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Coarse and Giant Particles are Ubiquitous in Saharan Dust Export Regions and are Radiatively Significant over the Sahara

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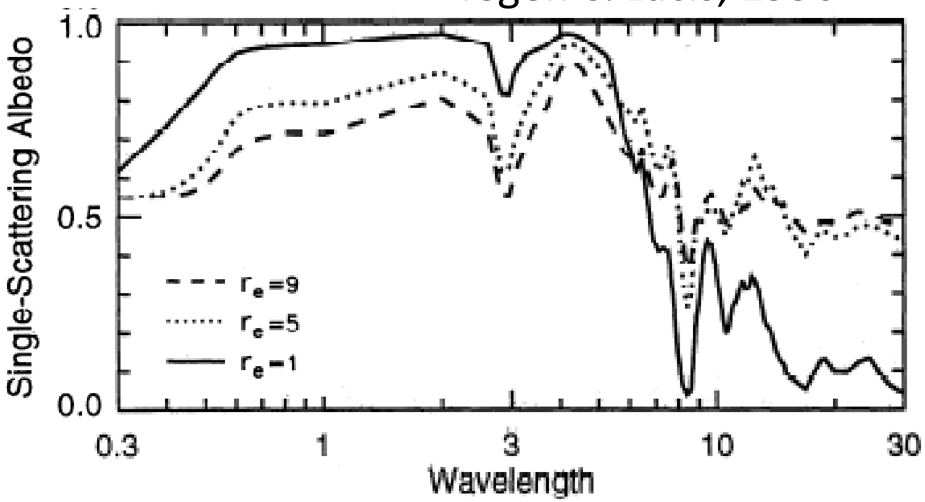
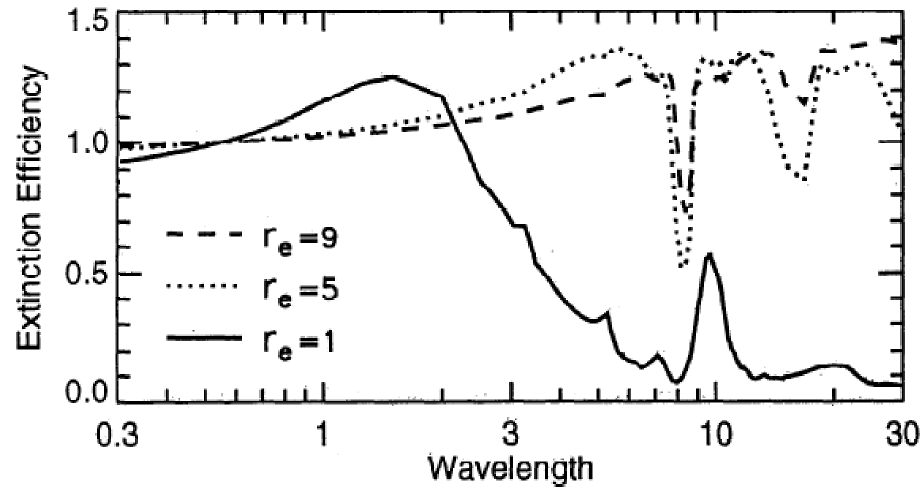
Dust size: the radiation perspective

Tegen & Lacis, 1996

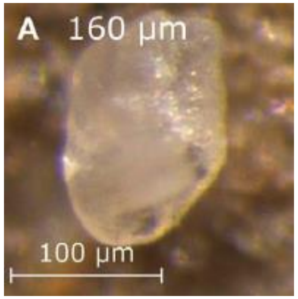


Extinction efficiency = Qext normalized to 0.55 µm value



- Solar wavelengths (SW):
  - Larger particles reduce Single Scattering albedo (SSA)
  - →TOA forcing more positive, more atmospheric heating
- Terrestrial wavelengths (LW):
  - Larger particles increase the extinction efficiency
  - Stronger positive TOA longwave radiative effect
- Overall – larger particles can make TOA dust radiative forcing more positive (warming effect)

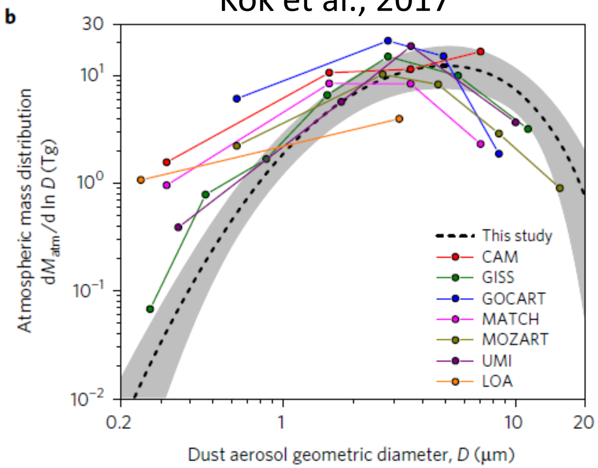
Motivation



Giant dust observed in long range dust transport
van der Does et al. (2018)

- Dust models typically:
  - Exclude the giant mode (d> 20µm)
  - Under-represent the coarse mode (d>2.5-5.0 µm)
  - Historically: assumed coarse particles rapidly deposited
- Challenge for measurements, especially airborne, coarse mode frequently not measured at all
- In the last 10 years, airborne dust observations have progressed, measuring larger particles, avoiding inlets and using non-optical techniques
- Multiple publications now report the presence of coarse and giant dust particles
- Models rarely include dust particles larger than 20µm, d>5µm: models start to underestimate dust concentration

