Is there bias in the estimated climate forcing by black carbon aerosols?

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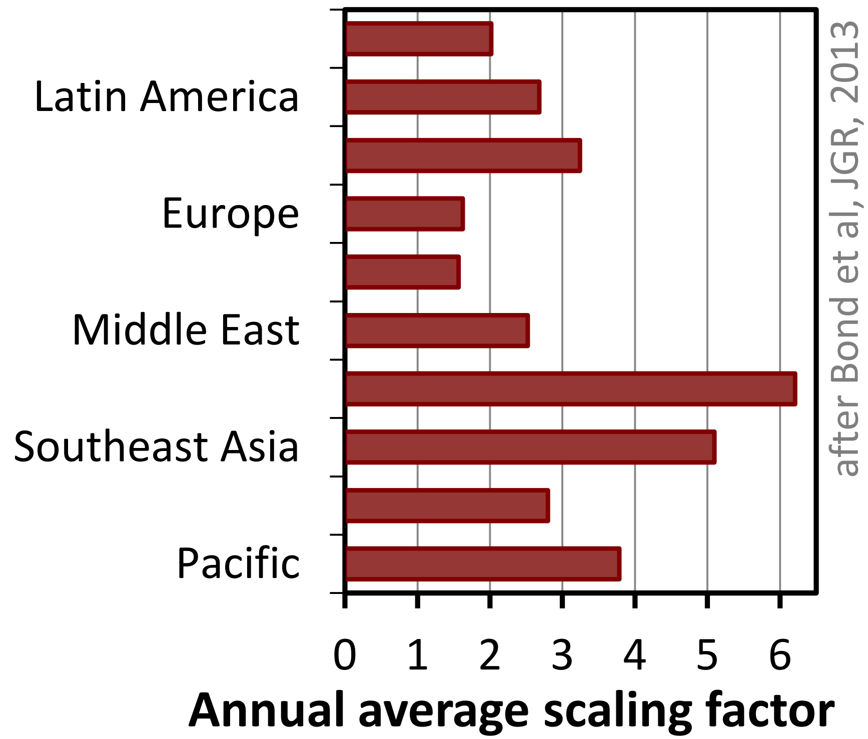
Black Carbon and Climate

- Black carbon, a.k.a. elemental carbon, refractory carbon, and soot, is the dominant light absorbing species in the atmospheric aerosol
- Light absorption by BC heats the atmosphere and decreases the reflectivity of clouds, snow, and ice
- These processes combine to cause a positive (warming) climate forcing that is claimed to be second only to CO_2
- Aerosol absorption optical depth (AAOD) has been used as a proxy for the column burden of BC

Are Model Estimates of BC too Low?

Bounding BC Assessment (Bond et al., JGR, 2013)

