Airborne HSRL Assessment of CALIOP Aerosol Extinction Retrievals Constrained by Column AOD

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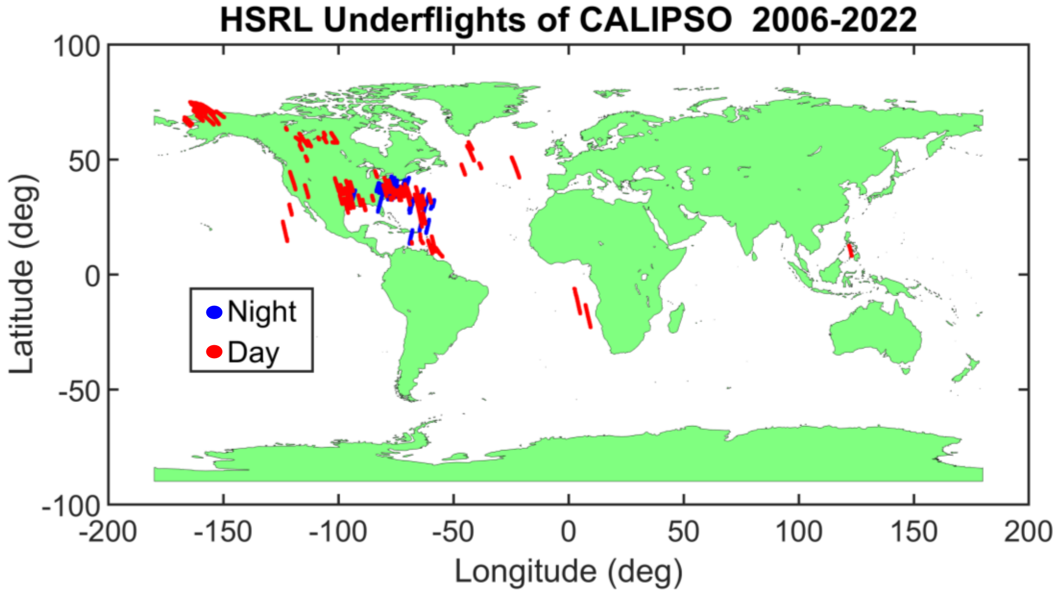
ROSES CALIPSO Project
"Assessing and Improving CALIPSO Aerosol Optical Properties"
(Ferrare, Burton, Schuster, Painemal, Vaughan, Powell, Ryan)

- Accurate aerosol extinction profiles crucial for assessing:
  - Aerosol radiative effects and forcing
  - Air quality
- CALIOP retrievals of aerosol extinction profiles have large uncertainties (30-50%), miss undetected layers (Thorsen and Fu, 2015; Kim et al., 2017)
- Constraining these retrievals using column AOD can be a method to reduce these uncertainties (Burton et al., 2010; Painemal et al. 2019)
  - Assessments using airborne HSRL found reduced bias and RMSE relative to CALIOP V4
  - Constrained retrieval accuracy depends on accuracy of constraining AOD
- AOS likely to pursue constrained retrievals

➢ **In this investigation, we use airborne HSRL measurements to assess CALIOP AOD, lidar ratios, and aerosol extinction profiles derived from constrained retrievals**

- **We take advantage of extensive airborne HSRL measurements below CALIOP**
  - Airborne HSRL provides direct measurements of AOD, lidar ratio, and aerosol extinction profiles
  - Extensive record (i.e. about 150 airborne HSRL underflights of CALIOP during 2006-2022)



Methods for Retrieving Aerosol Extinction Profiles with Elastic Backscatter Lidars

measured

2 unknowns

$$\beta'_t(r) = \frac{C_1}{r^2}[\beta_a(r) + \beta_m(r)]\exp\left\{-2\int_0^x [\sigma_m(r') + \sigma_a(r')]dr'\right\}$$

β_a= Aerosol Backscatter, σ_a= Aerosol Extinction

r is range (distance) from the instrument
C is instrument calibration constant
β_m and σ_m are molecular backscatter and extinction

- Use aerosol extinction/backscatter ratio (aka "lidar ratio") to relate these $S_a(r) = \sigma_a(r)/\beta_a(r)$
- Uncertainties in the lidar ratio are the largest source of systematic error (~30-50%) in CALIOP retrievals of AOD and aerosol extinction profiles [Winker et al., 2009; Schuster et al., 2012; Rogers et al., 2014].

How to get lidar ratio?

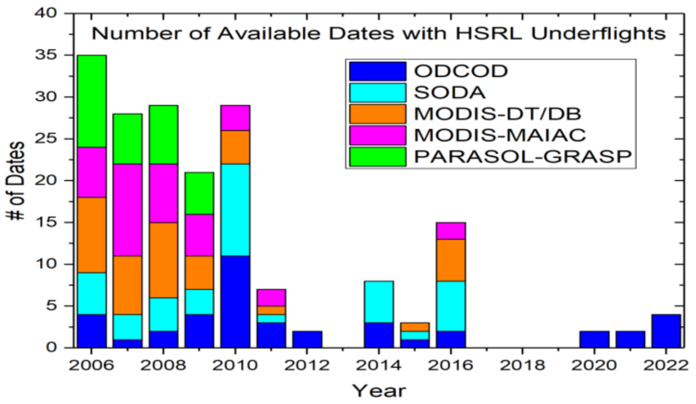
- **Unconstrained Retrievals** – used by majority of CALIOP operational retrievals (Kim et al., 2018)
  - 1) Infer aerosol type – CALIOP uses attenuated backscatter, depolarization, altitude, location
  - 2) Assign lidar ratio based on type
  - Advantages: allows multiple lidar ratios, non-attenuating clouds are OK
  - Disadvantages: Errors in assigning aerosol type, large variability in lidar ratio for a given type, mixtures
- **Constrained Retrievals** – some prior CALIOP studies (Burton et al., 2012; Painemal et al., 2019), MPLnet (using AERONET AOD) (Welton et al., 2000)
  - 1) Use column aerosol optical depth (AOD) as a constraint AOD = $\tau_a = \{-\int_0^x [\sigma_a(r')]dr'\}$
  - 2) Derive lidar ratio so that AOD matches constraint
  - Advantages: doesn't require aerosol type, column-integrated extinction matches AOD constraint
  - Disadvantage: requires accurate AOD, cloud-free column, assumes constant S_a with altitude

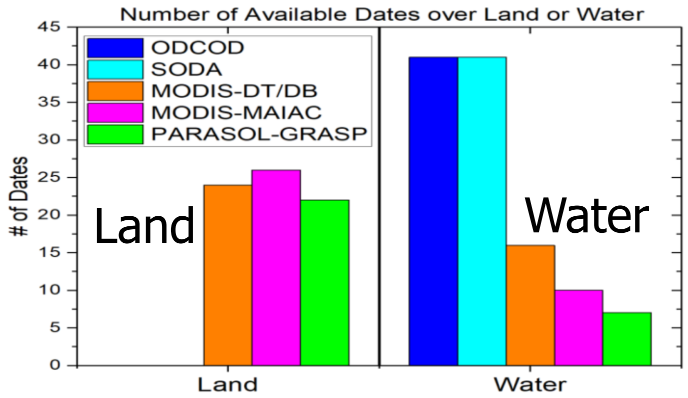
We study several AOD Constraints with the CALIOP Measurements

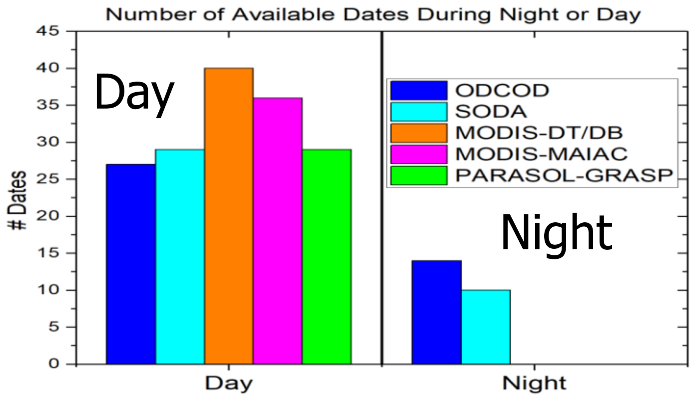
- **CALIOP ocean surface return** – over water, nighttime and daytime
  - Ocean-Derived Column Optical Depth (ODCOD) (V4.51) (Ryan et al., 2023;Venkata and Reagan, 2016)
    - CALIOP surface return with modeled surface wind speed
    - AOD derived from cloud-screened total column optical depth
    - Small bias (2%), RMSE (~72%) relative to AERONET (Thorsen et al., 2023)
  - Synergized Optical Depth of Aerosols (SODA) (V2.31)
    - CALIOP and CloudSat surface returns (Josset et al. 2008; 2011)
    - RMSE differences ~0.04 (25%) (Dawson et al., 2016;Painemal et al., 2019) with AERONET, HSRL
- **Passive sensor retrievals of AOD** – over land and water, daytime only
  - Aqua MODIS Dark Target/Deep Blue (Collection 6) (Levy et al., 2013)
    - combines results from separate algorithms for estimating surface reflectance over various surfaces
    - Expected errors ±(0.05+15%) over land; +(0.04+10%),-(0.02+10%) over water – (Levy et al. 2013)
  - MODIS Multi-Angle Implementation of Atmospheric Correction (MAIAC) (V6.1) (Lyapustin et al., 2018)
    - Improved surface reflectance over land using multiangle observations over several days
    - Global accuracy 0.05±0.1*AOD (or 10%) for 67% of measurements (Lyapustin et al., 2018; Martins et al., 2017)
  - PARASOL using GRASP retrieval algorithm (Dubovik et al., 2014)
    - Uses both radiance and polarization measurements, multipixel
    - Small biases (<0.02) over both land and water; 55% within max(0.04 or 0.1*AOD) (Chen et al., 2020)

HSRL and CALIOP Data and Methodology

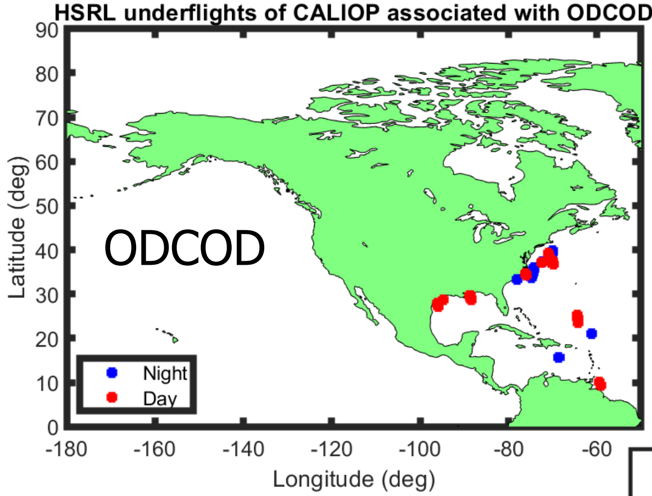
- Measurements from NASA/LaRC airborne HSRL-1,HSRL-2
  - HSRL technique at 532 nm
  - Backscatter, extinction, depolarization profiles and AOD at 532 nm
  - Typical Resolutions (horizontal ~6-12 km, vertical ~ 300 m)
- CALIOP, Satellite, HSRL coincidence criteria (20 km, 60 min)
- Cloud-free transparent products – cloud-clearing
  - ODCOD – compute AOD from cloud-cleared column OD (filtering and screening) as per Rob Ryan poster
  - CALIOP VFM cloud identification
  - MODIS, PARASOL, HSRL cloud screening
- Aerosol comparisons with HSRL correspond to tropospheric aerosols (below ~7.5 km)
  - Stratospheric AOD contribution estimated from CALIOP
- Comparisons with HSRL
  - AOD, lidar ratios, and aerosol extinction profiles from each of the (5) AOD constraints were compared with the corresponding HSRL values ~(0-7 km)
  - AOD and aerosol extinction profiles from matching cases of CALIOP v4.51 were also compared

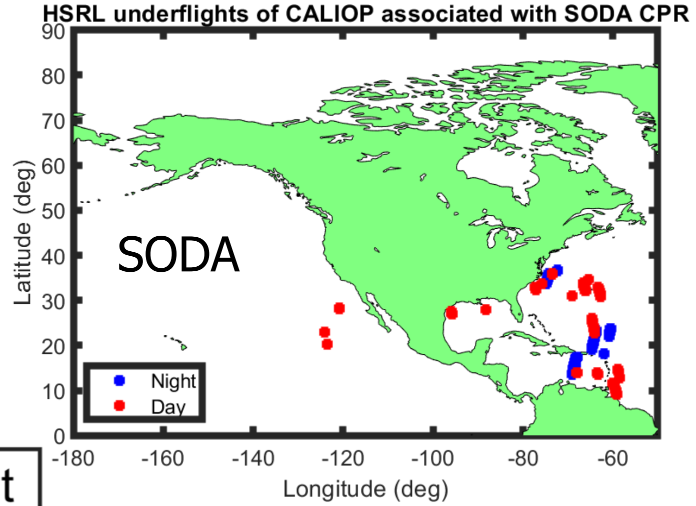






HSRL – CALIOP clear-sky data coincidence locations for the various AOD constraints

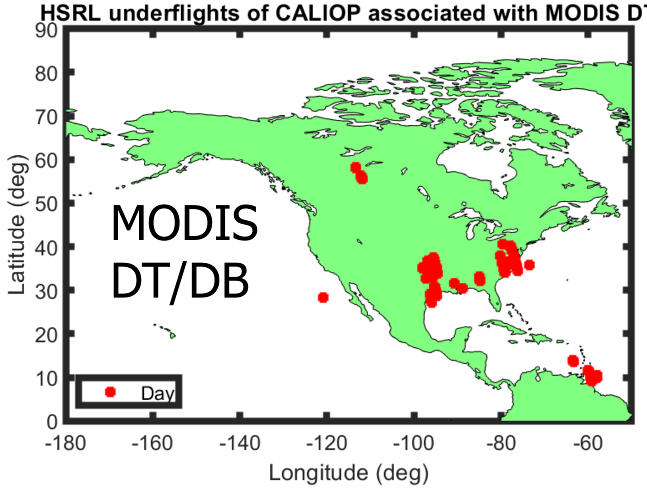


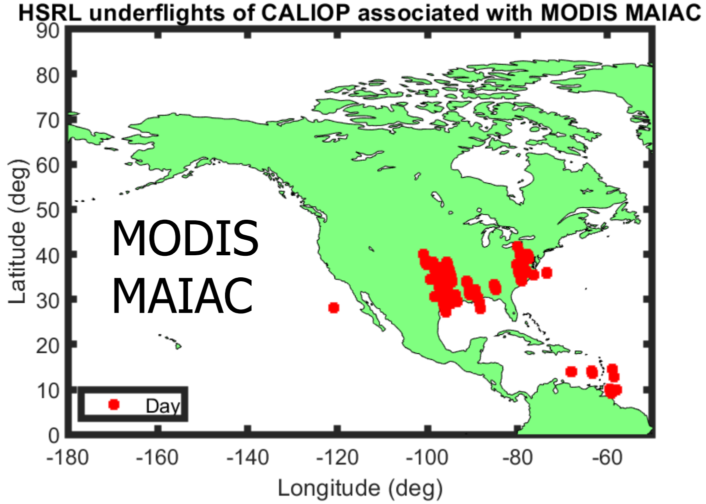


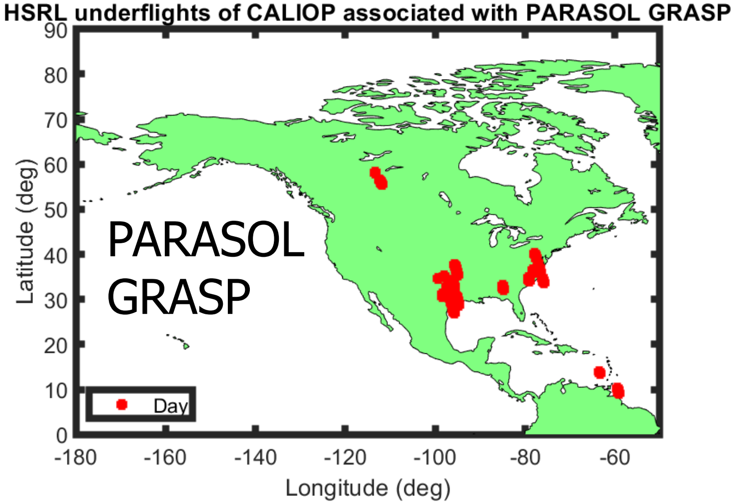
Night
Day

HSRL, Constrained CALIOP coincidences limited by:

- HSRL underflight opportunities
- Data availability, Orbit (e.g. PARASOL lifetime, SODA-CloudSat daytime only)
- Clouds!