Kok et al., 2017



Aims

- Contrast & characterize state-of-the art airborne dust size observations:
    - Measuring d ≥ 100µm
    - Close to dust sources and at the beginning of trans-Atlantic transport
- Provide mass concentration profiles for model comparisons
- Calculate the contribution of coarse & giant dust particles to optical properties (i.e. what models are missing)
- Evaluate the wider context of transport of coarse & giant dust particles
- Detailed results available in Ryder et al. (2019), ACP

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Coarse and giant particles are ubiquitous in Saharan dust export regions and are radiatively significant over the Sahara

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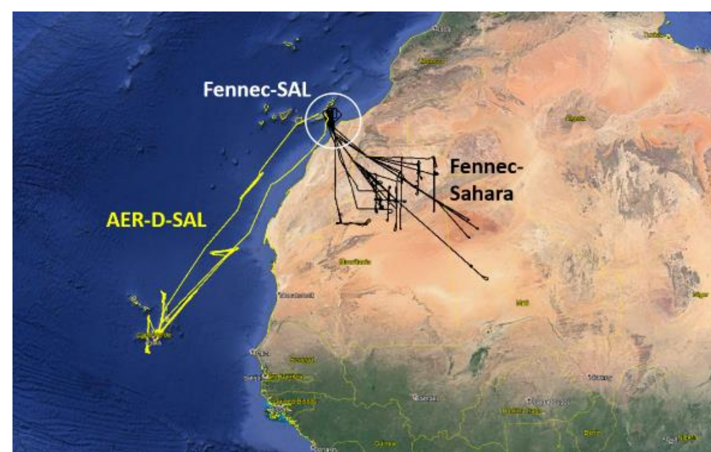
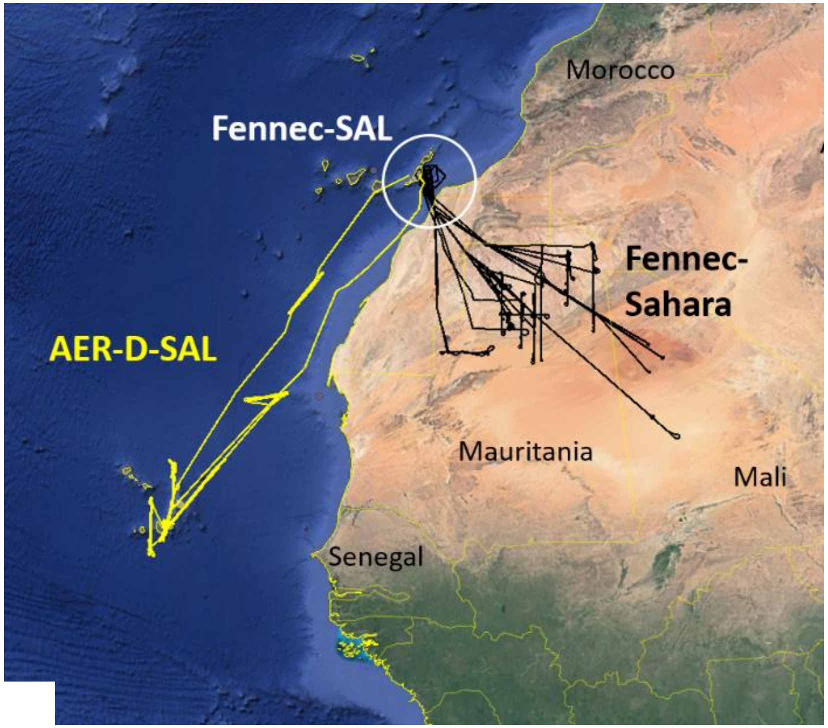
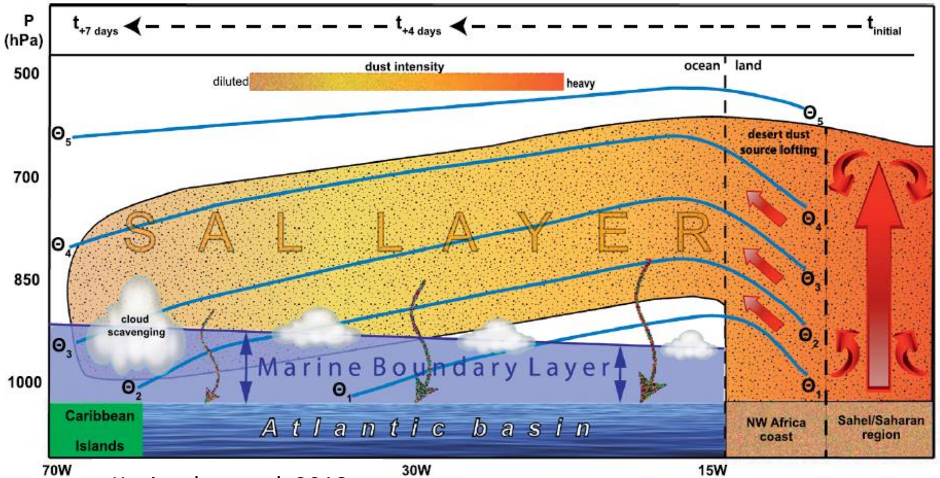


Aircraft Data

- Fennec
  - June 2011
  - Fennec-Sahara: Mali & Mauritania
    - 117 horizontal flight legs; 21 profiles
    - Ryder et al. 2013b (ACP), Ryder et al. 2015 (ACP), Washington et al. 2012 (CLIVAR)
  - Fennec-SAL: Canary Islands
    - 21 profiles
    - Ryder et al. (2013a, GRL)
- AER-D-SAL (AERosol properties - Dust)
  - August 2015
  - Cape Verde Islands
    - 19 horizontal flight legs; 31 profiles
    - Ryder et al. 2018 (ACP), Marenco et al. 2018 (ACP), Liu et al. 2018 (ACP), O'Sullivan et al. 2020 (ACPD)