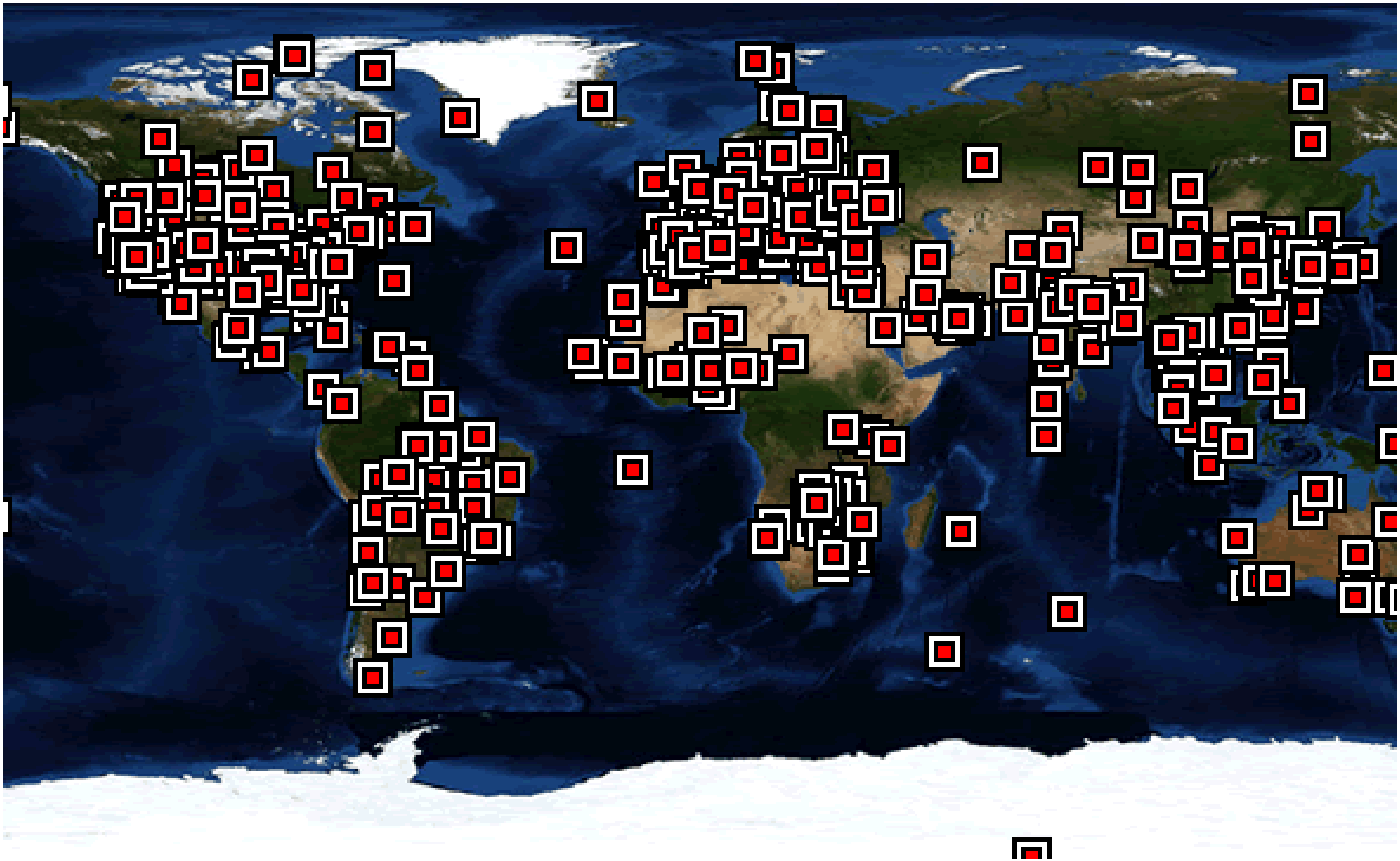
– BC assessed as #2 global-average warming species (+1.1 W m^{-2}, 90% bounds +0.17 to +2.1 W m^{-2})
– *"The AeroCom BC-AAOD values do not agree with the AERONET retrievals, so the BC-AAOD distribution from AeroCom is scaled to agree with the AERONET retrievals"*



– Global-average scaling factor was 2.5, varied by region

How do the AERONET AAOD retrievals compare with *in-situ* measurements?

