EarthCARE 2026 Science and Validation workshop

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Quantifying atmospheric aerosols using EarthCARE

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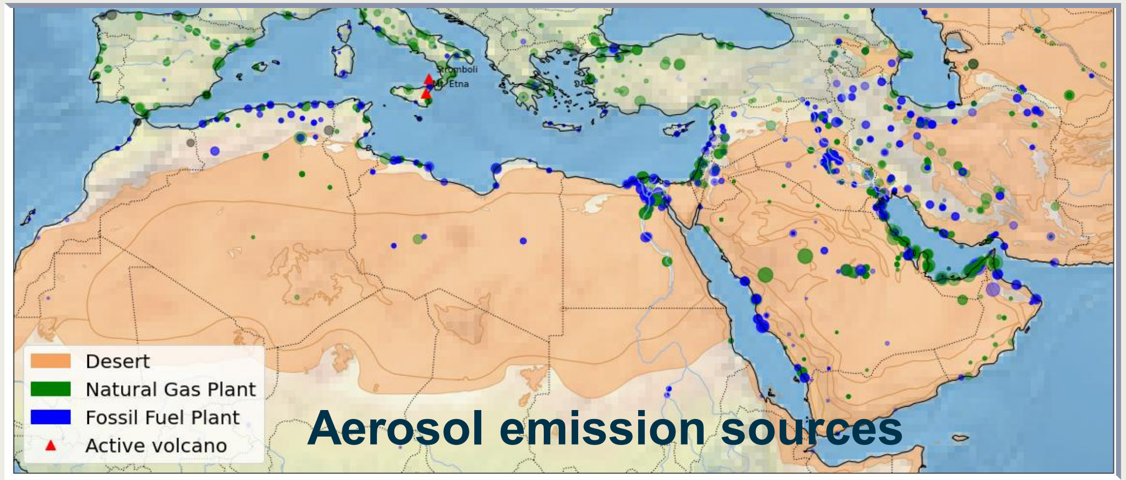
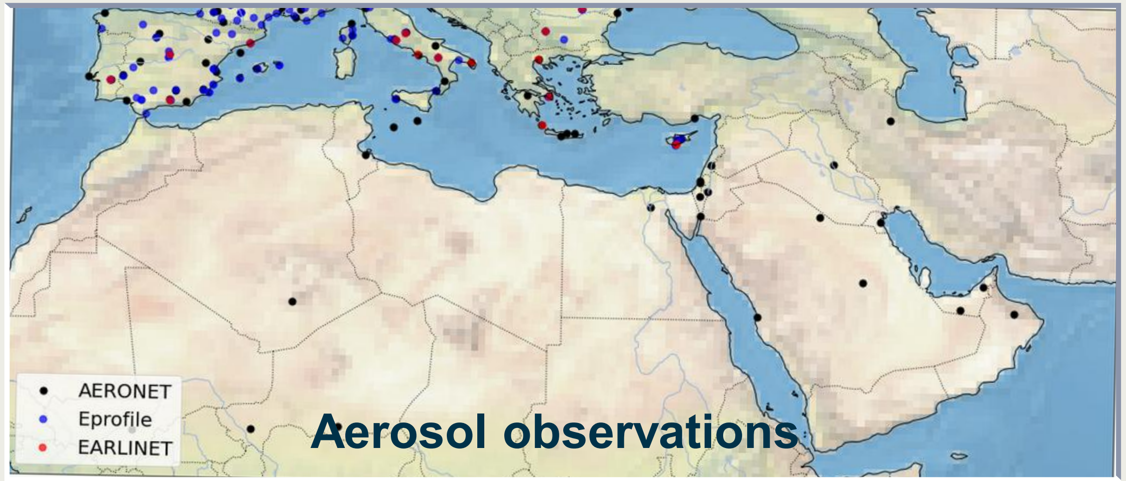
Observational gaps in the context of EarthCARE

- Limited observations of the vertical distribution of aerosols (specially near the source regions).
- Dominated by column-integrated observations (e.g. AOD).

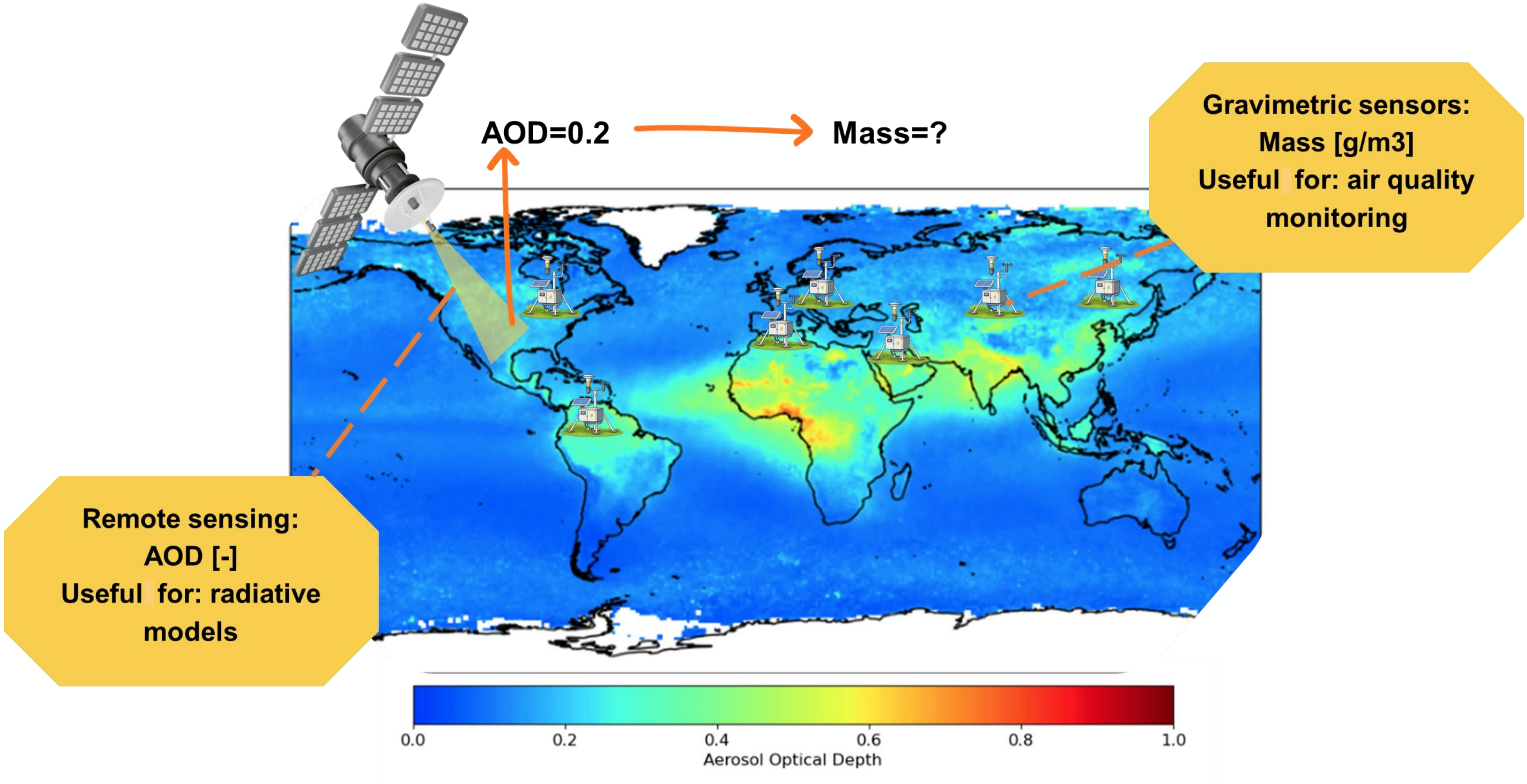
- Uncertainty on aerosol composition and mixing
- Super-coarse dust particles are often neglected (in models and in observations).
- Irregular dust and volcanic ash particle shapes are often not accounted for (the sphere is an easier shape).

- Uncertainties in linking optical and mass-based metrics.