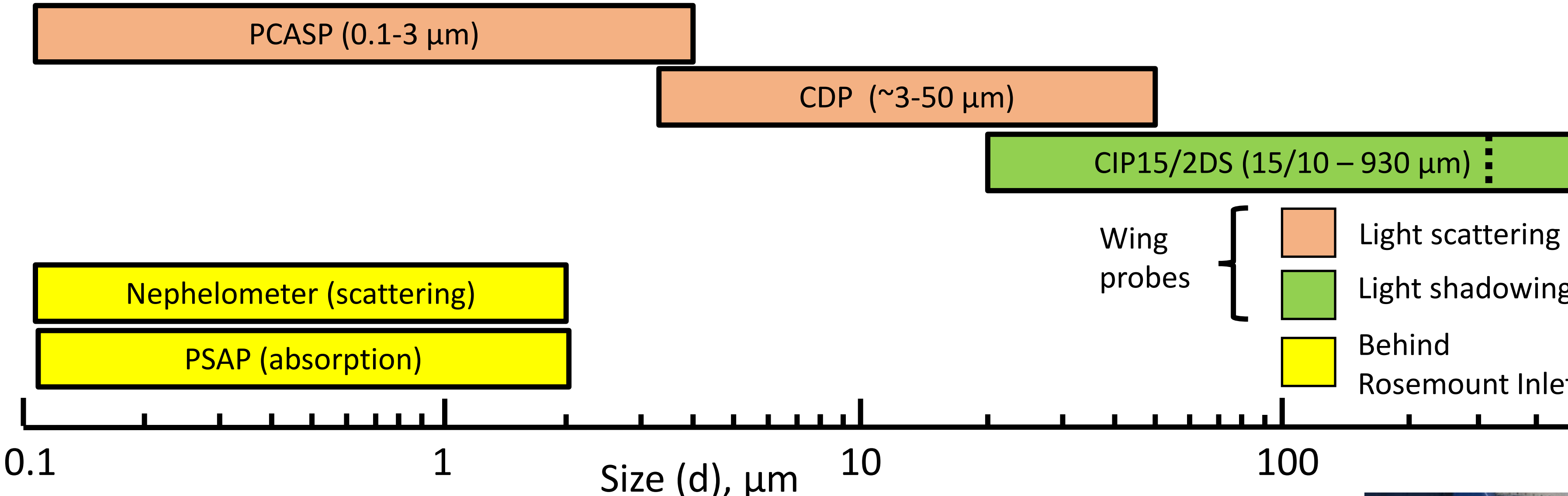




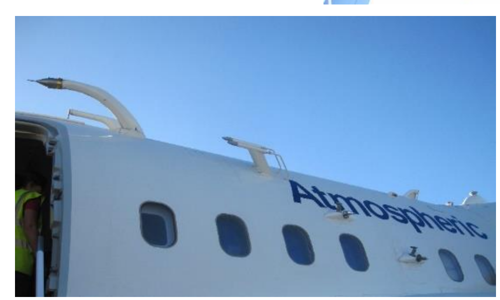
Kuciauskas et al. 2018

FAAM BAe146 Research Aircraft

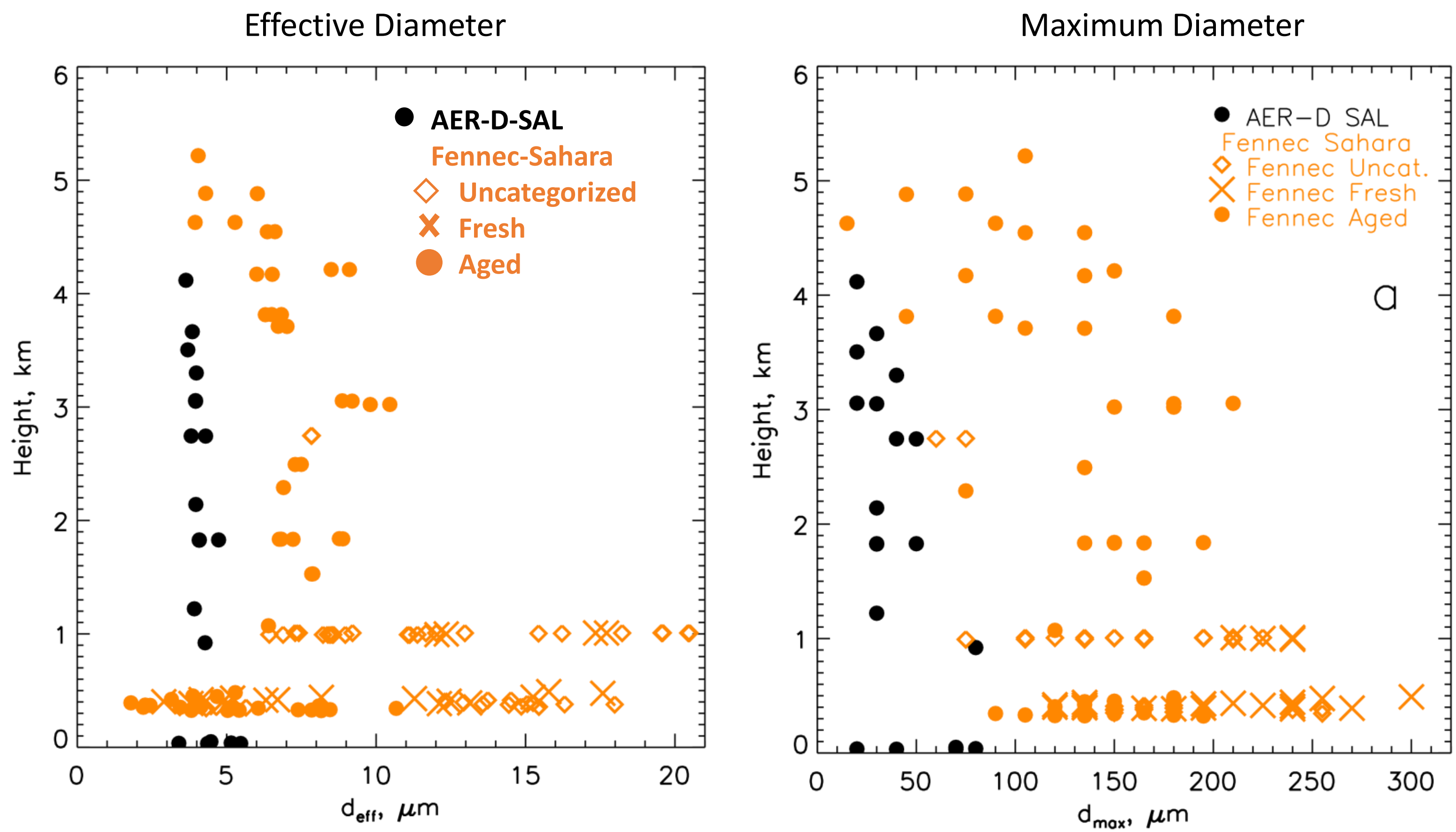
Fennec and AER-D Measurements of Aerosol Size