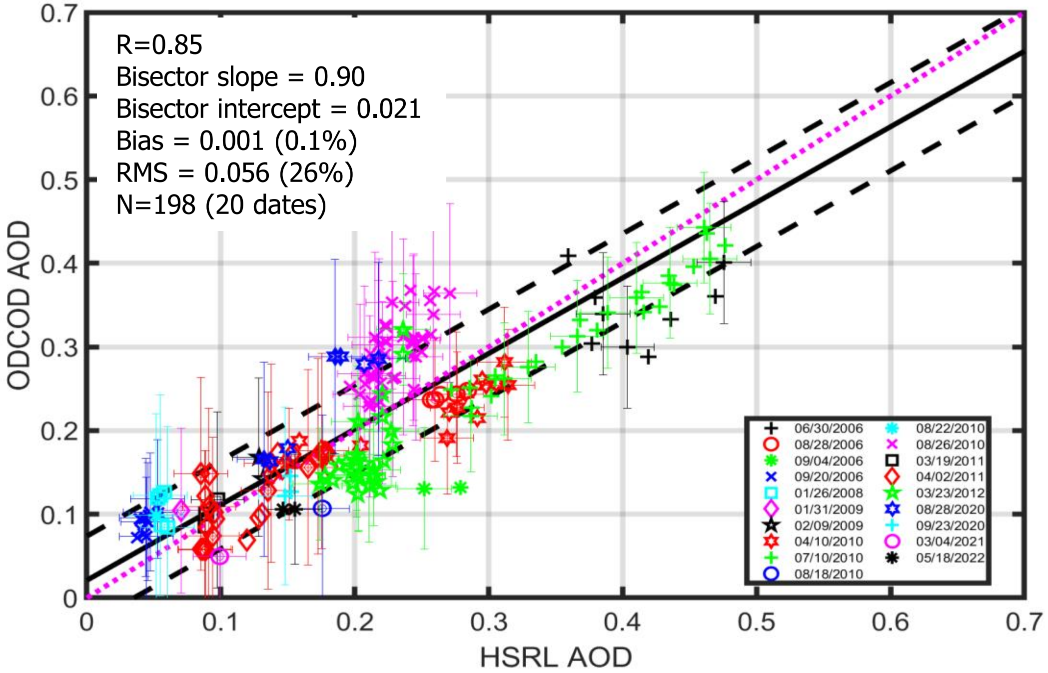




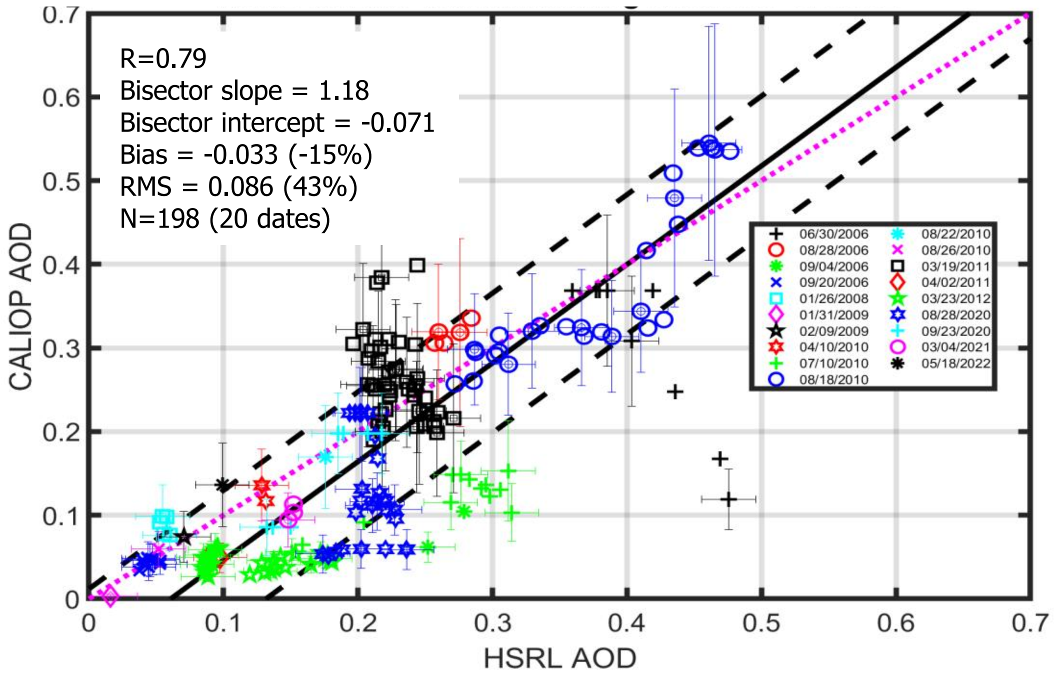
Example AOD Comparison: ODCOD, CALIOP vs. HSRL

- For ODCOD AOD relative to HSRL
  - Negligible low bias not significant at 5% level, average rms difference 0.056 (26%)
- For corresponding CALIOP v4.51 cases relative to HSRL
  - 0.04 (-18%) low bias - comparable to previous evaluations (Schuster e al. (2012); Omar et al., (2013); Thorsen (2023))
  - RMS difference 0.086 (43%)

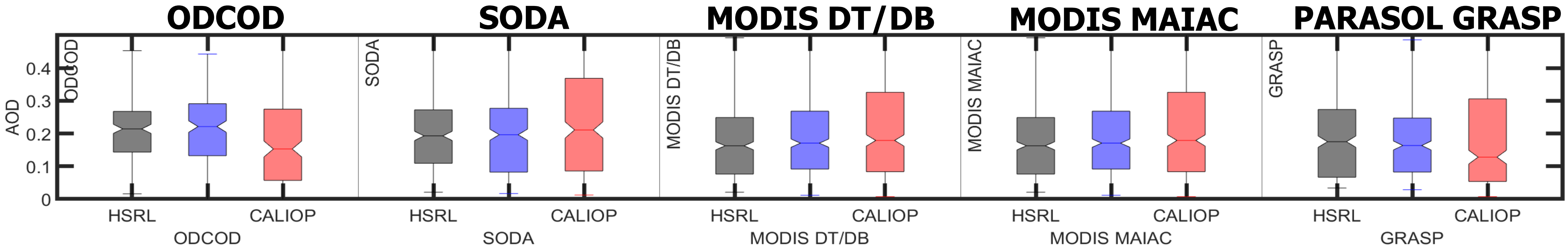
HSRL vs. ODCOD AOD



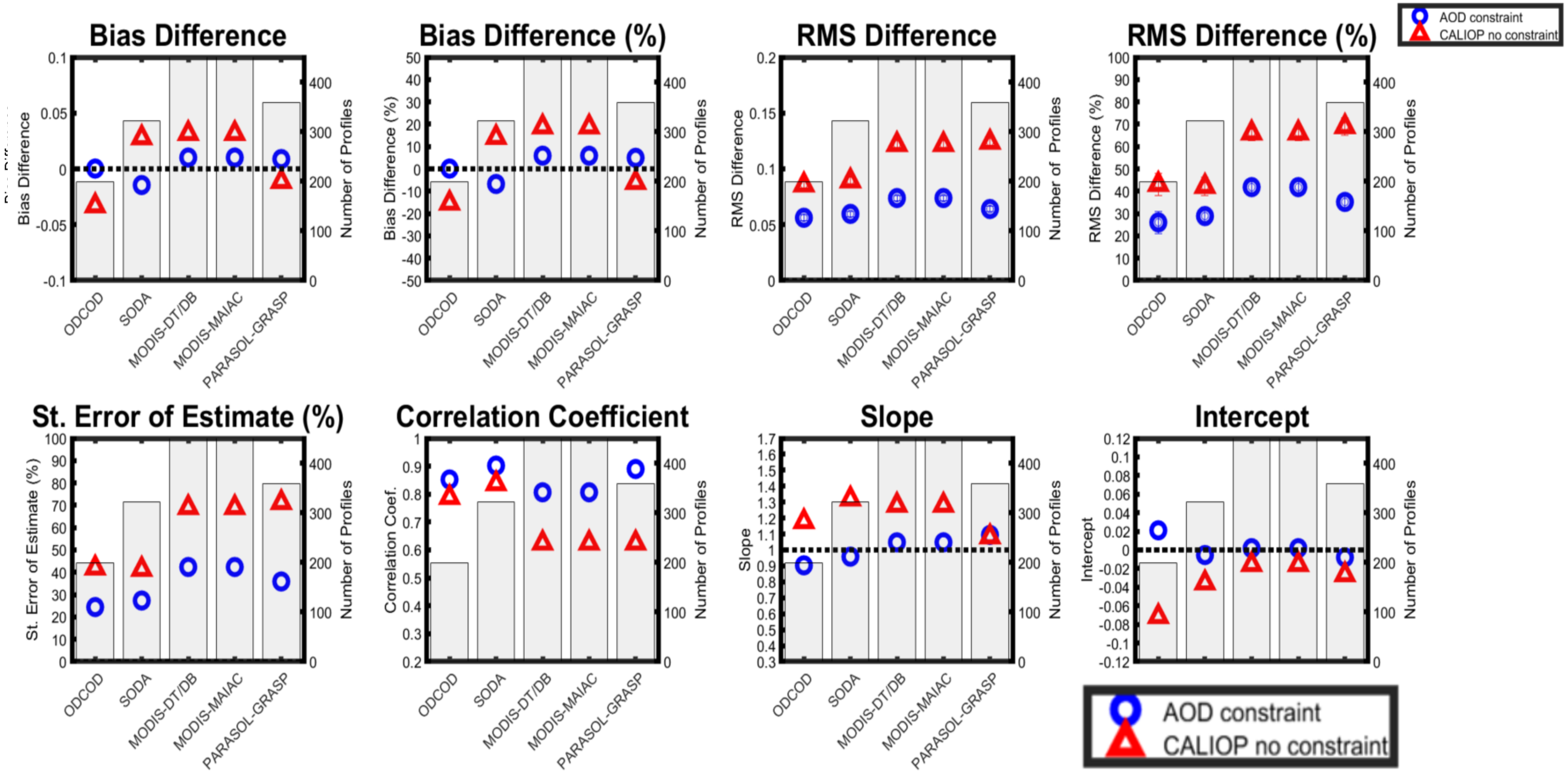
HSRL vs. CALIOP AOD



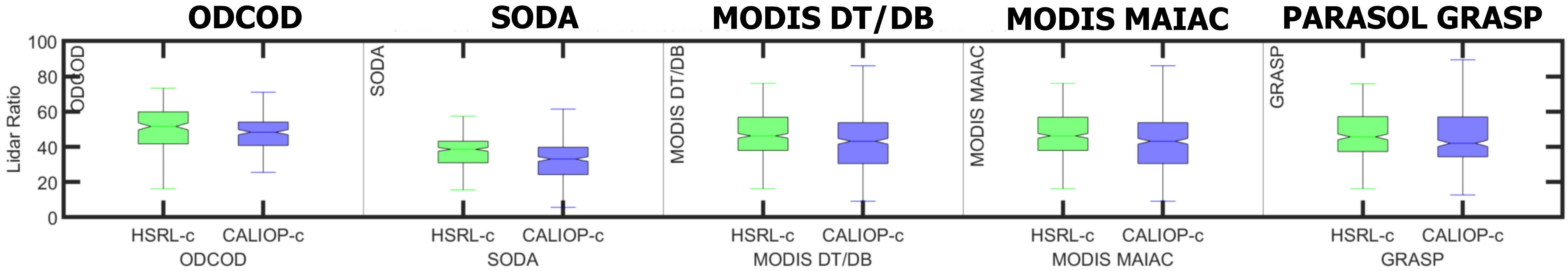
AOD Comparisons: HSRL vs. various AOD used to constrain CALIOP



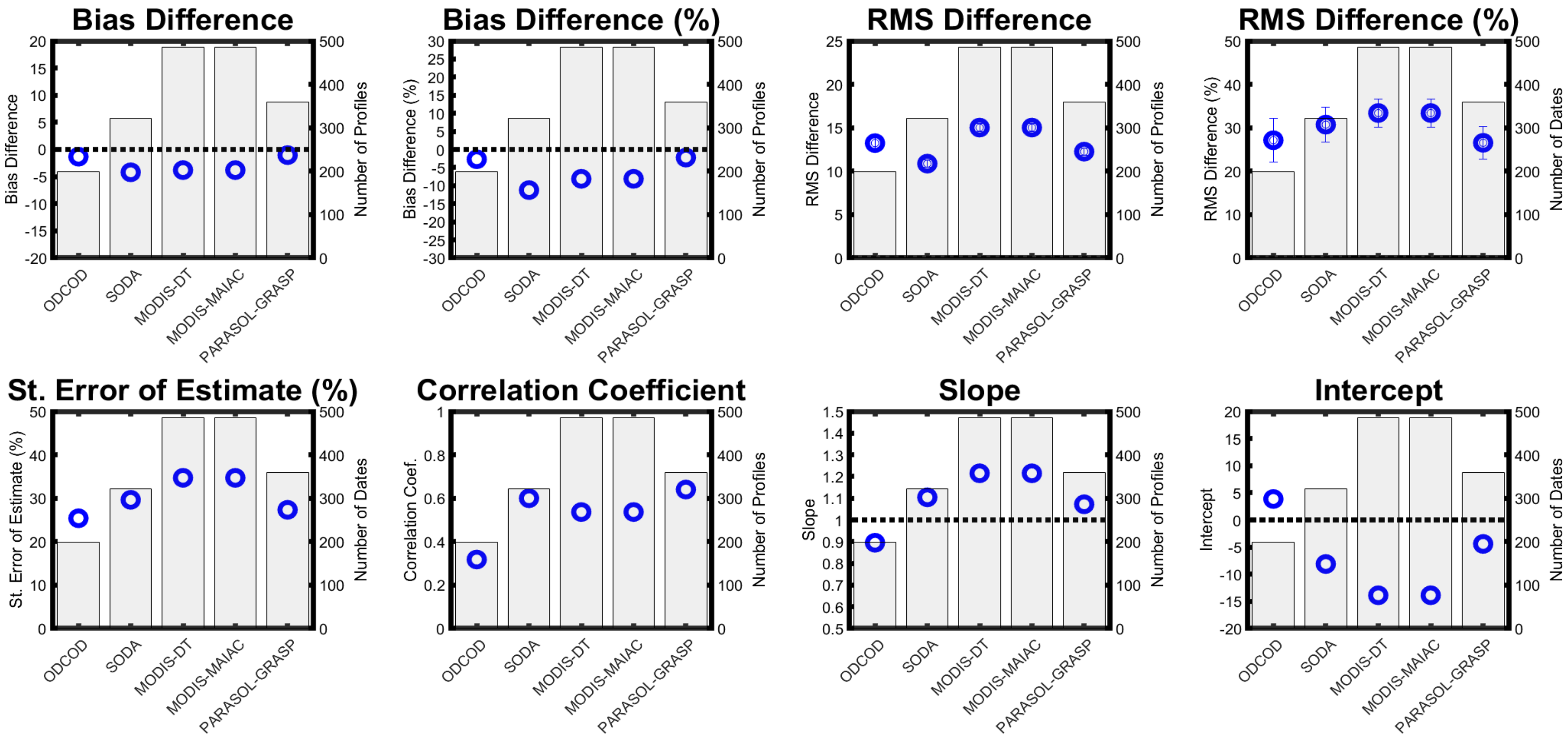
- On average, AOD from each of the (5) constraining methods :
  - were compared separately with the corresponding HSRL cases
  - provide AOD that is in good agreement with HSRL [mean bias differences within 0.02 (10%), rms differences within ~0.08 (40%)]
  - provide AOD with smaller RMS differences (25-40%) and higher correlations (>0.8) than the operational V4.51 CALIOP AOD (40-70%, >0.6)



