Net Radiative Effects of Dust in the Tropical North Atlantic Based on Integrated Satellite Observations and In Situ Measurements

Qianqian Song (UMBC), Zhibo Zhang (UMBC), Hongbin Yu (NASA)

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Objectives of our study

- Derive observation-based DRE of dust aerosols, in both SW and LW, from satellite remote sensing data. Try to avoid making pre-assumptions on dust properties as much as possible.

- Search for an optimal dust model that can fit the observed DRE.

- Study the sensitivity of dust DRE to dust optical and physical properties.

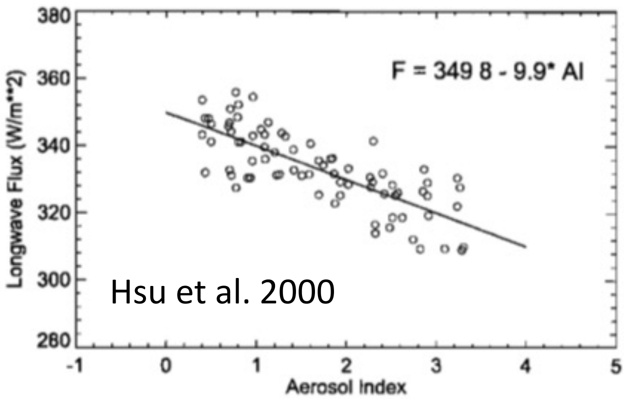
Dust direct radiative effects (DRE)

- Dust aerosols can have significant DRE in both SW and LW
  - **Negative** (cooling) SW DRE at TOA over dark surface (i.e., ocean) and **positive** (warming) DRE over bright surface (i.e., desert).
  - Dust is large enough to have LW DRE (usually **positive**).

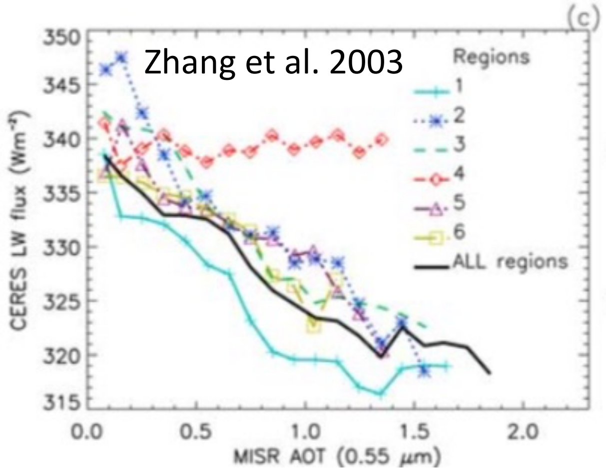
Table 16. Summary of the clear-sky radiative efficiency E_τ, defined as the aerosol radiative effect (Wm^{-2}) per unit aerosol optical depth (τ at 550 nm), in tropical North Atlantic.

Yu et al. (2006) dust SW DRE efficiency

Region	Period	Source	E_τ TOA	E_τ Surface
Zone 6 (ocean)	DJF	MODIS	−45	n/a
Tropical North Atlantic		CERES_A	−33	n/a
		CERES_B	−28	n/a
		MODIS_A	−40	−63
		Models	−16∼−35	−36∼−63
	JJA	MODIS	−34	n/a
		CERES_A	−32	n/a
		CERES_B	−25	n/a
		MODIS_A	−41	−72
		Models	−16∼−41	−27∼−68
West coast of North Africa	NDJ	Li et al. (2004)	−26	−81
	JJA		−35	−65
	July 1998	Liu et al. (2003)	−18	n/a
	February 1985	Hsu et al. (2000)	−62 (14:30 LT)	n/a
	July, 1985		−69 (14:30 LT)	
Puerto Rico	June–July, 2000 (daytime average)	Christopher et al. (2003)	−52	−78



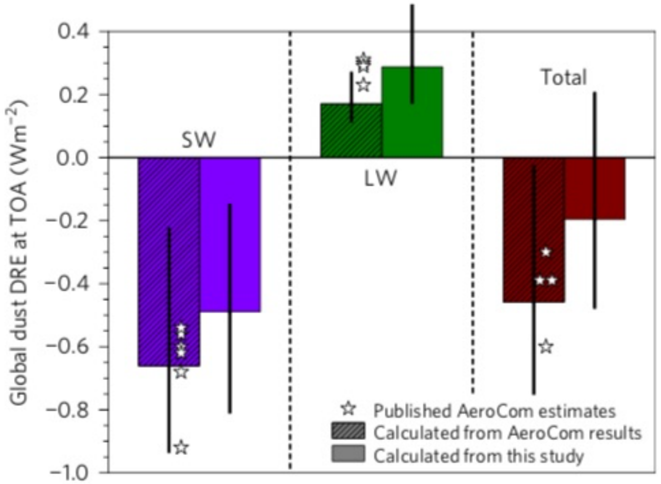
Hsu et al. 2000



Zhang et al. 2003

Recent advances and outstanding questions

- What is the net DRE of dust?
  - Are we overestimating the cooling effect of dust?
  - How much is the cooling SW DRE of dust compensated by the warming LW DRE?
- In situ measured dust aerosol sizes tend to be signficantly larger than remote sensing retrievals and model simulations, why?
- Can we use the remote sensing dust property product, retrieved mainly using visible/NIR, to close the radiative budget in both SW and LW?

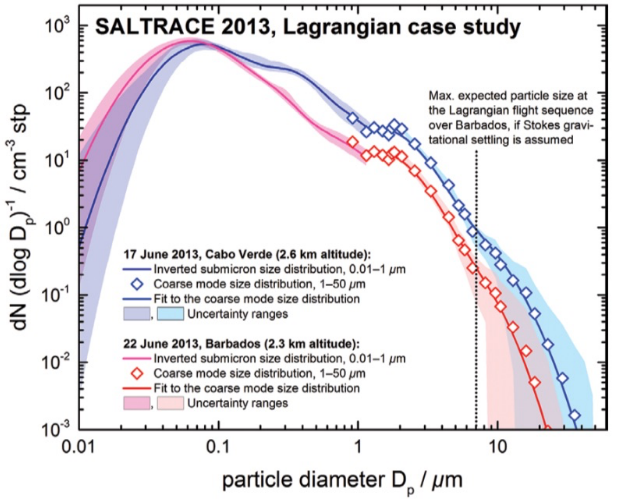


Kok et al .(2017)

"Our results suggest that dust cools the climate system substantially less than represented in current models, and raise the possibility that dust is actually net warming the planet." –Kok et al. (2017 Nature Geoscience)

"The detection of 10–30-µm particles in the Caribbean even after more than 4,000 km and 5 days of transport is unexpected." –Weinzierl et al. (2017 BAMS)

Weinzierl et al. (2017)

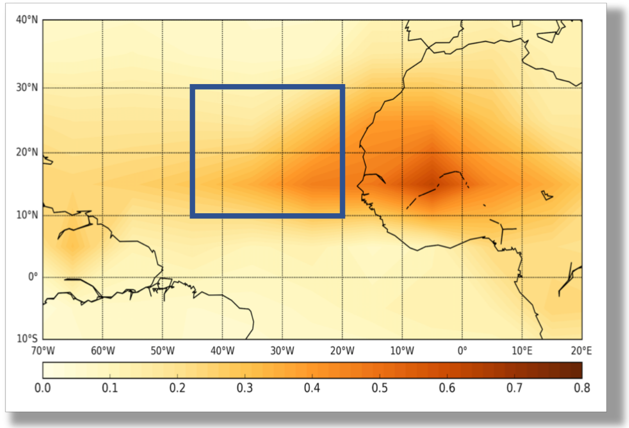


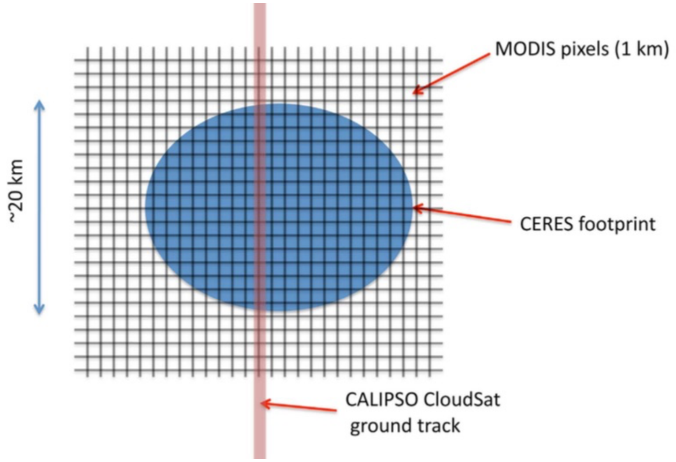
Data and model

- Dust AOD, vertical profile, SW and LW fluxes
  - The C3M (CERES, CALIPSO, CloudSat, MODIS) merged product
- Dust PSD
  - *In situ* measurements from Fennec 2013 field campaign (Ryder et al. 2013)
  - AERONET retrieval (Dubovik et al. 2002)
- Dust refractive index
  - SW: OPAC (Hess et al. 1998), AERONET (Colarco et al. 2014/Kim et al. 2011)
  - LW: OPAC (Hess et al. 1998), Di Biagio et al. (2017)
- Dust particle shape
  - Dubovik et al. (2006), Kandler et al. (2009)
- Dust particle scattering properties
  - database from P. Yang group (Meng et al. 2010)
- Radiative Transfer (RT) model
  - RRTM SW and LW

