Fog and Cloud Induced Aerosol Modification Observed by AERONET

T. F. Eck, B. N. Holben, J. S. Reid, D. M. Giles, M. A. Rivas, R. P. Singh, S. N. Tripathi, C. J. Bruegge, S. E. Platnick, G. T. Arnold, N. A. Krotkov, S.A. Carn, A. Sinyuk, O. Dubovik, A. Arola, J. S. Schafer, P. Artaxo, A. Smirnov, H. Chen, and P. Goloub

Manuscript submitted: *Journal of Geophysical Research - Atmospheres*

Aerosol Modification by Interaction with Clouds and/or Fog

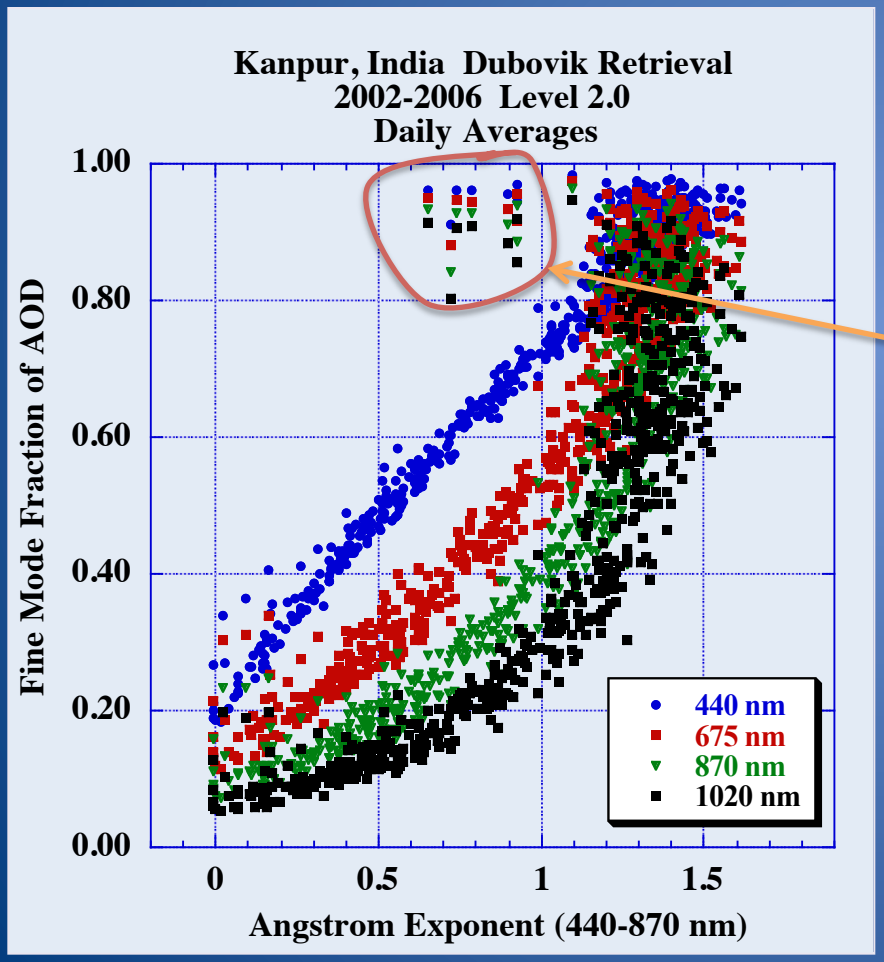
- Aerosols may be removed from the atmosphere by wet deposition during precipitation events

- **Aerosols may grow by humidification at higher Relative Humidity (RH) in the cloud or near-cloud environment**

- **Aerosols may be 'processed' by the cloud when aerosols activate cloud droplets and subsequent droplet evaporation results in modified aerosol – aqueous phase chemistry may occur inside the cloud droplet – results in aerosol growth**

- Enhanced aerosol growth in the vicinity of clouds and fog yield higher AOD and lower single scattering albedo, and that has implications for satellite remote sensing of aerosol and for aerosol radiative forcing

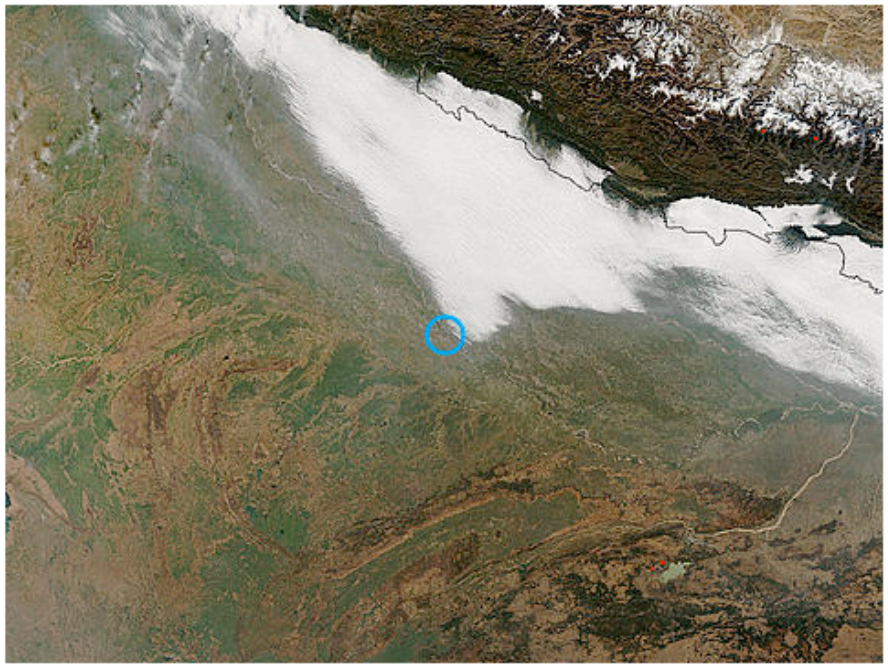
Multi-Year analysis at Kanpur (India) of the relationship between Fine Mode Fraction (FMF) of AOD as determined by the Dubovik retrievals of almucantar scans versus the Angstrom Exponent



All outliers on the Fine Mode Fraction versus Angstrom Exponent plot occurred during the **month of January**

Figure from *Eck et al. (2010) 'Climatological aspects of the optical properties of fine/coarse mode aerosol mixtures' – JGR*

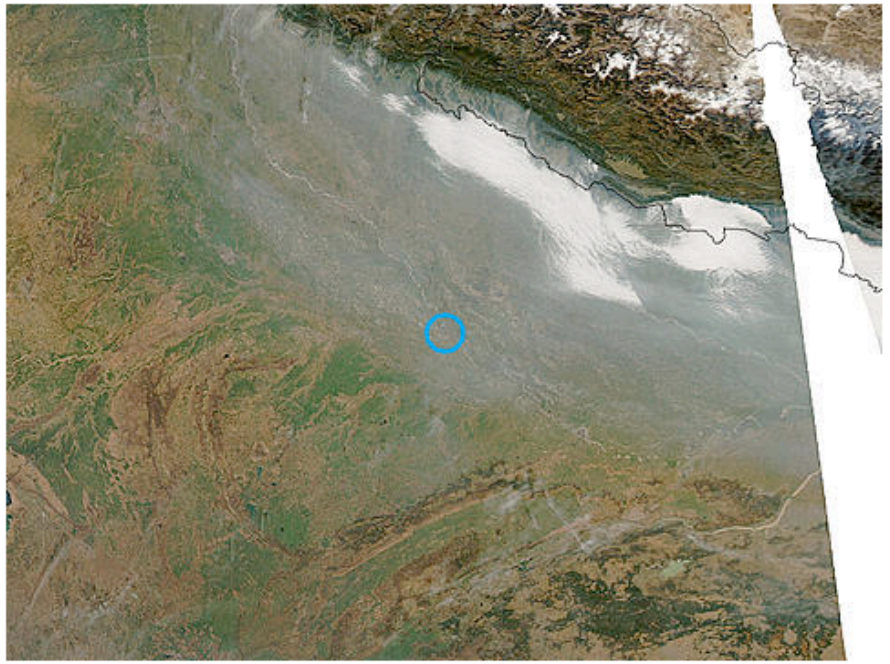
Composite TERRA-MODIS Image on JAN 5 of 2006; Centered on Kanpur



MODIS Images: 2000m 1000m 500m 250m

TERRA-MODIS Granule Overpass Time:
05:15 UTC

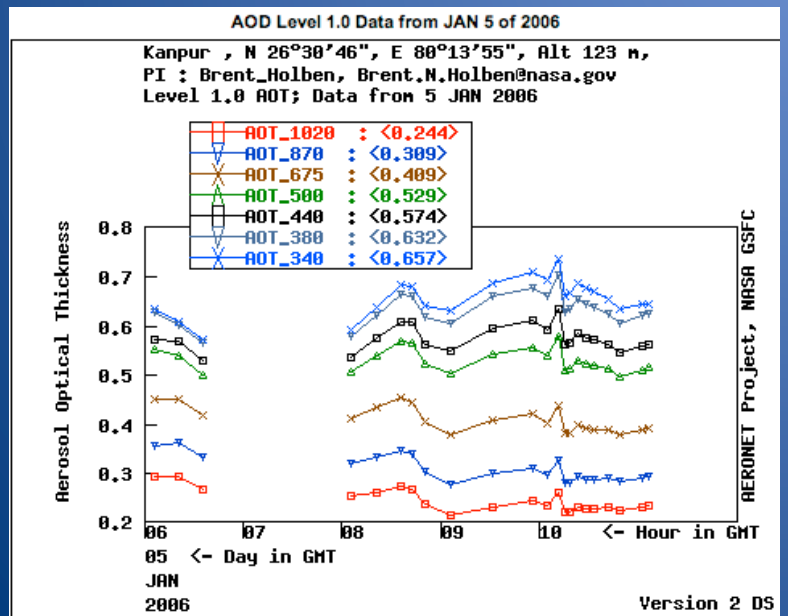
Composite AQUA-MODIS Image on JAN 5 of 2006; Centered on Kanpur



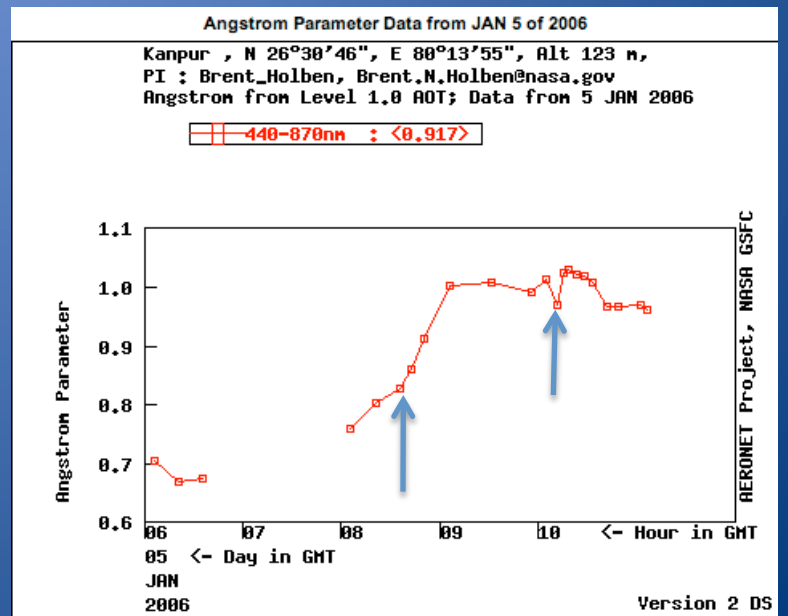
MODIS Images: 2000m 1000m 500m 250m

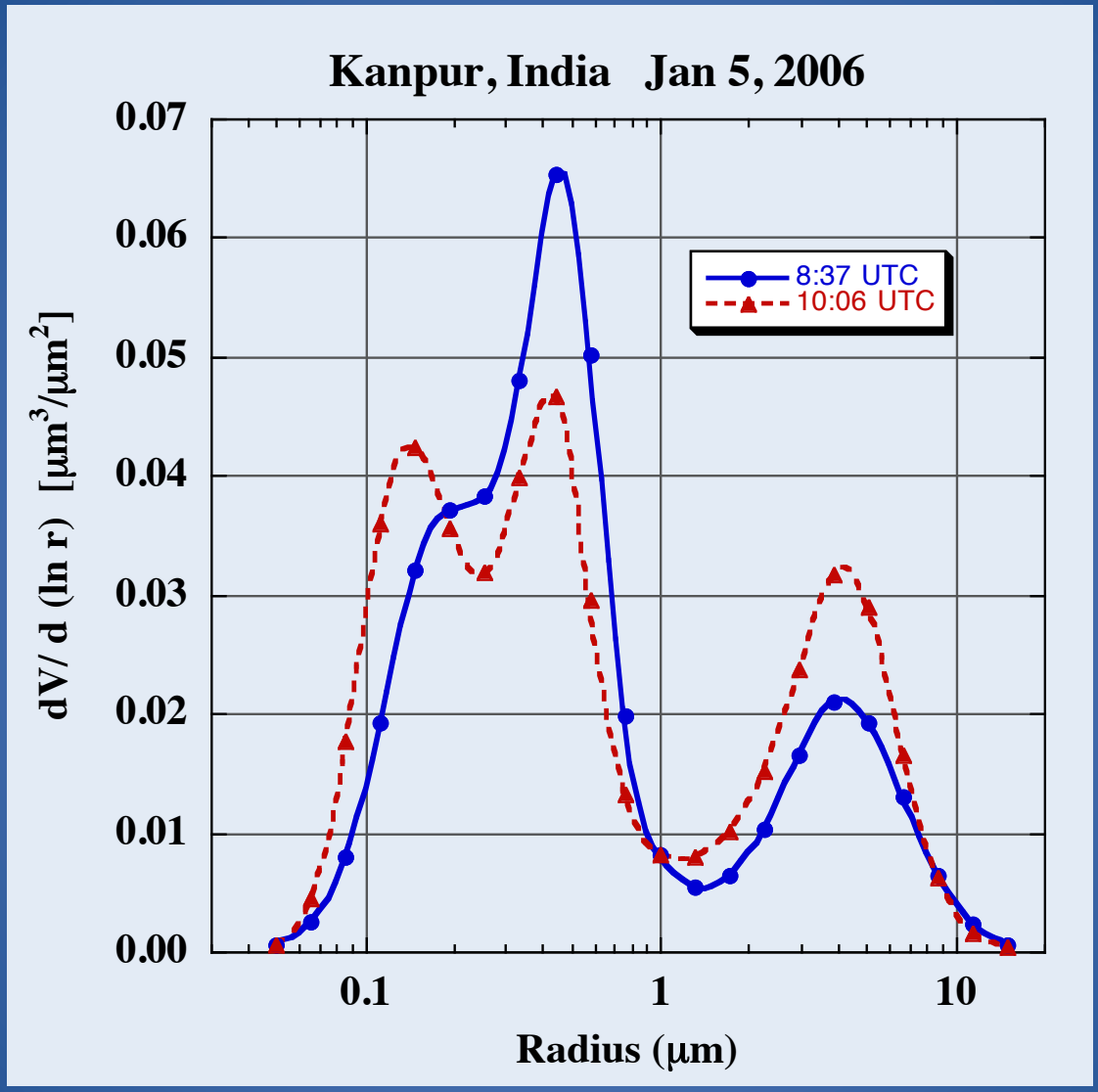
AQUA-MODIS Granule Overpass Times:
06:45, 08:20, 08:25 UTC

AOD Level 1.0 Data from JAN 5 of 2006



Angstrom Parameter Data from JAN 5 of 2006




Kanpur, India Jan 5, 2006
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
dV/ d (ln r) [μm³/μm²]
8:37 UTC
10:06 UTC
0.1
1
10
Radius (μm)

GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L09801, doi:10.1029/2006GL029020, 2007

Click Here for Full Article

Sulfur dioxide emissions from Peruvian copper smelters detected by the Ozone Monitoring Instrument

