DA (top middle map), which is in contrast with the enhancement of DOD within the Godzilla dust plume (Fig. 2 in Escribano et al. 2024). This suggests that on average MONARCH tends to overestimate DOD but underestimated the exceptional Godzilla plume. While the MONARCH analysis is closer to the ESA-CCI DOD (SLSTR SU v1.12) with respect to all metrics (bias, RMSE and correlations), there are reasons to believe that the ESA-CCI DOD underestimates DOD, as already discussed by Escribano et al. 2024. Also important to remind that total AOD has been assimilated in MONARCH, whereas the comparison in Fig. 6 only refers to DOD. Hence, while these results show better consistence between the MONARCH analysis and ESA-CCI product, some further evaluation including additional target datasets would be beneficial.

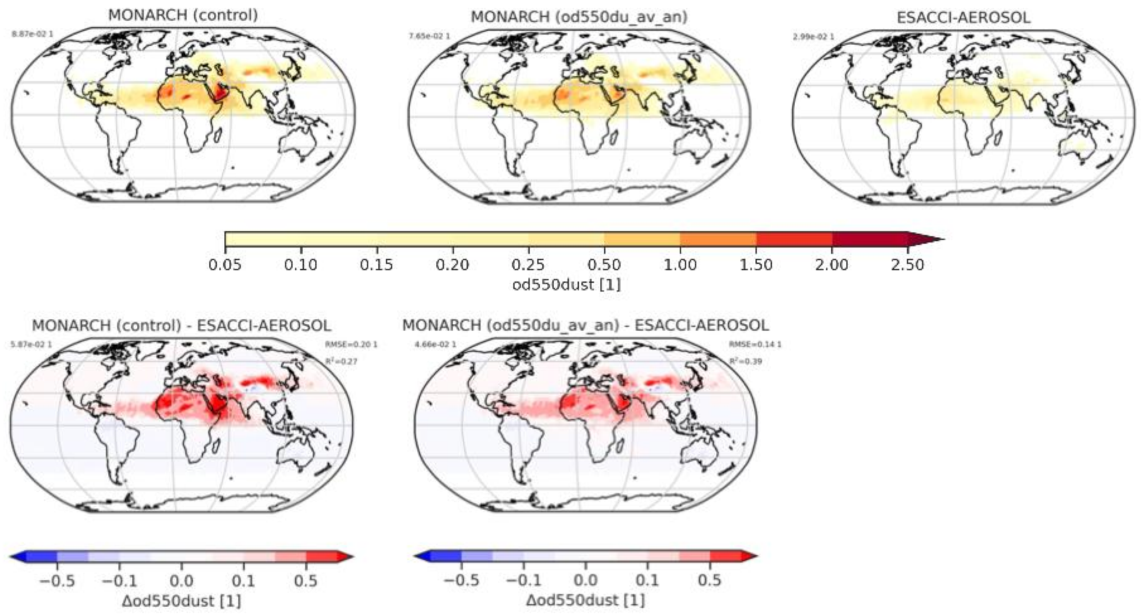

Figure 6: *Monthly averages of dust optical depth (DOD) at 550 nm computed using ESMValTool: MONARCH control simulation (FR experiment in table 2 of Escribano et al. 2024) in the top left map, MONARCH analysis (SLSTR-px3 experiment in table 2 of Escribano et al. 2024) in the top middle map, ESA-CCI (SLSTR SU 1.12) in the top right map. In the bottom: average differences between the control simulation and ESA-CCI (left map), average differences between the analysis and ESA-CCI (middle map). Spatial RMSE and squared correlation (R^2) are displayed on the right of differences maps.*

7. Conclusions

Overall, results from the evaluation of the ECMWF experiments assimilating the ESA CCI AOD and COD observations with ESMValTool is well in line with the results obtained in the first phase of the project and give valuable addition to the impact assessment. There is a positive impact on AOD, the ESA AEROSOL_CCI AOD v1.14 product has good quality and is a mature product ready to be assimilated in models. The results for cloud related observations are more mixed and consistent with the earlier verification, where degradation in temperature and humidity forecasts was found. The degradation originates from assimilating the COD product.

There are several suggestions how the impact of the COD assimilation could be improved from these first trials. First, the quality screening of the data could be made stricter. In these experiments we did not perform sensitivity tests with the first guess check where the observed value is compared to the model counterpart and rejected if they deviate too much. Second, the monitoring statistics indicate significant biases over some areas. Thus, implementing variational bias correction for the COD assimilation could be beneficial. Third, developing more sophisticated observation error model could be beneficial.

The COD product was tested in assimilation for the first time. Thus, no similar maturity can be expected as that of the AOD product. We would suggest focusing on developing further the quality information provided with the data. This includes both the uncertainty estimates which in our understanding are significantly too low in the current version, and the quality flags which now only screen out very few observations and do not improve the fit to the model background. If the COD product is aimed for operational assimilation, also discussions of the data format would be useful. Global observation files covering 24 hours are not optimal without pre-processing in any operational assimilation system as the assimilation windows are typically much shorter.

Results from the evaluation of BSC assimilation experiments with ESMValTool proved to be a useful addition to assess the average impact of SLSTR assimilation on modeled dust. Main conclusions and recommendations remain those found in the first phase of the project (Escribano et al. 2024).

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