C:\Users\User\Desktop\1212.png



Virtual Mobility Grant

Internal HARMONIA report [EXTENDED]

Action number: CA21119

Applicant name: Anna Moustaka

Email: [annamstk@noa.gr](mailto:annamstk@noa.gr)

**Virtual Mobility Details**

Title: Assessment of the CALIOP-CALIPSO retrievals towards estimating dust direct radiative effects in North Africa, Europe and Middle East

Start and end date: 14/07/2023 to 31/08/2023

**Main objective of the VM**

The overarching objective of this project is to assess the dust-induced shortwave (SW) direct radiative effects (DREs) within the Earth-Atmosphere system, under clear skies, via the synergy of the CALIOP-CALIPSO aerosol retrievals and a radiation transfer model (RTM). The study region encompasses the North Africa, Middle East and Europe (NAMEE domain) and the period of interest ranges from 2007 to 2020. A holistic approach involving spaceborne retrievals (CALIOP-CALIPSO, MODIS-Aqua) and ground-based sunphotometric measurements (AERONET) will be developed. Previous studies (e.g., [Kim et al., 2018](https://amt.copernicus.org/articles/11/6107/2018/)) have demonstrated that CALIOP underestimates aerosol optical depth (AOD), particularly in dust-rich areas, attributed to various factors (e.g., lidar ratio). In order to highlight the significance of an appropriate lidar ratio definition, emphasizing on DREs, various dust cases, near the sources (Sahara, Middle East) and over downwind areas (e.g., Mediterranean), will be investigated. For each one of them, the dust AODs, calculated based on the default lidar ratios and the revised values adopted from the DeLiAn database ([Floutsi et al., 2023](https://amt.copernicus.org/articles/16/2353/2023/amt-16-2353-2023-discussion.html)) will be compared against AERONET sun-direct measurements and possibly with satellite observations. At a following step, the CALIPSO dust extinction coefficient profiles will be used as inputs to the libRadtran Radiative Transfer Model (RTM) along with other key parameters.

1 Introduction

Atmospheric aerosols through interaction with the incoming shortwave (SW) and the outgoing longwave (LW) radiation fluxes perturb the radiation budget of the Earth-Atmosphere system, playing a dominant role on the energy budget at the surface, in the atmosphere and at the top of the atmosphere [[Gkikas et al., 2018](https://acp.copernicus.org/articles/18/8757/2018/)]. The quantification of SW radiative effects, defined as shortwave radiative forcing (SWRF), is resolved through numerical simulations which even if they have shown that aerosols, at global scale and over long-term periods, tend to cool the Earth-Atmosphere system, partly counterbalancing the induced planetary warming by the greenhouse gases (GHGs), global climate models continue to give diverging results regarding the SWRF magnitude as it is stated in the latest report of the Intergovernmental Panel on Climate Change [[IPCC, 2013](https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter07_FINAL-1.pdf)]. These uncertainties concerning the current SWRF magnitude and how these effects may change in the future are the source of much of the current unreliability in predicting global change [[Solmon et al., 2008](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008GL035900)].

Since April 2006, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board of Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite has provided new perception of aerosol and clouds interactions, and their roles in the climate system [[Winker et al., 2010](https://journals.ametsoc.org/view/journals/bams/91/9/2010bams3009_1.xml)]. CALIPSO pertains to A-train constellation with Aqua, Aura, CloudSat and PARASOL satellites [[Stephen et al., 2002](https://journals.ametsoc.org/view/journals/bams/83/12/bams-83-12-1771.xml?tab_body=abstract-display)].

The existing CALIOP version 4.10 (V4) level 2 aerosol classification scheme, released in November 2016, utilizes Level-1-layer-intergrated values of depolarization and attenuated backscatter together with external information on geographical location, surface type and layer altitude in order to assign simplified aerosol types. The predominant changes in the V4 tropospheric aerosol subtyping algorithm incorporate the addition of dusty marine aerosol type, for a proper classification of dust and marine aerosol mixtures, the allowance of all aerosol types to be identified in polar regions (in contrast with V3 enabling only clean and polluted continental aerosol subtypes) and the alternative definitions for polluted continental and smoke types [[Kim et al., 2018](https://amt.copernicus.org/articles/11/6107/2018/)].

