InDust Webinar Series, 24th March 2021

University of Reading

Giant Dust Particles

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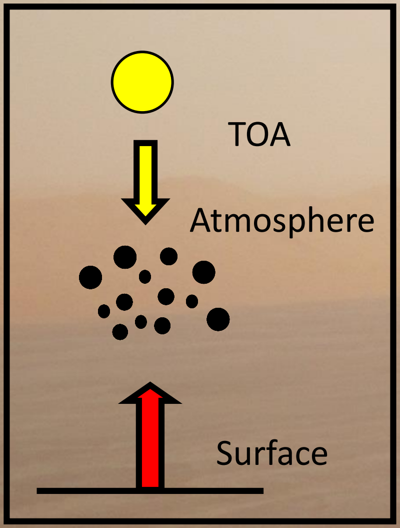
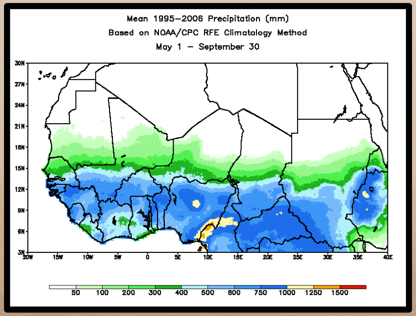
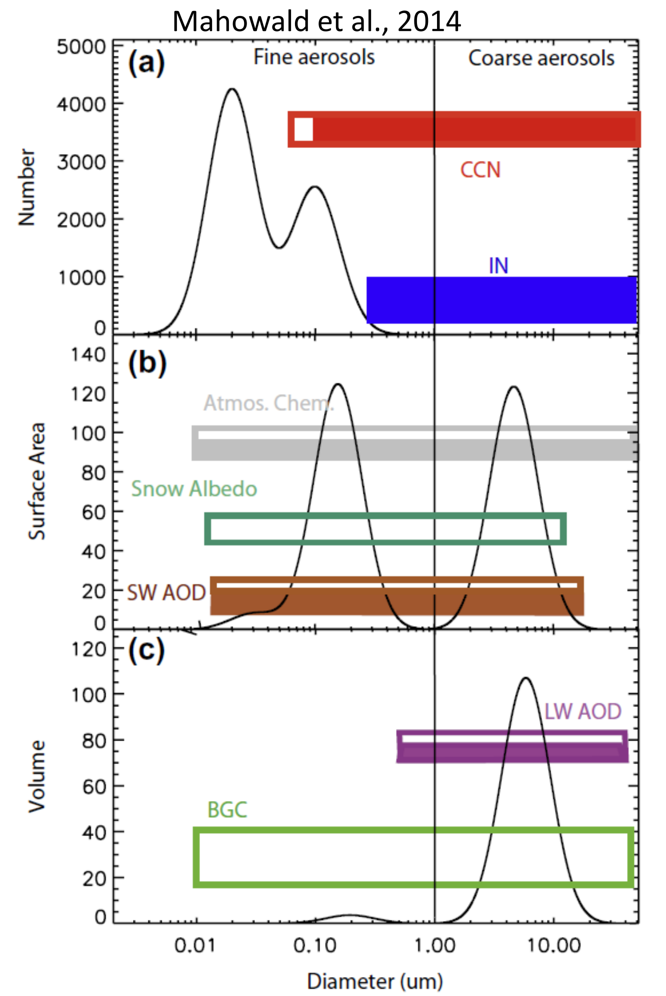
The Importance of Dust

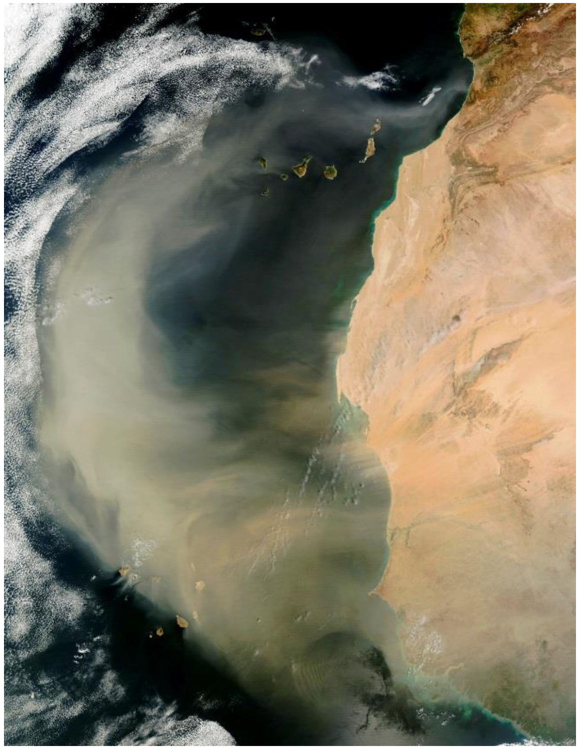




Importance of Dust Size Distribution

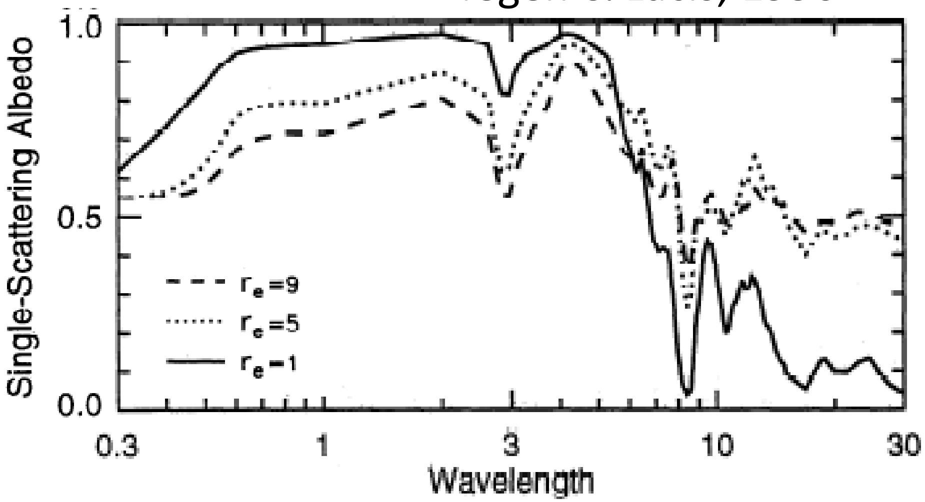


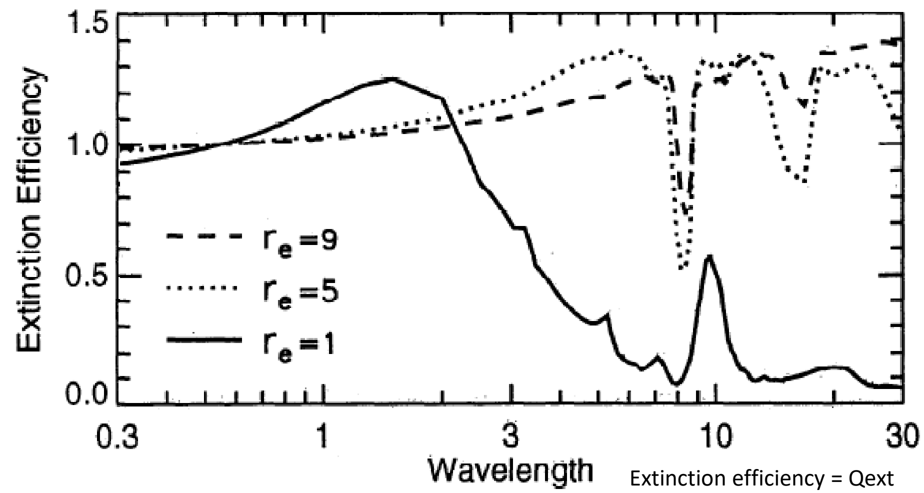
- Transport distances
- Dust Layer altitude



Dust size: the radiation perspective

Tegen & Lacis, 1996



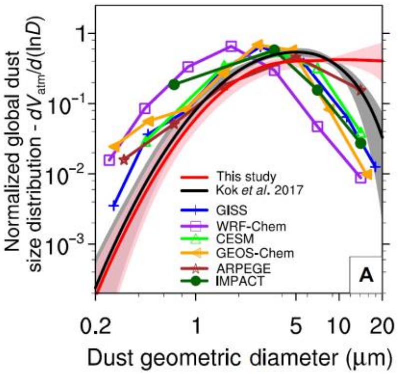


Extinction efficiency = Qext normalized to 0.55 µm value

- Solar wavelengths:
  - Larger particles reduce SSA
  - TOA forcing more positive, more atmospheric heating
- Terrestrial wavelengths:
  - Larger particles increase the extinction efficiency
  - Stronger longwave radiative effect

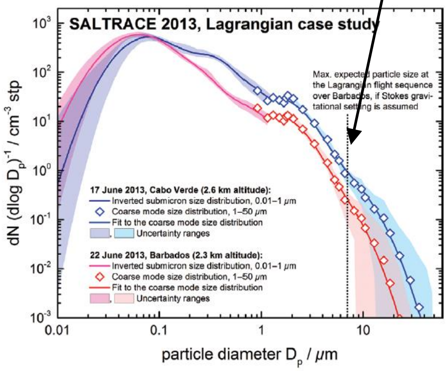
Motivation

- Historically: assumed coarse particles rapidly deposited
- Challenge for measurements, especially airborne, coarse mode frequently not measured at all
- Challenges where coarse mode was measured:
  - Inlets reducing transmission of coarse particles
  - Internal pipework causing loss of coarse particles
  - Uncertainties from optical scattering measurement techniques
- 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
  - Model dust is too cooling
- Aim:
  - Quantify the presence of coarse dust from aircraft observations in different regions
  - Quantify its contribution to optical properties



Adebiyi & Kok, 2020, Sci Adv:
- 4 times more coarse dust than climate models simulate
- Adds $0.15 Wm^{-2}$ warming

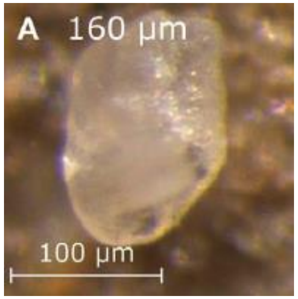
Max expected size at Barbados from gravitational settling

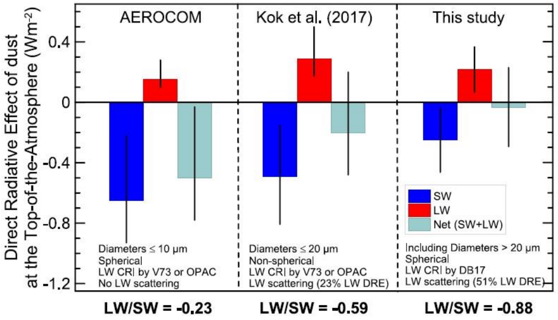


Weinzierl et al., 2017, BAMS

Di Biagio et al., 2020, GRL:
- Size extended beyond 20µm, CRI updated
- Global dust DRE $=0.03 Wm^{-1}$

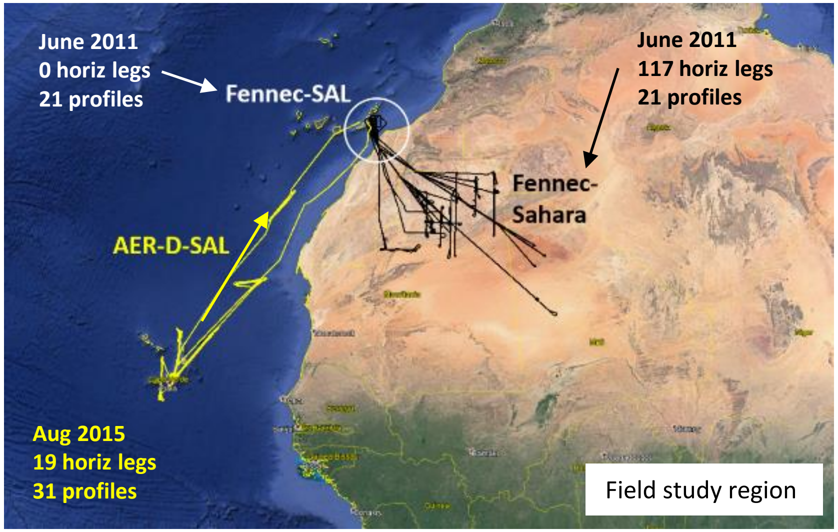
Giant dust observed in long range dust transport van der Does et al. (2018)