- In-cabin measurements (behind inlets)
  - Restrict measurement to a portion of the size range
  - Can bias optical properties
  - FAAM Rosemount inlets: 50% passing efficiency at 2.5 μm (Trembath 2012; Ryder et al. 2013)
- Light scattering sizing (Optical Particle Counters)
  - Scattering cross-section converted to particle size
  - Depends on refractive index (composition) of particle
  - Not a unique solution – uncertainties can be large
  - Rosenberg et al. (2012): Propagates uncertainties
- Light Shadowing (Optical Array Probes: CIP15; 2D-S)
  - <u>**No dependence on refractive index, no Mie dependence**</u>
  - Shape assumptions impact size



Desert vs SAL Dust Size Profiles



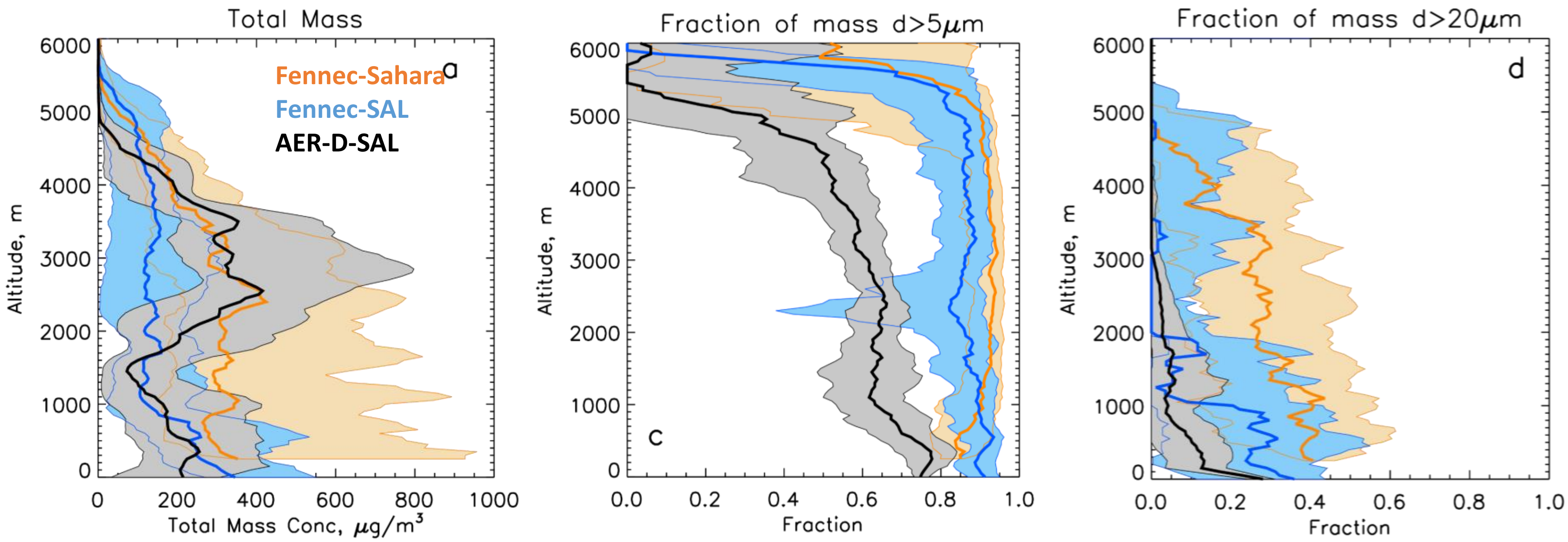
Measured over Sahara

× Fresh – under 12 h since uplift

● Aged – over 12 h since uplift

● Measured in the SAL

Mass Concentration Profiles



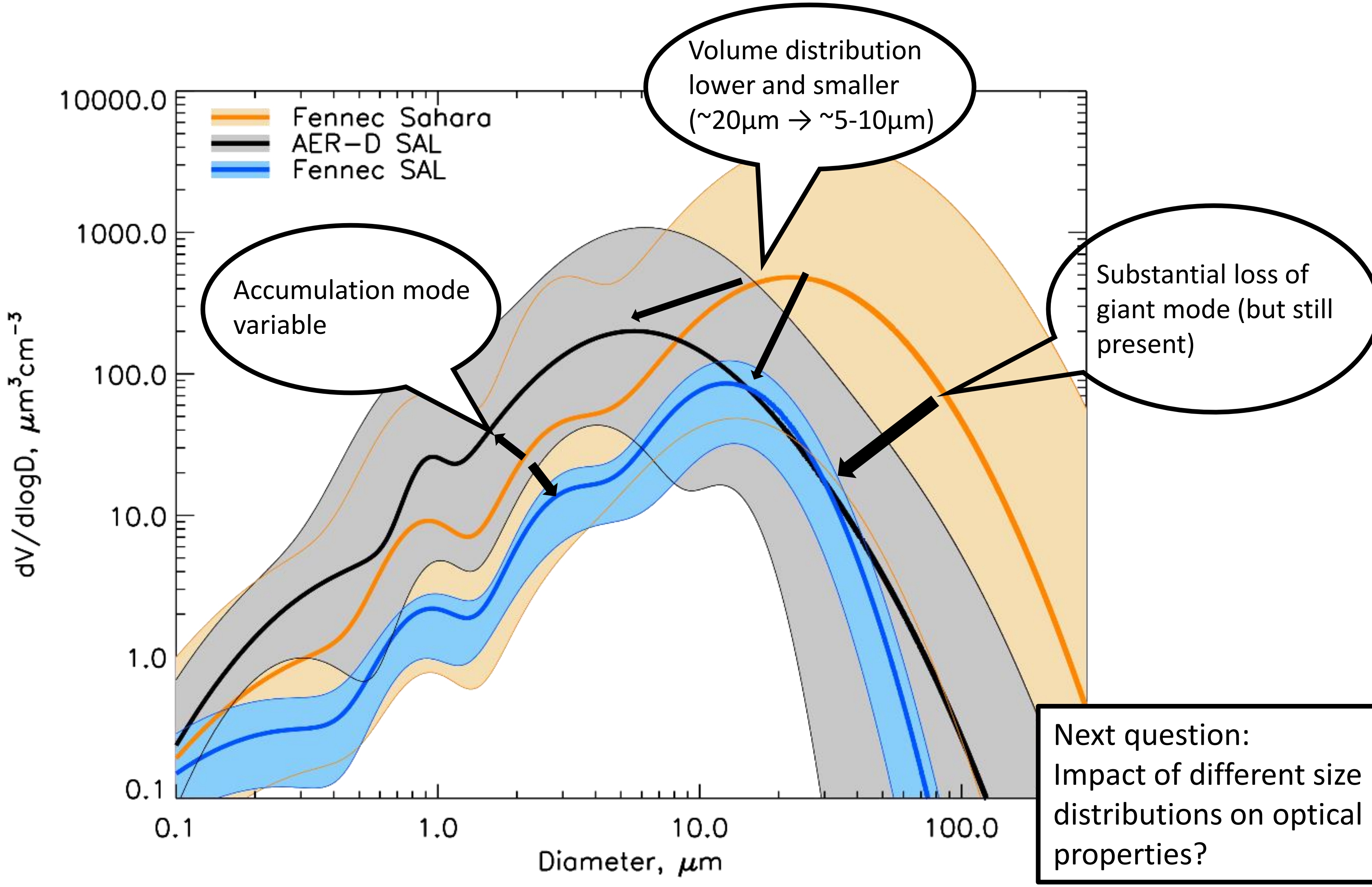
a) Total Mass
- Largest mass over Sahara; Decreases with altitude; SAL well-mixed

b) Fraction of mass d>5µm
- Fennec-Sahara: 92% beneath 4.5 km
- SAL: 61-87%

c) Fraction of mass d>20µm
- Fennec-Sahara: 27% mass at d>20µm
- SAL: 2%

- A significant amount of mass is being both completely excluded from models (d>20µm) and underestimated by models (d>5µm)

