Trans-Atlantic Dust Transport and Deposition - Models vs. Observations

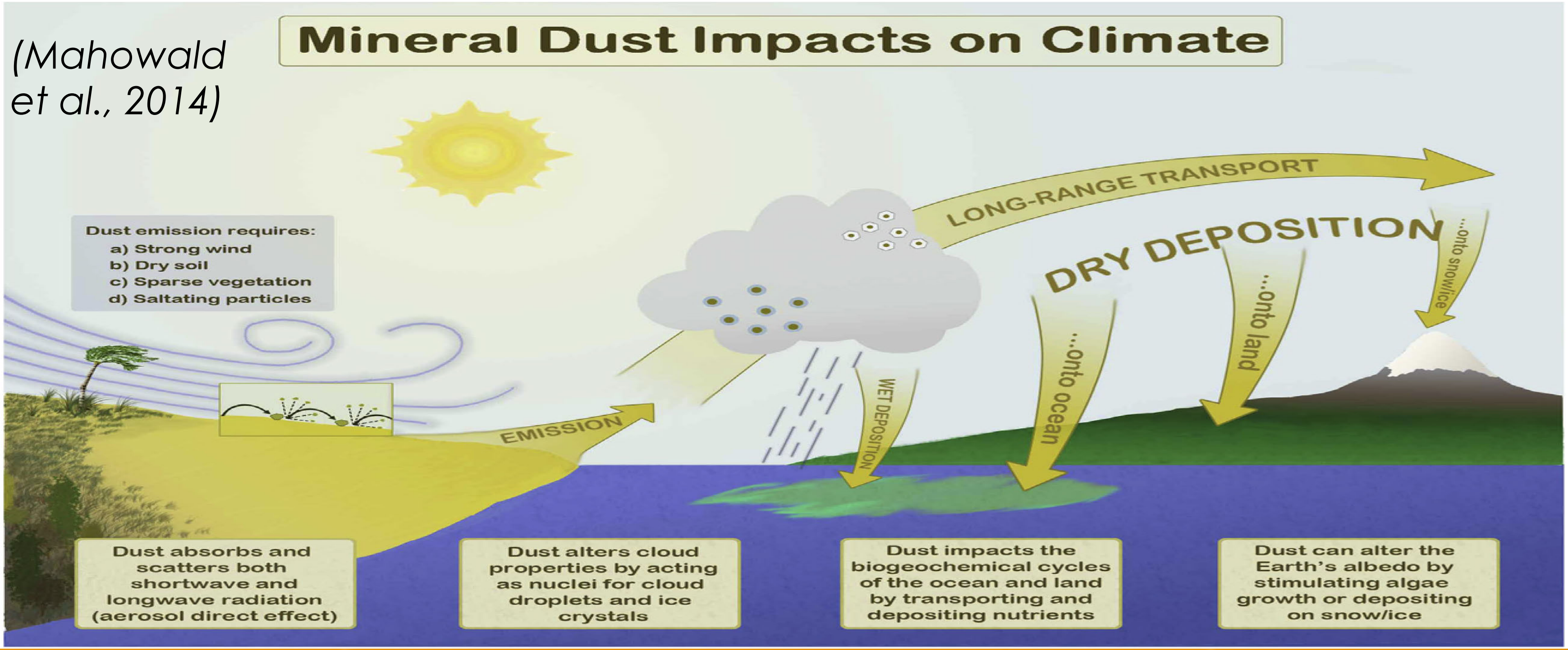
Hongbin Yu
University of Maryland & NASA GSFC

Mian Chin, Joe Prospero, Cynthia Randles, Arlindo da Silva, Huisheng Bian, Dongchul Kim

October 5, 2015
14th AeroCom Workshop, Frascati, Italy

Dust Interactions with Climate

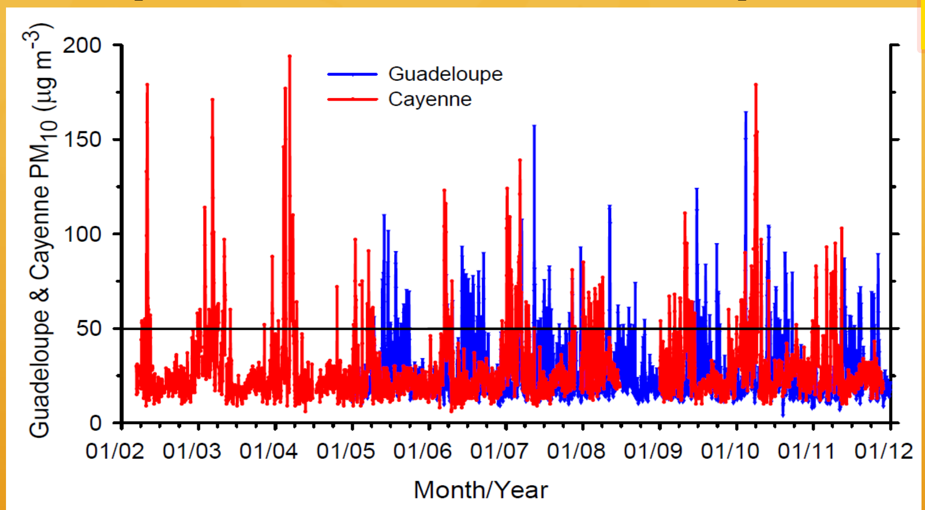
(Mahowald et al., 2014)



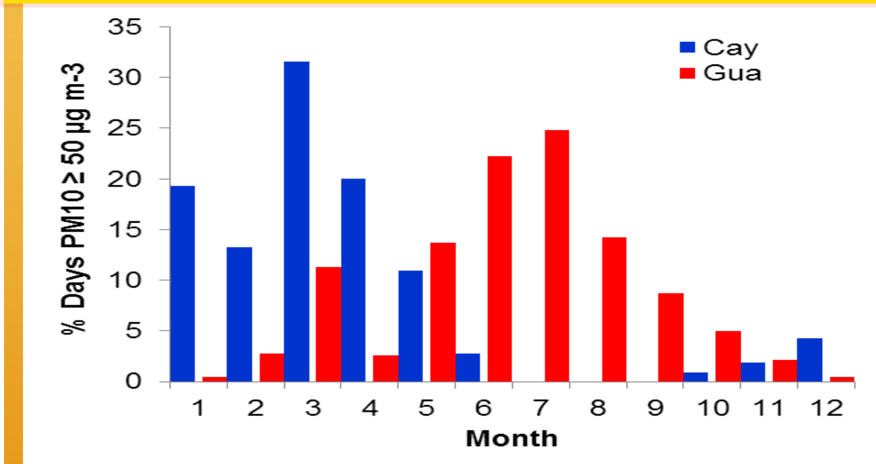
- Dust affects climate (and weather) in many ways (e.g., radiation, clouds, biogeochemical cycle, snow albedo)
- Dust emissions and transport are affected by climate.

Dust Impacts on Air Quality

(Prospero et al., GBC, 2014)



Percent of Days Exceeding 50 µ g m^{-3}



- African dust elevates the surface PM_{10} level exceeding WHO guideline in the Caribbean Basin.
- The rate of PM_{10} incompliance is comparable to those observed in major urban areas in Europe and the U.S.

Objectives

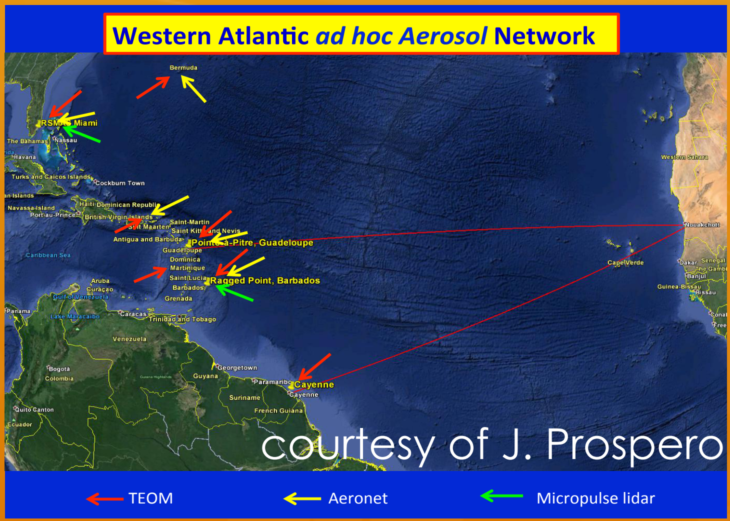
- To quantify altitude-resolved trans-Atlantic transport and deposition of dust from satellite observations
- To compare observations and models

DATA & MODELS

- CALIOP/CALIPSO observations of 3-D distribution of aerosols

- Model simulations
  - GOCART (1980-2009)
    - offline CTM driven by MERRA met.
    - 2.5x2 resolution
  - MERRA2 aerosol reanalysis (1979-2014)
    - GOCART module
    - 0.625x0.5 resolution
    - total AOD at single-λ is constrained by satellite obs.
    - composition and profile are not assimilated

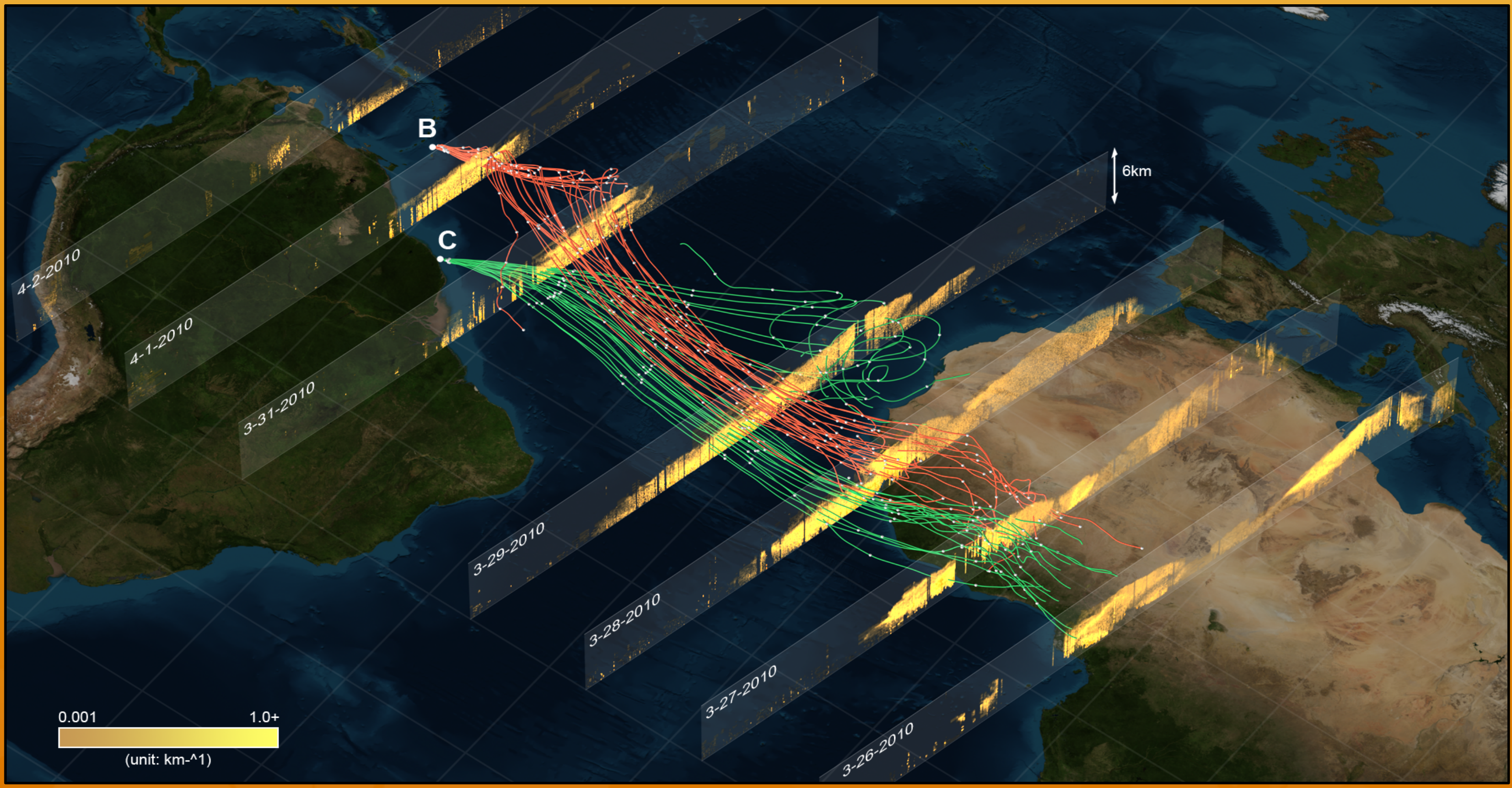
- Ground-based measurements
  - Dust concentration
  - AOD
  - PM10, PM2.5
  - Vertical profile