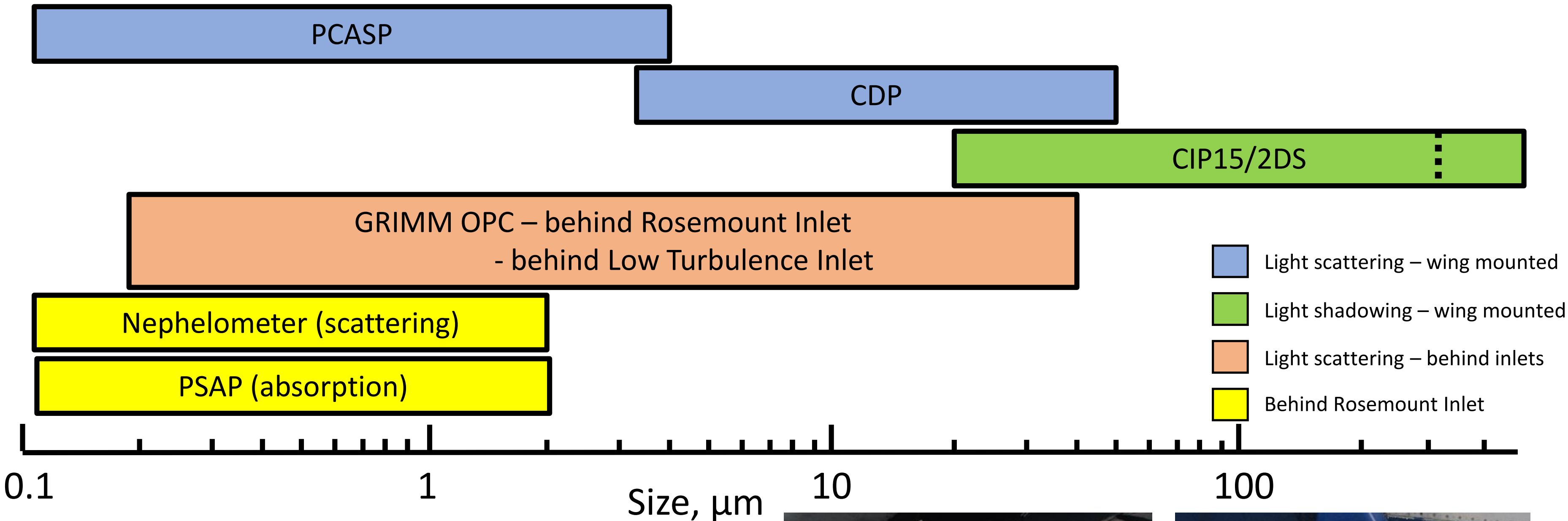
Fennec and AER-D Airborne Campaigns

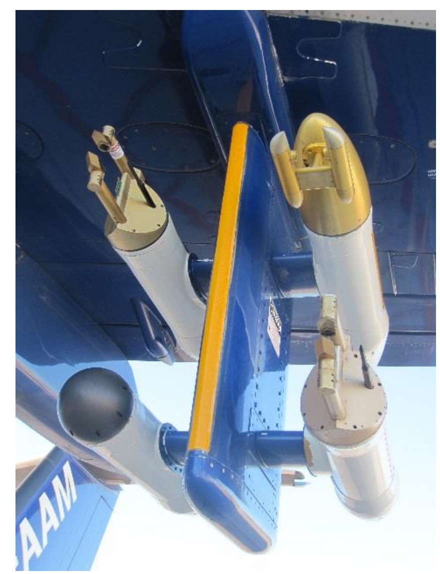
- Fennec
  - June 2011/June 2012
  - Canary Islands to Mauritania & Mali
  - Far into remote desert
  - Fresh uplift, aged background dust
  - Ryder et al. (2015)
- AER-D (AERosol Properties – Dust)
  - With ICE-D
  - August 2015
  - Praia, Cape Verde Islands
  - Marenco et al. (2018)
- Fennec Movie:
  - Into the Cauldron
  - http://fennec.ouce.ox.ac.uk/movie.html



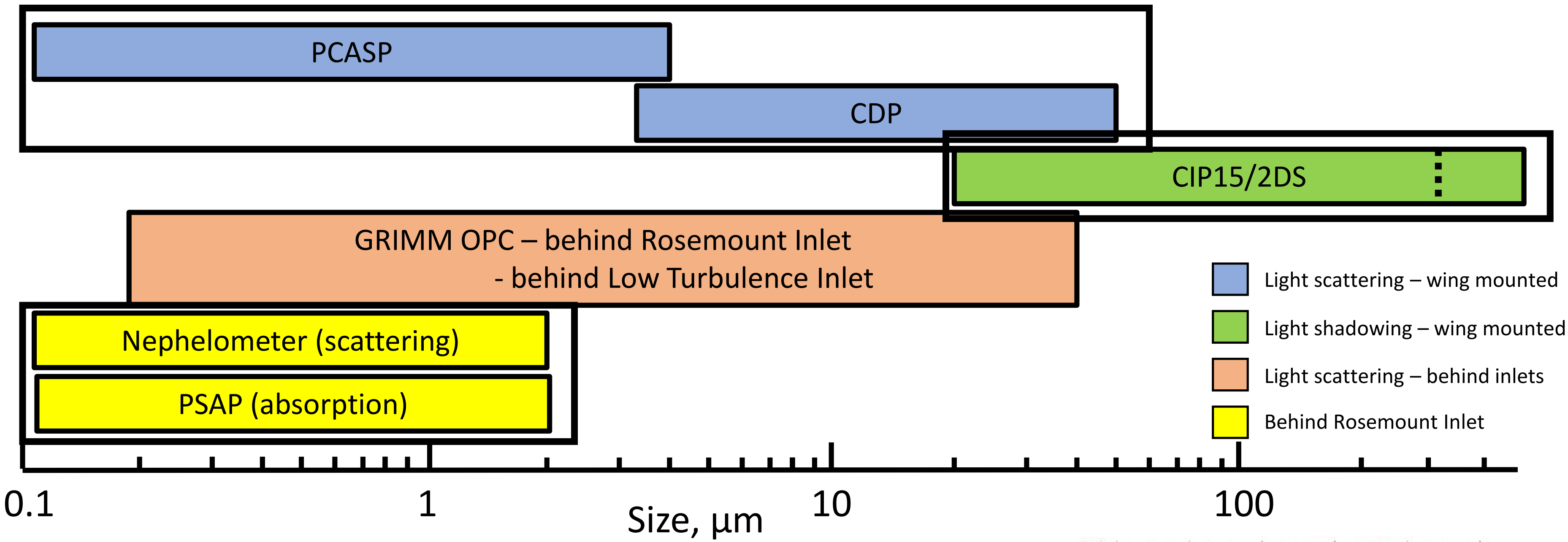
FAAM BAe146
Research Aircraft

Airborne Measurements of Aerosol Size

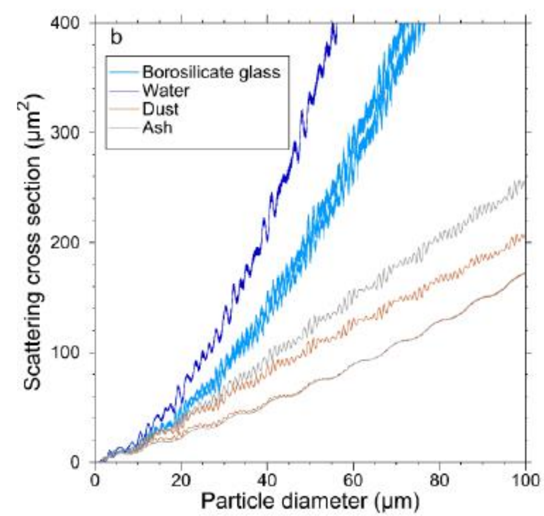




Airborne Measurements of Aerosol Size



- Light scattering
  - Scattering cross-section converted to particle size
  - Depends on refractive index (composition) of particle
  - Not a unique solution – uncertainties can be large
  - Wing Probes (no inlets)
- Light shadowing
  - OAPs (optical array probes) – geometric
  - Sensitive to sizing metric/shape
  - Wing Probes (no inlets)
- In-cabin measurements (behind inlets)
  - Restrict measurement to a portion of the size range
  - Can bias optical properties



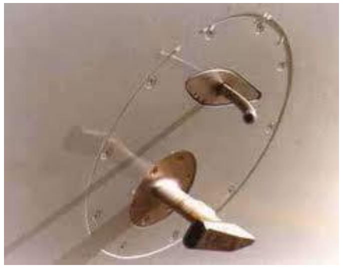
Rosenberg et al., 2012

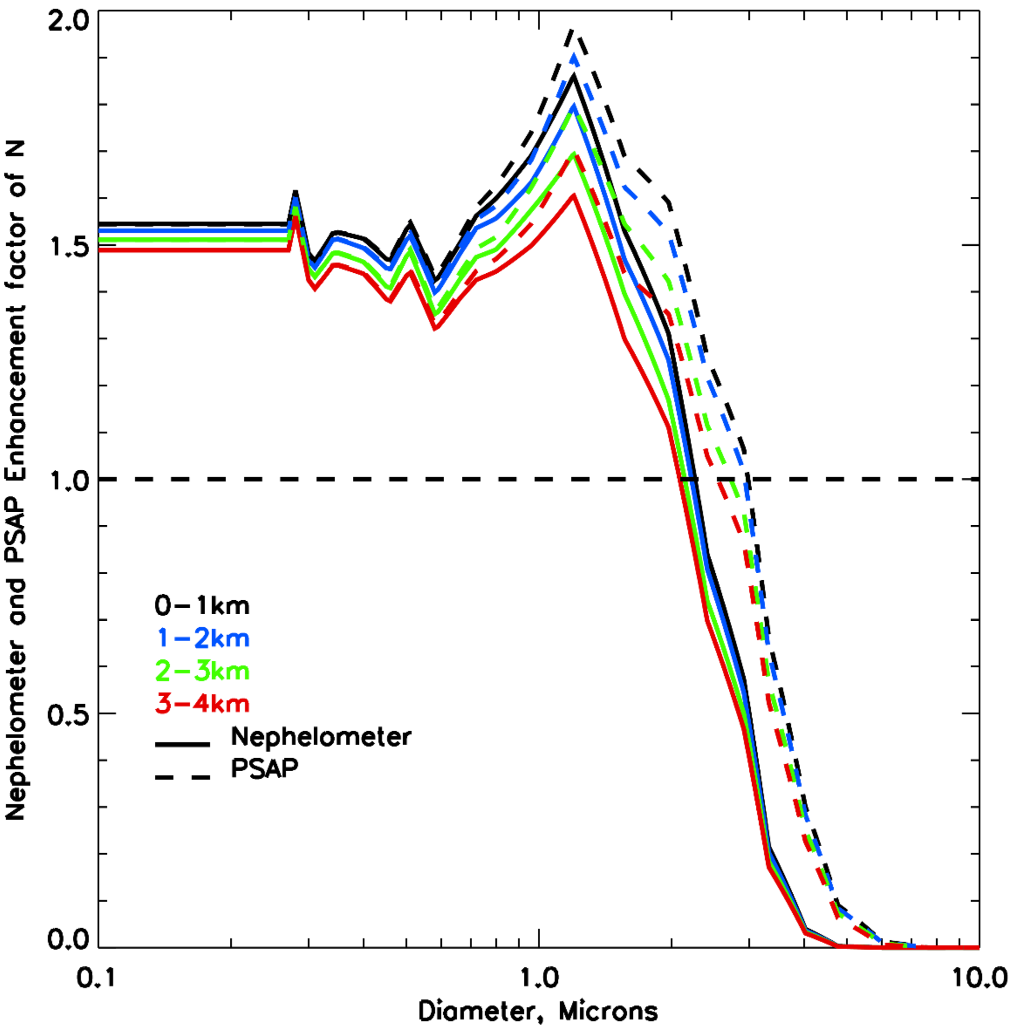
Fennec: Inlet Characterization

- Size distribution (PSD) measured behind
  - Rosemount inlets
    - Suffer loss of coarse particles
  - New Low Turbulence Inlet (LTI)
    - Size losses well-characterized
- Evaluate losses by Rosemount inlets for first time
- Modelled pipeline losses
- Nephelometer & PSAP (scattering, absorption: SSA) do not measure d>2.5µm
- Biased towards smaller sizes