Size Distributions

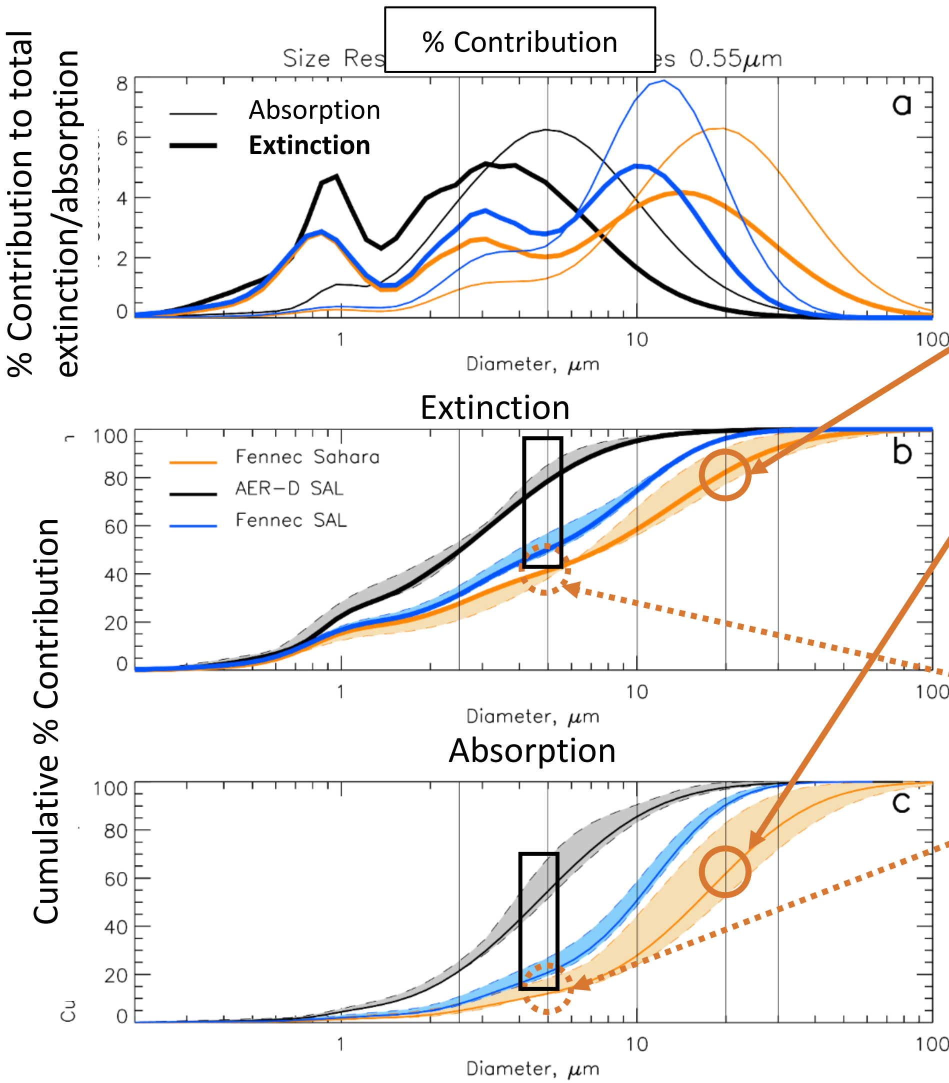


Next question:
Impact of different size distributions on optical properties?

Impact of Size Distributions on Optical Properties?

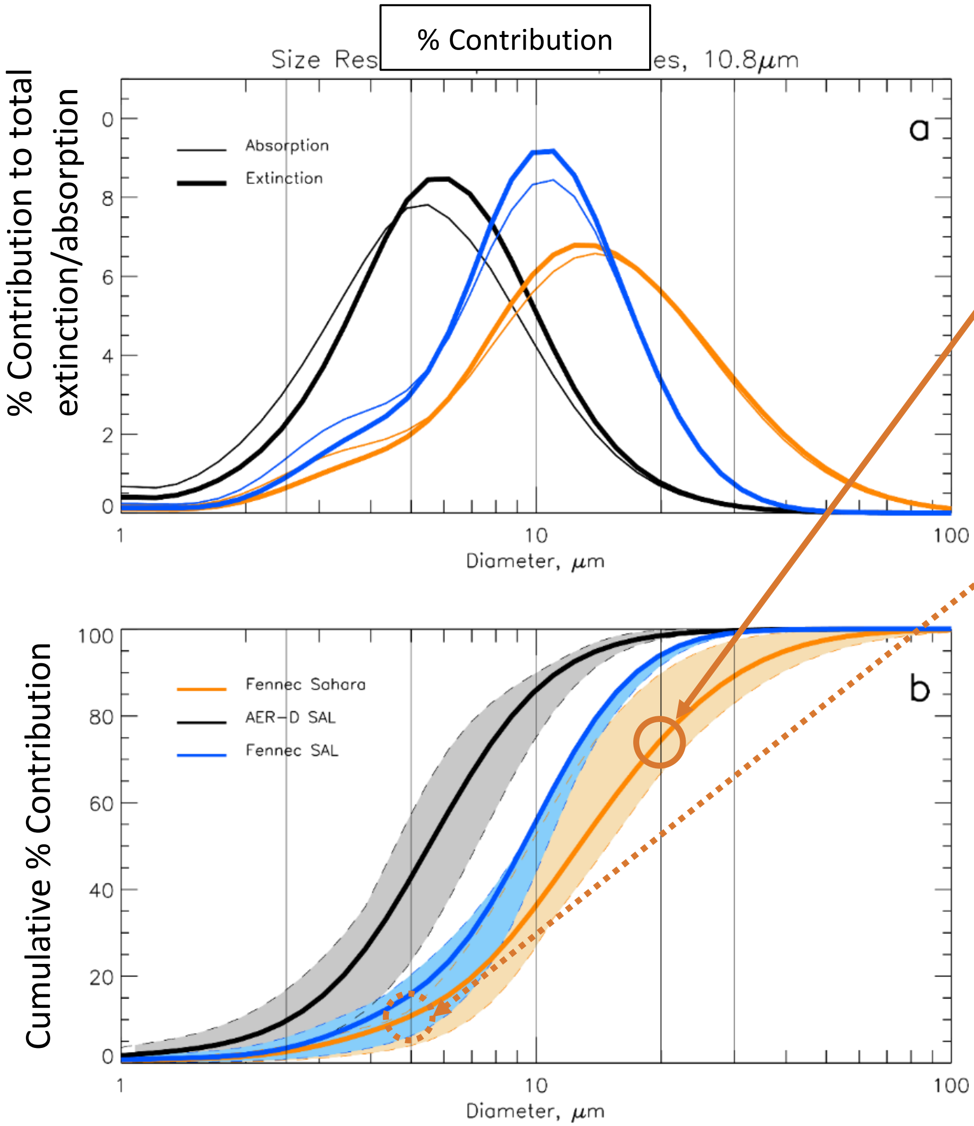
- Aim - assess the impact of the different measured size distributions on optical properties
- Method – Run Mie Scattering code with gradually incrementing maximum diameter for each field campaign. Use a range of refractive indices from the literature. Include uncertainty in measured size distribution
- Result – size resolved optical properties & uncertainties (next slide)

Size Resolved SW Extinction & Absorption



- At d=20μm we capture:
  - Fennec-Sahara:
    - 82% of extinction
    - 61% of absorption
  - SAL: (Fennec-SAL/AER-D SAL)
    - 96-99% of extinction
    - 90-98% of absorption
- At d=5μm we capture:
  - Fennec-Sahara:
    - 41% of extinction
    - 12% of absorption
  - SAL: (Fennec-SAL/AER-D SAL)
    - 50-78% of extinction
    - 20-53% of absorption