S. A. Carn,[1] A. J. Krueger,[1] N. A. Krotkov,[2] K. Yang,[2] and P. F. Levelt[3]

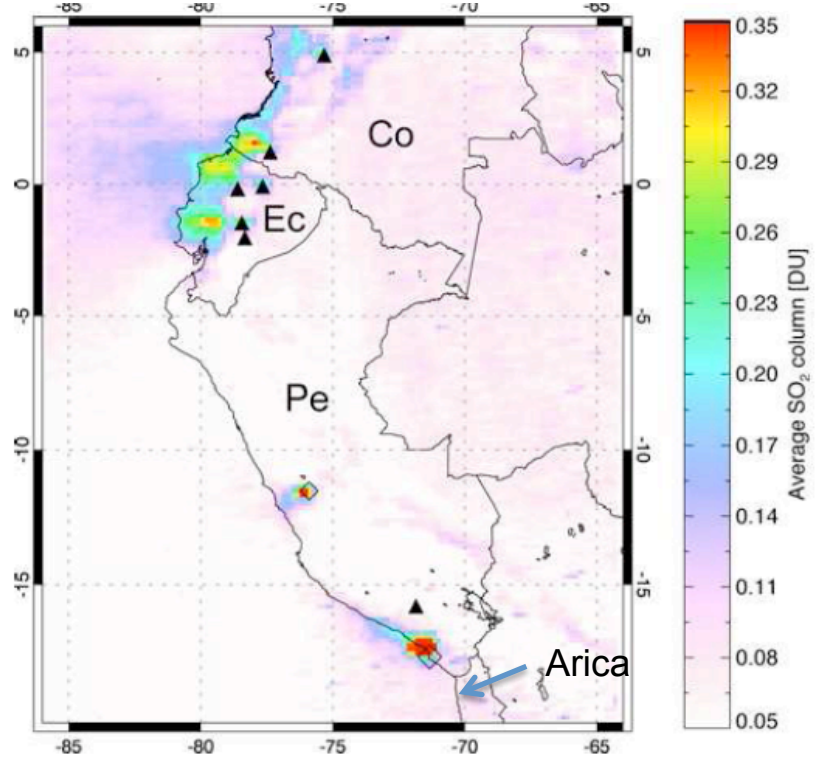


Figure 1. Average SO_2 column amounts measured by OMI over southern Colombia (Co), Ecuador (Ec), and Peru (Pe) between 1 September 2004 and 30 June 2005. Volcanoes (triangles), from north to south, are: Nevado del Ruiz, Galeras, Reventador, Guagua Pichincha, Tungurahua, Sangay, and Sabancaya. Peruvian copper smelters (diamonds; symbol size proportional to capacity) are located at La Oroya (11.53°S, 75.9°W) and Ilo (17.63°S, 71.33°W). Note the diffuse region of elevated SO_2 over the Pacific Ocean west of Ecuador and Colombia.

GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 16, PAGES 2501-2504, AUGUST 15, 2000

Reflectivity variations off the Peru Coast: Evidence for indirect effect of anthropogenic sulfate aerosols on clouds

Zhiming Kuang and Yuk L. Yung

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA

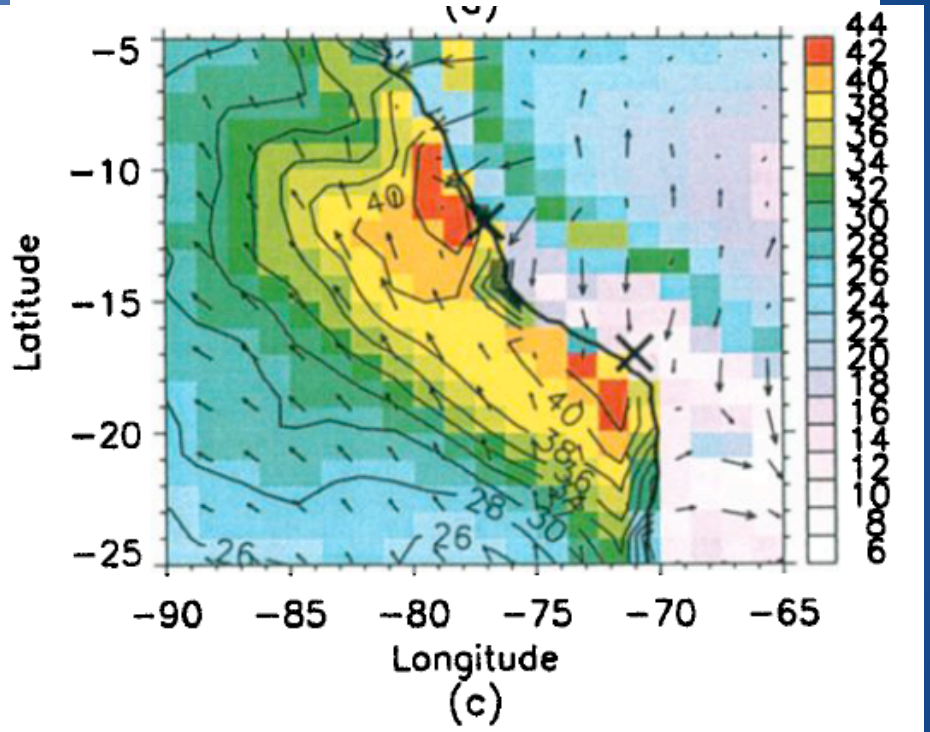
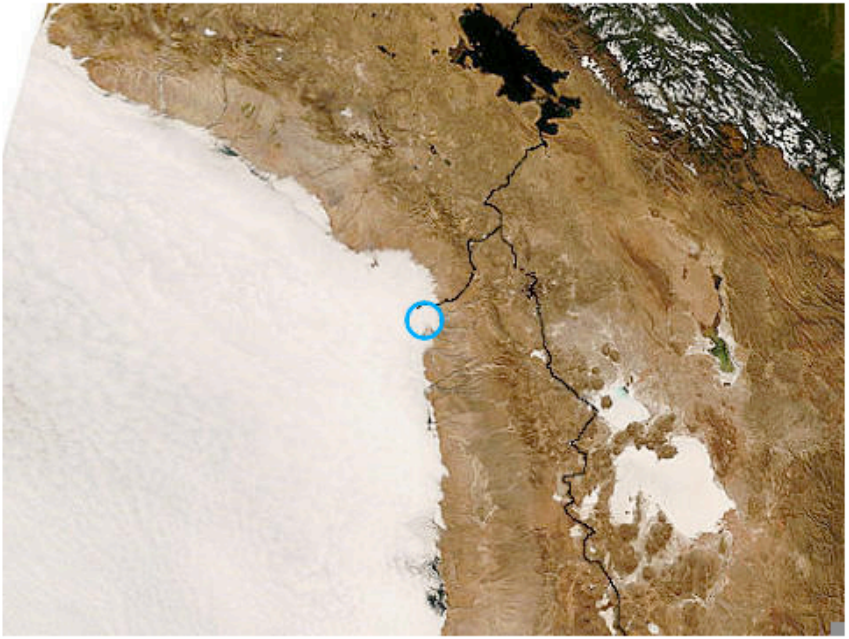


Figure 1. The climatological UV reflectivity for each month is constructed by averaging the TOMS measurements over the years 1979 to 1992. The reflectivity maps for February (a), May (b), August (c), and November (d) are shown for the Peru Coast. The coastline is over-plotted on the maps. In this work, we focus on the marine regions, i.e. the regions west of the coastline. Two major anthropogenic SO_2 emission sources, Lima (77°W, 12°S) and Ilo (71°W, 17°S) are marked by the × symbol. Contours are over-plotted on the maps from 24% to 42%, in steps of 2%, for the marine regions. The monthly surface wind stress averaged over the years 1979-1992 are overplotted for each month in arrows. The directions of the arrows have been reversed so that they are the same as the wind directions. The length of the arrow on the upper left corner of (a) represents a wind stress of 0.5 Nm^{-2}.

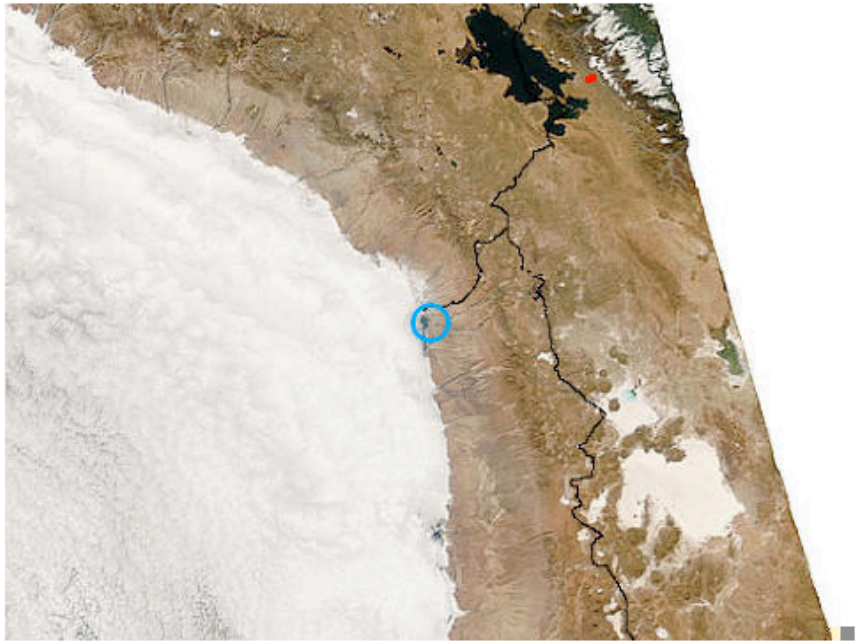
Composite TERRA-MODIS Image on JUL 13 of 2008; Centered on Arica



MODIS Images: 2000m 1000m 500m 250m

TERRA-MODIS Granule Overpass Times:
14:30, 14:35 UTC

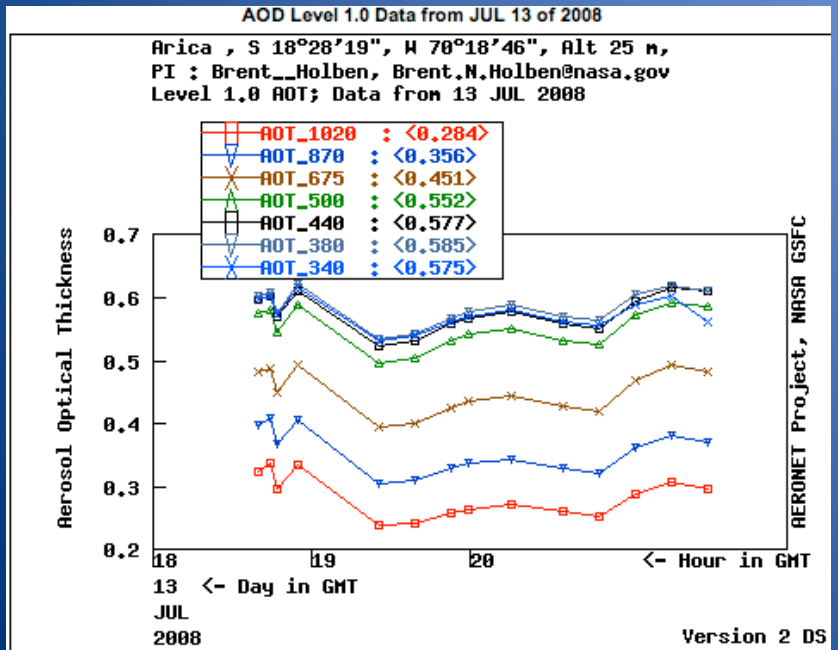
Composite AQUA-MODIS Image on JUL 13 of 2008; Centered on Arica



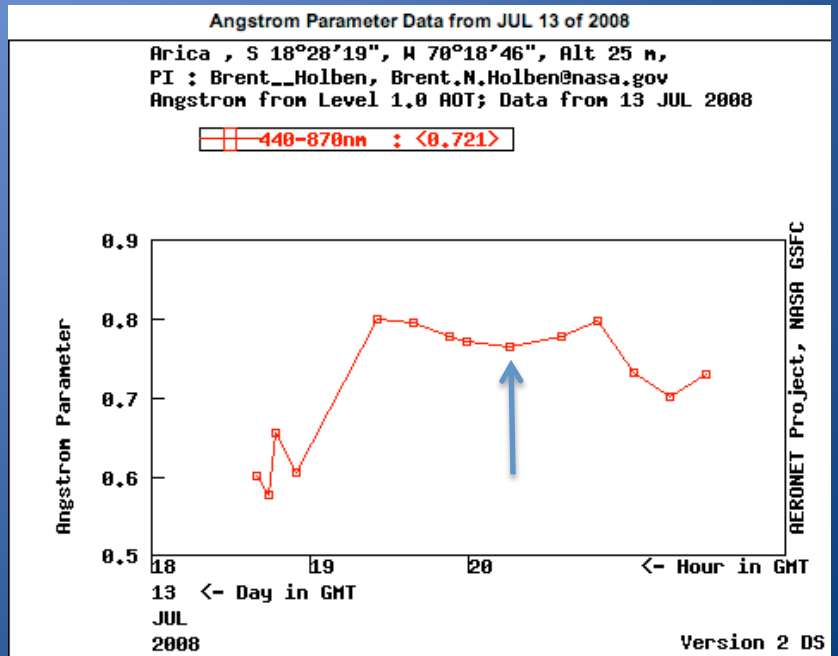
MODIS Images: 2000m 1000m 500m 250m

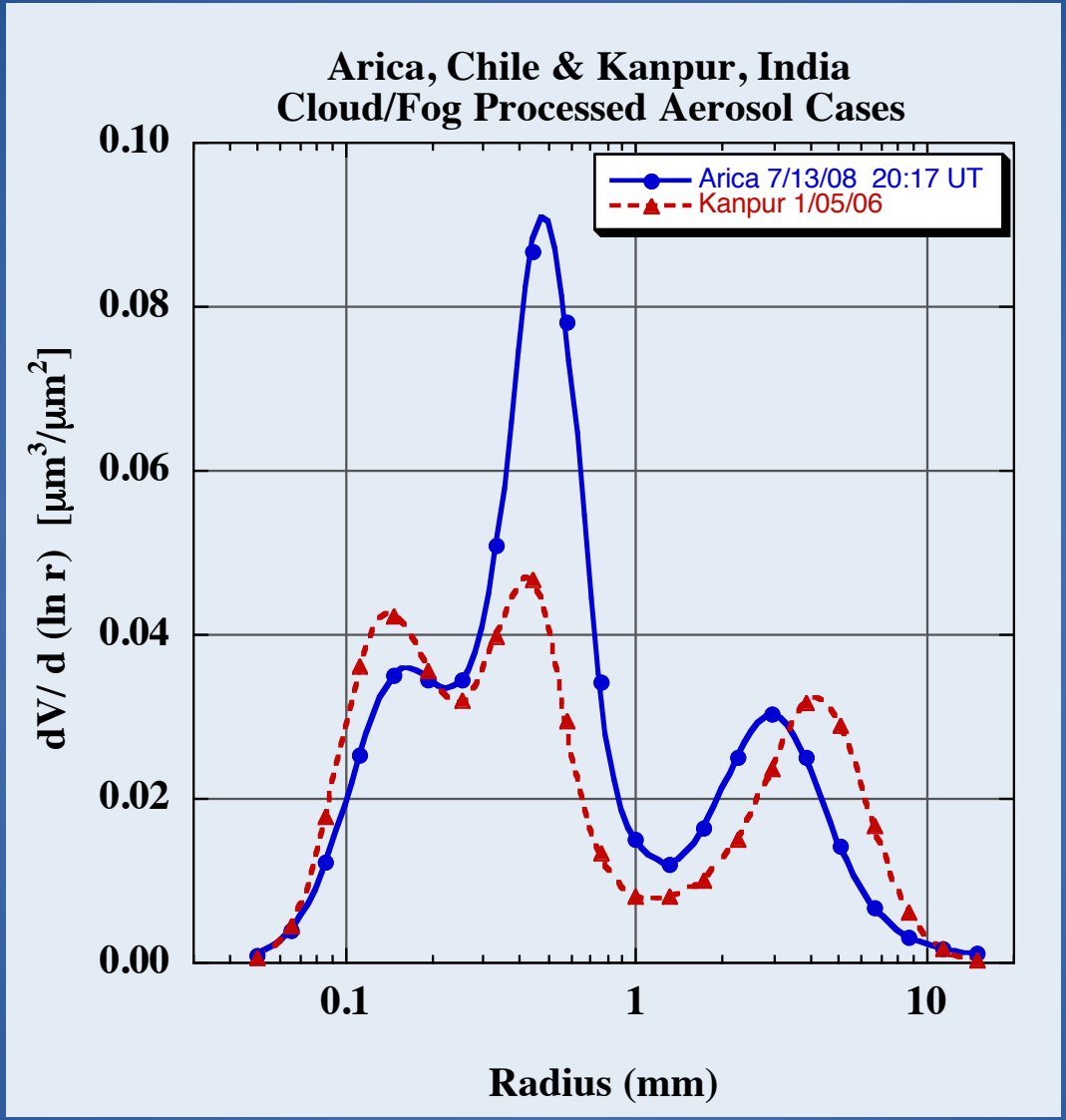
AQUA-MODIS Granule Overpass Times:
17:20, 18:55, 19:00 UTC