**2 Data and Methodology**

**2.1 Dataset**

**2.1.1 Aerosol retrievals**

For the purposes of this study, we exploit quality assured (QA) CALIPSO Level 2 (L2) Version 4.2 (V4) vertically resolved retrievals extracted from the LIVAS database [[Amiridis et al., 2015](https://acp.copernicus.org/articles/15/7127/2015/)].

The quality control process ensures the mitigation of the negative impact of: (i) layers misdetection and misclassification, (ii) errors of the extinction retrieval and (iii) biases caused by the negative signal anomaly, on aerosol retrievals. In addition, the possible cloud contamination has been minimized relying on the CAD score and the misclassified cirrus fringe filters [[Tackett et al., 2018](https://amt.copernicus.org/articles/11/4129/2018/),[Proestakis et al., 2018](https://acp.copernicus.org/articles/18/1337/2018/),[Marinou et al., 2017](https://acp.copernicus.org/articles/17/5893/2017/)]. Figure 1 depicts the “transition” from the raw (a) to the filtered (b) CALIOP backscatter coefficient profiles at 532 nm, along with the linear depolarization ratio (raw, c; filtered, d), for an example CALIPSO orbit.

|  |  |
| --- | --- |
| **(a)**  **(c)** | **(b)**  **(d)** |

**Figure 1.** Backscatter coefficient (upper panel) and particle depolarization ratio (bottom panel) for an individual nighttime granule (2019-08-12T00-36-47ZN) demonstrating (a,c) the CALIOP profiles after the application of the basic filters (surface, subsurface, nonQA) and after applying the quality assurance filters (b,d).

AERONET observations of AOD, single scattering albedo (SSA), asymmetry factor (ASYM) and Ångström exponent (AE) are also exploited for the purposes of this study. For the collocation, CALIPSO retrievals residing within a circle, centered at the AERONET site, of 100km radius are spatially averaged, while AERONET observations within a ±30min time window, centered at the CALIPSO overpass, are temporally averaged.

**2.1.2 Radiative transfer model**

For the Radiative Transfer (RT) simulations, in the SW spectral range [280-3000nm], the UVSPEC model from the libRadtran radiative transfer package [[Emde et al., 2016](https://gmd.copernicus.org/articles/9/1647/2016/)] has been used. The RTM inputs consist of the columnar AOD, the vertical profiles of the extinction coefficient at 532nm along with intensive aerosol optical properties (i.e., single scattering albedo, asymmetry parameter and *Ångström* exponent) extracted from the AERONET almucantar retrievals, after collocating ground-based and spaceborne (CALIPSO) observations. Additional parameters such as the surface albedo, ozone and water vapour columnar concentrations are all extracted from the MERRA-2 reanalysis.

In the present study, the clear-sky shortwave direct radiative effects (DREs) at the top of the atmosphere (TOA), within the atmosphere (ATM) and at the Earth's surface (NETSRFC) are calculated based on the following equations.

|  |
| --- |
| (1)  (2) |

**2.2 Region of Interest [ROI]**

The NAMEE (North Africa Middle East Europe) domain is one of the most vulnerable regions to environmental change, hosting a variety of aerosol species of natural and anthropogenic origin (Figure 2a). Dust from Saharan and Arabian deserts, sea salt aerosols (SSA) from Atlantic Ocean, Mediterranean and Red sea, pollution originated from the industrialized cities around Mediterranean and central Europe and smoke aerosols from Sahel, South European countries and Canadian fires, make up the major contributors to the atmospheric aerosol load in this region [[Basart et al., 2009](https://acp.copernicus.org/articles/9/8265/2009/)].

Regarding dust aerosols, North Africa contributes to over than the half global dust emissions [[Ginoux et al., 2012](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012RG000388)] with Bodélé depression characterized as one of the most intense dust sources in the world, while in Middle East the Mesopotamia continent is a well-known source of Asian dust since 1980 [[Middleton, 1986](https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.3370060207?casa_token=tqq0JLPyGF8AAAAA:2oPHHrO6sAm__jg1VJBELeojWhWce4umFr6gNtXNQ8NQfkx3LE_ZDGvuRKH-G-wvWN2NGQJ3gXbxSWzD)]. Contrasting cyclonic circulations prevailing over Mediterranean, Europe and North Africa [[Gkikas et al., 2014](https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.2466?casa_token=5-WYSVFbIuYAAAAA%3AuMNm0ywjcB8XfvvQ3mWTBG4ucItKhyNy4sUSMiUVom4252Fryd_Dm35EEB1uvKoGbCJOGekyDKVDk7ck)] develop ideal wind conditions for Saharan and Asian dust to be conveyed far away from sources. A long-term analysis performed over the ROI highlights

the predominance of dust aerosols among the different aerosol subtypes classified according to the CALIPSO V4 algorithm (see Figure 2b).