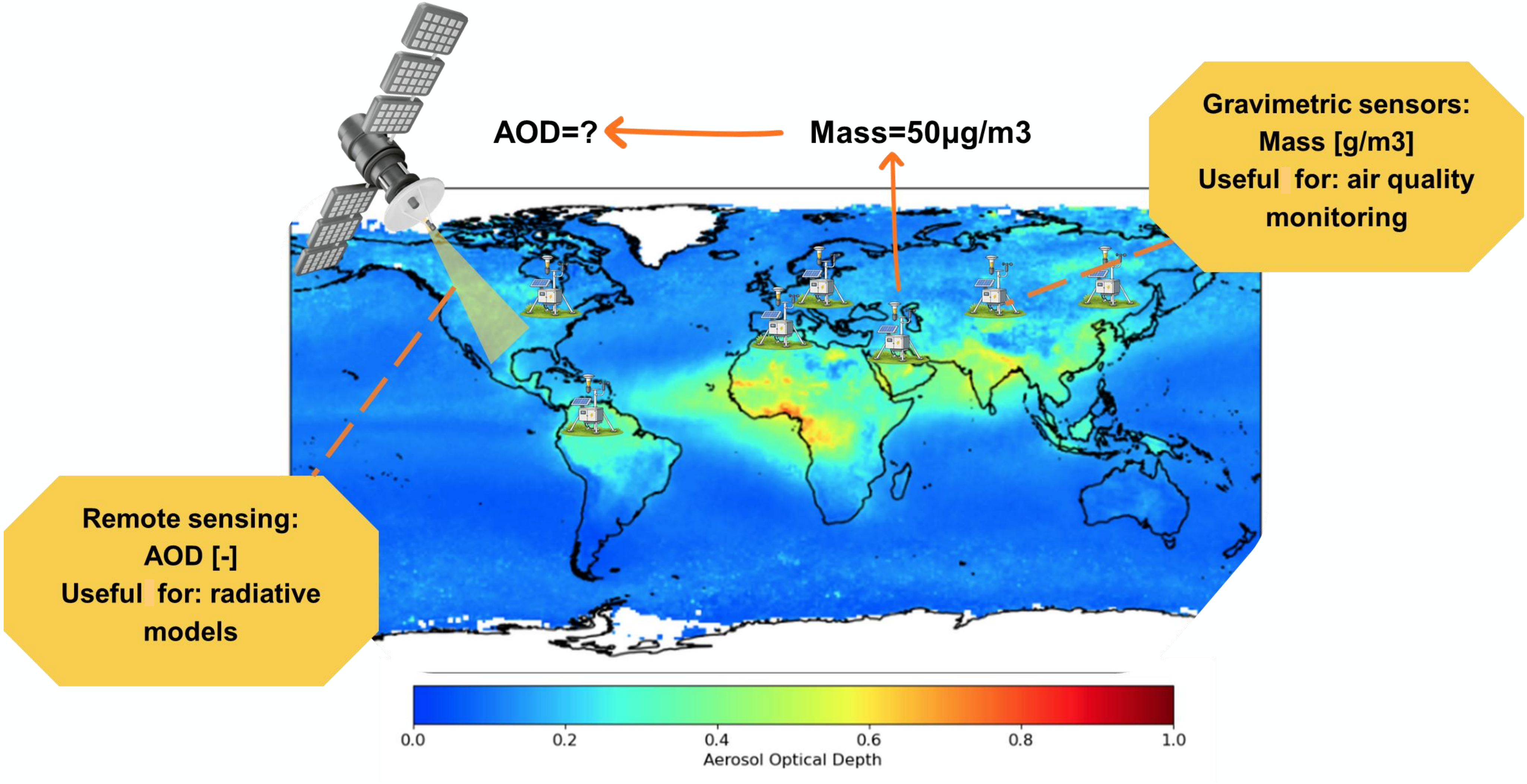




Uncertainties in linking optical and mass-based metrics



Uncertainties in linking optical and mass-based metrics



Understanding the specific extinction

$\alpha = M \cdot K_{\text{ext}}$

α = aerosol extinction (m^{-1}), M = aerosol concentration ($g\ m^{-3}$),

K_{ext} = extinction per unit mass ($m^2\ g^{-1}$)

$K_{\text{ext}} = \frac{1}{\rho \cdot \zeta}$

$$K_{\text{ext}} = \frac{3}{4} \cdot \frac{\overline{Q_{\text{ext}}}}{\rho \cdot \psi \cdot r_{\text{eff}}}$$

ρ = particle density ($g\ cm^{-3}$), ζ = volume-to-extinction ratio (μm)

$\zeta = \frac{4\, \psi\, r_{\text{eff}}}{3\, \overline{Q_{\text{ext}}}}$

ψ = sphericity (ψ=1 for spheres, ψ<1 for irregular particles)

ψ ≈ (aspect ratio)$^{-1/2}$ for certain shapes (= for ellipsoids)

$r_{\text{eff}} = \frac{\langle r^3 \rangle}{\langle r^2 \rangle} = \frac{3\, V}{4\, A_p}$

r_{eff} = effective radius, V = volume, A_p = projected area

$Q_{\text{ext}} = \frac{\sigma_{\text{ext}}}{A_p}$

Q_{ext} = extinction efficiency, σ_{ext} = extinction cross-section (m^2)

Papetta *et al*, Volume-to-extinction ratio: an important property of dust, https://doi.org/10.5194/acp-26-2055-2026 (2026).

Airborne lidar observations of volcanic ash

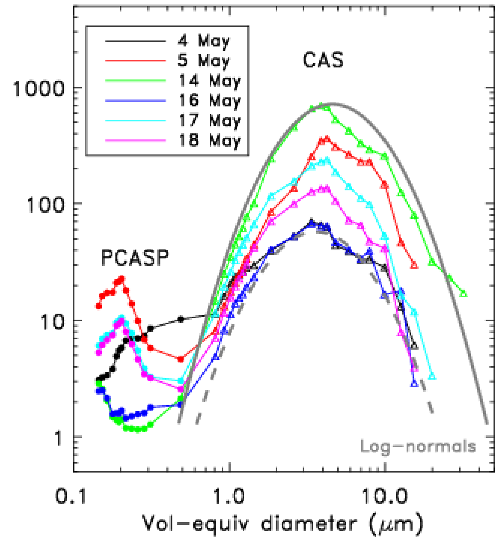
FAAM (2010)

Table 2. Per-Flight Estimate of Microphysical Parameters at 355 nm, Deduced From the Observed Size Distributions[a]

Date	Mie		Irregular	
	f_c	K_{ext} (m^2/g)	f_c	K_{ext} (m^2/g)
4 May	0.45	0.70	0.52	0.92
5 May	0.65	0.47	0.72	0.65
14 May	0.96	0.45	0.97	0.62
16 May	0.72	0.62	0.78	0.82
17 May	0.77	0.53	0.82	0.72
18 May	0.69	0.55	0.75	0.74

[a]Shown are coarse particle extinction fraction (f_c) and coarse particle specific extinction (K_{ext}), computed for the spherical (Mie) and irregular ash particle shapes. The values for irregular particles are used throughout this work, and the Mie scattering values are given for a comparison.