Low Turbulence Inlet

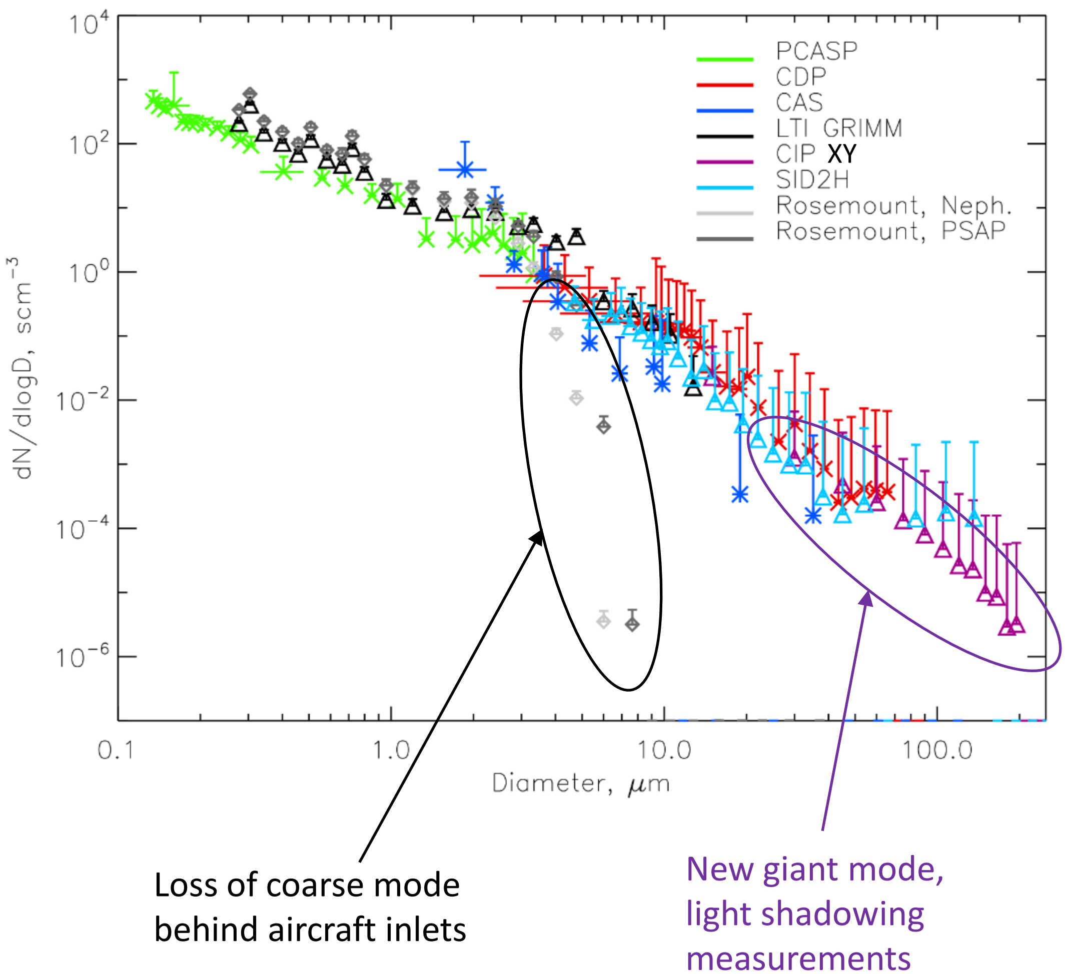
Rosemount Inlet





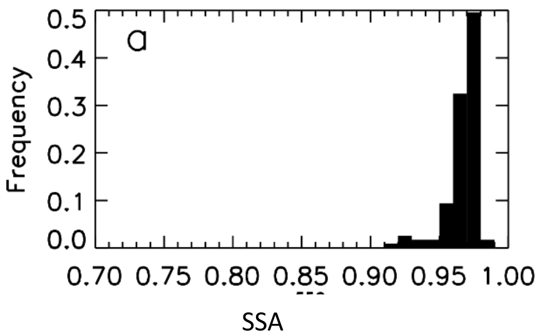
Fennec: Light Shadowing Measurements

- CIP15:Cloud Imaging Probe, wing-mounted
- Light shadowing Measurement technique
- First airborne CIP15 measurements in dust
- Confirmed presence of coarse and giant particles
- Validated optical probes measurements of coarse particles



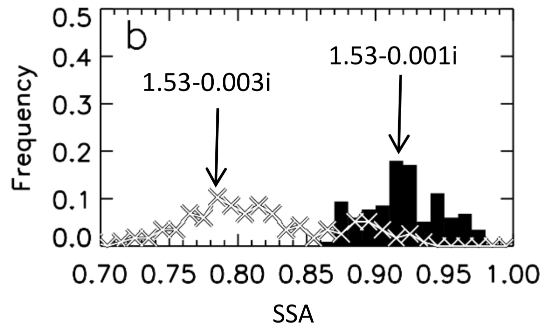
Ryder et al., 2013b, ACP

Impact of new Measurements on Optical Properties



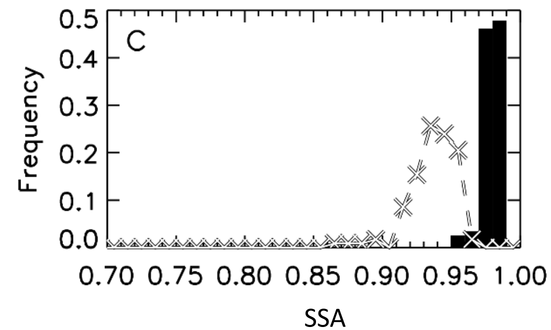
Observations, behind inlet

SSA=0.91-0.99



Mie Calculations,
Full Size Distribution

SSA=0.86-0.97



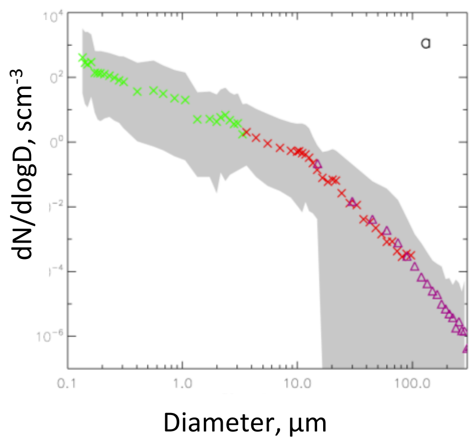
Mie Calculations,
Size Distribution behind inlet

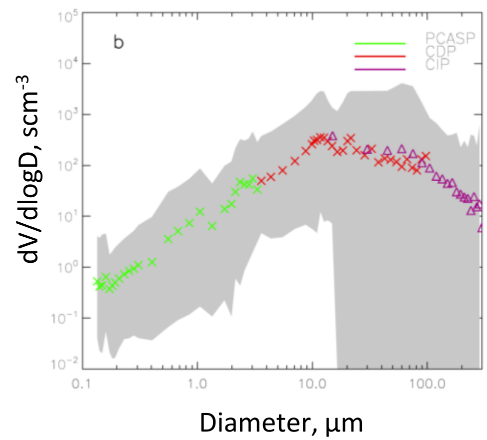
SSA=0.95-0.99

- Observations behind Rosemount inlets omit coarse particles
- 550nm SSA observations behind Rosemount inlets are an overestimate. I.e. absorption, (& warming effect) is underestimated
- Radiative transfer calculations: SW heating rates are 2-3 times greater with measured coarse particles

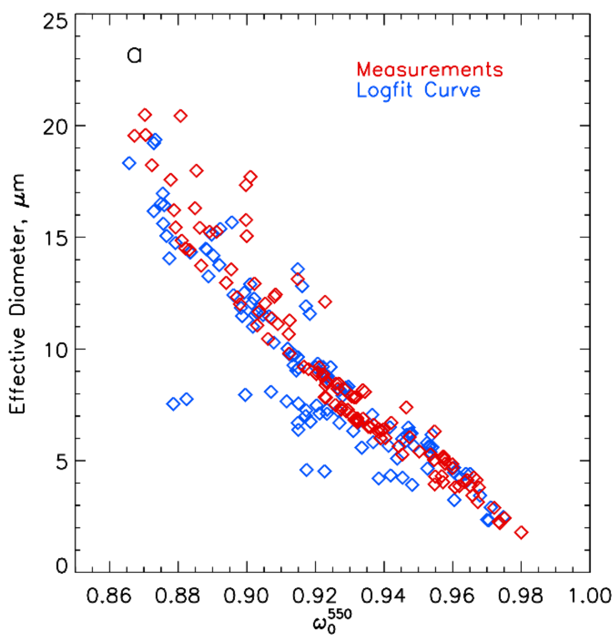
Ryder et al., 2013b, ACP

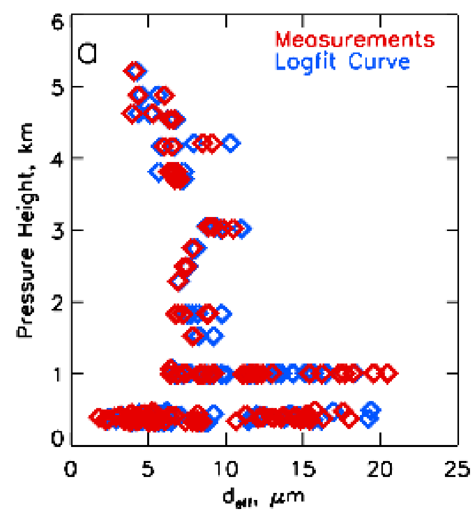
SSA vs Size in Fennec



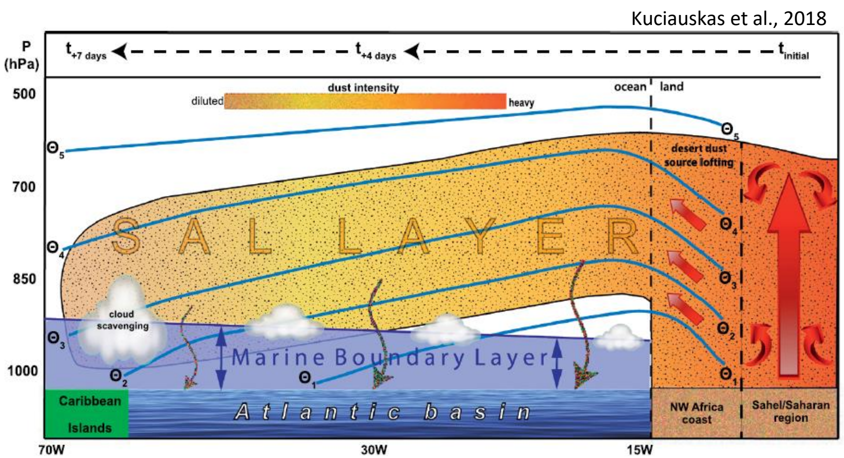


- During Fennec, size distribution was highly variable
- Volume PSD peak ~20µm
- SSA variability was strongly controlled by particle size distribution
- Largest sizes dominate at low altitudes, z<1km
- D_{eff} 4-10 µm found up to 5km throughout Saharan Residual Layer
- Potential for long transport times and radiative interactions