Size Resolved LW Extinction



- At d=20μm we capture:
  - Fennec-Sahara:
    - 74% of extinction
  - SAL: (Fennec-SAL/AER-D SAL)
    - 94-98% of extinction
- At d=5μm we capture:
  - Fennec-Sahara:
    - 10% of extinction
  - SAL: (Fennec-SAL/AER-D SAL)
    - 15-41% of extinction

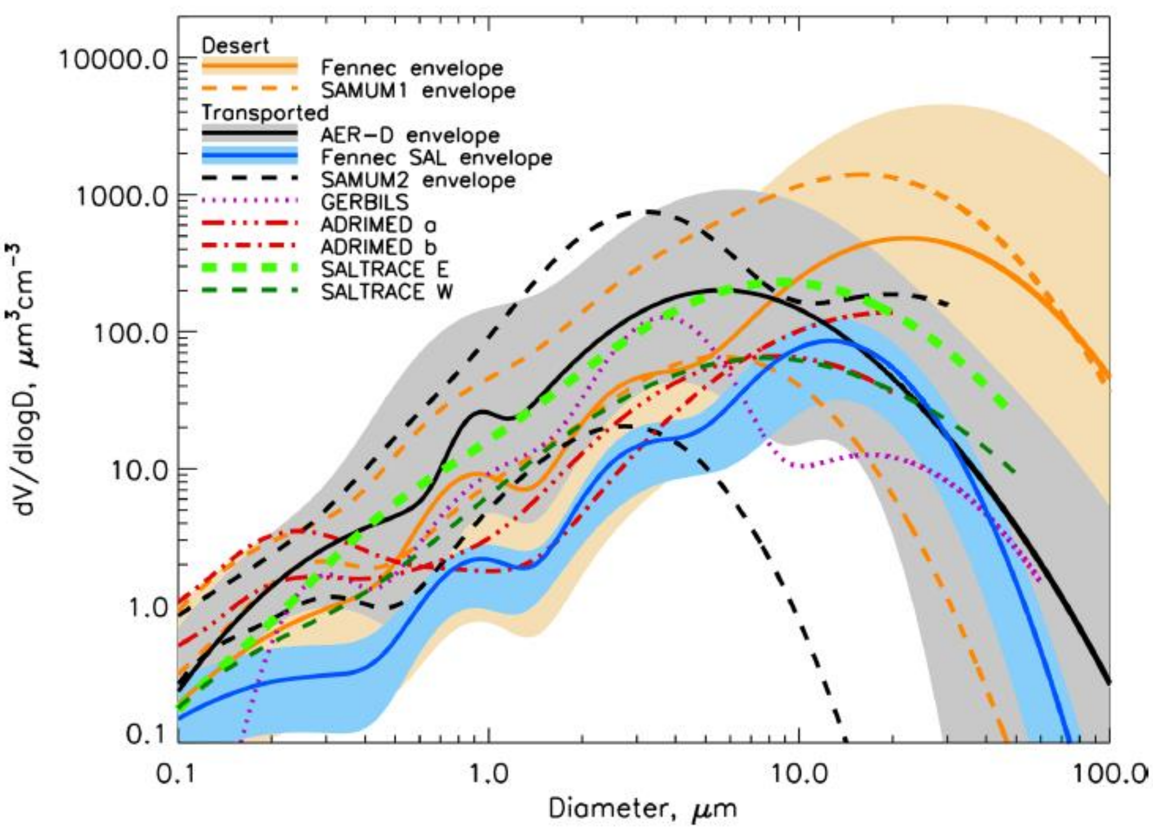
SW & LW Key Points

- Dust optical properties can be significantly different when accounting for the full size range.
- Measurement of dust properties behind aircraft inlets (e.g. d<2.5 microns or submicron) significantly underestimates optical properties. E.g. sampling only d<2.5µm will measure 20-50% of true SW extinction
- Models will be significantly underestimating SW and LW extinction and absorption over the Sahara by excluding and/or under-estimating the coarse dust concentrations
- Omitting or under representing coarse/giant mode → greater underestimation of LW extinction than SW, shifts dust DRE to more positive values
- Changes to atmospheric heating from incorrect model dust properties may impact atmospheric circulation in dusty regions

