Evaluation of Terra MODIS Aerosol and Water Vapor Measurements Using ARM SGP Data

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Outline

- MODIS aerosol comparisons
- MODIS water vapor comparisons
- Aerosol and water vapor profile diurnal variability
- Average aerosol and water vapor profiles during Terra overpass
- DOE ARM Aerosol IOP experiment
- Summary

DOE ARM SGP Measurements Used for MODIS Validation

- **Aerosol optical thickness (AOT)**
    - **Cimel Sun photometer (Cimel)**
    - **Multi-Filter Rotating Shadowband Radiometer (MFRSR)**

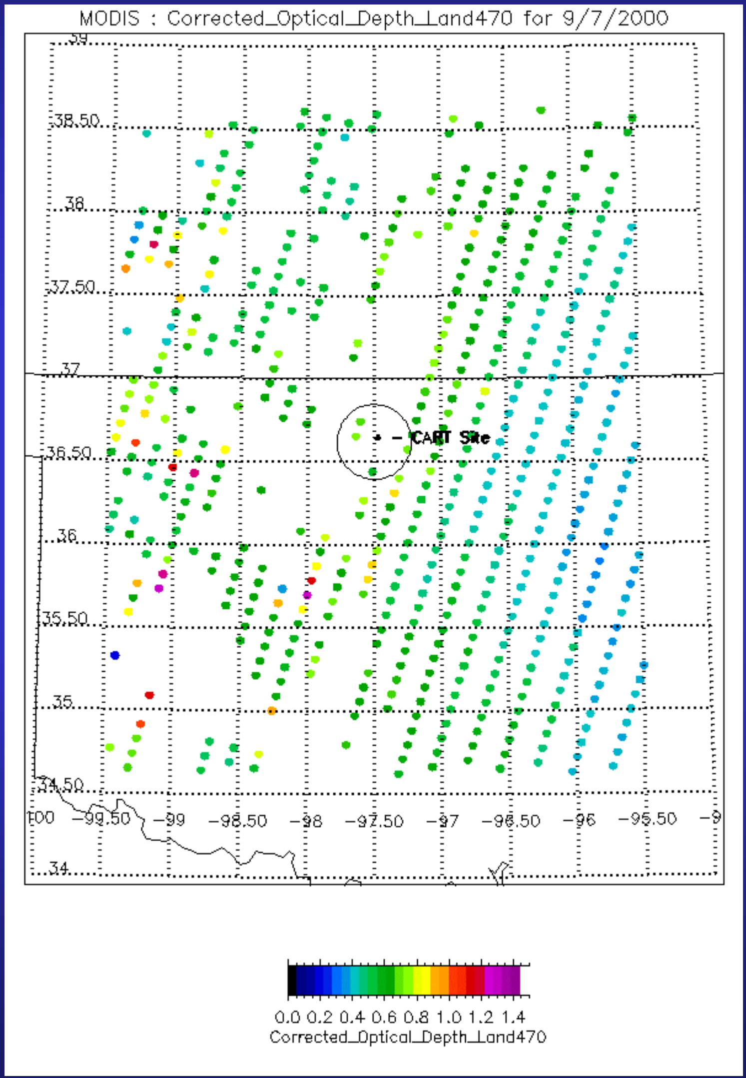
- **Precipitable Water Vapor (PWV)**
    - **Microwave Radiometer (MWR)**
    - **CART Raman Lidar (CARL)**
    - **Cimel Sun photometer (Cimel)**

- **Aerosol and Water Vapor Profiles**
    - **CART Raman Lidar (CARL)**

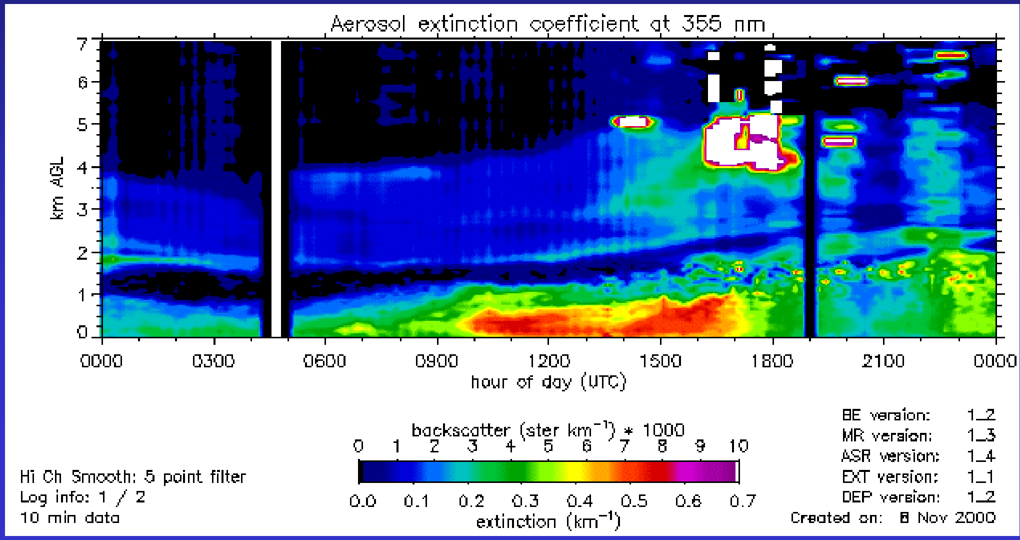
- **Used MODIS, SGP data from March 2000 through September 2001**

Example MODIS and SGP Aerosol Measurements

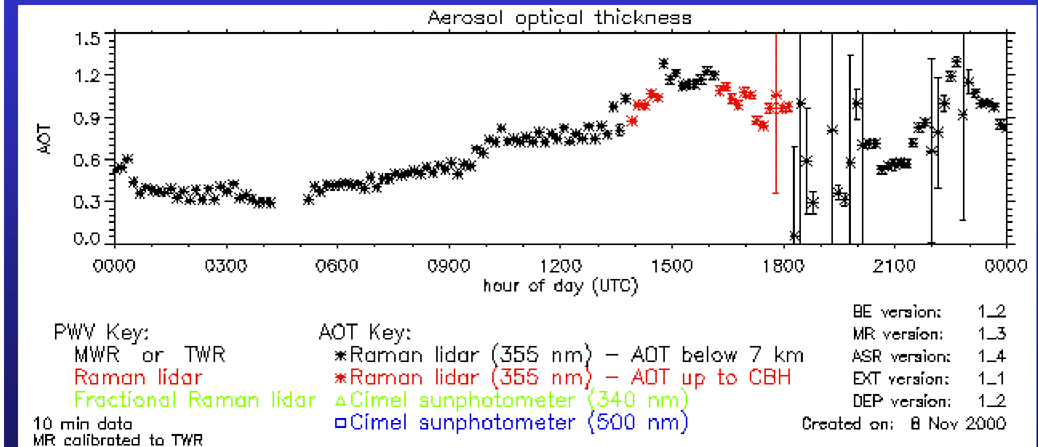
MODIS AOT (470 nm)



CARL aerosol extinction profiles



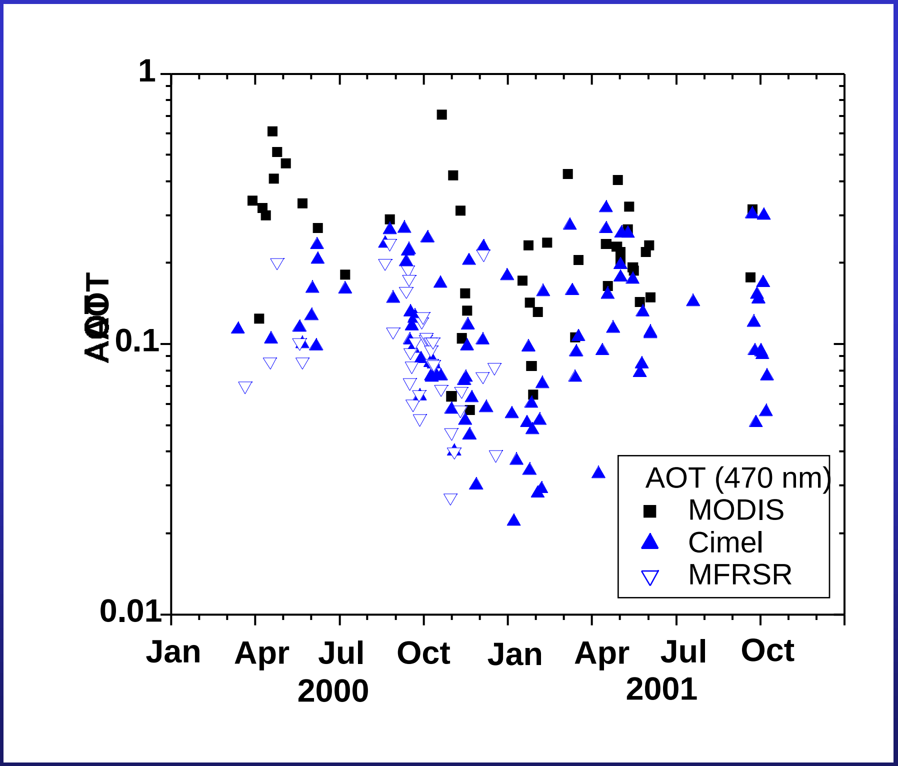
CARL and Cimel AOT



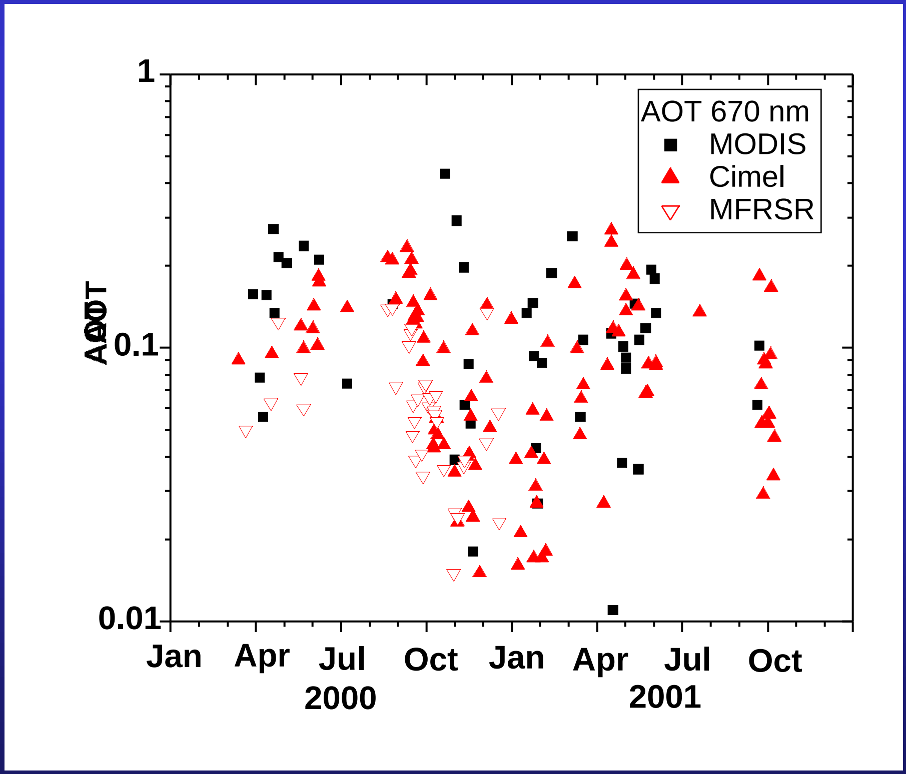
Aerosol optical thickness over SGP during MODIS measurements

- SGP AOT measured by Cimel, MFRSR
- AOT generally low (~between 0.02-0.3)

470 nm

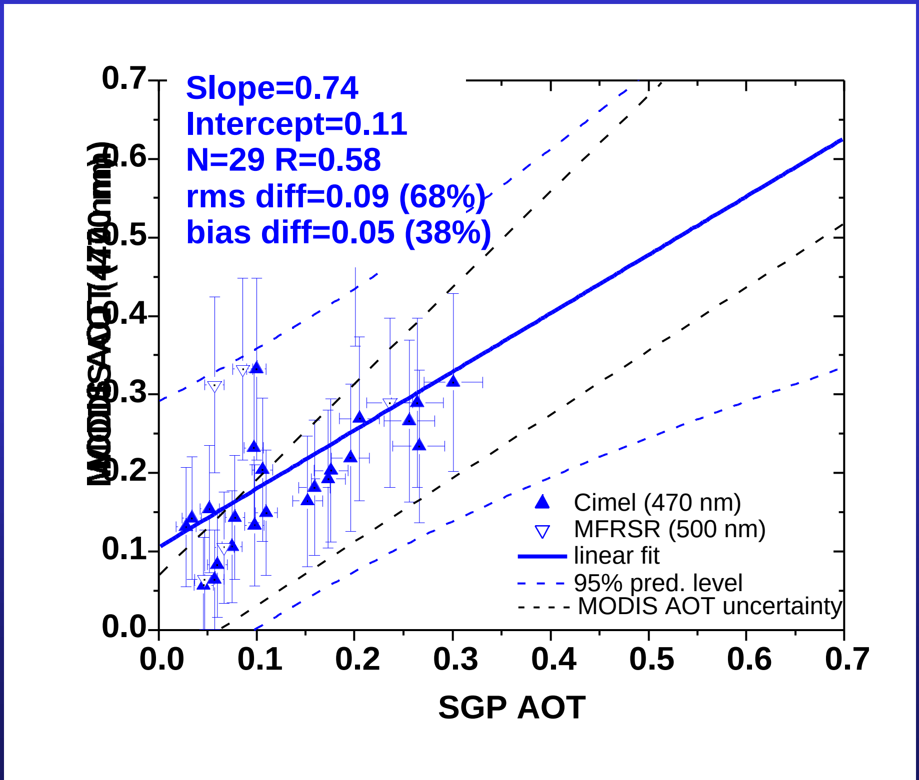


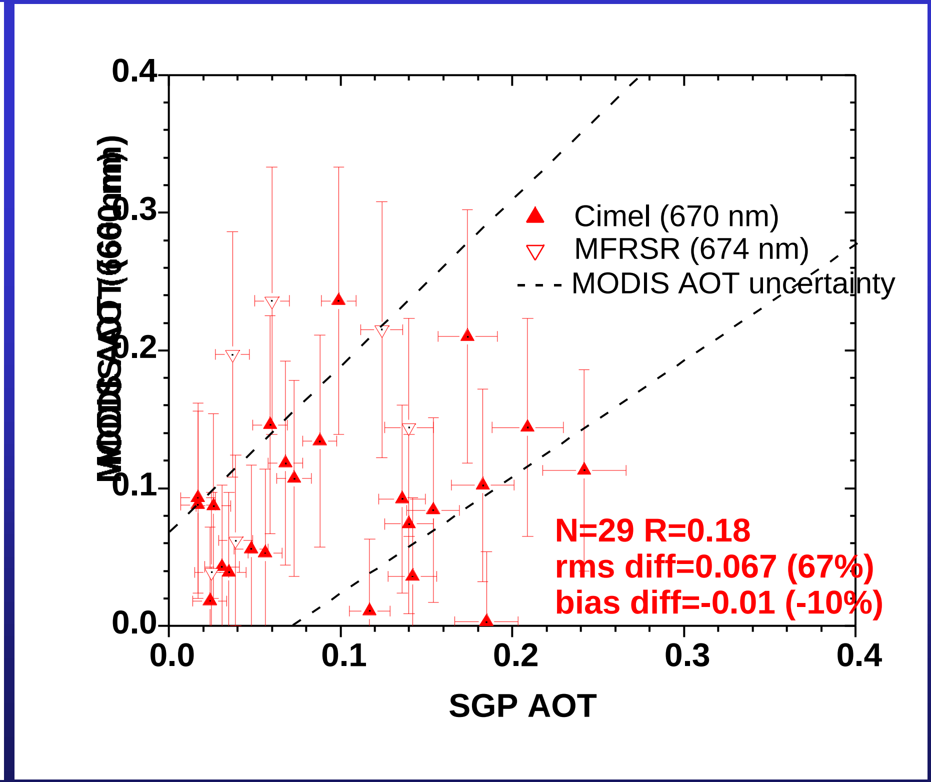
670 nm



MODIS AOT vs. SGP AOT

- (470 nm)
  - MODIS biased high at low AOT
  - differences generally within MODIS uncertainty
- (660 nm)
  - large scatter, no linear trend for low AOT
  - differences generally within MODIS uncertainty

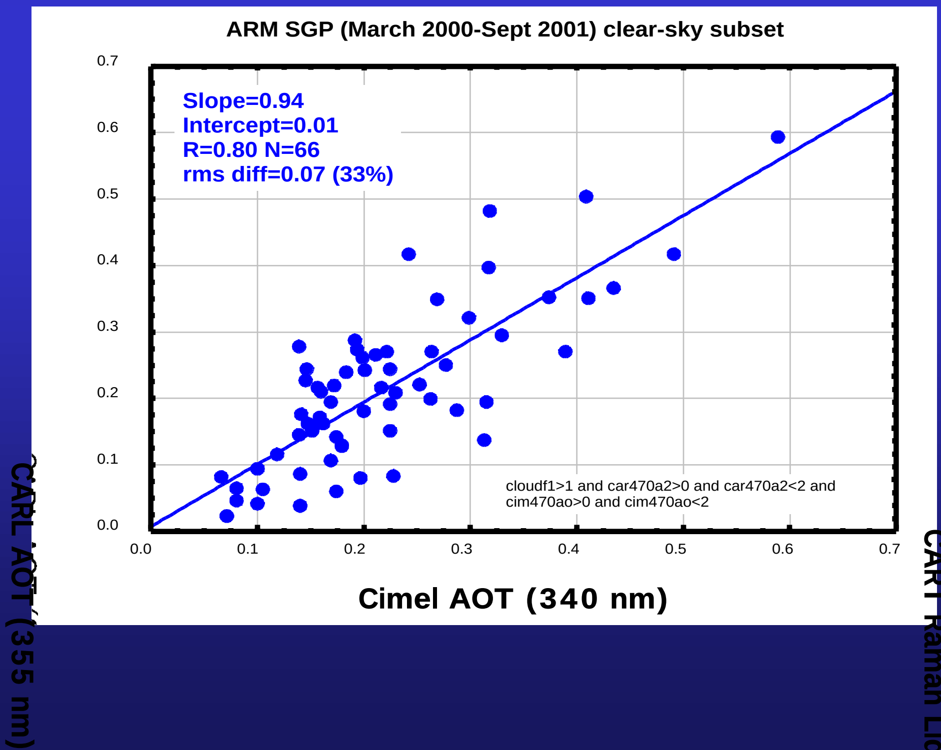


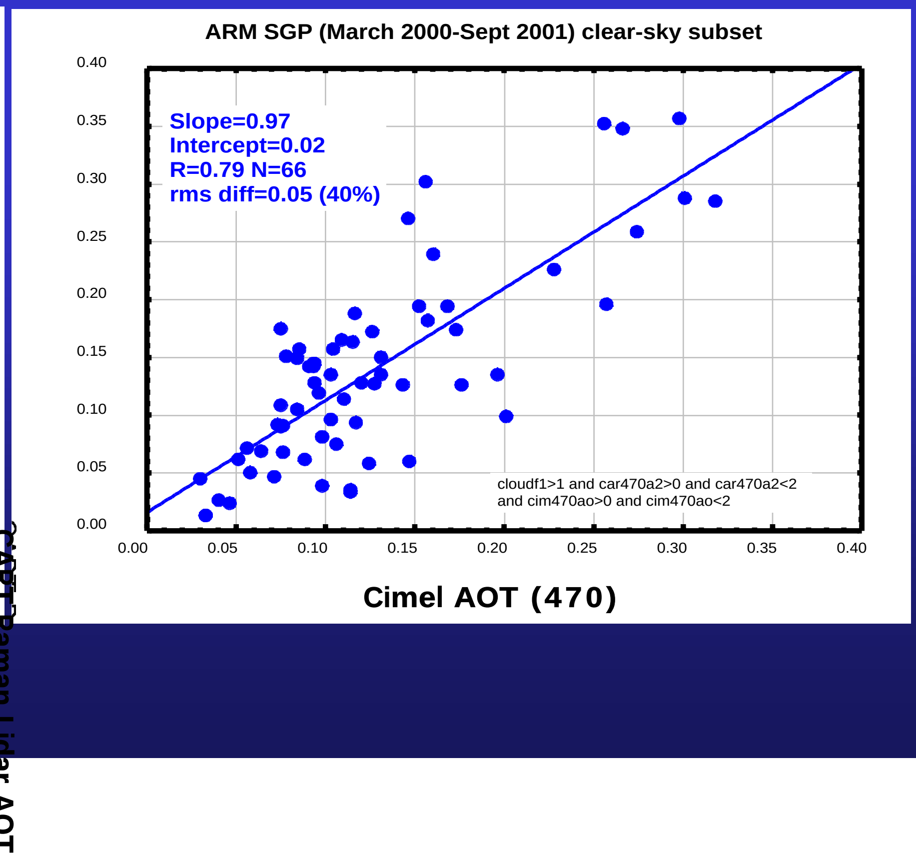


CART Raman lidar AOT vs. Cimel AOT

CART Raman lidar AOT (355 nm), Cimel AOT (340 nm) agree within about 5% in mean

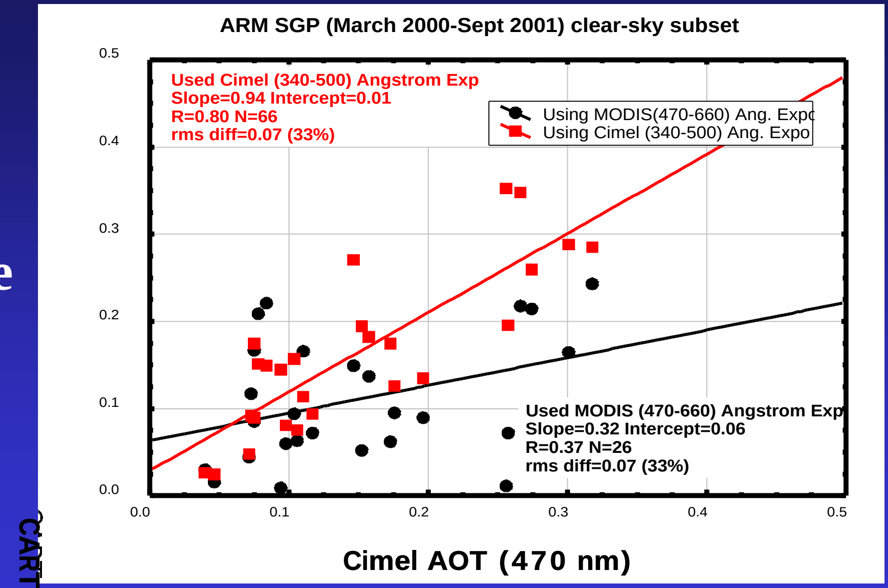
Using Angstrom exponent (340-500 nm) from Cimel AOT to extrapolate CARL AOT from 355 nm to 470 nm gives generally good results