Spatial Coverage of AERONET



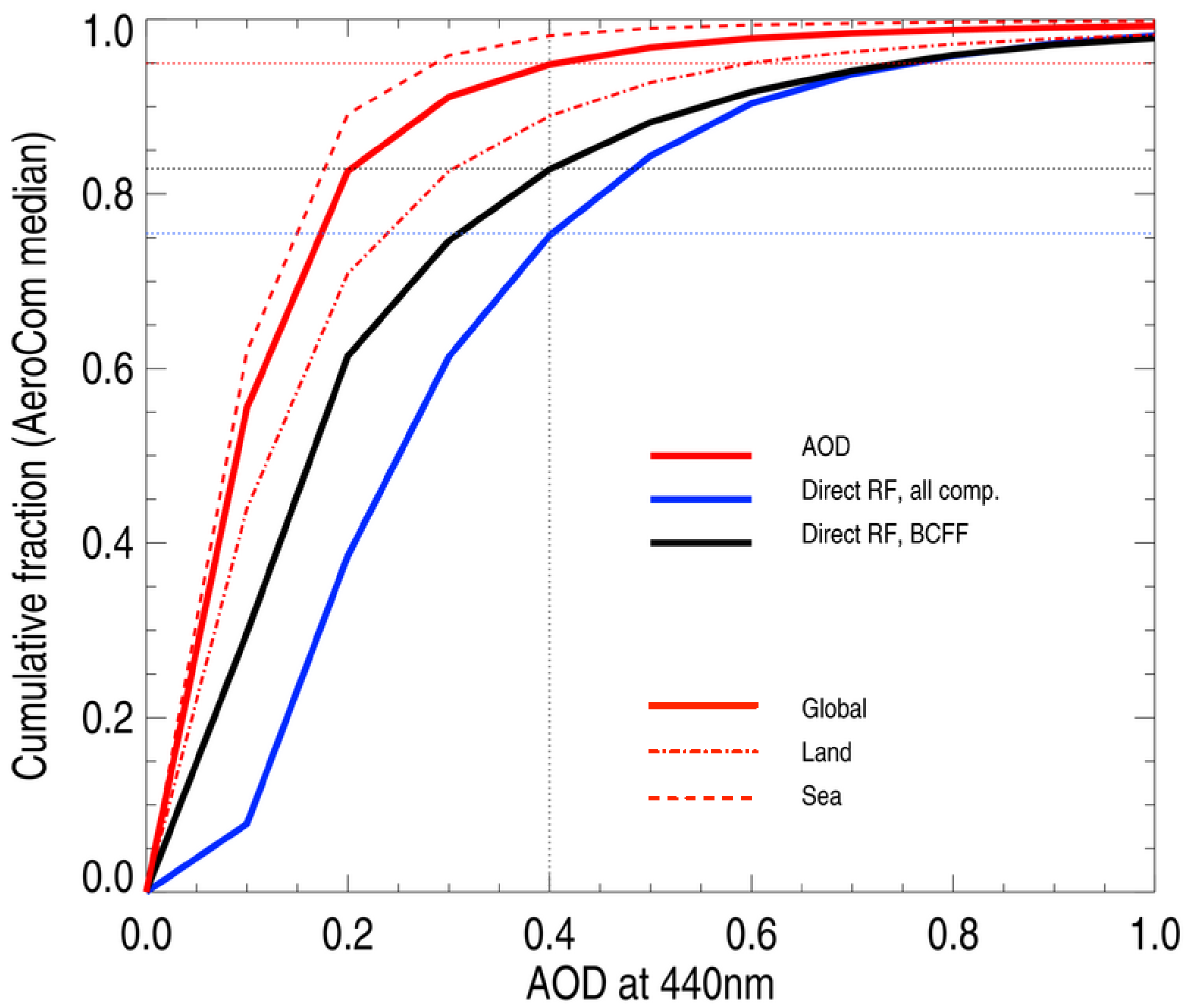
Areal coverage of AERONET retrievals

- AERONET Level 2.0 almucantar retrievals (highest quality) require aerosol optical depth at 440 nm wavelength (AOD_{440}) greater than 0.4, in addition to other quality-control criteria
- **How much of the globe meets these criteria?**
  - Four global models have submitted daily values of AOD_{440} and monthly values of total aerosol direct radiative forcing and fossil-fuel black carbon direct forcing for 2006-2008 to the AeroCom Phase II archive
  - These models were used to evaluate the fraction of Earth's surface where AERONET Level 2.0 AAOD retrievals are possible (ignoring clouds and darkness)

Cumulative fraction of AOD and forcing

95% of Earth's surface has modelled $AOD_{440} < 0.4$

83% of BC fossil-fuel forcing comes from areas with $AOD_{440} < 0.4$



How to increase areal coverage?

- Bond et al (2013) used AERONET Level 1.5 retrievals (greater uncertainty) to increase coverage
- To reduce uncertainty, they only included Level 1.5 retrievals where all of the Level 2.0 quality criteria were satisfied except for AOD_{440}>0.4 ("Level 1.5*")
- They assumed that the larger retrieval errors for the AOD_{440}<0.4 cases were random, and that sufficient averaging would reduce those errors

But, what if there are systematic errors in the retrievals when AOD is low?