Lidar Ratio Comparisons: HSRL constrained vs. CALIOP with AOD constraints

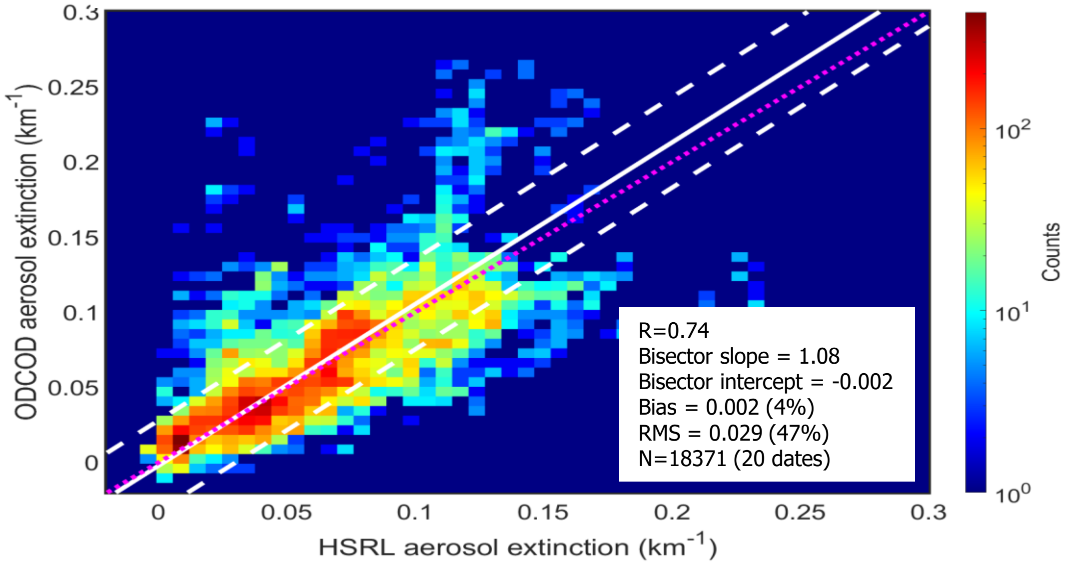


- On average, each of the (5) constraining methods provide column lidar ratio that is in agreement with HSRL column lidar ratio (small low bias-differences within 5 sr)
- On average, each of the (5) constraining methods provide column lidar ratio with RMS differences (25-35%) when compared to HSRL column lidar ratio

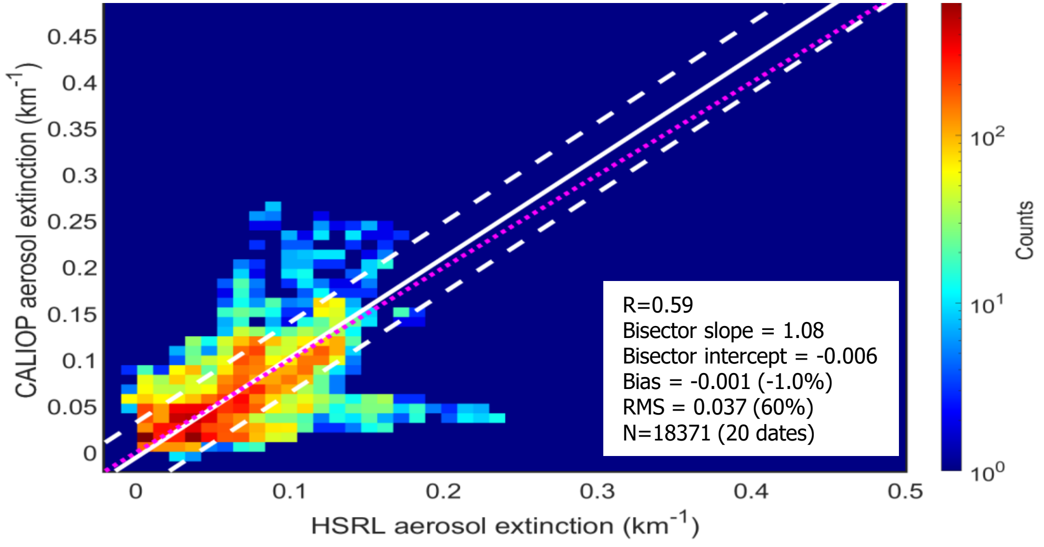


Example Aerosol Extinction Comparison: ODCOD, CALIOP vs. HSRL

HSRL vs. ODCOD Aerosol Extinction

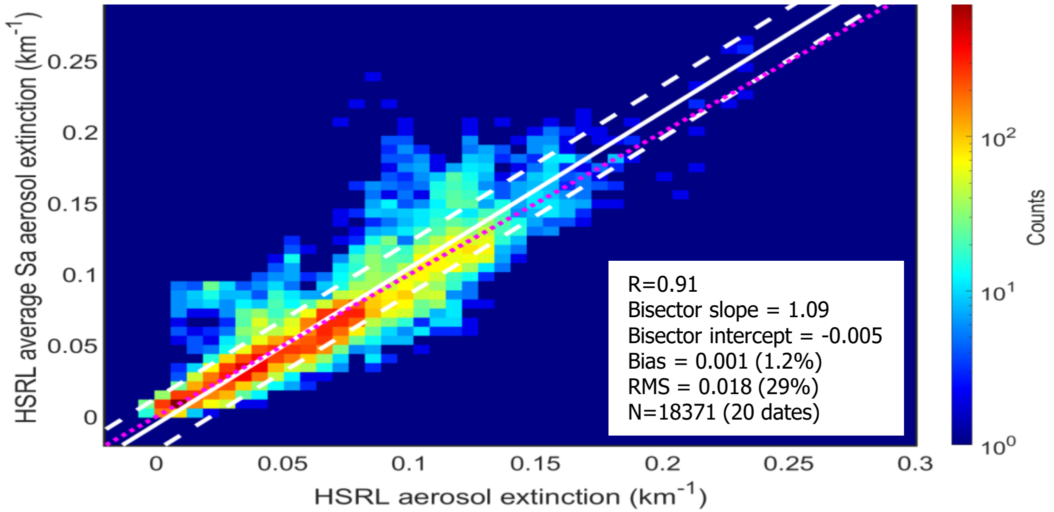


HSRL vs. CALIOP Aerosol Extinction

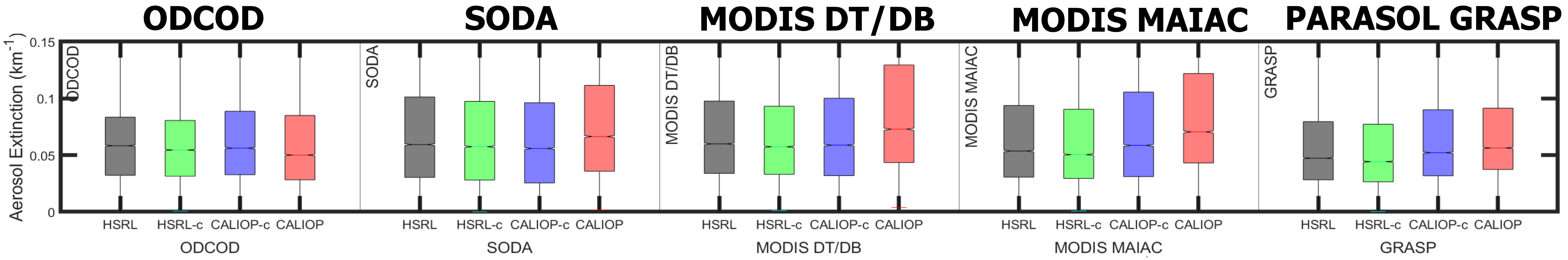


- For ODCOD constrained retrievals, average aerosol extinction relative to HSRL
  - Small bias (~0.002, 4%), rms diff (0.03, 47%)
- For corresponding CALIOP v4.51 cases relative to HSRL
  - Also small bias, but rms differences larger (~0.04, 60%)
- Matching HSRL AOD constrained HSRL cases
  - Little to no bias, small rms diff (0.02, 30%)
  - Provides an indication of impacts of variable lidar ratio

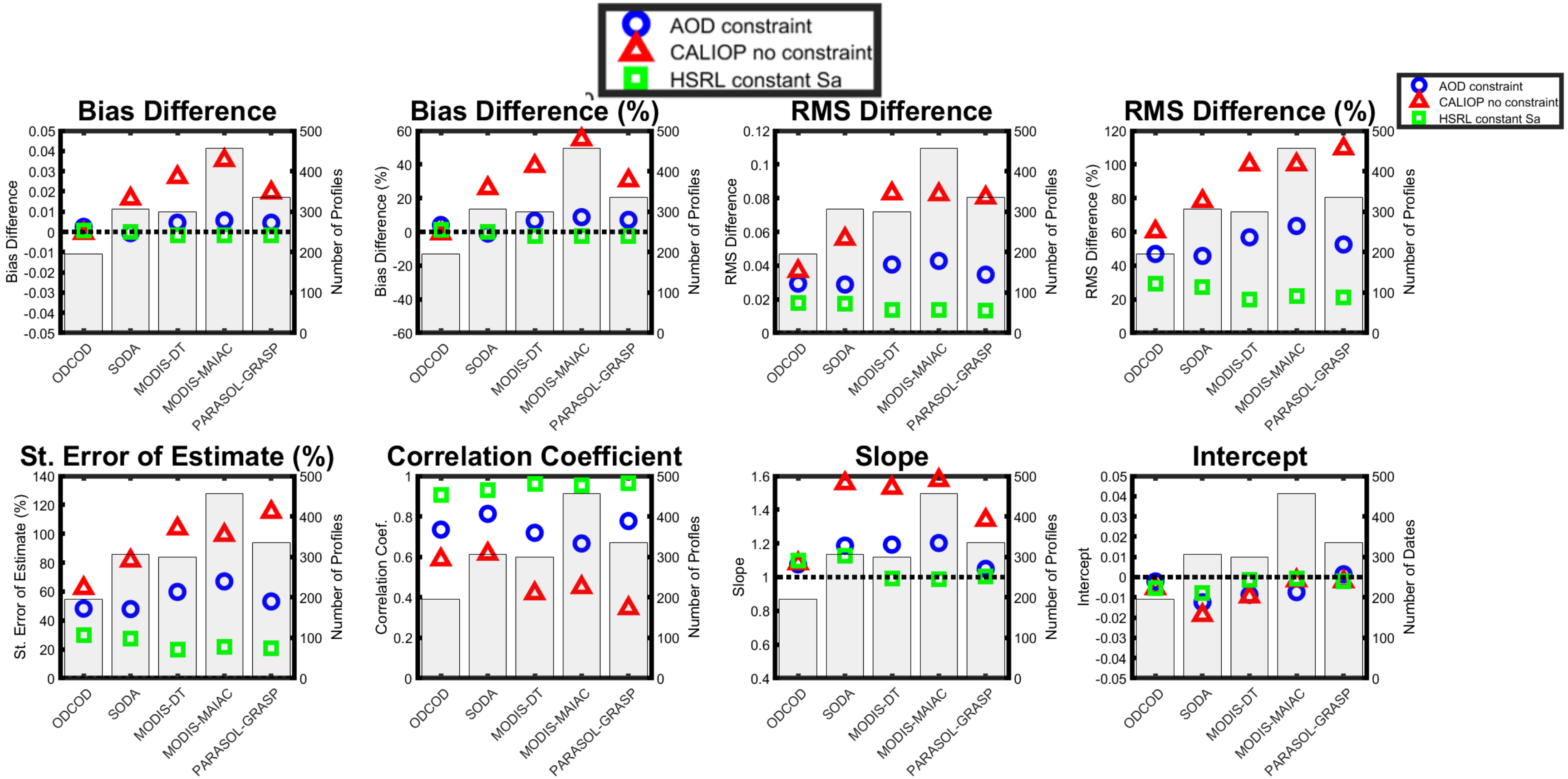
HSRL vs. HSRL (constrained) Aerosol Extinction