CALIOP/CALIPSO – 3D View of Dust Transport

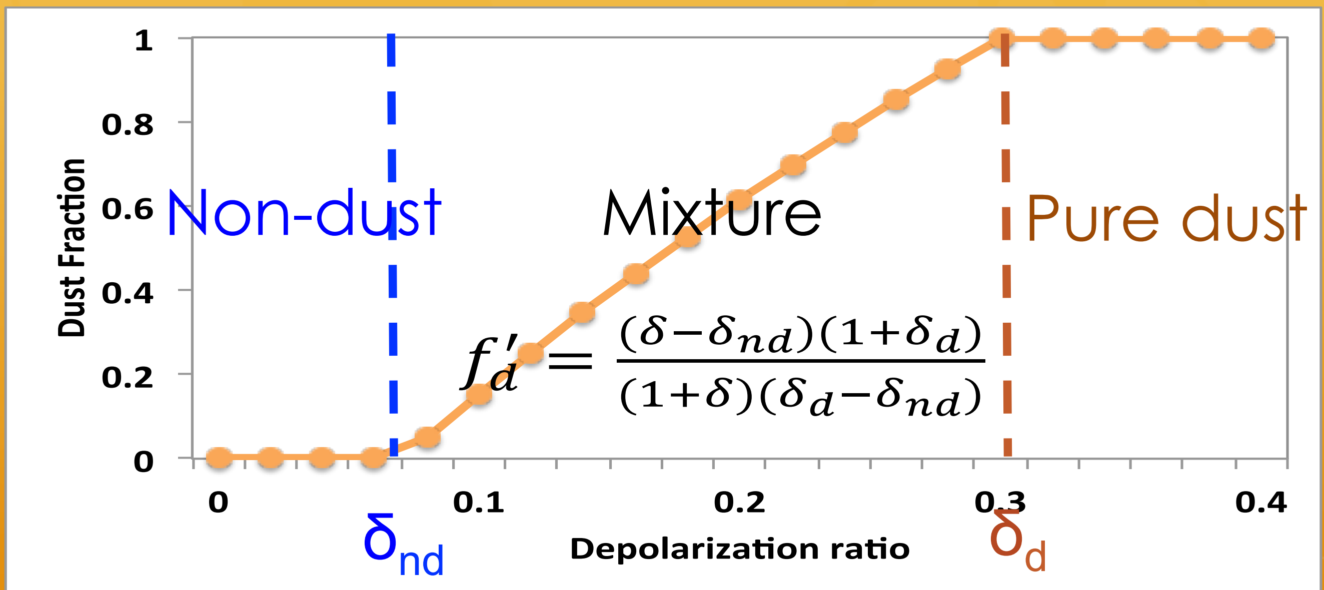
CALIOP is a polarization lidar onboard CALIPSO since June 2006

- 3D distributions of aerosol backscatter and extinction – realistic transport height
- Particulate depolarization ratio – separating dust from non-dust
- Above-cloud aerosol (ACA) profiles – new information



Separating Dust from Non-dust Aerosol

Dust particles are large in size and non-spherical in shape ⇨ They have significantly larger depolarization ratio than smoke and marine aerosol.



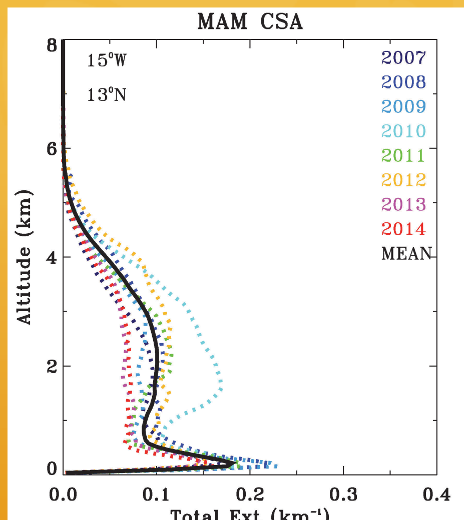
- ❑ **Lower-bound Dust Fraction (LDF):** $\delta_d = 0.30$, $\delta_{nd} = 0.07$
- ❑ **Upper-bound Dust Fraction (UDF):** $\delta_d = 0.20$, $\delta_{nd} = 0.02$

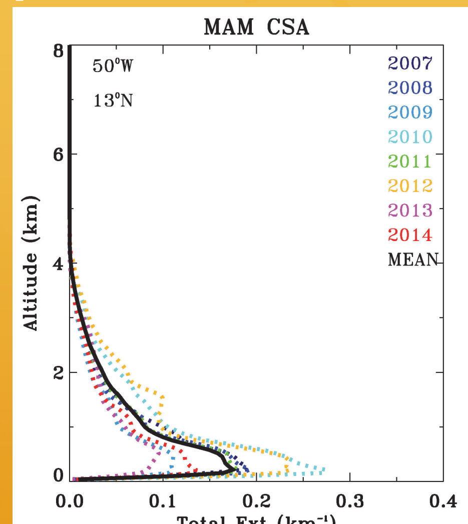
We use the average of LDF and UDF as the best estimate