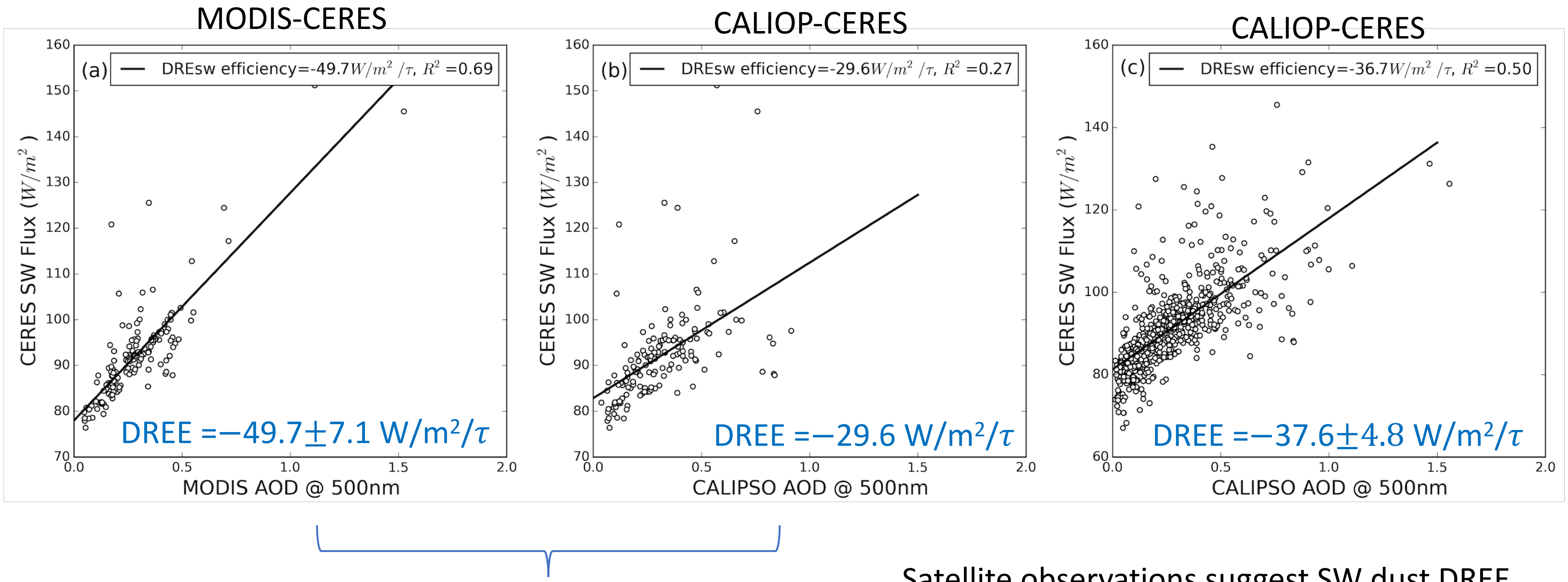
Case selection

- Summer months (JJA) over Tropical East Atlantic
- Cloud free
  - According to both CALIOP and MODIS
  - Very strong constraint–screen out ~ 95% CERES pixels in the region
- Dust dominant
  - >90% aerosols are dust according to CALIOP aerosol type ~ lidar depolarization
- 607 CERES pixels selected from 5 seasons of data (2007~2011)
  - 153 cases with both MODIS and CALIOP AOD
  - 454 cases with only CALIOP AOD



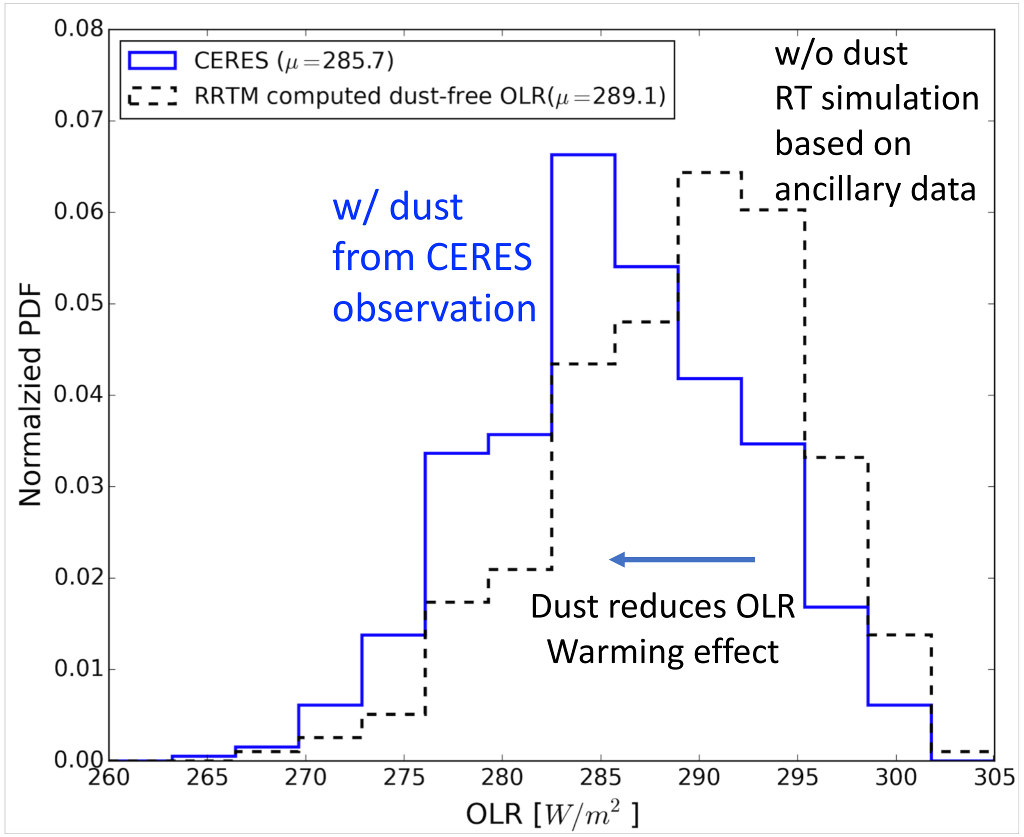


Observation-based dust instantaneous SW DRE efficiency



Satellite observations suggest SW dust DREE around $-38\ W/m^2/\tau$ ~ $-50\ W/m^2/\tau$

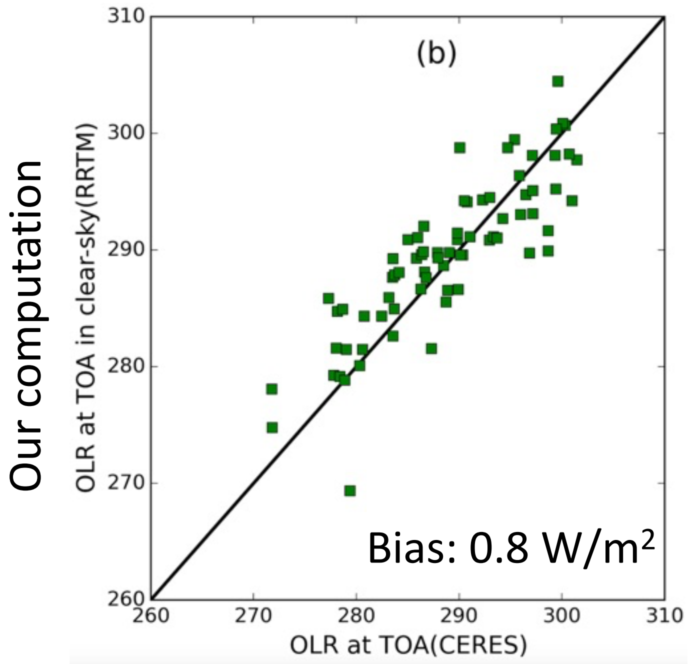
Observation-based instantaneous LW DRE



The absorption and scattering by dust aerosols reduces the OLR, leading to a warming effect at TOA