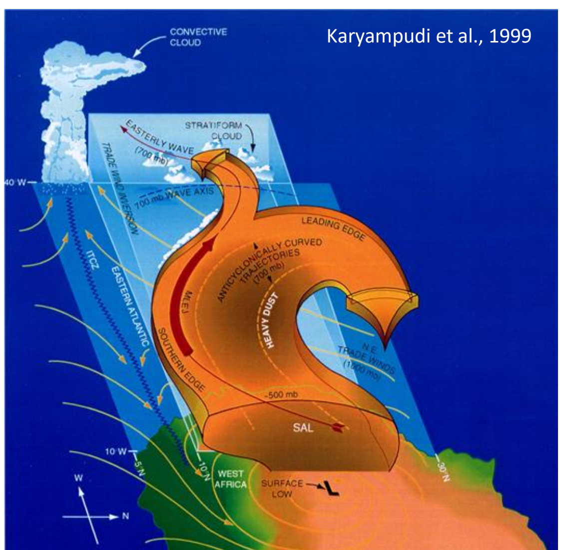


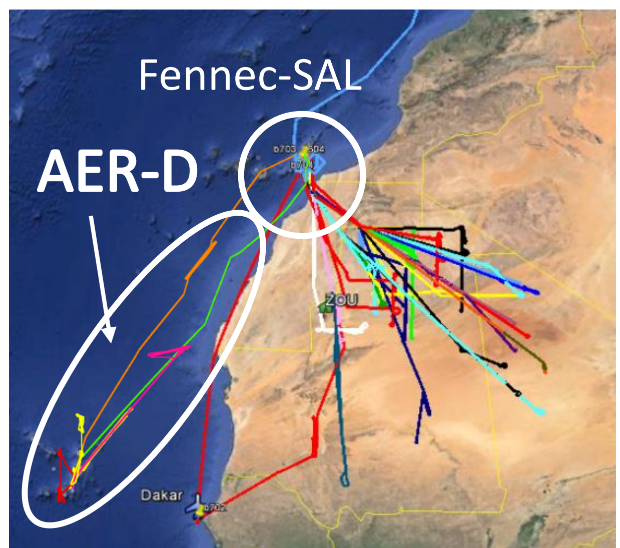
Coarse particles in long-range dust transport



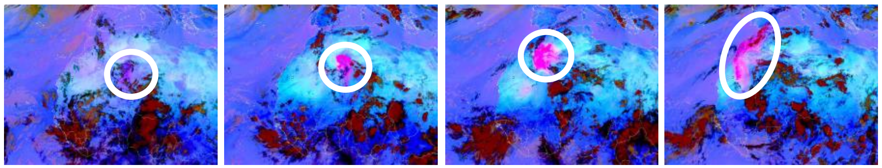
- Coarse particles are prevalent over the remote Sahara
- Are they present, and to what extent, over the tropical Atlantic?

1. Observations from Fennec over Canary Islands
2. Observations from AER-D in the Saharan Air Layer





Impact of Transport on size: Fennec

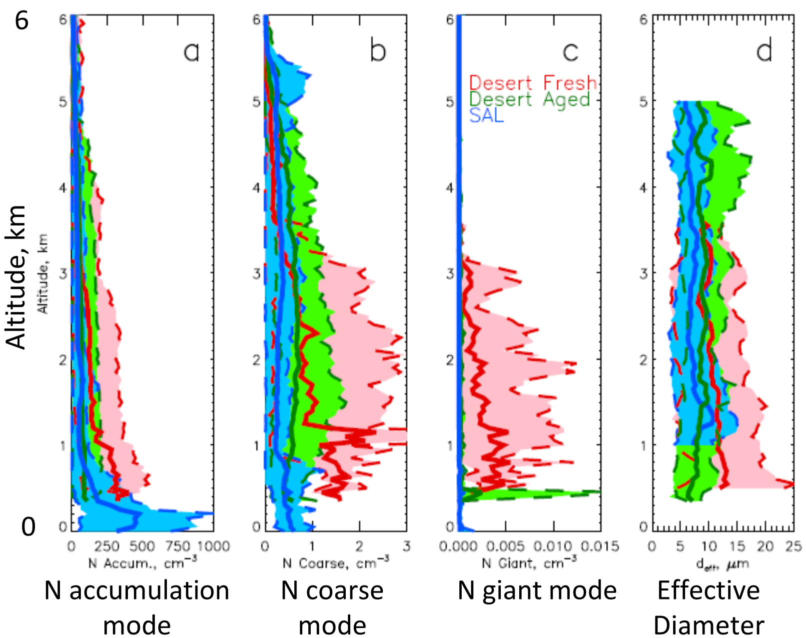


Estimating dust age:

Fresh: <12h since uplift

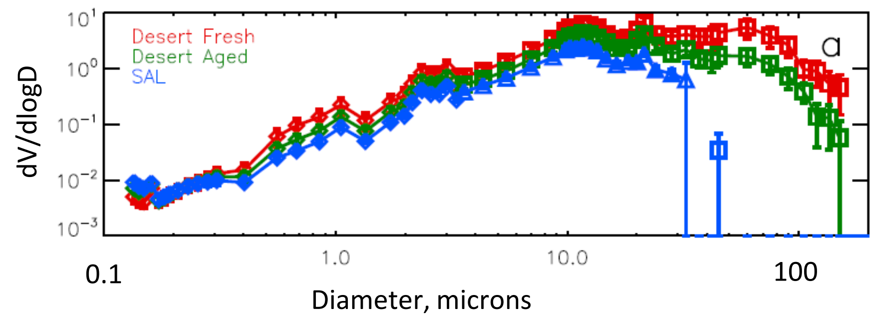
Aged: >12h since uplift

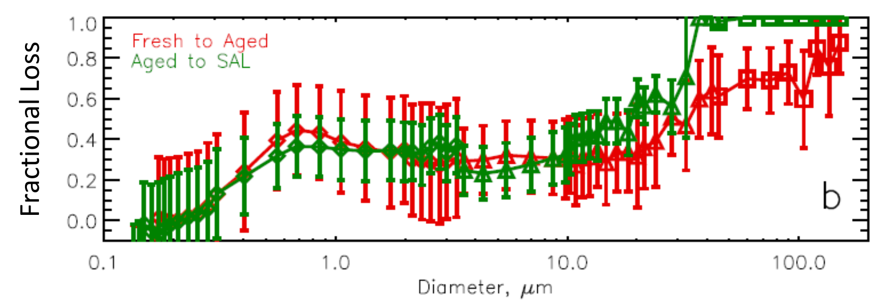
SAL: at Canary Islands, 18-120h since uplift



Ryder et al., 2013a, GRL

- Giant mode (d>37.5µm) expected to fall out within ~12h (5km SABL) – supported by observations
- Coarse mode fall 5km in 20h (30µm) or several days (4µm) – not observed

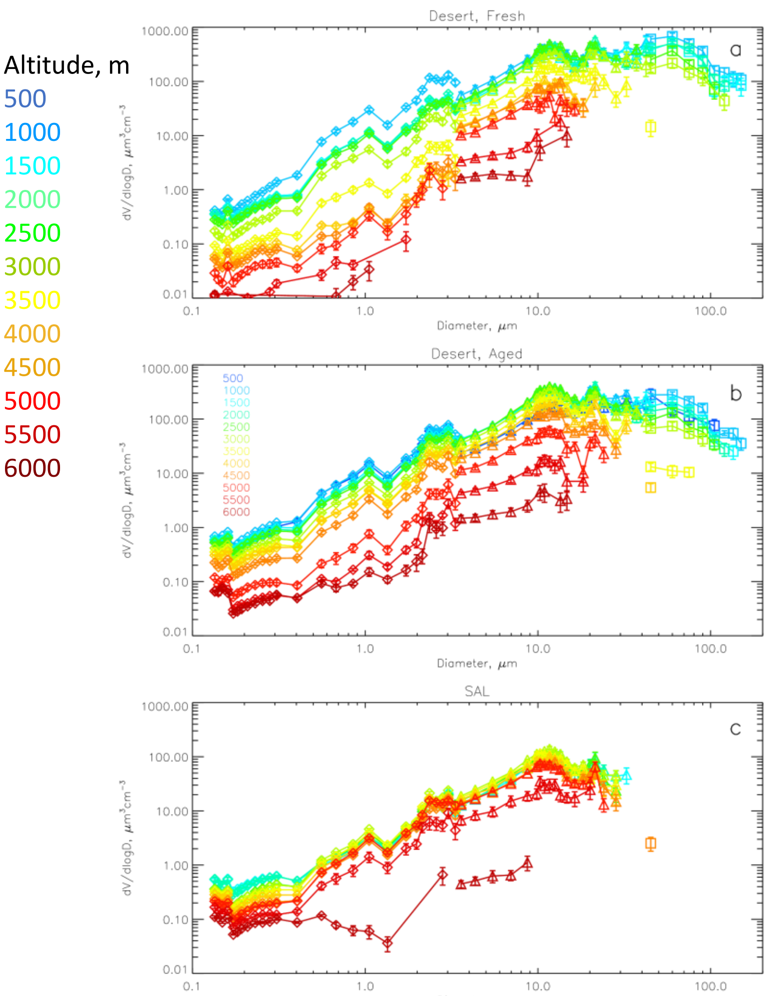




Ryder et al., 2013a, GRL, after Maring et al., 2003

Coarse/giant particles transported further than explained by settling velocities

Size Distribution: Transport & Altitude



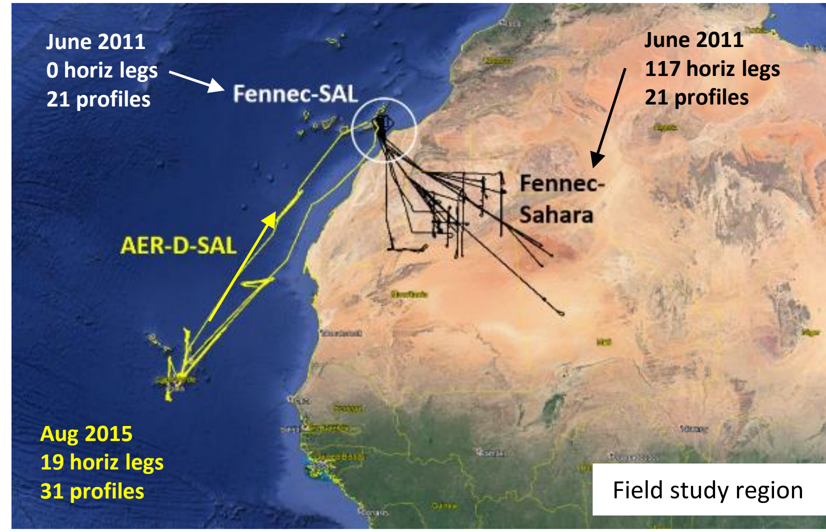
Ryder et al., 2013a, GRL

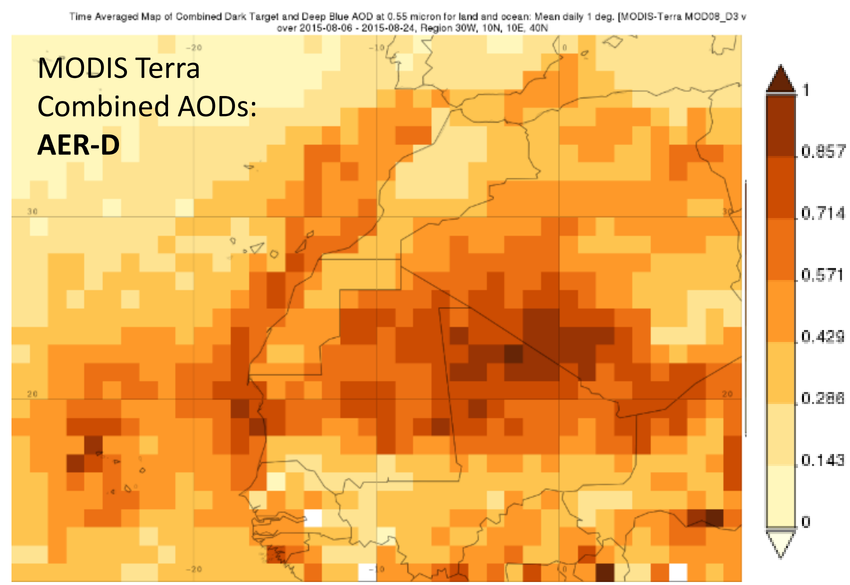
	SSA_{550}	g_{550}	MEC_{550} /m^2g^{-1}
Fresh (z<1.5km)	0.92	0.76	0.15
Aged (z<1.5km)	0.94	0.74	0.23
Aged (full column mean)	0.94	0.75	0.23
SAL (full column mean)	0.95	0.74	0.39

- Fresh
  - Coarse & giant consistently mixed up to 3km (lime green)
  - Giant particles absent above 3.5km
- Aged
  - Main change in concentration occurs at 5km (red) – top of SABL
- SAL
  - Well-mixed vertically, even more so than aged-desert. Few particles d>40µm.

