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Aircraft observations of Coarse Dust: Radiative Significance and Model Evaluation

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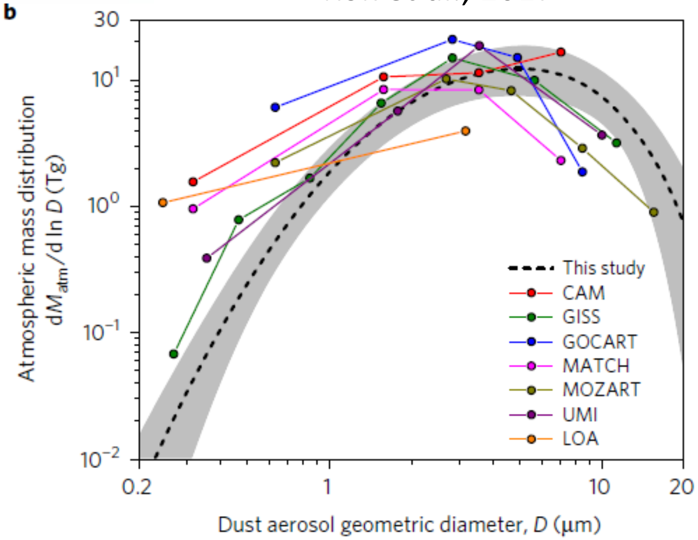
NASA GSFC: Matthew McGill, John Yorks, Patrick Selmer

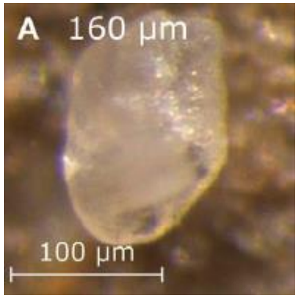
Motivation

- Historically: assumed coarse particles rapidly deposited
- Challenge for measurements, especially airborne, coarse mode frequently not measured at all
- Last 10 years: airborne dust observations 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
- Coarse/giant dust
  - → Reduce SW SSA, SW TOA DRE more positive, more atmospheric heating
  - → Increase LW extinction, LW TOA DRE more positive
  - Impacts on transport/sedimentation patterns, chemistry, cloud interactions, biogeochemical interactions


FAAM BAe146 aerosol measurement systems

Kok et al., 2017

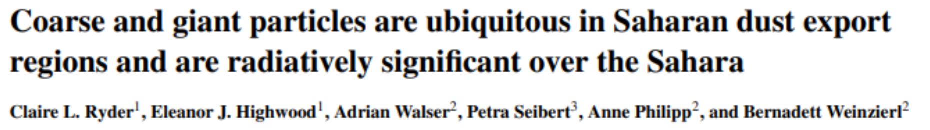




Giant dust observed in long range dust transport
van der Does et al. (2018)

Aims

- Contrast & characterize state-of-the art airborne dust size observations:
    - Measuring d ≥ 100µm; d>10µm from shadow probes: no dependence on refractive index
    - 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)
- Case study of modelled dust size distributions versus observations
- Evaluate the wider context of transport of coarse & giant dust particles
- Full results: Ryder et al. (2019), ACP; O'Sullivan et al. (2020), ACPD



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

Claire L. Ryder[1], Eleanor J. Highwood[1], Adrian Walser[2], Petra Seibert[3], Anne Philipp[2], and Bernadett Weinzierl[2]

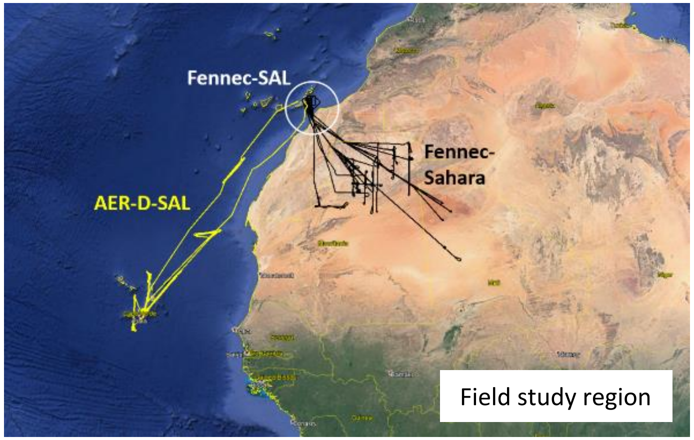
16 Apr 2020

Models transport Saharan dust too low in the atmosphere compared to observations

Debbie O'Sullivan[1], Franco Marenco[1], Claire L. Ryder[2], Yaswant Pradhan[1], Zak Kipling[3], Ben Johnson[1], Angela Benedetti[3], Melissa Brooks[1], Matthew McGill[4], John Yorks[4], and Patrick Selmer[4]