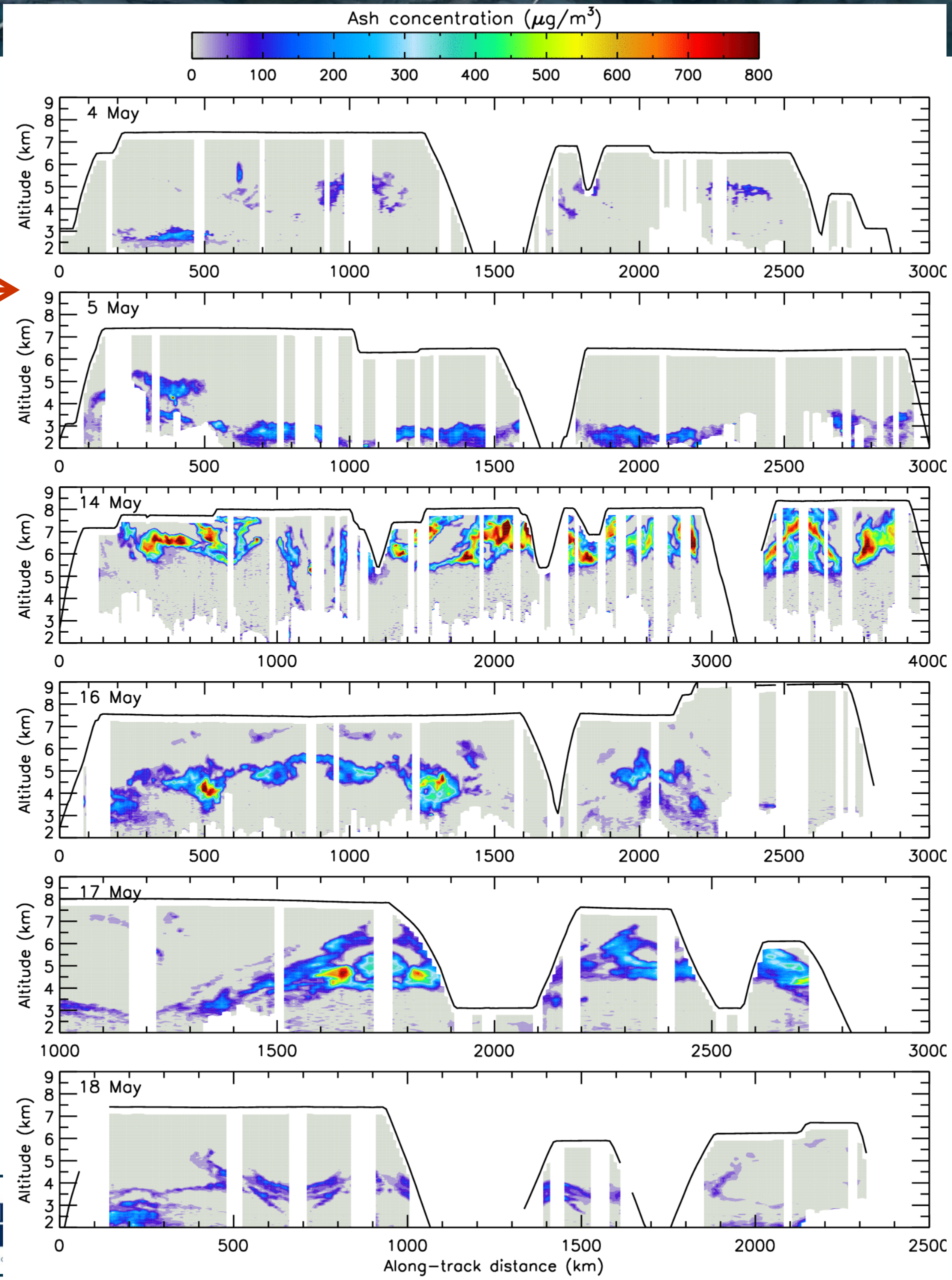
courtesy of B. Johnson (MO), and J. Dorsey + M. Gallagher (University of Manchester)



$$M = \frac{f_c \, \alpha}{K_{ext}}$$

Marenco et al, Airborne lidar observations of the 2010 Eyjafjallajökull volcanic ash plume, *J. Geophys. Res.* **116**, D00U05, doi: 10.1029/2011JD016396 (2011).

Uncertainty: ~ factor of 2



Deriving the specific extinction from AERONET

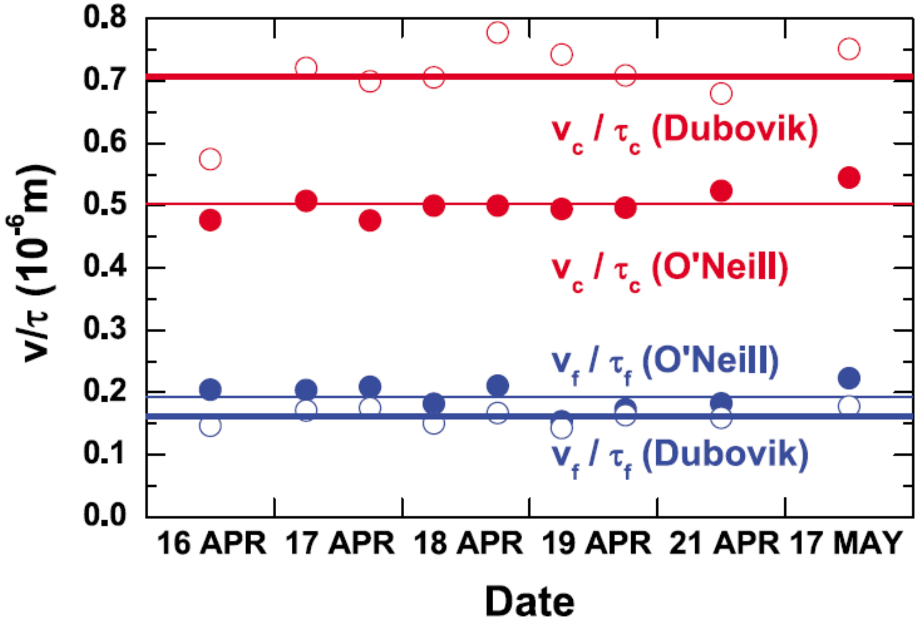


Figure 2. Ratio of volume concentration v to aerosol optical thickness τ (at 532 nm) for several days from 16 April to 17 May 2010. The horizontal lines indicate the mean values. The volume concentrations and optical thicknesses are computed from the Leipzig AERONET Sun photometer observations. The terms v_f and v_c denote fine-mode and coarse-mode volume concentration, respectively. Similarly, τ_f and τ_c denote fine-mode and coarse-mode particle optical thickness, respectively, computed after the Dubovik approach or the O'Neill method. See text for more details.

Table 1. Input Parameters in the Fine-Mode/Ash Separation Retrieval[a]

Parameter	Value
Ash depolarization ratio δ_a	0.36 ± 0.02
Non-ash depolarization ratio δ_{na}	0.01 ± 0.01
Ash lidar ratio S_a	50 ± 10 sr
Non-ash lidar ratio S_{na}	40–80 sr
Ash mass density ρ_a	2.6 ± 0.6 g/cm^3
Fine-mode mass density ρ_f	1.5 ± 0.3 g/cm^3
Ash conversion factor v_c/τ_c	$(0.605 \pm 0.1) \times 10^{-6}$ m
Fine-mode conversion factor v_f/τ_f	$(0.177 \pm 0.016) \times 10^{-6}$ m

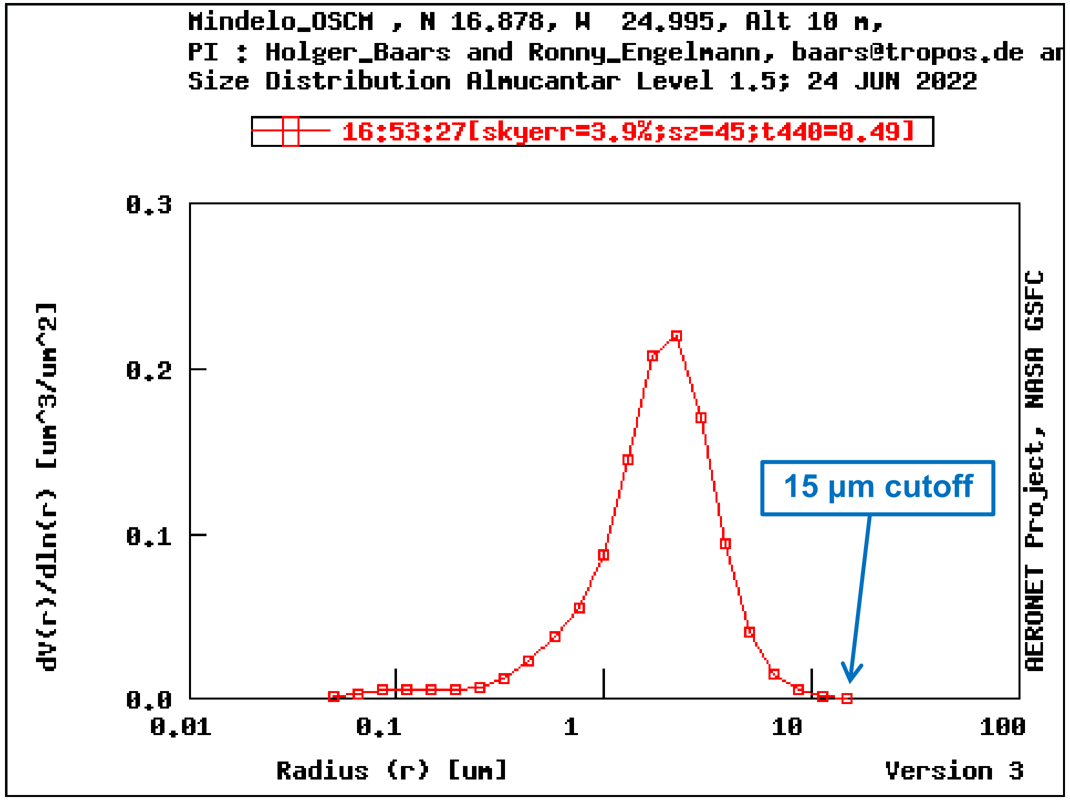
[a]Typical ranges of values are given. Optical properties at 532 nm are considered.

Ash: ζ=0.605 µm, $K_{ext} = 0.64\ \mathrm{m^2/g}$
Fine: ζ=0.177 µm, $K_{ext} = 3.8\ \mathrm{m^2/g}$

Ansmann *et al.*, Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajökull volcano in 2010, https://doi.org/10.1029/2010JD015567 (2011).