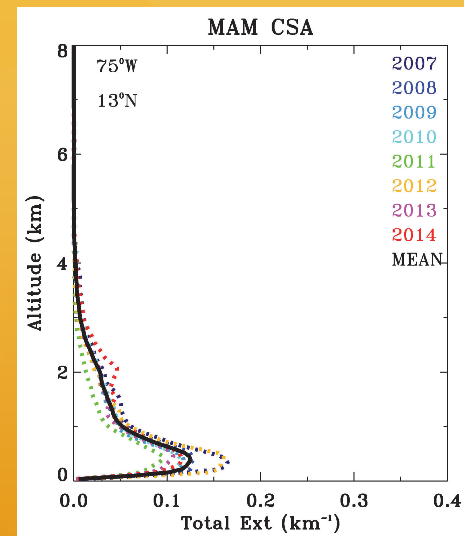
2007-2014 Extinction Profiles – Spring

African Coast | Upwind of Barbados | West Caribbean

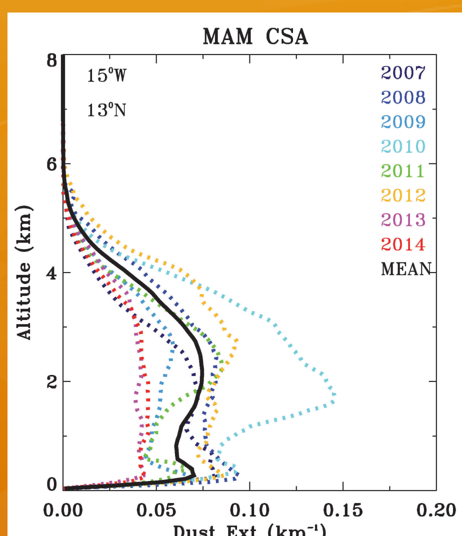
Total

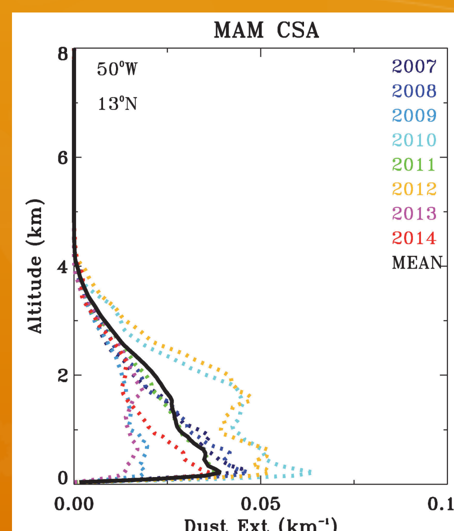


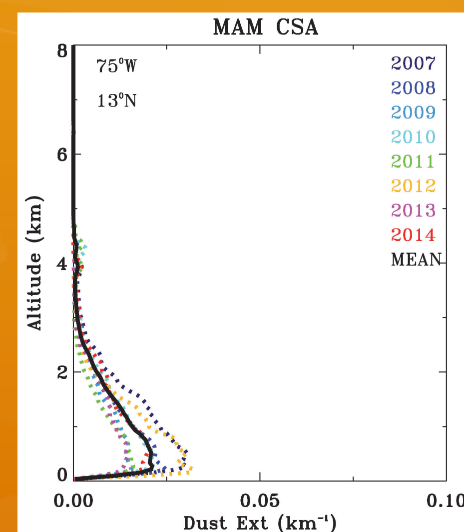




Dust

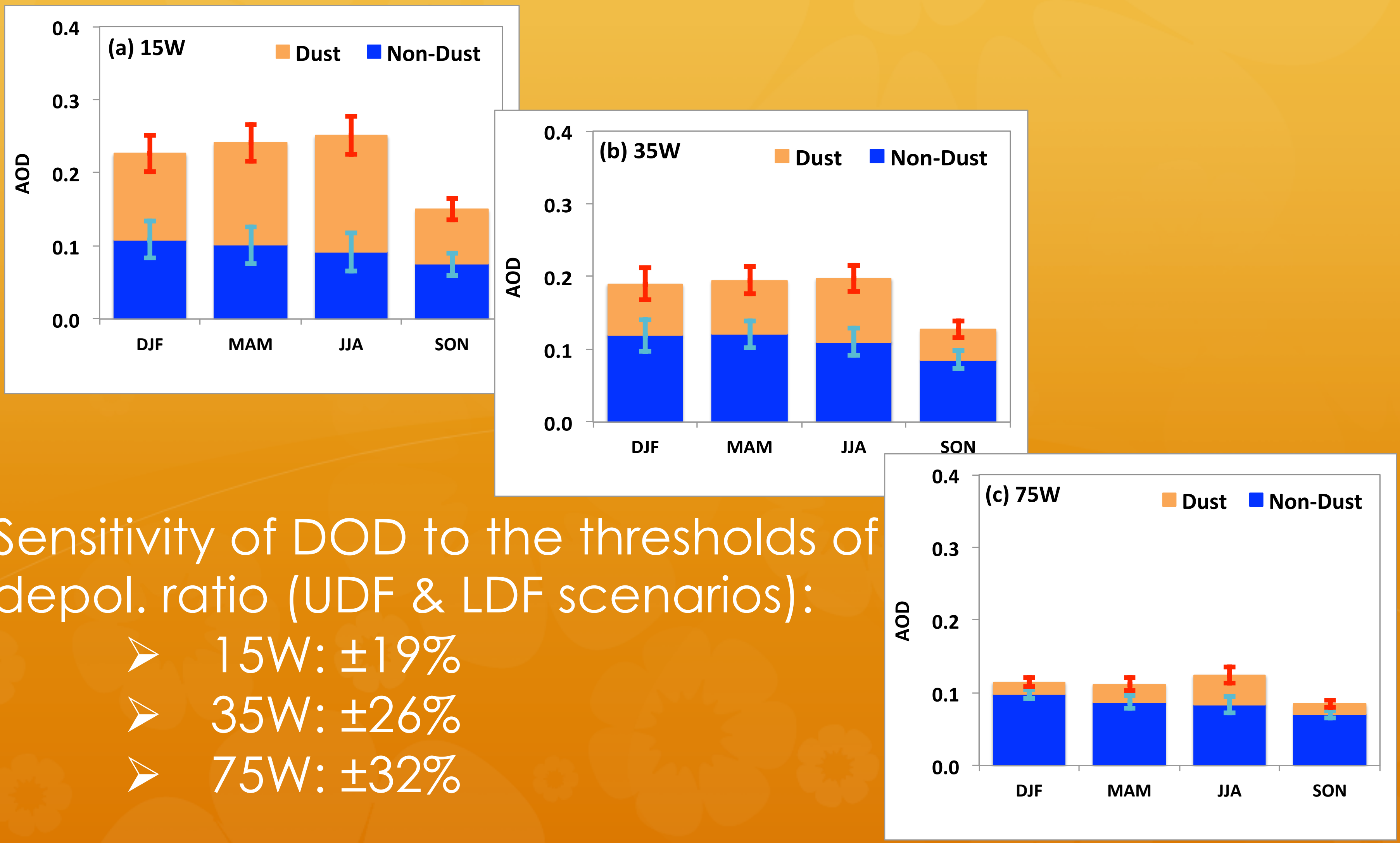






Partition of Dust & Non-Dust

2007-2014 & 10S - 30N Average



Sensitivity of DOD to the thresholds of depol. ratio (UDF & LDF scenarios):

- 15W: ±19%
- 35W: ±26%
- 75W: ±32%

Estimate of Dust Mass Flux from CALIOP

Dust backscatter/ extinction profile from CALIOP

MEE (Mass Extinction Efficiency)

Extinction (1/m) = Mass Conc. (g/m³) * MEE (=0.37 m²/g)

Profile of Dust Mass Concentration (m)

MERRA reanalysis wind field

Dust Mass Flux

$$F = \int m(z)u(z)\,dz$$

$$DD = -(\partial F_x / \partial x + \partial F_y / \partial y)$$

Dust deposition (DD) is estimated as the convergence of zonal & meridional fluxes (assuming no leak from the top)

Yu et al. (RSE, 2015)

Sources of Uncertainty

- Dust and non-dust separation: **± (15~34)%**
- Unchanged size: ±15% *(Maring et al., 2003)*
- CALIOP AOD low-bias: **-30%** *(Omar et al., 2013; Liu et al., 2014)*
- Low dust MEE/ high mass bias: **+30%** *(Ansmann et al., 2012)*
- Shape of vertical profile: *probably small*, **±10%**

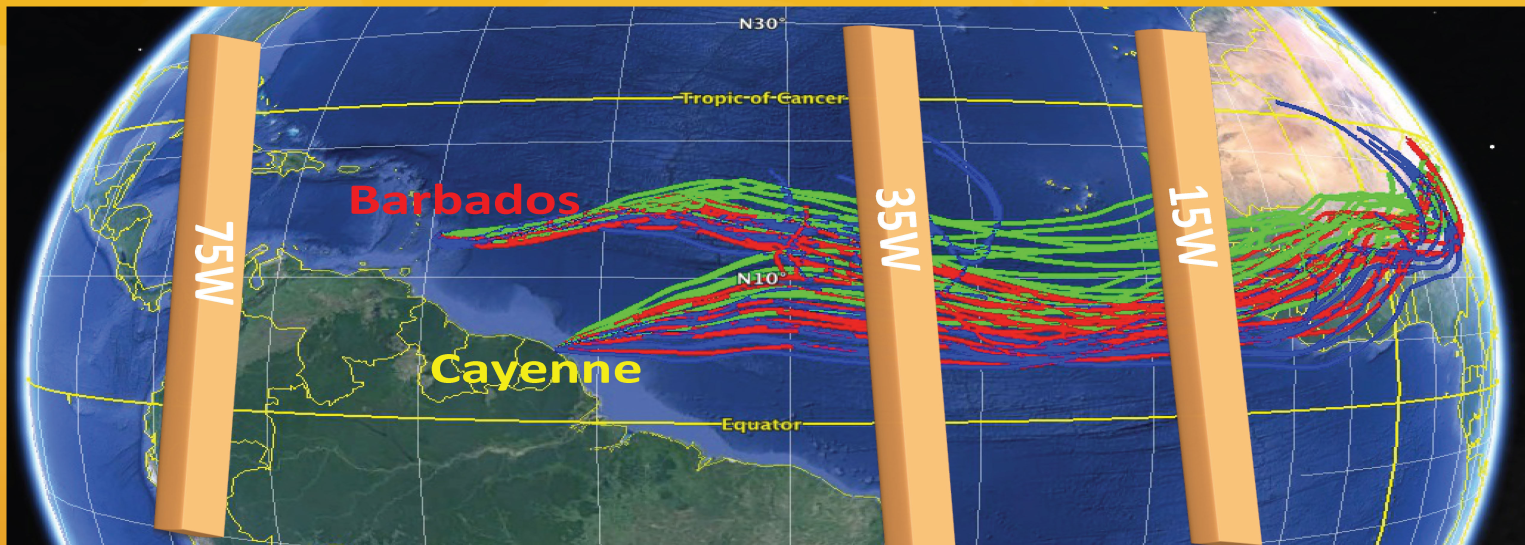
Overall known uncertainty: **± (45~70)%**

Other uncertainties:

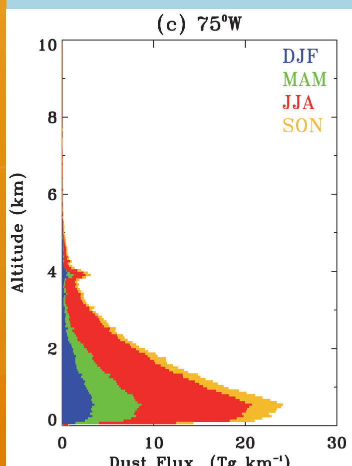
- ☒ Below-cloud dust
- ☒ Diurnal variation

Yu et al. (RSE, 2015)

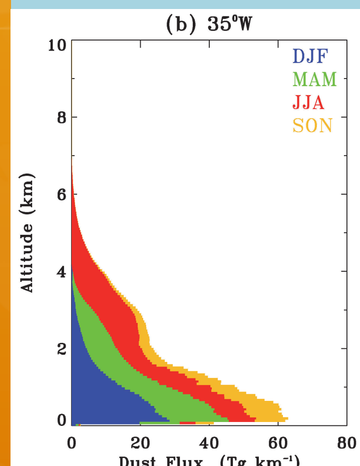
8-year Average Dust Flux & Vertical Profile