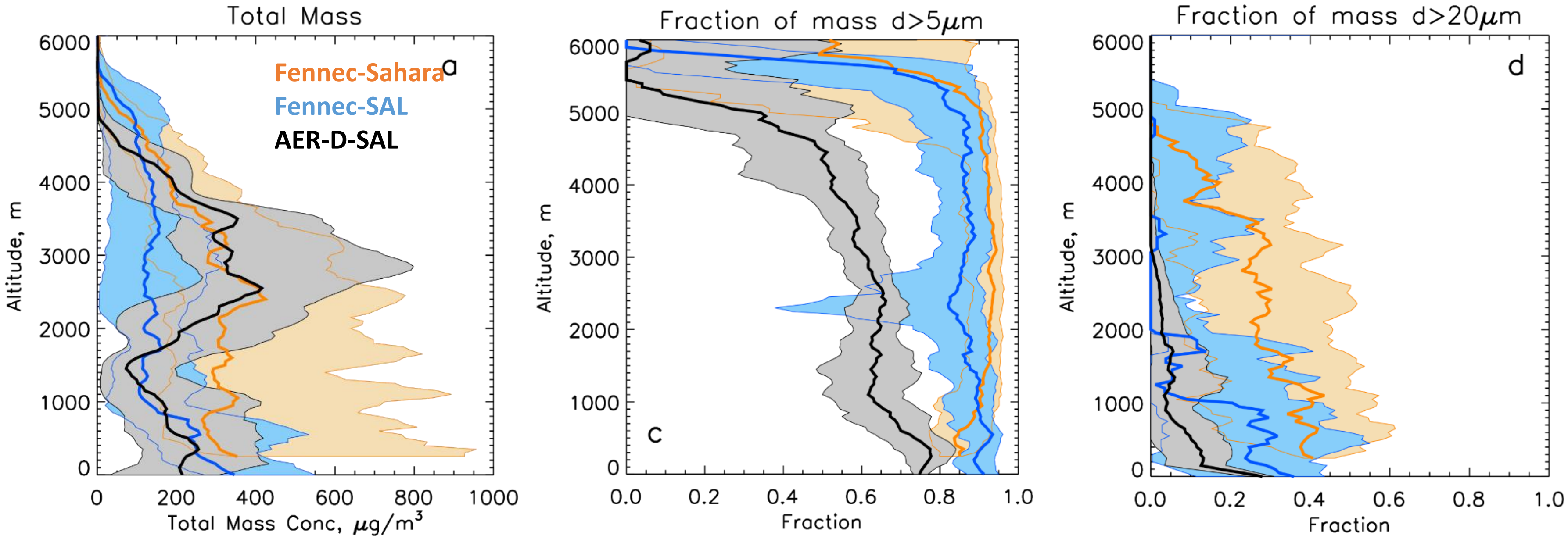
Review status

A revised version of this preprint was accepted for the journal ACP and is expected to appear here in due course.



Field study region

Mass Concentration Profiles



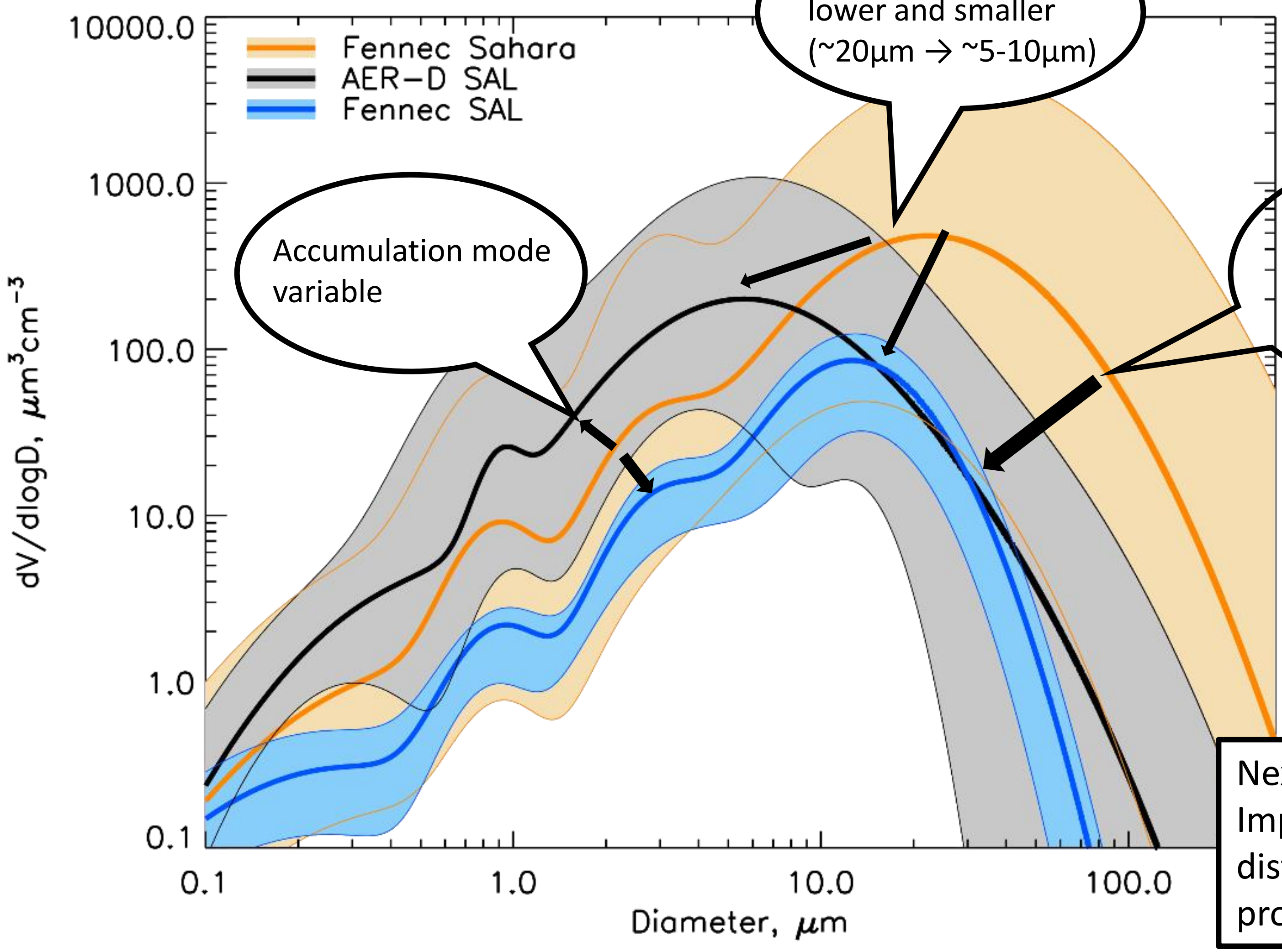
a) Total Mass
  - Largest mass over Sahara; Decreases with altitude; SAL well-mixed