Atlantic Ocean, Mediterranean and Red Sea are the main sources of SSA over NAMEE with wind speed playing the key role on their emission [[Sofiev et al., 2011](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010JD014713)]. The sea salt particles are injected into the atmosphere when the wind stress at the ocean surface leads to the formation of bubbles which finally burst.

Over European continent urban aerosols emitted from traffic, industry, or heating, affect the air quality while the prevailing meteorological conditions allow pollutants to travel in a local or regional extent [[Wang et al., 2019](https://acp.copernicus.org/articles/19/13097/2019/)]. Central Europe is highly influenced by long-range transported smoke particles from North America while major hot spots of fire events are concentrated over Eastern Europe and Iberian Peninsula especially in summer months. Smoke layers from Central African fires are generally restricted to African regions (i.e. Nigeria, Ivory Coast, Guinea Gulf etc.) and to lesser extent to regions around South-West Europe since their buoyancy is not sufficient to inject a considerable amount of biomass burning aerosols over the planetary boundary layer (PBL) and, by extension, to travel longer distances [[Groβ et al., 2017](https://www.tandfonline.com/doi/abs/10.1111/j.1600-0889.2011.00556.x)].

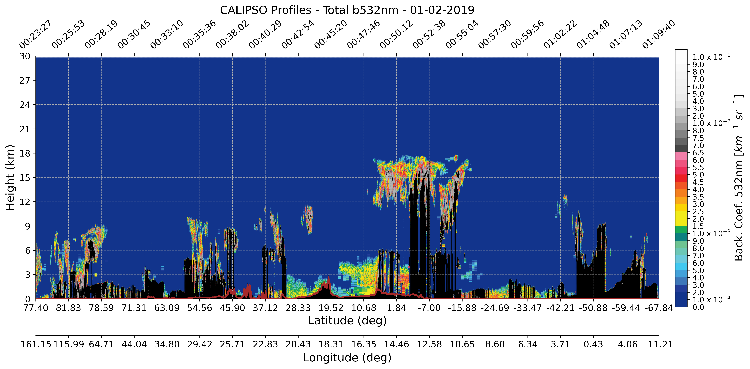
|  |  |
| --- | --- |
|  |  |
| (**a**) | (**b**) |

**Figure 2.** (**a**) Geographical limits of the NAMEE domain; (**b**) Frequency of occurrence for each aerosol subtype according to the existing CALIOP V4 classification scheme.

**3 Results**

**3.1 Evaluation of the CALIOP-CALIPSO retrievals**

Errors in the CALIPSO product can largely be attributed to either the mistyping of aerosol layers or the incorrect modelling of aerosol microphysics for particular types, which can result in large underestimations of the order of 13% in terms of AOD, as reported by [[Schuster et al., 2012](https://acp.copernicus.org/articles/12/7431/2012/)] for the previous CALIPSO version (V3). A significant source of uncertainty arises also from the limitation of CALIPSO algorithm to identify tenuous aerosol layers, while opaque cloud or aerosol layers significantly weaken or even cancel the transmission of the signal, making the detection of the layers below them infeasible (see Figure 3). This effect is clearly shown in Figure 3 with an opaque cloud layer totally diminishing all the features of lowermost aerosol layers (dashed line).