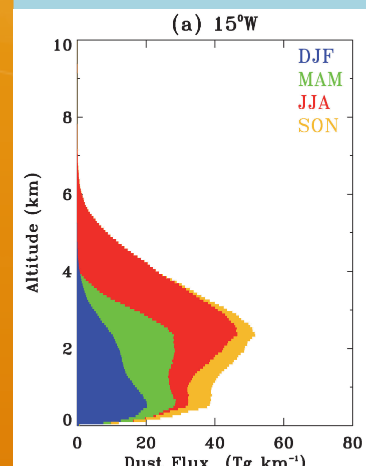
43 Tg



130 Tg



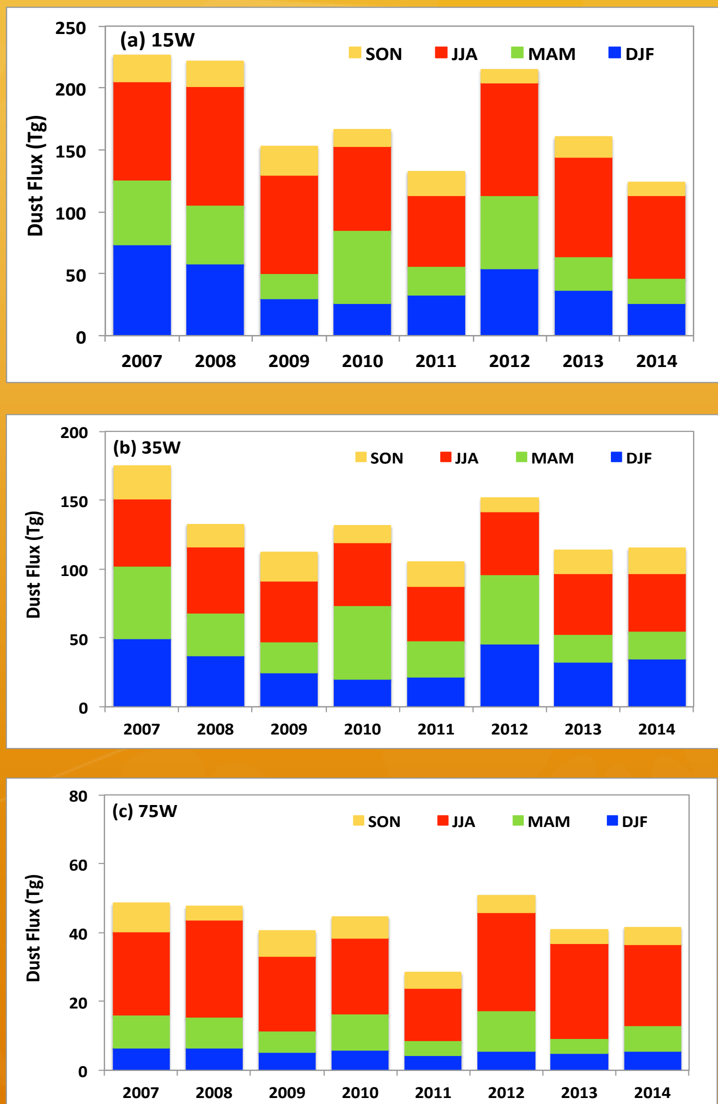
175 Tg

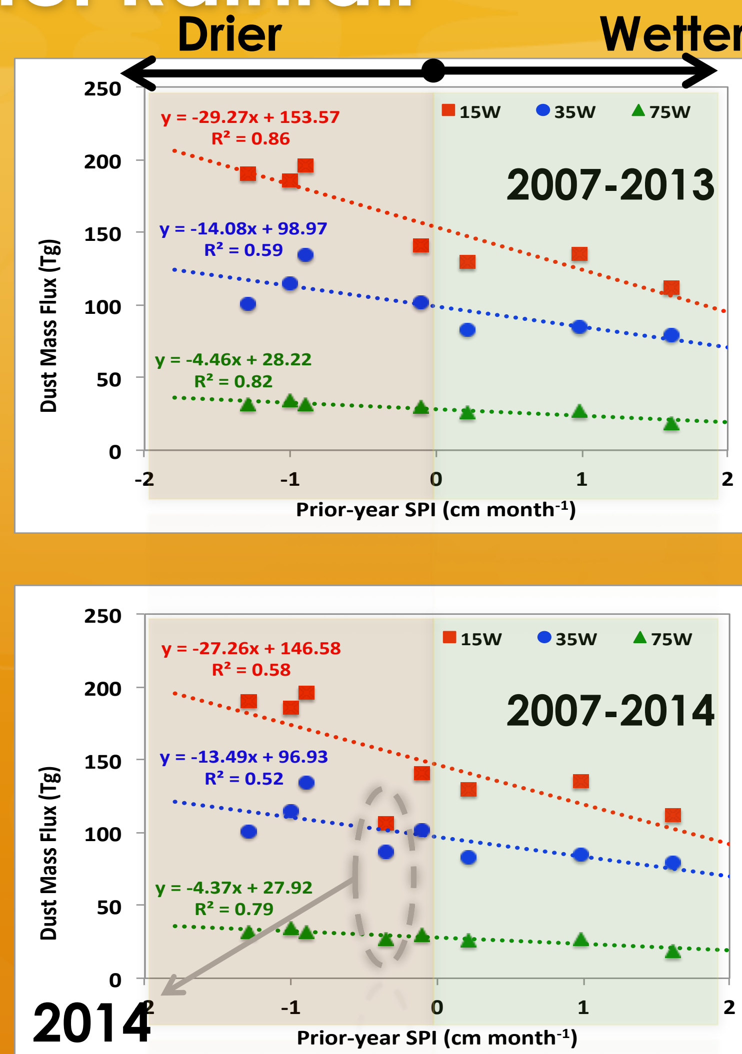


10°S-30°N integrated flux

1 Tg = 10^{12} g

Interannual variation of dust transport vs. prior-year Sahel Rainfall

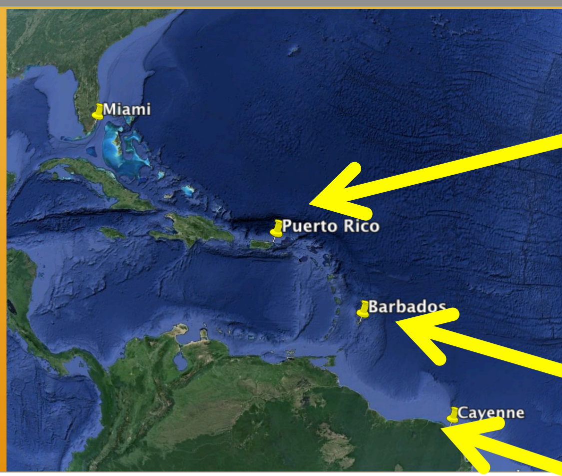


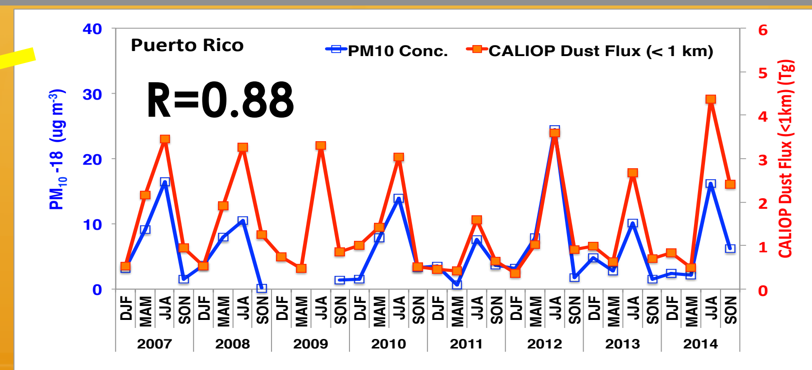


SPI - Sahel Precipitation Index (data from JISAO of NOAA & U. Washington)

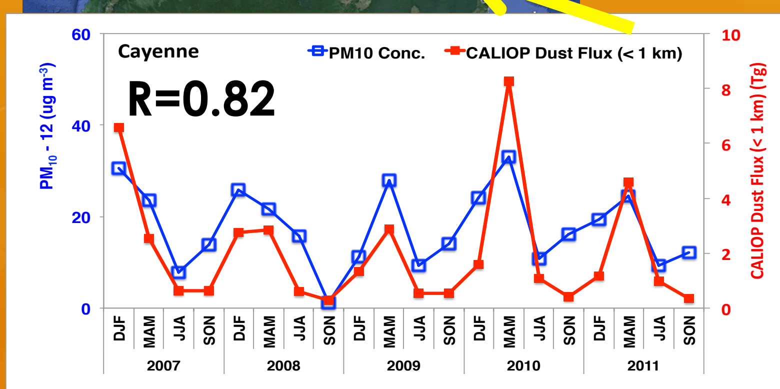
Correlation of Dust Flux with Surface Dust Concentration

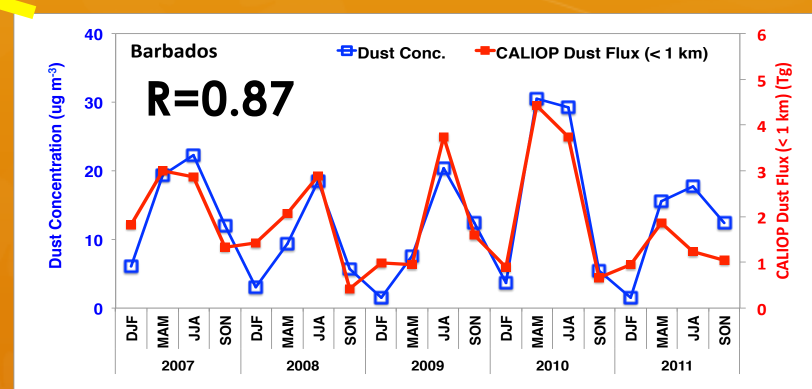
- Dust flux is calculated along the 550 km meridional line just upwind of the interested regions.
- Assume dust flux in the lowest 1km layer is responsible for dust detected in the surface.