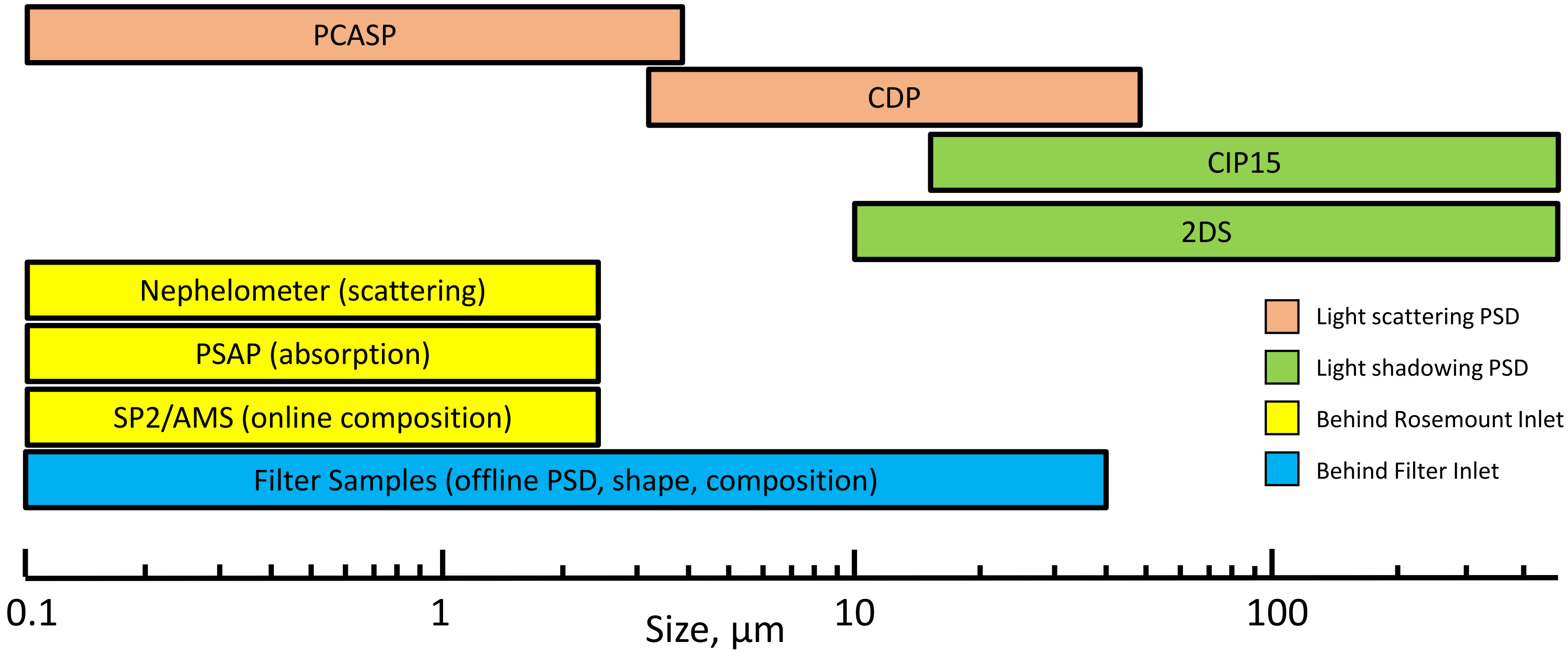
AER-D Airborne Campaign

- With ICE-D, August 2015
- Praia, Cape Verde Islands
- AODs up to 2.0, mostly 0.3-0.6
- AER-D publications:
    - Marenco et al. (2018, ACP): AER-D summary, extreme dust front event & giant particles
    - D. Liu et al. (2018, ACP: dust & hematite content)
    - Price et al. (2018, JGR, dust and ice nuclei)





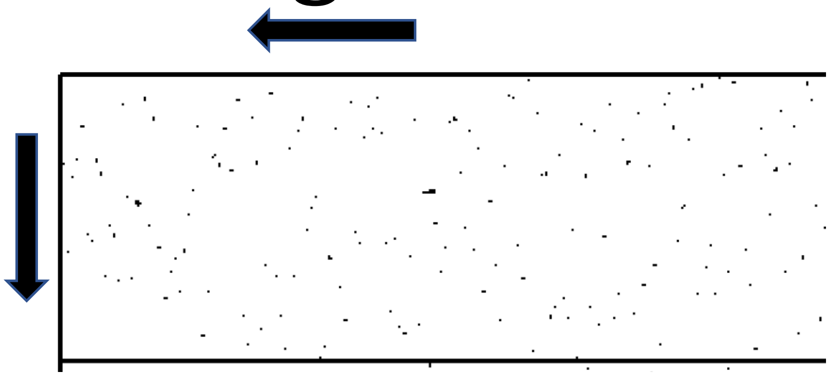
AER-D: FAAM In-situ Measurements of Aerosol

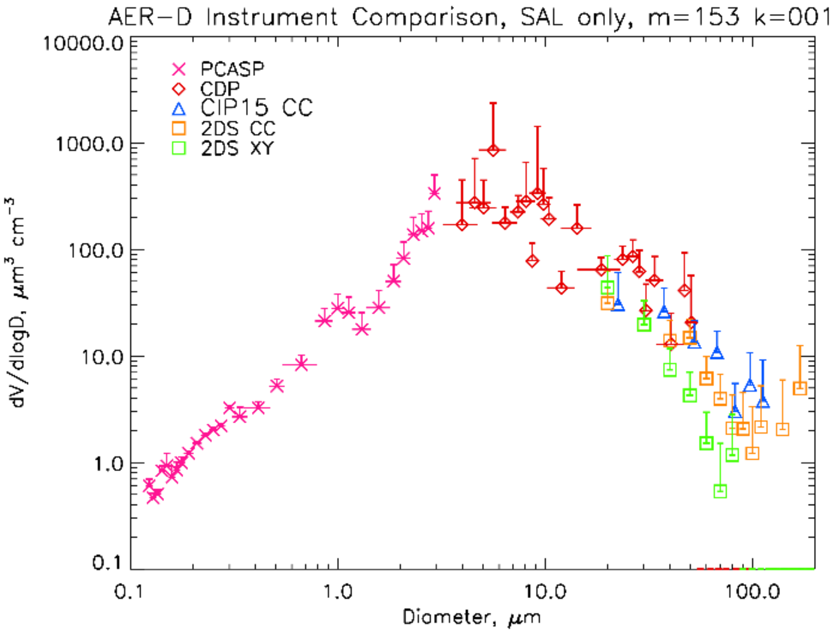


- 2DS in addition to CIP15
- Online accumulation mode composition
- Filter Samples

Optical Array Probe Sizing

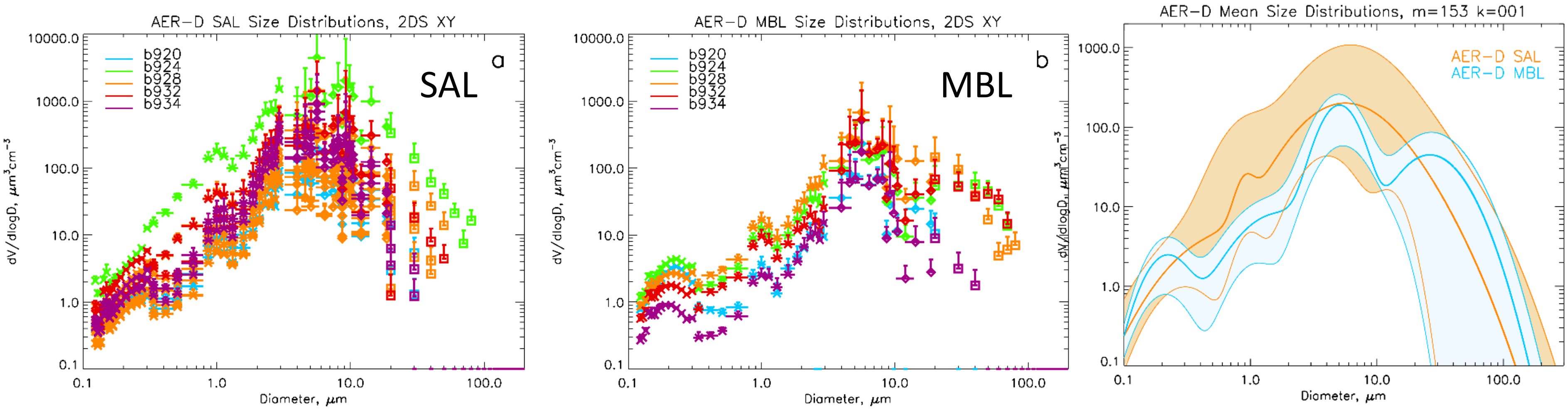
- CIP15/CIP100/2DS
- Light shadowing techniques
- Size measured across:
  - Direction of aircraft motion
  - Aligned with photodiode array
- Sizing by:
  - Mean x & y dimensions (XY)
  - Smallest circumscribing circle (CC)
  - Other methods (McFarquahr et al., 2017)
- Size distribution sensitive to size metric
- No requirement for refractive index knowledge/assumptions or Mie scattering conversions
- 2DS XY selected: consistent with Fennec (CIP15 XY)
  - Coarse & giant mode represent lower bounds





Ryder et al., 2018

AER-D Size Distributions

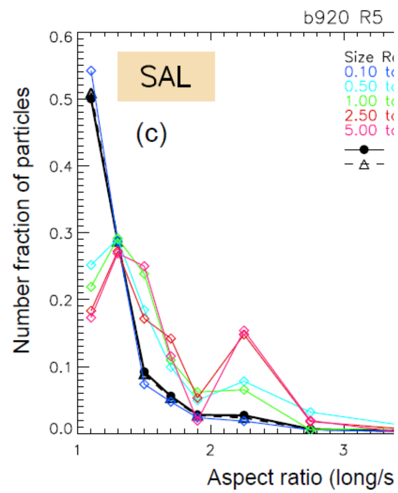


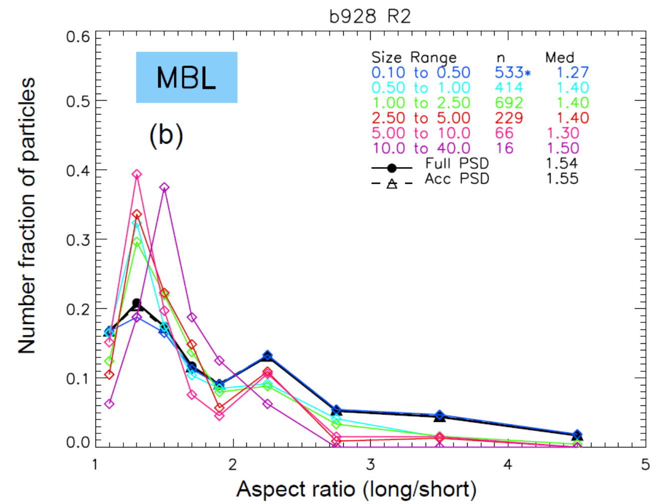
- SAL PSD shape consistent; concentrations rise and fall
- MBL PSD – enhanced fine mode, giant mode present d ~10-80 µm when loadings above in SAL are high
- Fit lognormals to smooth out instrumental noise, reproducibility