Deriving the specific extinction from AERONET

[24] A significant source of uncertainty in the entire AERONET retrieval scheme remains to be discussed. The AERONET algorithm considers particles with radii up to 15 μm only. Larger particles which are probably present in fresh volcanic plumes are neglected in the inversion method. This neglect can introduce a significant bias in the computation of the volume size distribution from the AERONET measurements [*Müller et al.*, 2010] with the result of a large underestimation of the ash mass load from the lidar data by more than 100%. In the presence of those large particles the coarse-mode volume-to-AOT conversion factor is much larger than the applied one of 0.605×10^{-6} m. This aspect is discussed in more detail in section 4.1. Further uncertainties in the retrieval of the volume size distribution originate from the unknown shape of the ash particles (and thus of the unknown scattering phase function). In the computation, the desert dust shape model (spheroid particles) is applied [*Dubovik et al.*, 2006]. *Gasteiger et al.* [2011] discuss shape effects in the retrieval of microphysical properties of volcanic ash from optical (lidar) measurements.



Ansmann *et al.*, Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajökull volcano in 2010, https://doi.org/10.1029/2010JD015567 (2011).

Specific extinction from the literature

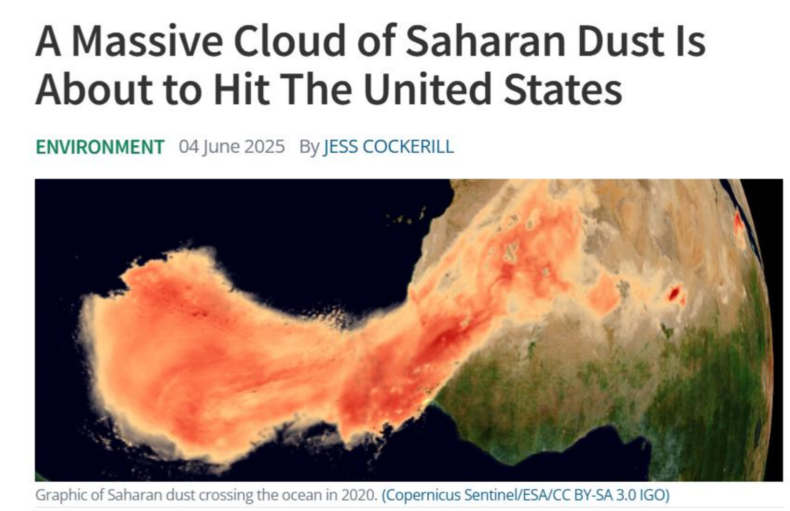
Reference	k_{ext} [$m^2 g^{-1}$]	$1/(k_{ext}\rho)$ [10^{-6} m]	Comment
Eyjafjallajökull volcanic dust, April–May 2010			
Johnson et al. (2012)	0.40–0.95	0.96–0.40	Airborne, in situ, near volcanic source, North Sea
	0.53	0.72	>1000 km distance from source, North Sea, UK
Marenco et al. (2011)	0.53–0.80	0.72–0.48	Airborne, in situ, comparison with lidar, North Sea, UK
Turnbull et al. (2012)	0.53–0.71	0.72–0.54	Airborne, in situ, North Sea
Hervo et al. (2012)	0.64	0.60	Ground-based, in situ, 1.5 km height, France
Gasteiger et al. (2011)	0.69 (0.43–1.11)	0.56 (0.89–0.35)	Scattering model, multi–λ lidar, photometer, Germany
Miffre et al. (2012)	0.69 ± 0.10	0.56 ± 0.09	Scattering model, lidar, France
Ansmann et al. (2010)	0.51	0.75	AERONET, remote sensing, first ash front (16 April), very large particles, central Germany
Devenish et al. (2012)	0.53	0.72	AERONET, remote sensing, first ash front (16 April), very large particles, southern UK
Ansmann et al. (2011b)	0.64 ± 0.10	0.60 ± 0.10	AERONET, remote sensing, Germany
Sicard et al. (2012)	0.38–0.43	1.00–0.89	AERONET, remote sensing, Spain
Grimsvötn volcanic dust, May 2011			
This study	0.43 ± 0.05	0.90 ± 0.05	AERONET, remote sensing, Germany
Saharan dust			
Hess et al. (1998)	0.64	0.60	OPAC model
Hess et al. (1998)	0.37	1.03	OPAC model, transported dust, free troposphere
Barnaba and Gobbi (2004)	0.54–1.50	0.71–0.26	Modeling study, full range of realistic size distributions
Johnson and Osborne (2011)	0.48 ± 0.10	0.80 ± 0.20	GERBILS, airborne, in situ, western and west of Africa
Osborne et al. (2008)	0.30–0.40	1.29–0.96	DABEX, DODO1, airborne, in situ, western Africa
Weinzierl et al. (2009)	0.45–0.70	0.85–0.55	SAMUM-1, airborne, in situ, South Morocco, >2 km height
Müller et al. (2012)	0.57 ± 0.04	0.68 ± 0.05	SAMUM-1, multi-λ lidar, South Morocco, >2 km height
This study	0.50 ± 0.05	0.77 ± 0.07	AERONET, remote sensing, Germany, Oct 2001, May 2008
This study	0.52 ± 0.03	0.74 ± 0.04	SAMUM–1, AERONET, remote sensing, South Morocco
This study	0.52 ± 0.06	0.74 ± 0.08	SAMUM–2, AERONET, remote sensing, Cape Verde
Continental particles (fine mode)			
Hess et al. (1998)	1.80 (2.40)	0.35 (0.26)	OPAC model, clean continental, rel. humidity 50 % (80 %)
Hess et al. (1998)	2.20 (2.90)	0.28 (0.22)	OPAC model, polluted continental, rel. humidity 50 % (80 %)
Barnaba and Gobbi (2004)	3.50 ± 0.1	0.18 ± 0.005	Modeling study, full range of realistic size distributions
Ansmann et al. (2011b)	3.50 ± 0.4	0.18 ± 0.02	AERONET, remote sensing, Germany
Sicard et al. (2012)	2.40 ± 0.1	0.25 ± 0.01	AERONET, remote sensing, Spain

Ash: ζ=0.35 – 1 µm, $K_{ext} = 0.38 - 0.95\ m^2/g$
Dust: ζ=0.26 – 1.29 µm, $K_{ext} = 0.3 - 1.5\ m^2/g$
Fine: ζ=0.18 – 0.35 µm, $K_{ext} = 1.8 - 3.5\ m^2/g$

Ansmann *et al.*, Profiling of fine and coarse particle mass: case studies of Saharan dust and Eyjafjallajökull/Grimsvötn volcanic plumes, https://doi.org/10.5194/acp-12-9399-2012 (2012).

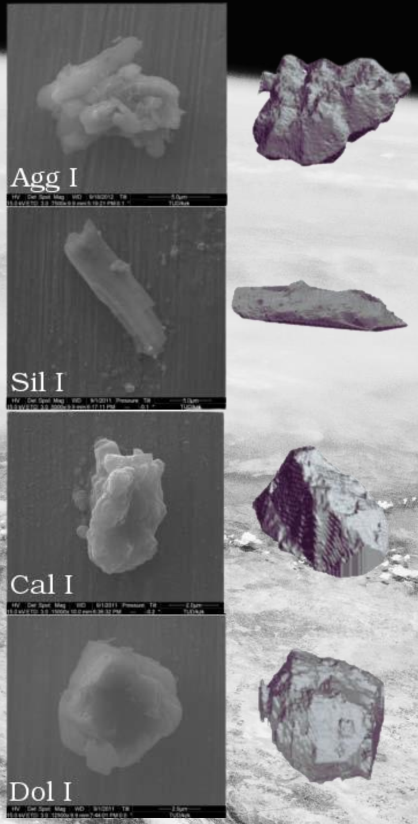
The challenge of dust

- The most abundant natural aerosol by mass (2000-3000 Tg/year).
- Can travel up to several thousands of km away from the source
- Wide range of sizes, shapes, and composition