****

**Figure 3.** CALIOP observation oftotal attenuated backscatter at 532nm (2019-02-01T00-23-28ZN).

Concerning mistyping uncertainty, a recent evaluation study [[Gui et al., 2022](https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.7599?casa_token=0zWxTNCjA8QAAAAA%3A-BPpQVdGw8E-5LONL3CzkvFPm4gF2FZXYJTmRrNQAiYWHYQj7s7q6gOb1nlNmSlOxmradLOLxK2FzbF3)], performed over East Asia for the years 2007-2019, revealed that in respect to MODIS AOD the latest version (V4) of CALIOP retrievals tend to overestimate aerosol loadings over the deserts and underestimate those in polluted regions such as northern China. Other studies have pointed out similar discrepancies versus ground-based reference measurements [[Kim et al., 2018](https://amt.copernicus.org/articles/11/6107/2018/)]. A comparison of the CALIPSO AOD versus AERONET (Fig. 4a) and MODIS-Aqua (Fig. 4b) has been performed. Overall, CALIPSO tends to underestimate AOD and the negative biases against AERONET increase as the intensity of aerosol loads increases (Fig. 4a). Biases against MODIS are highly distinguishable over the Saharan desert and specifically over well-known dust sources (e.g. Bodélé), an inadequacy strongly related to the presence of opaque dust layers completely attenuating the laser beam. Above seas, the negative CALIPSO-MODIS declinations are found in dust downwind regions. Slightly positive and negative differences are recorded in the central and northern Europe, respectively.

|  |  |
| --- | --- |
|  |  |
| (**a**) | (**b**) |

**Figure 4.** Comparison of CALIPSO AOD with(**a**) AERONET and (**b**) MODIS AOD, respectively.

|  |  |
| --- | --- |
| C:\Users\User\Desktop\1.png | **C:\Users\User\Desktop\2.png** |
| (**a**) | (**b**) | |

Regarding the aerosol classification error, the validation effort of [[Burton et al., 2013](https://amt.copernicus.org/articles/6/1397/2013/)] reported a very good agreement for dust, in contrast to polluted dust and smoke (one of the most absorbing aerosol types), while moderate level of agreement was found for marine and polluted continental. In polar regions, dust from Asian desserts [[Gui et al., 2022](https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.7599?casa_token=0zWxTNCjA8QAAAAA%3A-BPpQVdGw8E-5LONL3CzkvFPm4gF2FZXYJTmRrNQAiYWHYQj7s7q6gOb1nlNmSlOxmradLOLxK2FzbF3)] and smoke from Canadian wildfire smoke events [[Haarig et al., 2018](https://acp.copernicus.org/articles/18/11847/2018/)] were forced to be classified as either clean continental or polluted continental, the only aerosol subtypes allowed over snow, ice, or tundra. Layers of smoke at the bases of elevated smoke plumes were classified as clean marine [[Nowottnick et al., 2015](https://amt.copernicus.org/articles/8/3647/2015/)]. Comparison of the magnitude and spatial distribution of clean and dusty marine aerosols clarified that some dusty marine samples should be classified as marine [[Li et al., 2022](https://amt.copernicus.org/articles/15/2745/2022/)].

**Figure 5.** CALIPSO observations of V4 aerosol subtype product with (a) marine layers likely classified falsely as dusty marine and polluted continental smoke and (b) polluted continental/smoke layers identified as dust, respectively.

**3.2 Case studies**

For the derivation of the extinction coefficient and the columnar AOD it is required a Lidar Ratio (LR) (i.e., the ratio of extinction to backscatter), which is predefined for each aerosol type classified in the CALIPSO retrieval scheme. In order to examine the validity of the LRs used in CALIOP V4 retrievals we focus initially on dust cases using in parallel LRs adapted from the DeLiAn database [[Floutsi et al., 2023](https://amt.copernicus.org/articles/16/2353/2023/amt-16-2353-2023-discussion.html)].

**3.2.1 Saharan dust**

In Figure 6, pure dust layers extended over El Farafra, Lampedusa and IER Cinzana are presented. The respective attenuated backscatter at 532 nm is averaged along the orbits and the extinction coefficients are calculated with the CALIPSO default LR for dust (44 sr) (red line) and the revised Saharan dust LR from the DeLiAn database (53 sr) (green line). For the computation of AOD the extinction coefficient at 532nm is integrated for both LRs and the results are compared with the respective AERONET AODs temporally averaged for different time windows (±15, ±30, ±45 and ±60 minutes with respect to the satellite overpass). Thanks to the utilization of the revised dust LR, the bias against AERONET AODs is reduced by ~20%.