AOD Level 1.0 Data from JUL 13 of 2008



Angstrom Parameter Data from JUL 13 of 2008




Arica, Chile & Kanpur, India
Cloud/Fog Processed Aerosol Cases
Arica 7/13/08 20:17 UT
Kanpur 1/05/06
0.10
0.08
0.06
0.04
0.02
0.00
dV/ d (ln r) [μm3/μm2]
0.1
1
10
Radius (mm)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. D7, PAGES 14,443–14,459, JULY 20, 1994

Marine boundary layer measurements of new particle formation and the effects nonprecipitating clouds have on aerosol size distribution

W. A. Hoppel, G. M. Frick, and J. W. Fitzgerald
Remote Sensing Division, Naval Research Laboratory, Washington, D. C.

R. E. Larson[1]
SFA Incorporated, Landover, Maryland

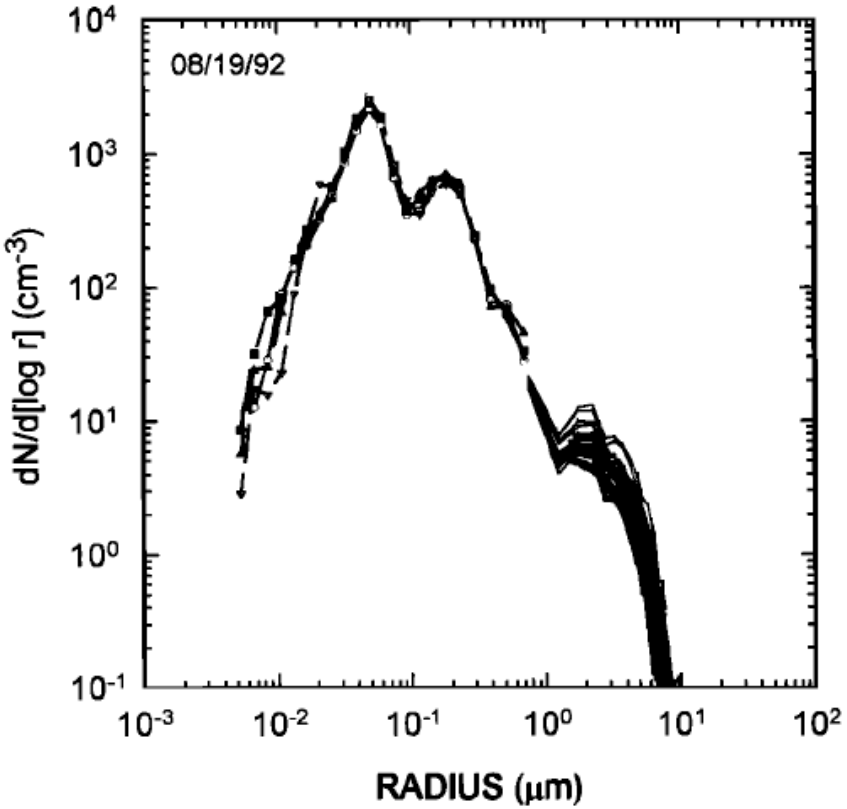


Figure 12. Composite of four DMA size distributions taken below the stratus deck together with a composite of all PMS-OPC size distributions during the same time period on August 19. The DMA size distributions are adjusted to ambient relative humidity (95%) for comparison with the PMS-OPC data.

Size distributions measured in situ (from an airship) below stratus cloud deck ~40 km off the Oregon coast

"The double-peaked DMA data are again believed to result from cloud processing."

"Based on the assumption that the peak at 0.2 μm is due to in-cloud conversion of SO_2 to H_2SO_4, the converted mass of H_2SO_4 is 3.6 μg m^{-3} which would require a little less than1 ppb of SO_2 to be converted in the droplets during multiple cloud cycles (during the life-time of the stratus)."

Atmos. Chem. Phys., 9, 2459–2469, 2009
www.atmos-chem-phys.net/9/2459/2009/
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Atmospheric Chemistry and Physics

Real-time secondary aerosol formation during a fog event in London

M. Dall'Osto[1,*], R. M. Harrison[1], H. Coe[2], and P. Williams[2]

HMS = hydroxymethanesulphonate: species [HSO3]−, [HSO4]− and [HOCH2SO3]− *found only during the fog event*

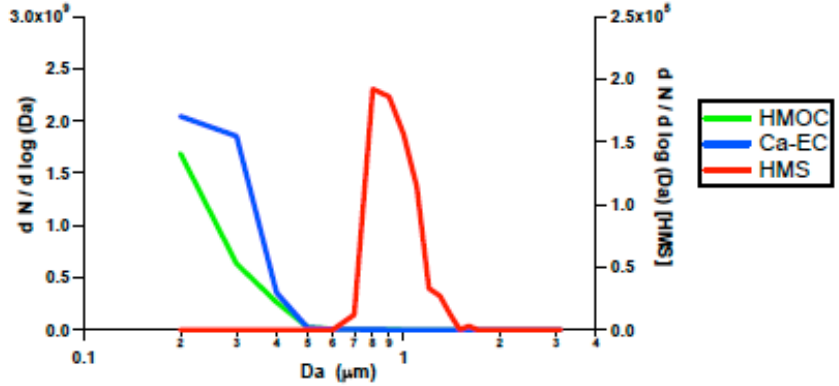
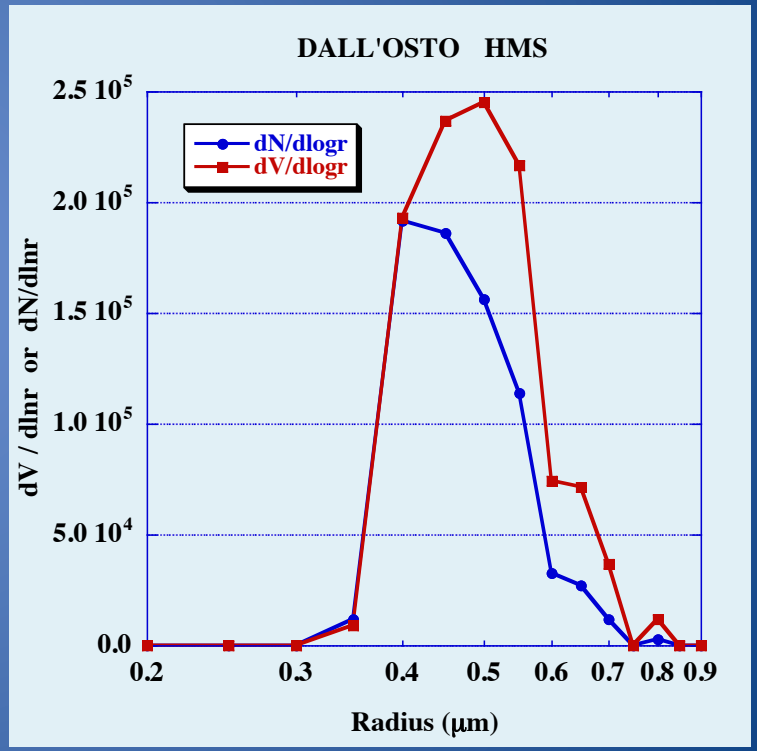


Fig. 7. ATOFMS scaled size distribution for particle types HMOC, Ca-EC and HMS.

HMS is exclusively formed in the aqueous phase, so its presence in particles is a valuable tracer for processing by aqueous phase chemistry.

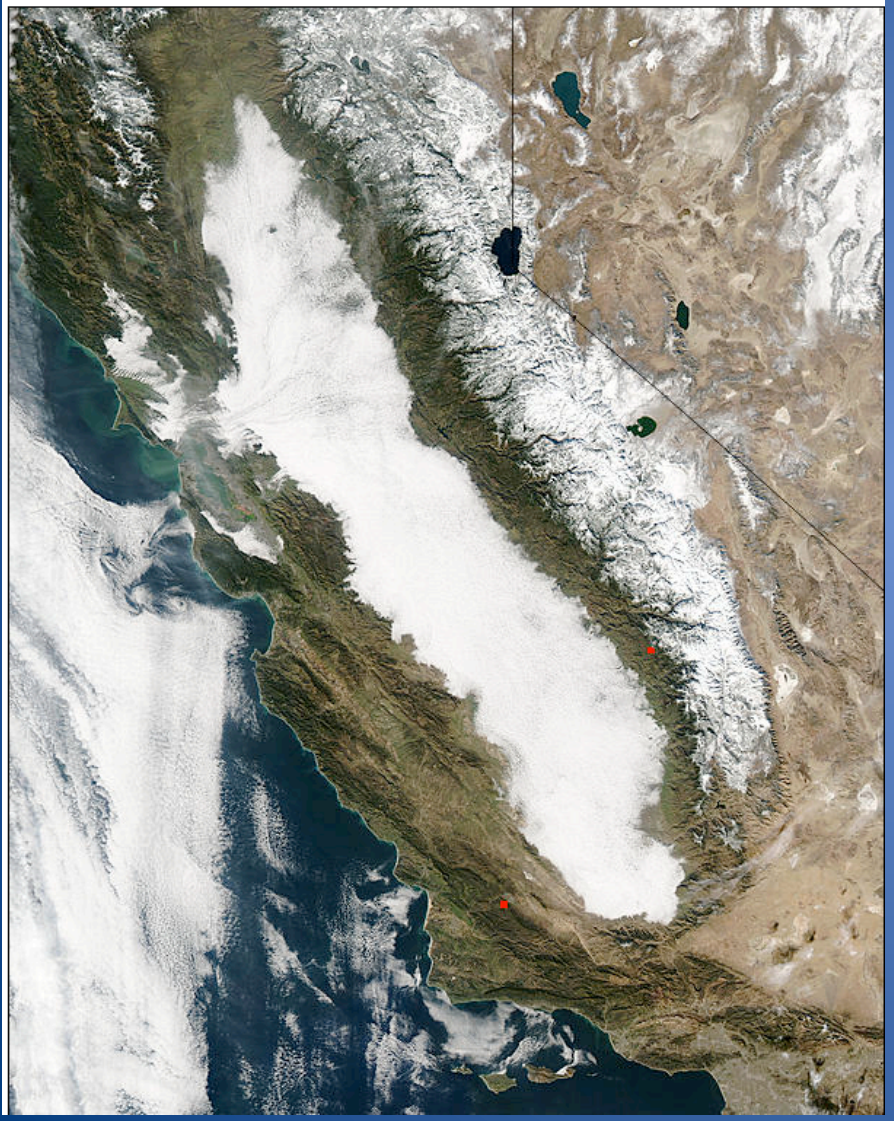


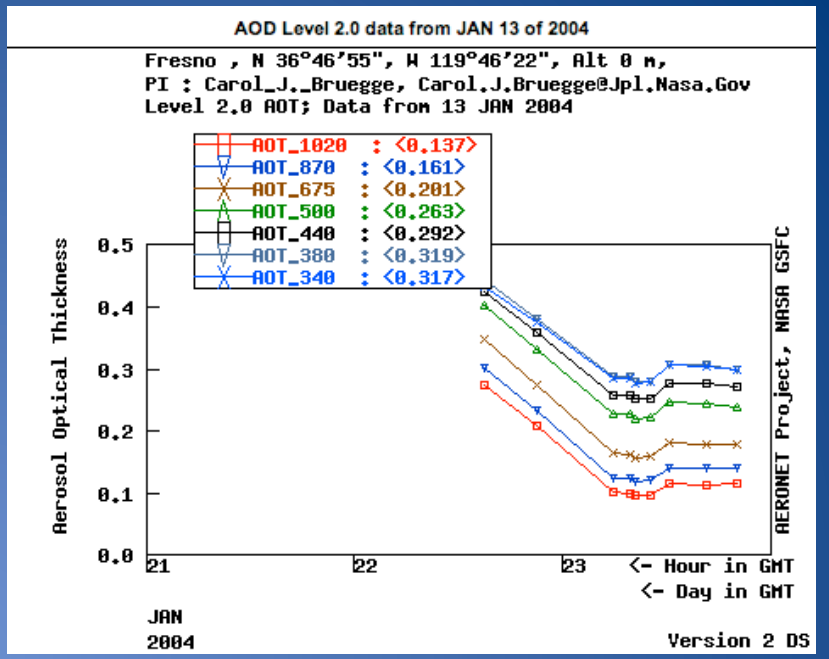
Similar size HMS particles were simultaneously measured by an APS

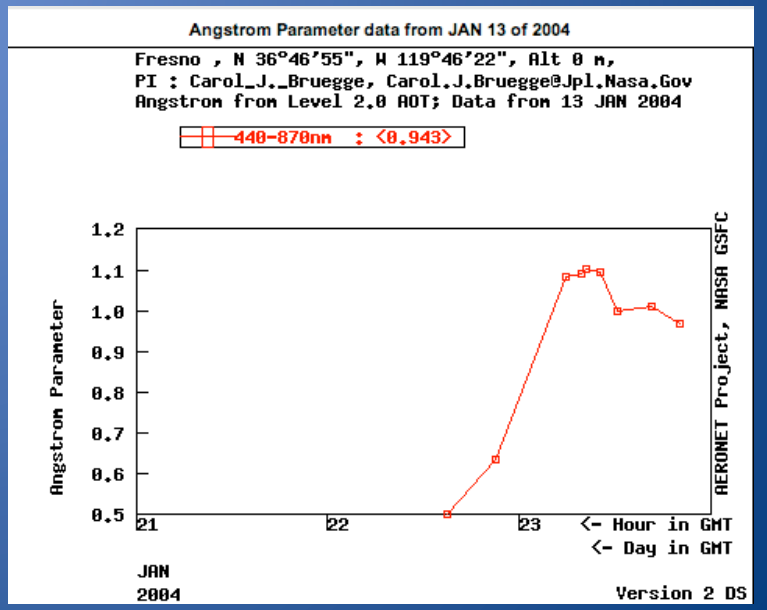
Munger et al. (1986,** Science) **measured HMS in Fog in Bakersfield, CA.