A Massive Cloud of Saharan Dust Is About to Hit The United States

ENVIRONMENT 04 June 2025 By JESS COCKERILL

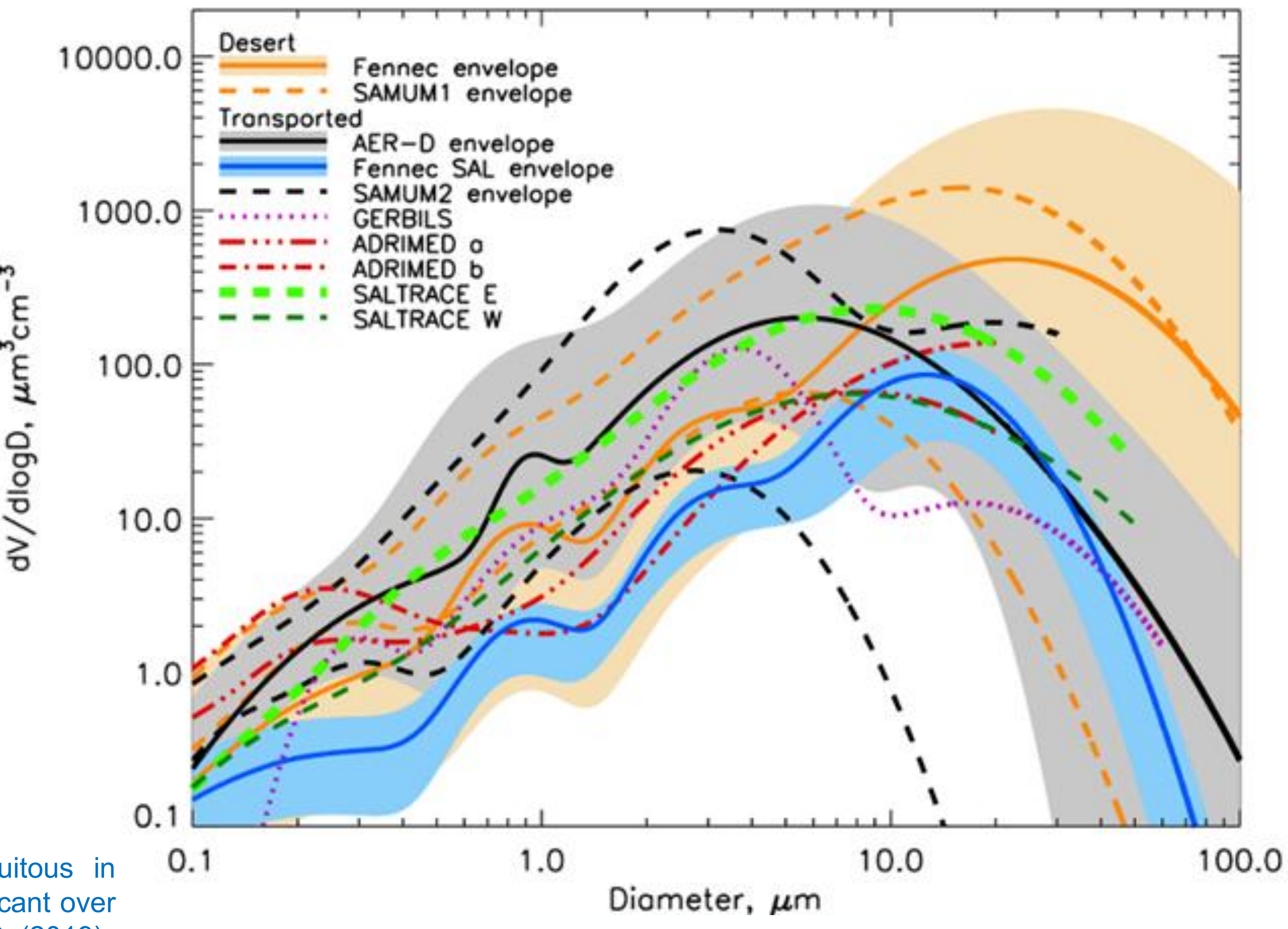
Graphic of Saharan dust crossing the ocean in 2020. (Copernicus Sentinel/ESA/CC BY-SA 3.0 IGO)



The dust particle size-distribution

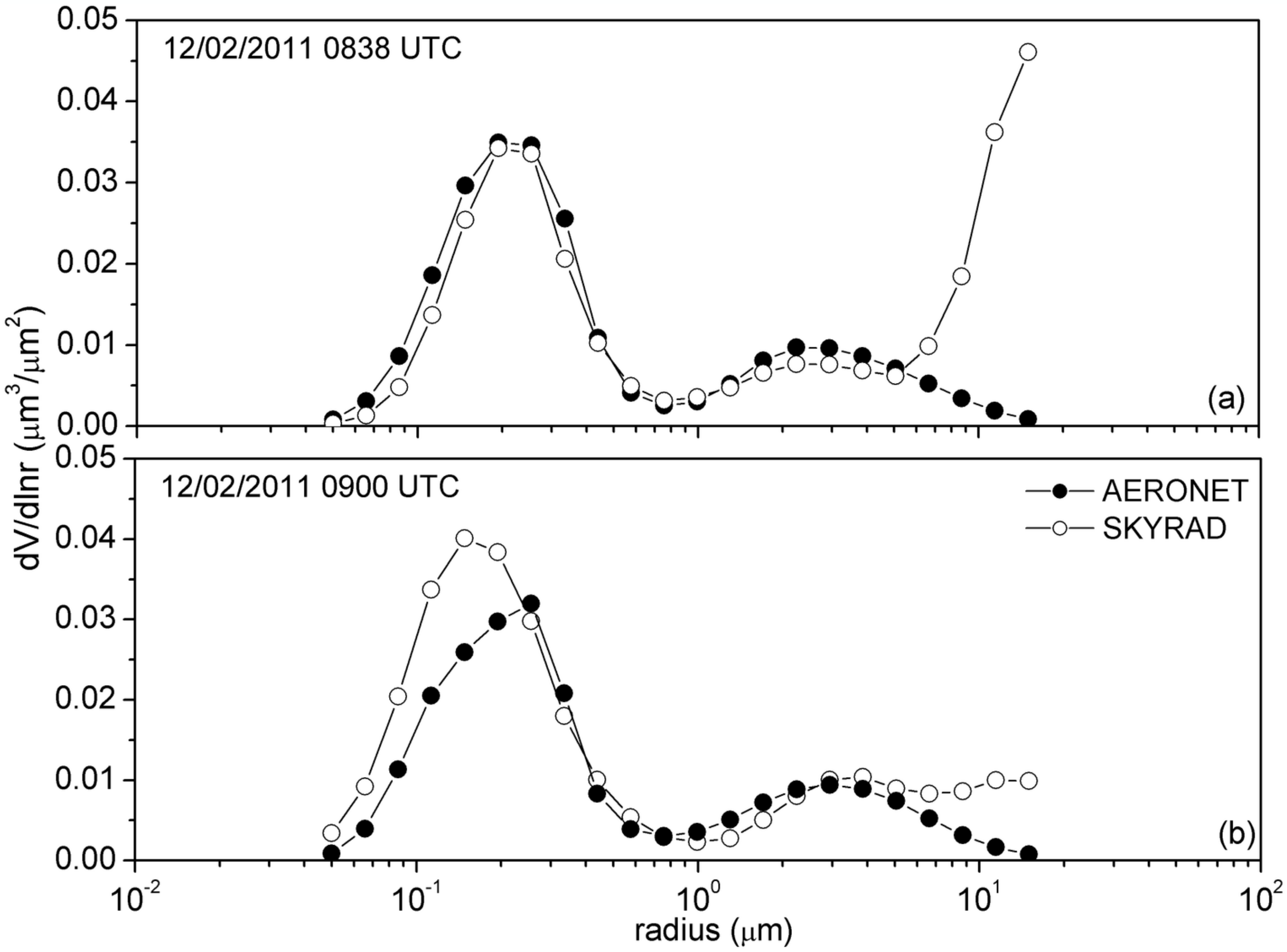
- Several airborne campaigns indicate particles up to ~ 100 µm (diameter), and even more
- Highly variable as well

- How frequent are super-coarse particles?
- Do the particles larger than 30 µm (diameter) cause AERONET to underestimate r_{eff} and therefore overestimate K_{ext} ?



Ryder *et al*, Coarse and giant particles are ubiquitous in Saharan dust export regions and are radiatively significant over the Sahara, https://doi.org/10.5194/acp-19-15353-2019, (2019).