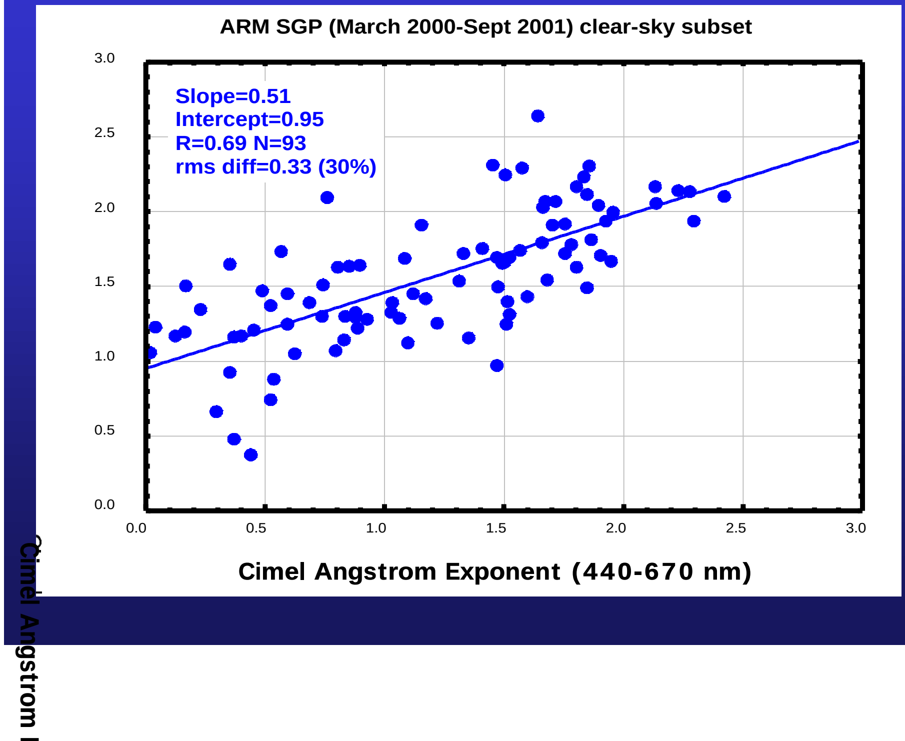
CARL AOT at 470 nm

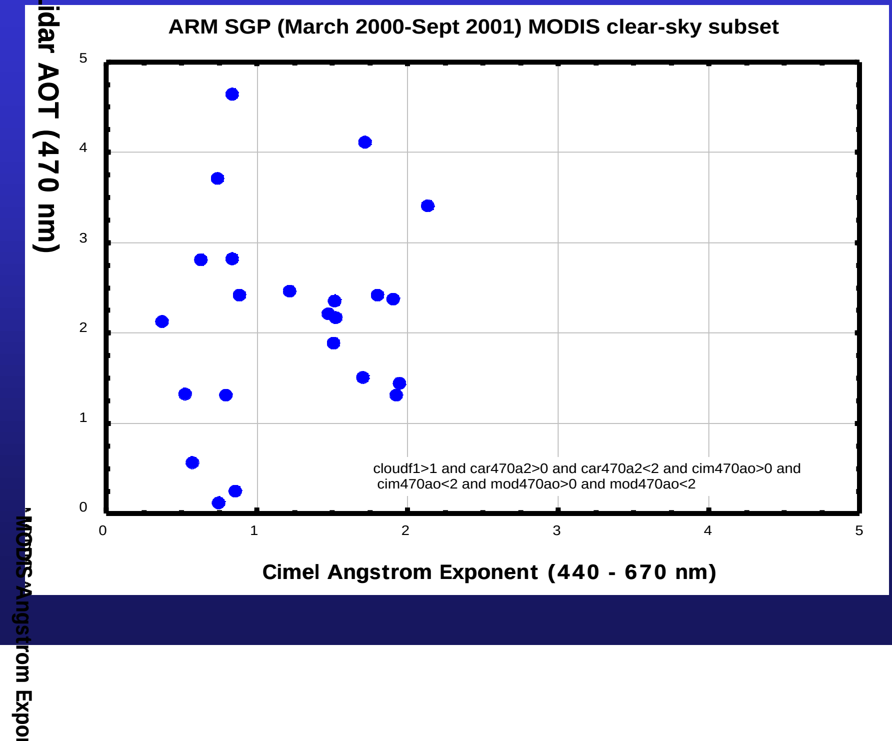
Can not use CARL AOT (355 nm) alone to evaluate MODIS AOT (470 nm) because we can not use MODIS Angstrom exponent δ (470-660 nm) to extrapolate CARL AOT from 355 nm to 470 nm



Cimel δ (350-500 nm) ≠ Cimel δ (470-660 nm)

MODIS δ (470-660 nm) ≠ Cimel δ (470-660 nm)

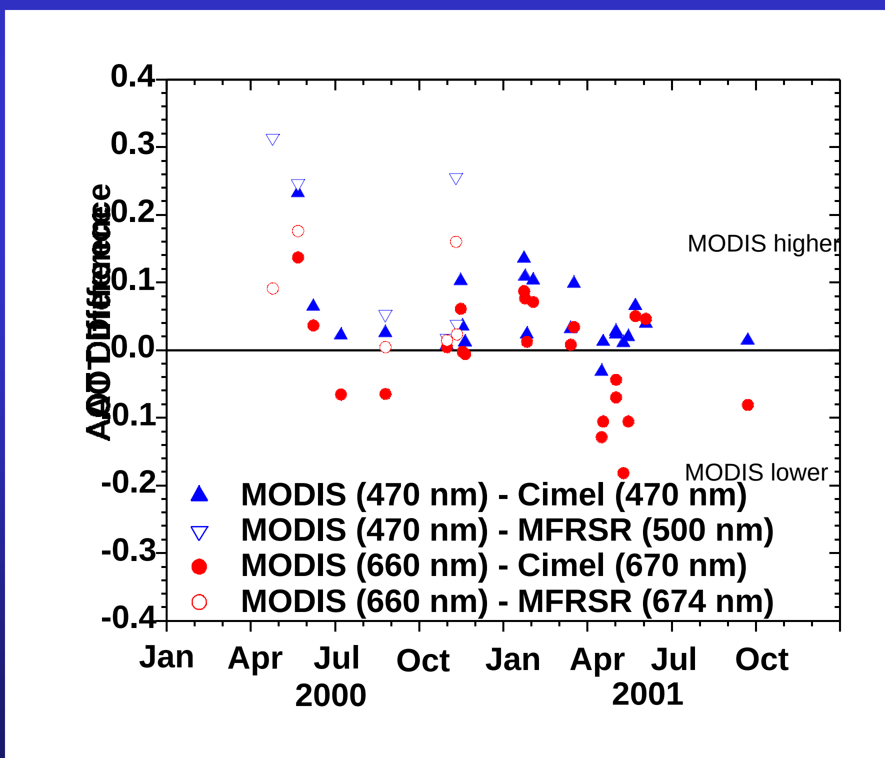




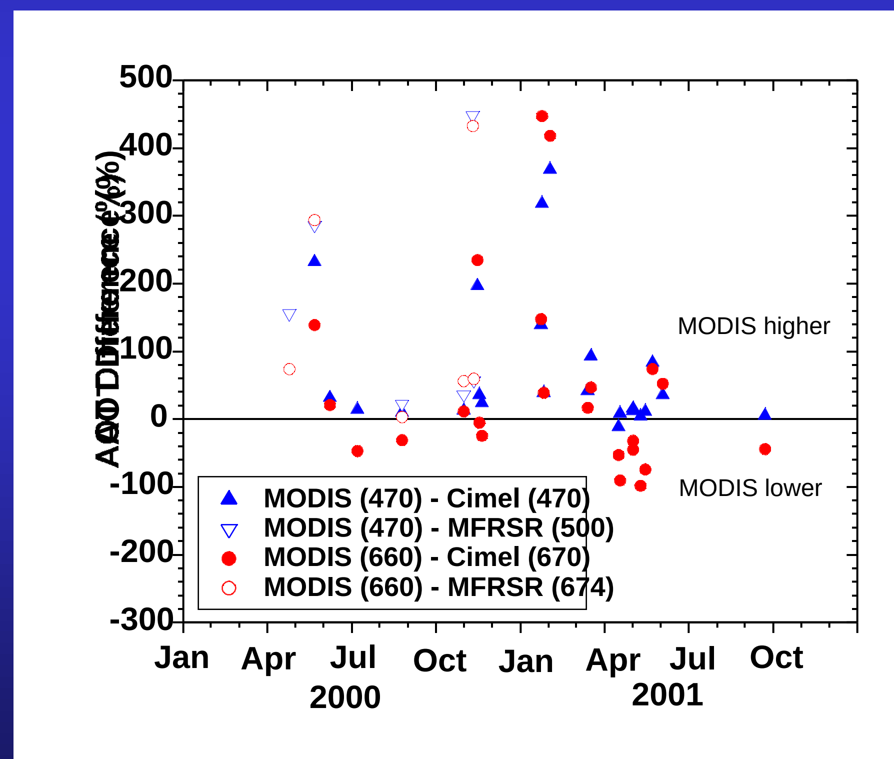
(MODIS - SGP) AOT difference vs. date

No obvious trend with time at either 470 or 660 nm

Absolute differences



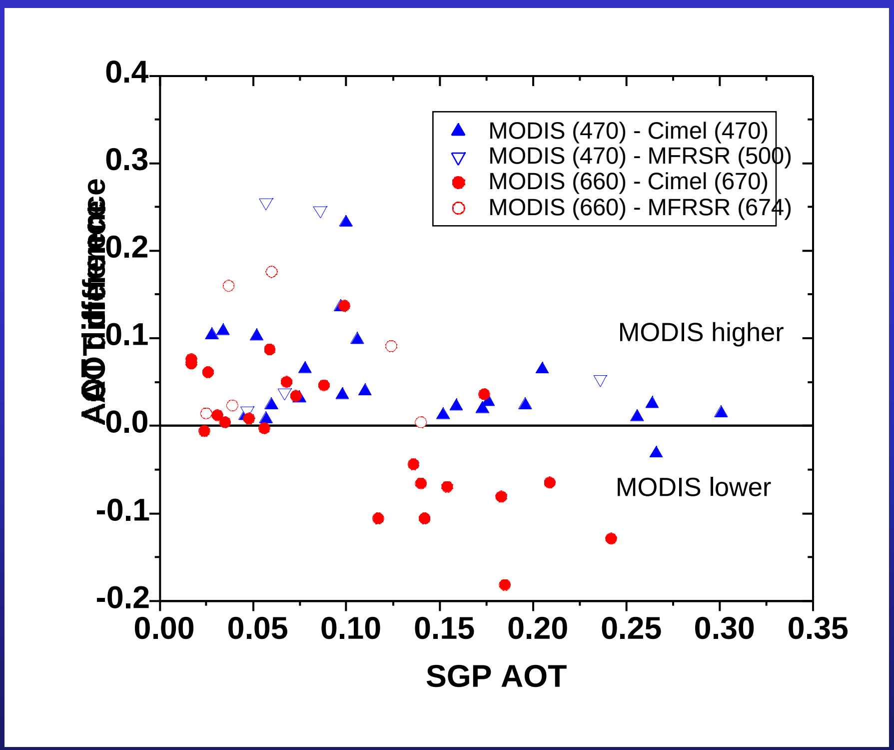
Relative differences



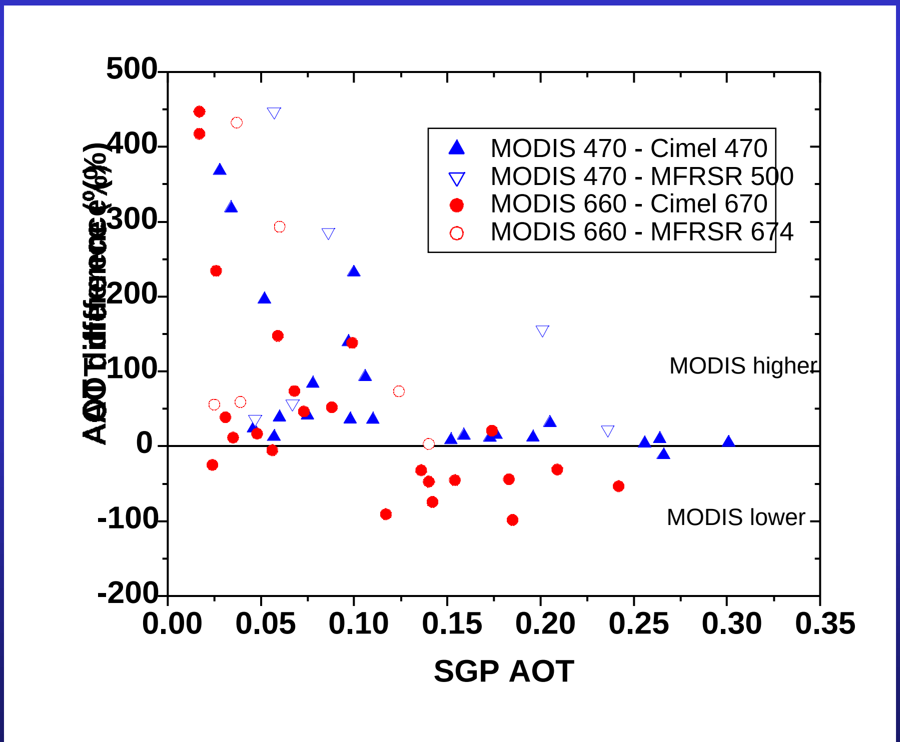
(MODIS - SGP) AOT difference vs. AOT

- Relative differences decrease with increasing AOT
- (470 nm) differences < 0-20% (MODIS higher) for AOT > 0.1