+3.4 ± 0.6 $W/m^2/\tau$

Sanity checks: OLR for cases without dust



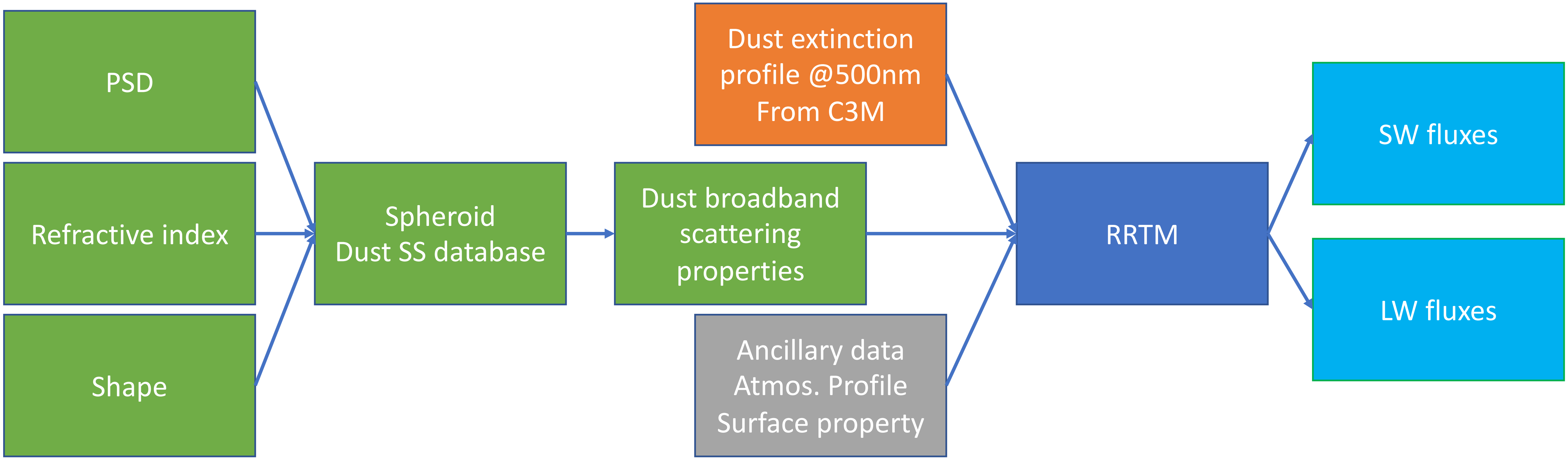
CERES observation

Observation-based instantaneous DREs

	TOA DRE_{SW} Efficiency $[W \cdot m^{-2} \cdot AOD^{-1}]$	TOA DRE_{SW} $[W \cdot m^{-2}]$	TOA DRE_{LW} $[W \cdot m^{-2}]$
CERES-MODIS AOD	-49.7±7.1	-14.2±2.0	3.1±0.60 (2.4±0.60)
CERES-CALIPSO AOD	-36.5±4.8	-10.4±1.4	3.4±0.32 (2.7±0.32)

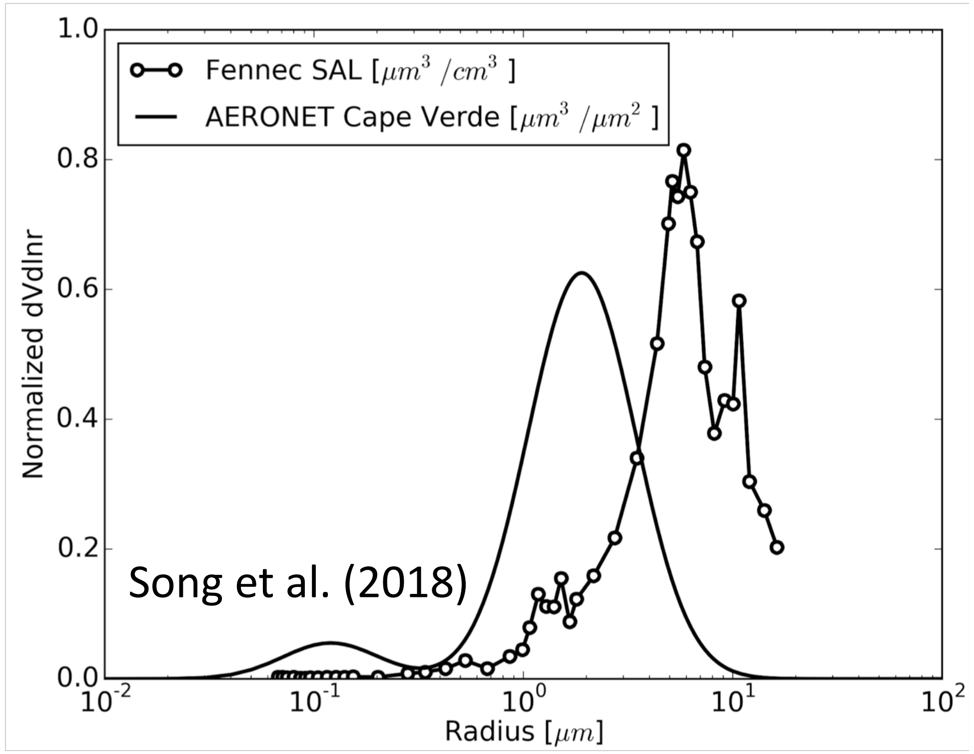
Can we find a set of optimal dust model that can fit the observed DRE?

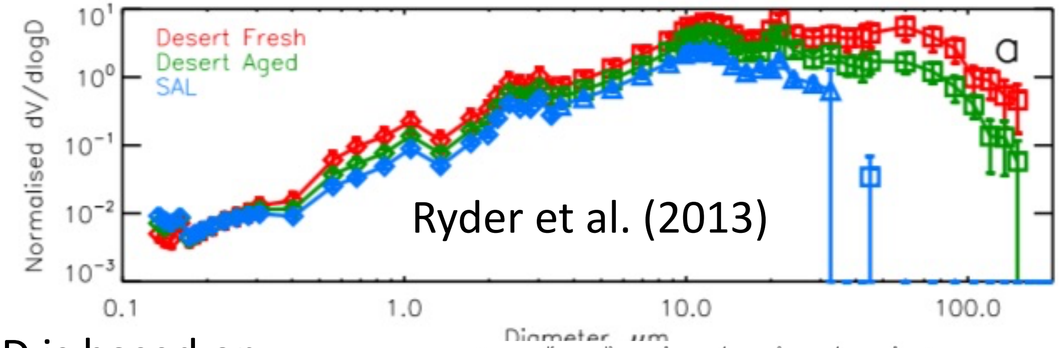
Dust DRE simulation



Search for the “optimal” dust model: Dust PSD

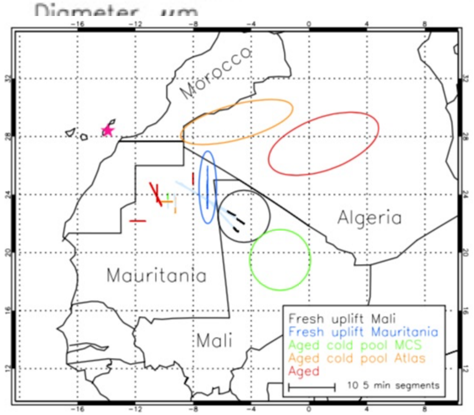
- Two sets of PSDs are selected for sensitivity study, one based on AERONET retrieval and the to her from in situ measurements