Measurement Methods and Data

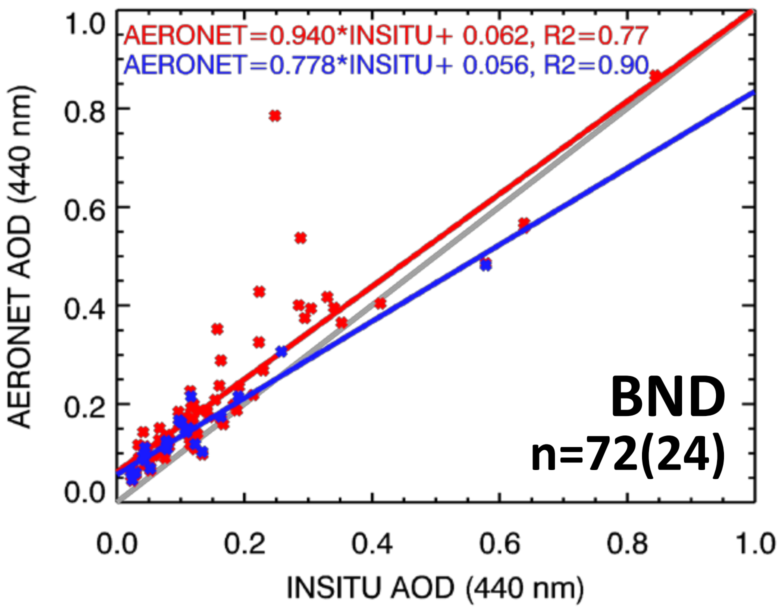
AERONET

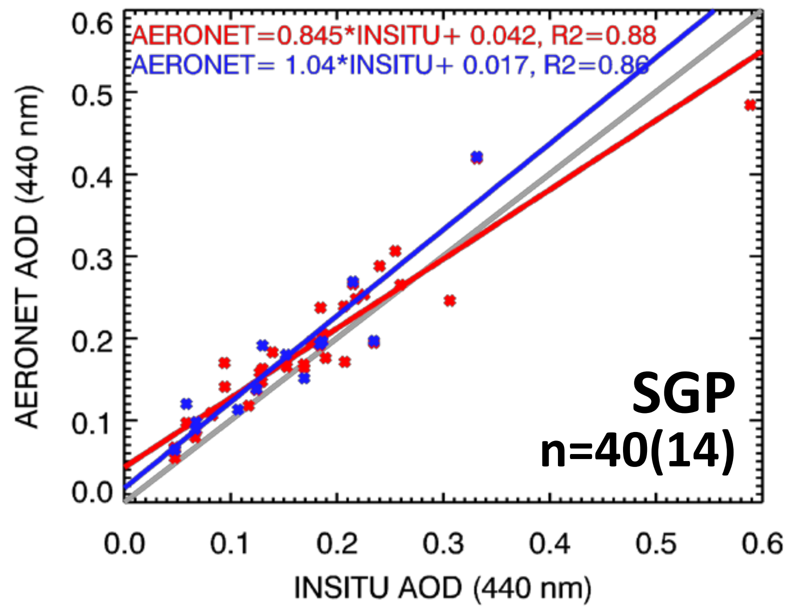
- CIMEL sun/sky radiometer at Bondville (BND) and Southern Great Plains (SGP) sites in USA
- Level 1.5 retrievals of AAOD and single-scattering albedo, limited to cases when Level 2.0 almucantar retrievals were available (Level 1.5*)
- Same selection procedure as used in Bond et al., 2013
- Measurement wavelengths ca. 440 and 670 nm

In-situ

- Cessna 206 airplane sampled particles with D<7μm
- 401 flights at BND (2006-2009), 302 at SGP (2005-2007)
- Particle-Soot Absorption Photometer measured light absorption coefficient at low RH
- Integrating nephelometer measured light scattering, adjusted to ambient RH
- Measurement wavelengths 467 and 660 nm (PSAP) and 450 and 700 nm (Neph), adjusted to 440 and 670 nm