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



Volume distribution lower and smaller (~20µm → ~5-10µm)

Accumulation mode variable

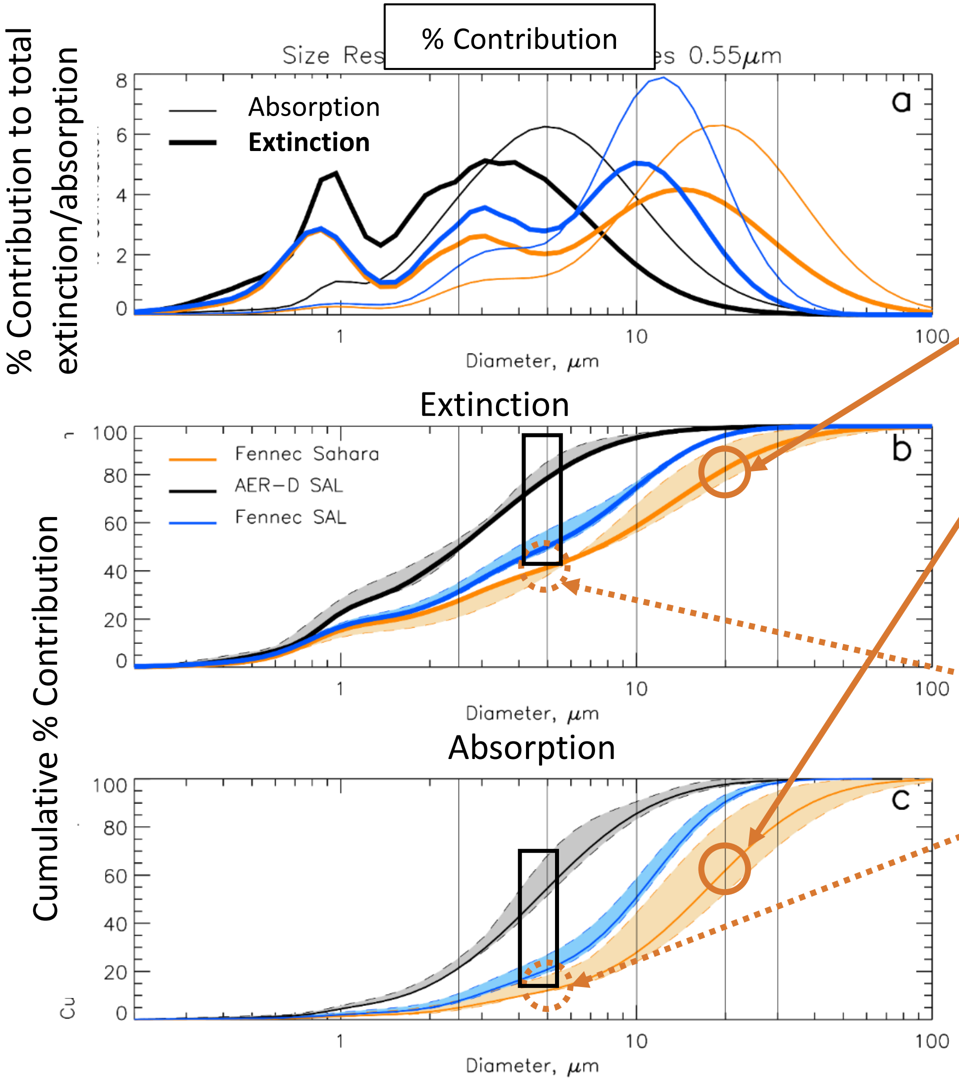
Substantial loss of giant mode (but still present)

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

Impact of Size Distributions on Optical Properties?