AERONET dust PSD is based on Cap Verde site in Dubovik et al. 2002

Fennec dust PSD is measured in situ around the Fuerteventura, Canary Islands

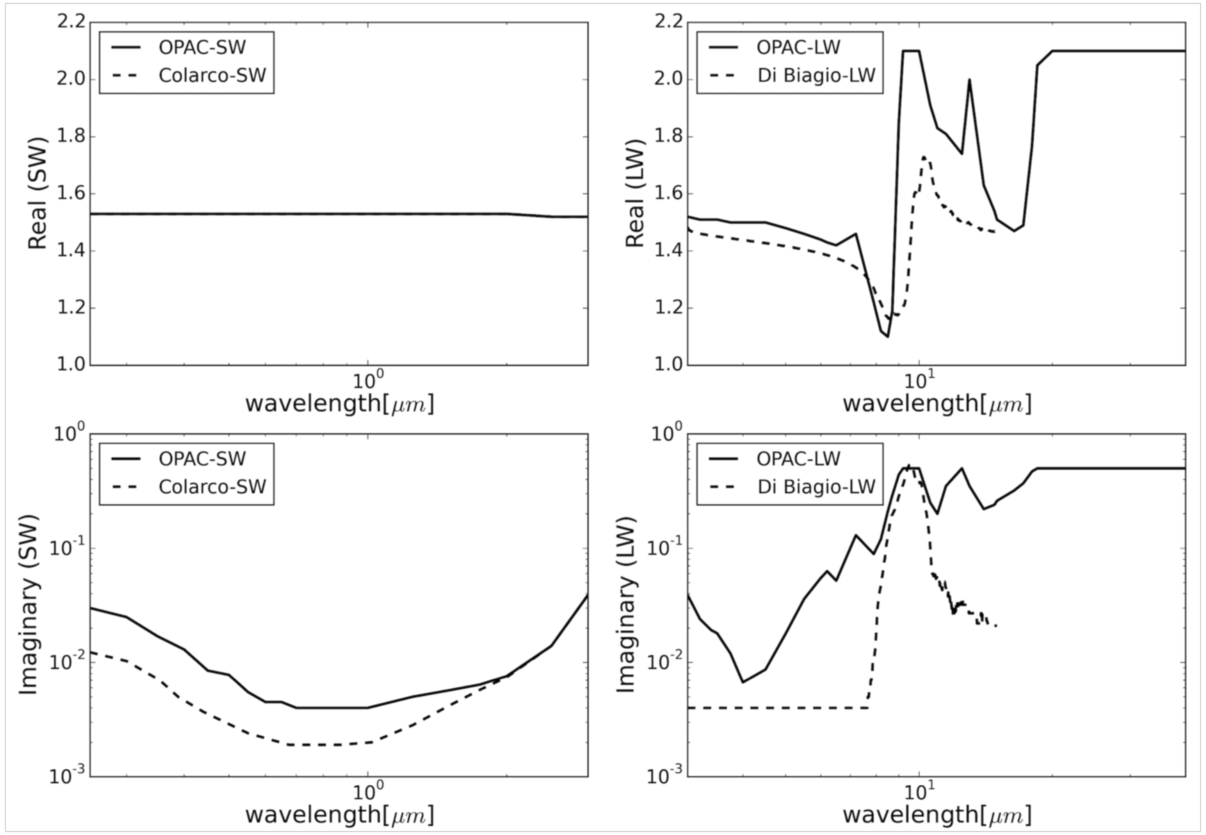


Search for the optimal dust model: Dust refractive index

- Three dust refractive index data sets are selected for sensitivity study

In the SW region:
- OPAC (Hess et al. 1998)
- Colarco et al. 2014, Kim et al. 2011

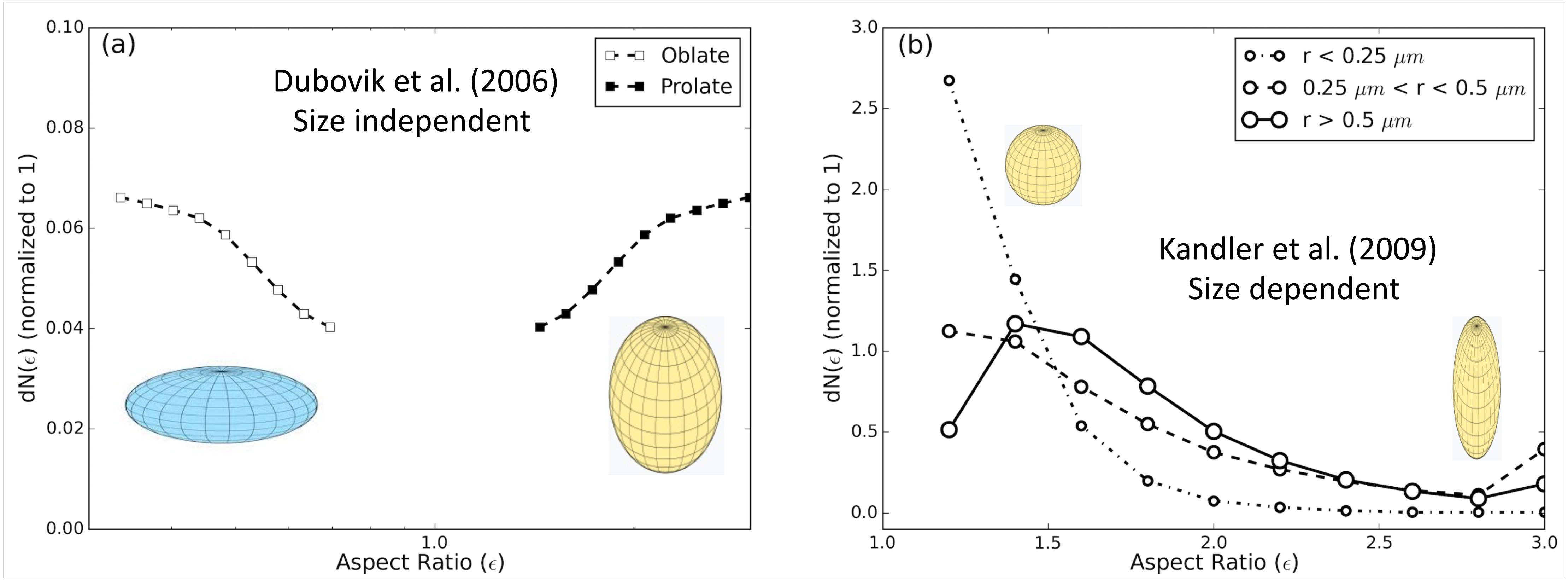
Colarco-SW RI is less absorptive than the OPAC RI in SW region



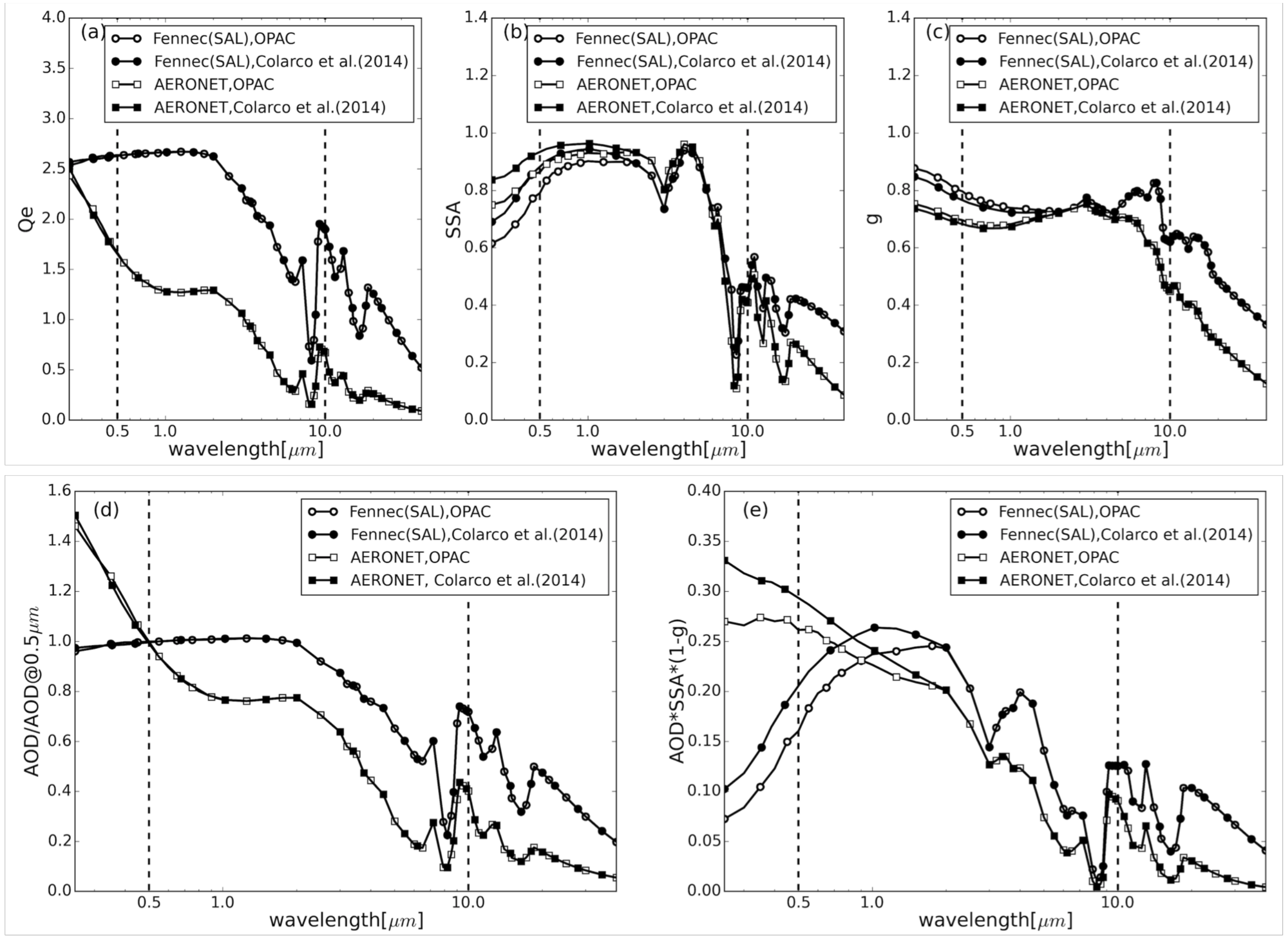
In the LW region:
- OPAC (Hess et al. 1998)
- Di Biagio et al. (2017)