|  |  |
| --- | --- |
|  |  |
| (**a**) | (**b**) |
| C:\Users\User\Desktop\Lampedusa_LIVAS_CALIPSO_L2_Orbit_2012-07-10T11-59-33ZD.png | C:\Users\User\Desktop\Calipso_ATLANTAS_Orbitary_Analysis\Dust_cases\Lampedusa_LIVAS_CALIPSO_L2_Orbit_2012-07-10T11-59-33ZD.png |
| (**c**) | (**d**) |
| C:\Users\User\Desktop\IER_Cinzana_LIVAS_CALIPSO_L2_Orbit_2011-06-22T13-38-39ZD.png | **C:\Users\User\Desktop\output.png** |
| (**e**) | (**f**) |

**Figure 6.** CALIPSO overpass from (a) El\_Farafra, (c) Lampedusa, (c) IER\_Cinzana stations and (b,d,f) the respective observations of V4 aerosol subtype product, Total attenuated backscatter coefficient 532 nm and the Extinction coefficient 532 nm along with the corresponding AOD.

**3.2.2 Middle Eastern dust**

Respectively, pure dust layers extended over El Farafra, Lampedusa and IER Cinzana are presented (Figure). The extinction coefficients are calculated with the CALIPSO default LR for dust (44 sr) (red line) and the revised Middle Eastern dust LR from the DeLiAn database (37.4 sr) (green line). Thanks to the utilization of the revised dust LR, the bias against AERONET AODs is effectively reduced.

|  |  |
| --- | --- |
| C:\Users\User\Desktop\Kuwait_University_LIVAS_CALIPSO_L2_Orbit_2009-05-28T09-54-42ZD.png | C:\Users\User\Desktop\kuwait_uni.png |
| (**a**) | (**b**) |
| C:\Users\User\Desktop\KAUST_Campus_LIVAS_CALIPSO_L2_Orbit_2014-04-09T10-29-43ZD.png | C:\Users\User\Desktop\kaust_campus.png |
| (**c**) | (**d**) |
| C:\Users\User\Desktop\Technion_Haifa_IL_LIVAS_CALIPSO_L2_Orbit_2017-05-10T10-38-14ZD.png | C:\Users\User\Desktop\technion_haifa.png |
| (**e**) | (**f**) |

**Figure 7.** CALIPSO overpass from (a) Kuwait\_University, (c) KAUST\_Campus, (c) Technion\_Haifa\_IL stations and (b,d,f) the respective observations of V4 aerosol subtype product, Total attenuated backscatter coefficient 532 nm and the Extinction coefficient 532 nm along with the corresponding AOD.

**3.3 RTM analysis**

**Table 1.** UVSPEC model input parameters.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Station** | **SZA** | **AOD**  **[532]** | **SSA** | **ASYM** | **AE**  **[440-870]** | **TCWV**  **[mm/cm2]** | **TCO**  **[DU]** | **ALBEDO** |
| El\_Farafra | 36.75 | 0.223/0.269\* | 0.94 | 0.72 | 0.15 | 20.46 | 272.96 | 0.30 |
| Lampedusa | 20.82 | 0.303/0.365 | 0.94 | 0.72 | 0.14 | 23.32 | 285.82 | 0.07 |
| IER\_Cinzana | 24.66 | 0.550/0.663 | 0.94 | 0.72 | 0.12 | 44.39 | 280.61 | 0.15 |
| Kuwait\_University | 22.98 | 0.704/0.599 | 0.94 | 0.72 | 0.51 | 18.96 | 277.73 | 0.22 |
| KAUST\_Campus | 26.85 | 0.491/0.417 | 0.94 | 0.72 | 0.21 | 36.71 | 264.85 | 0.17 |
| Technion\_Haifa\_IL | 25.34 | 0.278/0.236 | 0.94 | 0.72 | 0.35 | 15.98 | 307.6 | 0.09 |

\* **V4LR/revLR**

According to Figure 8, dust aerosols cause a large surface cooling and an atmospheric heating effect. These effects are strongest (DRESURFNET down to -79.8 W/m2 and DREATM up to 70.6 W/m2) at the station of Kuwait University and IER Cinzana respectively, where the AOD takes its maximum values. Moreover, the DREs are more pronounced in Lampedusa and KAUST Campus compared to El Farafra and Technion Haifa, due to the presence of higher aerosol loads. Besides aerosol load, DREATM is also strongly affected by surface albedo, because higher values result in an increase of the reflected solar radiation at the ground thus increasing the atmospheric absorption.