Aerosol Extinction Comparisons: HSRL vs. CALIOP with various constraints

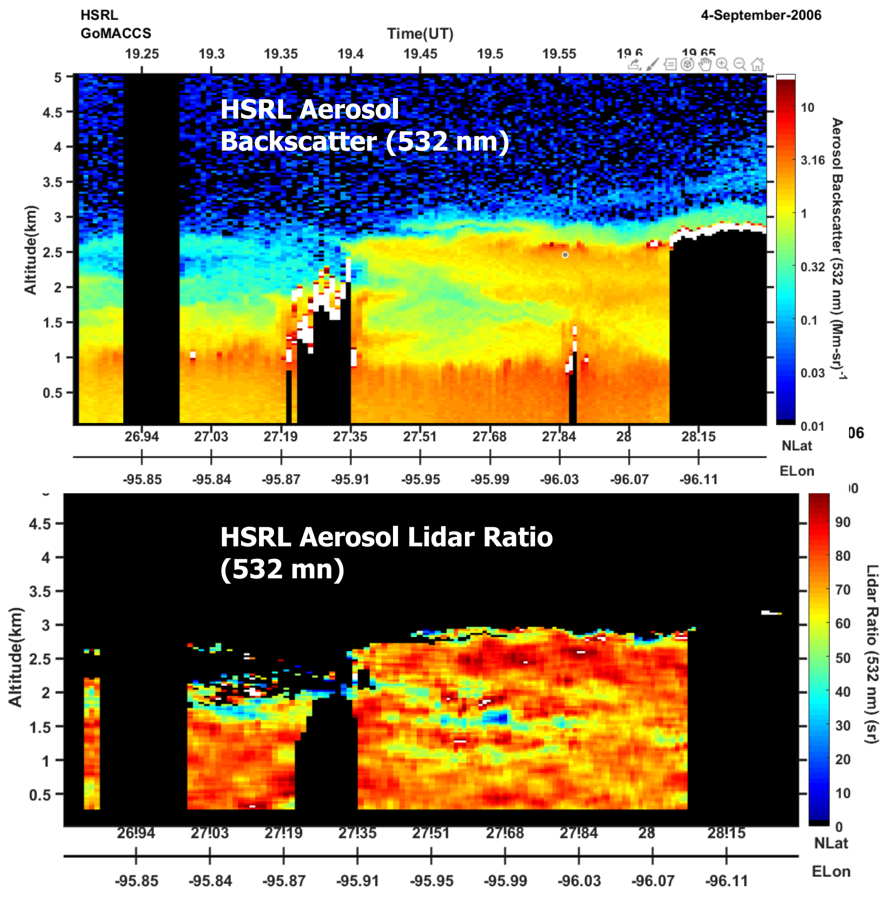


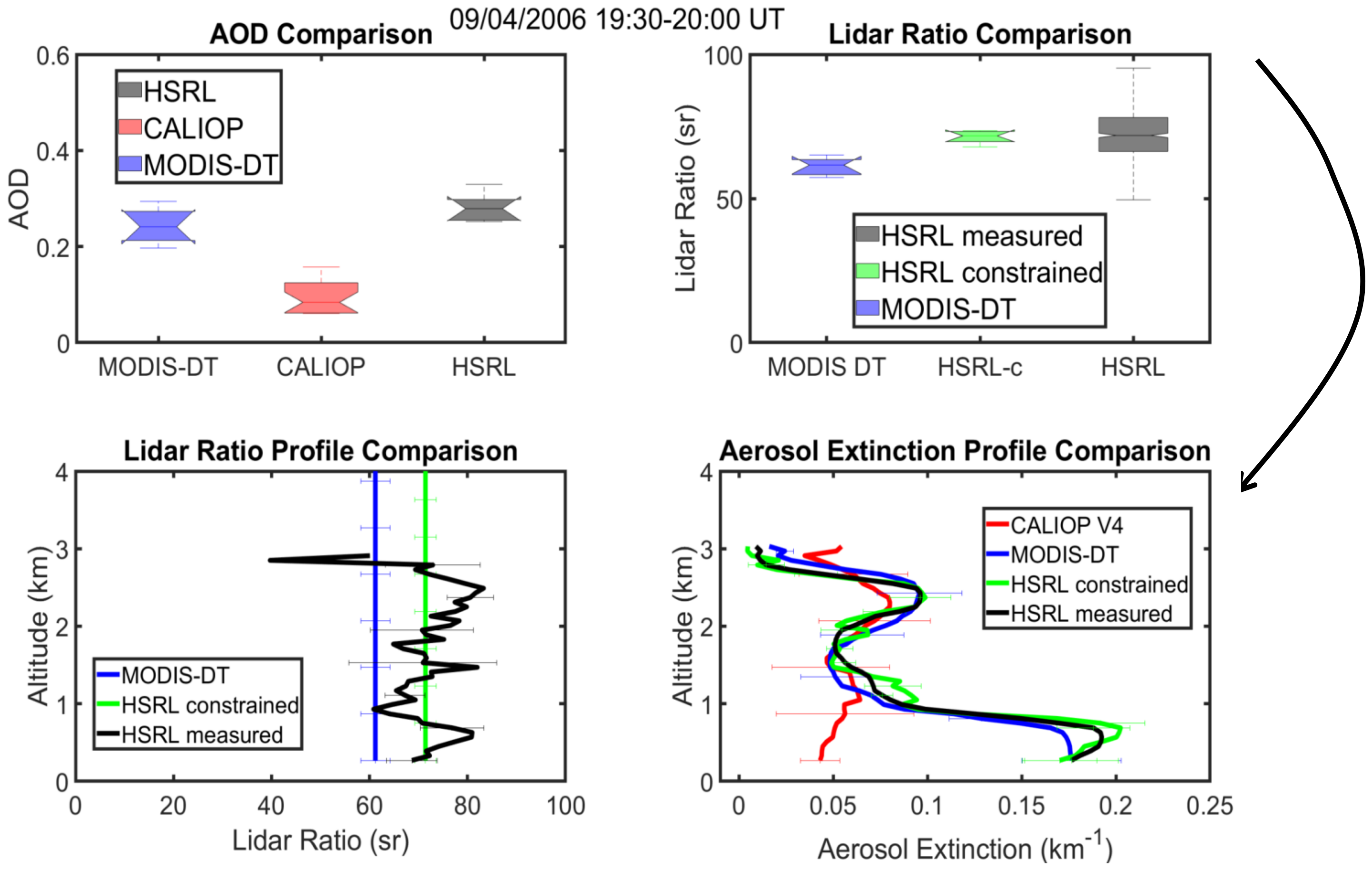
- Each of the (5) constraining methods provide aerosol extinction values that are, in average, in agreement with HSRL aerosol extinction (mean bias differences within 0.01, 10%)
- On average, each of the (5) constraining methods provide aerosol extinction with RMS differences (40-60%) when compared to HSRL aerosol extinction
- Overall, bias and rms differences are significantly smaller than from CALIOP operational v4.51
- HSRL constrained differences provide some indication of uncertainties due to assumption of constant lidar ratio



Example: MODIS DT/DB constrained retrieval on September 4, 2006

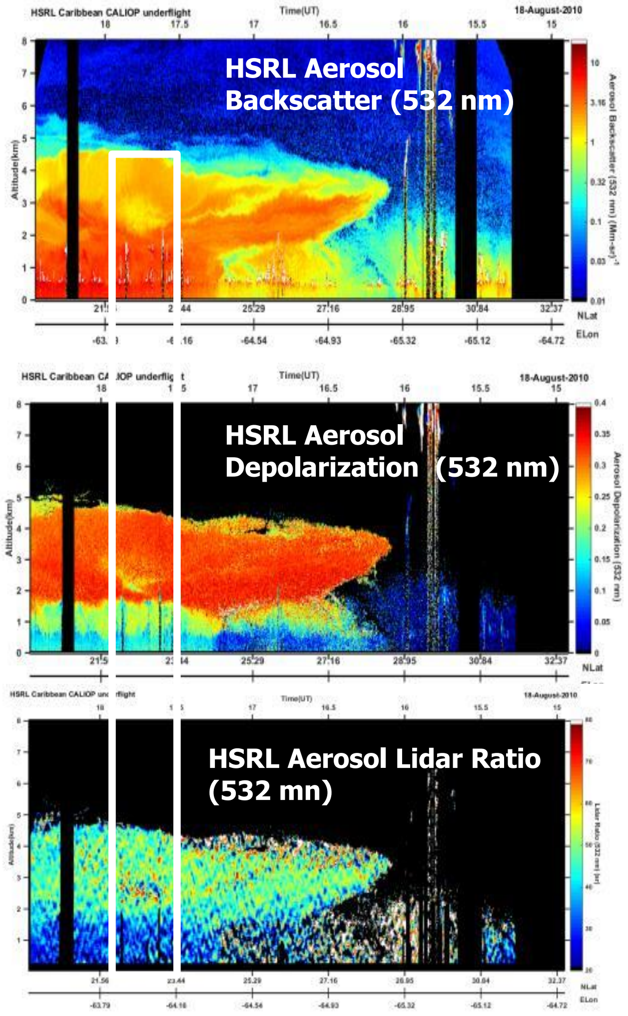
- Airborne HSRL measured high lidar ratio (~70 sr) associated with urban and/or smoke aerosol over the Gulf of Mexico south of Houston
- CALIOP inferred mostly maritime aerosol with low (~23 sr) lidar ratio
- MODIS DT/DB AOD constrained retrieval of aerosol extinction profiles improves agreement with HSRL





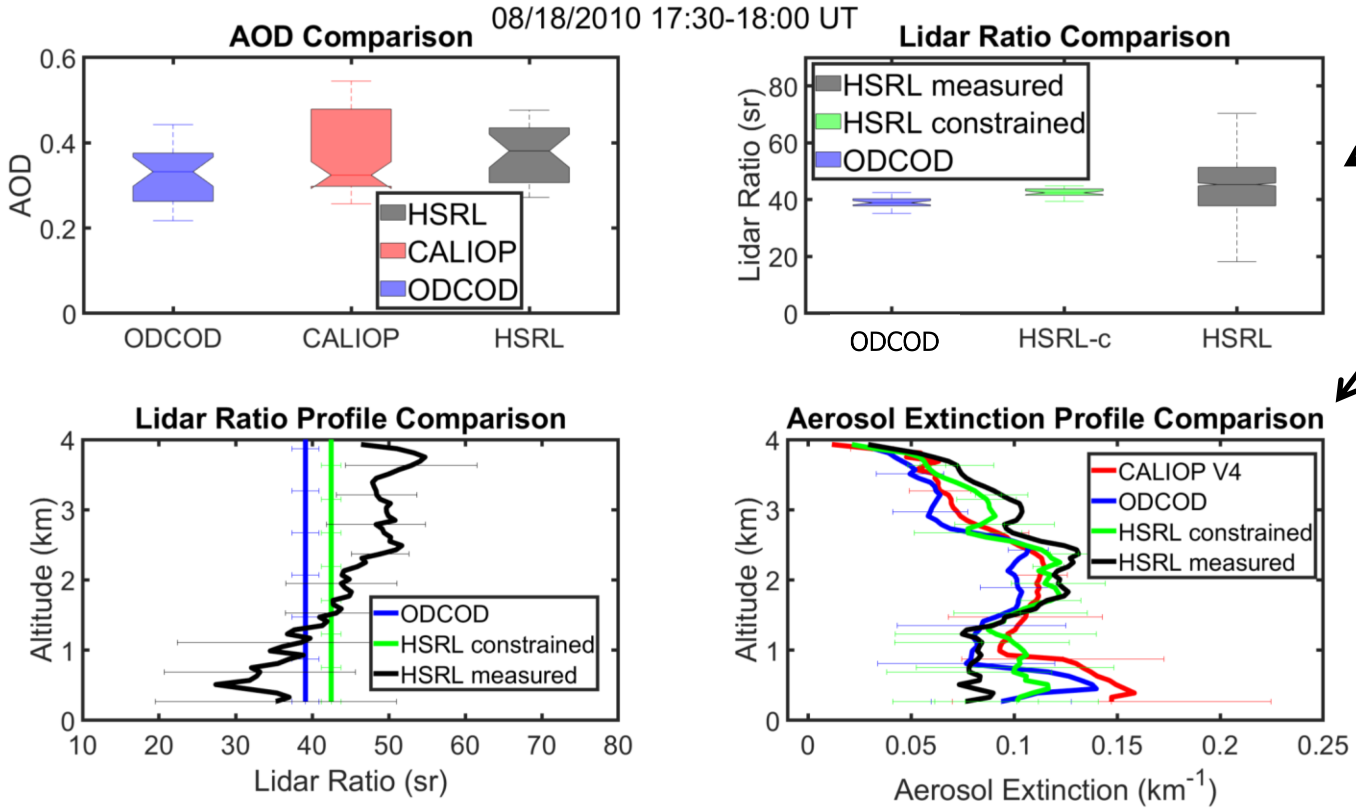
Constrained retrievals do not account for vertical variability of lidar ratio

- Assumption of constant lidar ratio with altitude can lead to errors in derived aerosol extinction profiles
- Example: Aug 18, 2010 Saharan dust above marine aerosol



Example: Aug 18, 2010 Saharan dust above marine aerosol

- HSRL, ODCOD, CALIOP have similar median values of AOD, column lidar ratio
- Constrained retrievals of aerosol extinction profiles are biased high (low) near surface (aloft)



Summary

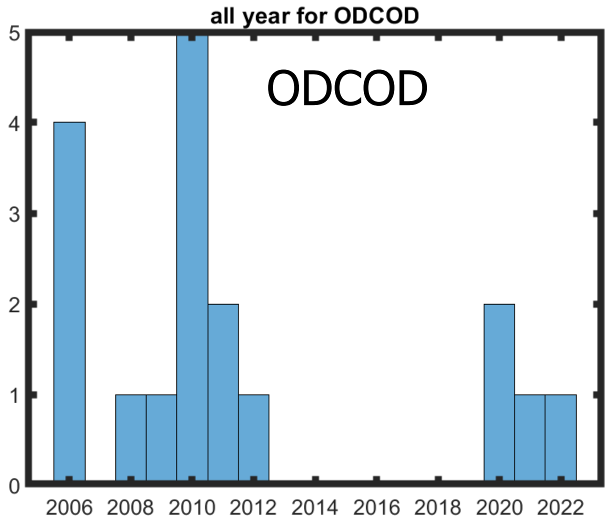
- Several methods that provide AOD to constrain CALIOP retrievals of lidar ratio and aerosol extinction profiles were examined using airborne HSRL measurements during coincident underflights. Each of the (5) constraining methods provide:
  - AOD that is, on average, in agreement with HSRL (mean bias differences within ~0.02 or 10%) and with smaller corresponding differences than CALIPO V4.51
  - Column lidar ratio that is, on average, in agreement with HSRL column lidar ratio (bias differences within 5 sr; rms differences within 25-35%)
  - Aerosol extinction values that are, on average, in agreement with HSRL aerosol extinction (mean bias differences within 0.01, 10%; mean rms differences 40-60%)
- Consistent with previous studies (Burton et al., 2012; Painemal et al., 2019), aerosol extinction profiles from constrained retrievals are, on average, in better agreement with HSRL than CALIOP V4.51
- Evaluation of coincident HSRL profiles constrained by HSRL AOD suggests that variability in lidar ratio leads to rms differences of 20-30% on average
- Such retrievals take advantage of well-calibrated (~1-2%) CALIOP measurements (e.g. Young et al., 2013, 2016, 2018; Thorsen study for AOS LWG, 2023)
  - ➢ **Well-calibrated lidar is critical for constrained retrievals from future backscatter lidars (e.g. AOS) (See Thorsen AOS LWG analysis-2023)**

Looking Ahead…CALIPO Constrained Clear-Sky Aerosol Extinction Profiles

- As part of the Mapping Aerosol Lidar Ratios for CALIPSO (MAC) Version 5 Project, global, multiyear, column lidar ratios and **clear-sky aerosol extinction profiles**, have been/are being computed from CALIOP v4.51 using various column constraints
  - ODCOD (2006-2021)
  - SODA (2009-2018)
  - MODIS-DT/DB (2006-2018)
  - MODIS-MAIAC (2006-2018)
  - We can try to make these available if there is a desire for such profiles
- Aerosol extinction profiles that are derived using MAC Version 5 maps of lidar ratios associated with various aerosol types will also be assessed using airborne HSRL measurements

- Backup Slides

Dates


all year for ODCOD
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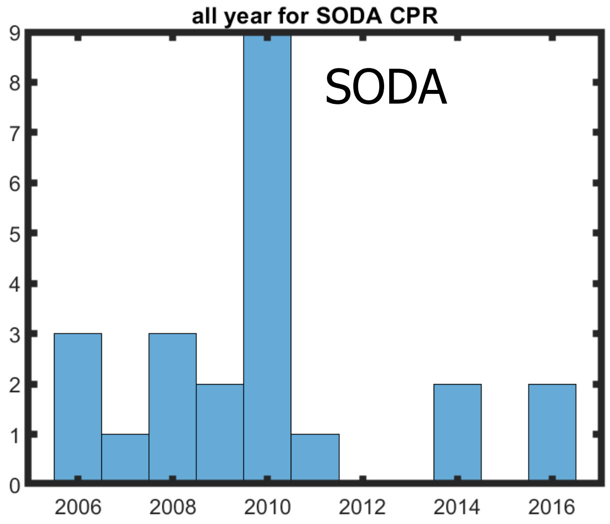
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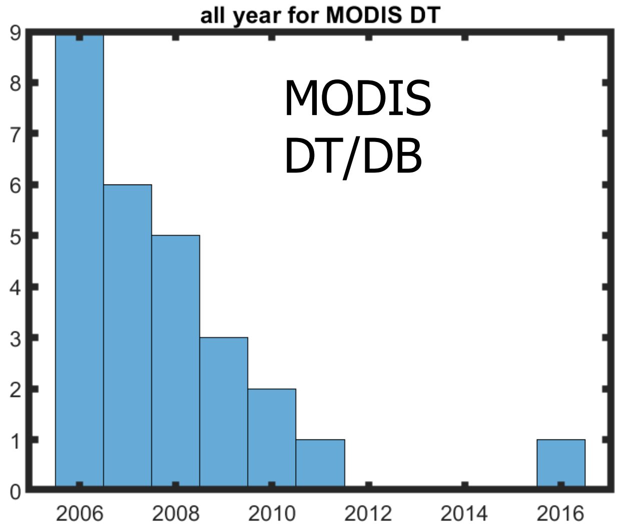
all year for MODIS DT
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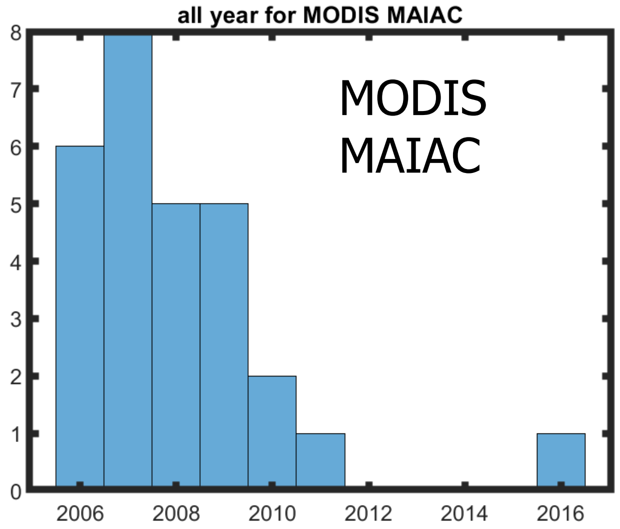
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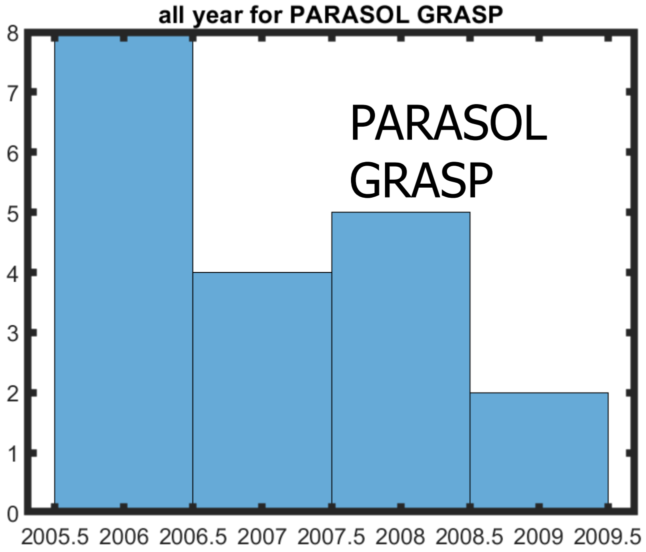
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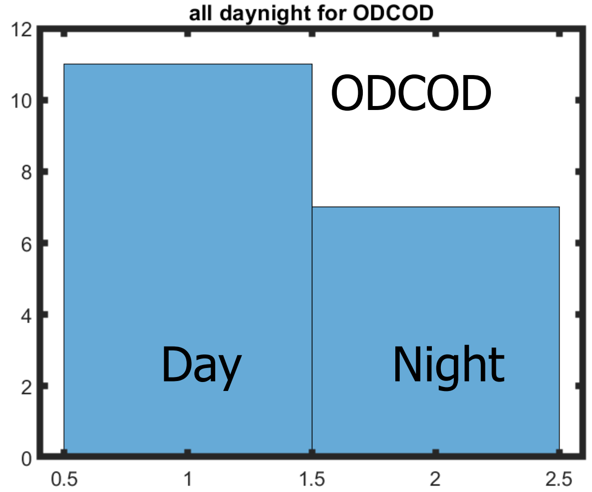
Day vs. Night