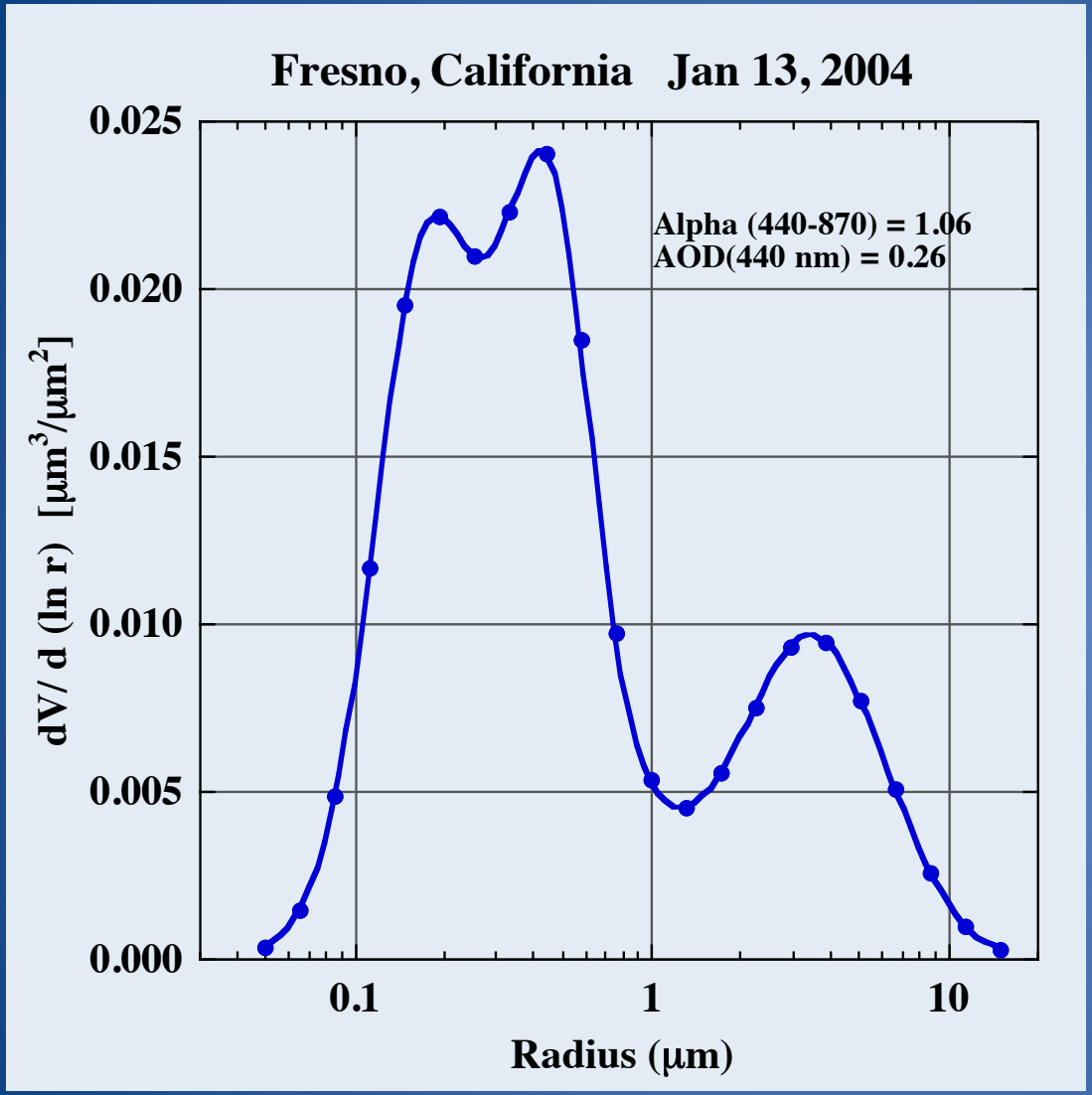
2004/013 - 01/13 at 21 :10 UTC
Fog in California
Satellite: Aqua - Pixel size: 1km - Alternate pixel size: 500m | 250m
More info - Download a worldfile (for GIS users) - Download a KML file for GoogleEart

Return to the image gallery main page



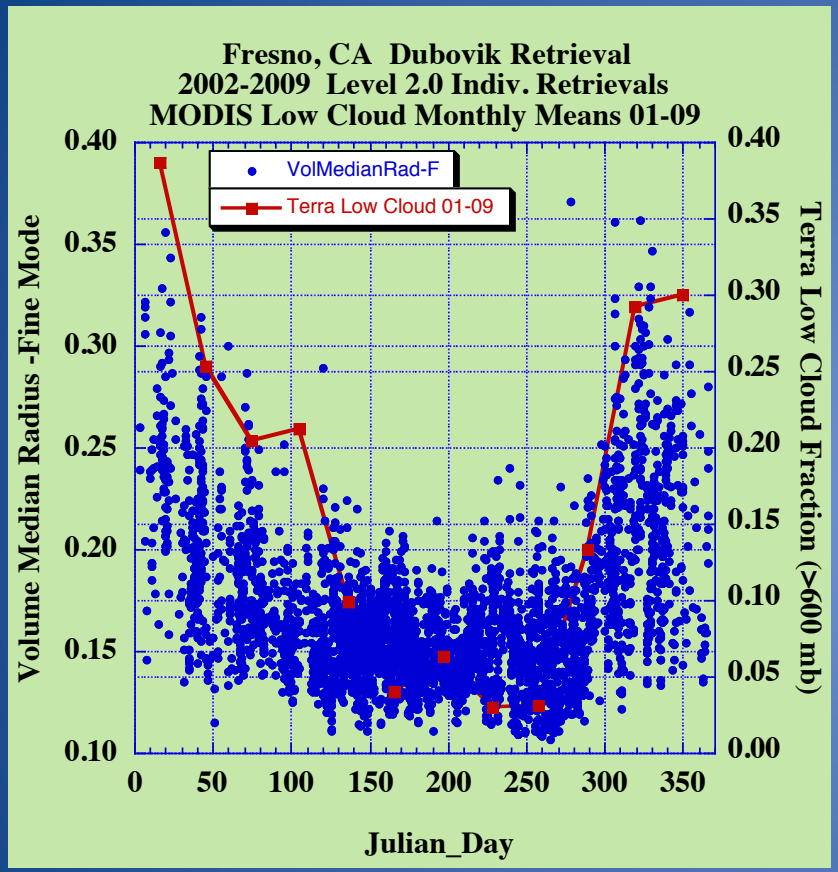


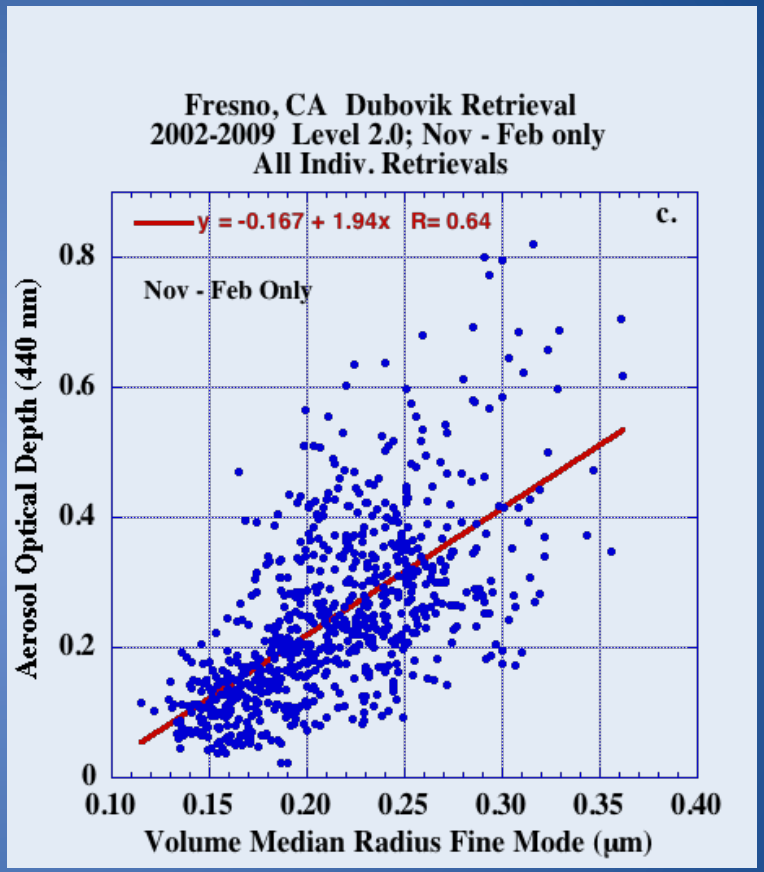




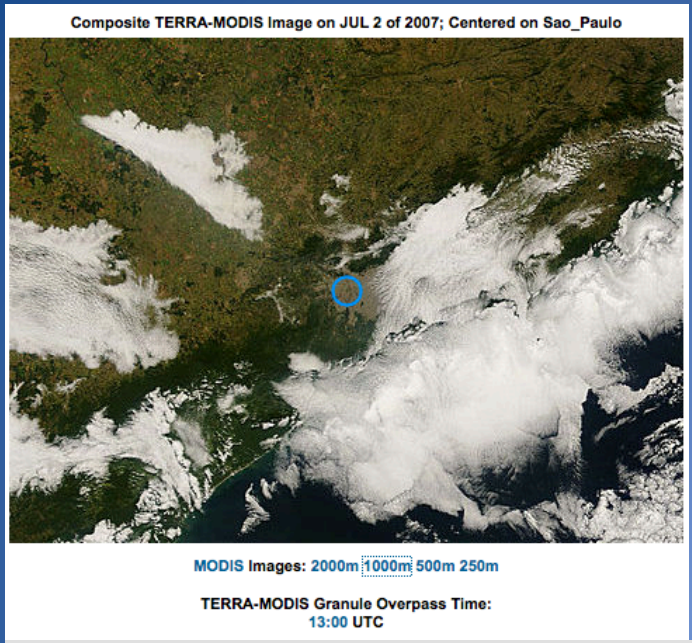
HSRL Lidar in Feb 2007 showed shallow aerosol layer of ~1 km suggesting that fog may possibly interact with a significant fraction of the aerosol layer in the San Joaquin Valley (Lewis et al., 2010)

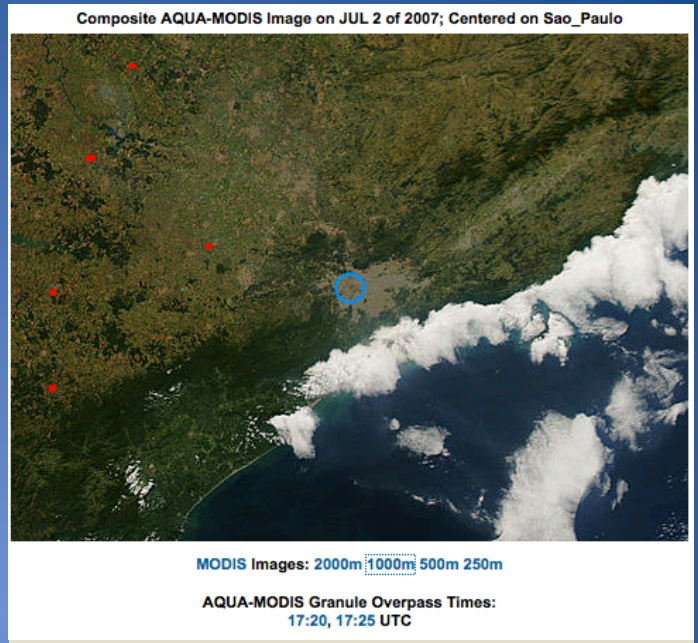
Several studies have measured HMS in the San Joaquin Valley in fog droplets and in ambient aerosol during the dissipation phase of fog [Whiteaker et al., 2003; Rao and Collett, 1995; Jacob et al., 1989; Munger et al., 1986]

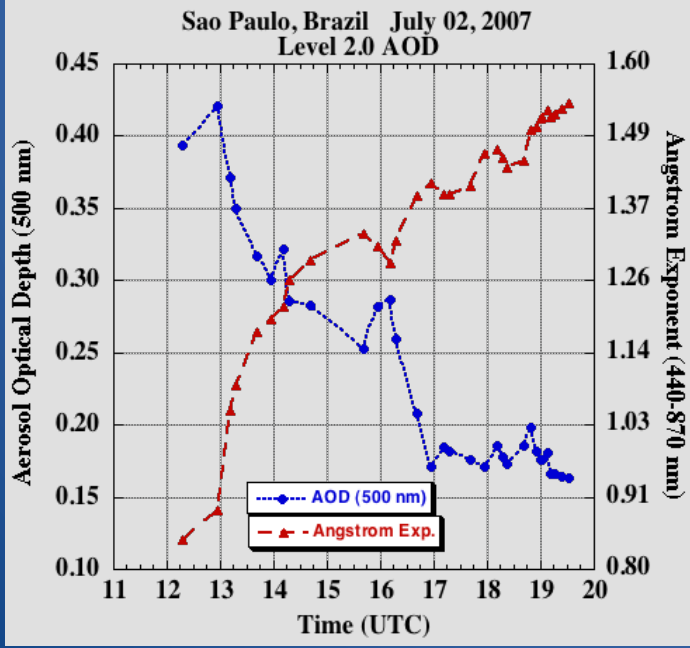

Fresno, CA Dubovik Retrieval
2002-2009 Level 2.0 Indiv. Retrievals
MODIS Low Cloud Monthly Means 01-09
VolMedianRad-F
Terra Low Cloud 01-09
Volume Median Radius -Fine Mode
Terra Low Cloud Fraction (<600 mb)
Julian_Day
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350

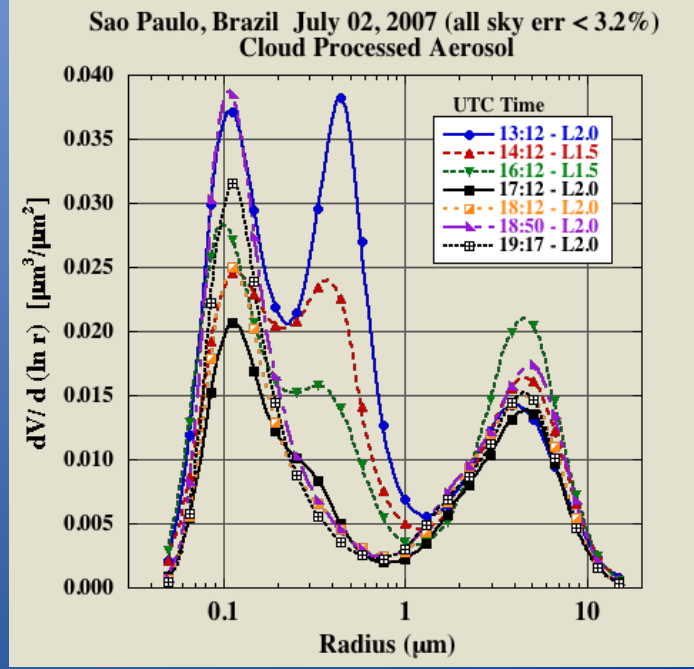

Fresno, CA Dubovik Retrieval
2002-2009 Level 2.0; Nov - Feb only
All Indiv. Retrievals
y = -0.167 + 1.94x R= 0.64
c.
Nov - Feb Only
Aerosol Optical Depth (440 nm)
Volume Median Radius Fine Mode (µm)
0.8
0.6
0.4
0.2
0
0.10
0.15
0.20
0.25
0.30
0.35
0.40