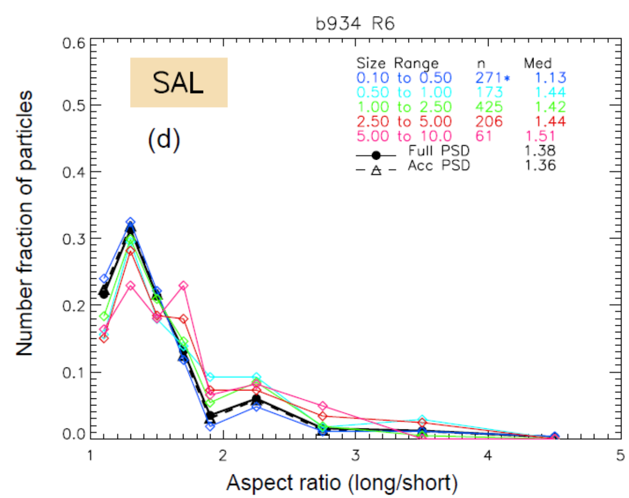
Ryder et al., 2018

Filter Sample Analysis: Aspect Ratios

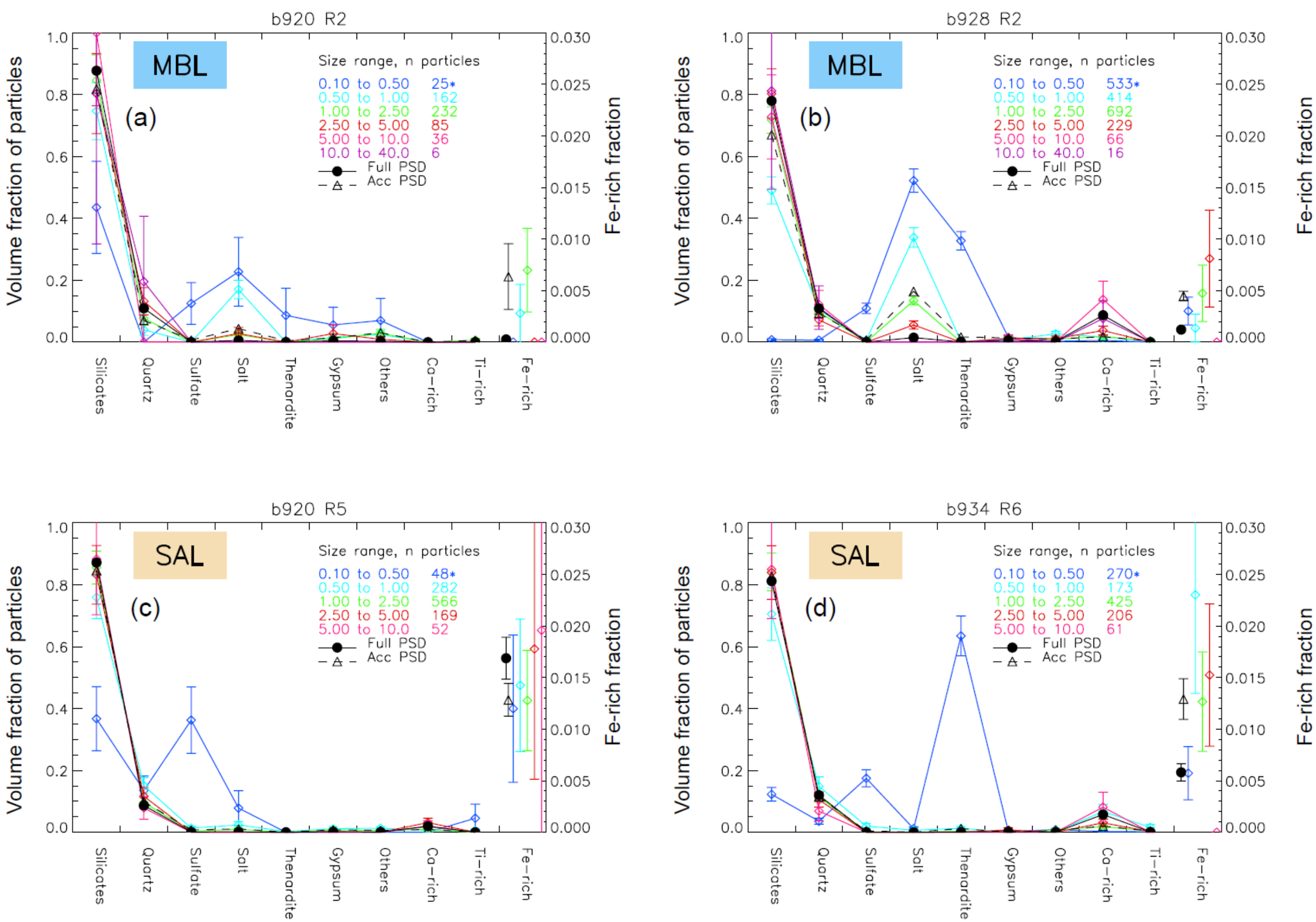
- Ellipse fitted to area projecti particle
- Diameter = circular area equivalent diameter
- Aspect Ratio (AR) measured
- 2D projected size of 3D non-spherical particle
- Plate-like flat particles will fa.. flat on substrate and particles will be oversized
- Chou et al. (2008) height=length/3
- D=5-40µm median AR 1.3-1.5
- D=0.5-45µm median AR 1.3-1.4
- MBL Giant mode more non-spherical







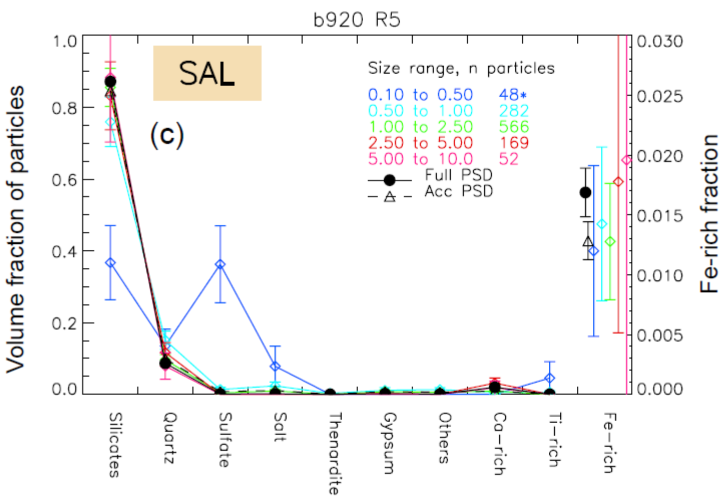
Composition from Filter Samples

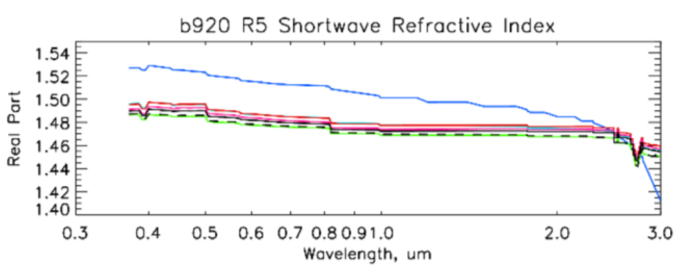


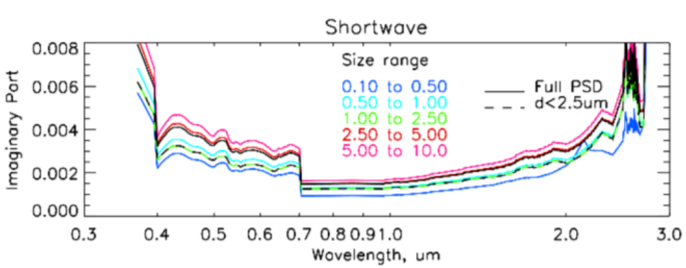
- Particle by particle SEM analysis
- d<0.5µm dominated by sulfates & salts
- Giant mode MBL (d>10µm) is dust
- Dust dominates at d>0.5µm
- Fe-rich fraction small but important for refractive index; higher in SAL than MBL

Ryder et al., 2018

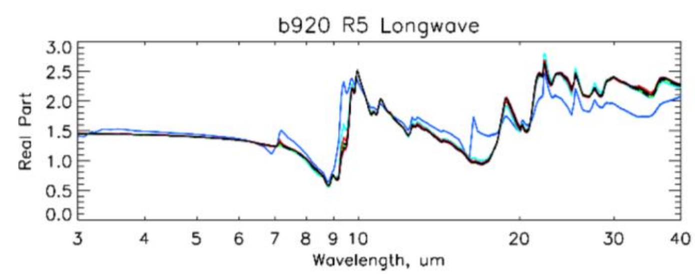
AER-D Composition & Refractive Indices

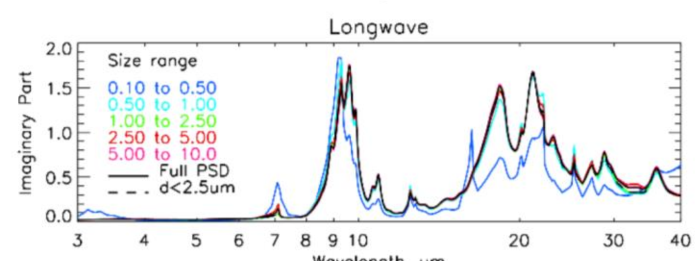






- Shortwave:
  - Real part d=0.1-0.5µm high – sulfates
  - Increasing size → higher imaginary part – Fe
  - Larger particles more absorbing (in this case)
  - Very sensitive to Fe content
- Longwave:
  - Sulfates content, and quartz vs silicate content is main control on RI
  - Differences for d=0.1-0.5µm – sulfates
  - Quartz:silicate ratio fairly constant: not much variation with size