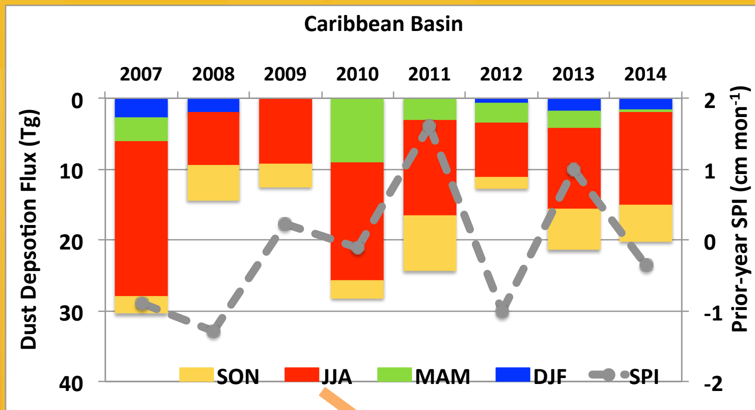
18 ug/m^3 is the lowest seasonal mean

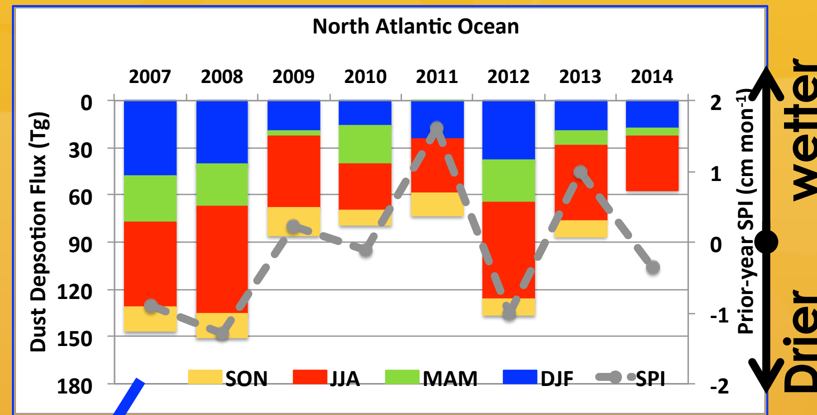




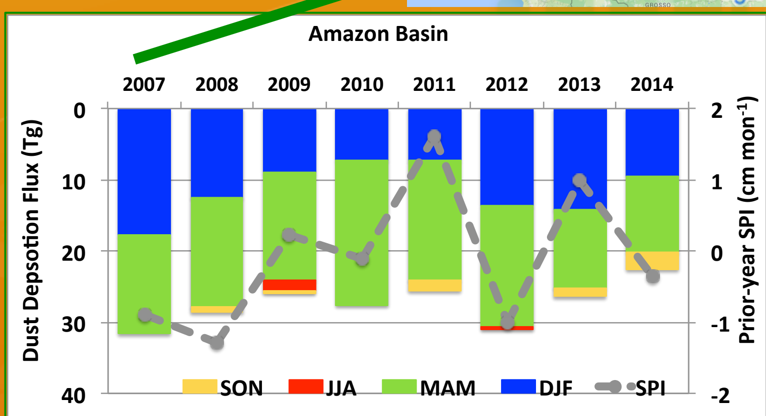
12 ug/m^3 is the lowest seasonal mean

Dust Deposition into Ocean and Amazon





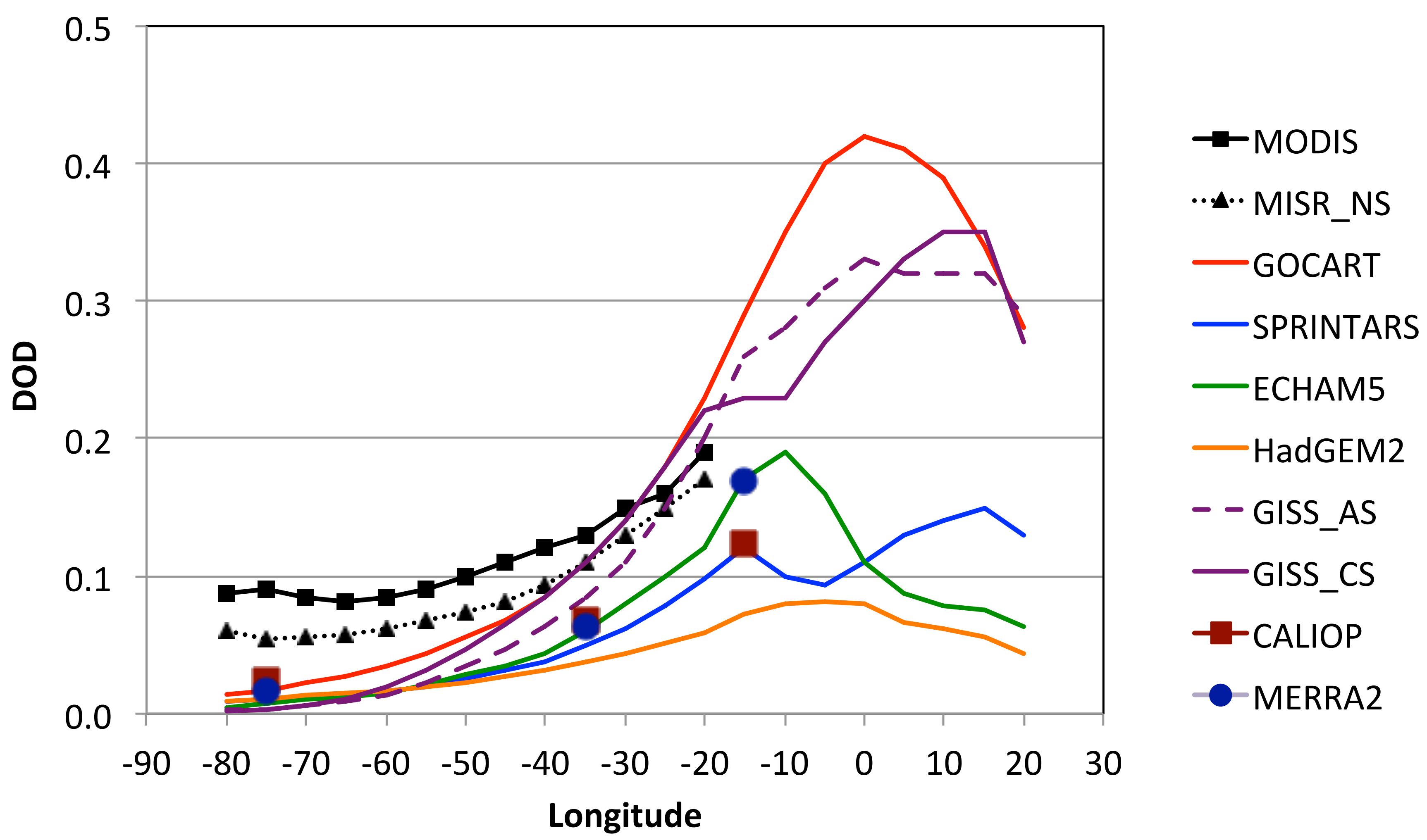
DD vs. SPI: R= -0.71 (07-14)
R= -0.88 (07-13)



- African dust adds 23 (7-39) g ha^{-1} a^{-1} phosphorus (P) to P-deficient Amazon Basin, which replenishes the loss of P by rains and flood.
- African dust may play an important fertilizing role in the Amazon rainforests on the long term

(Yu et al., GRL, 2015)

CALIOP vs. MERRA2



Dust Deposition: CALIOP vs. MODELS

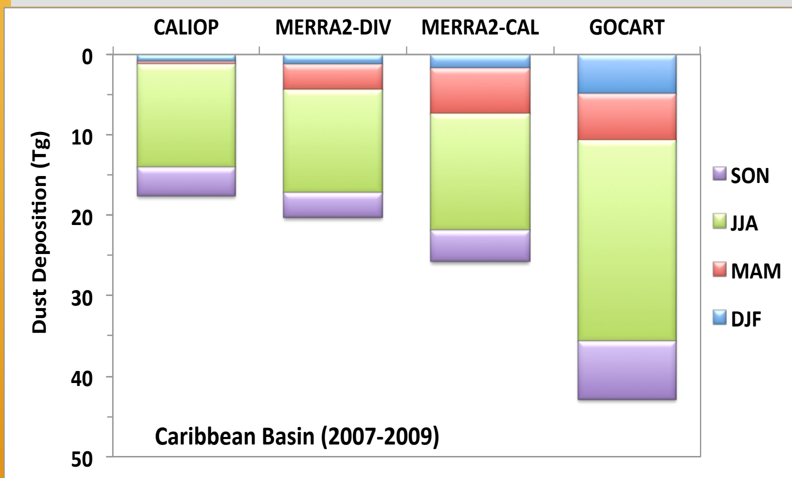
Two types of dust deposition estimates

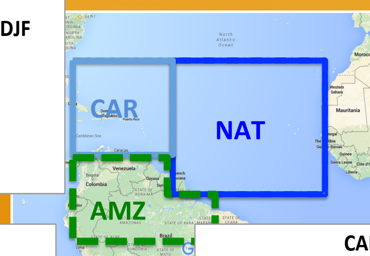
- CAL – based on para. of dry & wet removals
- DIV – diagnosed from flux divergence

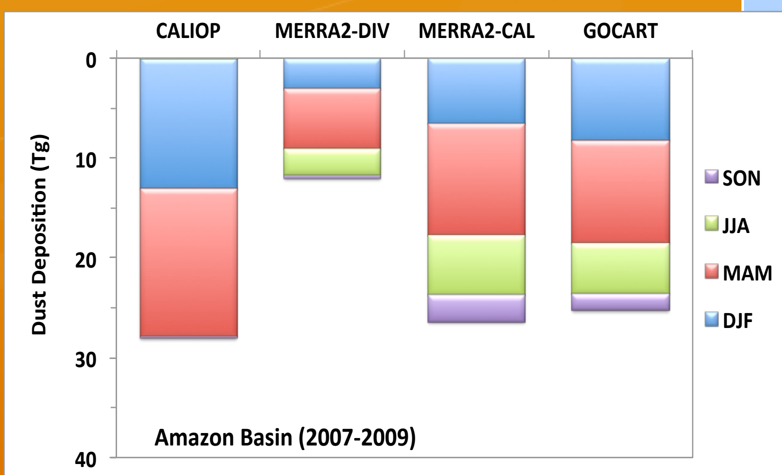
	CAL	DIV
CALIOP		X
MERRA2	X	X
GOCART	X	

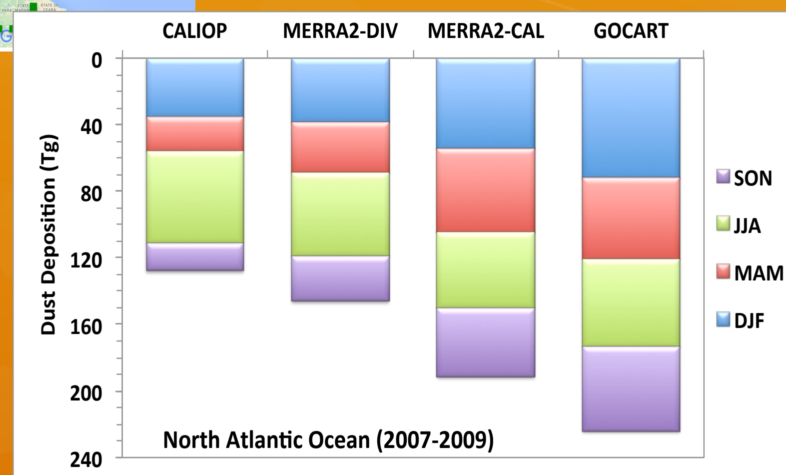
GOCART, CAL = DIV
(mass balance)

MERRA2, CAL > DIV if its removal mechanisms are too efficient (adtl. source)







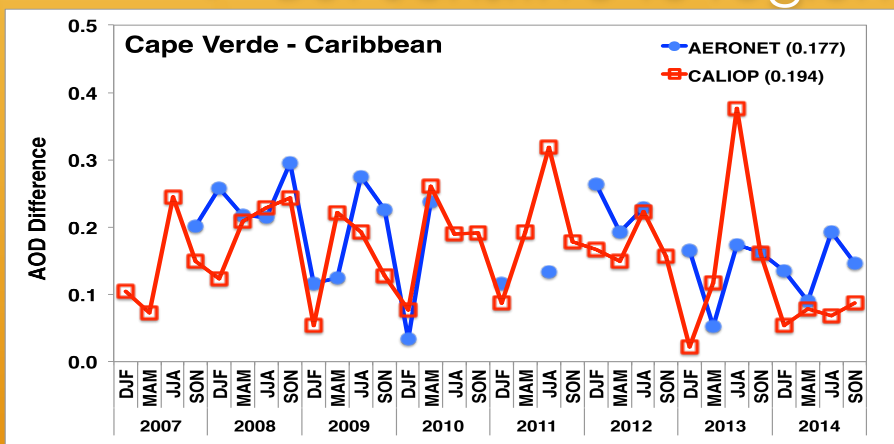


Dust Lifetime Estimate

Dust Lifetime (d) = [DOD/MEE] (gm^{-2})

÷ [Dust Deposition Flux] ($gm^{-2}d^{-1}$)

- Not sensitive to MEE
- But Sensitive to region-mean DOD to DOD gradient

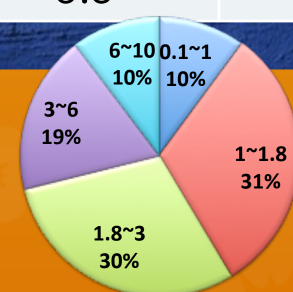


- Dust deposition into NAT & CAR is 123 Tg a^{-1} or 6.7 gm^{-2} a^{-1}
- Regional mean DOD = 0.058
- Dust lifetime = ~ 9 days

Cape Verde

Estimated lifetime (d) from AeroCom models (Kim et al., 2014)				
GOCART	GISS	SPRINTARS	ECHAM5	HadGEM2
4.9	5.0	4.2	5.3	5.7

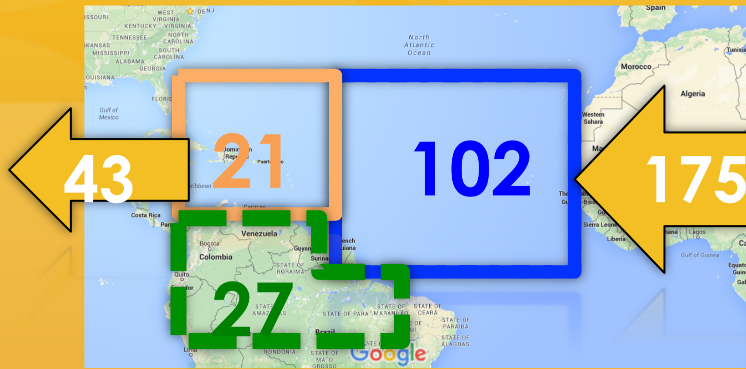
Caveat: CALIOP-based dust deposition is underestimated because of non-sensitivity to coarse particles