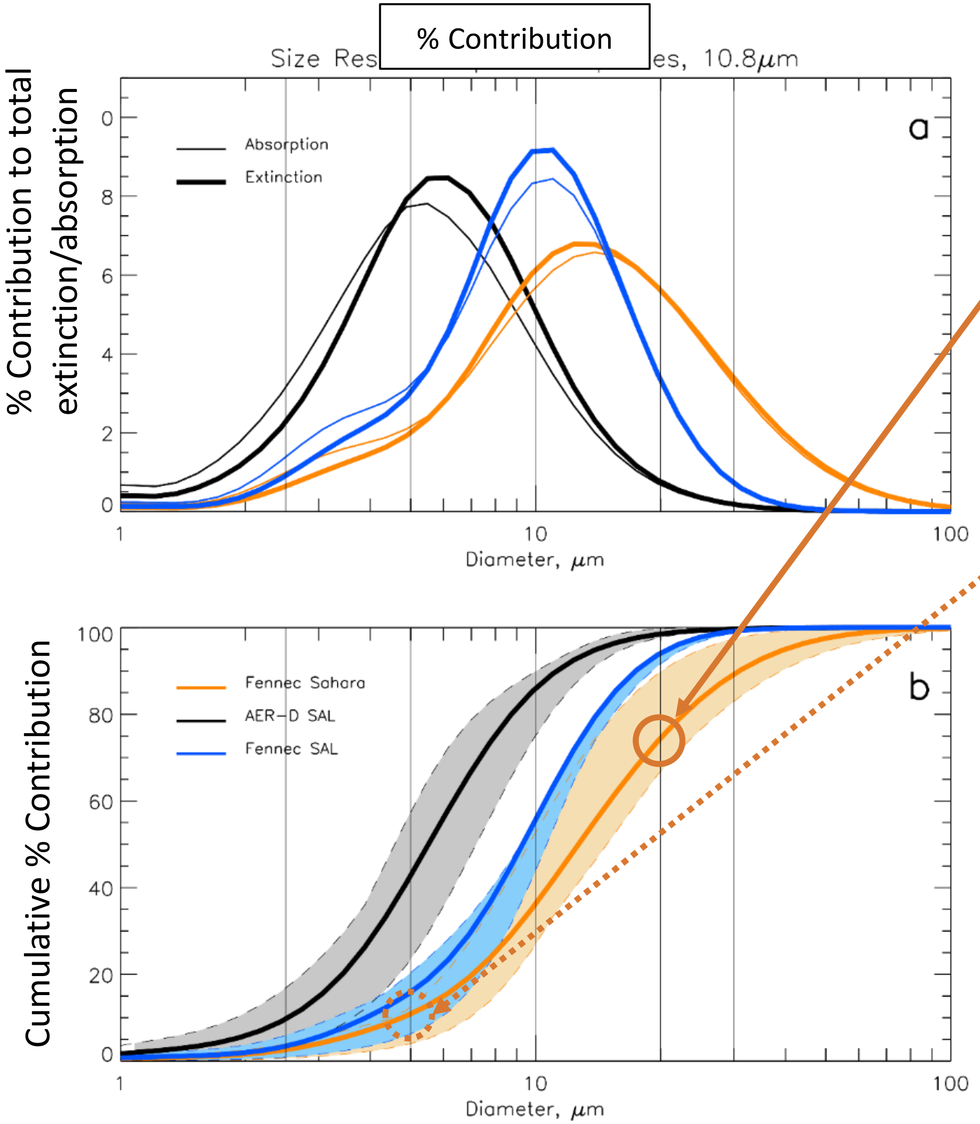
- Aim - assess the impact of the different measured size distributions on optical properties
- Method – Run Mie Scattering code with gradually incrementing maximum diameter for each field campaign. Use a range of refractive indices from the literature. Include uncertainty in measured size distribution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