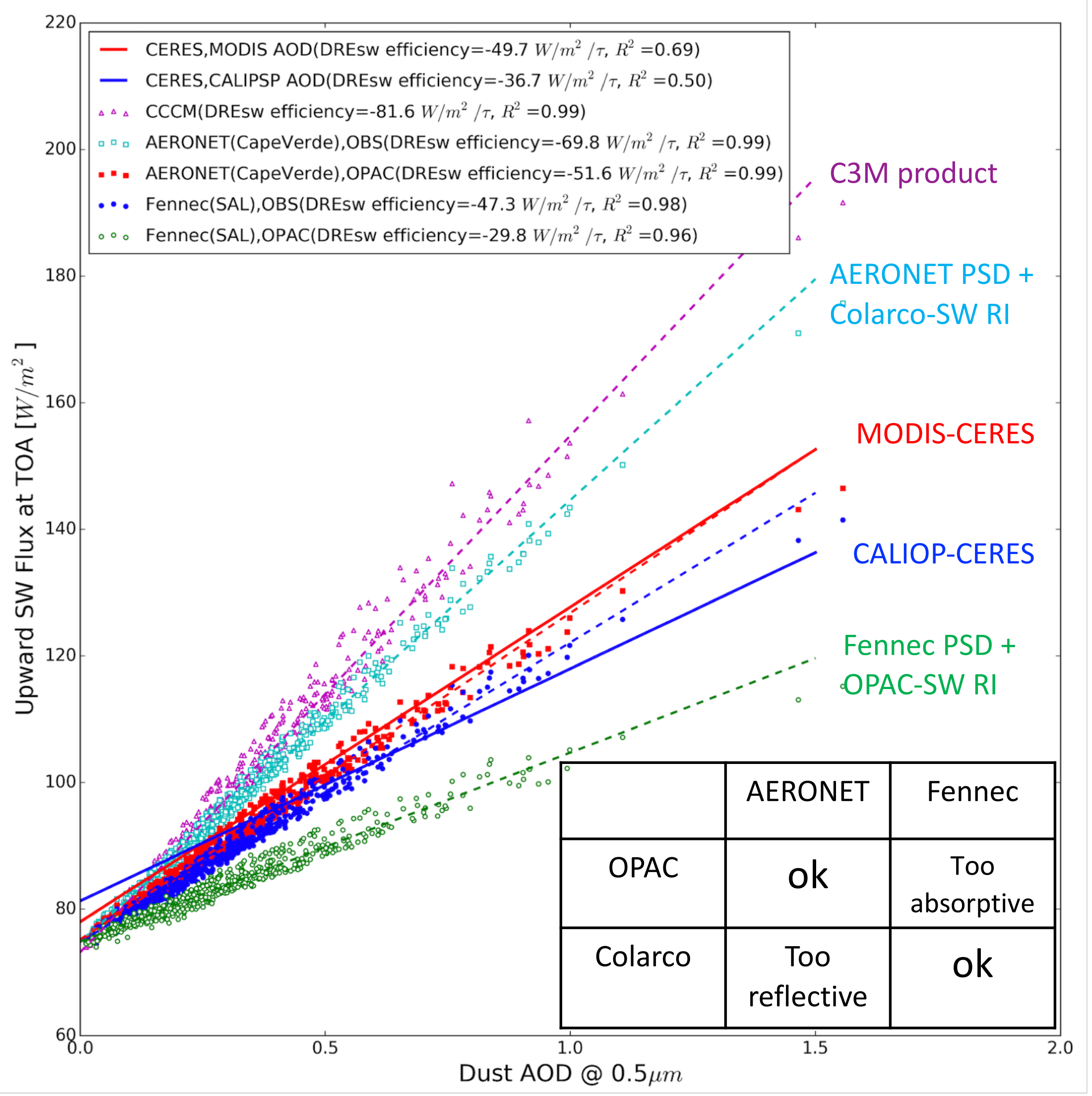
Di Biagio data base provide region-dependent RI (the RI from the Mauritania region is used in this study)

Search for the optimal dust model: Dust shape



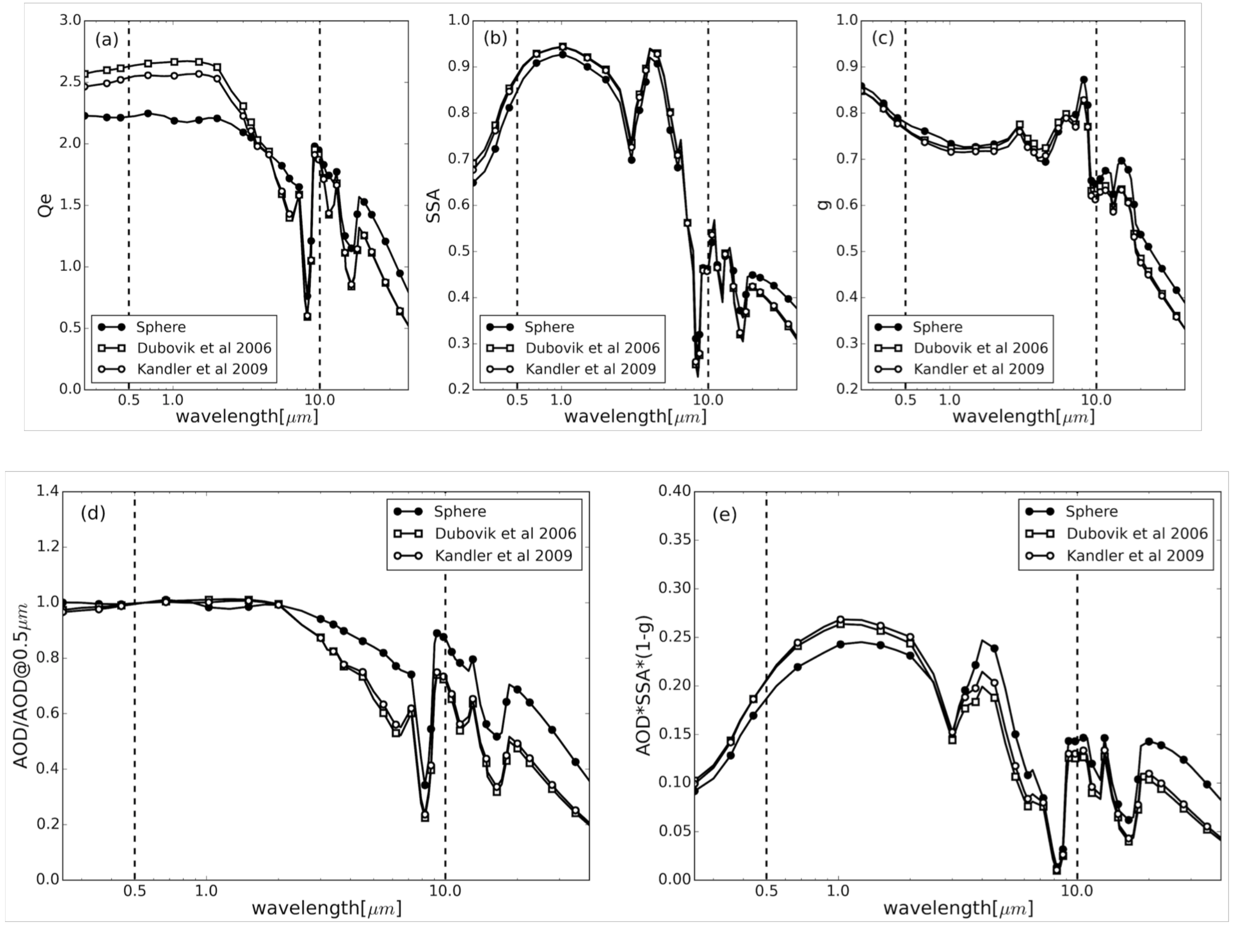
Dust broadband scattering properties and DRE