GOCART: 29% of dust dep. By particles with radius >3 um

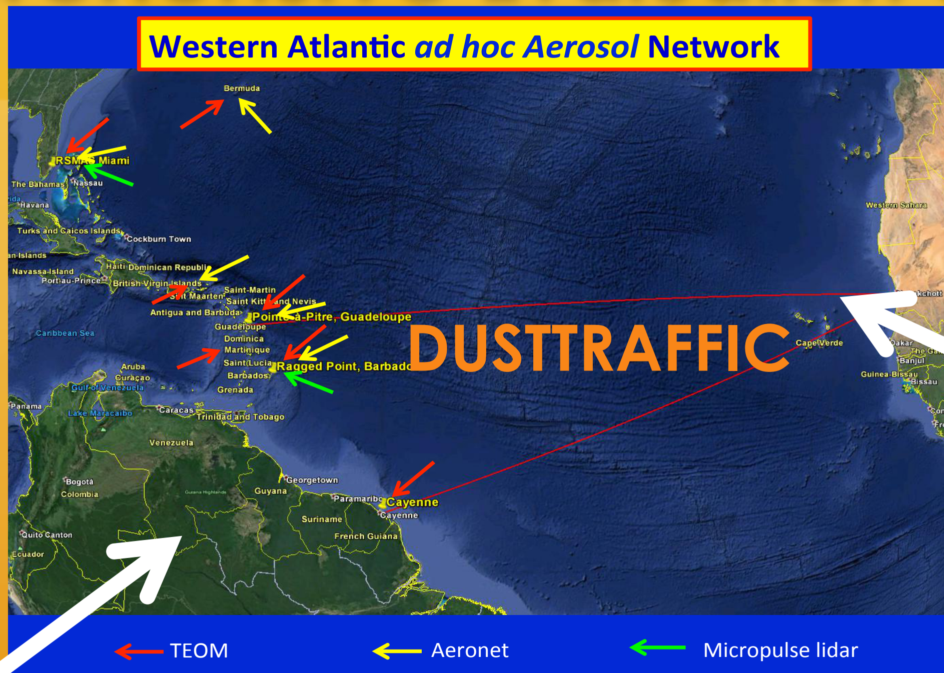
CONCLUSIONS

- dust transport and deposition based on 8-yr CALIOP data record



- The CALIOP-based dust flux in the lowest 1km layer correlates with surface dust conc. in the Caribbean Basin (R=0.82-0.88)
- The CALIOP-based dust transport and deposition show modest correlation with prior-year Sahel rainfall. *Longer data record is needed for getting a robust relationship.*
- Significant differences in dust transport and deposition exist between CALIOP and MERRA2. MERRA2 shows larger east-west gradient than CALIOP. Further comparison of vertical profile is needed (on going).
- Dust lifetime based on CALIOP observations is estimated at ~9 days, significantly longer than AeroCom models. But caveats exist.

Comprehensive Evaluation of Models



AERONET etc.

(courtesy of J. Prospero)

Long-term measurements (filter, lidar, AERONET) in the Amazon [Paulo Artaxo]

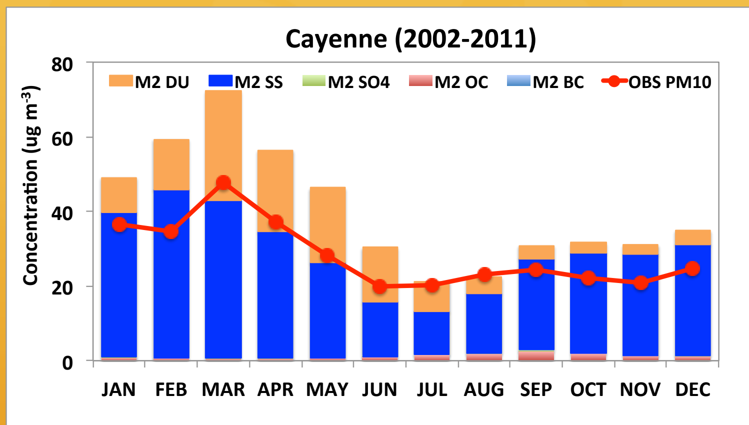
A suite of satellite measurements and derived products (e.g., passive & active, polar orbiting & geostationary)

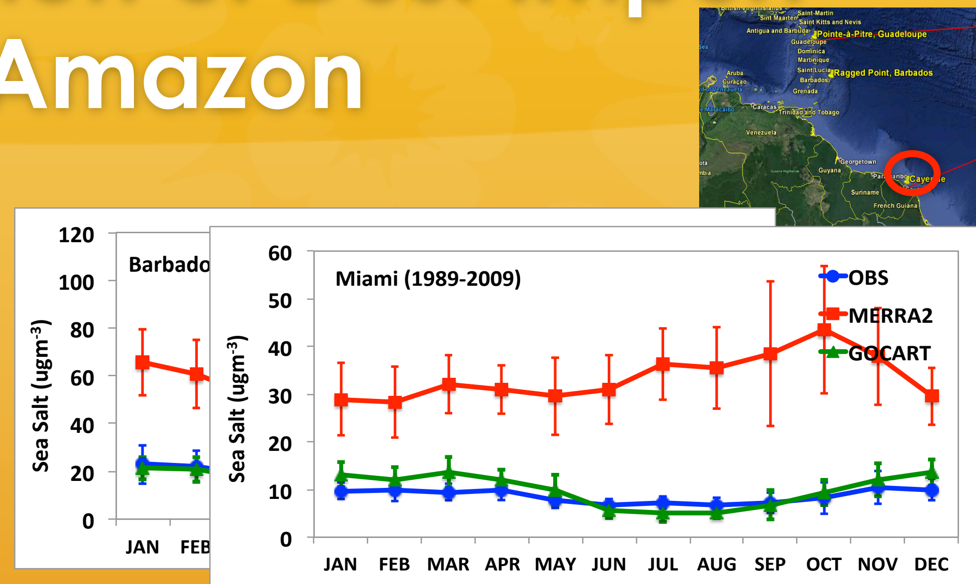
Thank you for your attention!

Questions?

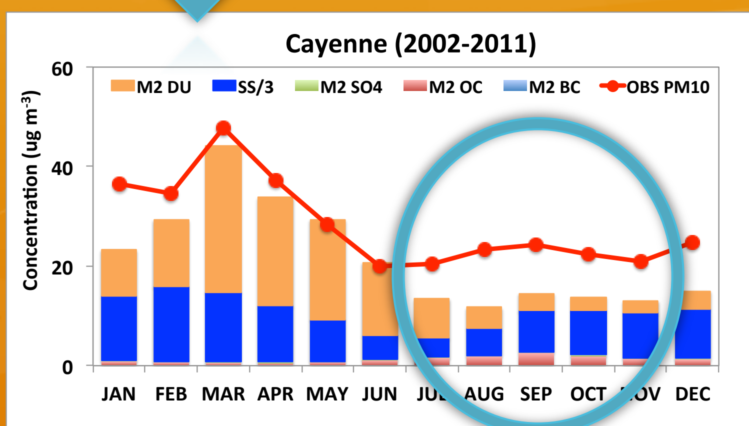
Model Simulation of Dust Import into Amazon

MERRA2

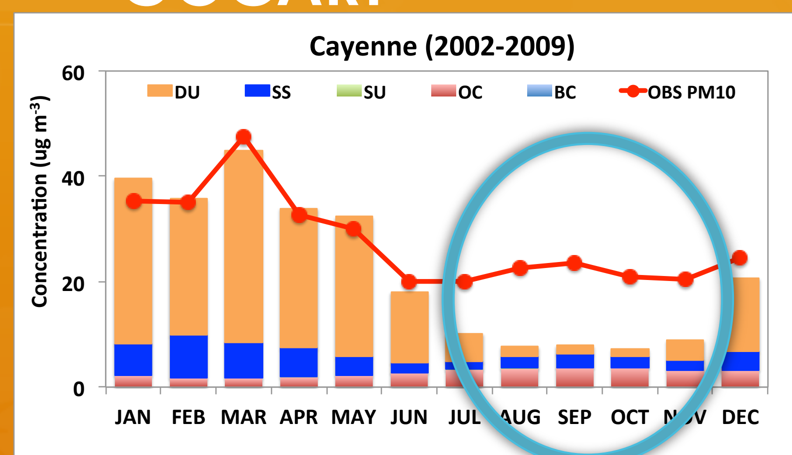




Scaling sea-salt by 1/3



GOCART



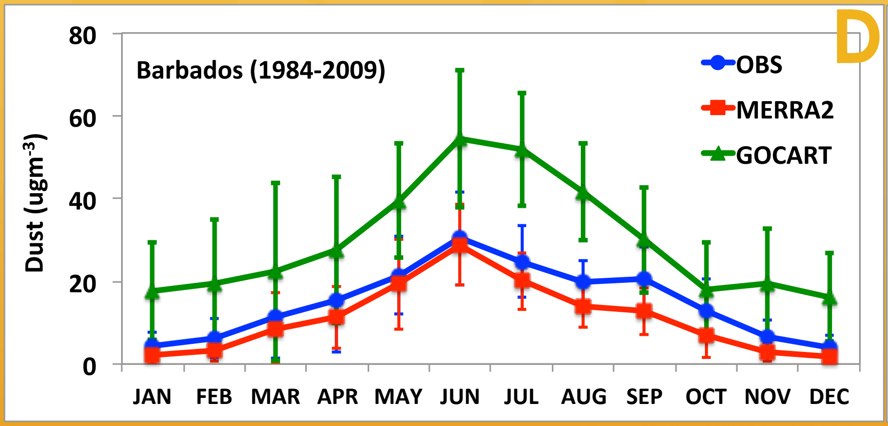
Missing sources in non-dust season (e.g., transport of smoke from Brazil)?

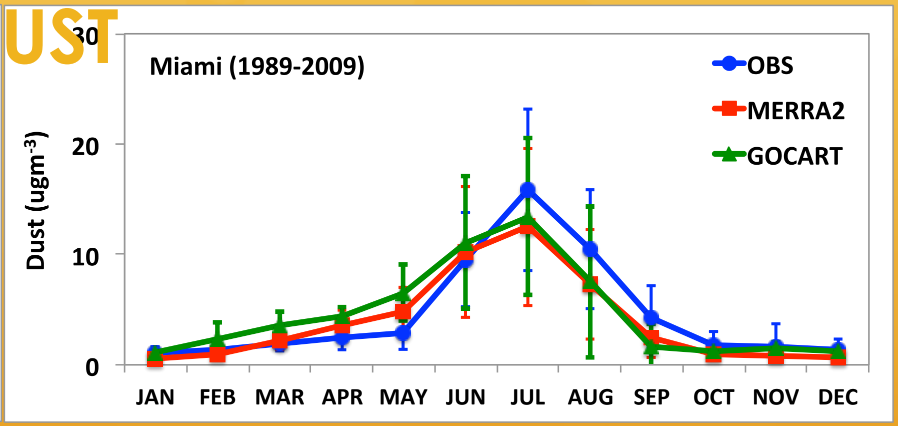
MODELS vs. OBS.