Sao Paulo, Brazil July 2, 2007 - Cloud/Fog aerosol processing

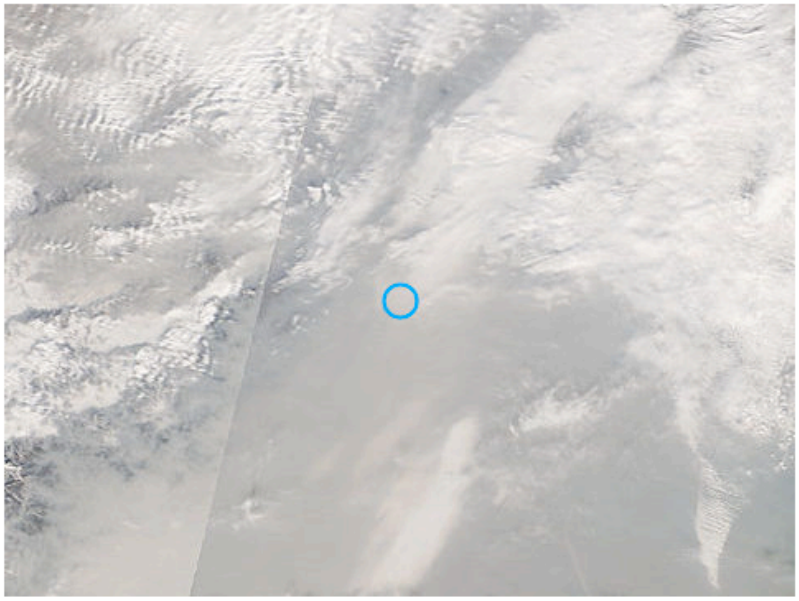








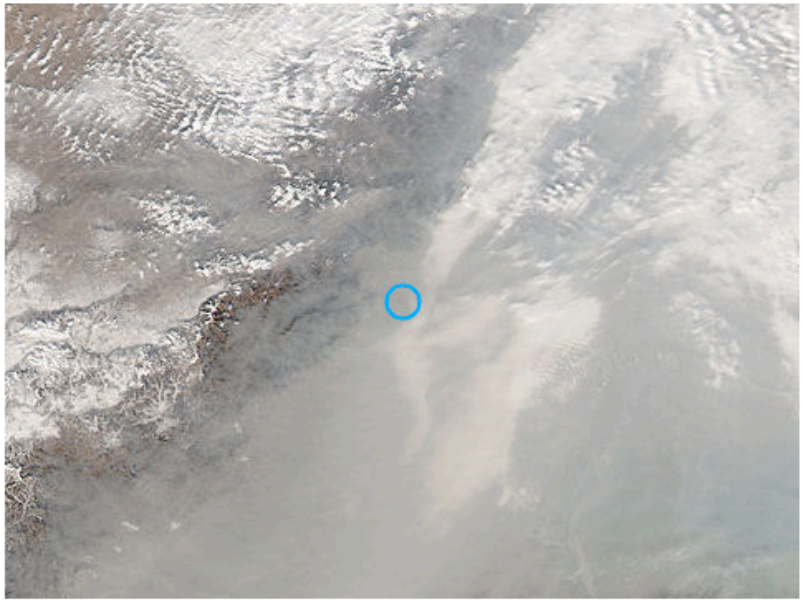
Composite TERRA-MODIS Image on JAN 24 of 2006; Centered on Beijing



MODIS Images: 2000m 1000m 500m 250m

TERRA-MODIS Granule Overpass Times:
02:25, 04:00, 04:05 UTC

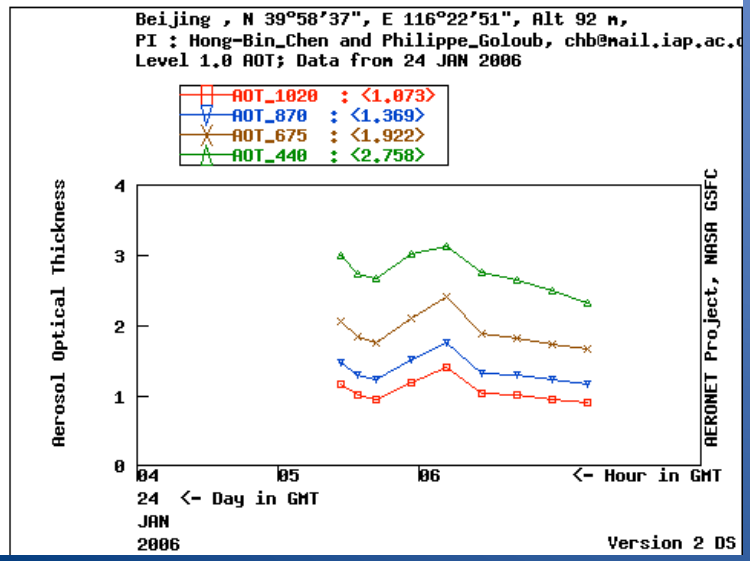
Composite AQUA-MODIS Image on JAN 24 of 2006; Centered on Beijing



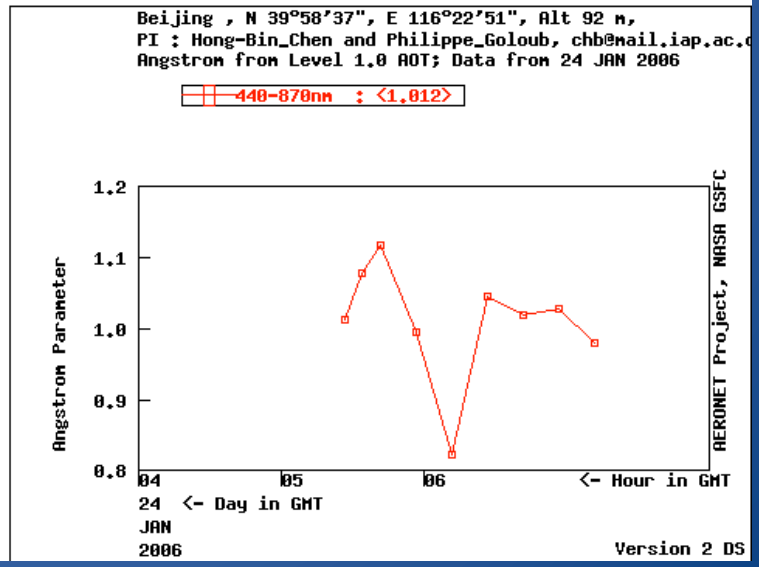
MODIS Images: 2000m 1000m 500m 250m

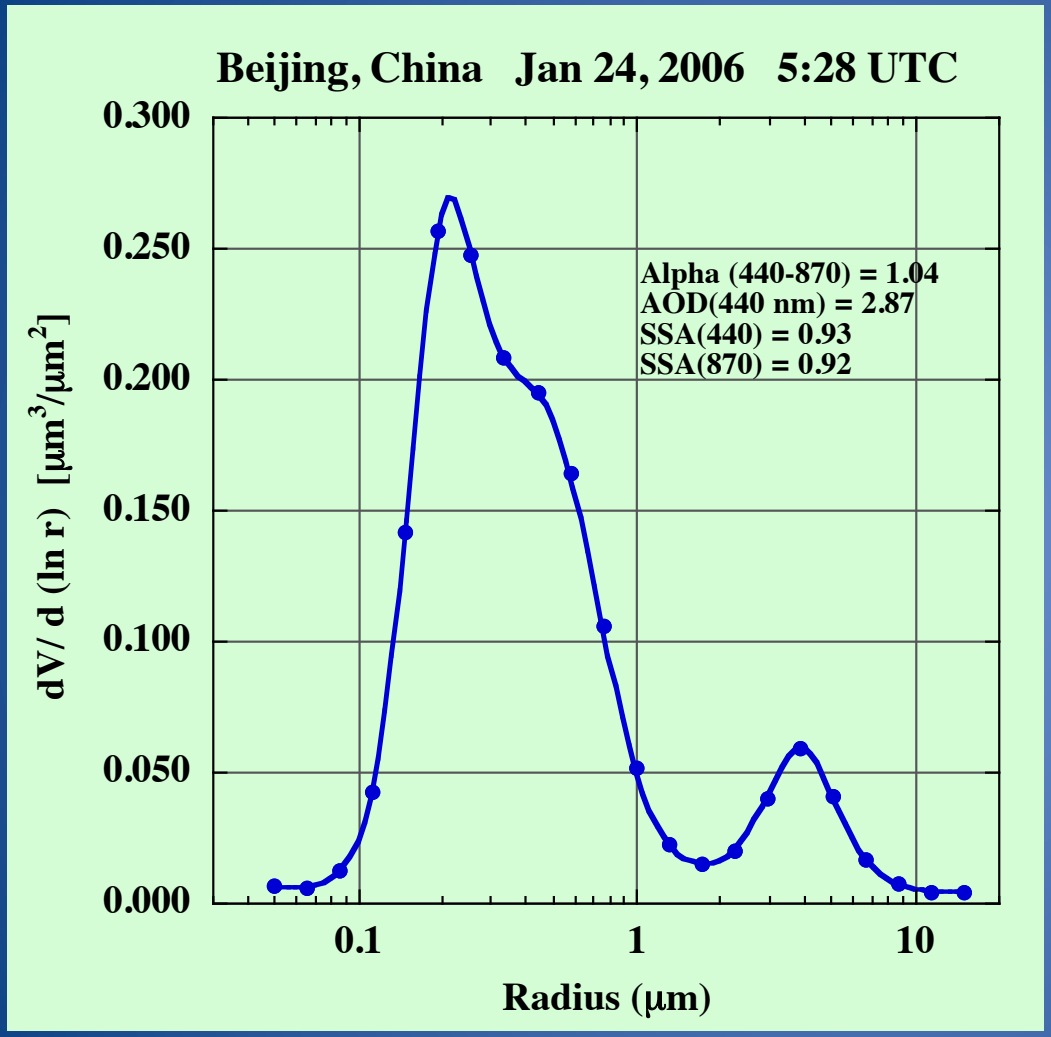
AQUA-MODIS Granule Overpass Times:
04:00, 04:05, 05:40 UTC

AOD Level 1.0 Data from JAN 24 of 2006



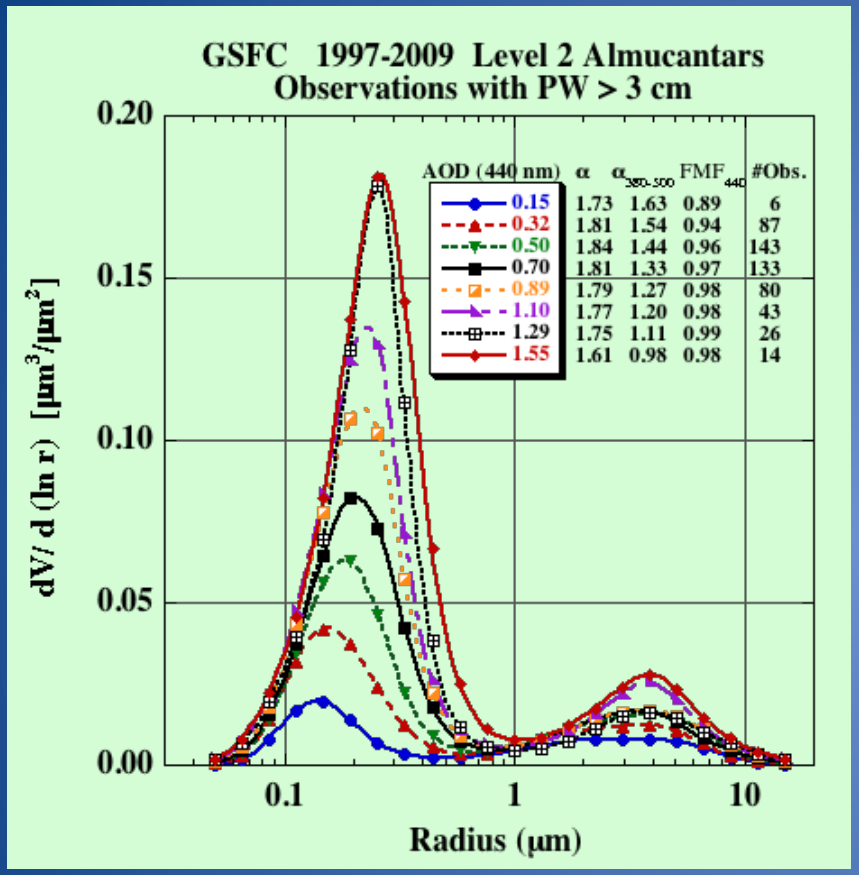
Angstrom Parameter Data from JAN 24 of 2006

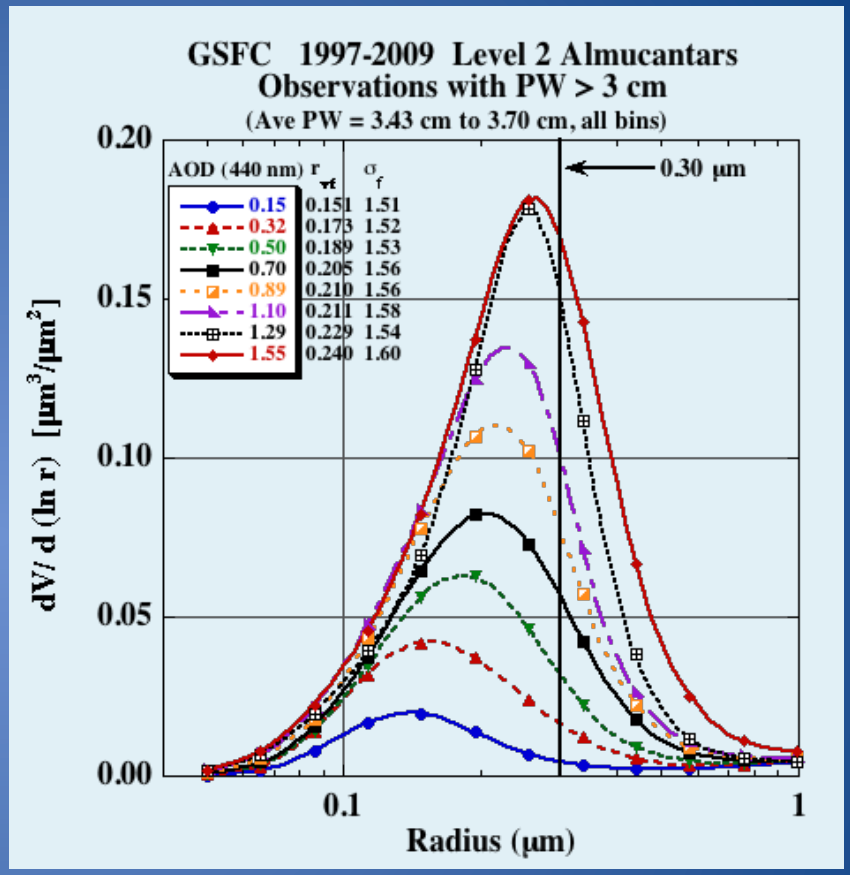




Niu et al. (2010; JGR in press) show that the frequencies of fog events in wintertime over eastern-central China have doubled over the past three decades. This has likely resulted in increased modification of aerosol by fog processing.

Climatology of Size Distribution Retrievals at the GSFC (Greenbelt, MD, USA) site for High Water Vapor Conditions (PW > 3 cm)





- High PW days more likely to have higher relative humidity and cloud cover than days with low PW.
- Increase in fine mode radius as AOD increased may have largely resulted from aerosol coagulation
- Aerosol-cloud interactions may have resulted in some increase in the larger tail of the fine mode
- As the AOD increases it is highly probable that an increasing fraction of the aerosols are aged from one to several days increasing the probability of interaction with clouds.