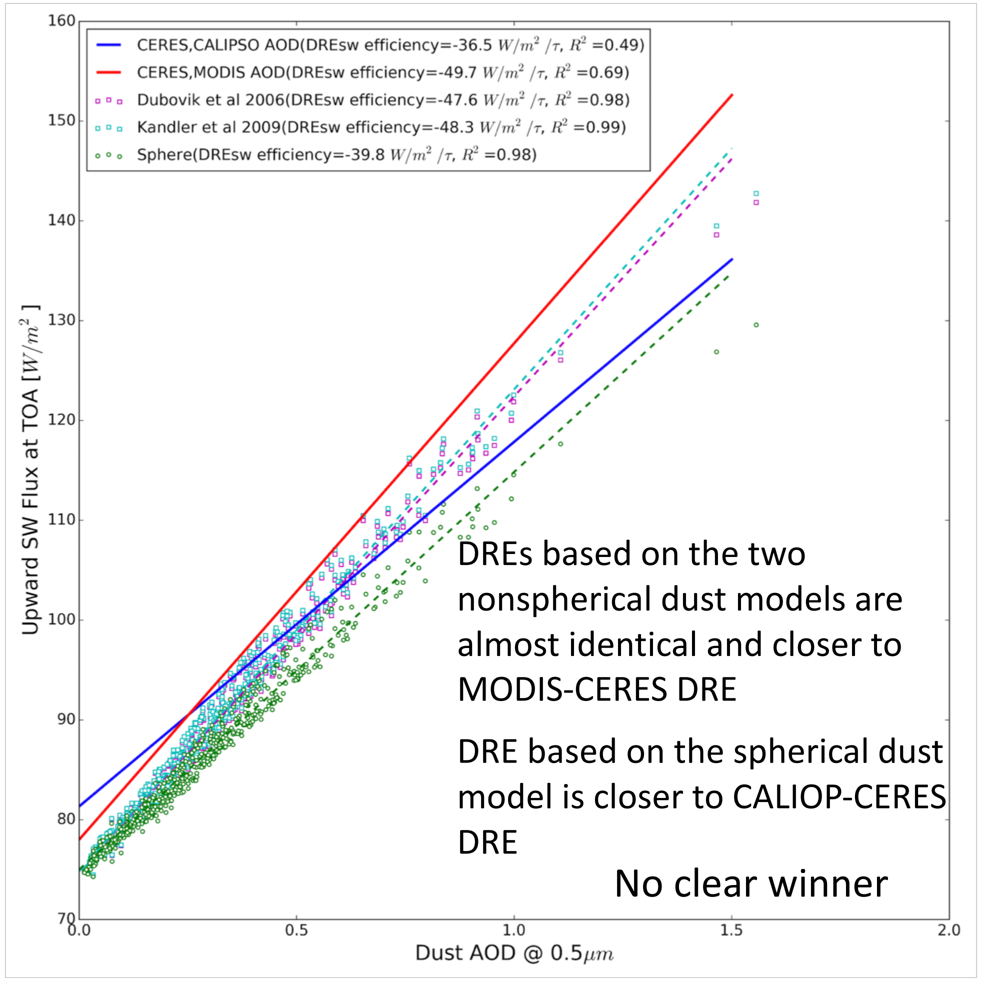




	AERONET	Fennec
OPAC	ok	Too absorptive
Colarco	Too reflective	ok

Dust broadband scattering properties and DRE





DREs based on the two nonspherical dust models are almost identical and closer to MODIS-CERES DRE

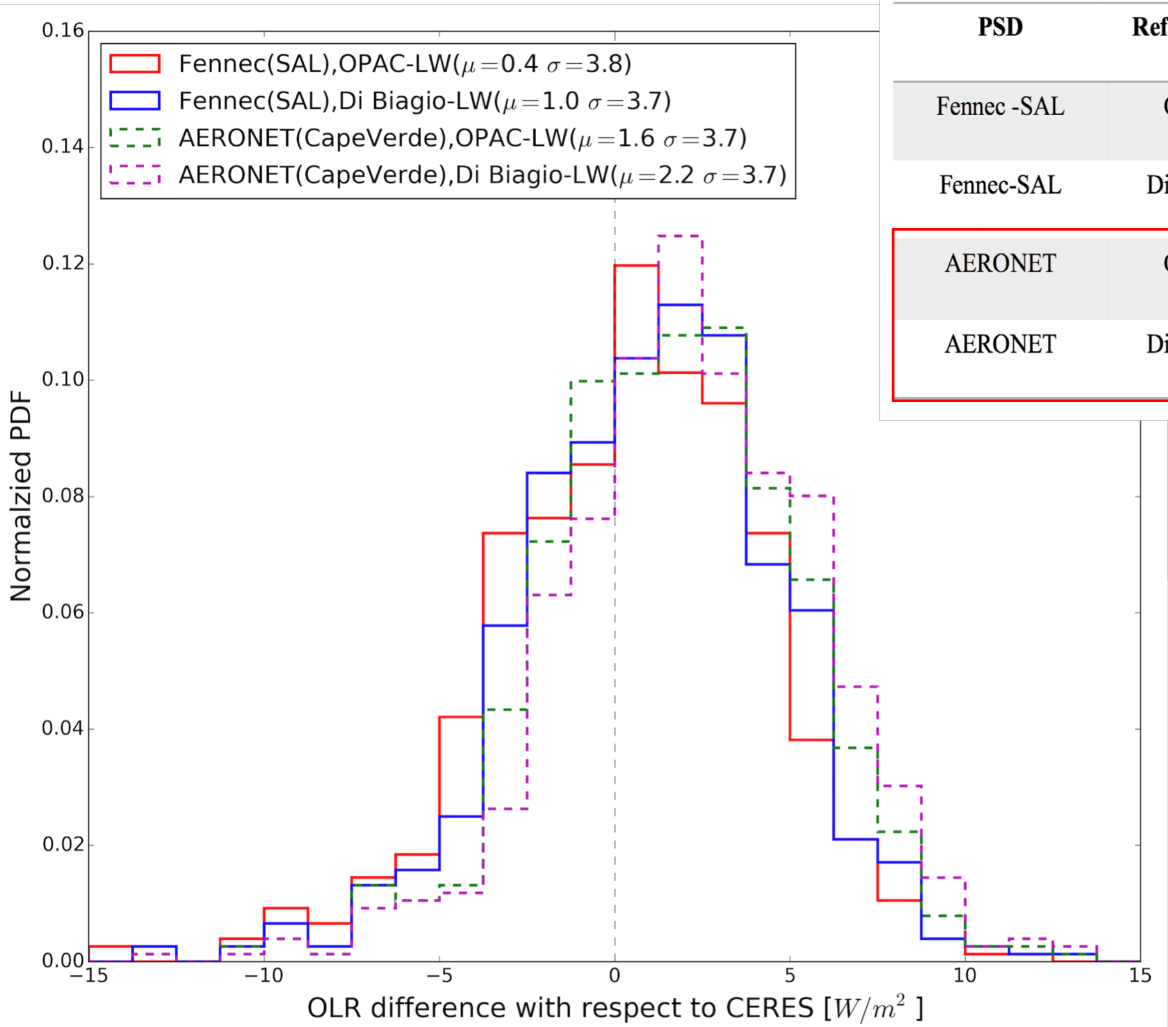
DRE based on the spherical dust model is closer to CALIOP-CERES DRE

No clear winner

Lessons learned from SW DRE closure

- The combination of smaller size (AERONET PSD) + more absorptive refractive index (OPAC) is equivalent of the combination of larger size (Fennec) + more reflective refractive index (Colarco-SW) in terms of SW DRE closure, both in good agreement with observation-based DRE.
- When other things equal, the two nonspherical dust shape models, although substantially different, yield almost identical SW DRE; the DRE based on the spherical model is slightly weaker (less negative) but still within observation range.