Barbados

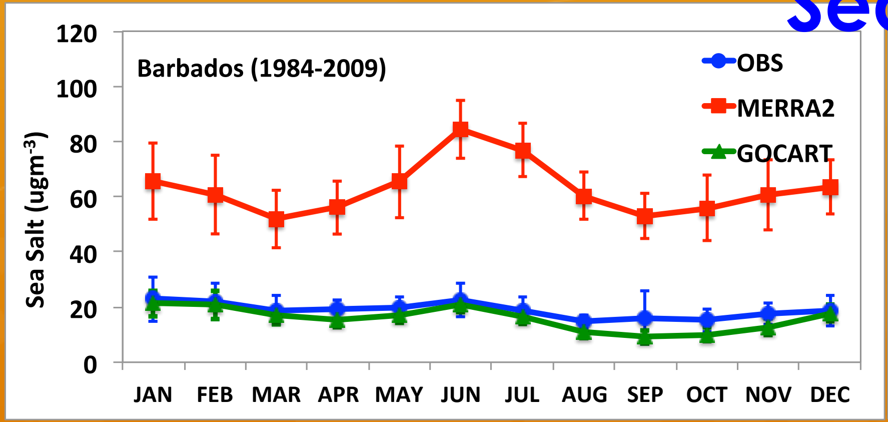
Miami

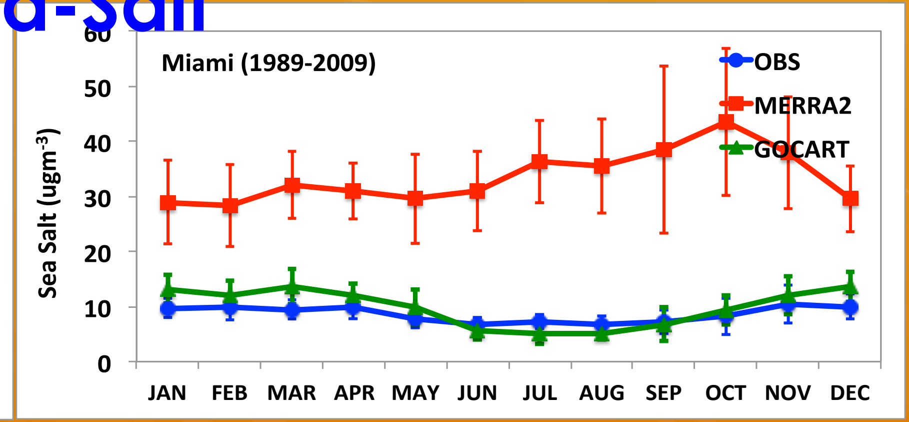
DUST

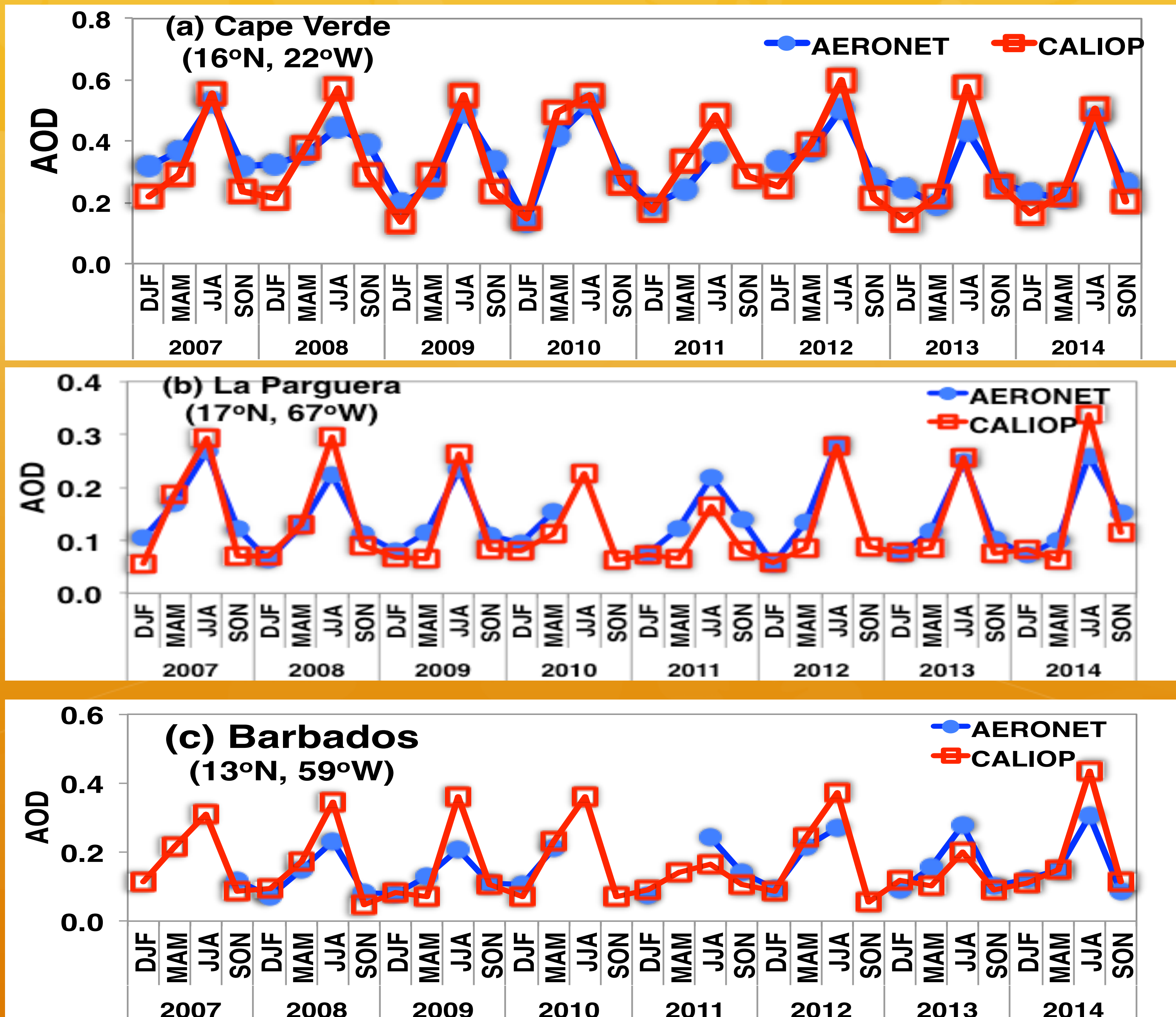




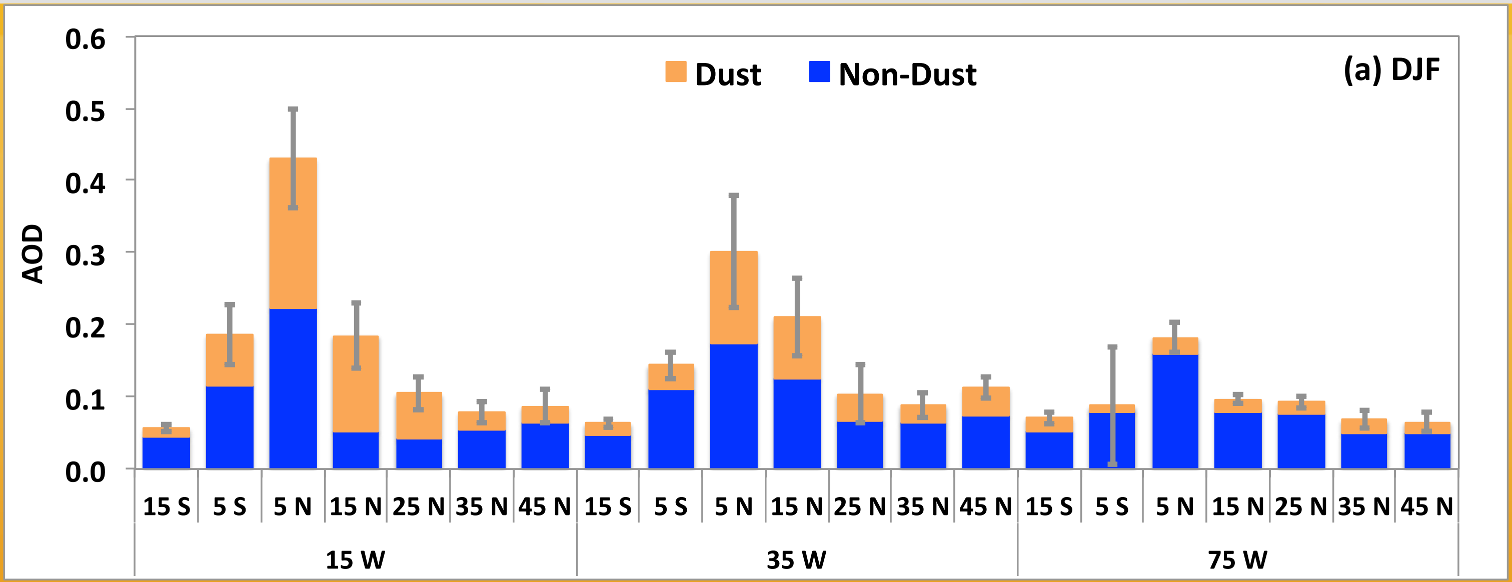
Sea-Salt

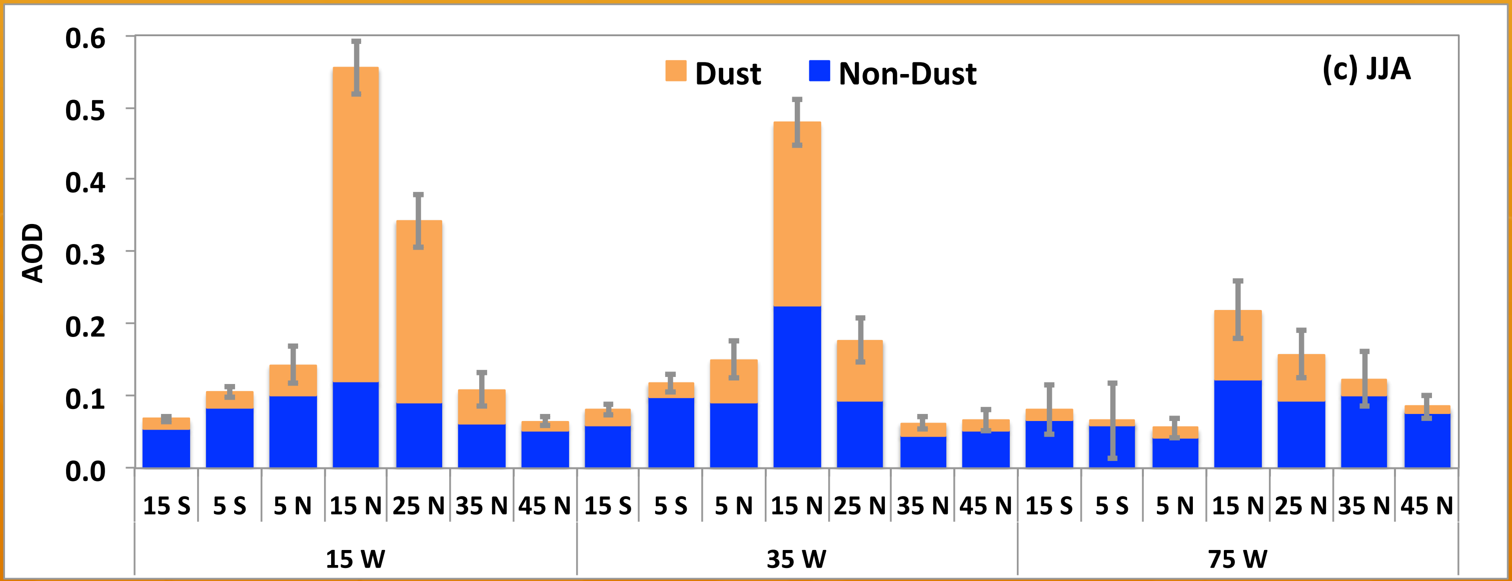





(a) Cape Verde
(16°N, 22°W)
AERONET
CALIOP
AOD
0.8
0.6
0.4
0.2
0.0
DJF MAM JJA SON
2007 2008 2009 2010 2011 2012 2013 2014
(b) La Parguera
(17°N, 67°W)
AERONET
CALIOP
AOD
0.4
0.3
0.2
0.1
0.0
DJF MAM JJA SON
2007 2008 2009 2010 2011 2012 2013 2014
(c) Barbados
(13°N, 59°W)
AERONET
CALIOP
AOD
0.6
0.4
0.2
0.0
DJF MAM JJA SON
2007 2008 2009 2010 2011 2012 2013 2014