all daynight for ODCOD
ODCOD
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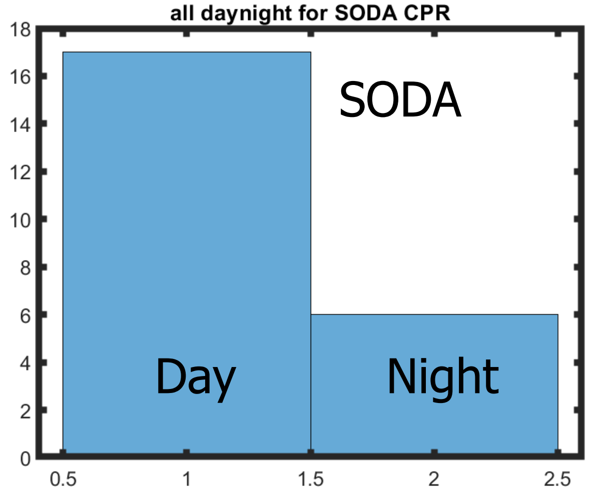
all daynight for SODA CPR
SODA
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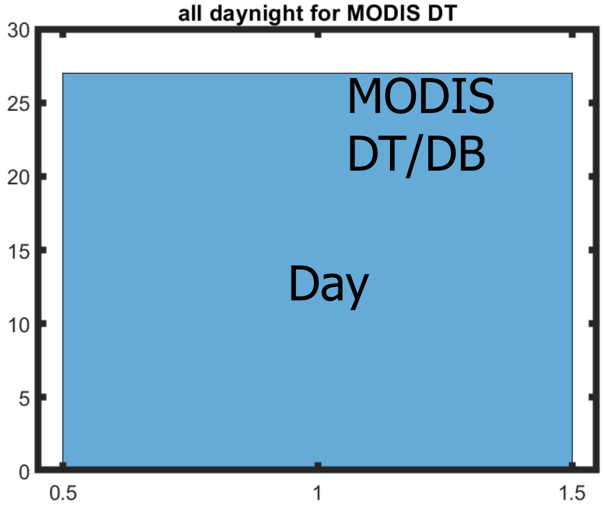
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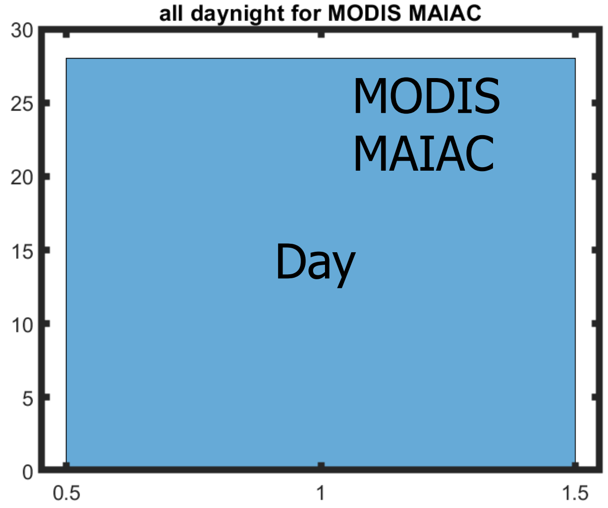
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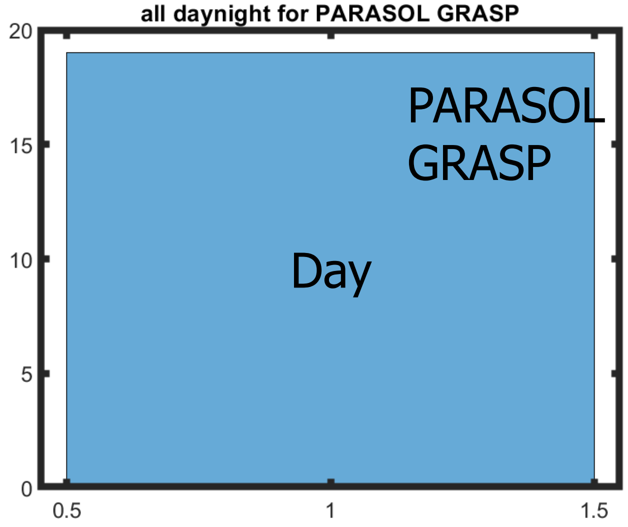
all daynight for PARASOL GRASP
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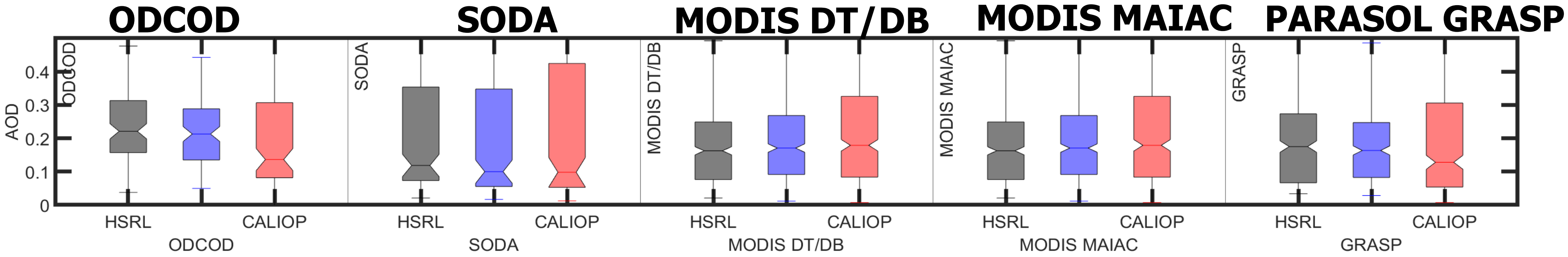
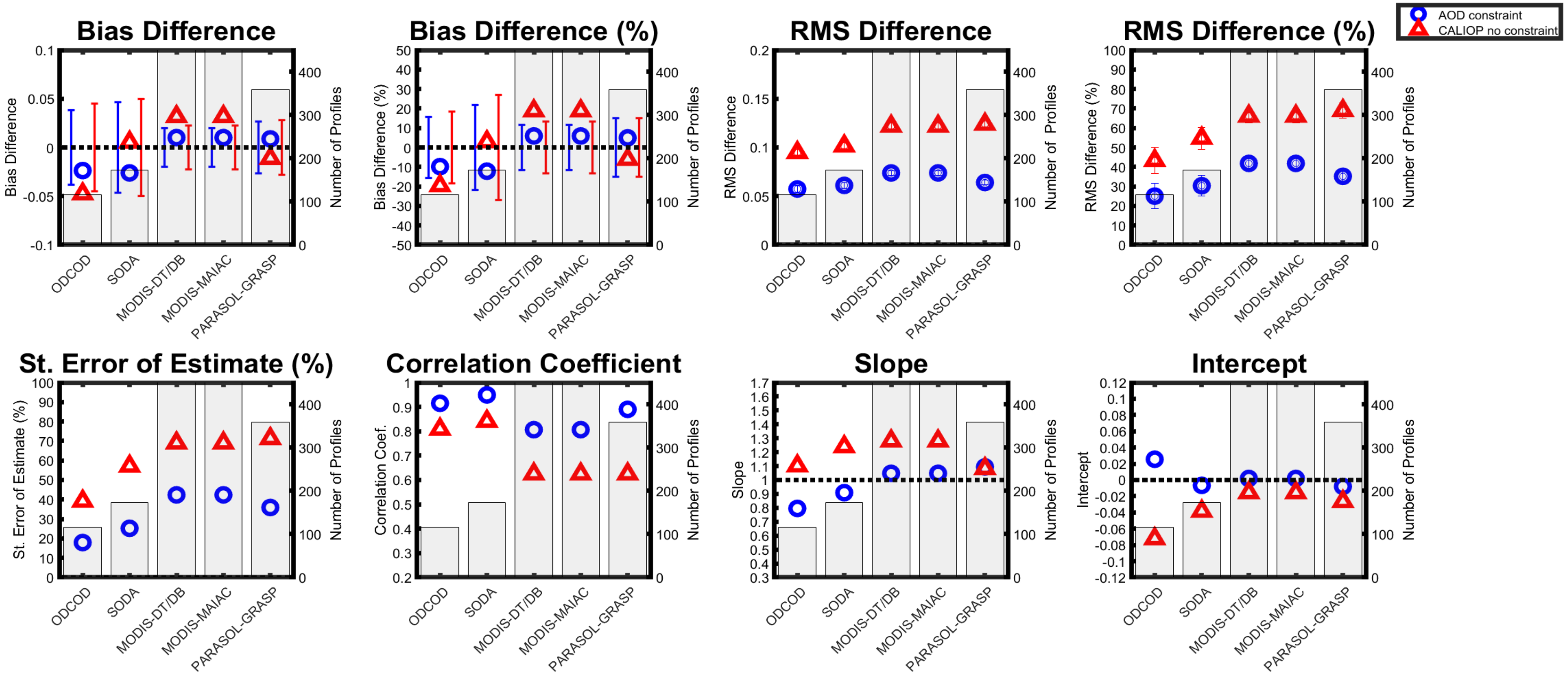
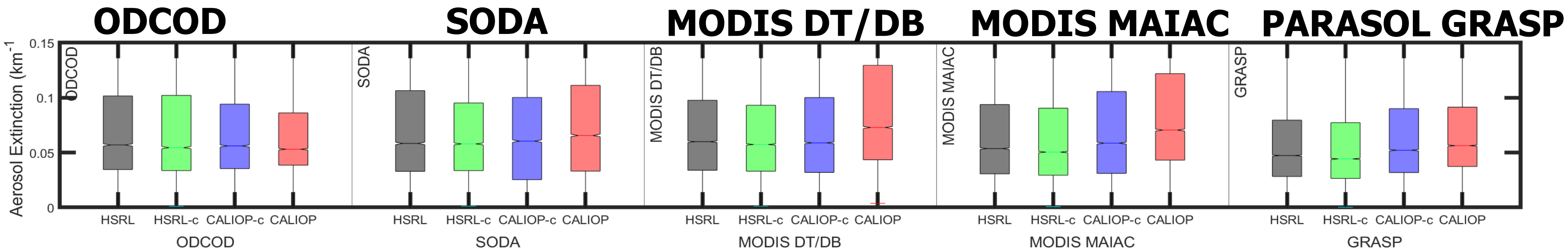
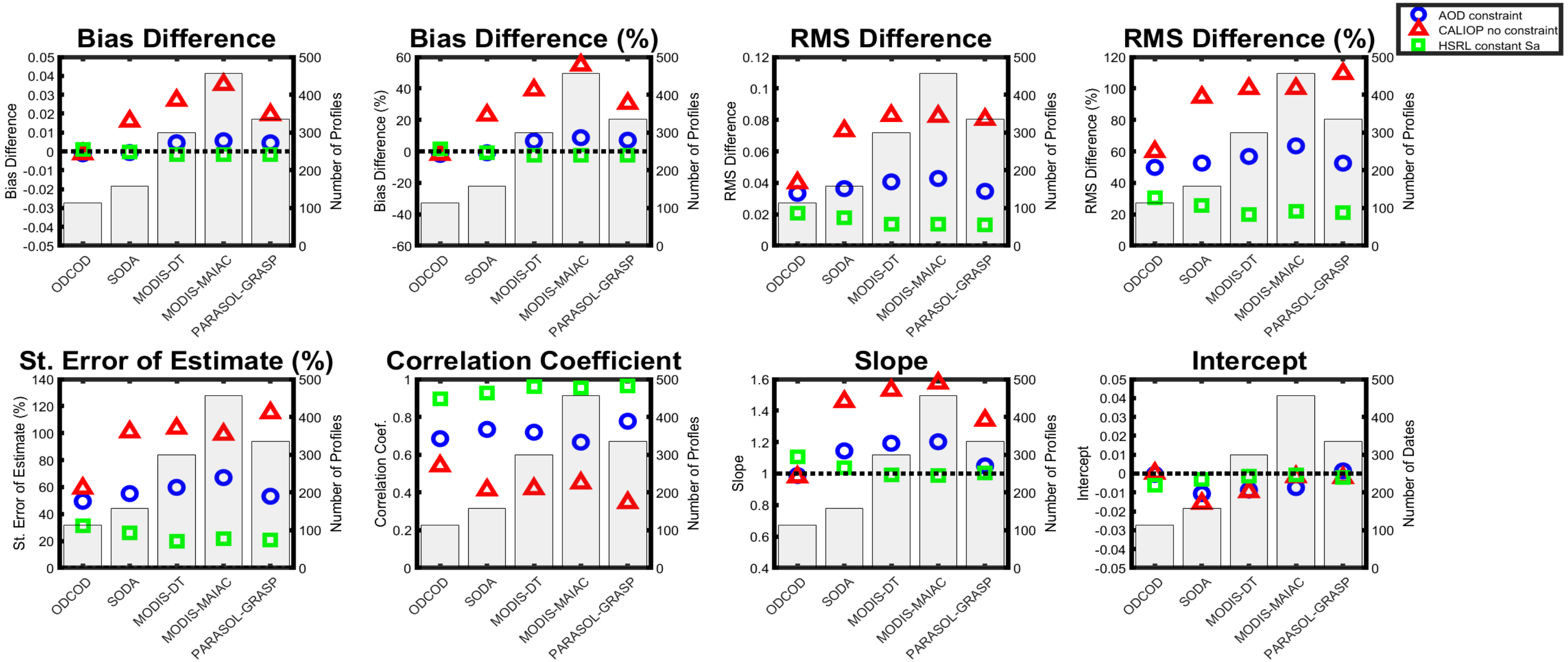
Daytime Only - AOD