AOD Comparison

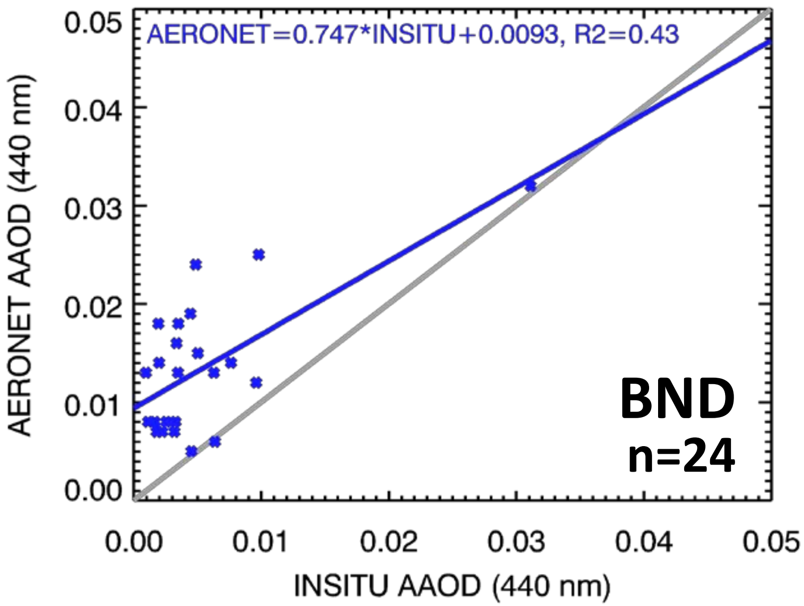


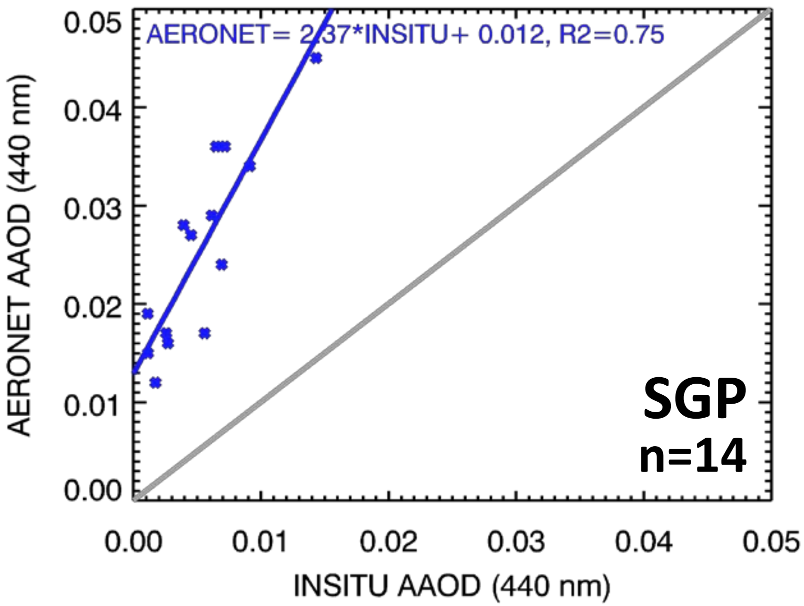


- Good agreement (ca. 20%) between AERONET and in-situ measurements of aerosol extinction
- Similar results for 440 and 670 nm wavelengths

Red points: All Level 2.0 AOD. Blue points: Level 2.0 AOD with almucantar retrievals
n=72(24) denotes 72 flights with Level 2.0 AOD, 24 flights with almucantar retrievals