|  |  |  |
| --- | --- | --- |
| **C:\Users\User\Desktop\libRadtran\dust_cases\RTM_figures_dust_cases_SaharanDustLR\DREs_Bar_plots\LIVAS_CALIPSO_L2_Orbit_2014-09-26T11-03-31ZD.png(a)** | **C:\Users\User\Desktop\libRadtran\dust_cases\RTM_figures_dust_cases_SaharanDustLR\DREs_Bar_plots\LIVAS_CALIPSO_L2_Orbit_2012-07-10T11-59-33ZD.png(b)** | **C:\Users\User\Desktop\libRadtran\dust_cases\RTM_figures_dust_cases_SaharanDustLR\DREs_Bar_plots\LIVAS_CALIPSO_L2_Orbit_2011-06-22T13-38-39ZD.png(c)** |
| **C:\Users\User\Desktop\libRadtran\dust_cases\RTM_figures_dust_cases_MiddleEasternDustLR\DREs_Bar_plots\LIVAS_CALIPSO_L2_Orbit_2009-05-28T09-54-42ZD.png(d)** | **C:\Users\User\Desktop\libRadtran\dust_cases\RTM_figures_dust_cases_MiddleEasternDustLR\DREs_Bar_plots\LIVAS_CALIPSO_L2_Orbit_2014-04-09T10-29-43ZD.png(e)** | **C:\Users\User\Desktop\libRadtran\dust_cases\RTM_figures_dust_cases_MiddleEasternDustLR\DREs_Bar_plots\LIVAS_CALIPSO_L2_Orbit_2017-05-10T10-38-14ZD.png(f)** |

**Figure 8.** Dust DREs at the top of the atmosphere (TOA), in the atmosphere (ATM) and at the surface (SRFC) over (a) El\_Farafra, (b) Lampedusa, (c) IER\_Cinzana, (d) Kuwait\_University, (e) KAUST\_Campus and (f) Technion\_Haifa\_IL stations, with the green and red colors denoting the different AODs used in RT simulations (red-with CALIPSO default LR and green-with LR from DeLiAn database).

The role of the underlying surface albedo is crucial for the determination of the sign and the magnitude of the aerosol-induced DRE at TOA (planetary effect). According to our results, dust causes a planetary cooling effect over the 5 stations (surface albedo ranging from 0.07 and 0.22), while over El\_ Farafra the multiple scattering between the relatively absorbing dust particles and the underlying highly reflective surface (surface albedo 0.30) results in a planetary warming effect (positive sign of the DRETOA). We also found that the employment of the AOD computed with the revised dust LR (DeLiAn database) in the DRE calculations leads to an enhancement and diminution of the surface cooling and atmospheric warming effects by up to ~22% in Saharan and Middle eastern dust cases, respectively.

**4 Conclusions**

According the results of this VM, CALIOP underestimates AOD with respect to AERONET sunphotometers, whereas via the intercomparison against MODIS-Aqua it is revealed that maximum and moderate negative biases are recorded in dust sources and dust downwind areas, respectively. Such deficiencies are expected to affect the estimations of the induced direct radiative effects. Representative case studies for dust layers are examined due to the predominance of this type among other aerosol species. An adaptation of a more realistic dust LR selection scheme improves the level of agreement with ground-based observations. Such corrections, among others, will strengthen the reliability of the estimated aerosol direct radiative effects relying on the synergy of CALIOP-CALIPSO aerosol retrievals and radiative transfer models. For the same case studies, dust DREs at TOA, in the atmosphere and at the SRFC are computed using the default CALIPSO dust lidar ratio (44 sr) and the corresponding value from the DeLiAn database (53 and 37.4 sr, for Saharan and Middle eastern dust, respectively). This analysis has also been implemented for different aerosol scenes while at a next step, the simulated radiation fields at TOA and at the surface will be evaluated against satellite (CERES) and ground-based (BSRN, GEBA) observations, respectively.