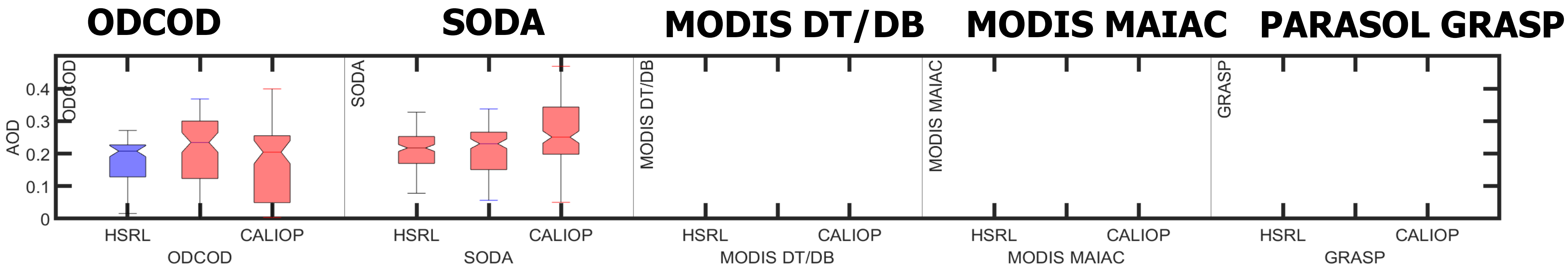


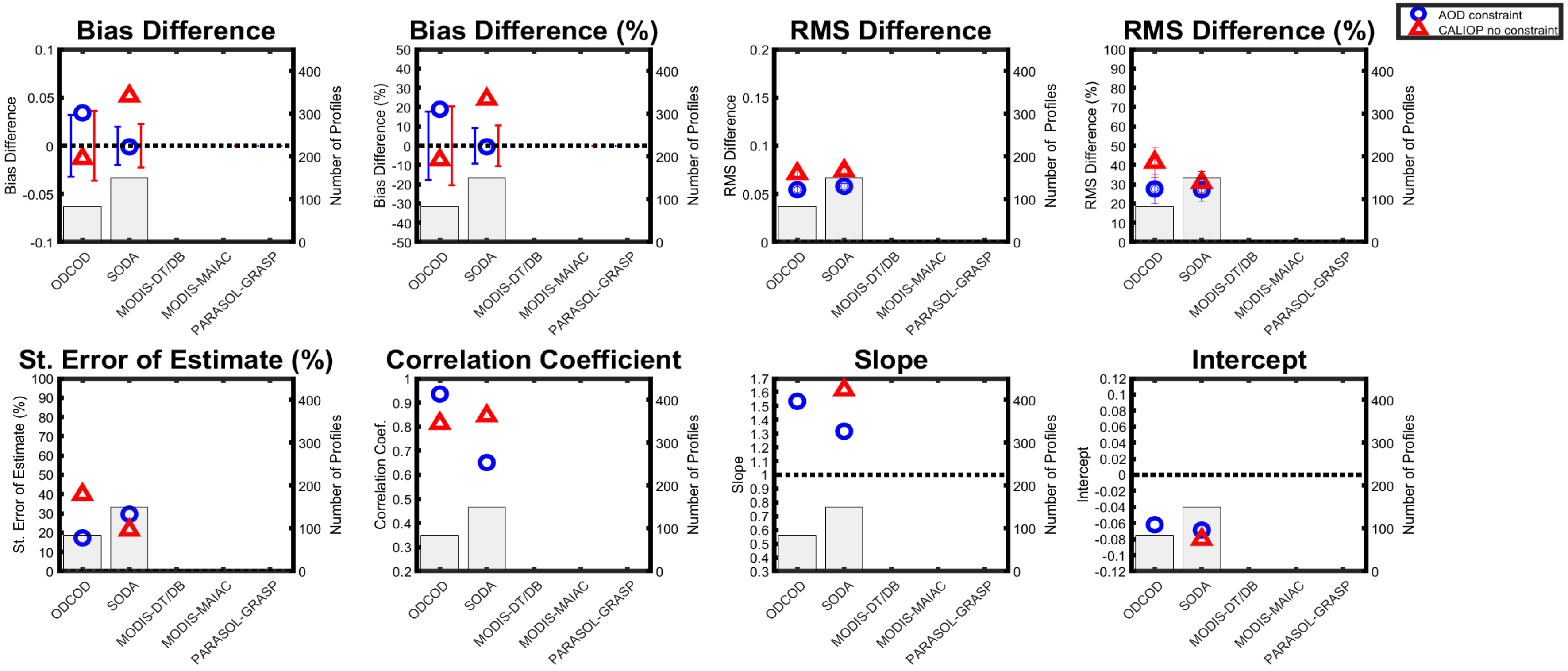
Daytime Only – Aerosol Extinction



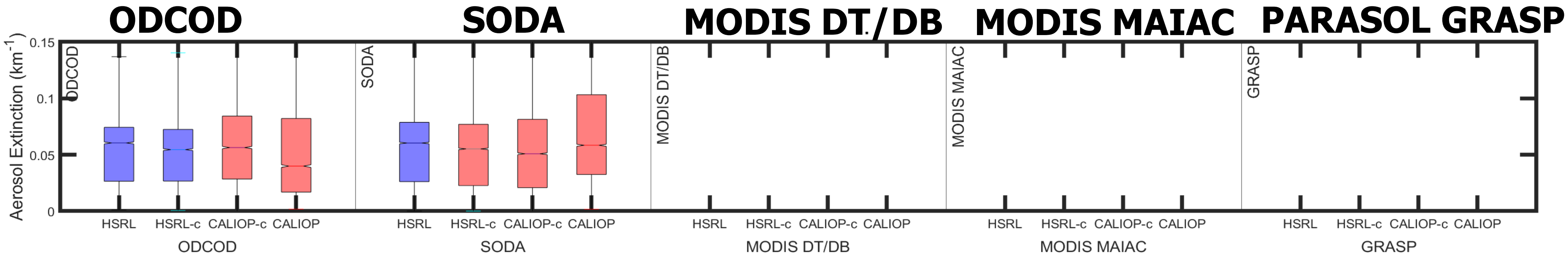


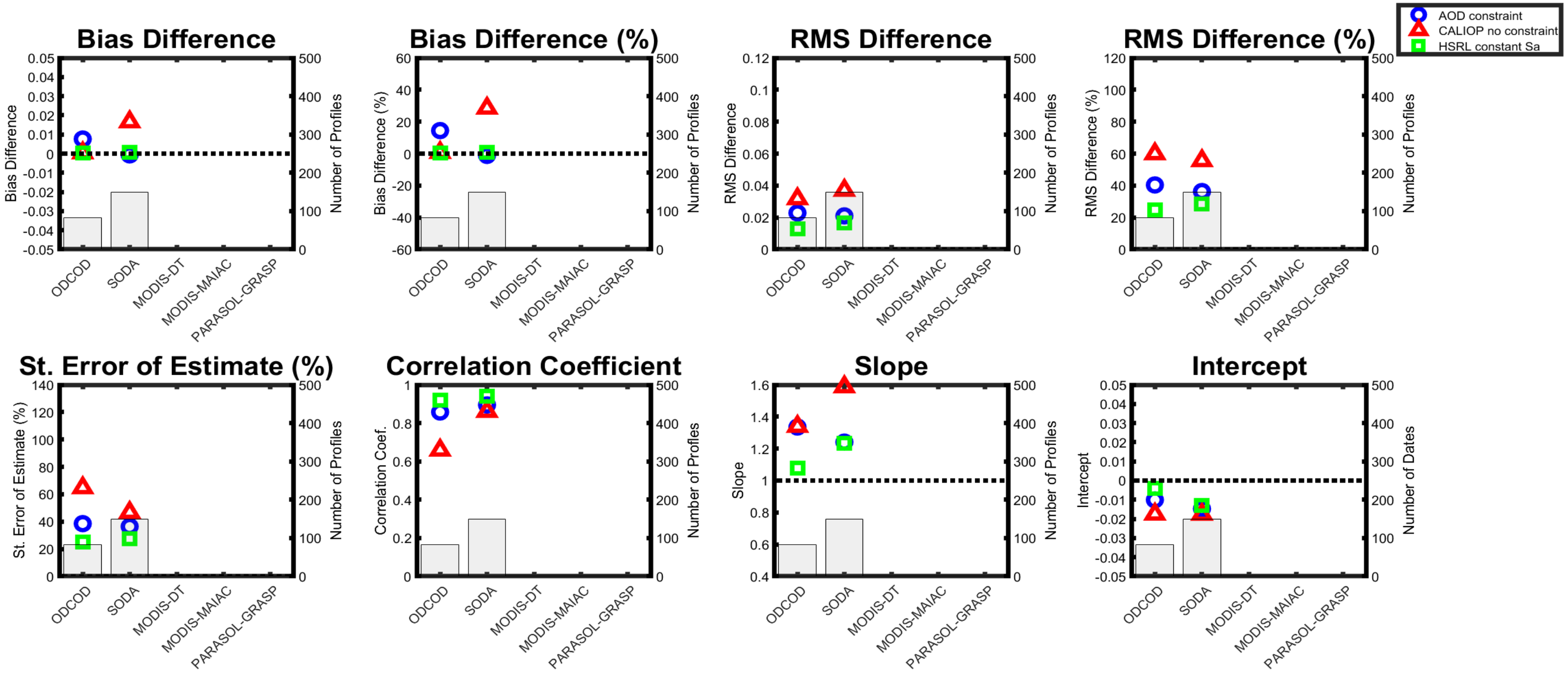
Nighttime Only - AOD



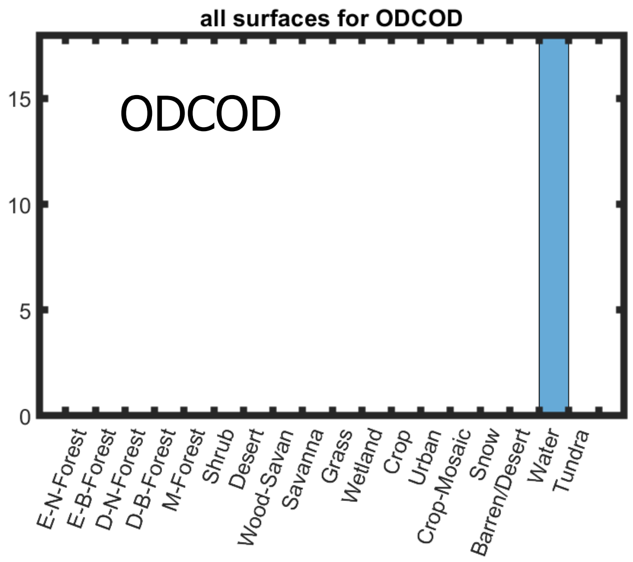


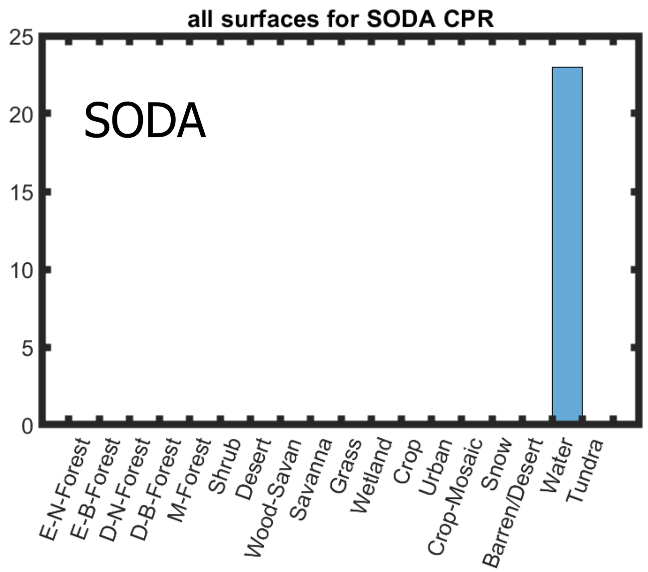
Nighttime Only – Aerosol Extinction

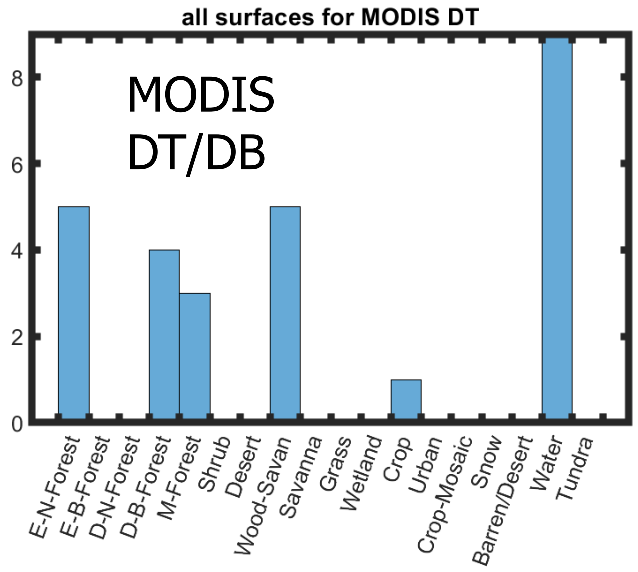


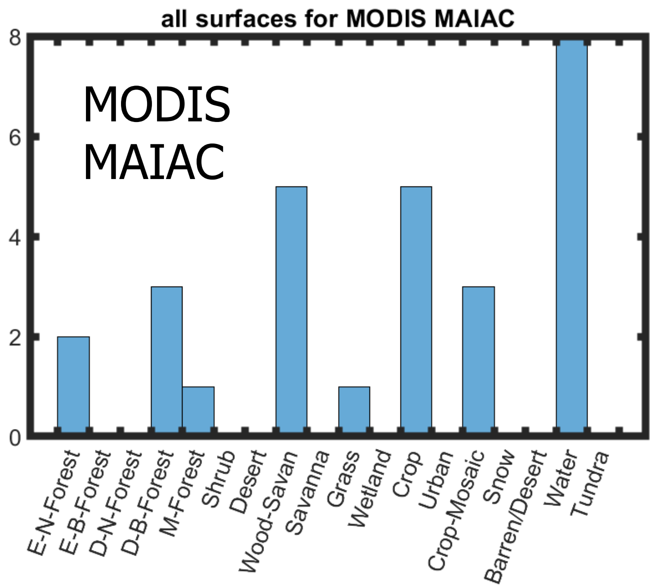


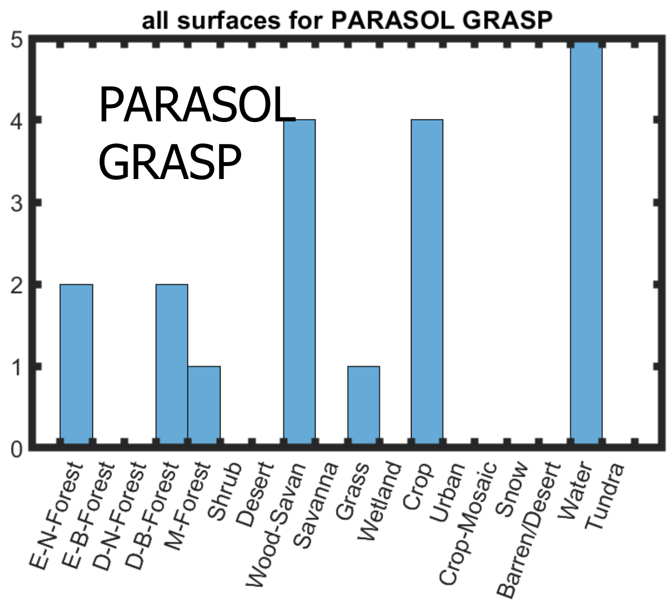
Land Surfaces



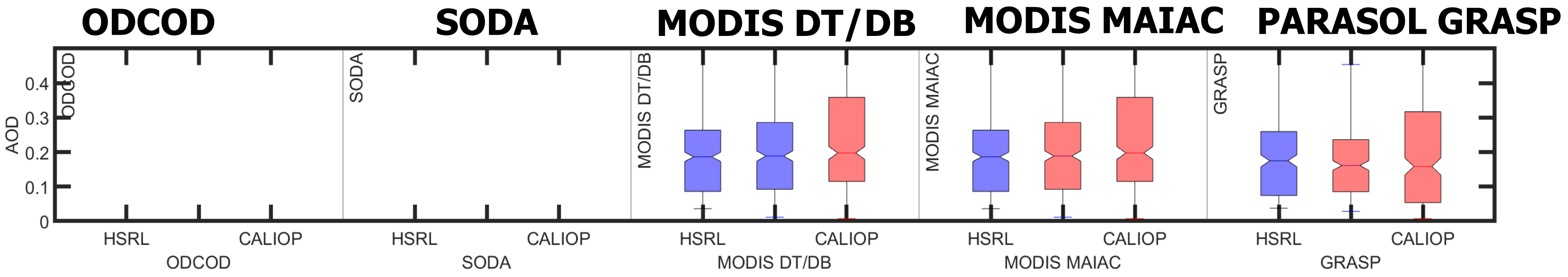


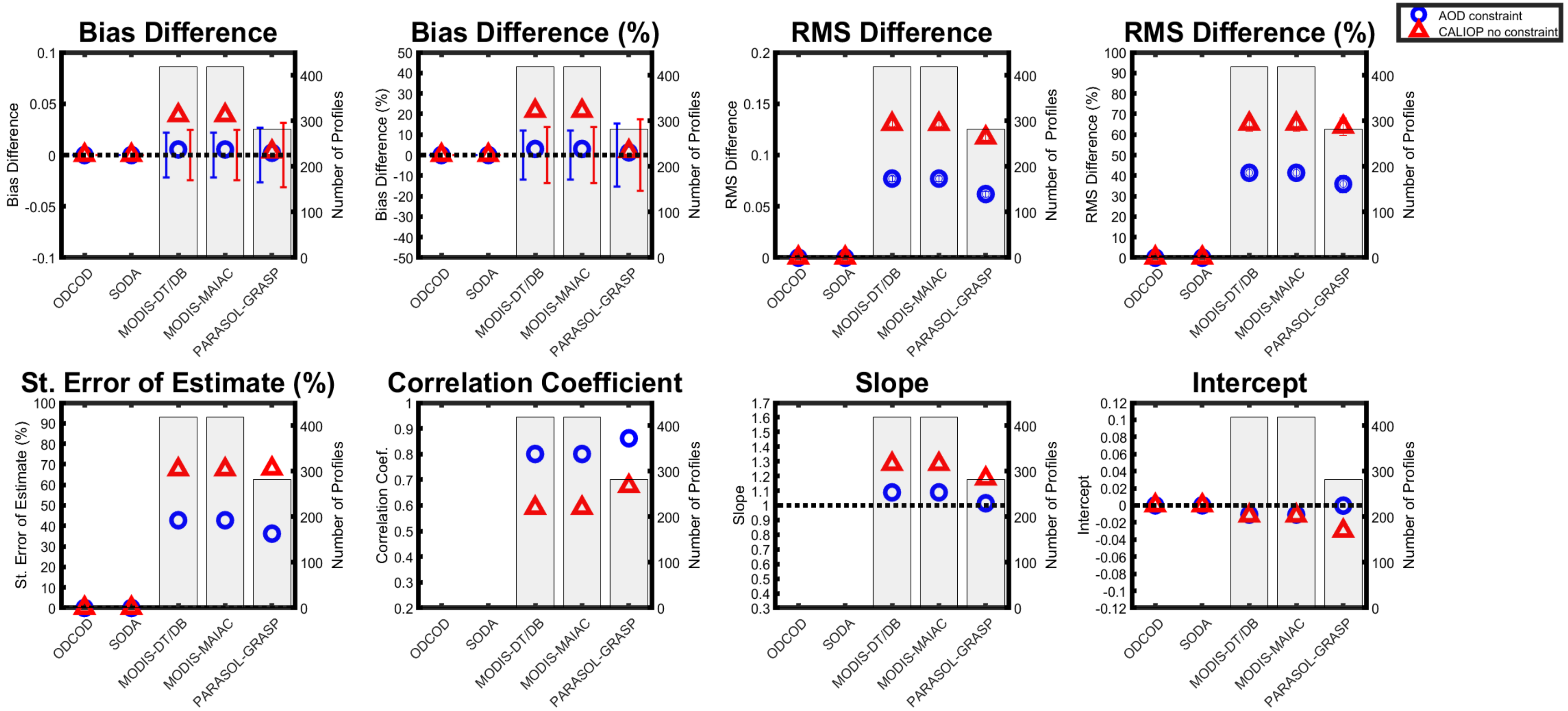




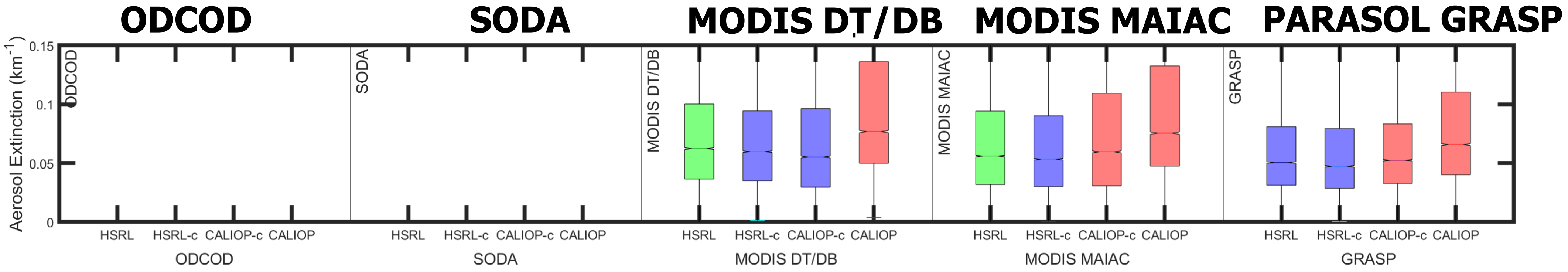


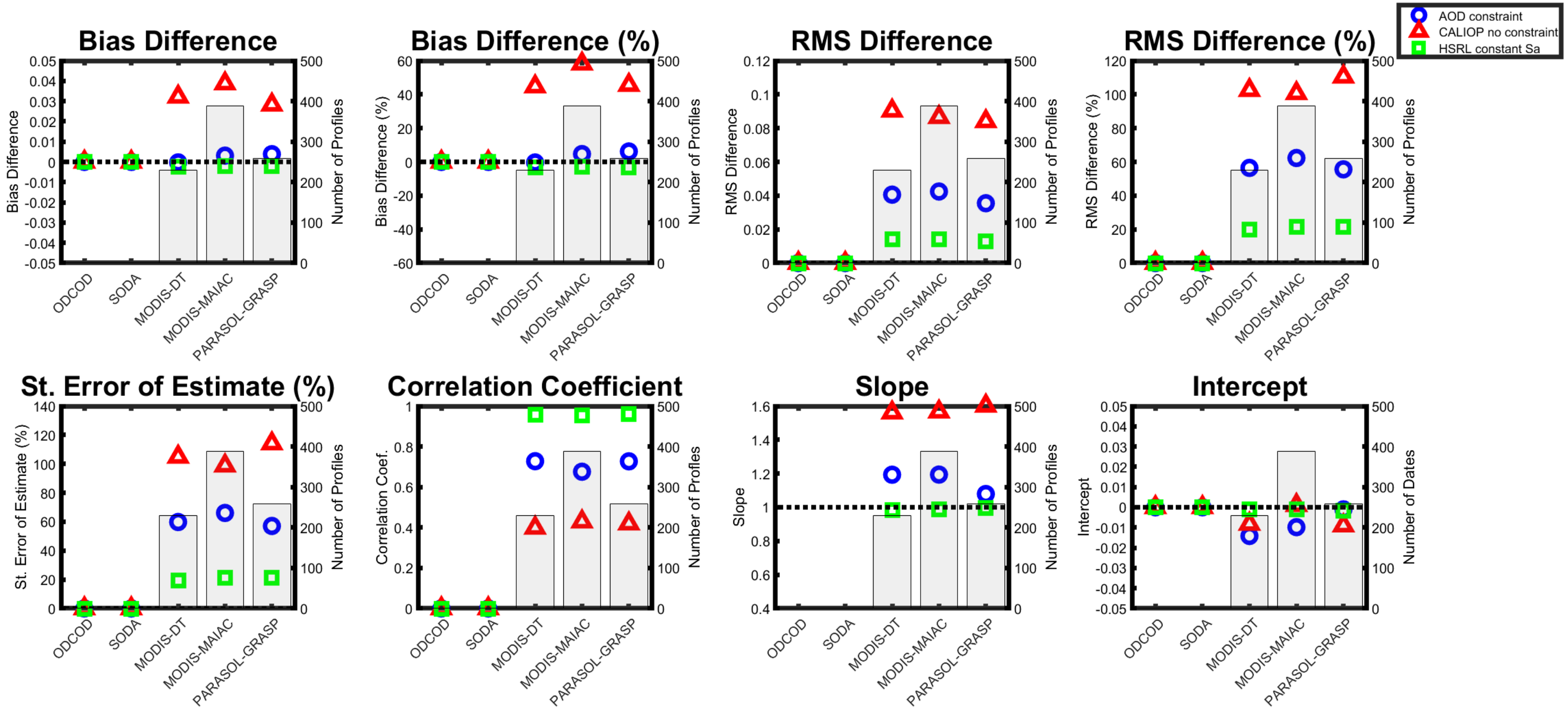
Land Only - AOD



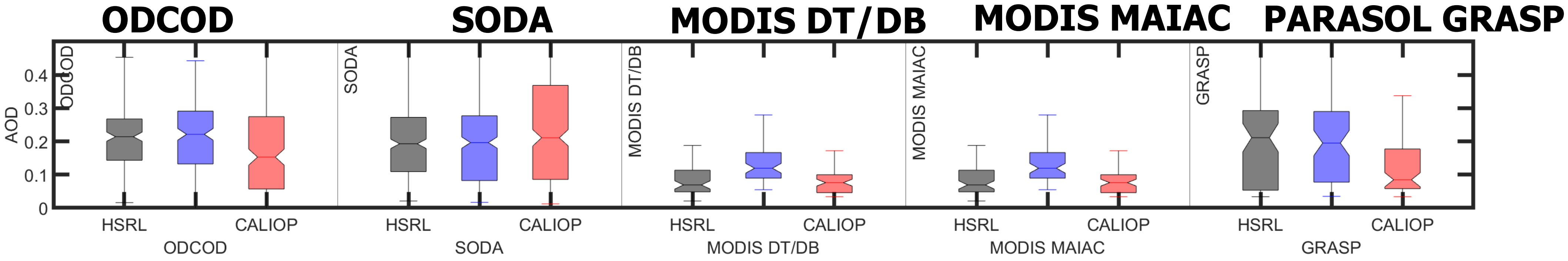


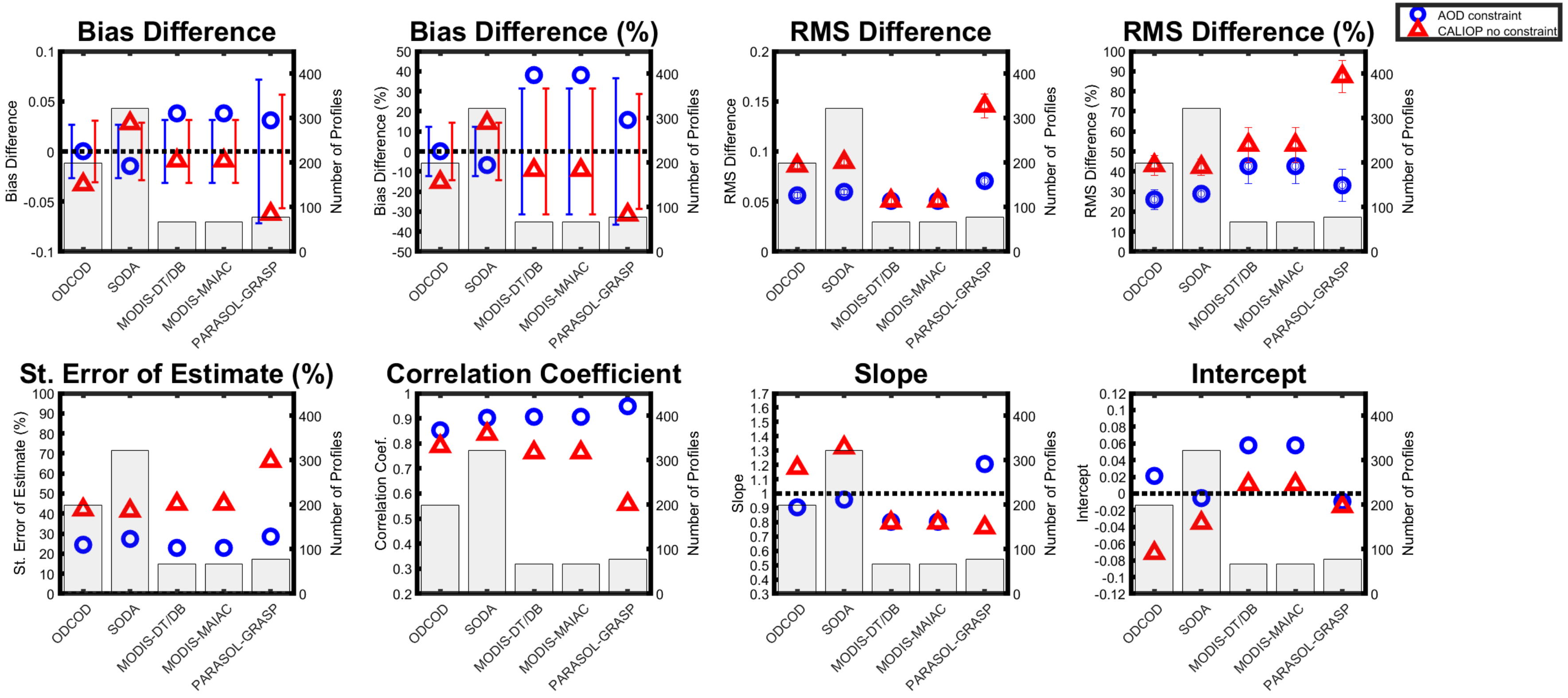
Land Only – Aerosol Extinction