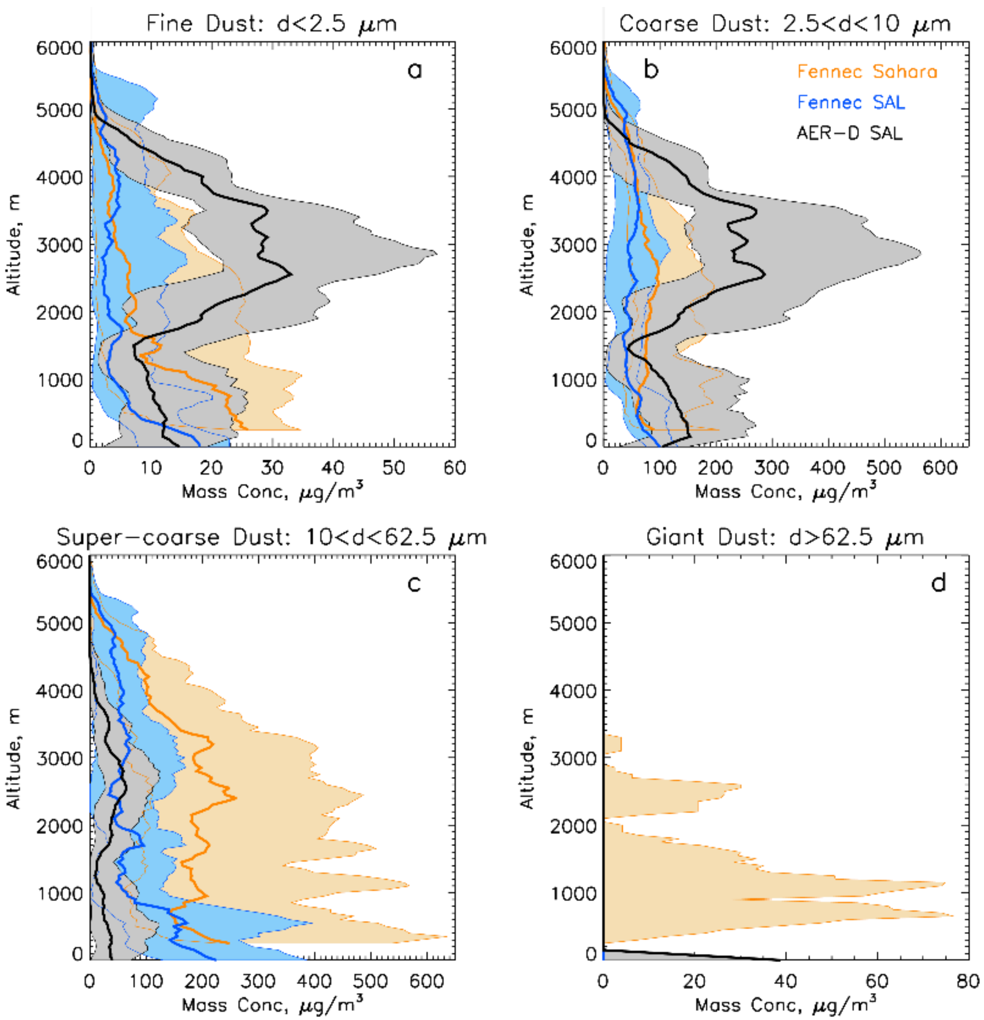




Ryder et al., 2018

Combining Fennec-Sahara, Fennec-SAL, AER-D

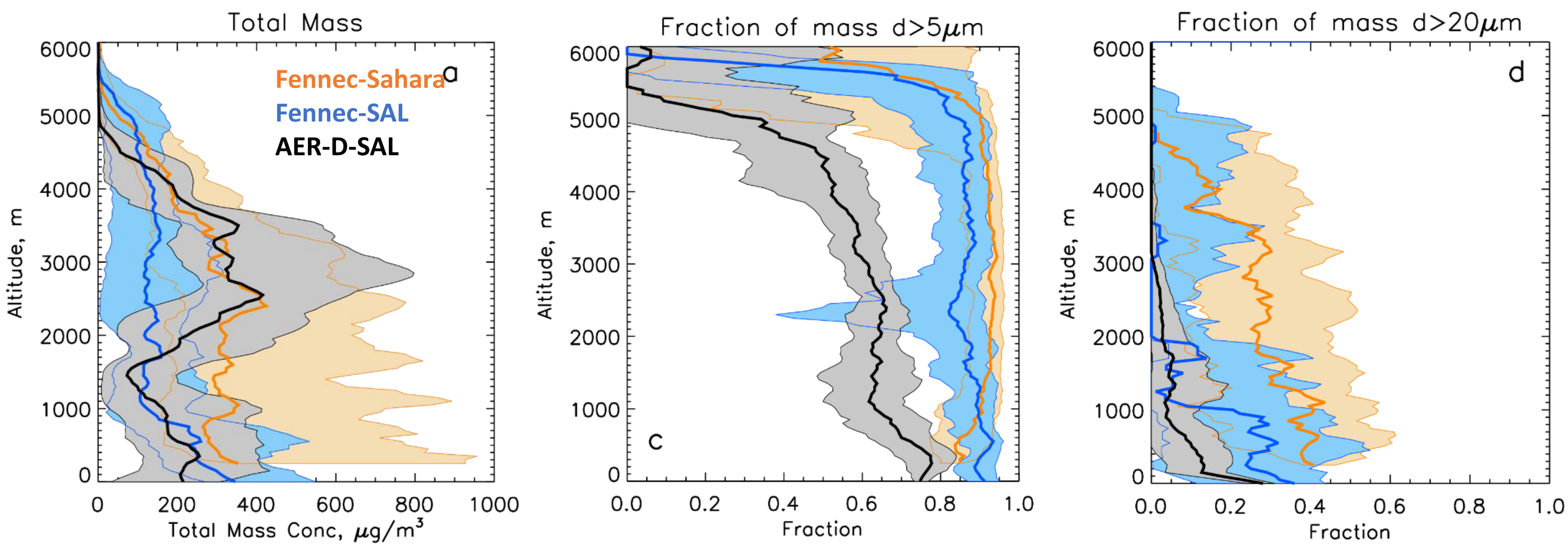
Dust Mass Concentration Profiles



- Largest mass over Sahara; Decreases with altitude; SAL well-mixed
- Desert higher in concentrations of super-coarse and giant dust
- AER-D: slightly different size distribution, more fine & coarse particles
- Aim to provide data suitable for model comparisons

Mass Concentration Profiles

Ryder et al., 2019



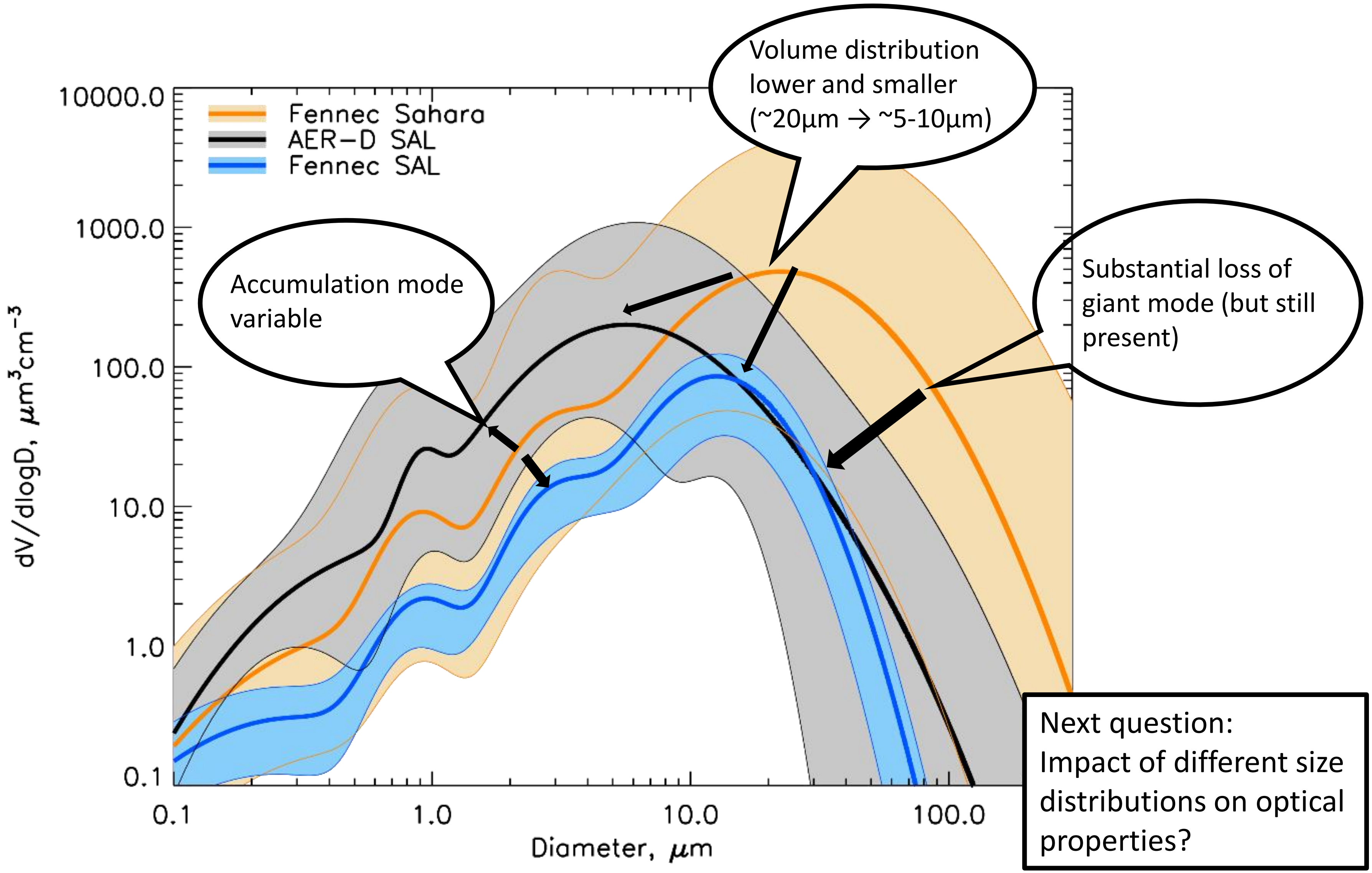
a) Fraction of mass d>5µm
   - Fennec-Sahara: 92% beneath 4.5 km
   - SAL: 61-87%

b) 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)