**References**

Gkikas, A., Obiso, V., Perez Garcia-Pando, C., Jorba, O., Hatzianastassiou, N., Vendrell, L., Basart, S., Solomos., S., Gásso, S. & Baldasano, J. M. Direct radiative effects during intense Mediterranean desert dust outbreaks. *Atmospheric Chemistry and Physics* **2018**, *18*(12), 8757-8787.

IPCC: Summary for Policymakers, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., *Cambridge University Press* **2013**, Cambridge, UK and New York, NY, USA.

Solmon, F., Mallet, M., Elguindi, N., Giorgi, F., Zakey, A., & Konaré, A. Dust aerosol impact on regional precipitation over western Africa, mechanisms and sensitivity to absorption properties. *Geophysical Research Letters* **2008**, *35*(24)

Winker, D. M., Pelon, J., Coakley Jr, J. A., Ackerman, S. A., Charlson, R. J., Colarco, P. R., Flamant, P., Fu, Q., Hoff, R.M., Kittaka, C., Kubar, T.L., Le Treut, H., Mccormick, M.P., Mégie, G., Poole, L., Powell, K., Trepte, C., Vaughan, M.A. & Wielicki, B. A. The CALIPSO mission: A global 3D view of aerosols and clouds. *Bulletin of the American Meteorological Society* **2010**, *91*(9), 1211-1230.

Stephen, G. L. The CloudSat mission and the A-Train.-A new dimension of space-based observations of clouds and precipitation. *Bull. Amer. Meteor. Soc.* **2002**, *83*, 1771-1790.

Kim, M. H., Omar, A. H., Tackett, J. L., Vaughan, M. A., Winker, D. M., Trepte, C. R., Hu, Y., Liu, Z., Poole, L.R., Pitts, M.C., Kar, J. & Magill, B. E. The CALIPSO version 4 automated aerosol classification and lidar ratio selection algorithm. *Atmospheric measurement techniques* **2018**, *11*(11), 6107-6135.

Amiridis, V., Marinou, E., Tsekeri, A., Wandinger, U., Schwarz, A., Giannakaki, E., Mamouri, R., Kokkalis, P., Binietoglou, I., Solomos, S., Herekakis, T., Kazadzis, S., Gerasopoulos, E., Proestakis, E., Kottas, M., Balis, D., Papayannis, A., Kontoes, C., Kourtidis, K., Papagiannopoulos, N., Mona, L., Pappalardo, G., Le Rille, O. & Ansmann, A. LIVAS: a 3-D multi-wavelength aerosol/cloud database based on CALIPSO and EARLINET, *Atmos. Chem. Phys.* **2015**, *15*, 7127–7153.

Tackett, J. L., Winker, D. M., Getzewich, B. J., Vaughan, M. A., Young, S. A., and Kar, J. CALIPSO lidar level 3 aerosol profile product: version 3 algorithm design, *Atmos. Meas. Tech.* **2018**, *11*, 4129–4152.

Proestakis, E., Amiridis, V., Marinou, E., Georgoulias, A. K., Solomos, S., Kazadzis, S., Chimot, J., Che, H., Alexandri, G., Binietoglou, I., Daskalopoulou, V., Kourtidis, K. A., de Leeuw, G., and van der A, R. J. Nine-year spatial and temporal evolution of desert dust aerosols over South and East Asia as revealed by CALIOP, *Atmos. Chem. Phys.* **2018**, *18*, 1337–1362.

Marinou, E., Amiridis, V., Binietoglou, I., Tsikerdekis, A., Solomos, S., Proestakis, E., Konsta, D., Papagiannopoulos, N., Tsekeri, A., Vlastou, G., Zanis, P., Balis, D., Wandinger, U., and Ansmann, A. Three-dimensional evolution of Saharan dust transport towards Europe based on a 9-year EARLINET-optimized CALIPSO dataset, *Atmos. Chem. Phys.* **2017**, *17*, 5893–5919.

Basart, S., Pérez, C., Cuevas, E., Baldasano, J. M., and Gobbi, G. P. Aerosol characterization in Northern Africa, Northeastern Atlantic, Mediterranean Basin and Middle East from direct-sun AERONET observations, *Atmos. Chem. Phys.* **2009**, *9*, 8265–8282.

Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., & Zhao, M. Global‐scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Reviews of Geophysics* **2012**, *50*(3).