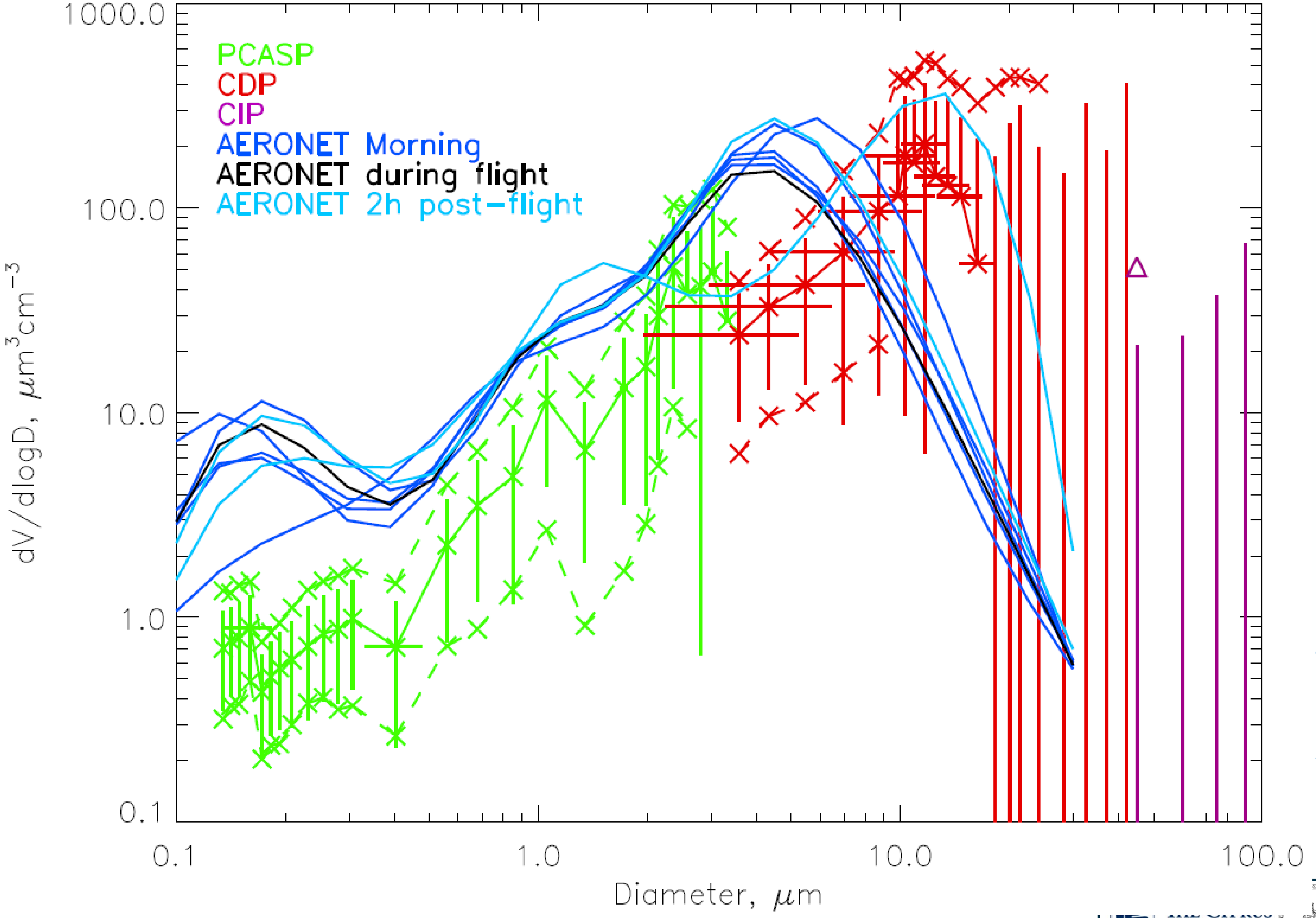
AERONET vs SKYRAD



- AERONET does not only limit the PSD to 15 μm, it also forces it to zero!
- SKYRAD is also limited in particle size, but it does not impose this forcing to zero.
- Differences between the two have been observed, due to this difference.

Courtesy of Victor Estelles and Monica Campanelli

Fennec Campaign (2011)

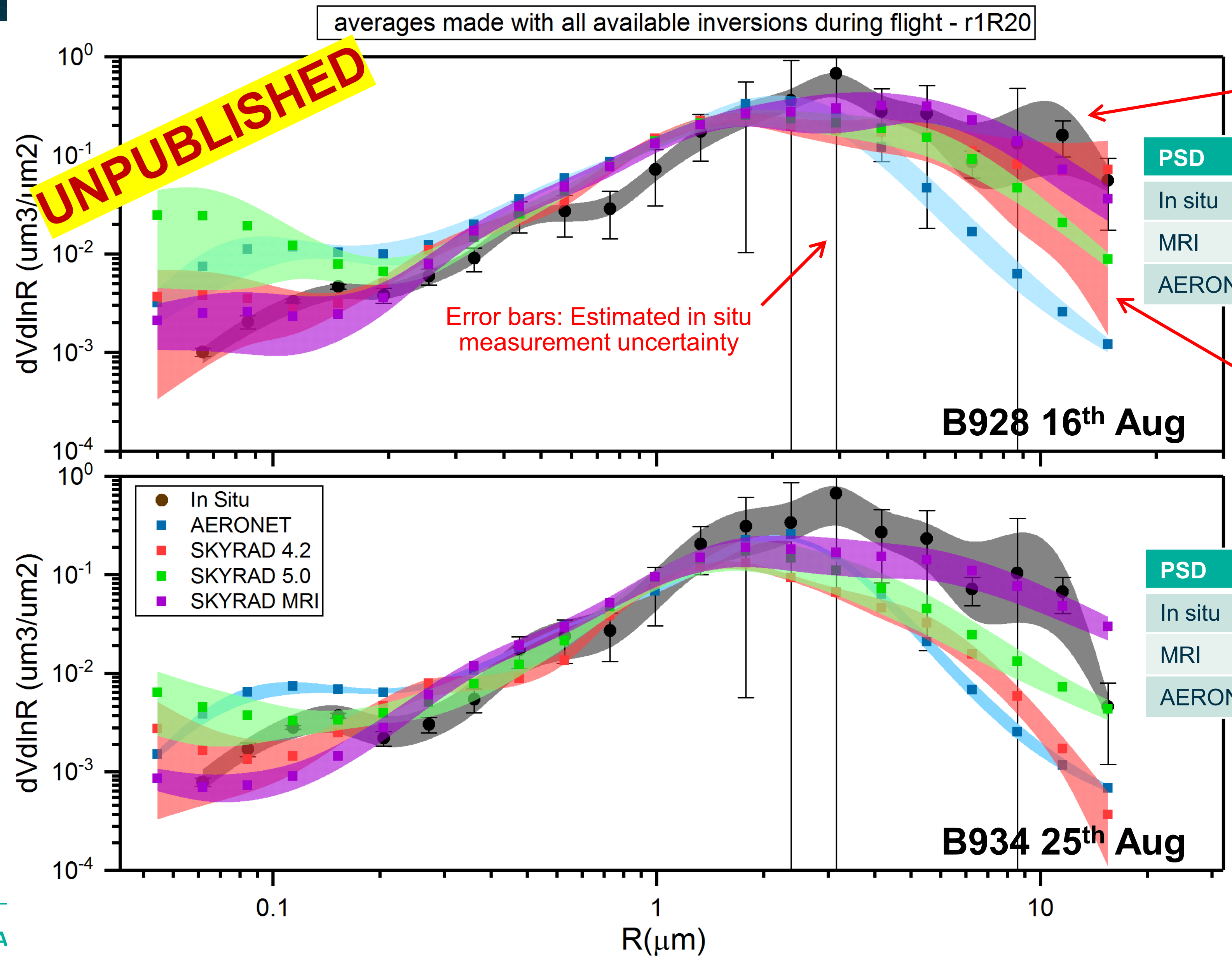


FAAM (2011)
Fennec campaign

Ryder et al, Advances in understanding mineral dust and boundary layer processes over the Sahara from Fennec aircraft observations, https://doi.org/10.5194/acp-15-8479-2015 (2015).

Also in: Adebiyi et al, A review of coarse mineral dust in the Earth system, https://doi.org/10.1016/j.aeolia.2022.100849 (2023).

SAVEX-D experiment (2015)



In situ shaded area: dependence on retrieval assumptions (R.I.)