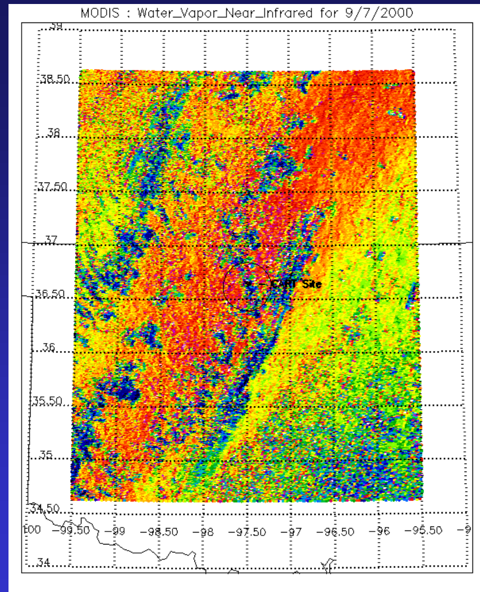
Absolute differences



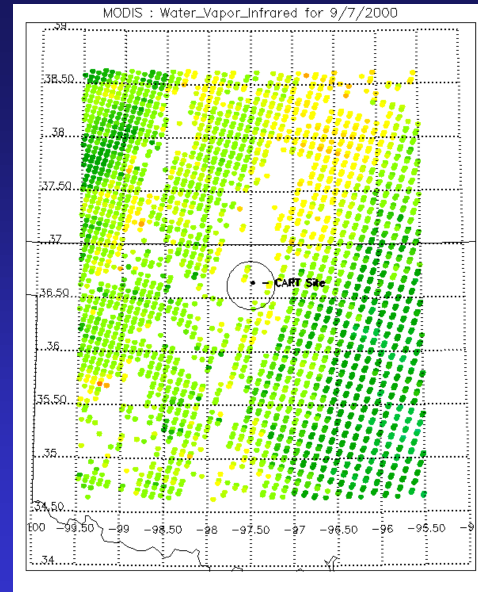
Relative differences

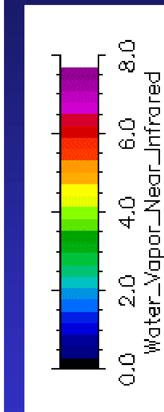


MODIS near IR PWV

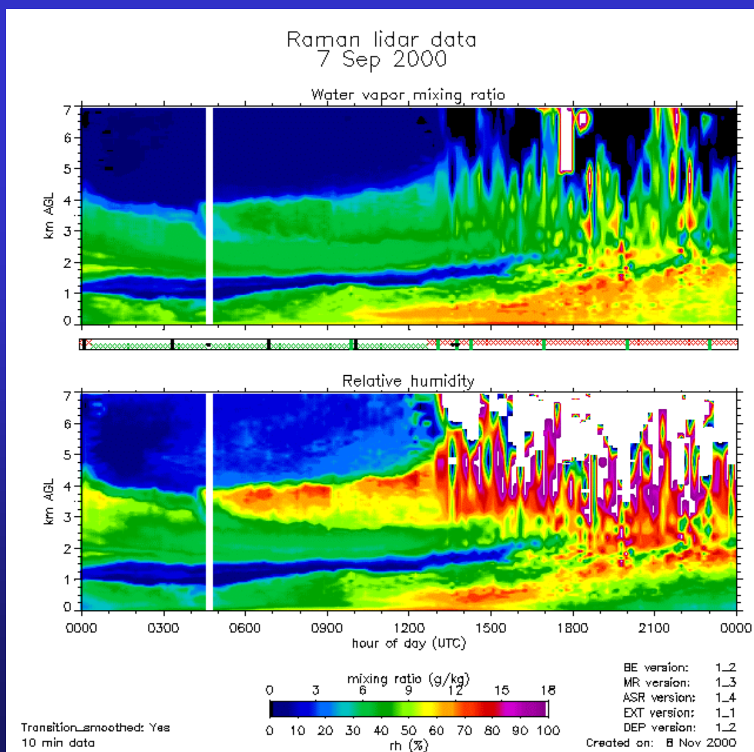


MODIS IR PWV

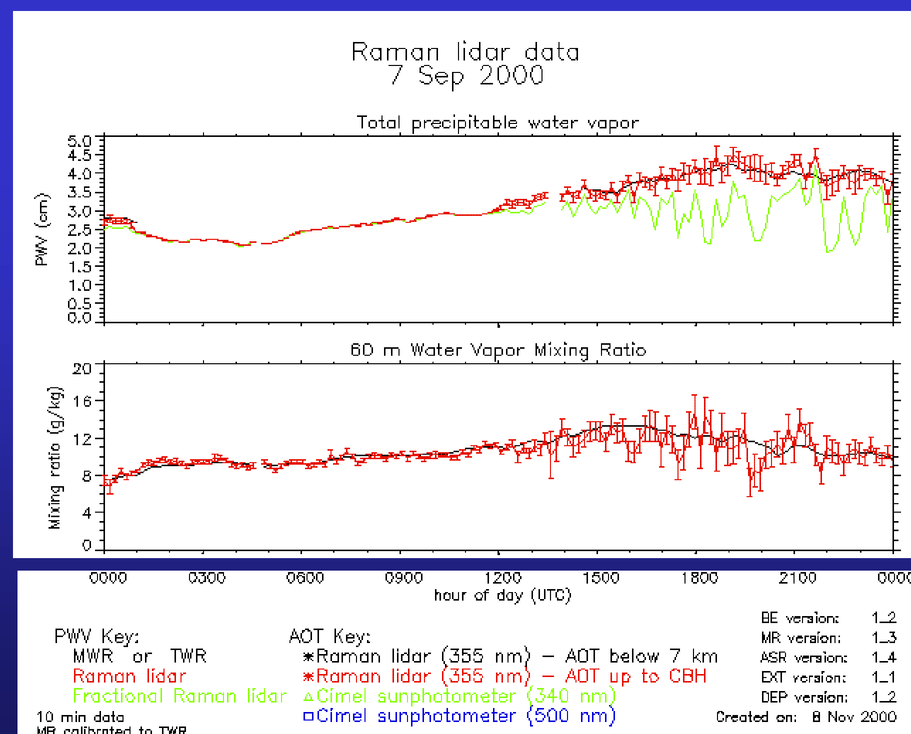




CARL water vapor profiles

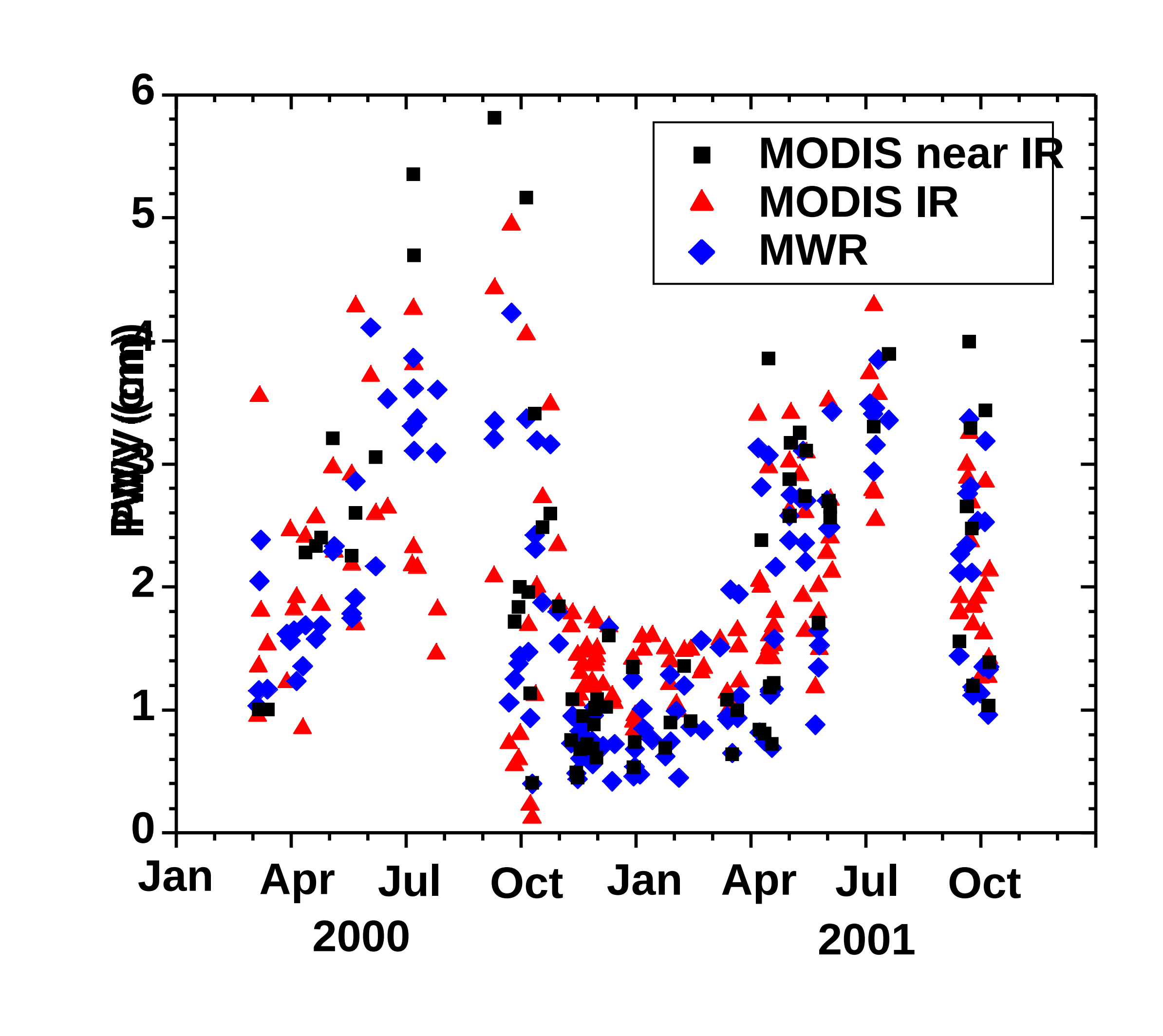


CARL and MWR PWV



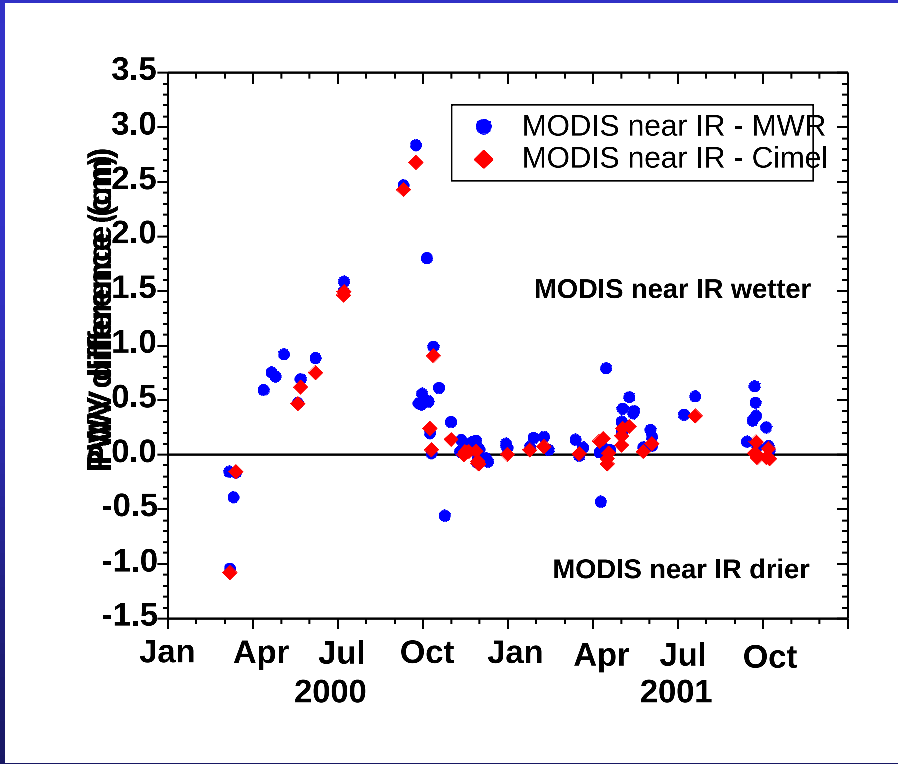
Precipitable water vapor over SGP during MODIS measurements

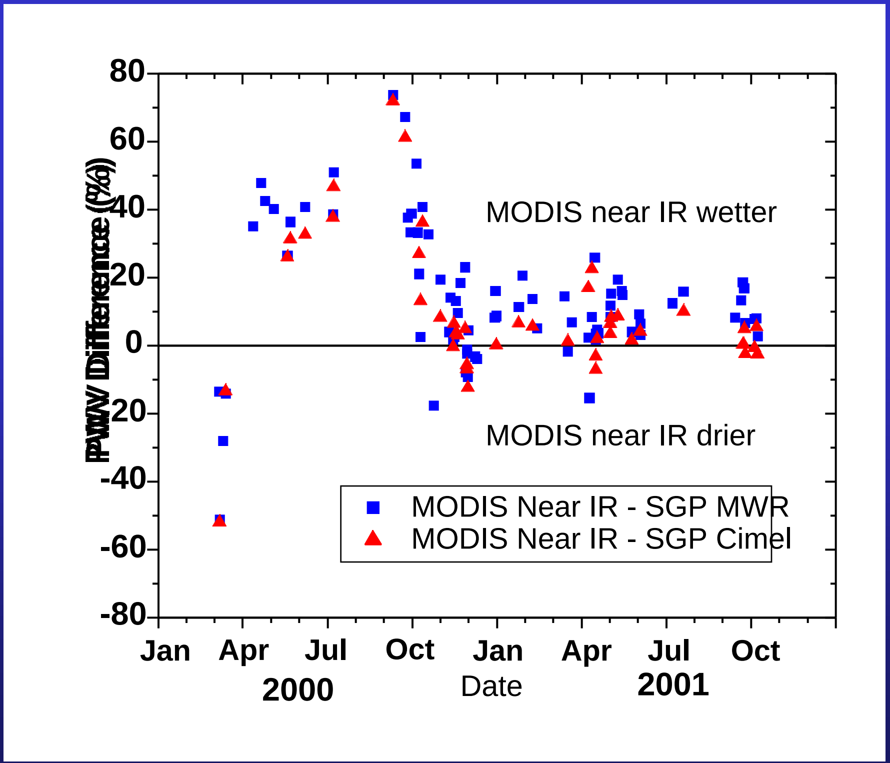
PWV varies between 5 – 50 mm



(MODIS near IR - SGP) PWV difference vs. date

- Nov. 1 2000
  - modified water vapor transmittance lookup table to improve "continuum" absorption
  - changed to side b electronics improved 1.24 μm radiometric calibration
  - changes reduced MODIS near IR overestimates of PWV
- Jun. 1 2000 regenerated lookup tables using new HITRAN2000 database
  - have not yet analyzed sufficient data to evaluate change

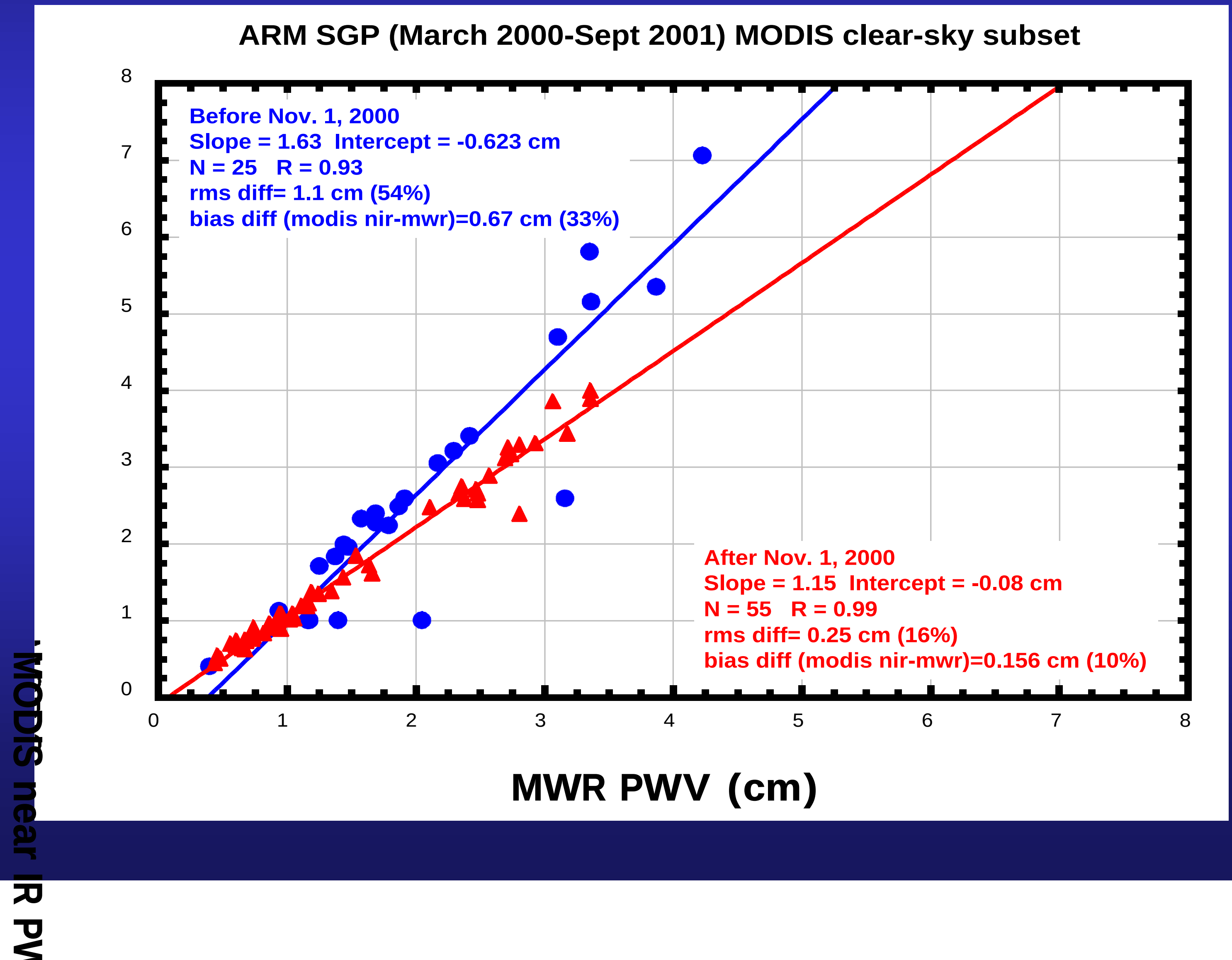




MODIS near IR PWV comparison vs. Microwave radiometer (MWR)

After Nov. 1, 2000

- **bias difference decreases from 0.67 cm (33%) to 0.16 cm (10%)**
- **rms difference decreases from 1.1 cm (54%) to 0.25 cm (16%)**



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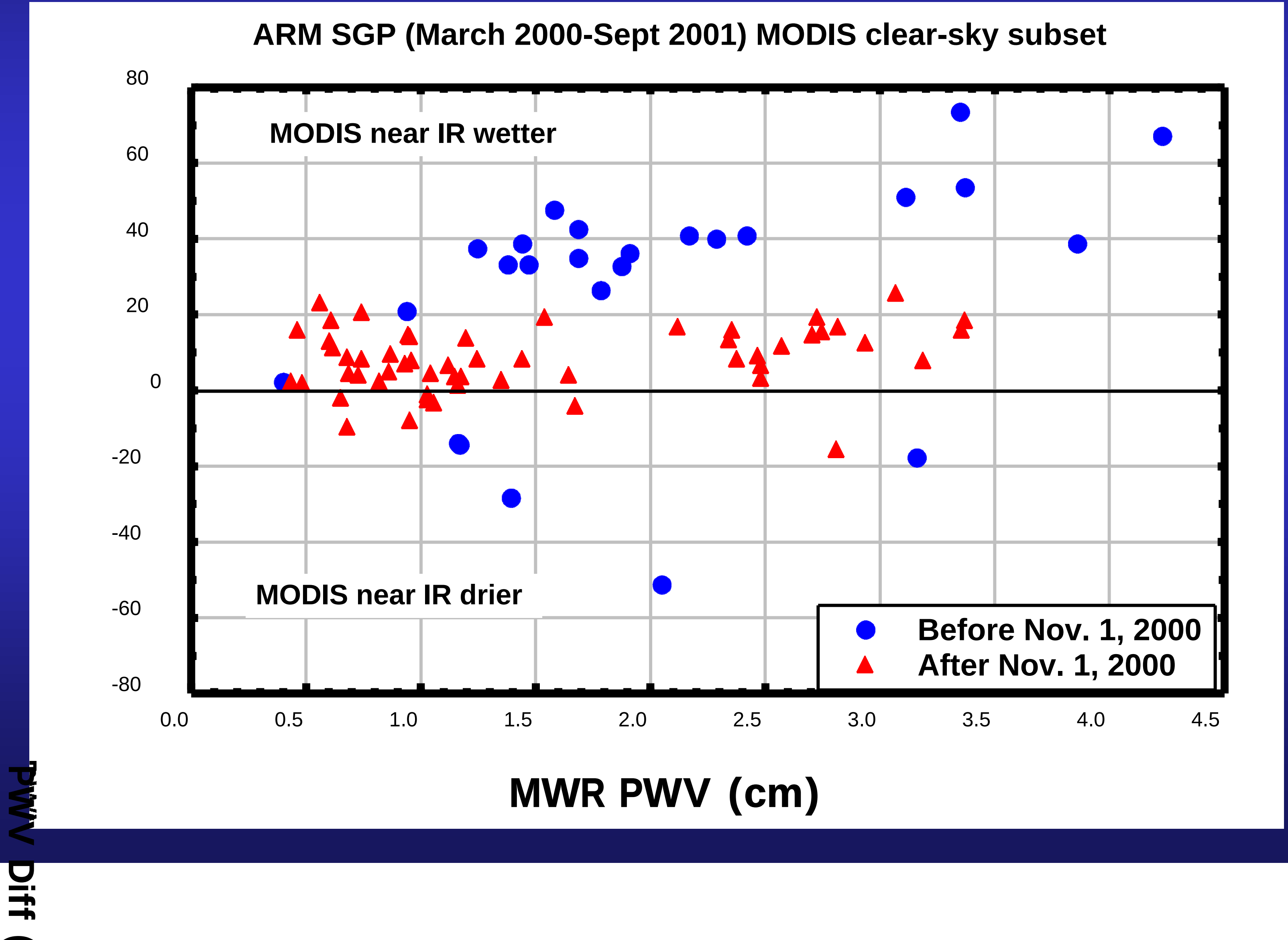
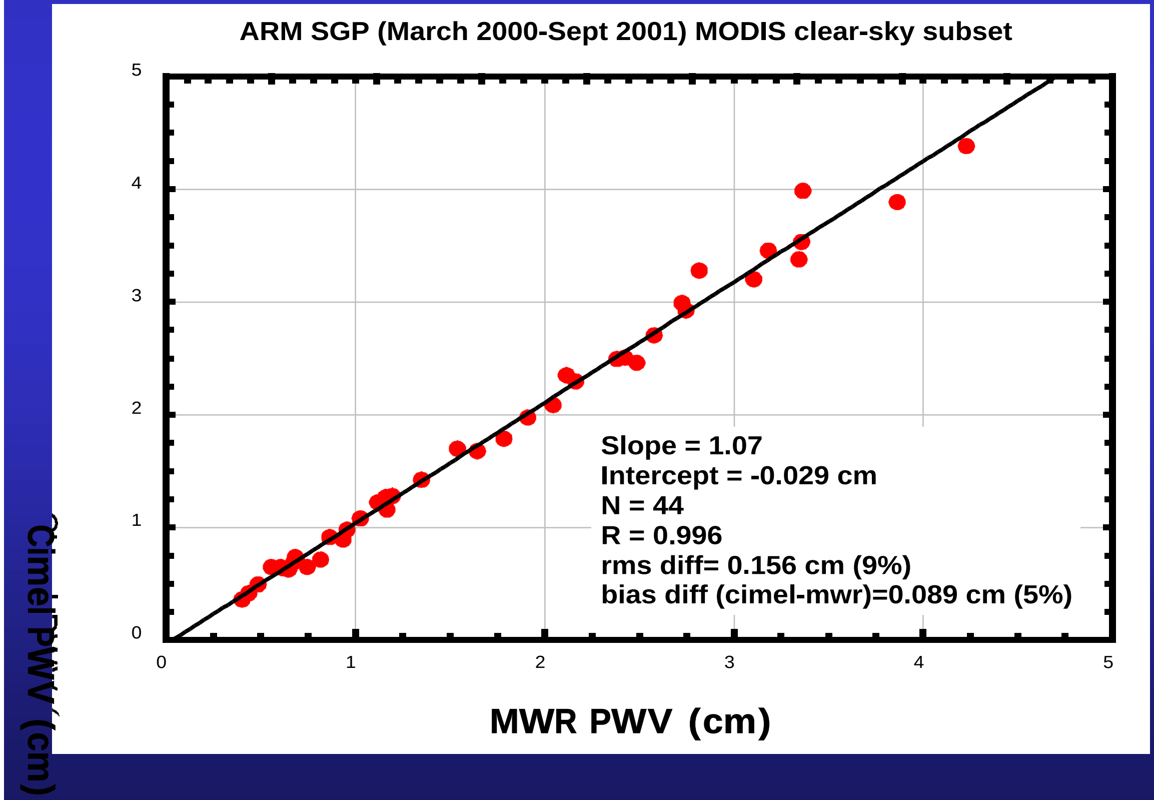


MWR vs. Cimel PWV comparison

If you use Cimel PWV to validate MODIS…

PWV derived using Cimel processing using LOWTRAN 7 database is about 5-8% higher than ARM MWR



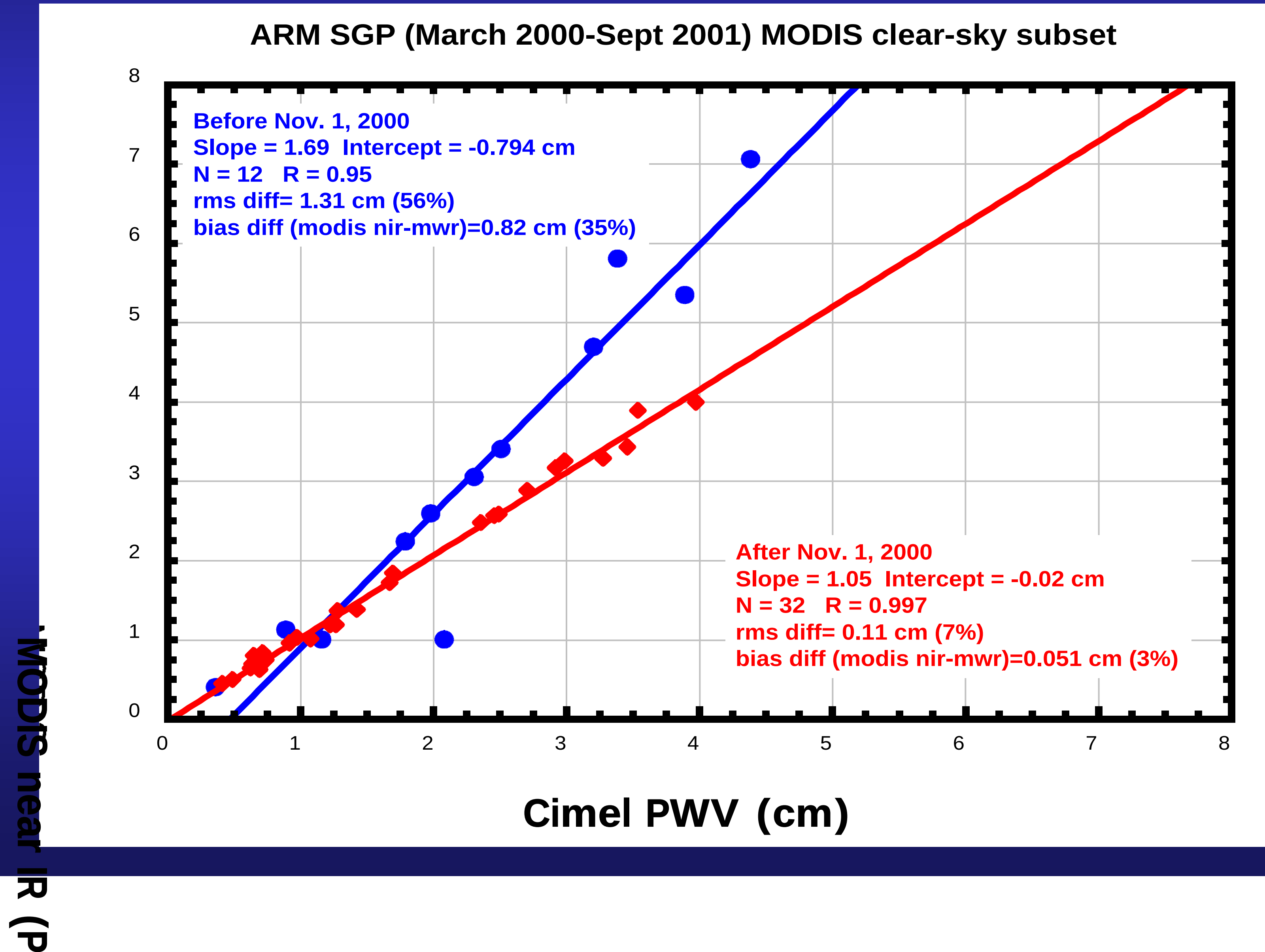
[If Cimel PWV processing used Giver corrected HITRAN database (which increased 940 nm line strengths by ~14%), then Cimel PWV decreases by about 14%.]

See Schmid et al. Comparison of columnar water-vapor measurements from solar transmittance methods. Applied Optics, Vol. 40, No. 12, 1886-1896 (2001).