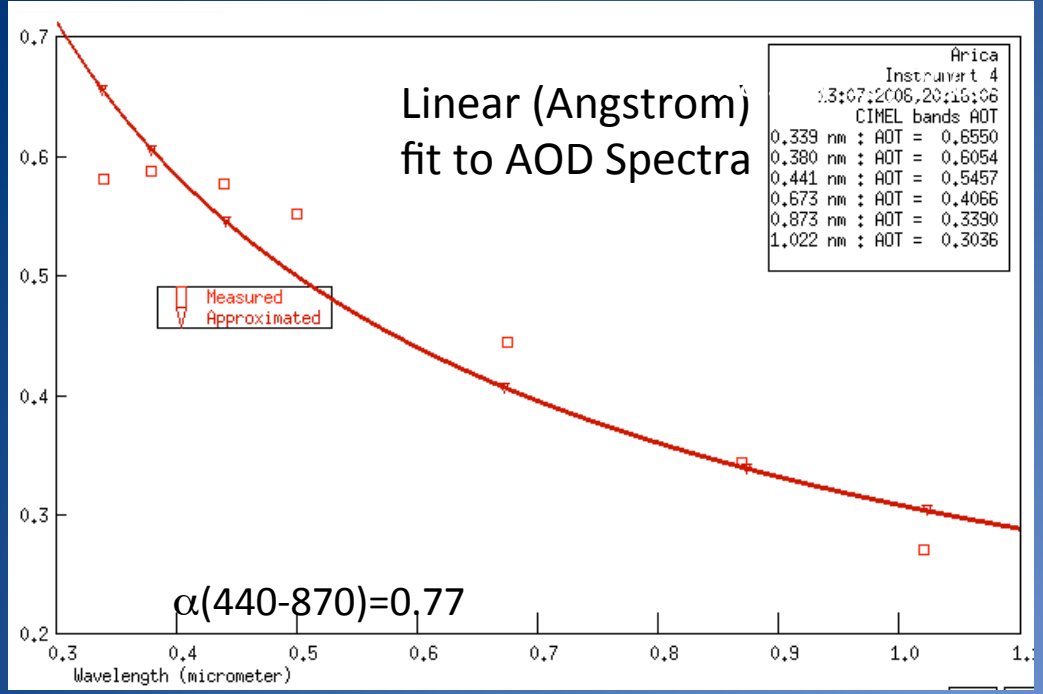
Summary and Conclusions

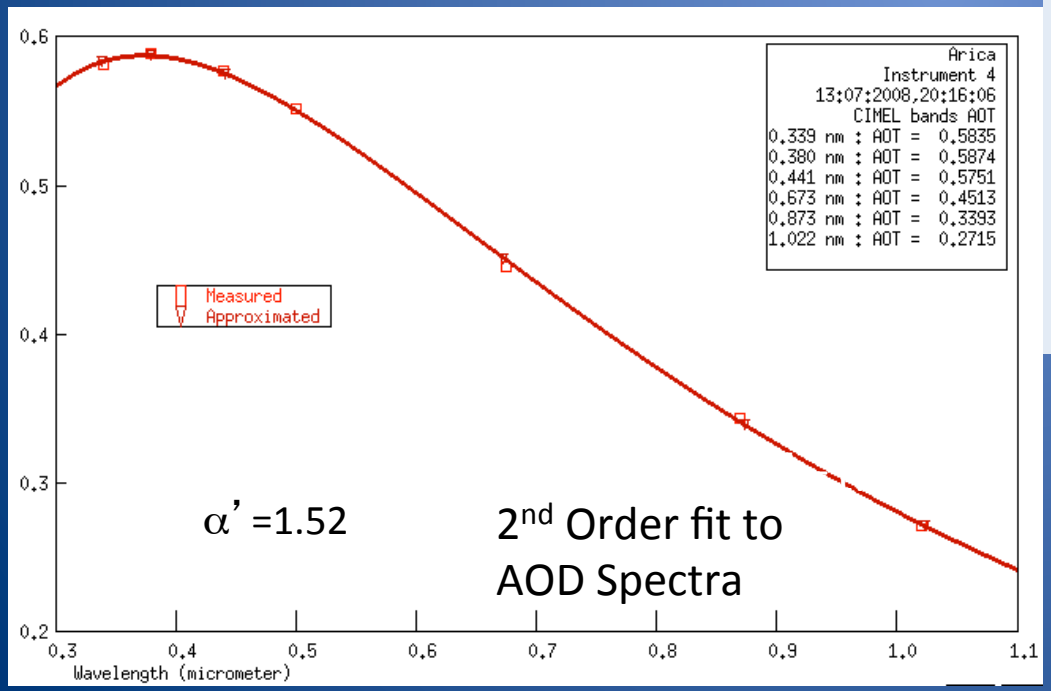
- **The largest radius fine mode aerosol retrieved from AERONET have been observed after fog or cloud dissipation**

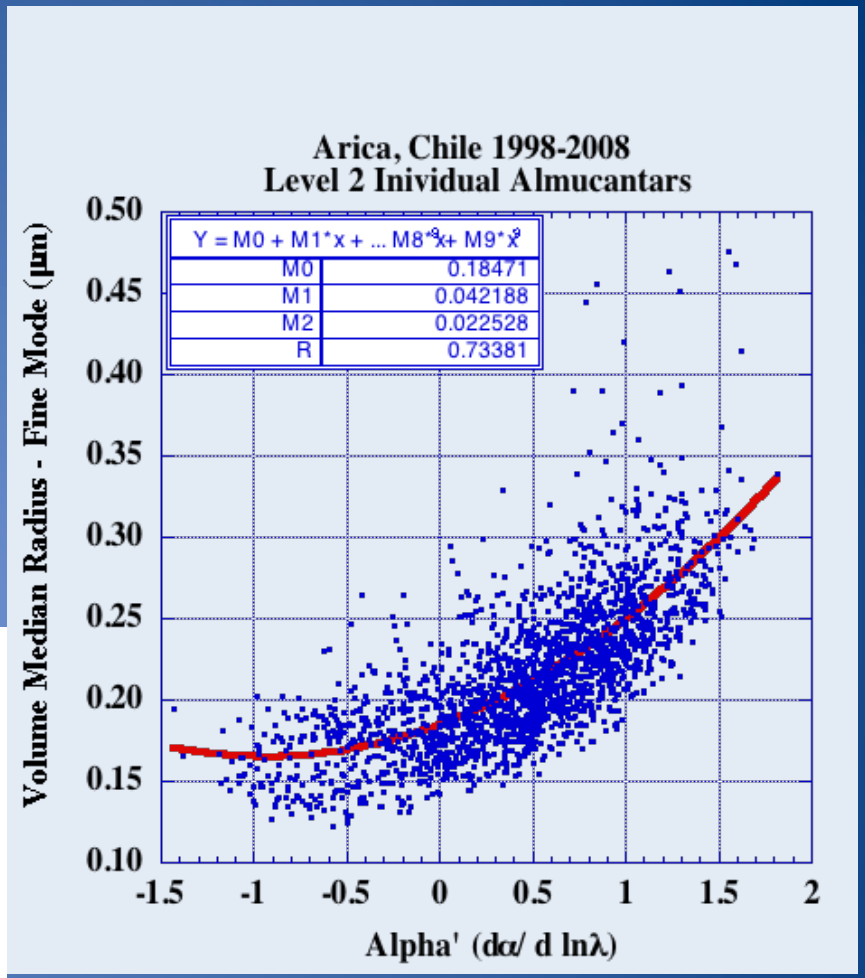
- **These cases with 'cloud processed' aerosol are often bimodal in the accumulation mode with the large size mode at ~0.4 – 0.5 μm radius; the smaller mode at ~0.15 μm may be interstitial aerosol that were not modified by incorporation in droplets**

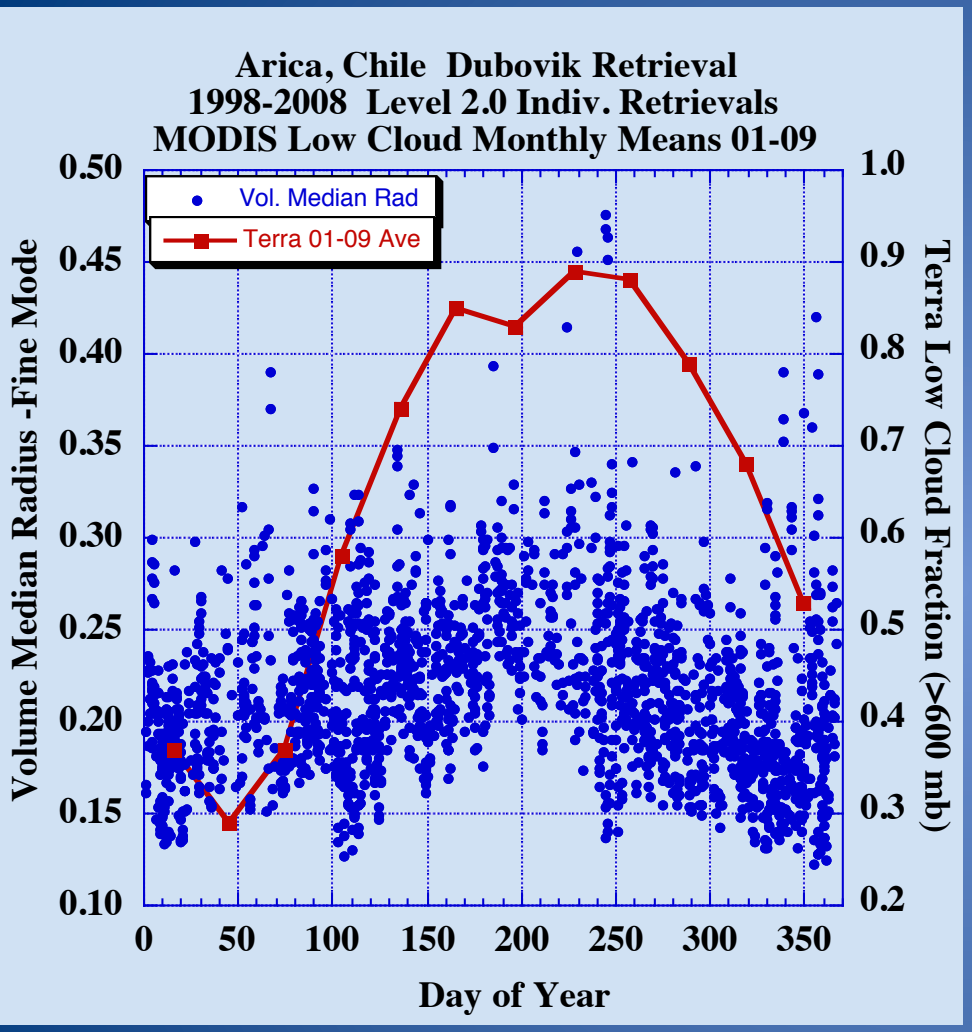
- **In situ measurements of ambient aerosols after fog dissipation (in both London, England and the San Joaquin Valley, CA) have shown particles in the same size range (peak at ~0.4 – 0.5 μm) that are composed of HMS, which are formed exclusively in the aqueous phase**

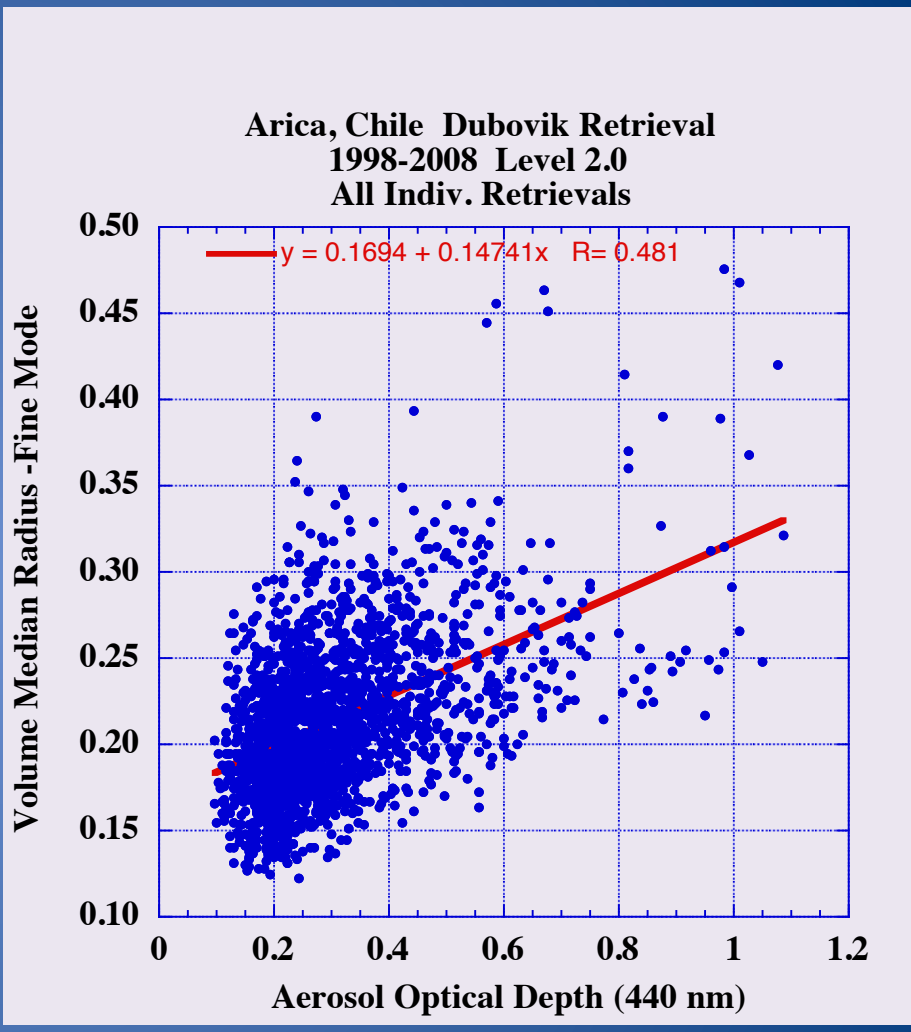
- **Aerosols of this type and large size range may also be formed in partly cloudy conditions in lower concentrations and may contribute to the 'shoulder' of larger size particles in regions where sulfate aerosol is a significant component.**

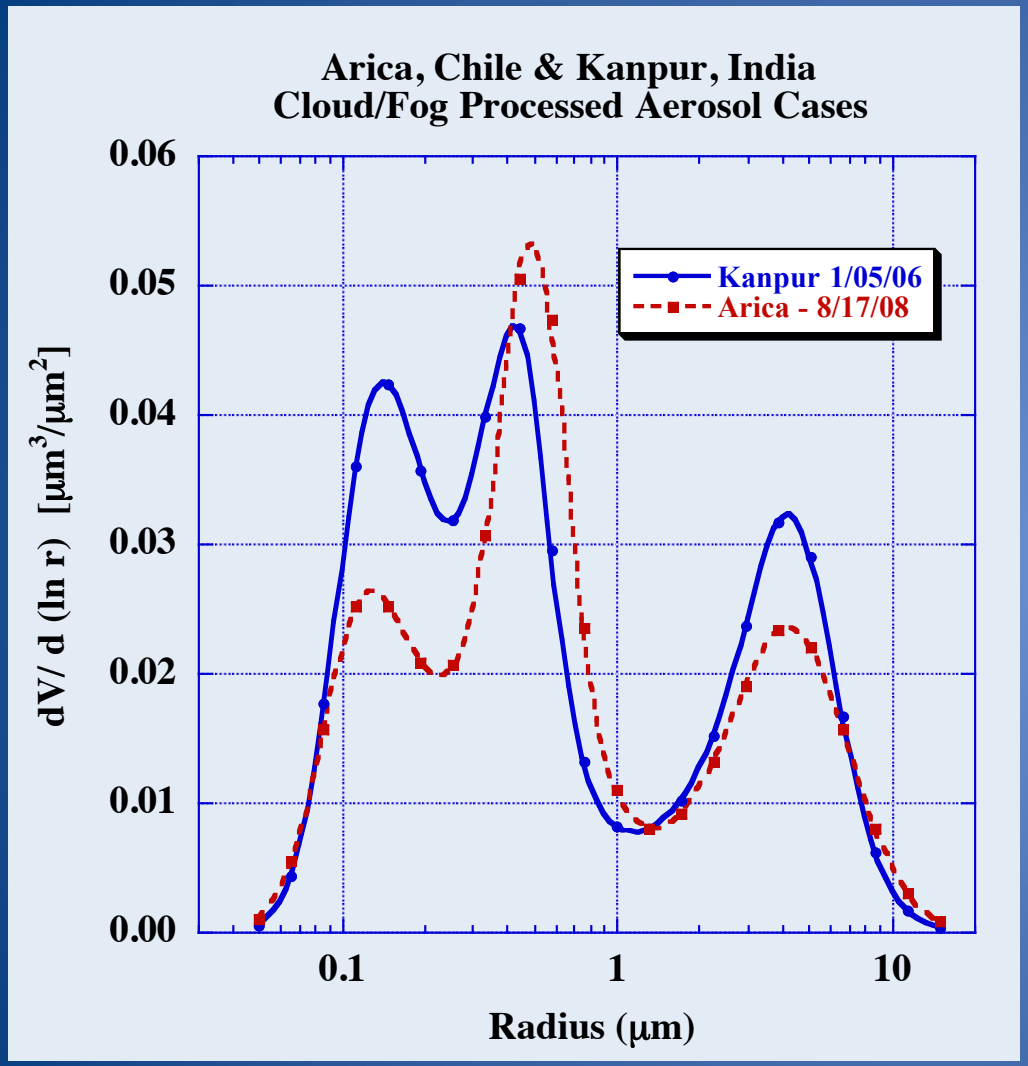

Linear (Angstrom) fit to AOD Spectra
Arica
Instrument 4
13:07:2008,20:16:06
CIMEL bands AOT
0.339 nm : AOT = 0.6550
0.380 nm : AOT = 0.6054
0.441 nm : AOT = 0.5457
0.673 nm : AOT = 0.4066
0.873 nm : AOT = 0.3390
1.022 nm : AOT = 0.3036
Measured
Approximated
α(440-870)=0.77
Wavelength (micrometer)