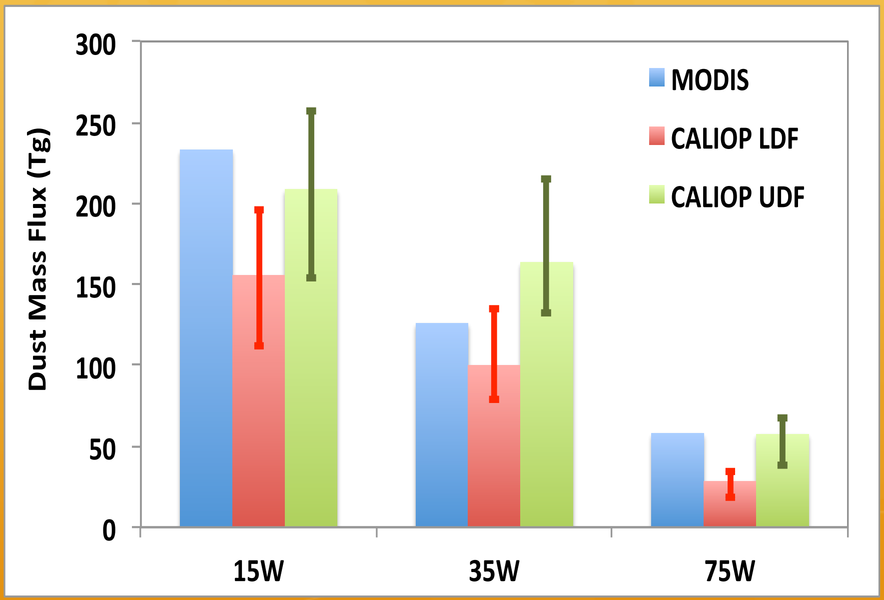
Partition of Dust & Non-Dust





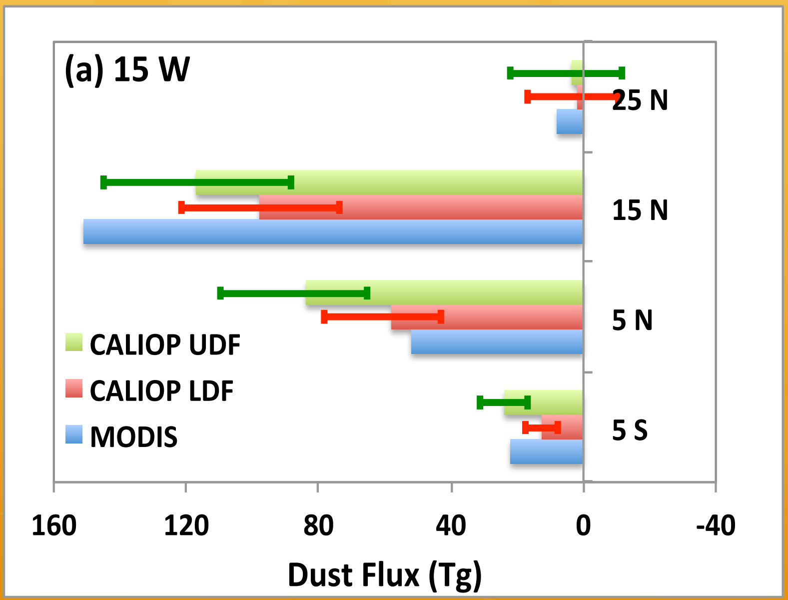
CALIOP vs. MODIS

10°S-30°N Integrated



MODIS-based dust mass flux (Kaufman et al., 2005) generally agrees well with CALIOP upper-bound estimate.

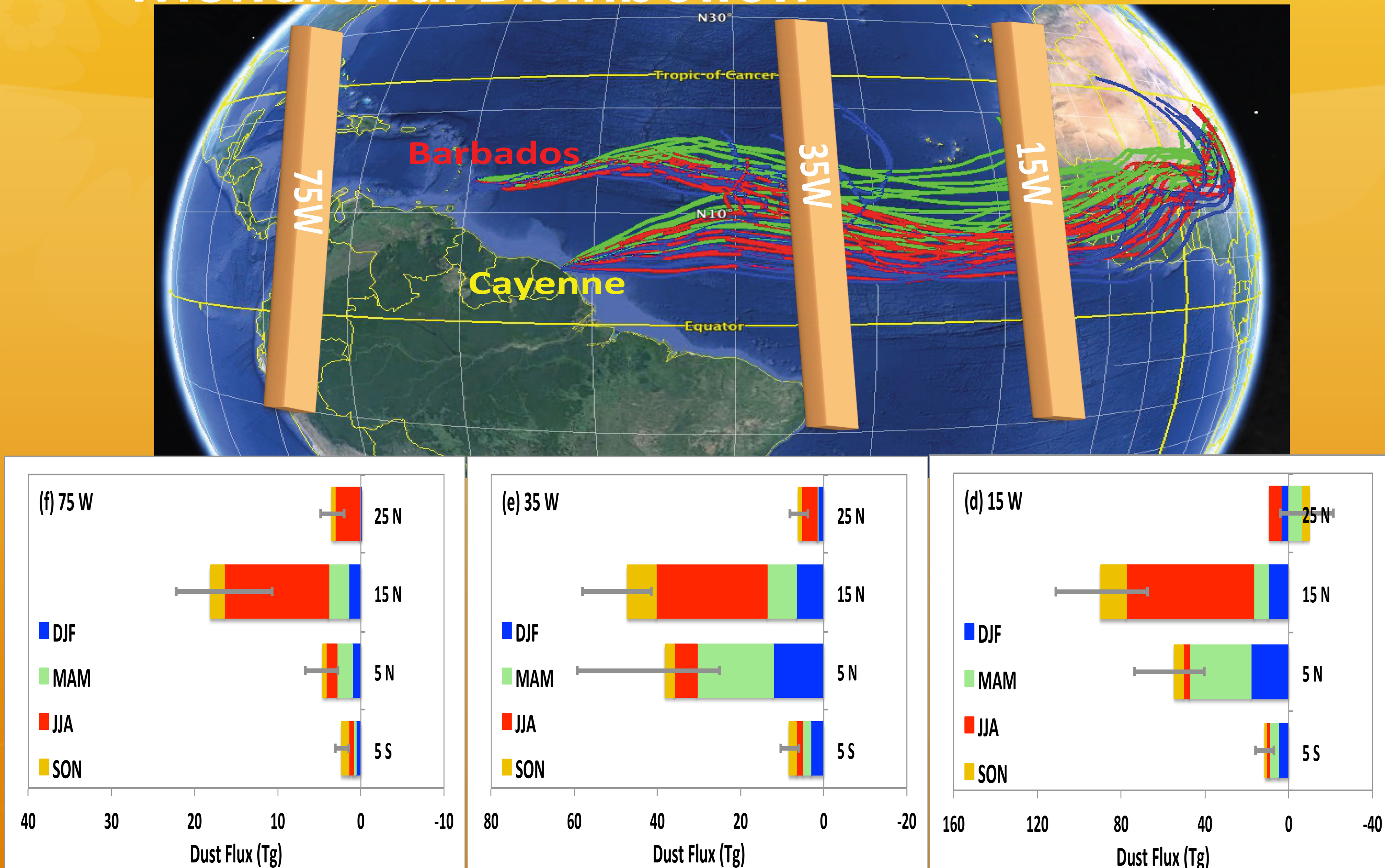
Meridional Distribution



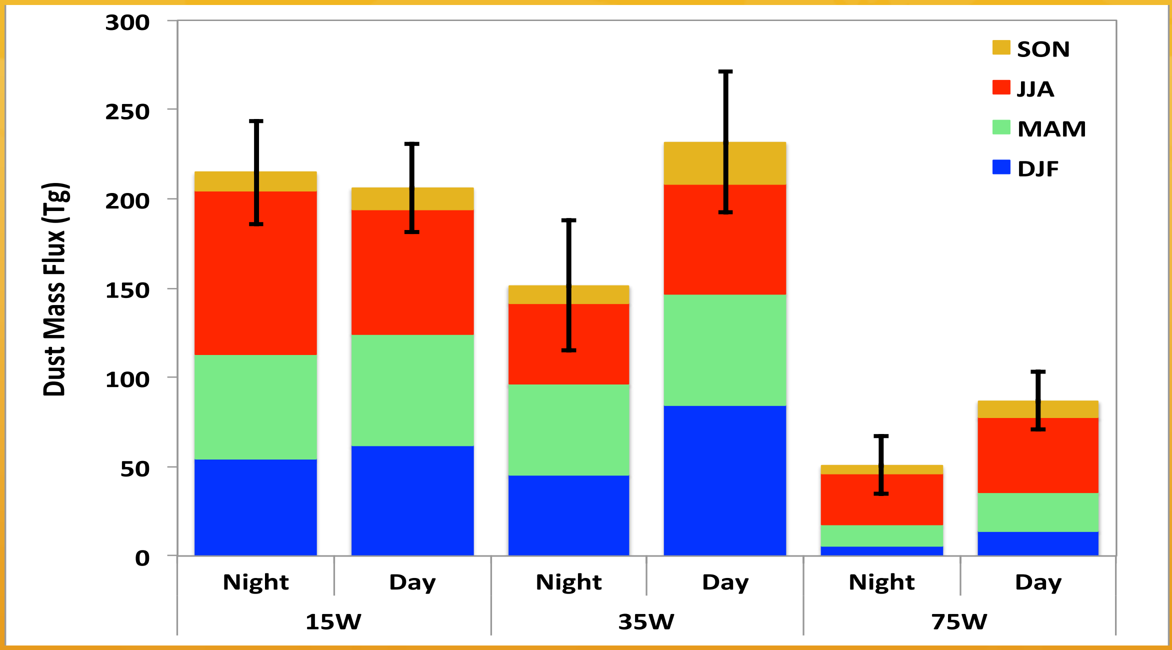
Larger differences in the meridional distribution.

Error bar indicates the range over the 7-year period.

Meridional Distribution



Daytime vs nighttime



- But we can't attribute the day-night difference to physical processes, because CALIOP daytime and nighttime data have different quality.
- AERONET AOD in trans-Atlantic dust route shows small daytime variations *(Smirnov et al, 2002; Zhang et al., 2012)*