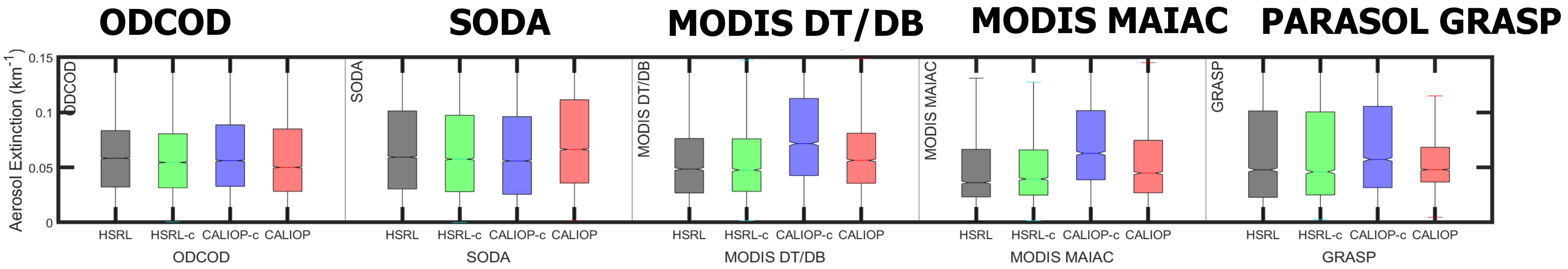


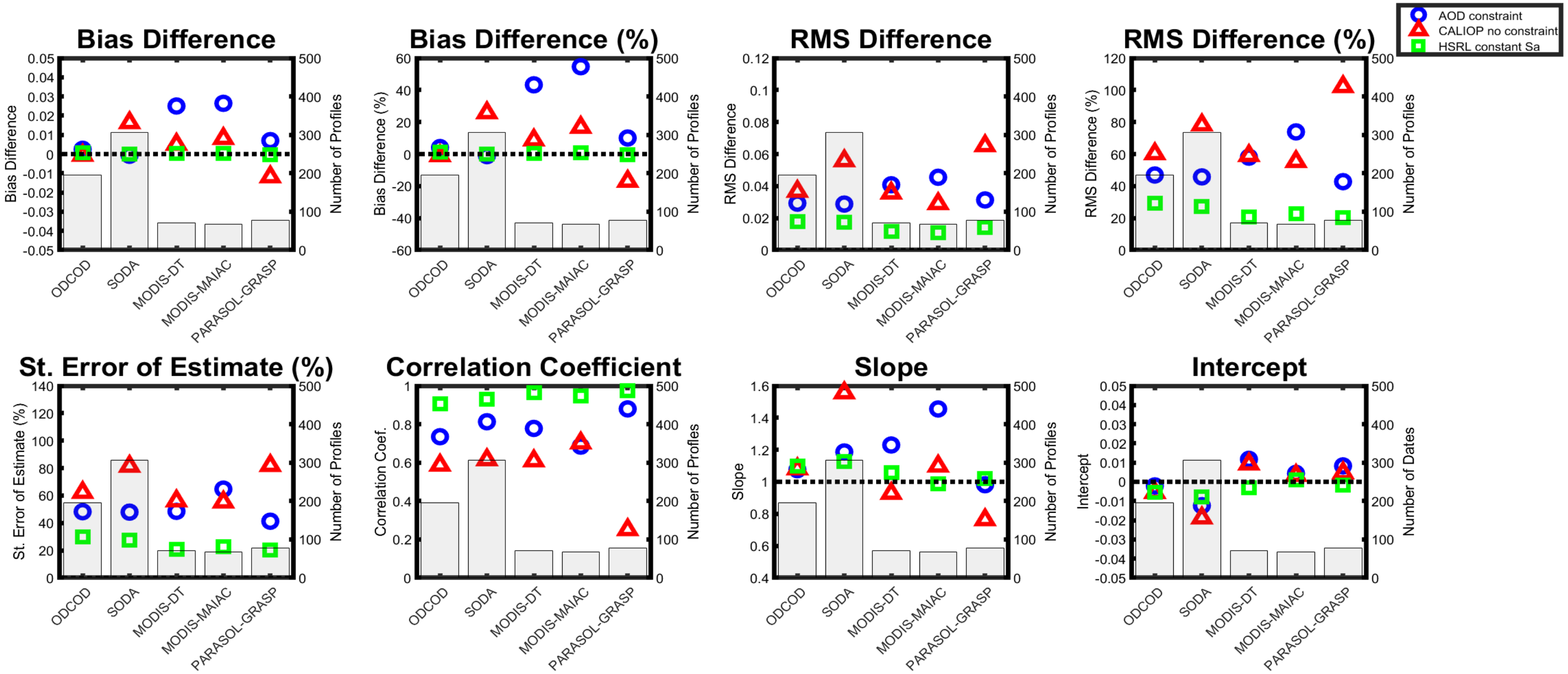
Water Only - AOD



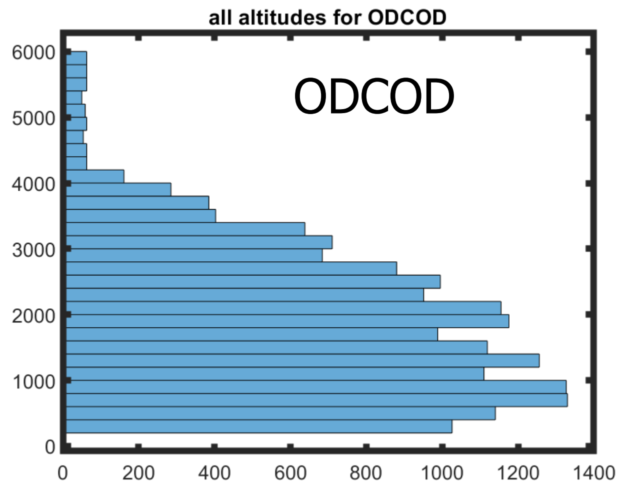


Water Only – Aerosol Extinction

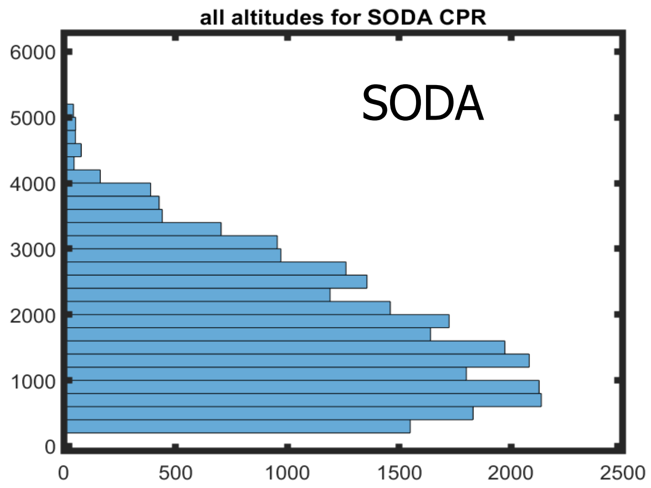




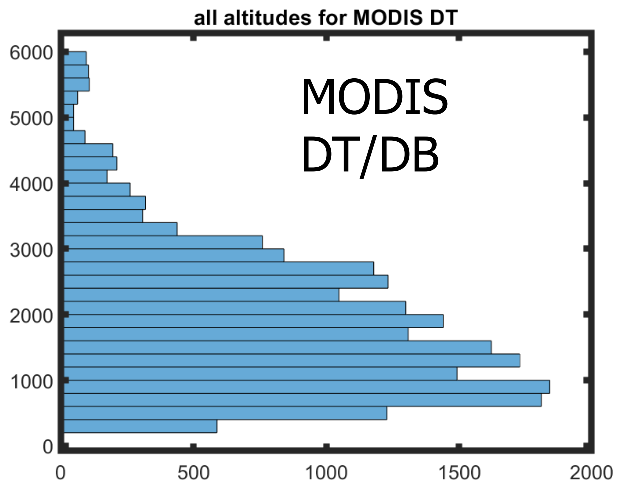
Altitudes



all altitudes for ODCOD
ODCOD
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400



all altitudes for SODA CPR
SODA
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500



all altitudes for MODIS DT
MODIS
DT/DB
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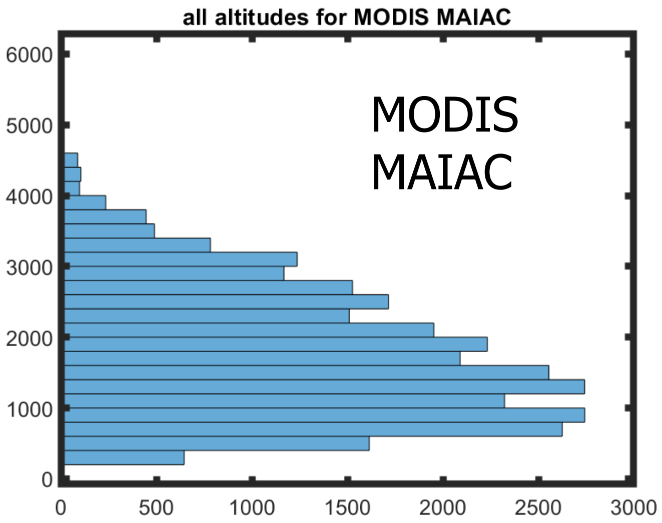
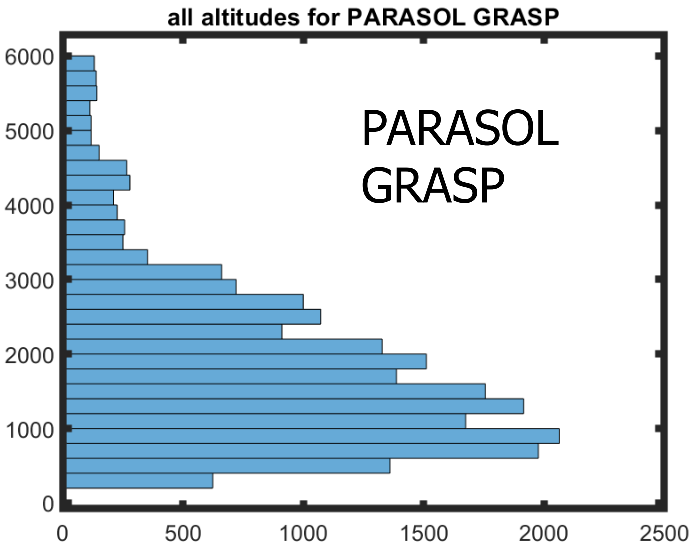
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000

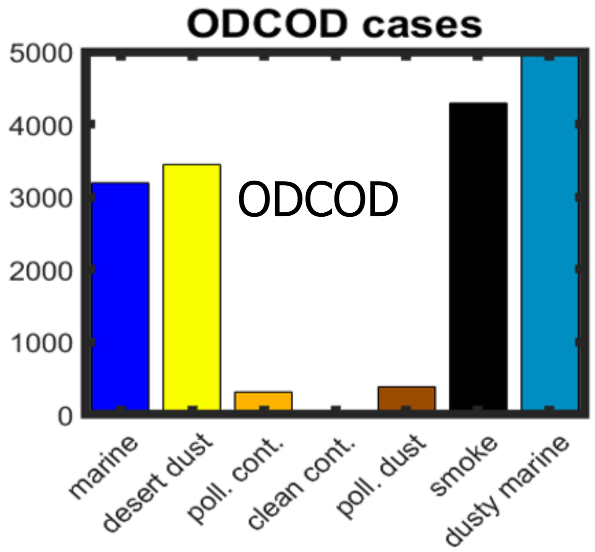


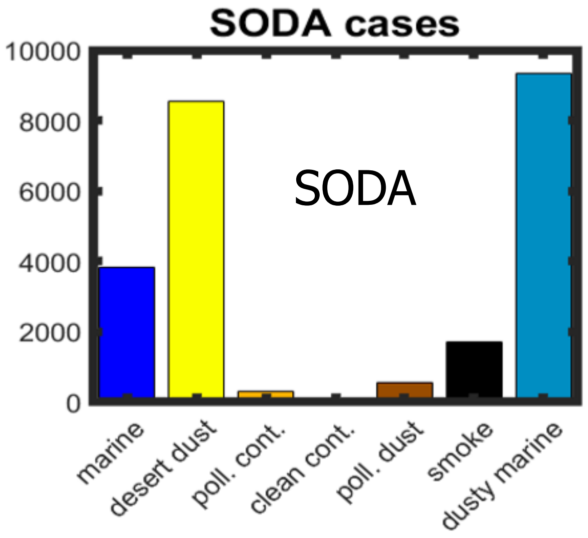