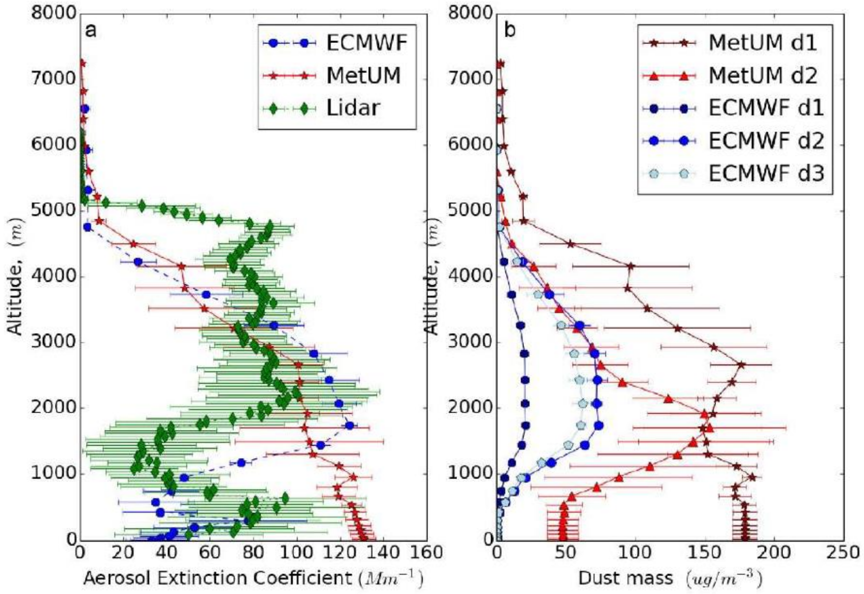
SW & LW Key Points

- 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

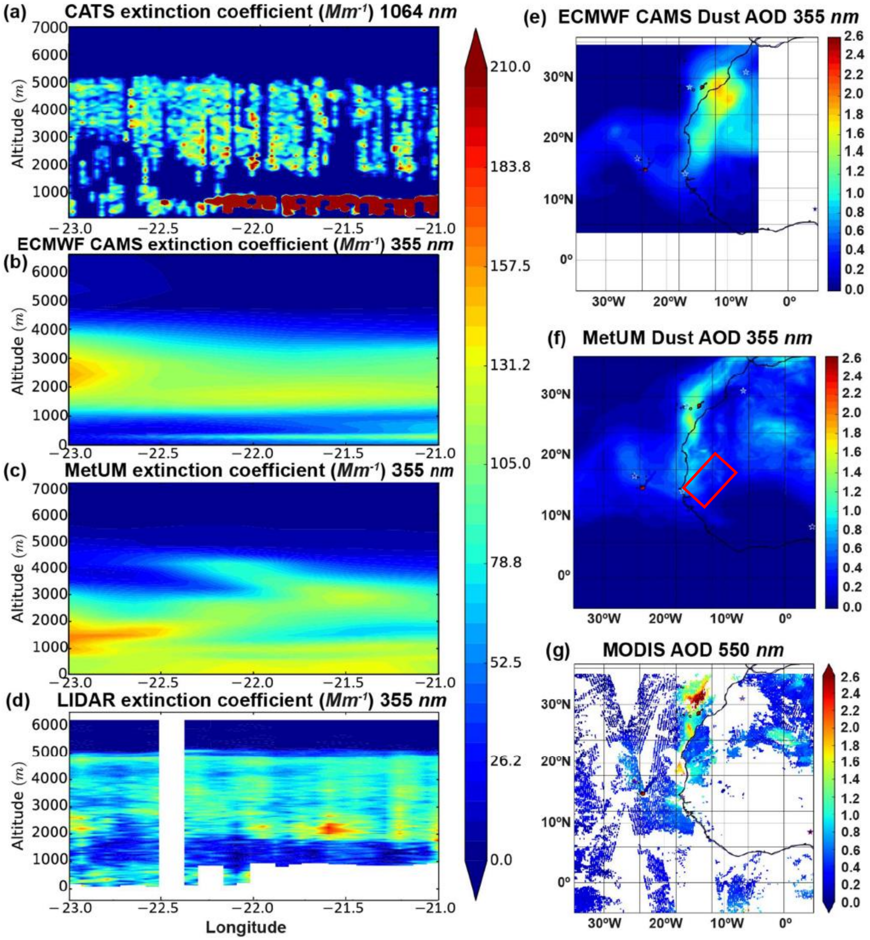
NWP Model Evaluation in the SAL

- Comparison between aircraft, models & satellite
  - Unique opportunity for model evaluation, where vertically resolved size distributions including giant particles are also available
  - 4 case studies evaluated (1 shown here)
- Models: both assimilate MODIS AOD, short range (<12h) forecasts used
- ECMWF Copernicus Atmospheric Monitoring Service (CAMS) operational forecasts
  - Resolution ~80km
  - 3 dust bins: d1 (0.06-1.1μm), d2 (1.1-1.8μm), d3 (1.8-40μm)
- Met Office Unified Model (MetUM), global NWP forecasts
  - Resolution ~40km at equator
  - 2 dust bins: d1 (0.2-4μm), d2 (4-20μm)
- Aircraft in-situ observations – vertical distribution of size-resolved mass
- Lidar extinction from aircraft and CATS
- MODIS C6.1 AOD

Case Study 1: Transect Comparisons



- Aircraft lidar AODs 0.28-0.44
- Spatial distribution of AOD & plume show some differences, models underpredict max AOD by 0.9-0.6
- Extinction
  - CATS & airborne lidar – dust 2-5km
  - CAMS dust 1-4km, MetUM 0-4km
  - Magnitudes comparable
- Model dust concs very different despite agreement in extinction