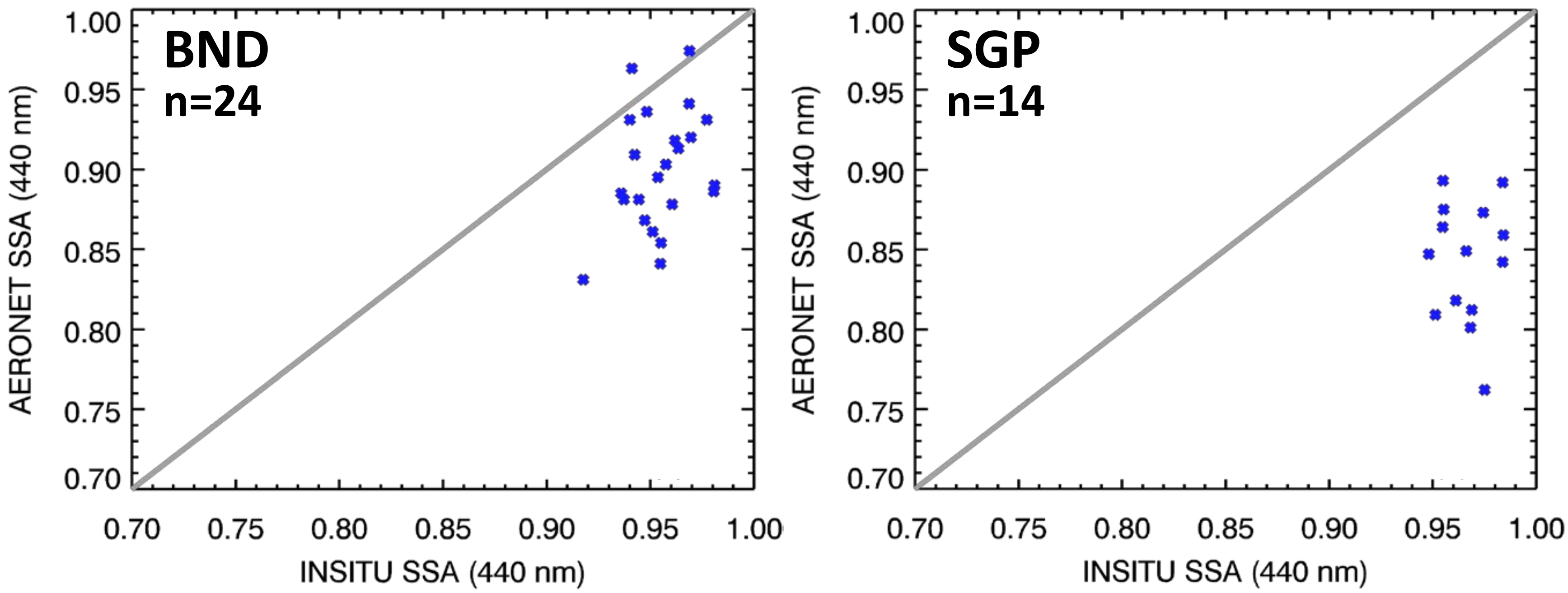
AAOD Comparison





- AERONET Level 1.5* results are significantly greater than in-situ
- Poorer correlation than for AOD, especially at BND
- Similar results for 440 and 670 nm wavelengths

SSA Comparison



- AERONET Level 1.5* results are significantly more strongly absorbing than in-situ
- AERONET and in-situ results are poorly correlated
- Similar results for 440 and 670 nm wavelengths

Summary of Direct Matchups

AERONET AOD tends to be slightly higher than and highly correlated with in-situ AOD

- Could be caused by using a low humidification multiplier for the in-situ scattering data
- Undersampling of supermicrometer particles also possible

AERONET Level 1.5* retrievals yield more absorption than in-situ measurements

- Humidification multiplier of scattering data is not involved in AAOD comparison
- Possible undersampling of supermicrometer particles is not important for AAOD comparison because most of the absorption is due to submicrometer particles

Conclusions

- Direct comparisons of in-situ measurements at two continental US site, indicate that the AERONET retrievals are biased towards stronger absorption under conditions of $AOD_{440} < 0.4$
- Direct comparisons in the published literature nearly all show that AERONET retrievals yield more aerosol absorption than in-situ measurements
- Statistical comparisons of results from models and in-situ measurements also suggest a bias in the retrievals at low AOD
- Up-scaling of modelled BC amounts to agree with AERONET AAOD retrievals does not appear to be warranted