MODIS near IR PWV comparison vs. Cimel

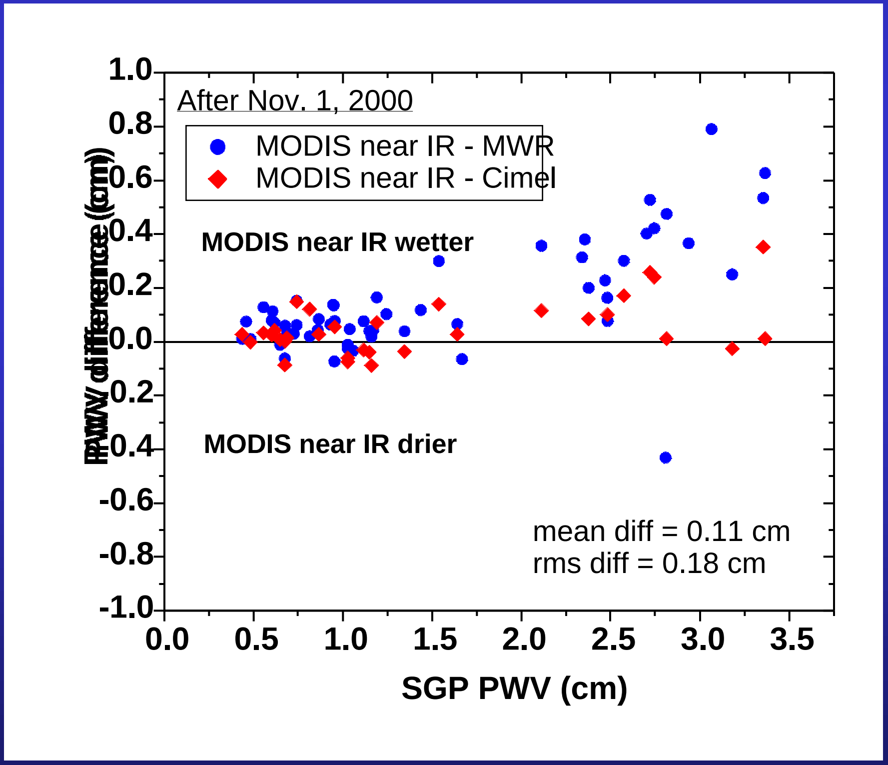
After Nov. 1, 2000

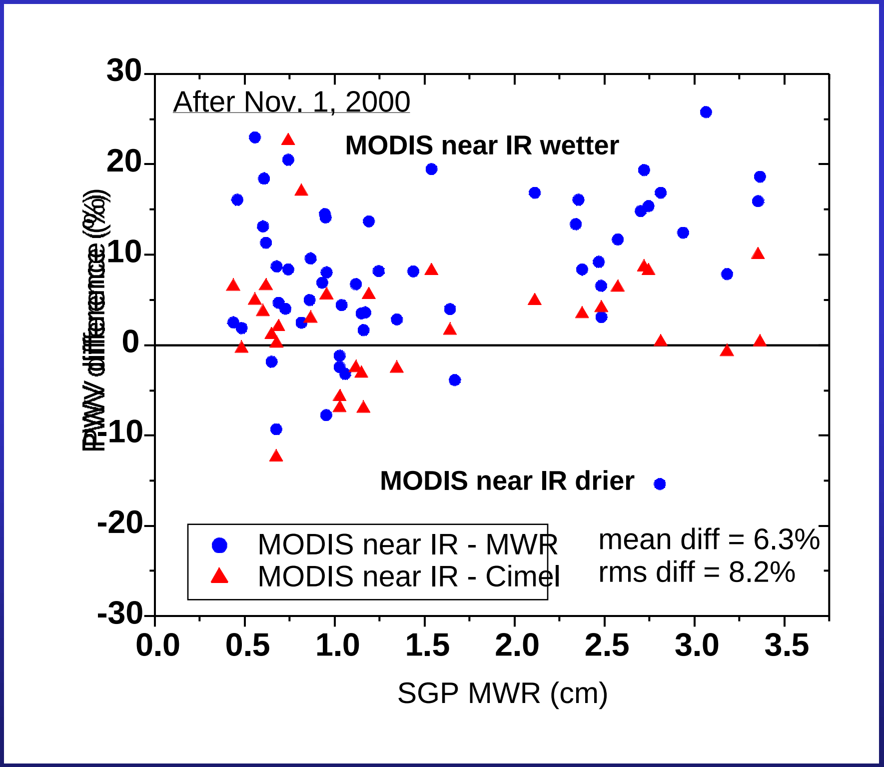
- bias difference decreases from 0.82 cm (35%) to 0.05 cm (3%)
- rms difference decreases from 1.3 cm (54%) to 0.11 cm (3%)



(MODIS near IR - SGP) PWV difference vs. PWV

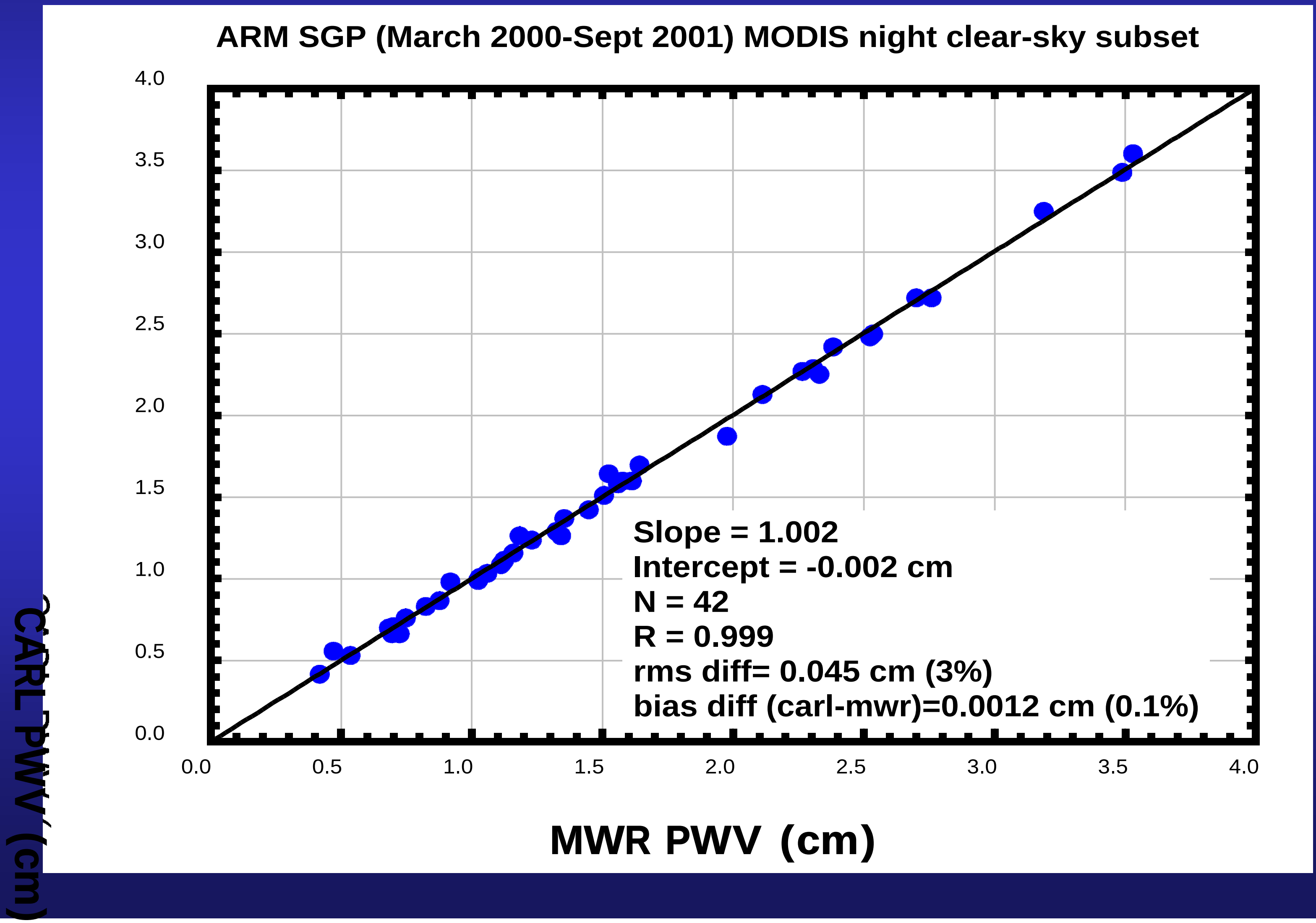
- MODIS near IR PWV about 5-15% higher than SGP MWR and Cimel PWV
- No systematic variations with PWV





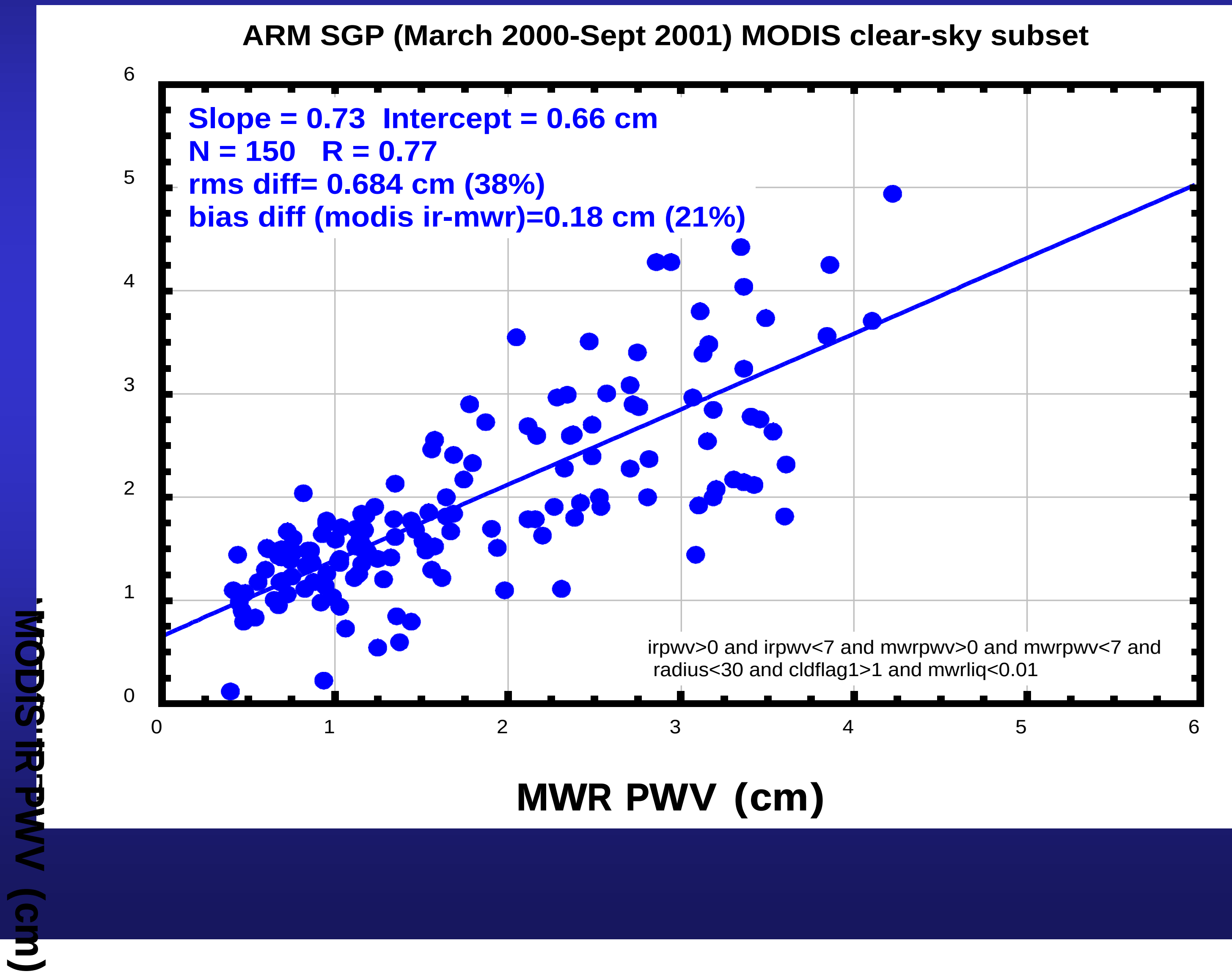
CART Raman Lidar water vapor measurements

- **Nighttime profiles extend through troposphere (0.06 – 10 km) permitting PWV retrievals**
- **Daytime profiles limited by background skylight (0.06 - ~ 3.5 km) – no PWV retrieved**
- **CARL calibrated so that CARL PWV matches MWR PWV**
- **CARL PWV has excellent long-term stability when compared with MWR**



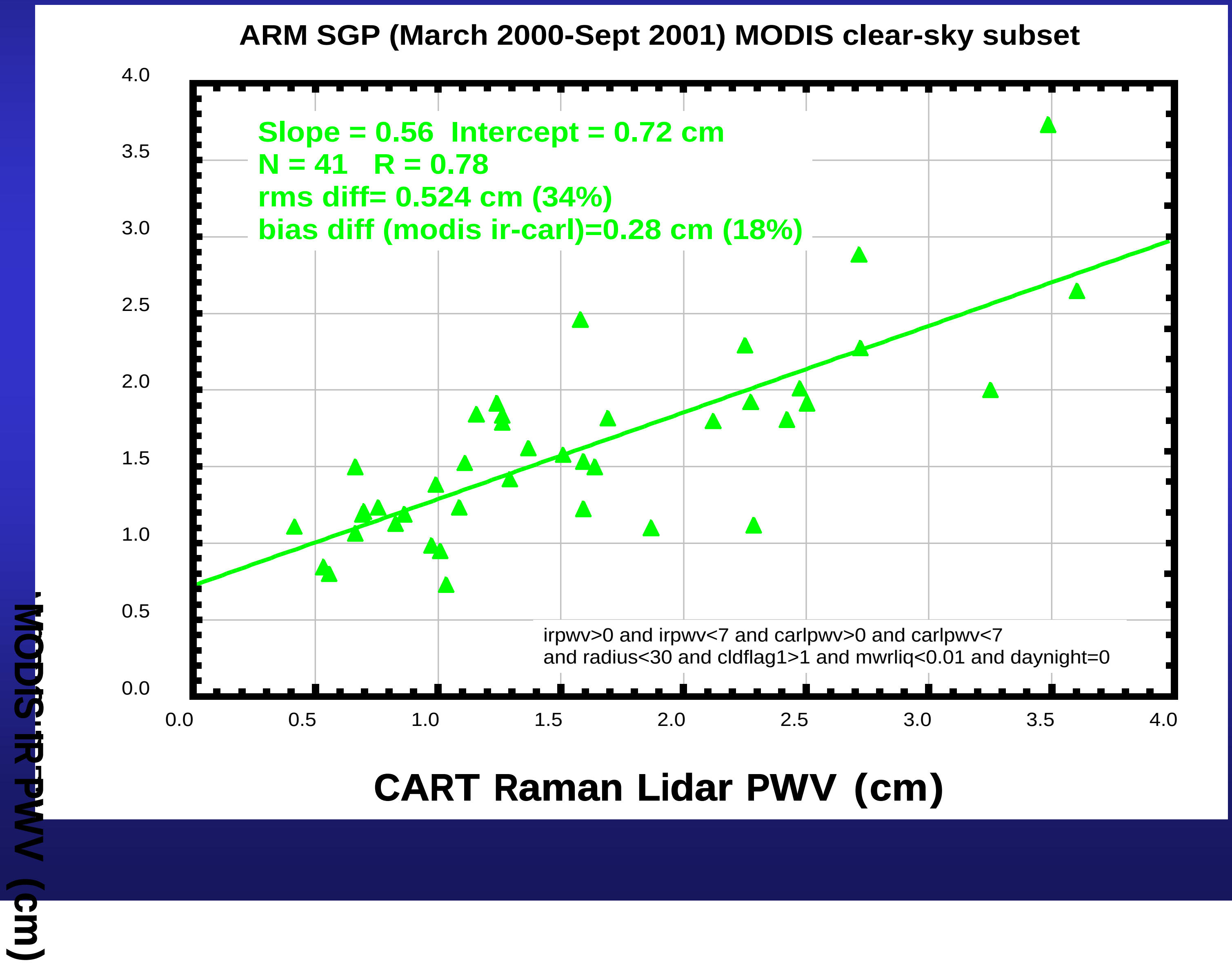
MODIS IR PWV vs. MWR PWV

- (daytime+nighttime) offset (intercept) = 6.8 mm
- bias difference ~ 2 mm (~20%) (MODIS IR wetter), rms difference 7 mm (~40%)



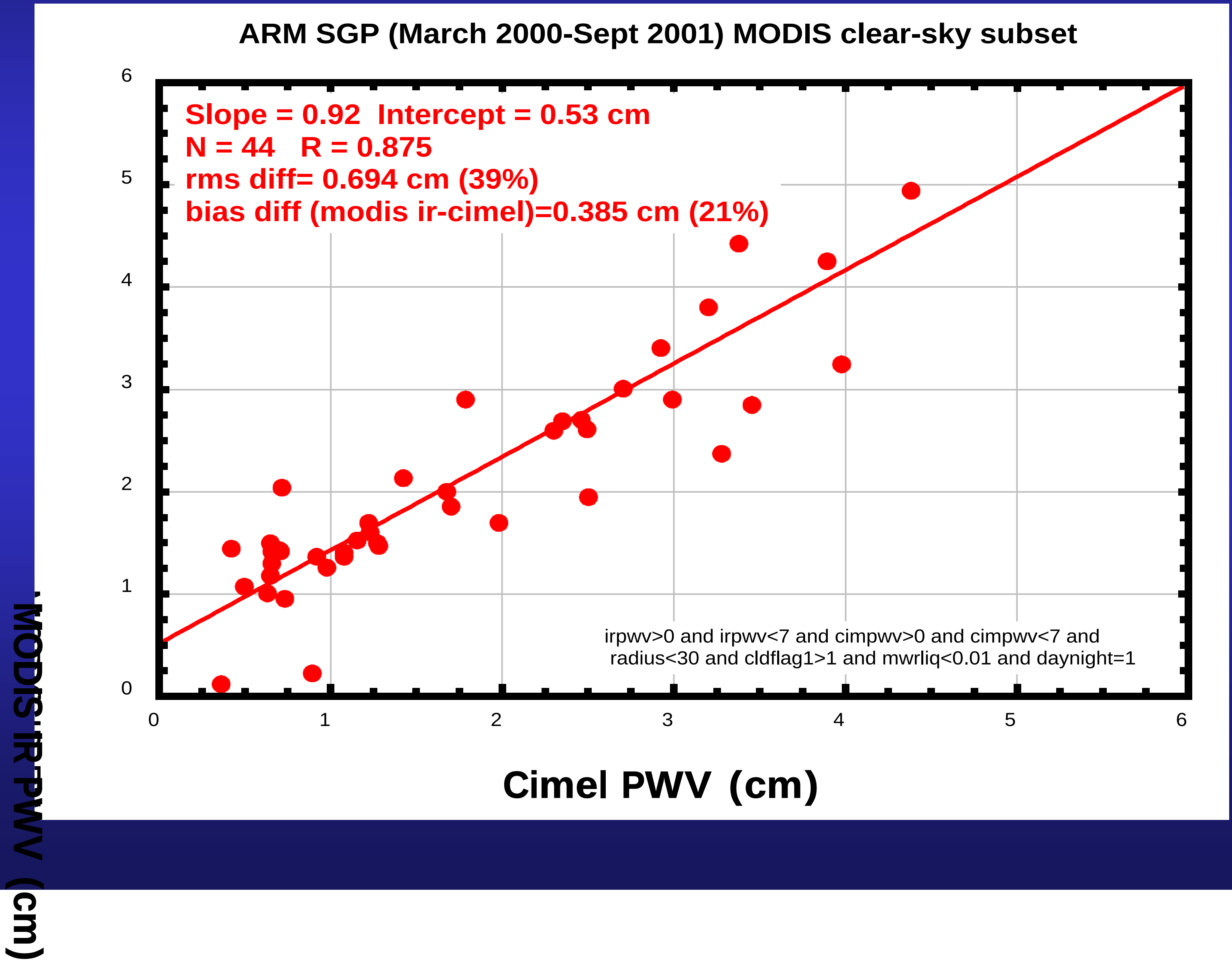
MODIS IR PWV vs. CARL PWV

- (nighttime) offset (intercept) = 7 mm
- bias difference ~ 3 mm (~20%) (MODIS IR wetter), rms difference 5 mm (~30%)



MODIS IR PWV vs. Cimel PWV

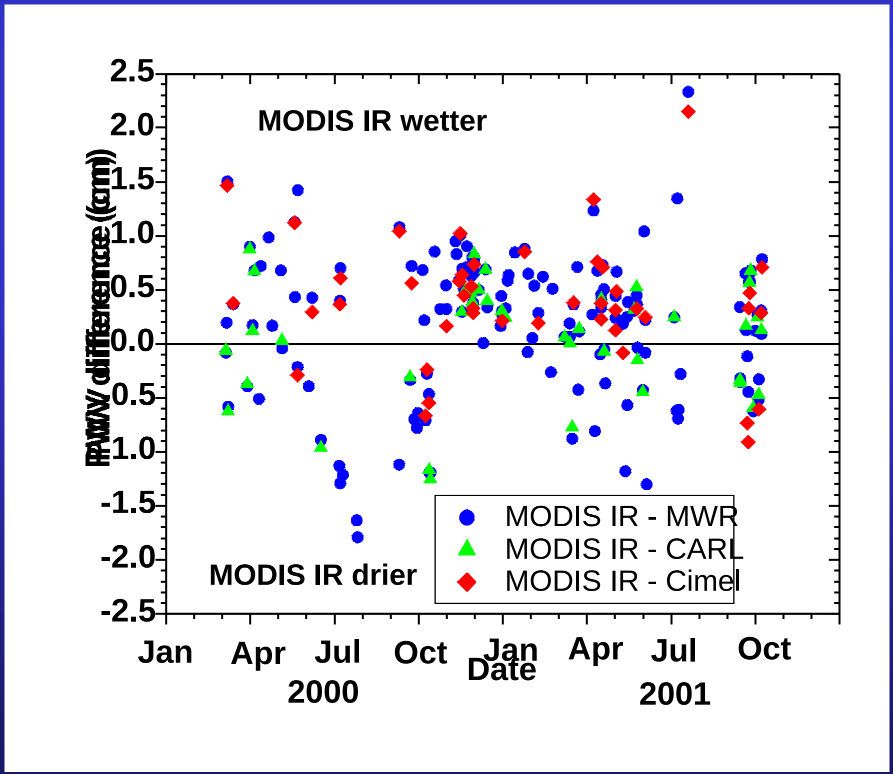
- (daytime) offset (intercept) = 5 mm
- bias difference ~ 4 mm (~20%) (MODIS IR wetter), rms difference 7 mm (~40%)