Shaded areas: variability (standard deviation)

PSD	ζ	K_{ext}
In situ	1.24	0.32
MRI	1.07	0.38
AERONET	0.72	0.56

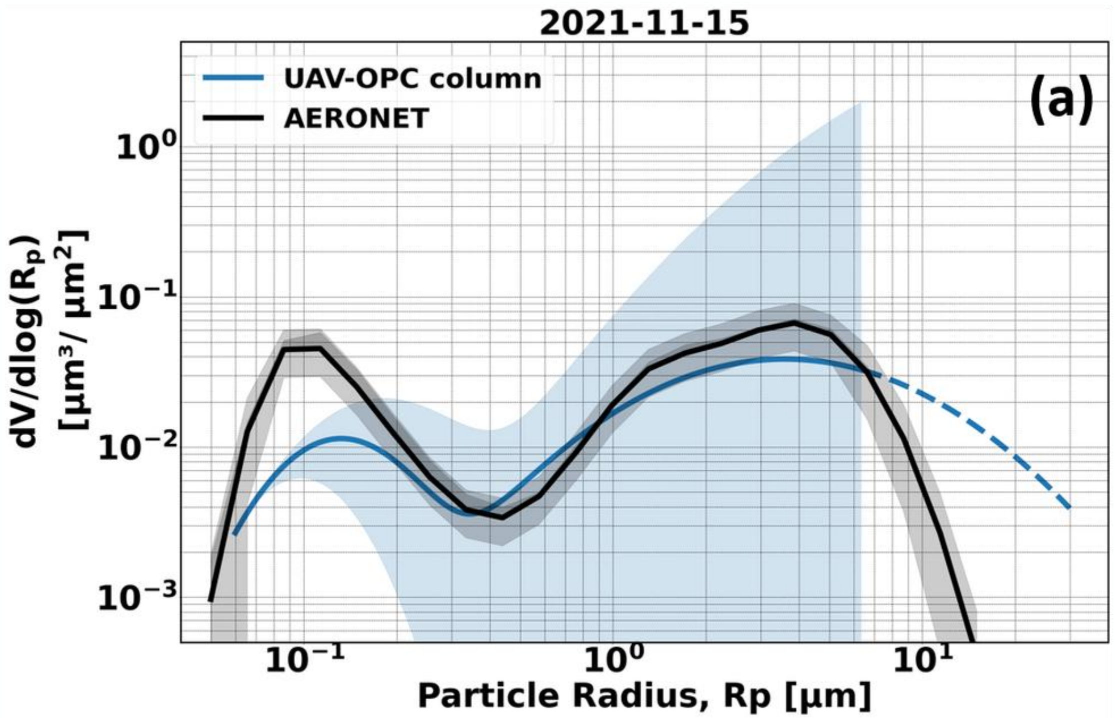
FAAM (2015)
AER-D campaign
SAVEX-D experiment

PSD	ζ	K_{ext}
In situ	1.08	0.37
MRI	1.00	0.40
AERONET	0 90	0.44

SKYRAD flavours:
4.2 (official version)
5.0 (improved minimisation)
MRI – Met. Res. Inst. Japan (non-spherical)

Courtesy of Victor Estelles
Presented at 9th International Workshop on Sand/Duststorms and Associated Dustfall, 2018, Tenerife, Spain.

PSD: AERONET vs airborne in-situ



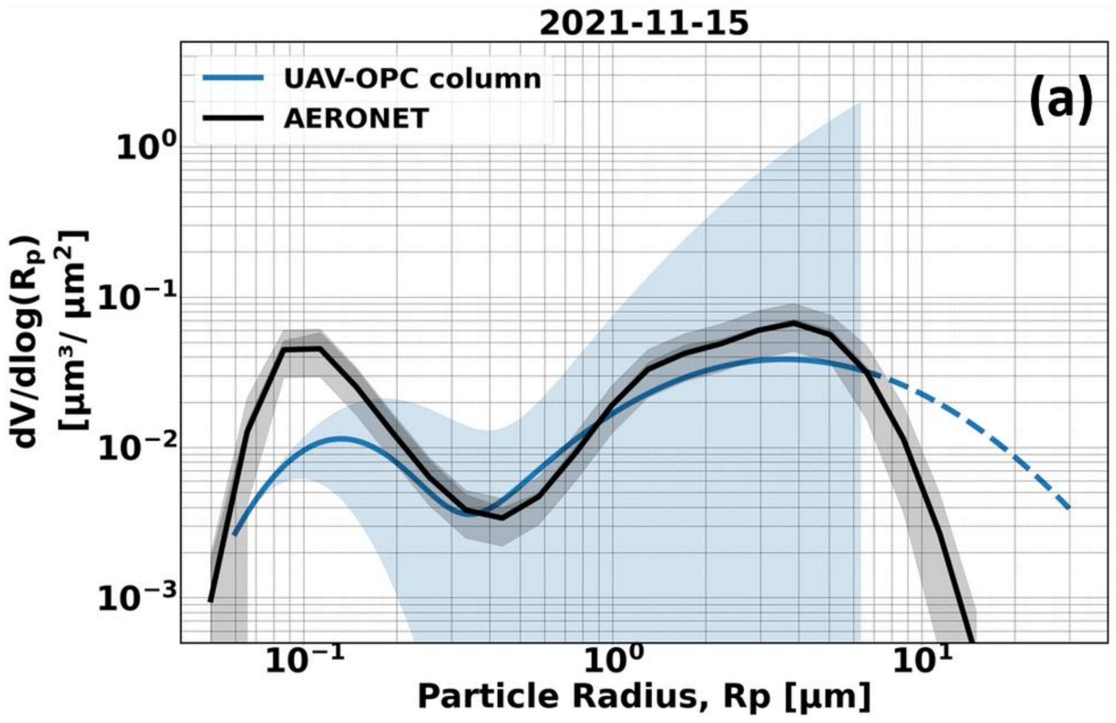
MIXED DUST CASE

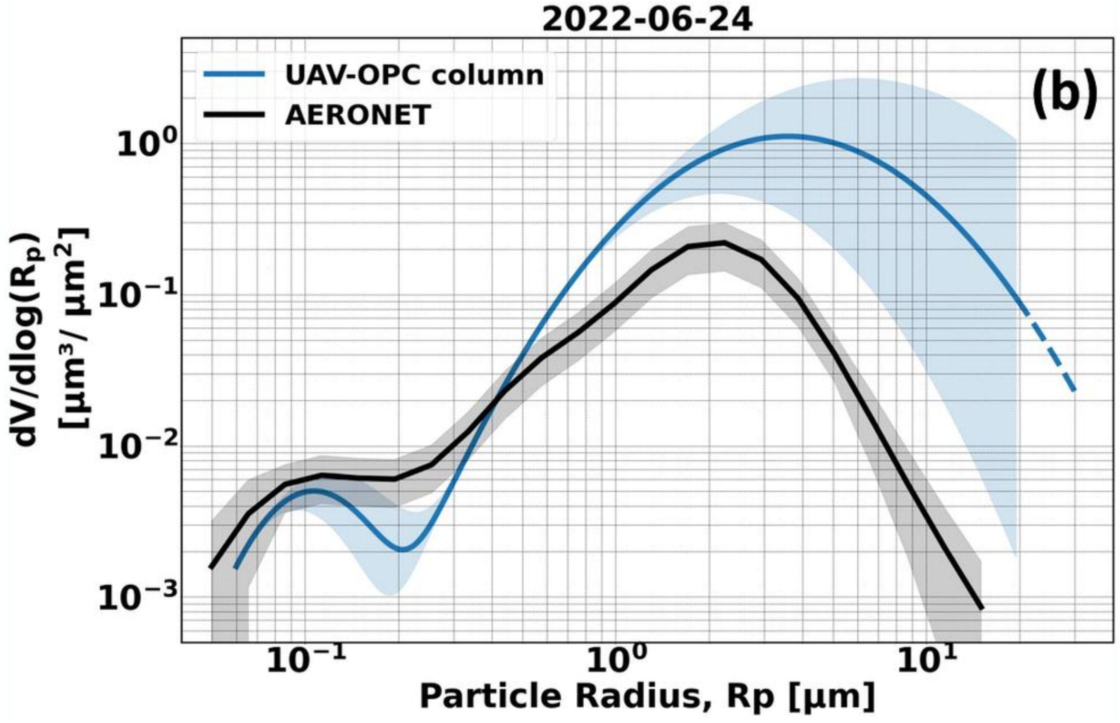
- Good agreement.

Papetta *et al*, Volume-to-extinction ratio: an important property of dust, https://doi.org/10.5194/acp-26-2055-2026 (2026).

*AERONET upper size limit 15 μm (radius)

PSD: AERONET vs airborne in-situ





MIXED DUST CASE

- Good agreement.