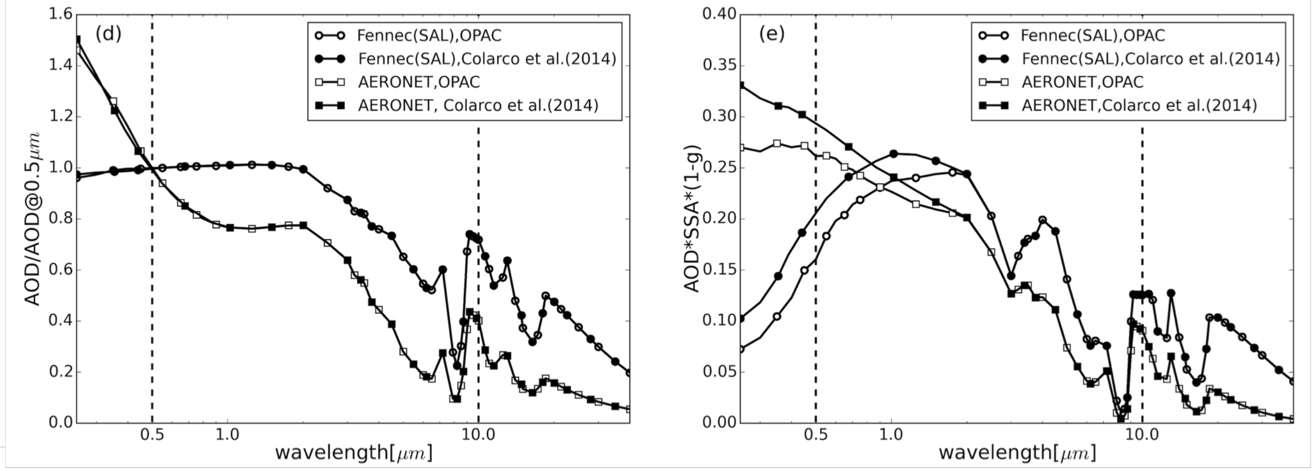
Which one can also close the LW DRE?



Simulated – CERES OLR

PSD	Refractive index	shape	Mean Difference	Standard Deviation	t-score	p-value
Fennec -SAL	OPAC-LW	Dubovik	0.5 (-0.2)	3.8	1.2 (-0.62)	0.23 (0.55)
Fennec-SAL	Di-Biagio-LW	Dubovik	1.0 (0.3)	3.7	2.67 (0.83)	0.008 (0.41)
AERONET	OPAC-LW	Dubovik	1.6 (0.9)	3.7	4.21 (2.36)	2.7e-5 (0.02)
AERONET	Di-Biagio-LW	Dubovik	2.2 (1.5)	3.7	5.82 (3.94)	7.7e-9 (8.5e-5)

Although equivalent in the SW, the AERONET PSD (finer) leads to warm bias in OLR and the Fennec PSD (coarser) yields almost perfect match.



Computed diurnal mean DRE

PSD	Refractive index	Shape	TOA DRE_{SW} Efficiency ($W/m^2/AOD$)	TOA DRE_{SW} (W/m^2)	Surface DRE_{SW} Efficiency ($W/m^2/AOD$)	Surface DRE_{SW} (W/m^2)
Fennec-SAL	Colarco-SW	Dubovik	-28	-9.9	-82.1	-26.0
AERONET	OPAC-SW	Dubovik	-29.4	-10.3	-85.7	-27.2
Fennec-SAL	Colarco-SW	Spherical	-22.8	-8.2	-89.6	-28.5

PSD	Refractive index	Shape	TOA DRE_{LW} (W/m^2)	Surface DRE_{LW} (W/m^2)
Fennec-SAL	OPAC-LW	Dubovik	3.0	7.7
AERONET	OPAC-LW	Dubovik	1.8	4.7
Fennec-SAL	Di-Biagio-LW	Dubovik	2.4	5.4
Fennec-SAL	OPAC-LW	Spherical	3.6	9.4

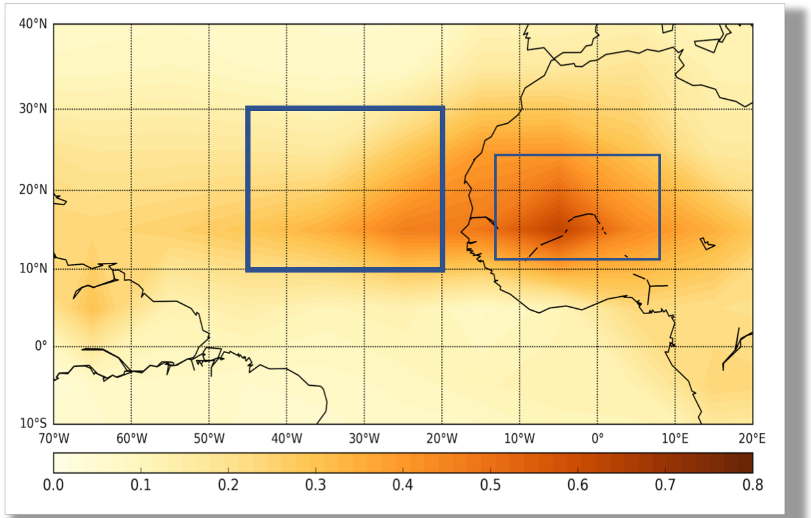
Assuming the "optimal" dust model, (Fennec PSD+Colarco-SW+OPAC-LW) the diurnal mean TOA SW DRE is about -10 W/m^2 and the LW DRE is about $+3$ W/m^2

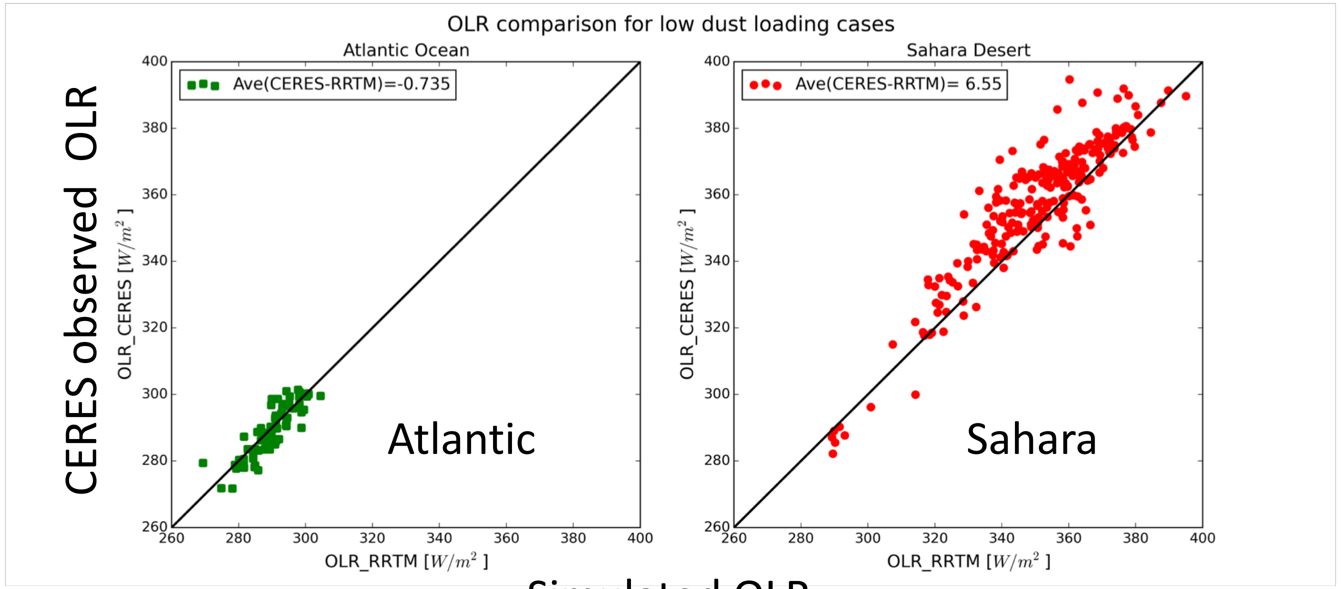
Summary

- Observation-based instantaneous DREs are derived for the dust aerosols in the TNEA from the combination of CALIOP-MODIS-CERES data.
  - SW DREE ~ -38 W/m^2/τ ~ -50 W/m^2/τ; DRE -10 W/m^2 ~ -14 W/m^2;
  - LW DRE ~ $+3.1$ W/m^2 ~ $+3.4$ W/m^2
- Smaller dust size + absorptive RI or larger dust size + reflective RI both can close the SW DRE.
- But, only larger dust size can also close the LW DRE
- Based on the optimal dust model, the positive LW DRE cancels about 30% of the negative SW dust DRE