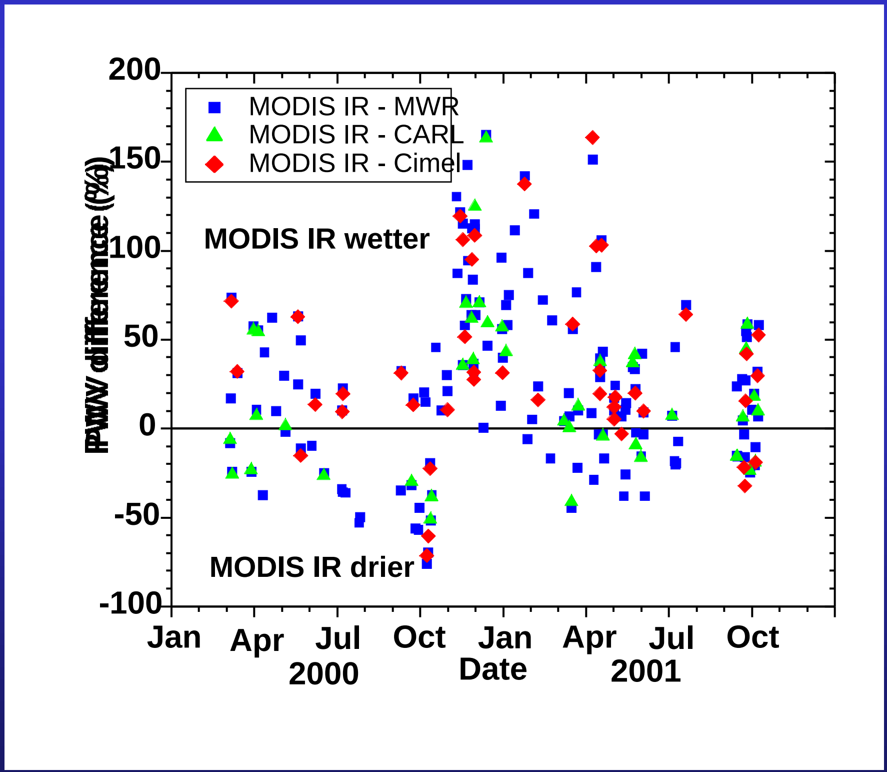
(MODIS IR - SGP) PWV difference vs. Date

- relative error increases in winter due to low PWV

Absolute differences

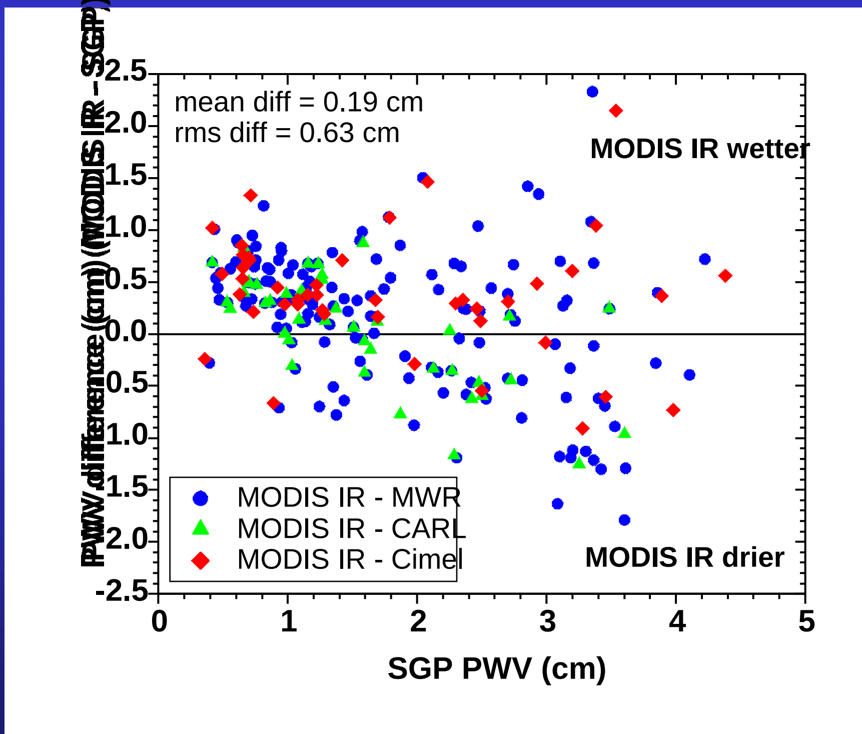


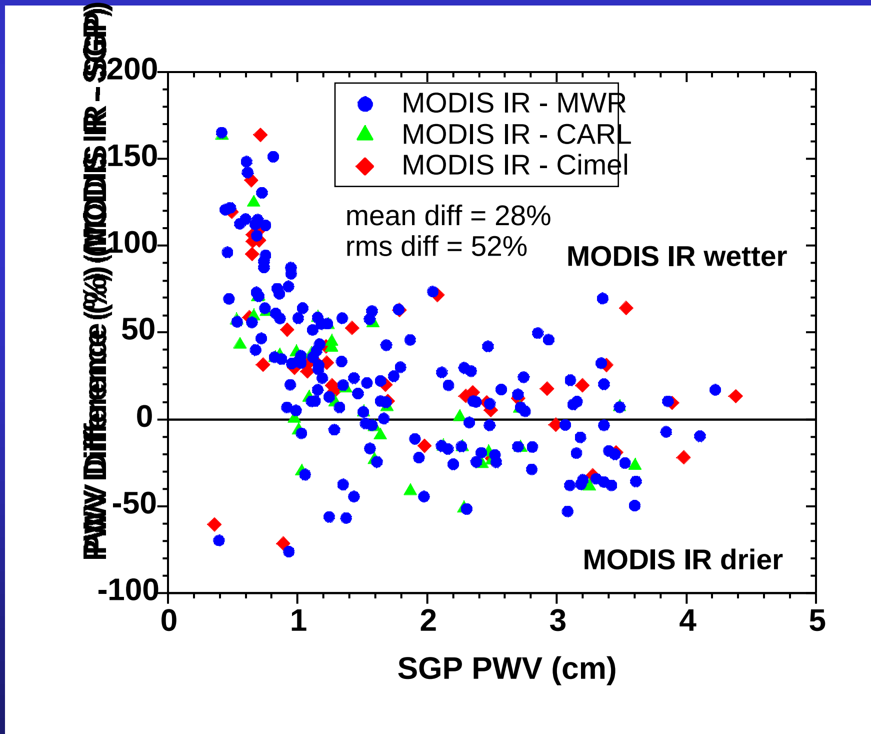
Relative differences



(MODIS IR - SGP) PWV difference vs. PWV

- **large relative error at low PWV due to MODIS IR PWV offset (floor around 5-7 mm)**
- **mean difference ~ 2 mm (~25%) (MODIS wetter), rms difference 6 mm (~50%)**

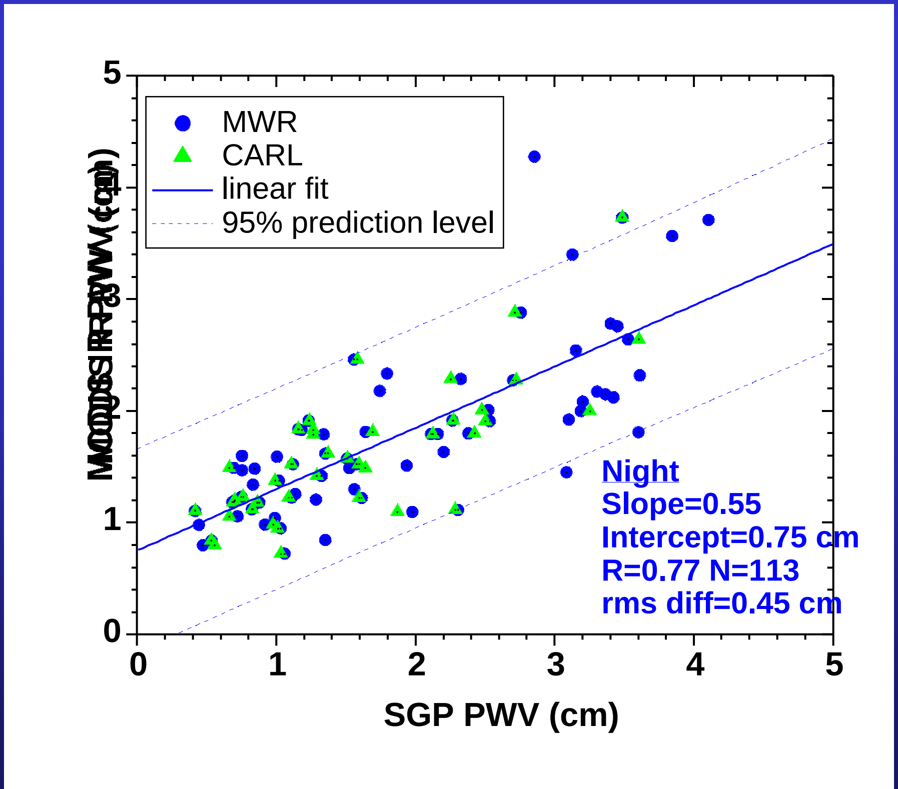




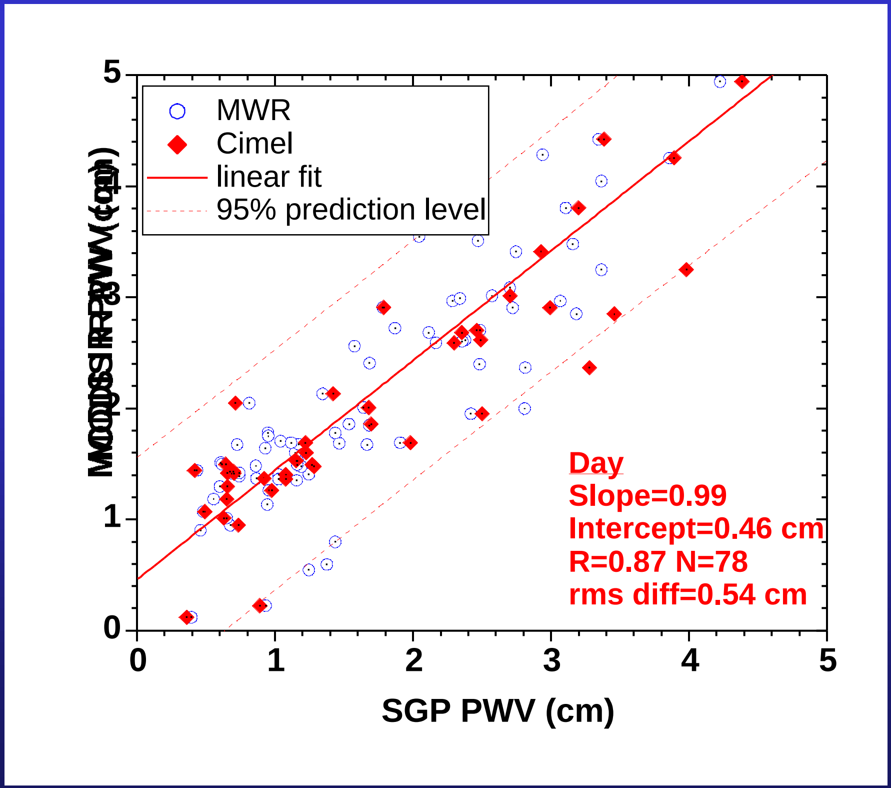
(MODIS IR - SGP) PWV daytime vs. nighttime performance

MODIS IR PWV has better agreement with SGP PWV for daytime measurements (smaller offset, increase in slope closer to unity, higher linear correlation)

Night



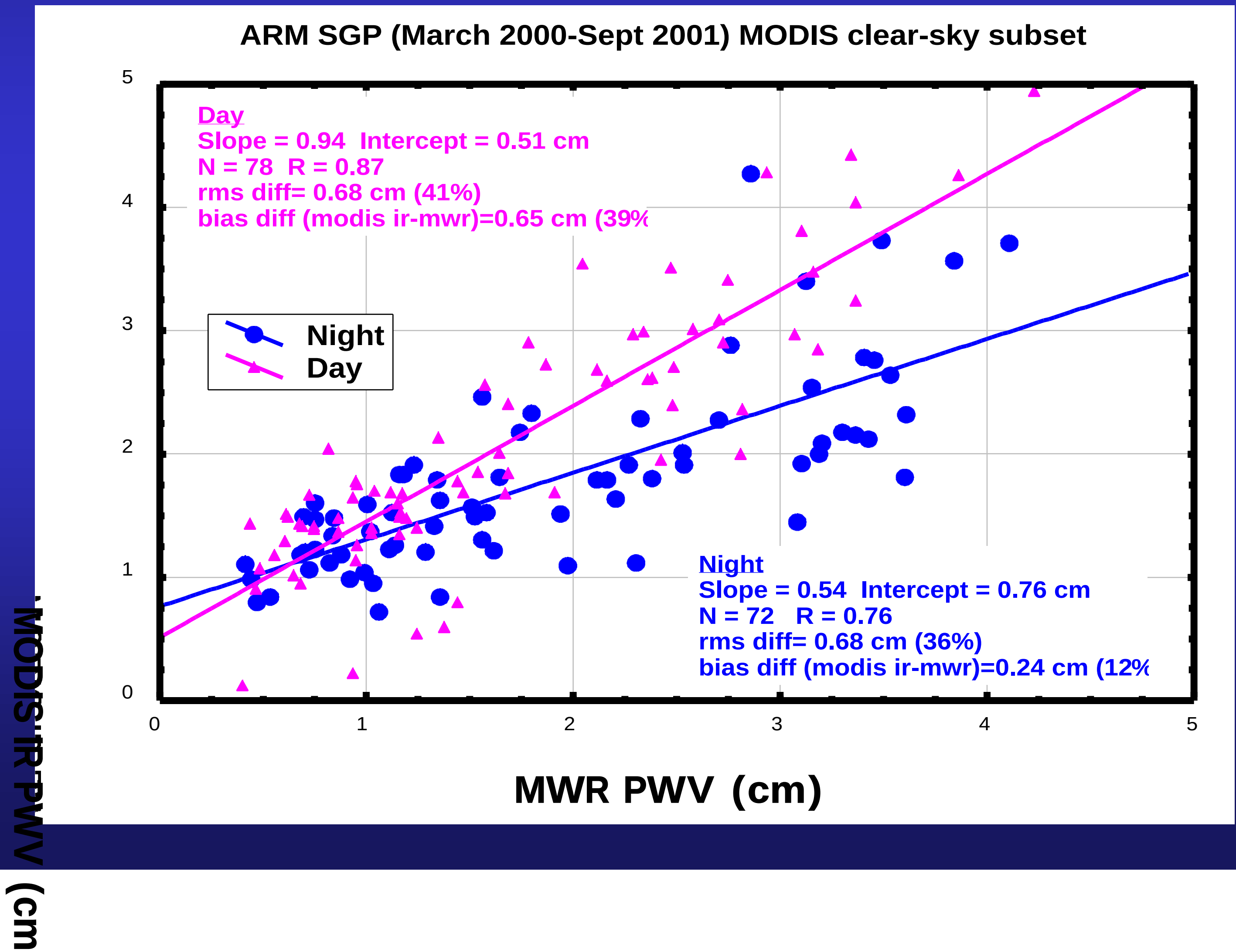
Day



(MODIS IR - SGP) PWV daytime vs. nighttime performance

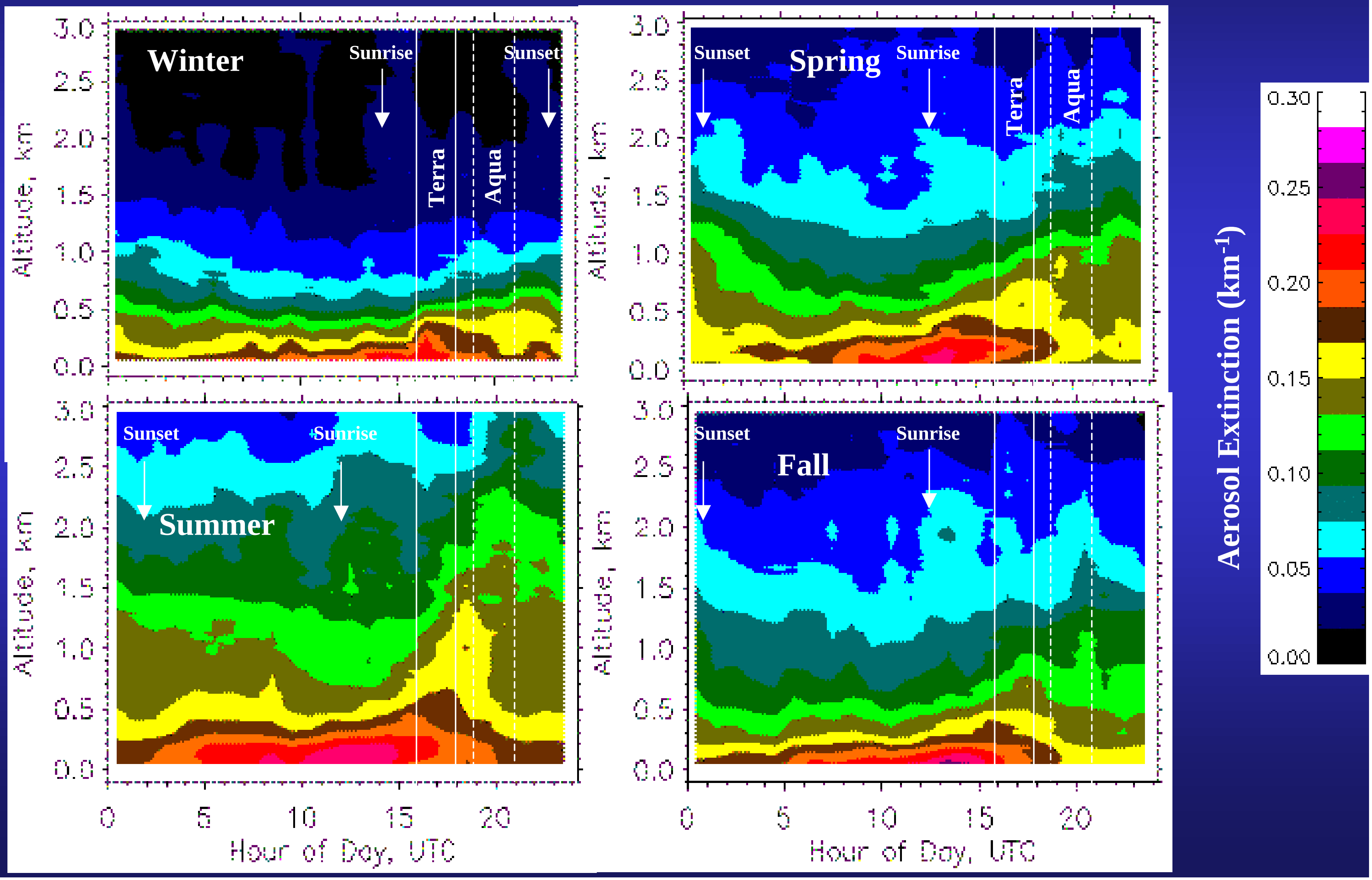
MODIS IR PWV has better agreement with SGP MWR PWV for daytime measurements (smaller offset, increase in slope closer to unity, higher linear correlation)

(This time used single instrument, MWR, to look at diurnal changes)



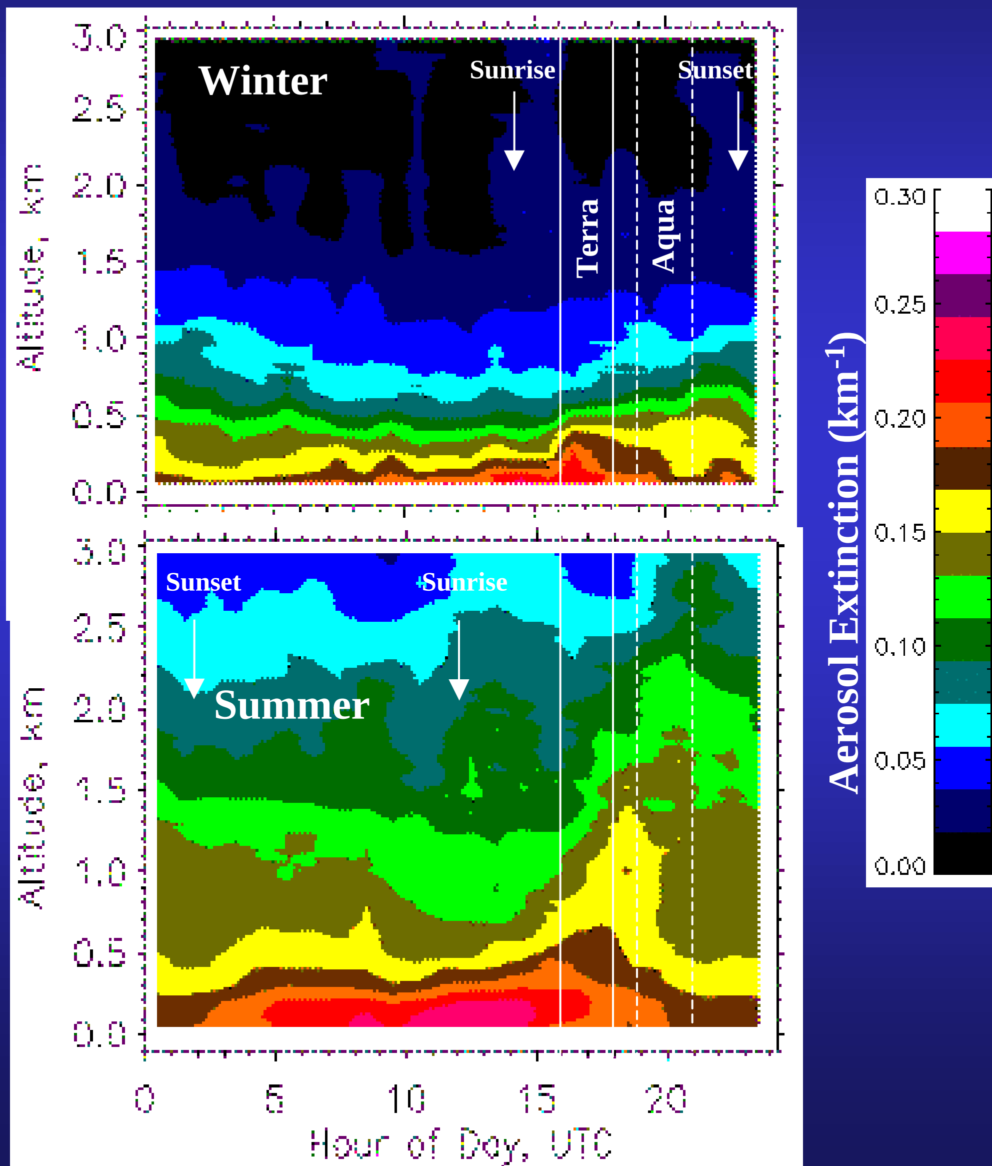
Average Diurnal Variation of Aerosol Extinction Profiles