Middleton, N. J. A geography of dust storms in South‐west Asia. *Journal of Climatology* **1986**, *6*(2), 183-196.

Gkikas, A., Houssos, E. E., Lolis, C. J., Bartzokas, A., Mihalopoulos, N., & Hatzianastassiou, N. Atmospheric circulation evolution related to desert‐dust episodes over the Mediterranean. *Quarterly Journal of the Royal Meteorological Society* **2015**, *141*(690), 1634-1645.

Sofiev, M., Soares, J., Prank, M., de Leeuw, G., & Kukkonen, J. A regional‐to‐global model of emission and transport of sea salt particles in the atmosphere. *Journal of Geophysical Research: Atmospheres* **2011**, *116*(D21).

Monahan, E. C. The ocean as a source for atmospheric particles, *Springer Netherlands* **1986**, 129-163.

Wang, D., Szczepanik, D., & Stachlewska, I. S. Interrelations between surface, boundary layer, and columnar aerosol properties derived in summer and early autumn over a continental urban site in Warsaw, Poland. *Atmospheric Chemistry and Physics* **2019**, *19*(20), 13097-13128.

Groß, S., Tesche, M., Freudenthaler, V., Toledano, C., Wiegner, M., Ansmann, A., Althausen, D., and Seefeldner, M. Characterization of Saharan dust, marine aerosols and mixtures of biomass-burning aerosols and dust by means of multi-wavelength depolarization and Raman lidar measurements during SAMUM–2, *Tellus B* **2011**, *63*, 706–724.

Schuster, G. L., Vaughan, M., MacDonnell, D., Su, W., Winker, D., Dubovik, O., Lapyonok, T., and Trepte, C. Comparison of CALIPSO aerosol optical depth retrievals to AERONET measurements, and a climatology for the lidar ratio of dust, *Atmos. Chem. Phys.* **2012**, *12*, 7431–7452.

Burton, S. P., Ferrare, R. A., Vaughan, M. A., Omar, A. H., Rogers, R. R., Hostetler, C. A., & Hair, J. W. Aerosol classification from airborne HSRL and comparisons with the CALIPSO vertical feature mask. *Atmospheric Measurement Techniques* **2013**, *6*(5), 1397-1412.

Gui, L.; Tao, M.; Wang, Y.; Wang, L.; Chen, L.; Lin, C.; Tao, J.; Wang, J.; Yu, C. Climatology of aerosol types and their vertical distribution over East Asia based on CALIPSO lidar measurements, *Int. J. Clim.* **2022**, *42*, 6042–6054

Haarig, M., Ansmann, A., Baars, H., Jimenez, C., Veselovskii, I., Engelmann, R., and Althausen, D. Depolarization and lidar ratios at 355, 532, and 1064 nm and microphysical properties of aged tropospheric and stratospheric Canadian wildfire smoke, *Atmos. Chem. Phys.* **2018**, *18*, 11847–11861.

Nowottnick, E. P., Colarco, P. R., Welton, E. J., and da Silva, A. Use of the CALIOP vertical feature mask for evaluating global aerosol models, *Atmos. Meas. Tech.* **2015**, *8*, 3647–3669.

Li, Z., Painemal, D., Schuster, G., Clayton, M., Ferrare, R., Vaughan, M., Josset, D., Kar, J., and Trepte, C. Assessment of tropospheric CALIPSO Version 4.2 aerosol types over the ocean using independent CALIPSO–SODA lidar ratios, *Atmos. Meas. Tech.* **2022**, *15*, 2745–2766.

Floutsi, A. A., Baars, H., Engelmann, R., Althausen, D., Ansmann, A., Bohlmann, S., Heese, B., Hofer, J., Kanitz, T., Haarig, M., Ohneiser, K., Radenz, M., Seifert, P., Skupin, A., Yin, Z., Abdullaev, S. F., Komppula, M., Filioglou, M., Giannakaki, E., Stachlewska, I. S., Janicka, L., Bortoli, D., Marinou, E., Amiridis, V., Gialitaki, A., Mamouri, R.-E., Barja, B., and Wandinger, U. DeLiAn – a growing collection of depolarization ratio, lidar ratio and Ångström exponent for different aerosol types and mixtures from ground-based lidar observations, *Atmos. Meas. Tech.* **2022**, *16*, 2353–2379.