On-going research: DRE of dust over **Sahara**

- Data used:
  - Dust profile: **CALIPSO**
  - TOA fluxes: **CERES**
  - Atmos. Profiles: **Merra-2**
  - Surface emissivity: **UW Baseline Fit Ems. Database**
  - Surface Skin temperature: **MODIS LST product (MOD11)**





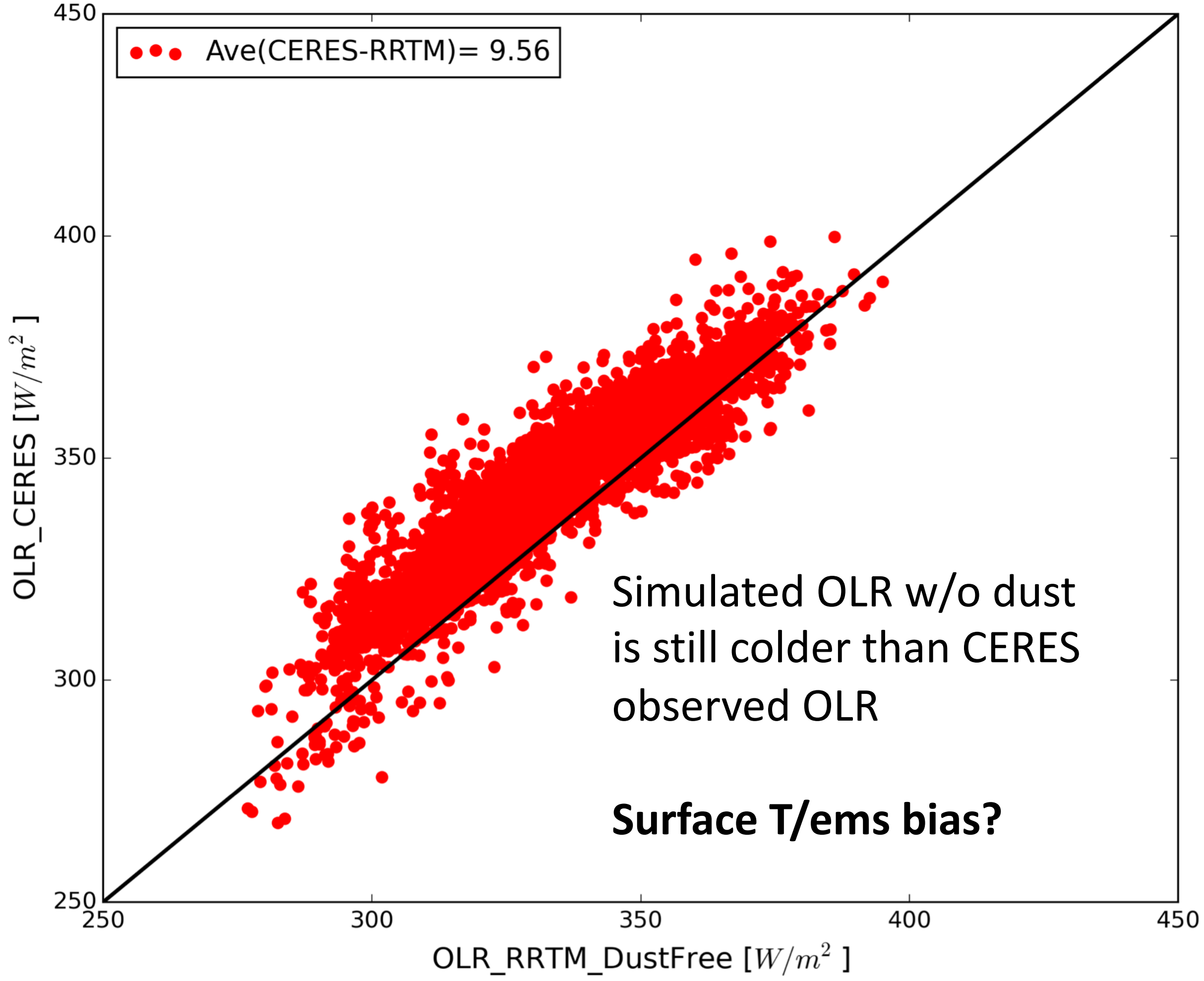
Simulated OLR

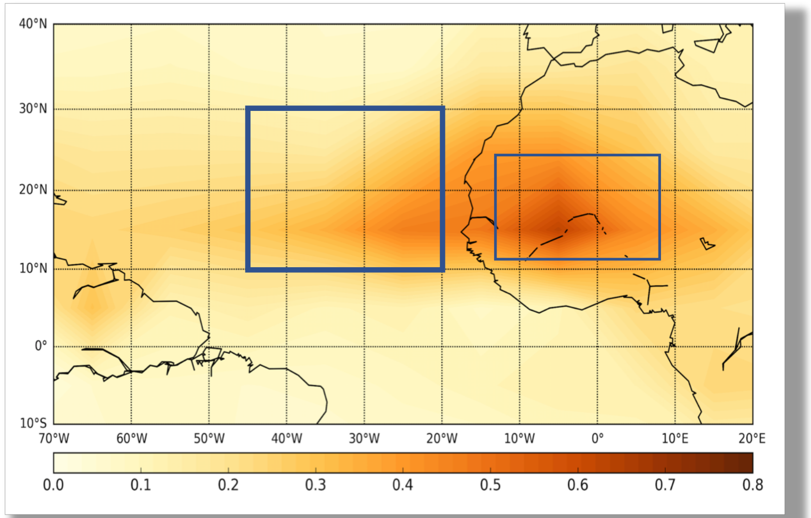
Problem/questions:

Simulated OLR is too cold (−6 W/m²)

Surface emissivity/temperature are biased low?

On-going research: DRE of dust over **Sahara**





Problem/questions:

Simulated OLR is too cold (−6 W/m²)

Surface emissivity/temperature are biased low?

Clear sky closure test for RRTM calculations with different surface

Surface properties	OLR_AVE For Low dust loading cases (AOD<=0.05) (CERES-RRTM, 247 samples)
Ts:C3M Ɛ : Huang	12.2
Ts:C3M Ɛ : MYD_BF	11.7
Ts:MYD11 Ɛ : MYD_BF	6.5

		DRE_LW	OLR Difference Ave (CERES-C3M)
C3M calculations	CCCM clear sky calculations (for cases AOD<=0.05)	-	5.5
	CCCM calculations (For all cases)	12.9	11.4

Using RRTM to calculate DRE_LW for different dust models.

Dust Models	DRE_LW (based on RRTM)			OLR Difference Ave for dust loading cases (CERES - RRTM)			AOD_0.55/10 (SSA @10)
	Ts:c3m Ɛ : Huang	Ts:c3m Ɛ : MYD_BF	Ts:MYD11 Ɛ : MYD_BF	Ts:c3m Ɛ : Huang	Ts:c3m Ɛ : MYD_BF	Ts:MYD11 Ɛ : MYD_BF	
AERONET Cape Verde PSD,OPAC RI	7.0	7.0	6.1	12.2	11.8	15.7	2.3 (0.41)
AERONET Cape Verde PSD, Mauritania RI	4.5	4.4	3.8	9.6	9.2	13.4	2.3 (0.33)
Fennec SAL PSD,OPAC RI	11.5	11.4	10.1	16.6	16.3	19.6	1.3(0.46)
Fennec SAL PSD, Mauritania RI	8.4	8.3	7.3	13.4	13.1	16.7	1.3(0.42)