- **CARL aerosol extinction profiles averaged over 837 days between March 98 - October 01**
- **Higher extinction concentrated over smaller vertical extent at night**

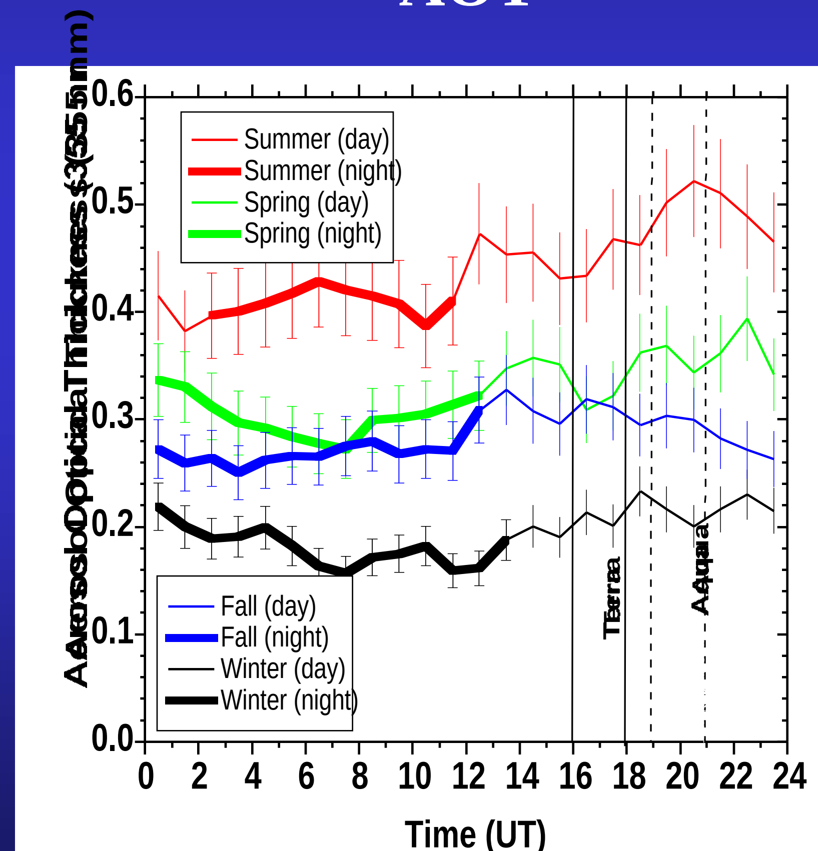


Average Diurnal Variation of Aerosol Extinction Profiles and AOT

- Large changes in vertical profile; smaller changes in AOT (st. dev ~ 10%)

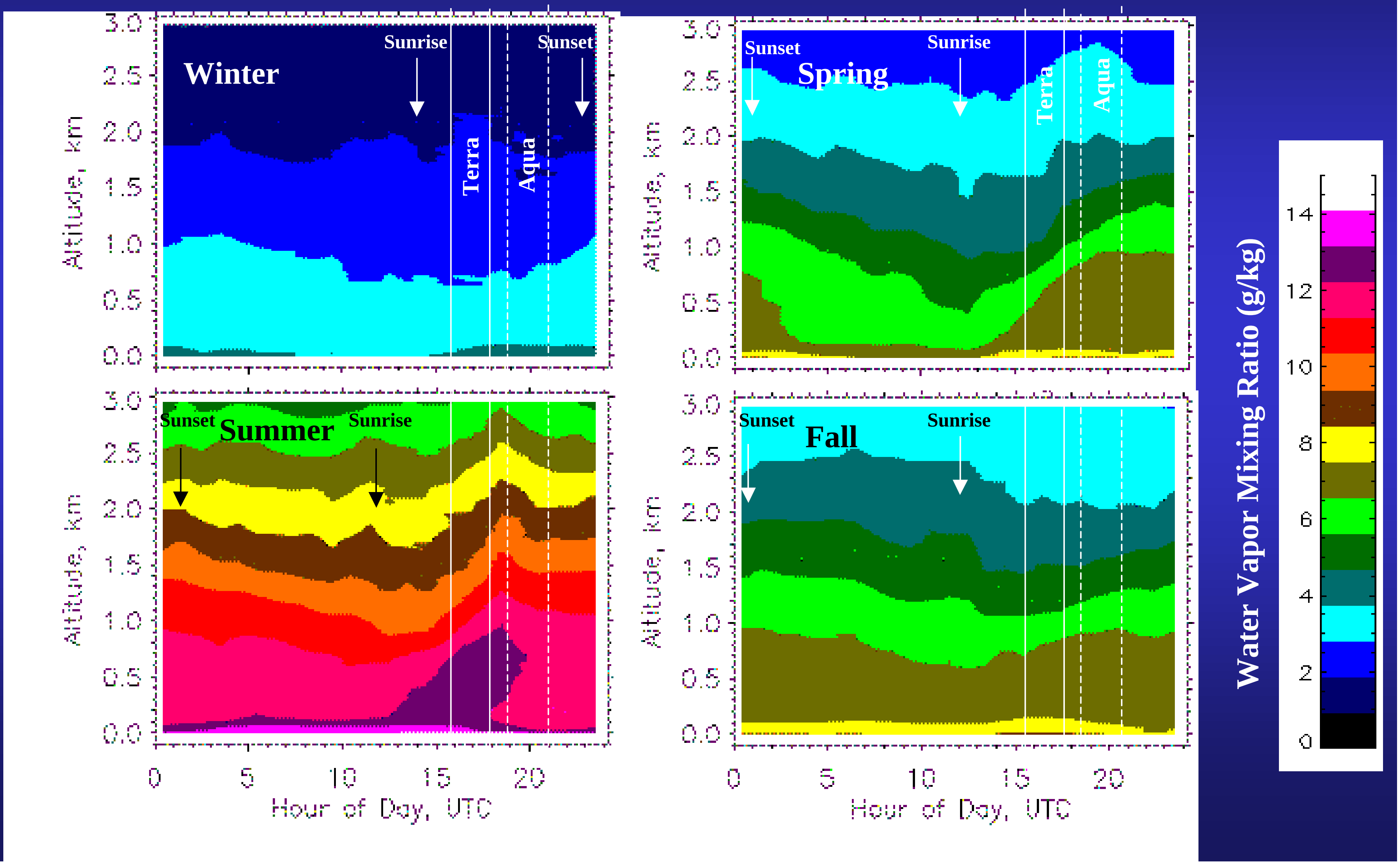


AOT



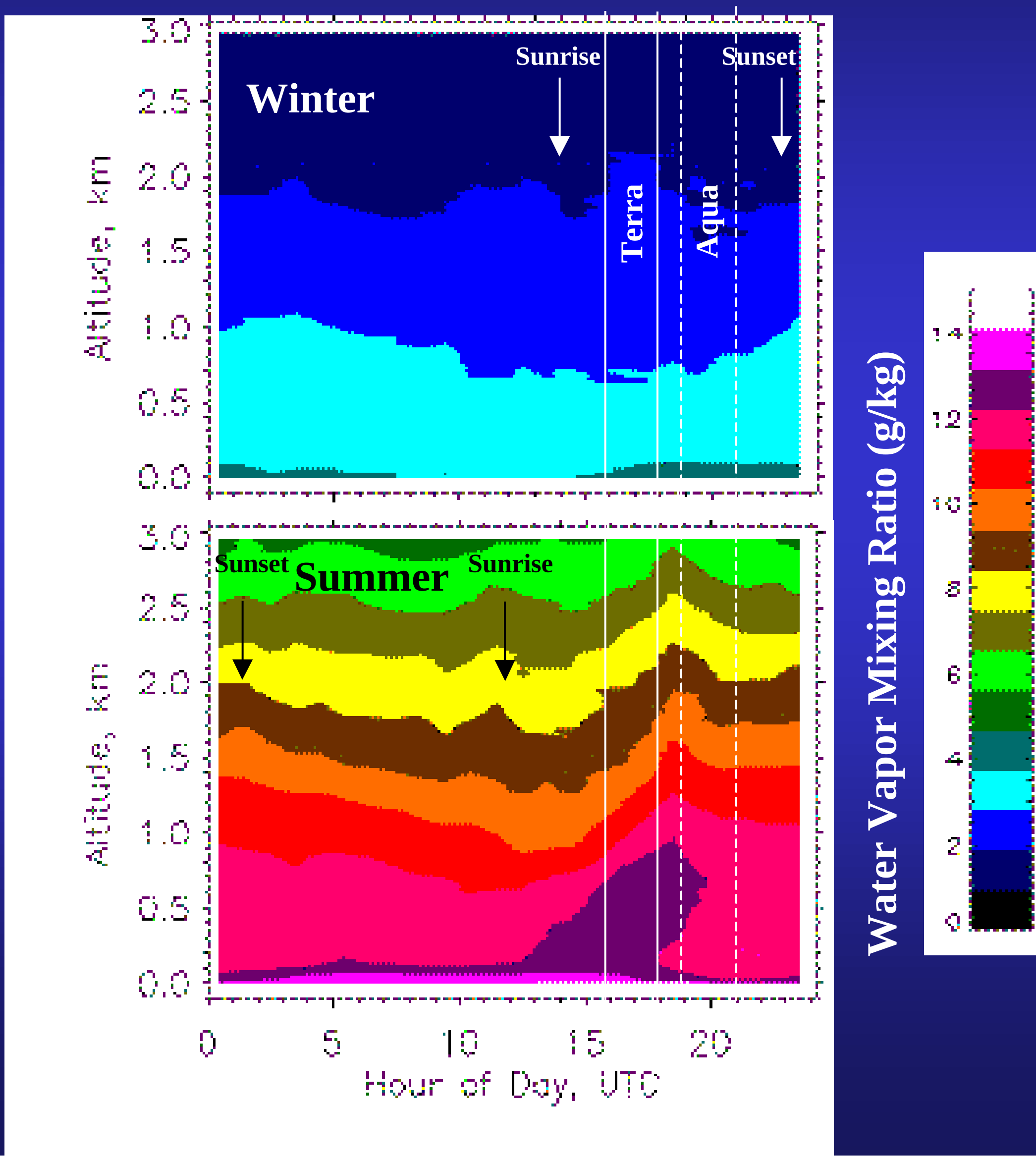
Average Diurnal Variation of Water Vapor Profiles

- generally smaller diurnal changes than aerosol extinction near the surface
- larger diurnal changes in spring and summer near top of mixed layer

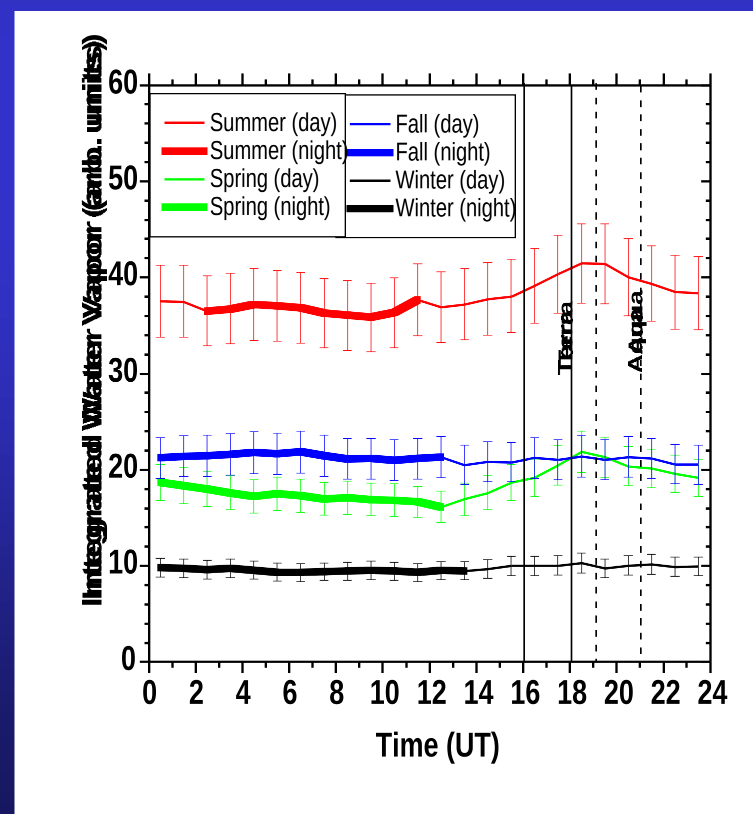


Average Diurnal Variation of Water Vapor Profiles

- smaller diurnal changes in profiles and integrated water vapor (st. dev ~3-5%)

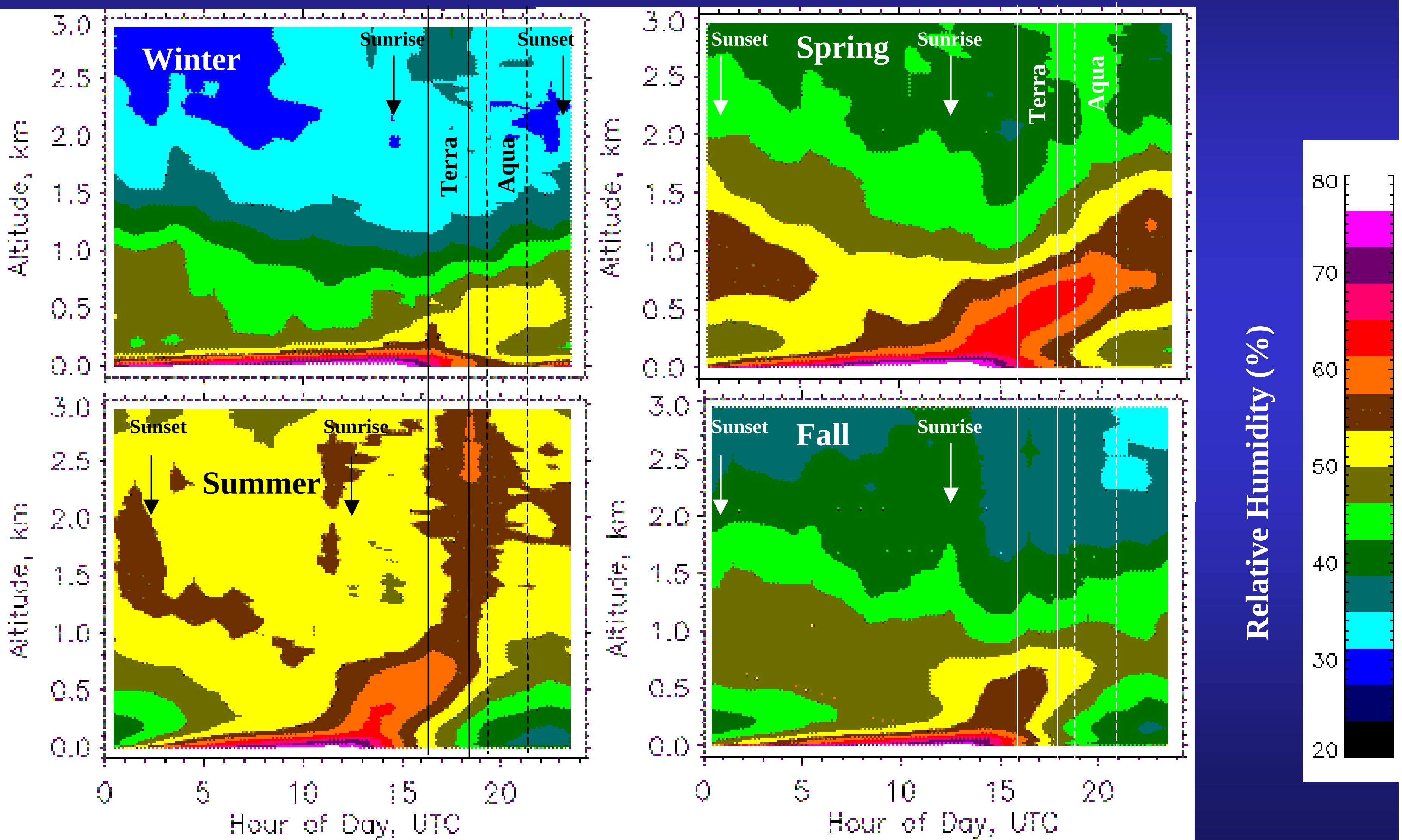


Integrated water vapor



Average Diurnal Variation of Relative Humidity Profiles

- RH computed using CARL water vapor, AERI+model temperatures
- Increase in aerosol extinction near surface at night correlated to RH
- Terra, Aqua measurements occur when RH (and aerosol size, composition?) vary with z

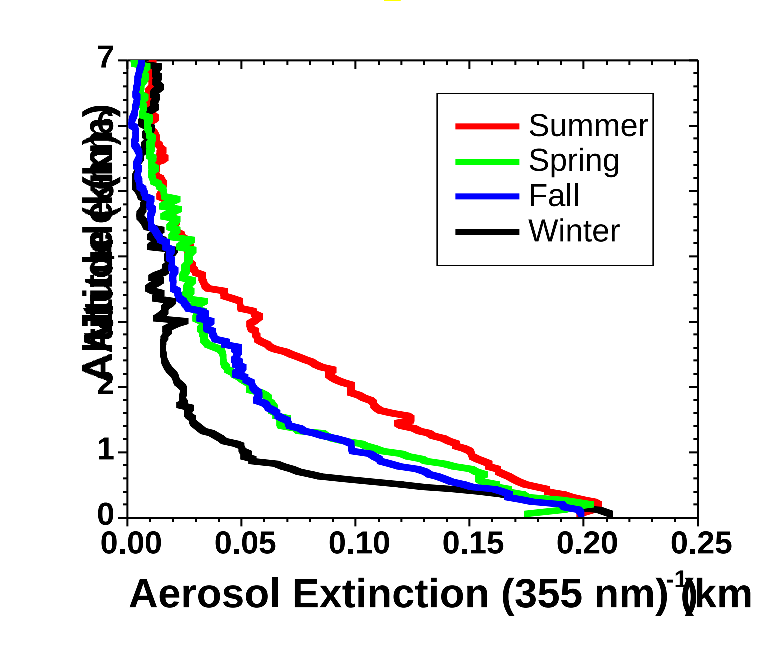


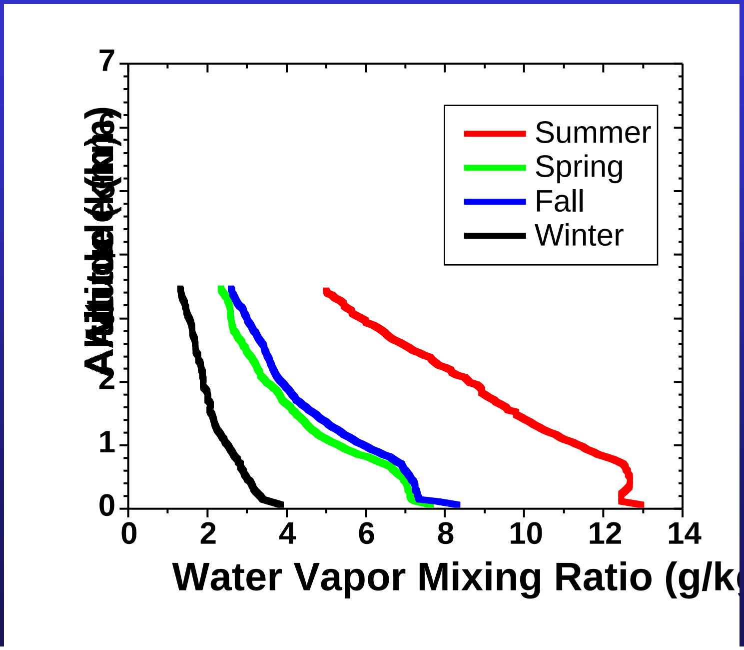
Average Profiles at time of Terra Overpass

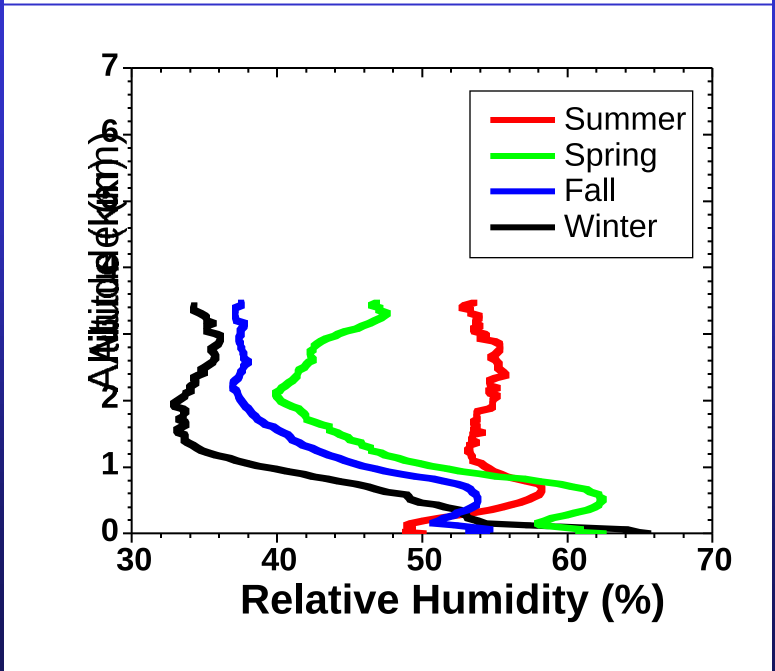
- Aerosol extinction:
  - profile shape varies with season
  - scale height varies with season and AOT

- Water Vapor
  - profile shape and scale height are constant

See Turner, Ferrare, Brasseur, GRL, 28, 4441-4444, 2001.