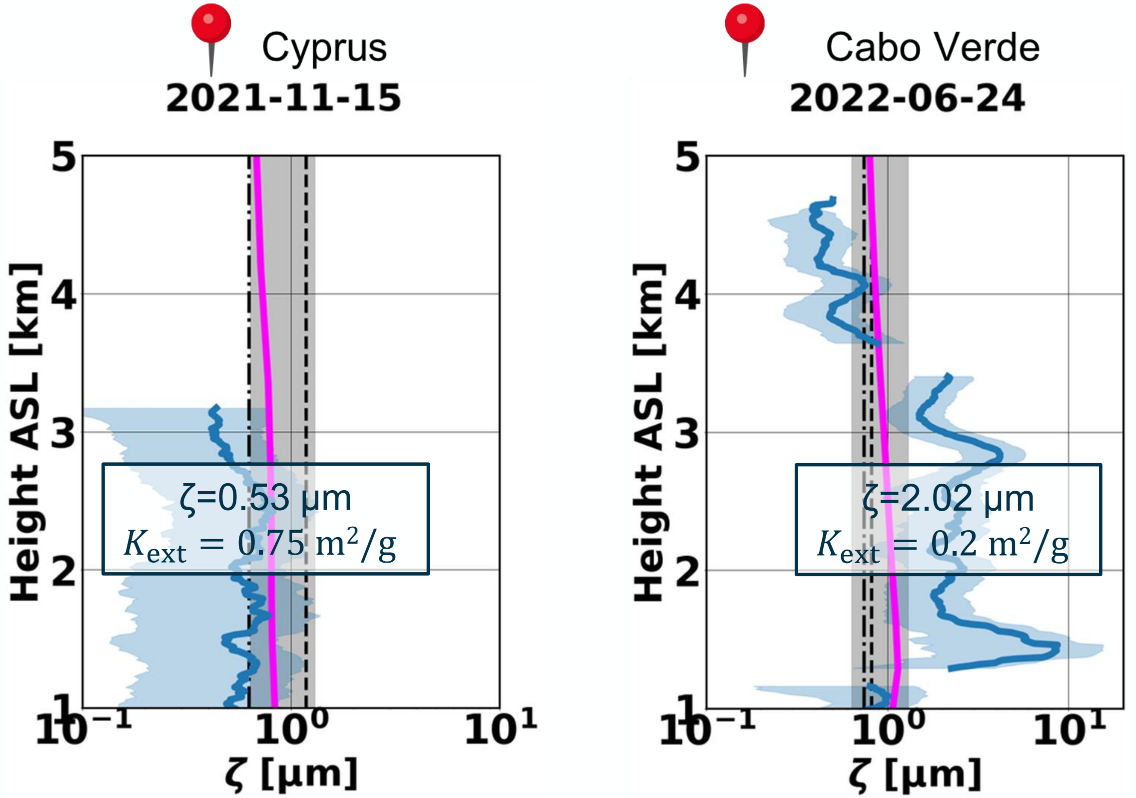
PURE DUST- NEAR TO THE SOURCE

- Disagreement in the coarse mode.
- Indication of super-coarse particles existence.

*AERONET upper size limit 15 μm (radius)

Papetta *et al*, Volume-to-extinction ratio: an important property of dust, https://doi.org/10.5194/acp-26-2055-2026 (2026).

Estimated volume-to-extinction ratio

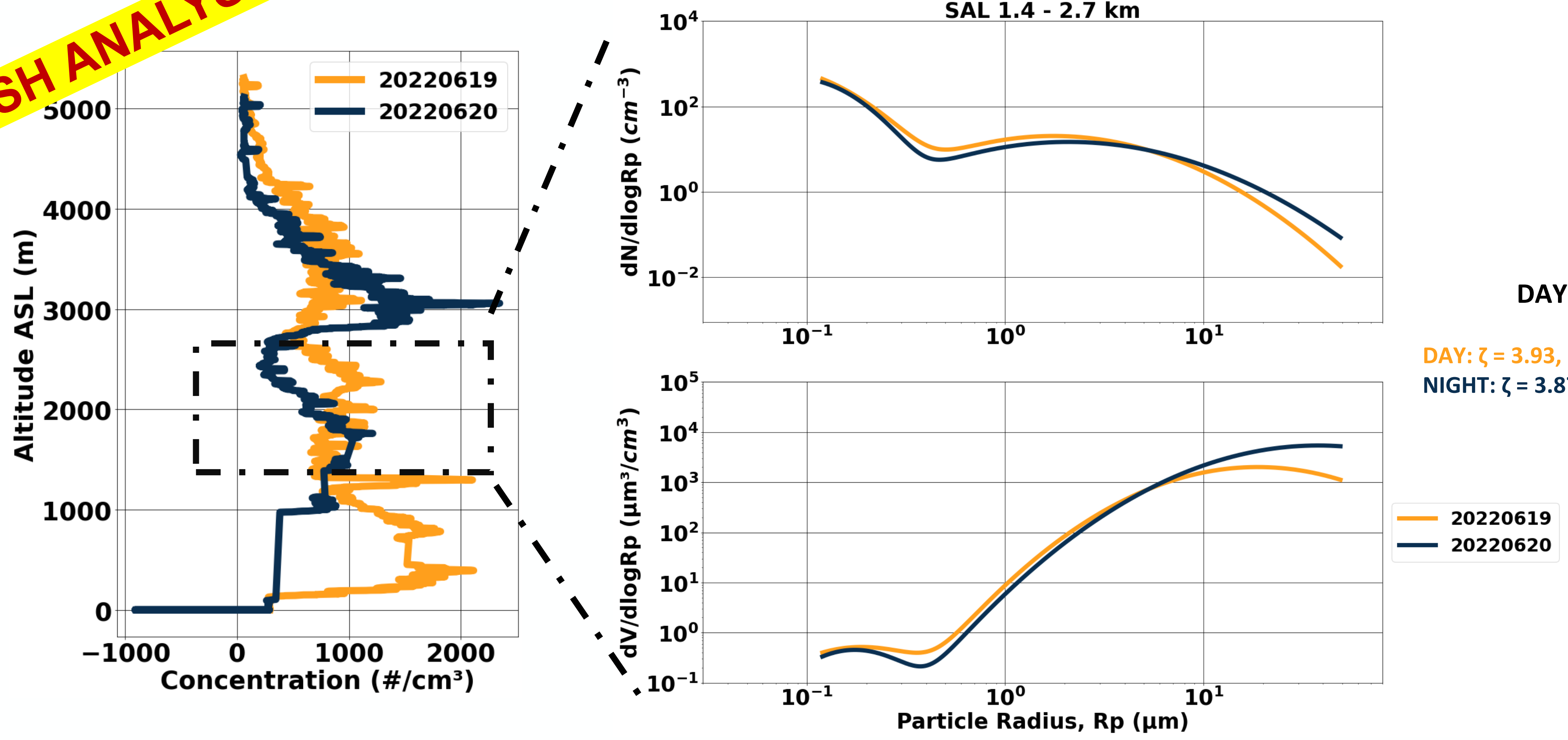


	Cyprus	Cabo Verde
Literature:	Agrees within uncertainty	Big deviations (more than 70%)
AERONET:	Agrees within uncertainty	**Up to 150% differences**
WRF:	Agrees within uncertainty	Mostly disagree

Papetta *et al*, Volume-to-extinction ratio: an important property of dust, https://doi.org/10.5194/acp-26-2055-2026 (2026).

ASKOS day vs night / DAZSAL project

FRESH ANALYSIS



DAY vs NIGHT

DAY: ζ = 3.93, $K_{\text{ext}} = 0.1\ \text{m}^2/\text{g}$

NIGHT: ζ = 3.87 , $K_{\text{ext}} = 0.1\ \text{m}^2/\text{g}$

Courtesy of Alkistis Papetta

Conclusions

Brief Summary (so far)

Ash: ζ = 0.35 – 1 μm, $K_{ext} = 0.38 - 0.95\ m^2/g$
Dust: ζ = 0.26 – 3.93 μm, $K_{ext} = 0.1 - 1.5\ m^2/g$
Fine: ζ = 0.18 – 0.35 μm, $K_{ext} = 1.8 - 3.5\ m^2/g$

- The specific extinction can be highly variable in time and space
- It depends upon particle size, shape, density and refractive index
- **The most sensitive parameter is probably the particle size**
- Advantages of constraining the specific extinction from remote sensing:
  - Global or near-global coverage
  - Consistent methodology
- Limitations of constraining the specific extinction from remote sensing:
  - Broad PSDs may not be fully captured by remote sensing retrievals
  - Not generally validated with in-situ
  - In particular, super-coarse dust clearly causes a problem with this method
- Modelling does not generally fill this gap, due to most models not being fully constrained in terms of the particle size-distribution. Models are mainly constrained to global AOD observations.
- **Desirable: A global study on the specific extinction of each aerosol type, including the combination of remote sensing and airborne in-situ methodologies. Dust may be the most problematic aerosol.**

Acknowledgment

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www.cost.eu

Thanks for your attention!

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