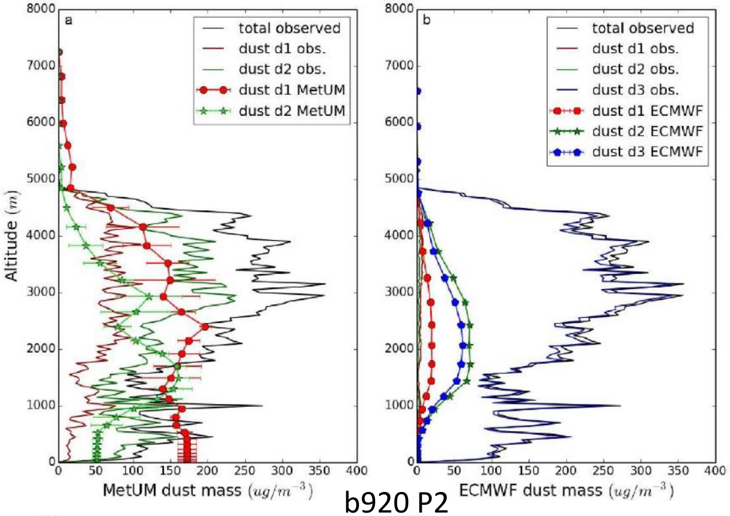


B920, 7th Aug 2015

Case Study 1: In-situ profile comparisons

CAMS
d1: 0.06-1.1µm
d2:1.1-1.8µm
d3: 1.8-40µm
MetUM
d1:(0.2-4µm
d2: 4-20µm

MetUM v Obs b920 P1 CAMS v Obs



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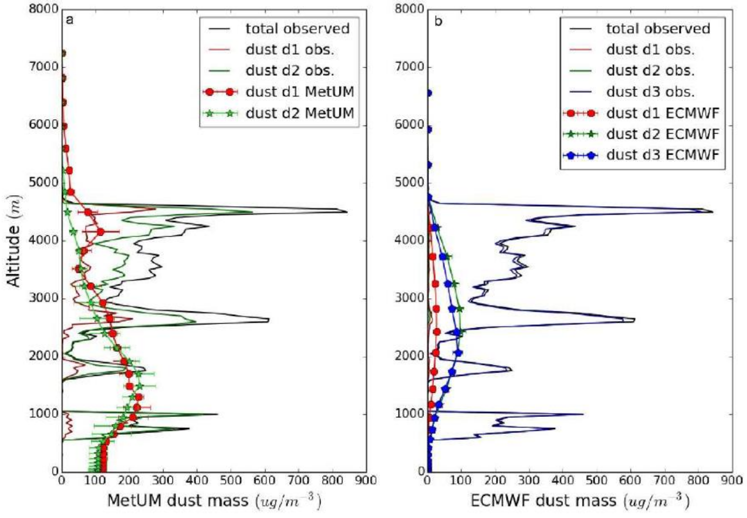
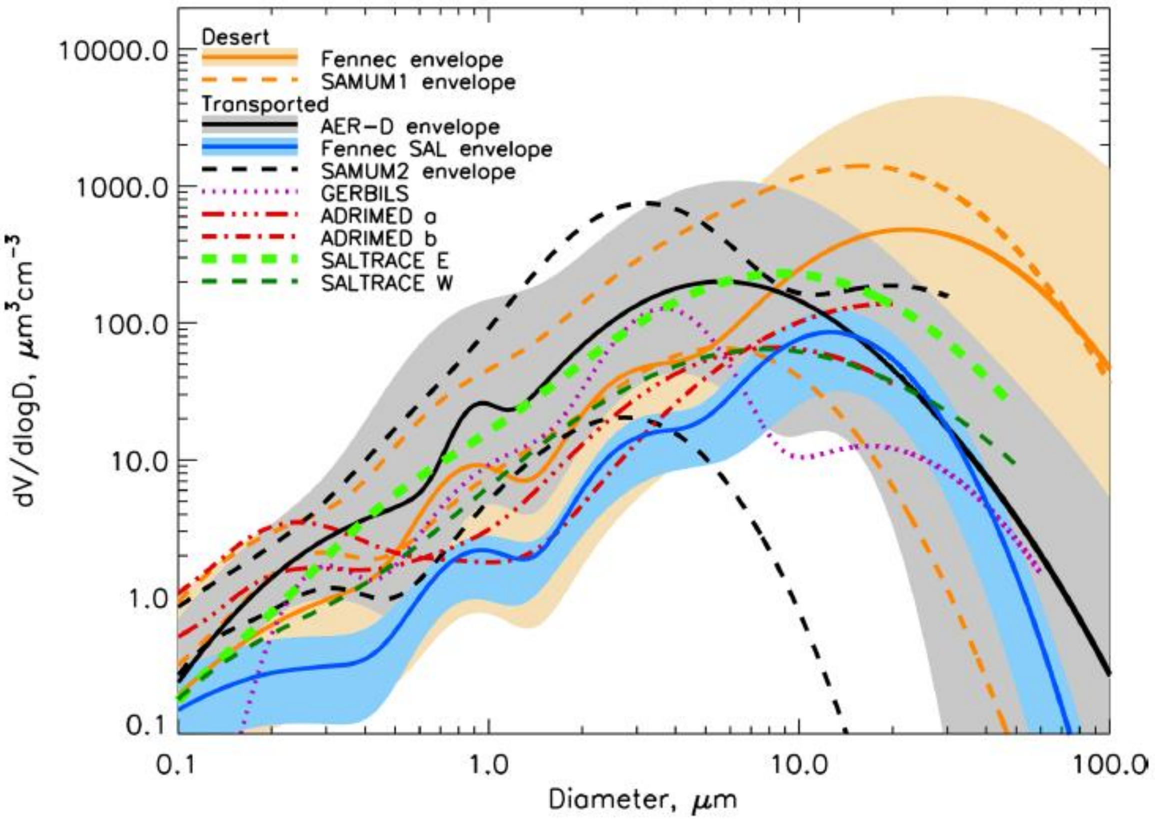


- Models struggle to capture dust concentration for each size bin compared to observations
- Models underestimate mass in larger size bins, overestimate mass in smaller size bins
- Model peak dust higher than observed