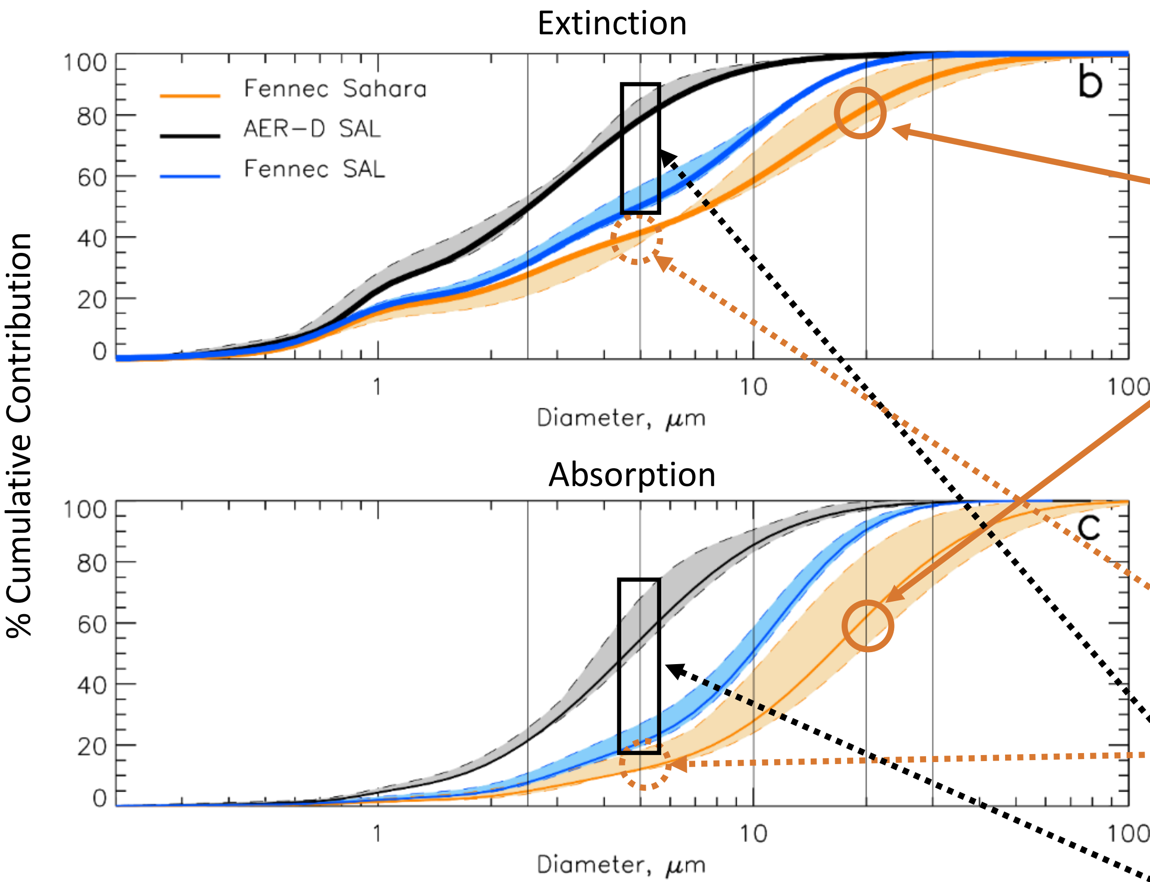
Ryder et al., 2019

Size Distributions



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

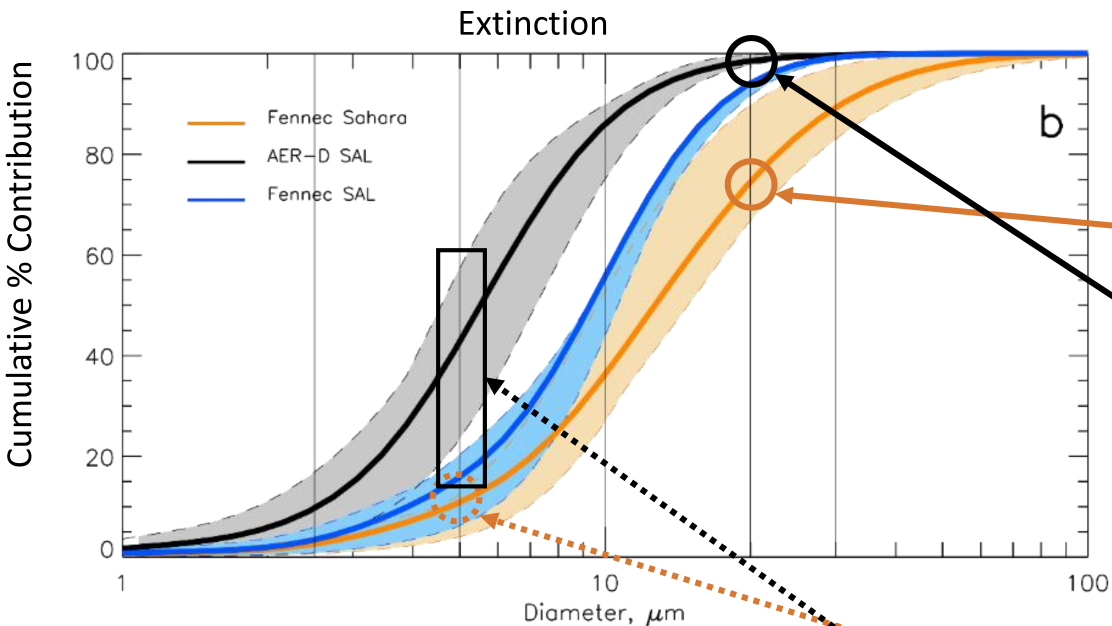
Size Resolved SW Extinction & Absorption



- 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

Ryder et al., 2019

Size Resolved LW Extinction



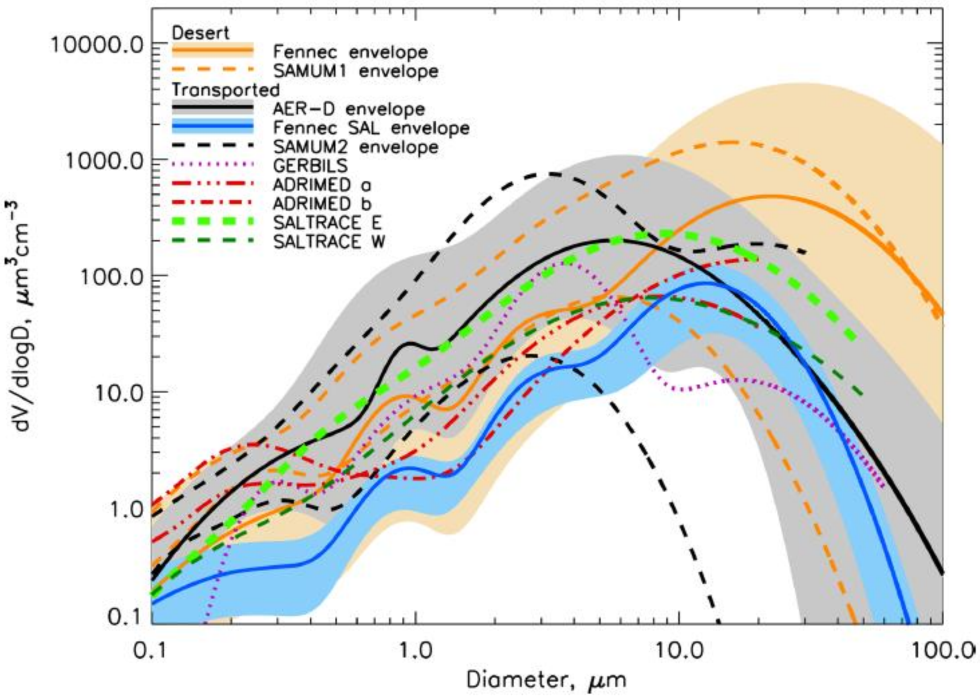
- At d=20μm we capture:
  - Fennec-Sahara:
    - 74% of extinction
  - SAL: (Fennec-SAL/AER-D SAL)
    - 94-98% of extinction
- At d=5μm we capture:
  - Fennec-Sahara:
    - 10% of extinction
  - SAL: (Fennec-SAL/AER-D SAL)
    - 15-41% of extinction

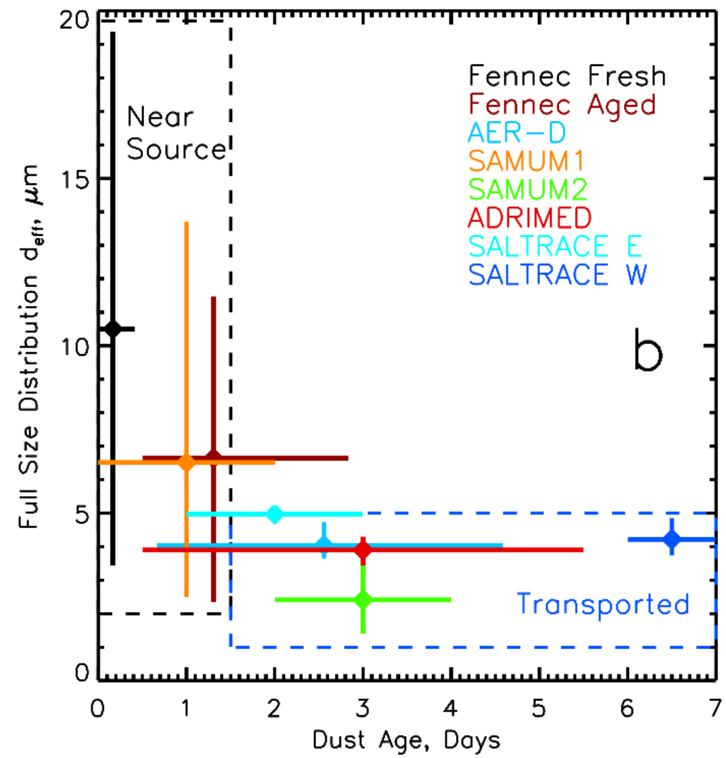
- **Models will significantly underestimate SW and LW extinction and absorption over the Sahara by excluding and/or under-estimating the coarse dust concentrations**
- Greater underestimation of LW extinction than SW, shifts dust DRE to more positive values
- Changes to atmospheric heating from incorrect model dust properties may impact atmospheric circulation in dusty regions

Ryder et al., 2019

Change in Dust Size with Age

Ryder et al., 2019





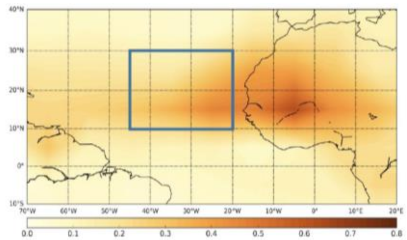
- Compilation of airborne observations measuring Saharan dust, including d≥20µm
- Always a significant contribution from dust particles sized d>5 µm
- Close to sources, there is also a strong contribution from particles larger than 20 µm diameter

- 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

Summary

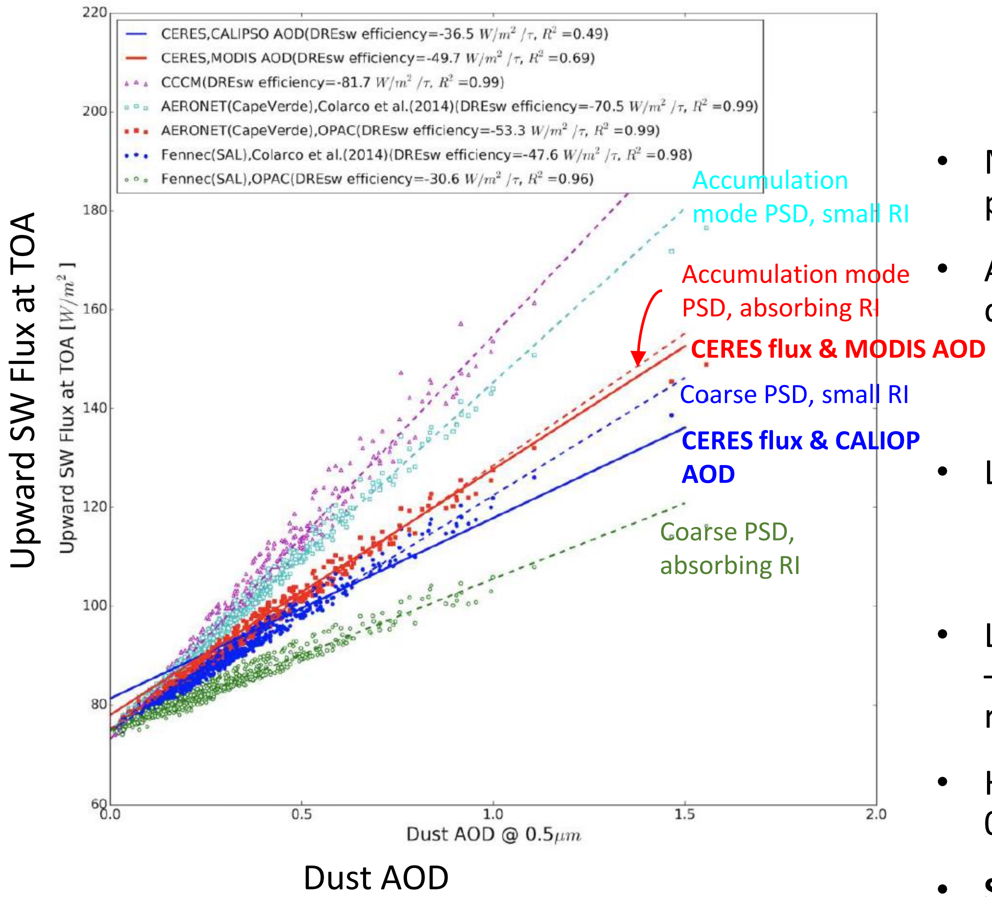
- Improved quantification of coarse & giant dust size distributions via:
  - Improved understanding of inlet behaviour
  - Use of Optical Array Probes
- Substantial coarse mode, and giant mode over desert
  - VMDs: Fennec-Sahara 21μm, Fennec-SAL 12μm, AER-D 6μm
- Impacts optical properties
  - E.g. 39% of absorption originates from d>20μm over desert
- Areas deserving further research:
  - Mechanisms & sensitivities for uplift, transport & deposition of coarse & giant particles

Satellite-based assessment of dust size



CALIOP JJA AOD 2007-2011 and region of analysis

Song et al., 2018, ACP



- Observed SW DRE efficiency (CERES, MODIS, CALIOP) vs RTM model values
- Sensitivity tests to dust properties:
  - PSD: Coarse (Fennec SAL) vs accumulation mode (AERONET)
  - Refractive index: OPAC (absorbing) vs Colarco 2014 (less absorbing)
- Most reflective dust → greatest DRE efficiency (smaller particles, less absorbing RI)
- Agreement with observations is possible with only 2 dust combinations:
  - Coarse PSD + low absorption
  - Accumulation mode PSD + high absorption
- LW sensitivity tests : Model minus CERES:
  - Coarse PSD, OPAC LW RI, 0.5 Wm^{-2}
  - Accumulation mode PSD, OPAC LW RI, 1.6 Wm^{-2}
- LW observations used to narrow down dust properties – only significant coarse mode presence can lead to reasonable agreement in both SW and LW
- High absorption (OPAC) of ~0.008i deemed unlikely, 0.0015i more realistic (Balkanski et al., 2007)
- **Significant coarse mode presence is required to match observations**