DOE ARM Proposed Aerosol Experiment

- <u>Aerosol IOP (Intensive Operations Period) (~May, 2003 at SGP)</u>

  Objectives:

  - **Diffuse Flux closure**

    Use new and additional measurements of aerosol absorption and extinction to accurately constrain aerosol absorption to resolve differences between measured and modeled diffuse radiation

  - **CCN**

    Investigate relationship between CCN number concentrations at the surface and cloud base, and determine whether profiles of aerosol extinction and RH can be used to determine cloud nucleating properties just below cloud base

  - **AOT closure**

    Characterize routine (Raman, MPL) lidar and aircraft in situ profiling measurements of aerosol scattering and extinction and how aerosol humidification factor varies with altitude

  Measurements:

  - **Use one (possibly two) instrumented aircraft**
  - **Additional surface aerosol and radiation measurements**
  - **Possible coordination with DOE Tropospheric Aerosol Program (TAP) (i.e. chemistry)**

<u>Potential MODIS Terra, Aqua validation/science opportunity</u>

Summary

- Aerosol Optical Thickness (AOT)
  - low range of AOT (0-0.3) hampers full evaluation and gives large rms differences
  - MODIS AOT (470 nm) higher by 30-40% for all AOT, 10-20% for AOT>0.1
  - MODIS AOT (660 nm) not well correlated to SGP AOT for low AOT
  - comparisons show results generally fall within MODIS AOT uncertainties
- Precipitable Water Vapor (PWV)
  - before Nov. 1, 2000 MODIS near-IR biased high by about 35-40%
  - after Nov. 1, 2000 MODIS near-IR biased high by ~10%
  - relatively small (10-20%) rms differences
  - MODIS IR has apparent offset (PWV floor around 5-7 mm)
  - MODIS IR biased high 2-4 mm(~10-20%) due to offset, rms diff ~ 6 mm (50%)
  - MODIS IR daytime retrievals in better agreement with SGP than nighttime
- Vertical Variability of Aerosols
  - Raman lidar profiles show diurnal variability in aerosol, water vapor profiles
  - diurnal variability of AOT ~ 10% (st. dev), PWV ~ 3-5% (st. dev)
  - average aerosol extinction profiles vary with season and AOT
  - average water vapor profiles have constant shape and scale with PWV
- Proposed DOE ARM Aerosol IOP (SGP, ~ May 2003)
  - Diffuse radiation (aerosol absorption) and AOT closure, CCN
  - Potential for joint Terra/Aqua validation/science

Recent Publications

Turner, D.D., W.F. Feltz, and R.A. Ferrare, Continuous water vapor profiles from operational ground-based active and passive remote sensors, *Bull. Amer. Meteor. Soc.*, 81, 1301-1317, 2000.

Kato, S., M.H. Bergin, T.P. Ackerman, T.P. Charlock, E.E. Clothiaux, R.A. Ferrare, R.N. Halthore, N. Laulainen, G.G. Mace, J. Michalsky, and D.D. Turner, A comparison of the aerosol optical thickness derived from ground-based and airborne measurements, *J. Geophys. Res.*, 105, No. D11, 14701-14717, 2000.

Peppler, R.A., C.P. Bahrmann, J.C. Barnard, J.R. Campbell, M.-D. Cheng, R.A. Ferrare, R.N. Halthore, L.A. Heilman, D.L. Hlavka, N.S. Laulainen, C.-J., Lin, J.A. Ogren, M.R. Poellot, L.A. Remer, K. Sassen, J.D. Spinhirne, M.E. Splitt, D.D. Turner, ARM Southern Great Plains Site Observations of the Smoke Pall Associated with the 1998 Central American Fires, *Bull. Amer. Meteor. Soc.*, 81, 2563-2592, 2000.

Whiteman, D.N., G. Schwemmer, D. O'C. Starr, K.D. Evans, B. Demoz, T. Berkoff, S.H. Melfi, M. Cadirola, and G. Jedlovec, "The use of Raman Lidar in Cloud Studies", in Advances in Laser Remote Sensing, Selected Papers Presented at the 20th International Laser Radar Conference (ILRC), Vichy, France, 10-14 July 2000, A. Dabas, C. Loth, and J. Pelon, eds., Ecole polytechnique, France, pp. 271-274, 2001.

Turner, D.D., R.A. Ferrare, L.A. Heilman, T. T. Tooman, A Two Year Climatology of Water Vapor and Aerosols in the Lower Troposphere Measured by a Raman Lidar, in Advances in Laser Remote Sensing, Selected Papers Presented at the 20th International Laser Radar Conference (ILRC), Vichy, France, 10-14 July 2000, A. Dabas, C. Loth, and J. Pelon, eds., Ecole polytechnique, France, pp. 309-312, 2001.

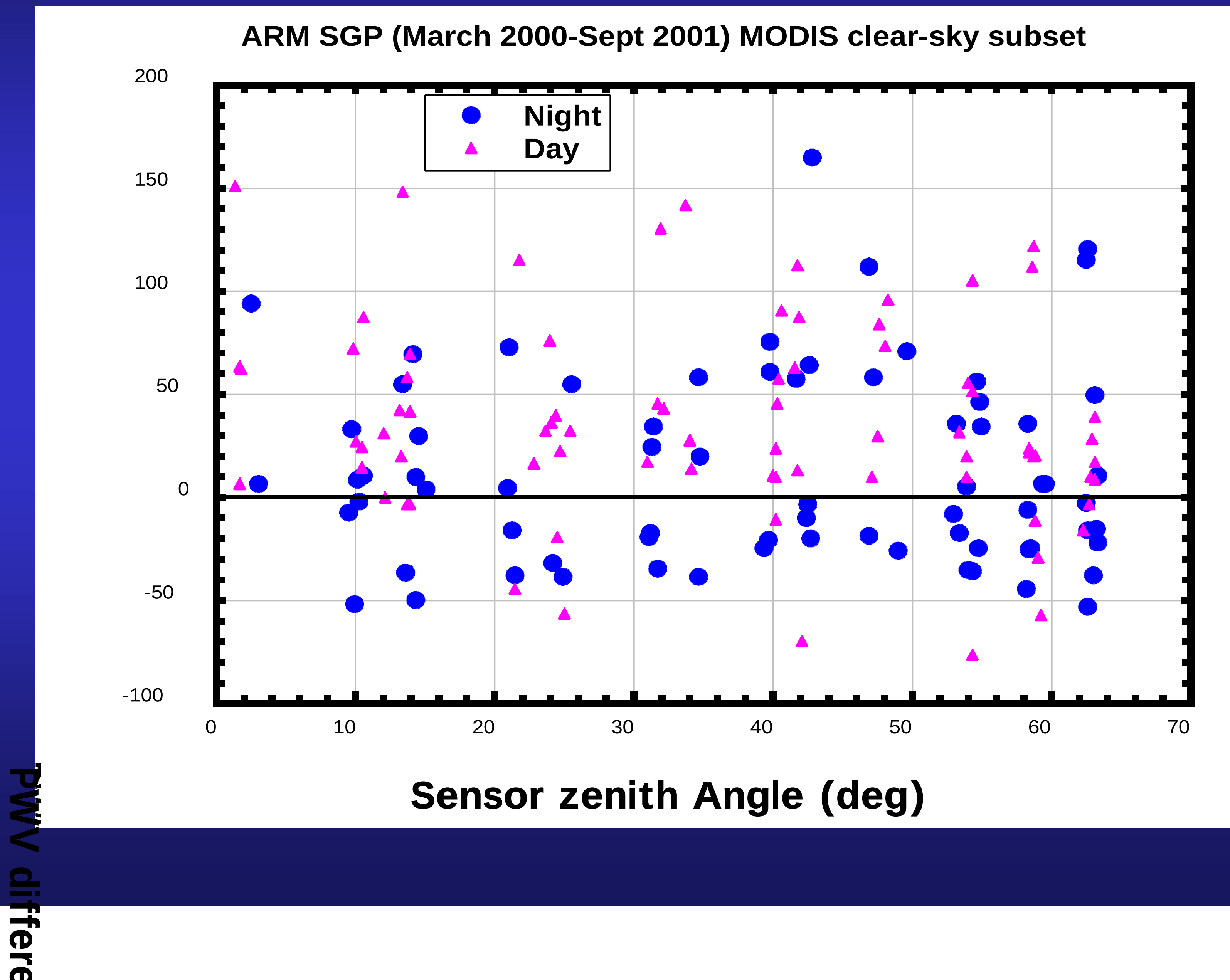
Whiteman, D. N., K. D. Evans, B. Demoz, D. O'C. Starr, D. Tobin, W. Feltz, G. J. Jedlovec, S. I. Gutman, G. K. Schwemmer, M. Cadirola, S. H. Melfi, F. J. Schmidlin, 2001: Raman lidar measurements of water vapor and cirrus clouds during the passage of hurricane Bonnie, *J. of Geophys. Res*., 106, No. D6, 5211-5225.

Ferrare, R.A., D.D. Turner, L.A. Heilman, O. Dubovik, and W. Feltz, Raman Lidar Measurements of the Aerosol Extinction-to-Backscatter Ratio Over the Southern Great Plains, *J. Geophys. Res.*, 106, 20333-20347, 2001.

Turner, D.D., R.A. Ferrare, and L.A. Brasseur, Average aerosol extinction and water vapor profiles over the Southern Great Plains, Geophys. Res. Letters, 28, 4441-4444, 2001.

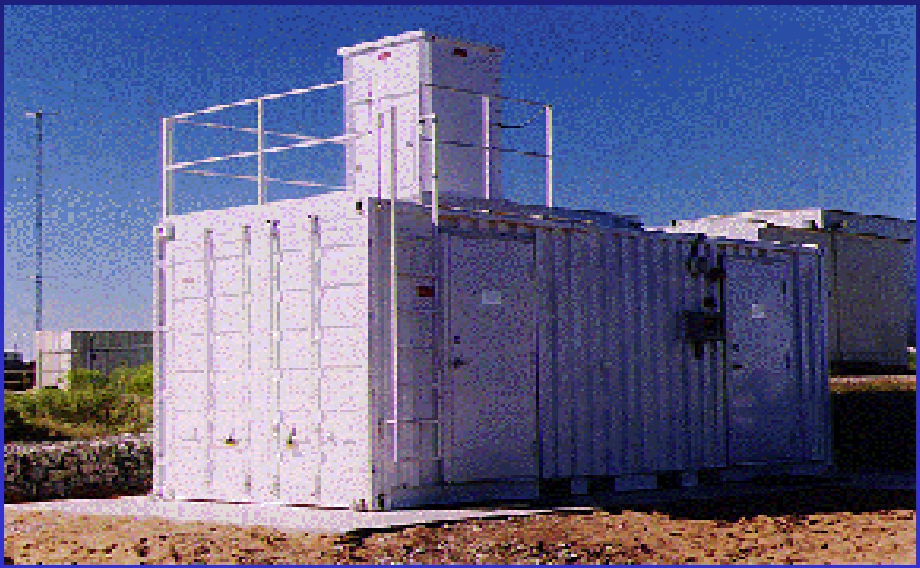
Turner, D.D., R.A. Ferrare, L.A. Heilman, W.F. Feltz, and T. Tooman, Automated Retrievals of Water Vapor and Aerosol Profiles over Oklahoma from an Operational Raman Lidar, *J. Atmos. Oceanic Tech.*, in press, July, 2001.

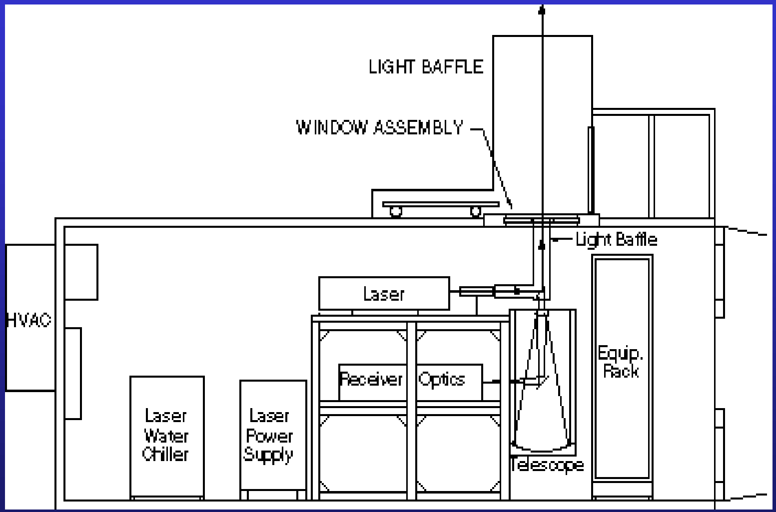
(MODIS IR - SGP) PWV difference vs. sensor zenith angle



Southern Great Plains (SGP) CART Raman Lidar (CARL)

- Nearly Continuous Operation
- Nd:YAG (355 nm) (day/night)
  - 12 W
- 61 cm telescope
- Wavelengths
  - Rayleigh/Aerosol (355 nm)
  - Depolarization (355 nm)
  - Raman water vapor (408 nm)
  - Raman nitrogen (387 nm)
- 39 meter range resolution
- low, high sensitivity channels
- measures
  - water vapor and aerosol profiles
  - precipitable water vapor and aerosol optical thickness
  - aerosol and cloud depolarization

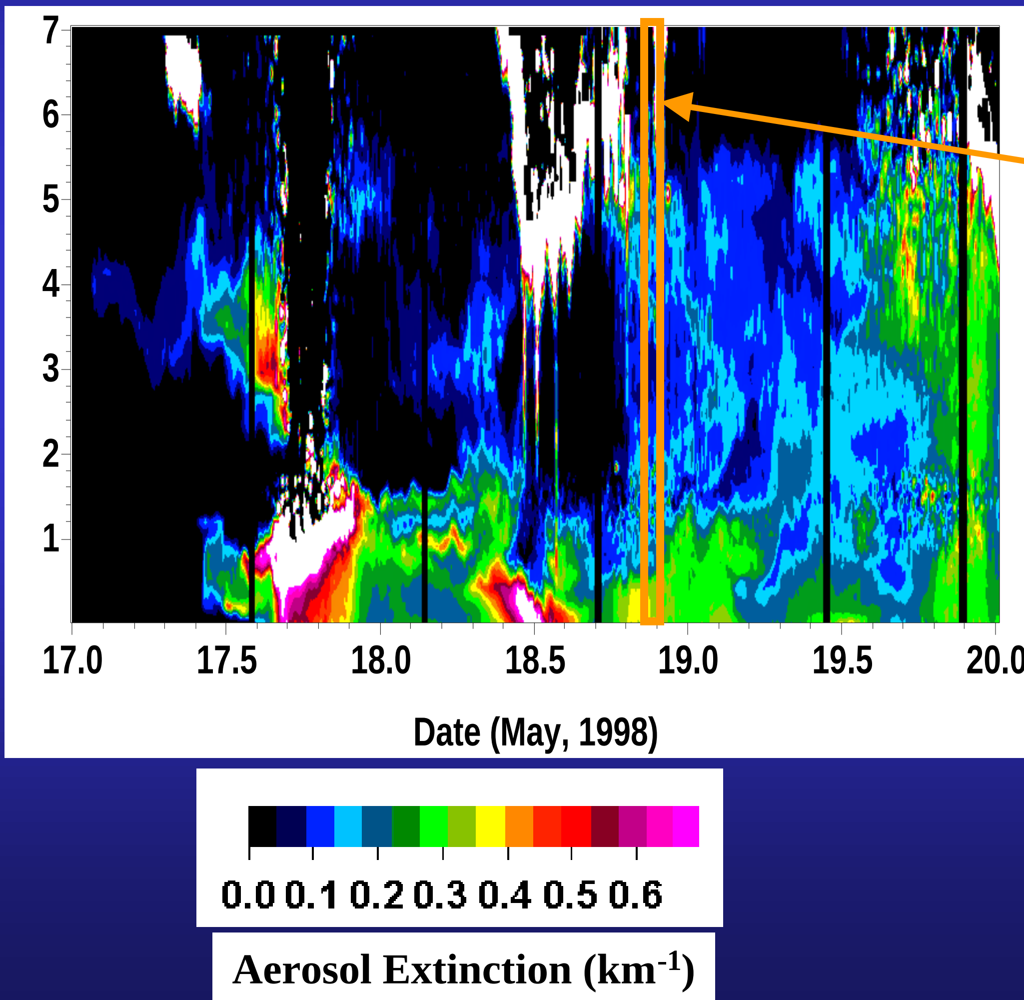


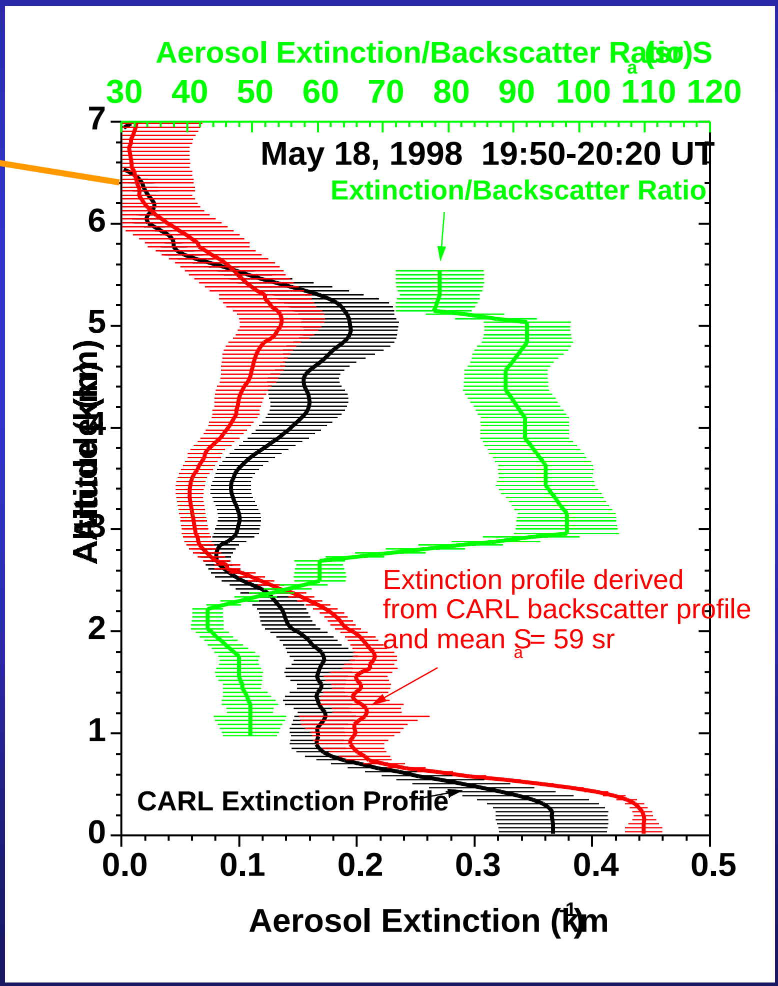


Additional information: http://www.arm.gov/docs/instruments/static/rl.html

Raman lidar observations of the aerosol vertical variability

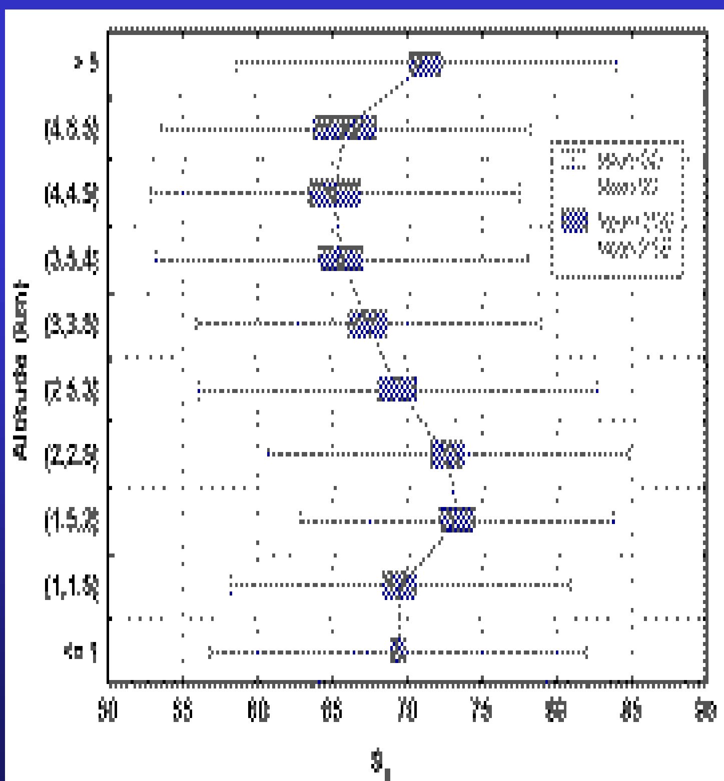
- measures vertical variability in aerosol extinction/backscatter (S_a)
- variability due to changes in size, composition of aerosols

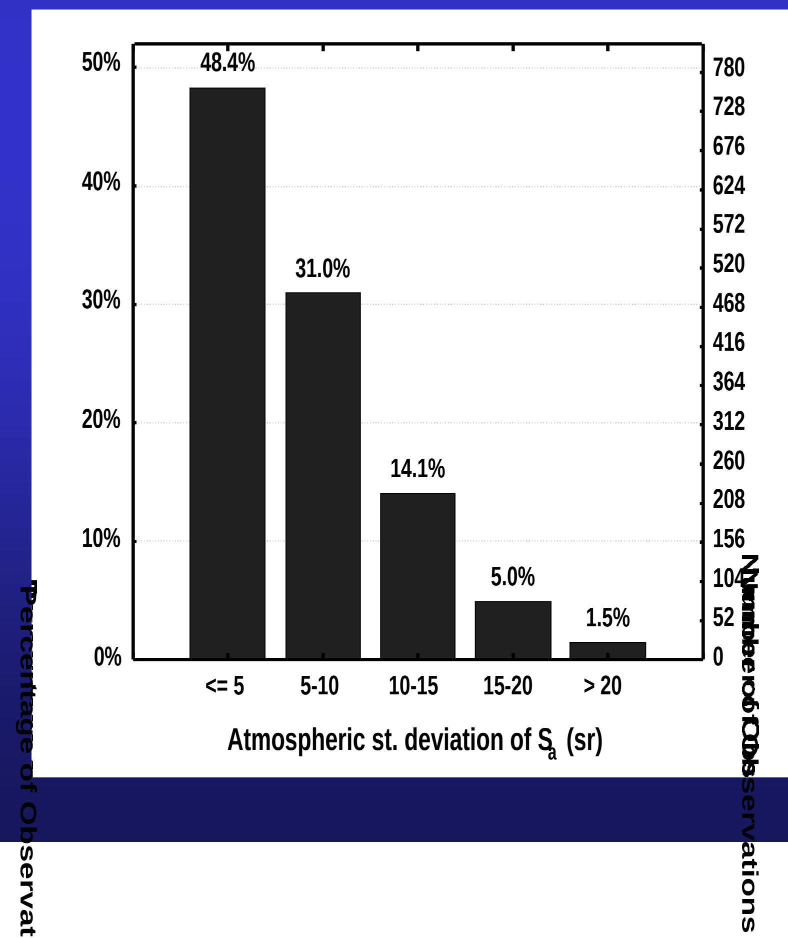




Raman lidar measurements of aerosol extinction/backscatter ratio S_a

- Average values show increase at top of BL, then a slight decrease with altitude
- Large (>20% or >10 sr) variations in S_a vertical profile occur about 20% of time