Caveats

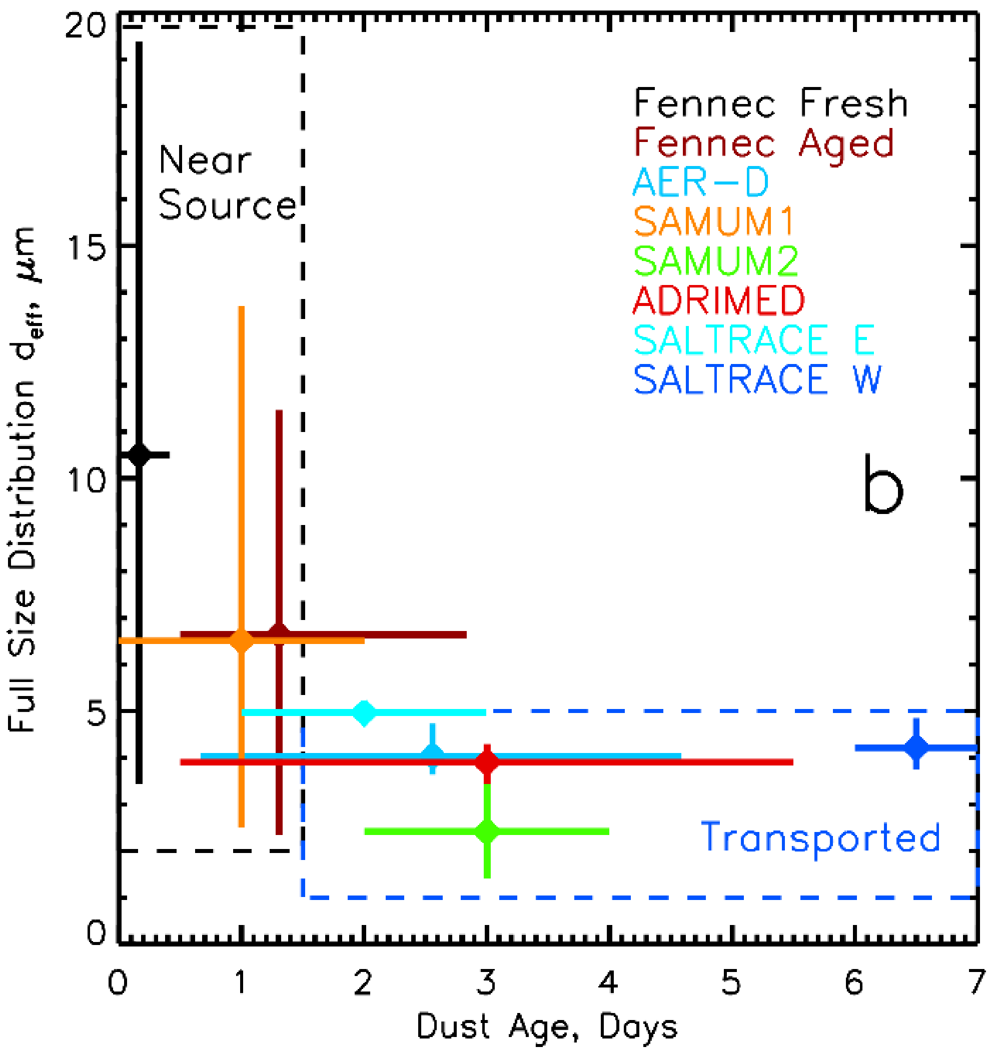
- Results account for absolute exclusion of coarse/giant particles – not additional underestimation of coarse mode by models
  - →Results underestimate impact of coarse mode
- Spherical particle assumptions
  - Little impact in LW
  - Results represent lower bound impact of coarse mode – non-spherical dust increases extinction of coarse particles by ~50%
  - →Results underestimate impact of coarse mode
- Summertime observations used here
  - Peak dust loads in Sahara/SAL
  - Potentially greater contribution from coarse/giant particles (McConnell et al., 2008)
  - →Results may overestimate annual impact of coarse mode

Multi-Campaign Size Distributions



- Compilation of airborne observations measuring Saharan dust, including d≥20μm
- There is always a significant contribution from dust particles sized d>5 μm
- When dust is closer to the source, there is also a strong contribution from particles larger than 20 μm diameter

Change in Dust Size with Age



- Very large particles evident immediately after uplift with high d_{eff} values of 6 to 10μm
- d_{eff} decreases rapidly until around 1.5 days after uplift
- After this observations suggest little change in d_{eff}
- Size distribution stabilizes through transported regime
- Contrary to expectations from gravitational sedimentation

Transport/Deposition Processes

- …Need further investigation to
  a) Improve understanding of coarse particle retention
  b) Improve dust transport in models
- Suggestions…
  - Turbulence
    - AER-D - measured vertical velocities within the SAL were over ±30cms^{-1} in all cases, and sometimes up to ±80cms^{-1}, and mostly net positive in the SAL.
    - Fennec-Sahara – vertical velocities generally >200 cms^{-1} within the convective boundary layer, and frequently >50 cms^{-1} up to 5 km altitude.
    - Gravitational settling velocity of d=10μm particle ~1.1 cms^{-1}, for d=100μm ~28 cms^{-1}.
    - Turbulence could significantly enhance particle lifetime
    - Could be further amplified by solar absorption of coarse/giant particles
  - Other possibilities examined by van der Does (2018, Science Advances):
    - Strong winds, electrical levitation, repeated convective lifting

Conclusions

- Coarse and Giant mode observed over Sahara (Fennec)
  - Strong influence of altitude and dust age, observed d=100 µm up to 3km, 20 µm up to 5km, d_{eff}=2-20 µm
- Over the Tropical Eastern Atlantic (SAL) (AER-D)
  - deff ~ 4µm, vertically homogeneous, d=20µm always present
- Giant mode depleted, in agreement with settling velocities
- Coarse mode depleted with transport, but
  - Still present at long distances from sources
  - Depleted less than expected from sedimentation theory
  - Size distribution appears invariant following initial transport
  - Additional missing mechanisms for retention of coarse mode?
- Considering that at d>5µm (where models begin to under represent coarse dust concentrations), and at d>20µm (models rarely include dust this large), we find:
- Over desert:
  - d>5µm accounts for 59% of SW extinction, 88% SW absorption and 90% of LW extinction
  - d>20µm accounts for 18% of SW extinction, 39% of SW absorption, 26% of LW extinction
  - Large radiative impacts of incorrect size distribution over Sahara desert
- In the SAL:
  - d>5µm accounts for 22-50% of SW extinction, 47-80% of SW absorption and 59-85% of LW extinction
  - d>20µm accounts for 1% of SW extinction, 2% of SW absorption, 2% of LW extinction
  - Moderate impacts of incorrect size distribution in the SAL
- Dust Mass:
  - Over Sahara: ~92% mass in d>5µm, 27% of mass in d>20µm
  - In SAL: 61-87% mass in d>5µm, 2% of mass in d>20µm
- **Coarse/Giant dust particles exist – implications for models - especially over the Sahara!**

See also O'Sullivan et al., 2020, ACPD, 'Models transport Saharan dust too low in the atmosphere compared to observations'