Arica
Instrument 4
13:07:2008,20:16:06
CIMEL bands AOT
0.339 nm : AOT = 0.5835
0.380 nm : AOT = 0.5874
0.441 nm : AOT = 0.5751
0.673 nm : AOT = 0.4513
0.873 nm : AOT = 0.3393
1.022 nm : AOT = 0.2715
Measured
Approximated
α' =1.52
2nd Order fit to AOD Spectra
Wavelength (micrometer)


Arica, Chile 1998-2008
Level 2 Inividual Almucantars
Y = M0 + M1*x + ... M8*x^8 + M9*x^9
M0 0.18471
M1 0.042188
M2 0.022528
R 0.73381
Volume Median Radius - Fine Mode (µm)
Alpha' (dα/ d lnλ)

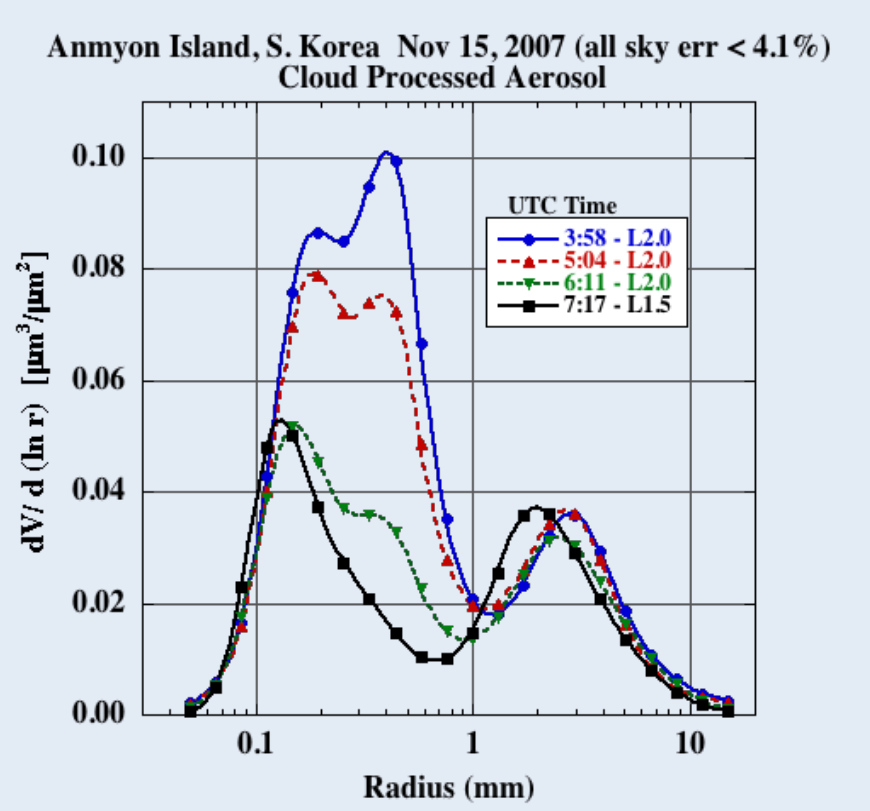

Arica, Chile Dubovik Retrieval
1998-2008 Level 2.0 Indiv. Retrievals
MODIS Low Cloud Monthly Means 01-09
Vol. Median Rad
Terra 01-09 Ave
Volume Median Radius -Fine Mode
Terra Low Cloud Fraction (<600 mb)
Day of Year
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
50
100
150
200
250
300
350

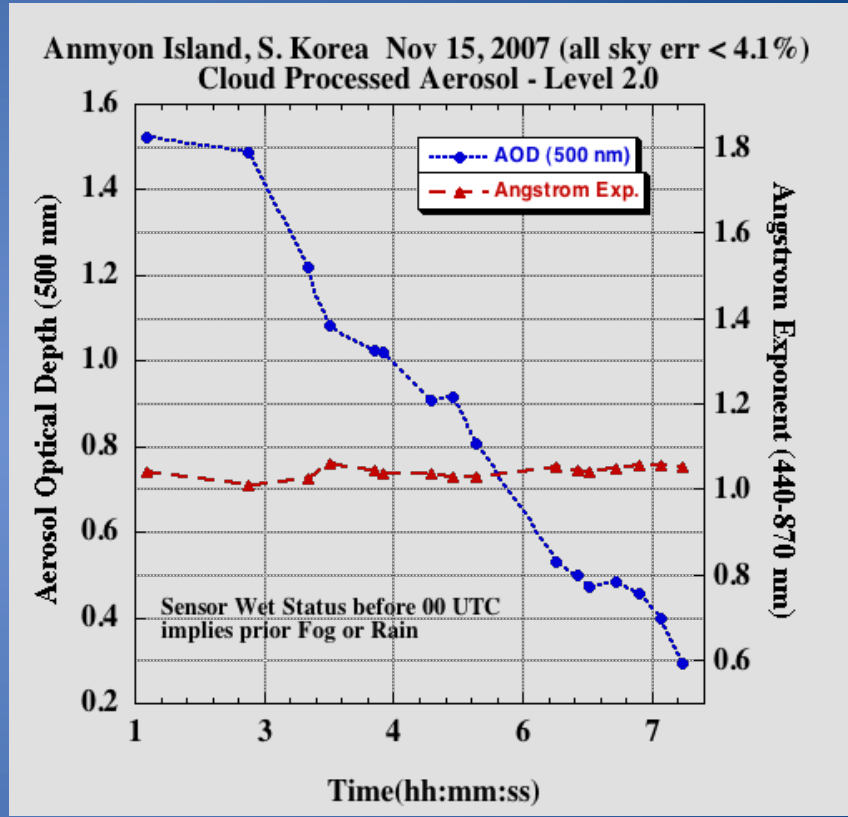

Arica, Chile Dubovik Retrieval
1998-2008 Level 2.0
All Indiv. Retrievals
y = 0.1694 + 0.14741x R= 0.481
Volume Median Radius -Fine Mode
Aerosol Optical Depth (440 nm)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0
0.2
0.4
0.6
0.8
1
1.2

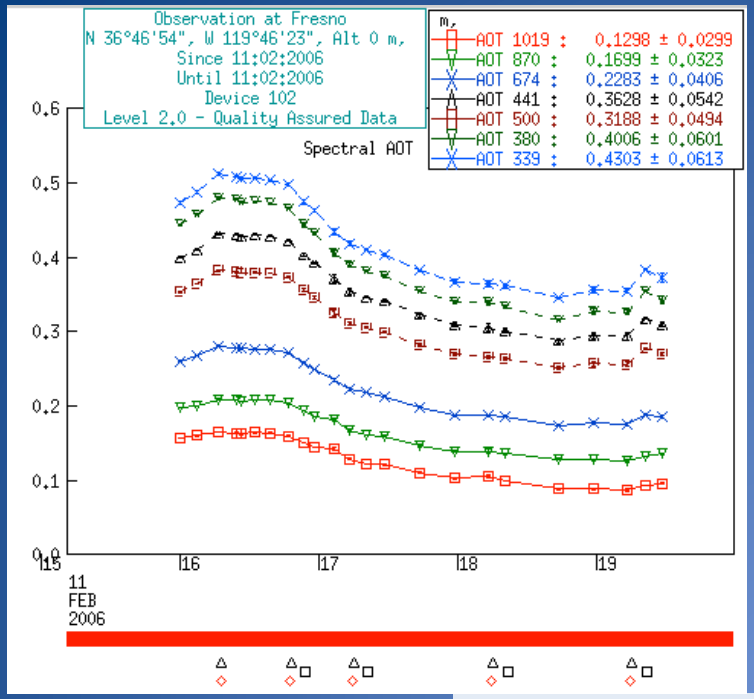


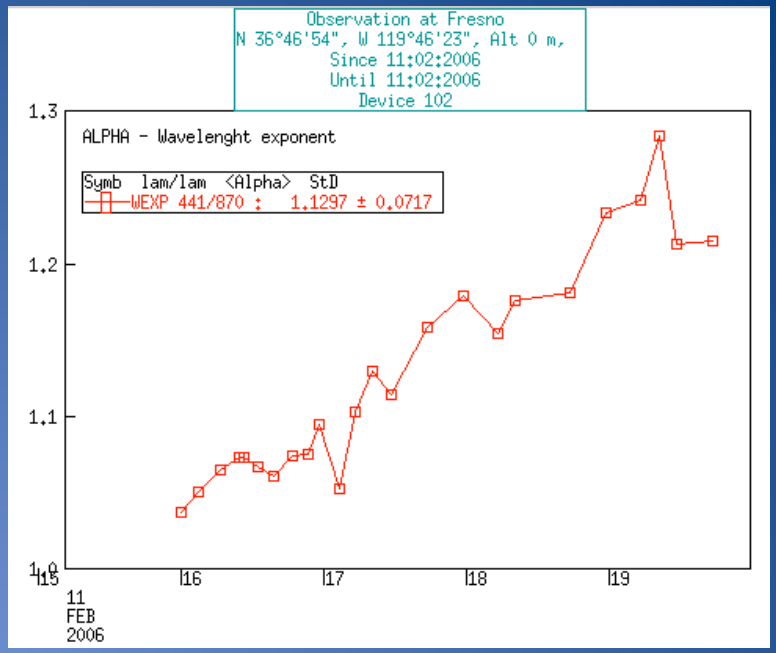
Cloud/fog processing cases;
2 Sub-micron modes:
0.13-0.15 μm radius - interstitial
~0.4-0.5 μm radius – "cloud processed"

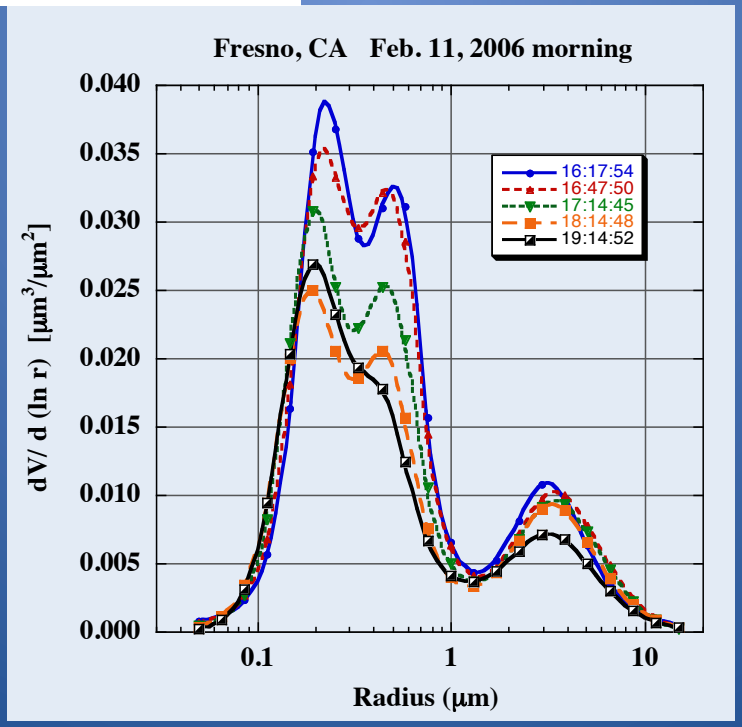
Anmyon, Island, S. Korea - Cloud Processed Aerosol Case