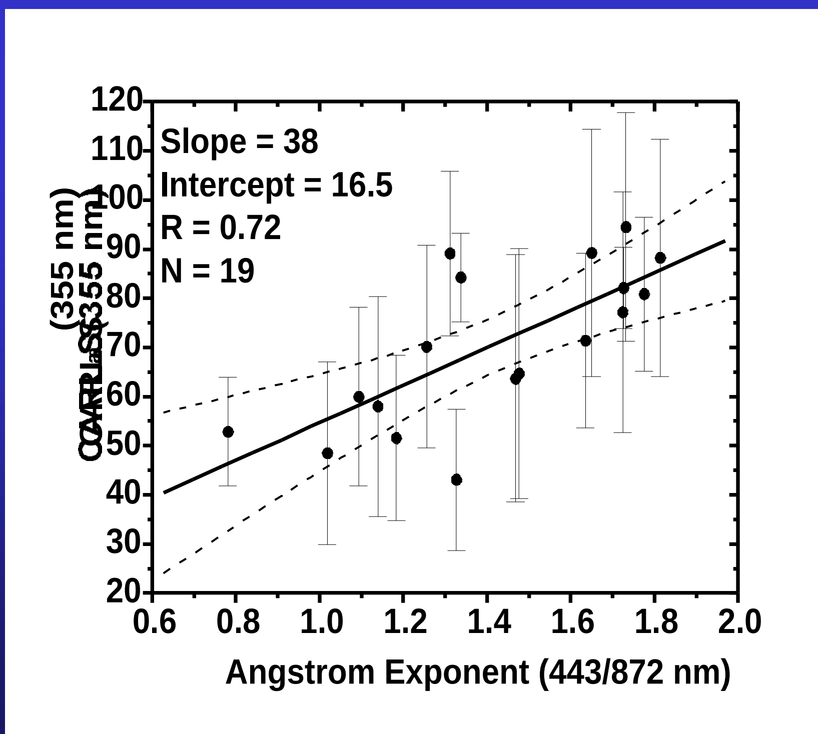


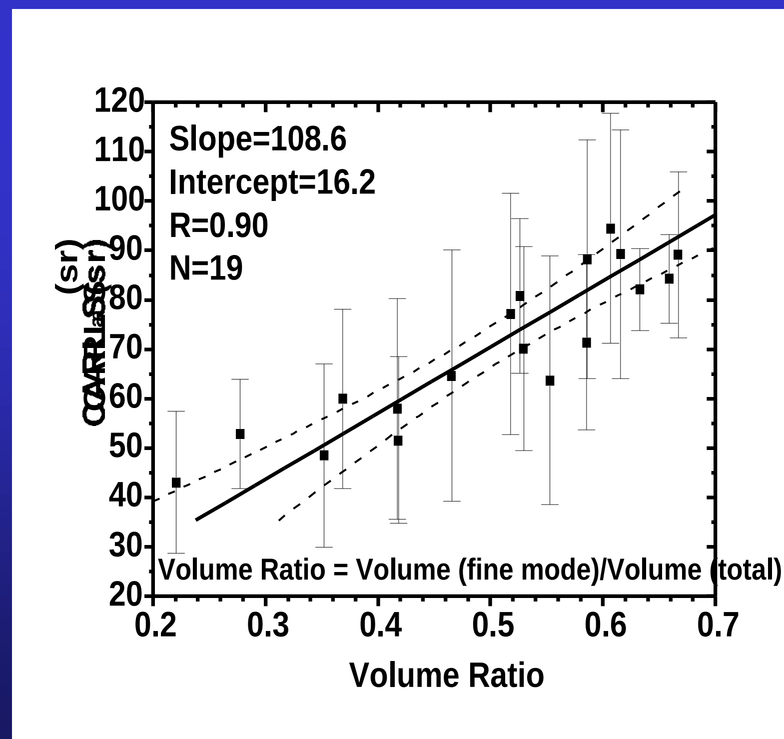


Comparison of Raman lidar S_a with Cimel aerosol measurements

- Sa increases with accumulation mode aerosol
- limited to cases with small Sa vertical variability and large AOT (>0.4)

How does Sa profile correlate with IAP measurements of
- Angstrom exponent profile
- single scattering albedo profile



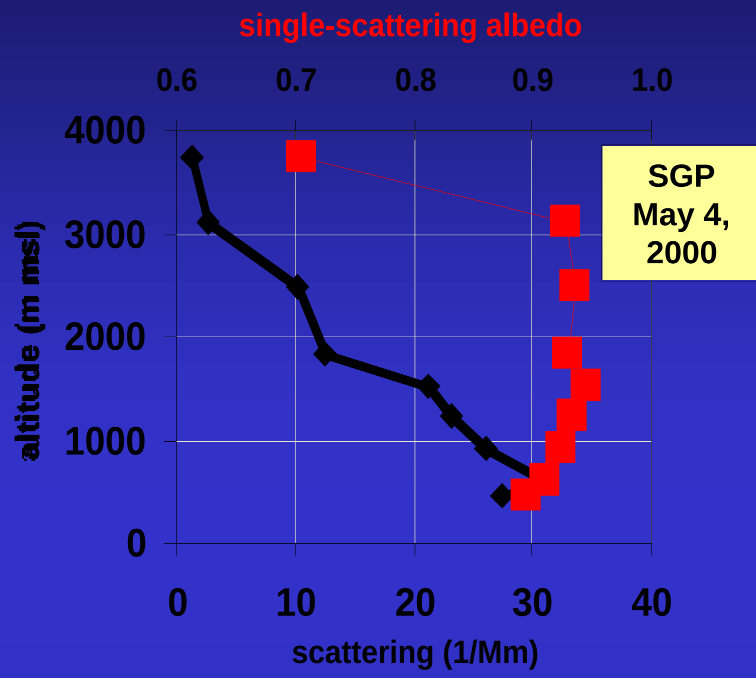


DOE ARM In-Situ Aerosol Profiling

Objective: Obtain a statistically-significant data set of vertical distribution of aerosol properties

Measurements: aerosol scattering and absorption, plus chemical composition, above a similarly instrumented surface site

2-3 profiles/week for 1 year



Sample Inlet

Port view of rack

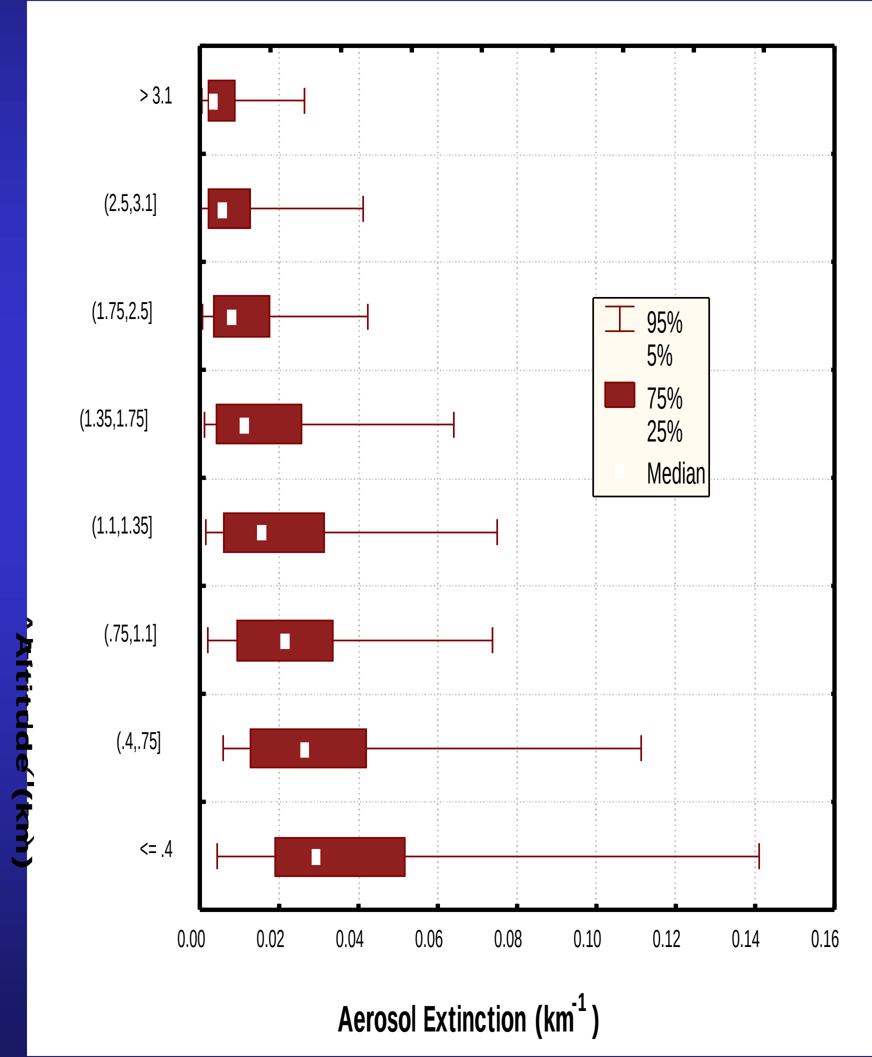
John Ogren, Betsy Andrews
NOAA/CMDL

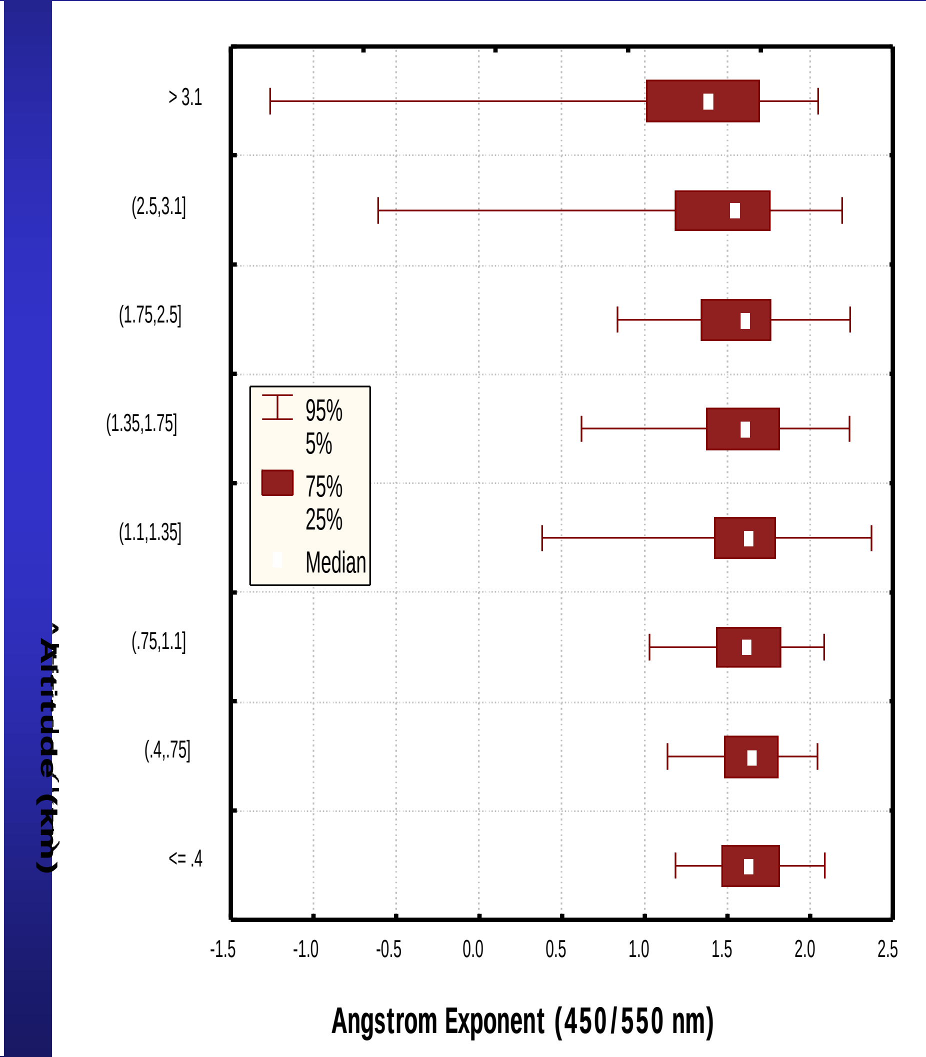
Summary of IAP Flight Hours

Flight period	March 25 – December 31, 2000
Total days	98 flight days/ 280 day period
Total flights	104 flights
Total flight time	215 hours
Average flight duration	2.1 hours
# complete profiles -over CART site -with SGP data	96 75 93

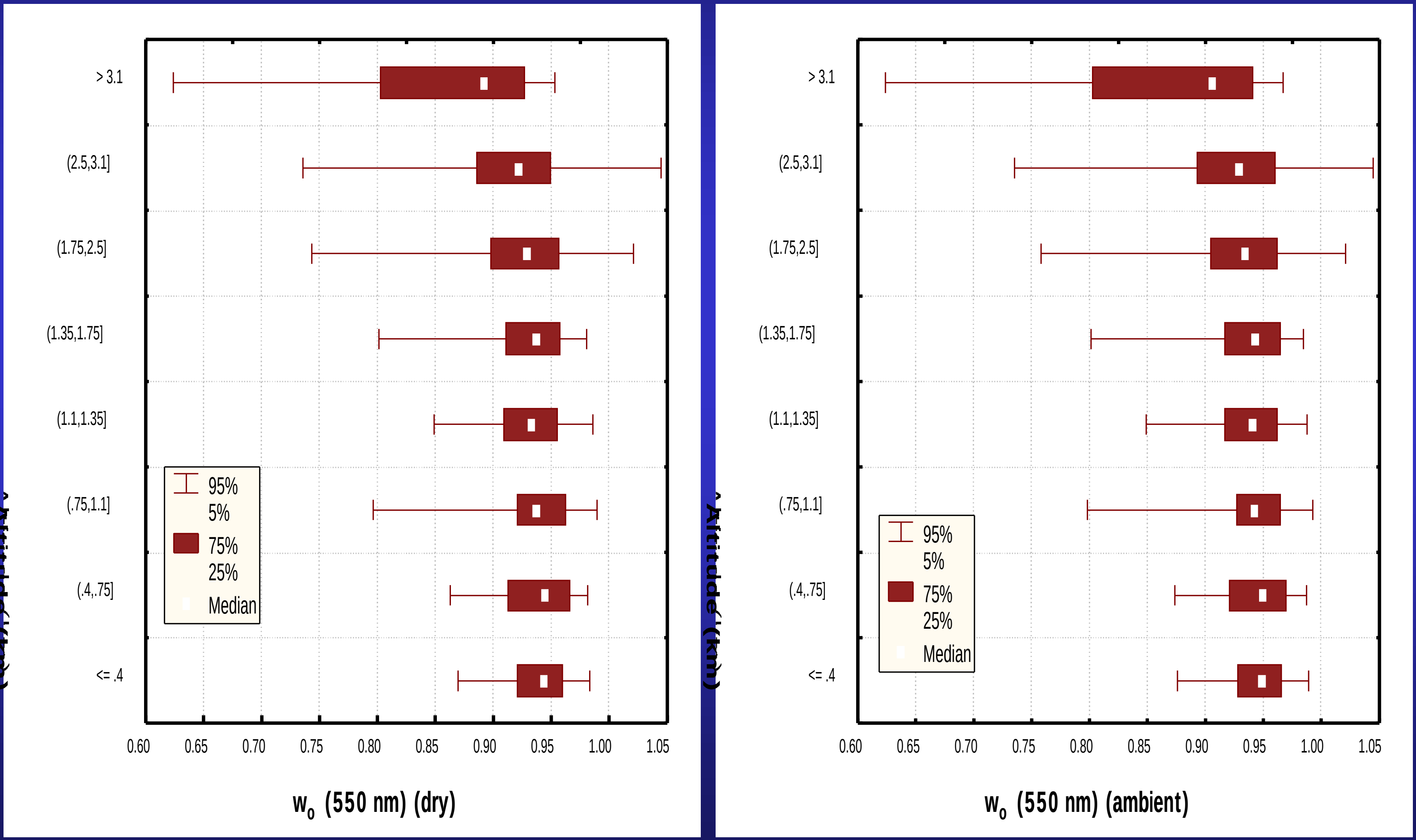
John Ogren
Betsy Andrews
NOAA/CMDL

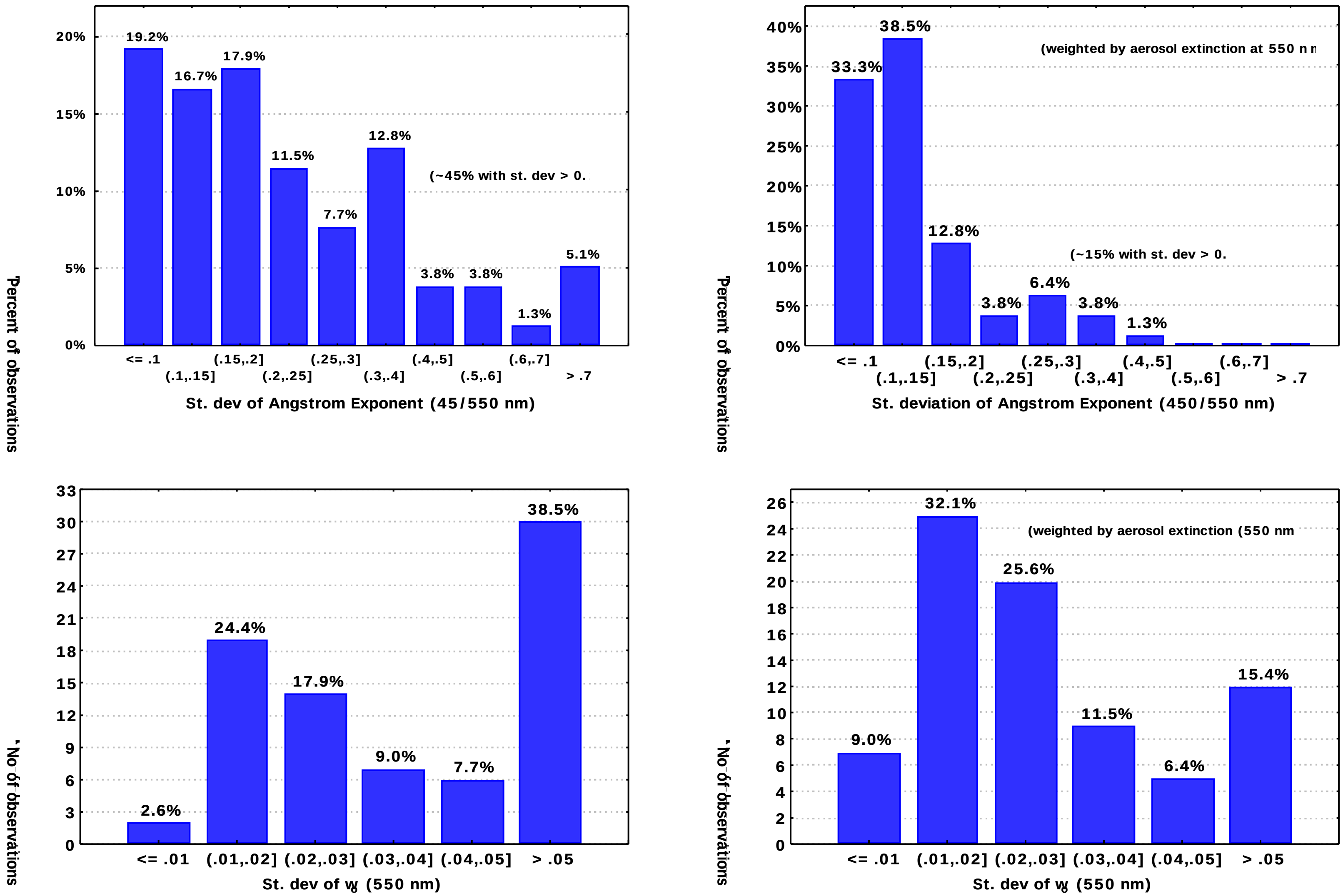
SGP IAP measurements





SGP IAP measurements





Percent of observations
20%
15%
10%
5%
0%
19.2%
16.7%
17.9%
11.5%
7.7%
12.8%
3.8%
3.8%
1.3%
5.1%
(~45% with st. dev > 0.
<= .1
(.1,.15]
(.15,.2]
(.2,.25]
(.25,.3]
(.3,.4]
(.4,.5]
(.5,.6]
(.6,.7]
> .7
St. dev of Angstrom Exponent (45/550 nm)
Percent of observations
40%
35%
30%
25%
20%
15%
10%
5%
0%
33.3%
38.5%
12.8%
3.8%
6.4%
3.8%
1.3%
(weighted by aerosol extinction at 550 n
(~15% with st. dev > 0.
<= .1
(.1,.15]
(.15,.2]
(.2,.25]
(.25,.3]
(.3,.4]
(.4,.5]
(.5,.6]
(.6,.7]
> .7
St. deviation of Angstrom Exponent (450/550 nm)
No of observations
33
30
27
24
21
18
15
12
9
6
3
0
2.6%
24.4%
17.9%
9.0%
7.7%
38.5%
<= .01
(.01,.02]
(.02,.03]
(.03,.04]
(.04,.05]
> .05
St. dev of w (550 nm)
No of observations
26
24
22
20
18
16
14
12
10
8
6
4
2
0
9.0%
32.1%
25.6%
11.5%
6.4%
15.4%
(weighted by aerosol extinction (550 nm
<= .01
(.01,.02]
(.02,.03]
(.03,.04]
(.04,.05]
> .05
St. dev of w (550 nm)