General Findings from case studies

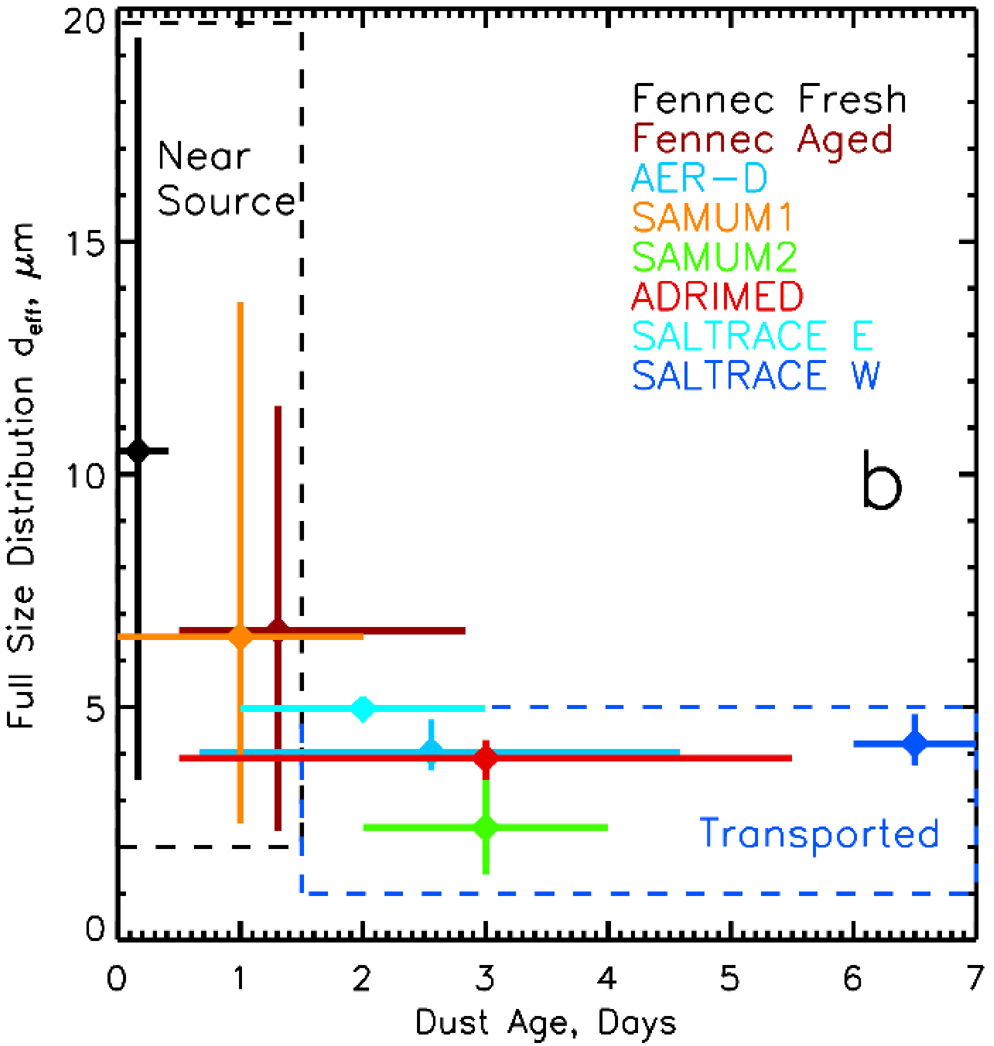
- Models underpredicted AOD by ~0.6-1.5
- Extinction profiles showed both models predicted dust 0.5-2.5km too low in the atmosphere; CAMS slightly better
- Modelled extinction within 50% of observations
- Modelled dust concentration differences 25-100% from observations. Most cases had around a factor of 2 too much dust mass in the smaller size bins.
- Models validated/tuned against AOD, and assimilate AOD, even though dust mass is the modelled quantity
- AOD (extinction) pulled towards observations even though microphysical properties are out of scale
- Mismatch in concentrations can be compensated for through a bias in size distribution, with enhanced fine particles which have higher extinction efficiency
- Some suggestion that models are depositing the coarse particles too rapidly
- Vertical distribution & size distribution impact dust transport, e.g. AOD gradient across Atlantic