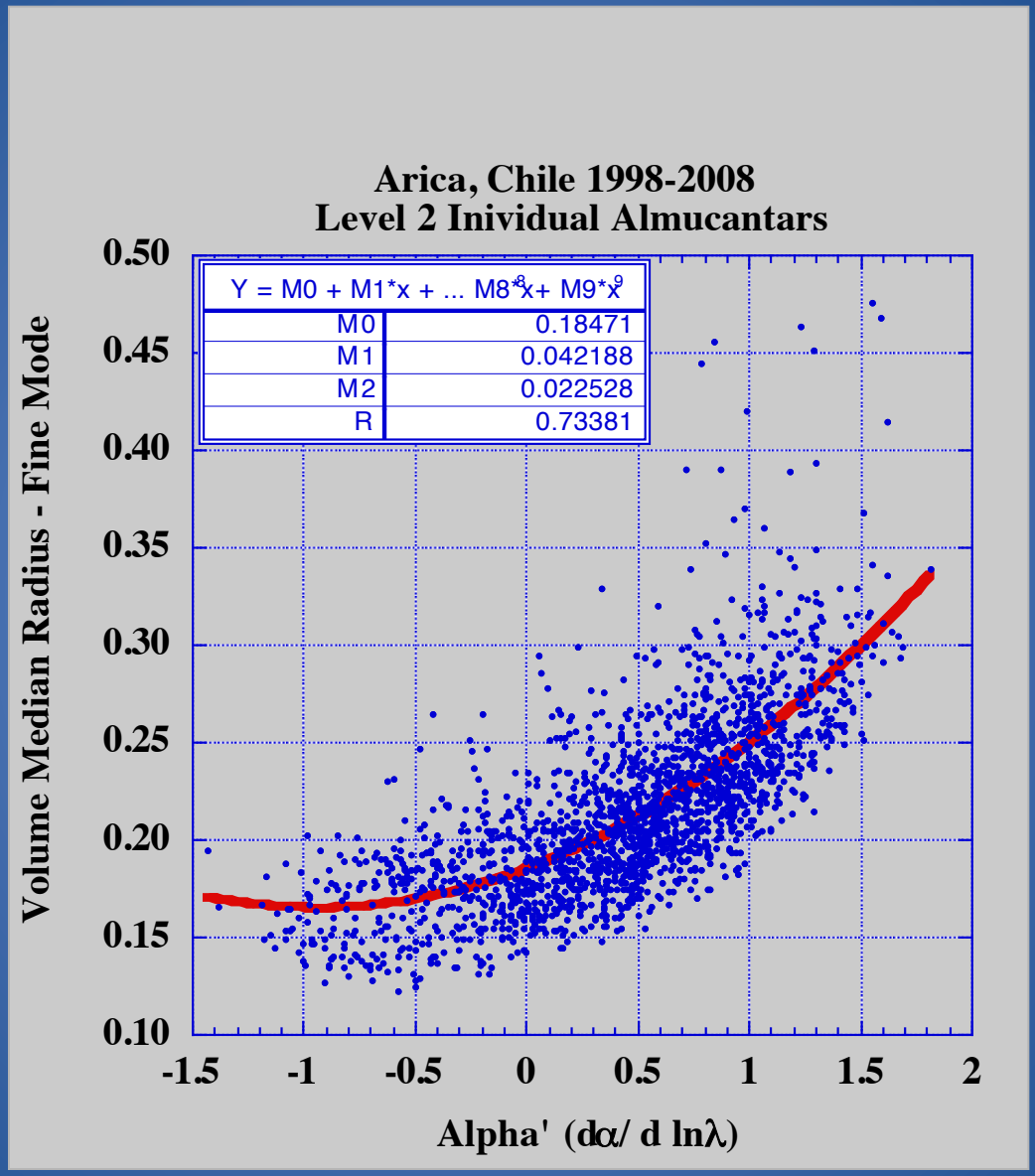


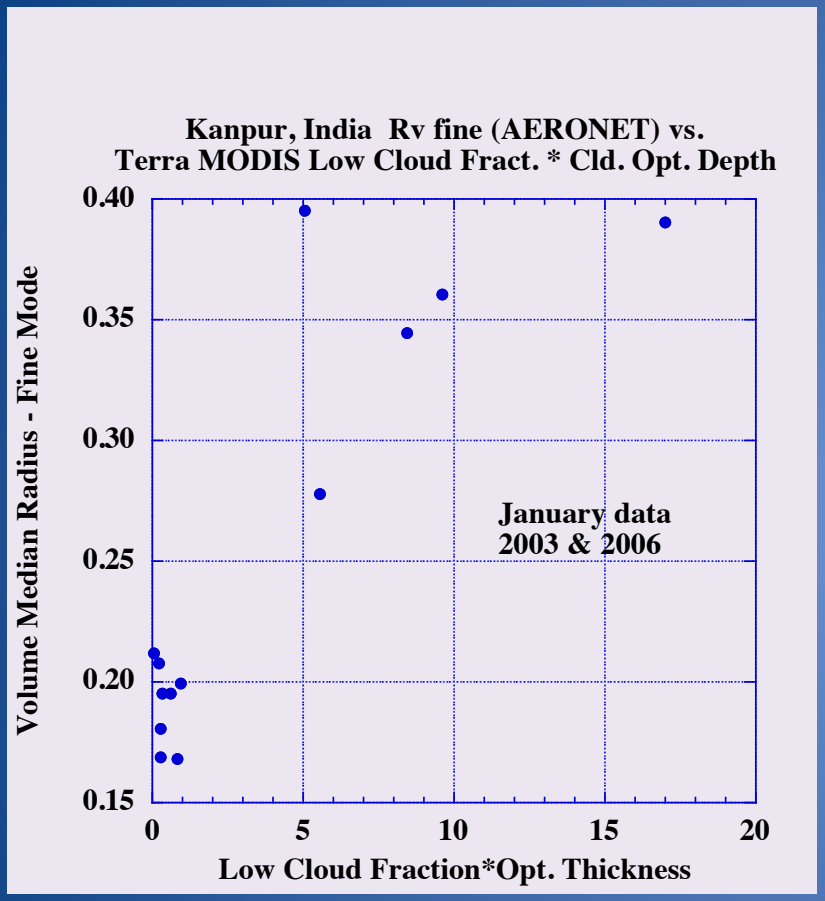


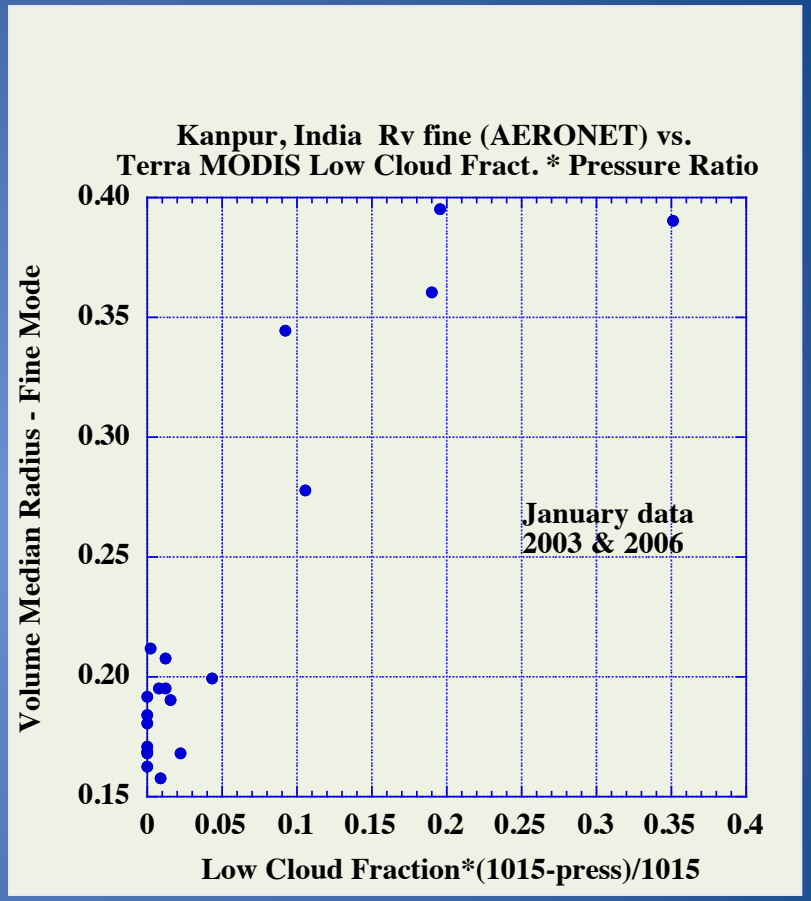

Observation at Fresno
N 36°46'54", W 119°46'23", Alt 0 m,
Since 11:02:2006
Until 11:02:2006
Device 102
Level 2.0 - Quality Assured Data
Spectral AOT
m,
AOT 1019 : 0.1298 ± 0.0299
AOT 870 : 0.1699 ± 0.0323
AOT 674 : 0.2283 ± 0.0406
AOT 441 : 0.3628 ± 0.0542
AOT 500 : 0.3188 ± 0.0494
AOT 380 : 0.4006 ± 0.0601
AOT 339 : 0.4303 ± 0.0613
0.6
0.5
0.4
0.3
0.2
0.1
0.0
15
16
17
18
19
11
FEB
2006

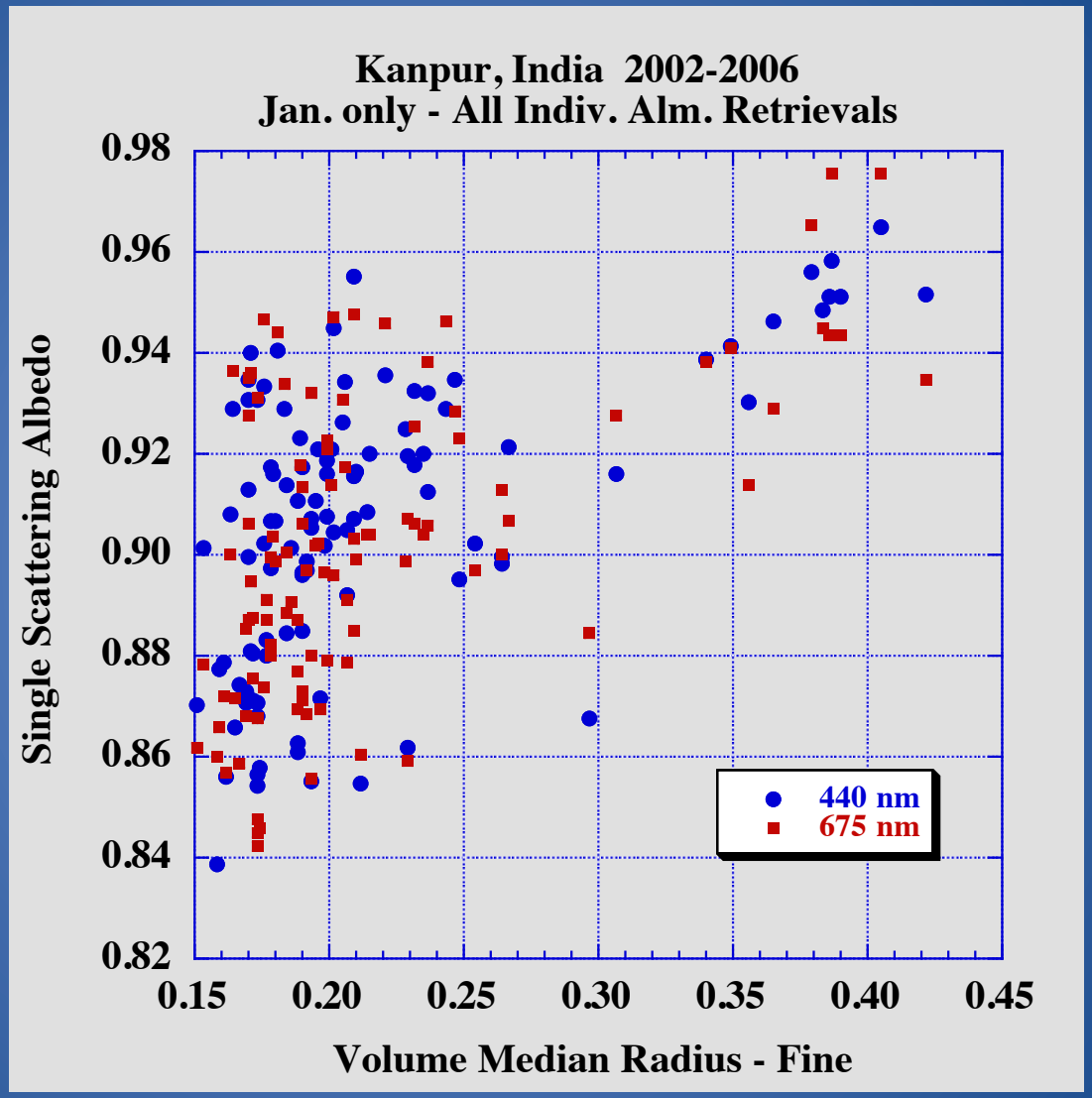

Observation at Fresno
N 36°46'54", W 119°46'23", Alt 0 m,
Since 11:02:2006
Until 11:02:2006
Device 102
ALPHA - Wavelenght exponent
Symb lam/lam <Alpha> StD
WEXP 441/870 : 1.1297 ± 0.0717
1.3
1.2
1.1
1.0
15
16
17
18
19
11
FEB
2006


Fresno, CA Feb. 11, 2006 morning
dV/ d (ln r) [µm³/µm²]
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.1
1
10
Radius (µm)
16:17:54
16:47:50
17:14:45
18:14:48
19:14:52


Arica, Chile 1998-2008
Level 2 Inividual Almucantars
Y = M0 + M1*x + ... M8*x^8 + M9*x^9
M0 0.18471
M1 0.042188
M2 0.022528
R 0.73381
Volume Median Radius - Fine Mode
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
-1.5
-1
-0.5
0
0.5
1
1.5
2
Alpha' (dα/ d lnλ)


Kanpur, India Rv fine (AERONET) vs.
Terra MODIS Low Cloud Fract. * Cld. Opt. Depth
Volume Median Radius - Fine Mode
0.40
0.35
0.30
0.25
0.20
0.15
0
5
10
15
20
Low Cloud Fraction*Opt. Thickness
January data
2003 & 2006


Kanpur, India Rv fine (AERONET) vs.
Terra MODIS Low Cloud Fract. * Pressure Ratio
Volume Median Radius - Fine Mode
0.40
0.35
0.30
0.25
0.20
0.15
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Low Cloud Fraction*(1015-press)/1015
January data
2003 & 2006


Kanpur, India 2002-2006
Jan. only - All Indiv. Alm. Retrievals
Single Scattering Albedo
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Volume Median Radius - Fine
440 nm
675 nm

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The influence of size-dependent droplet composition on pollutant processing by fogs

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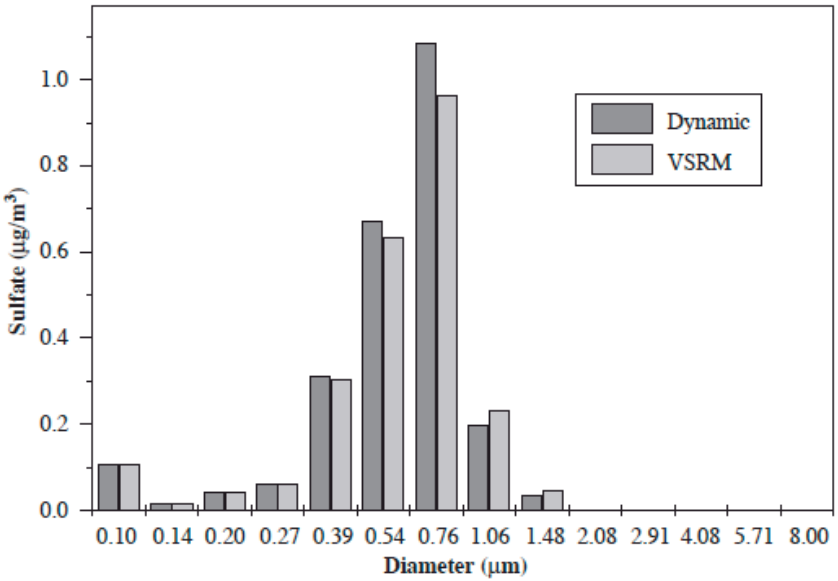
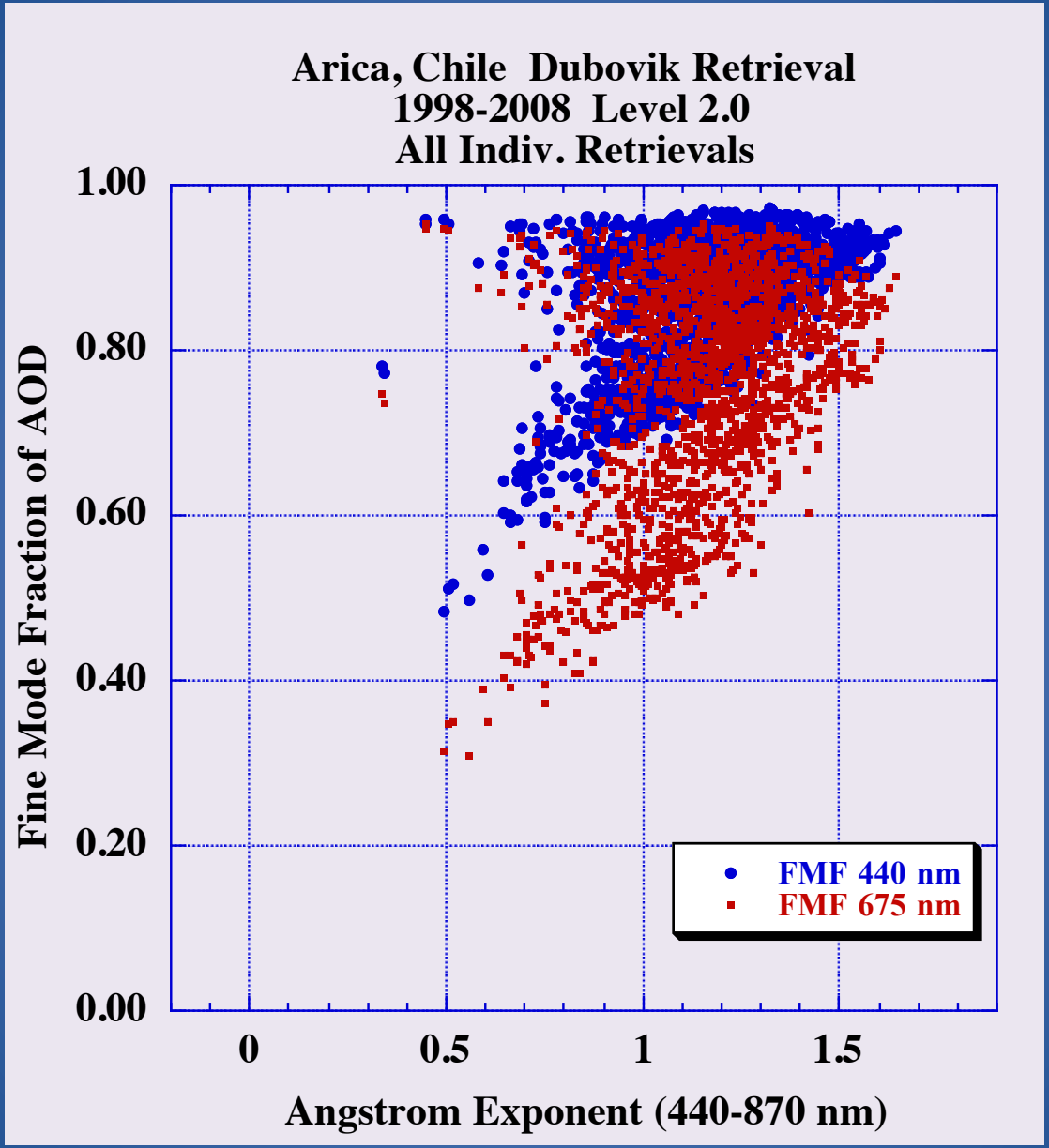


Fig. 9. The final size distribution of sulfate predicted by the VSRM and dynamic fog model. With a good estimate of deposition rates, the VSRM approaches the predicted size distribution of a much more highly size-resolved model but for a much lower computational cost. Time zero is the beginning of the simulation at 6 p.m. of the first day.

Modeled Sulfate Mass distribution – Fog Processing


Arica, Chile Dubovik Retrieval
1998-2008 Level 2.0
All Indiv. Retrievals
Fine Mode Fraction of AOD
1.00
0.80
0.60
0.40
0.20
0.00
0
0.5
1
1.5
Angstrom Exponent (440-870 nm)
FMF 440 nm
FMF 675 nm