all altitudes for MODIS MAIAC
MODIS
MAIAC
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500
3000

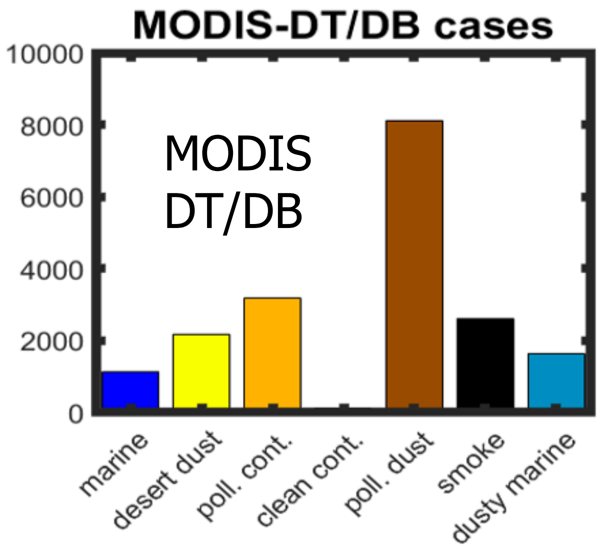


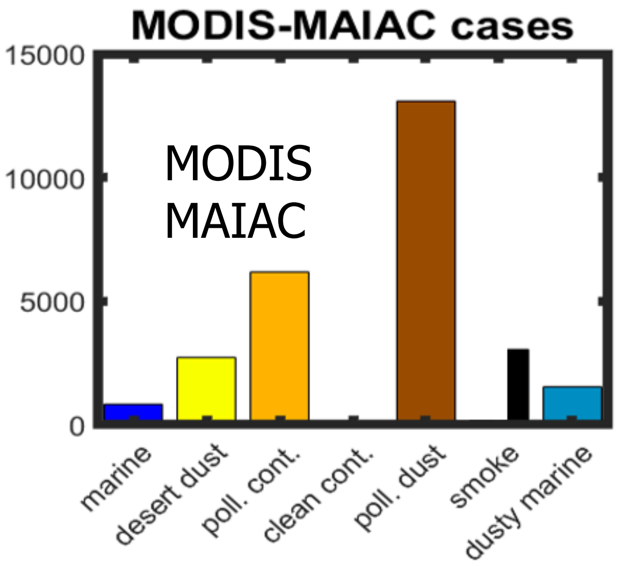
all altitudes for PARASOL GRASP
PARASOL
GRASP
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500

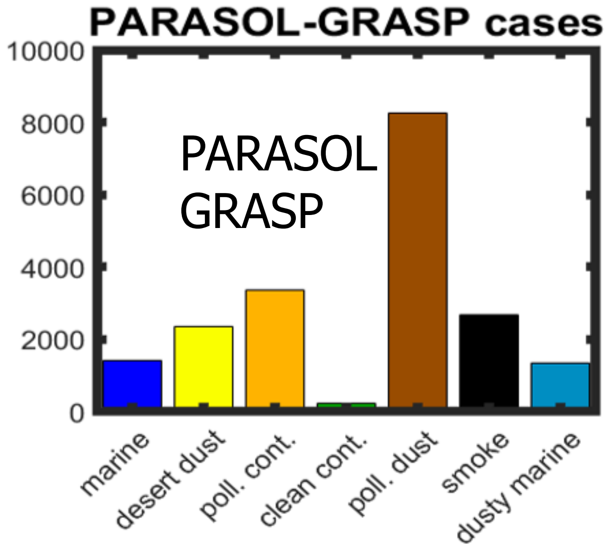
CALIOP Aerosol Types for the Various AOD Constraint Data Sets



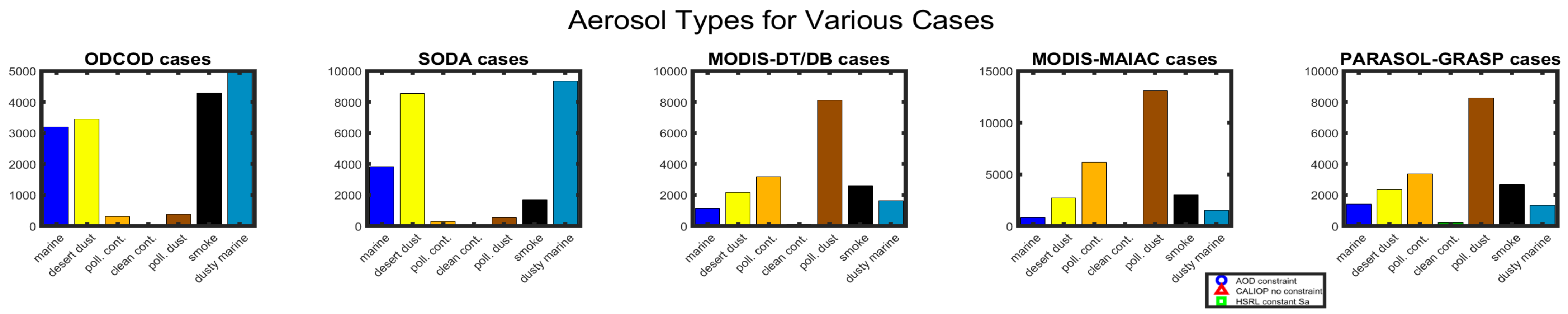


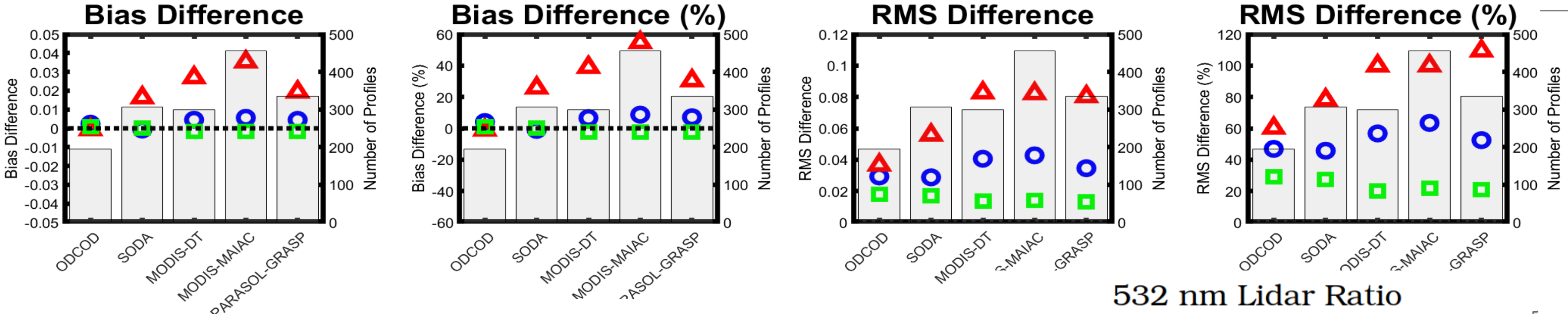






CALIOP Aerosol Types for the Various AOD Constraint Data Sets





Aerosol type	S_{532} (sr)
Clean marine	23 ± 5 (0.2174)
Dust	44 ± 9 (0.2045)
Polluted continental/smoke	70 ± 25 (0.3571)
Clean continental	53 ± 24 (0.4528)
Polluted dust	55 ± 22 (0.4000)
Elevated smoke	70 ± 16 (0.2286)
Dusty marine	37 ± 15 (0.4054)