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

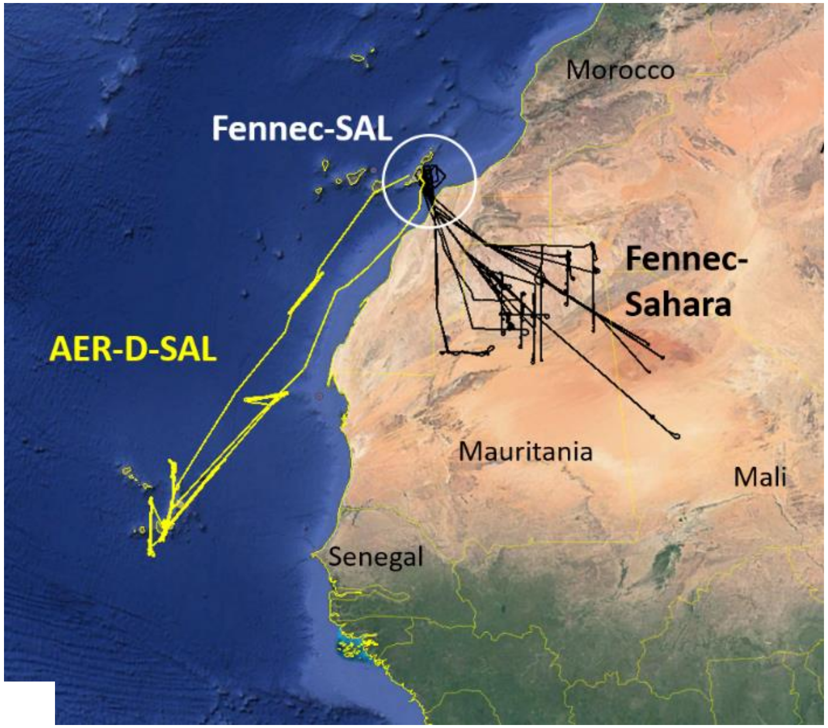
Conclusions

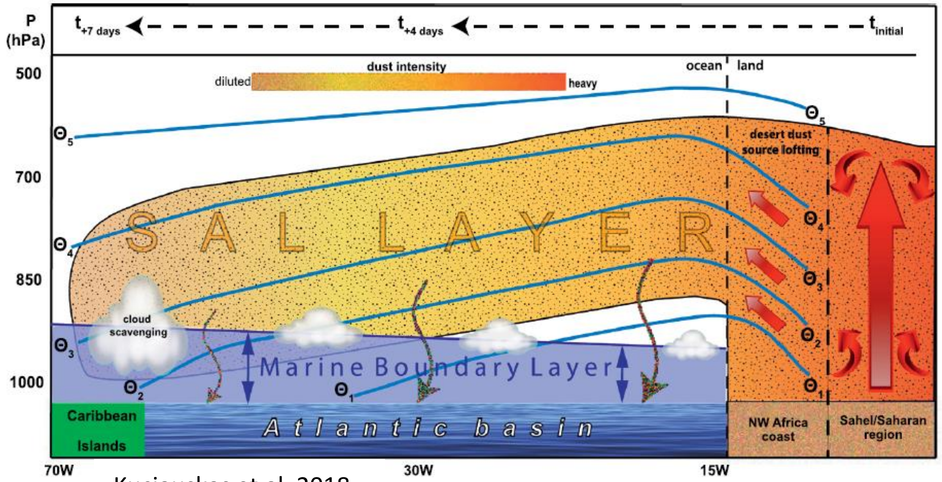
- Coarse and Giant mode observed over the Sahara and Eastern Tropical Atlantic
- Giant mode depleted, in agreement with settling velocities
- Coarse mode depleted with transport, but
  - Still present at long distances from sources
  - Depleted less than expected from sedimentation theory
  - Size distribution appears invariant following initial transport
- 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
- Dust in CAMS & MetUM models
  - Too low in the atmosphere
  - Coarse mass underestimated, fine mass overestimated
  - PSD bias can exist despite good agreement of AOD and extinction due to tuning & assimilation of AOD
- **Coarse/Giant dust particles exist – implications for models - over the Sahara but also downstream**

Supplementary Slides

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)

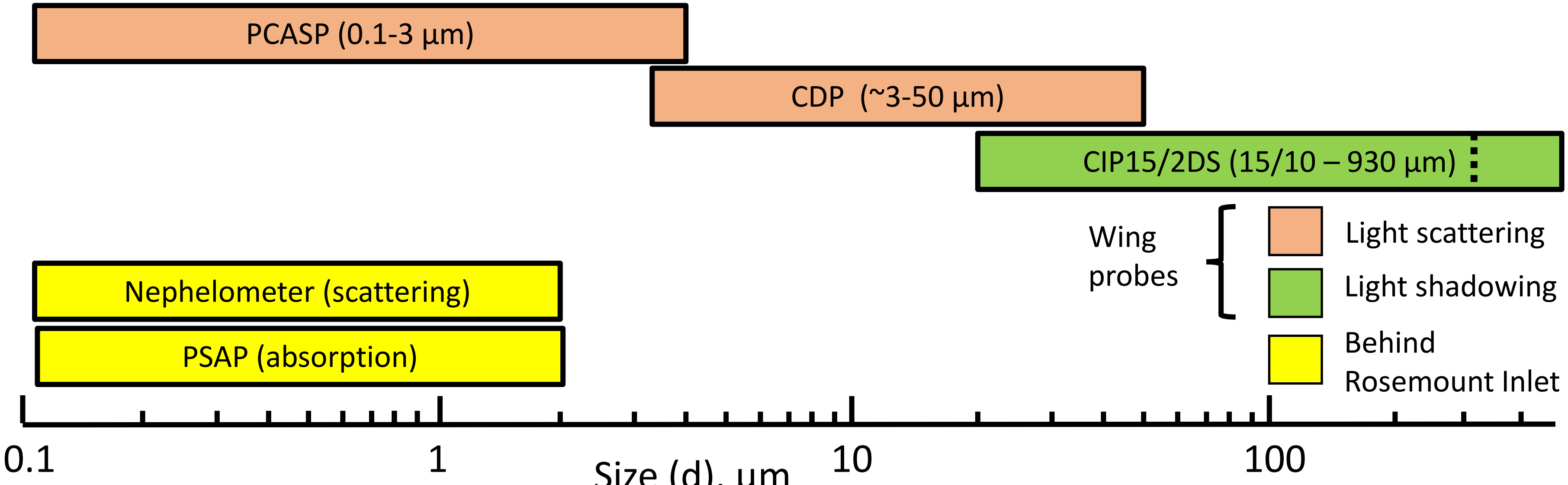




Kuciauskas et al. 2018

FAAM BAe146 Research Aircraft

Fennec and AER-D Measurements of Aerosol Size



PCASP (0.1-3 µm)

CDP (~3-50 µm)

CIP15/2DS (15/10 – 930 µm)

Nephelometer (scattering)

PSAP (absorption)

Wing probes
🟧 Light scattering
🟩 Light shadowing

🟨 Behind Rosemount Inlet

0.1 1 10 100

Size (d), µm

- 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 derived size

LW/SW 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