The published BC average climate forcing of +1.1 W m^{-2} may be an over-estimate, but may still be within the published 90% confidence interval of +0.17 to +2.1 W m^{-2}

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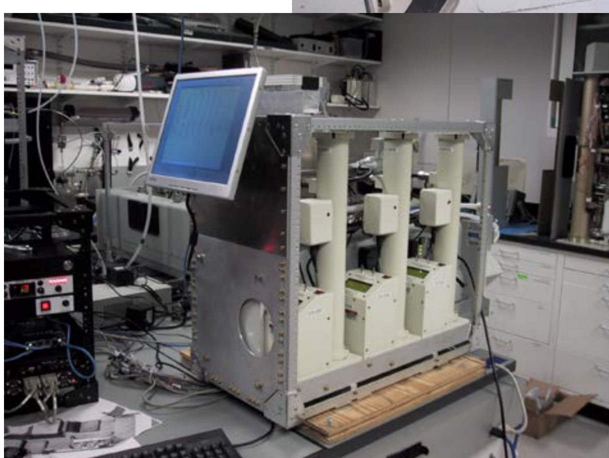
Supplementary Material

- Sensitivity of results to width of match window
- Climatology of vertical profiles of extinction and SSA
- Seasonality of vertical profiles of scattering and SSA
- Time-height cross-sections of light scattering

What does AERONET measure?

- The **AE**rosol **RO**botic **NET**work is a global federation of ground-based, remote sensing, aerosol networks that measures sun and sky radiance at visible and near-IR wavelengths
- Spectral aerosol optical depth is derived from the sun-pointing measurements: $AOD = \int_{SFC}^{TOA} (\sigma_{sp} + \sigma_{ap}) dz$ where σ_{sp} and σ_{ap} are the light scattering and absorption coefficients
- Single-scattering albedo, SSA = σ_{sp} / (σ_{sp}+σ_{ap}), AAOD = AOD * (1-SSA), and much more are retrieved from the sky radiance measurements (almucantar scans) using an inversion algorithm

Airborne Aerosol Observatory

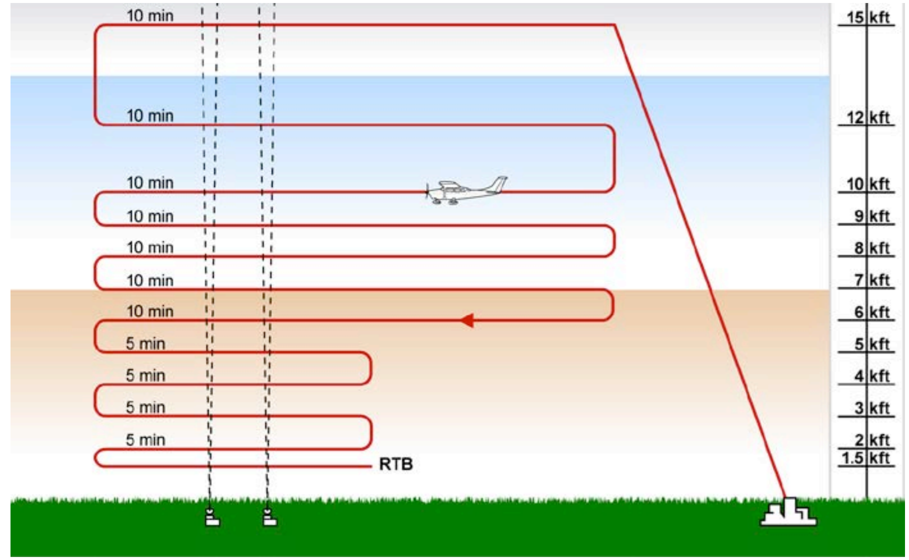


- Routine vertical profiles, 10 levels, 0.5 – 4.6 km asl (0.2-4.3 km agl), near Bondville, Illinois
- Daytime flights only, at arbitrary times during the day
- Aerosol optical, chemical, and microphysical properties were measured
- Trace gas (flask) and ozone (continuous) measurements
- Similar instruments and profiles were flown over SGP

Airborne Aerosol Observatory

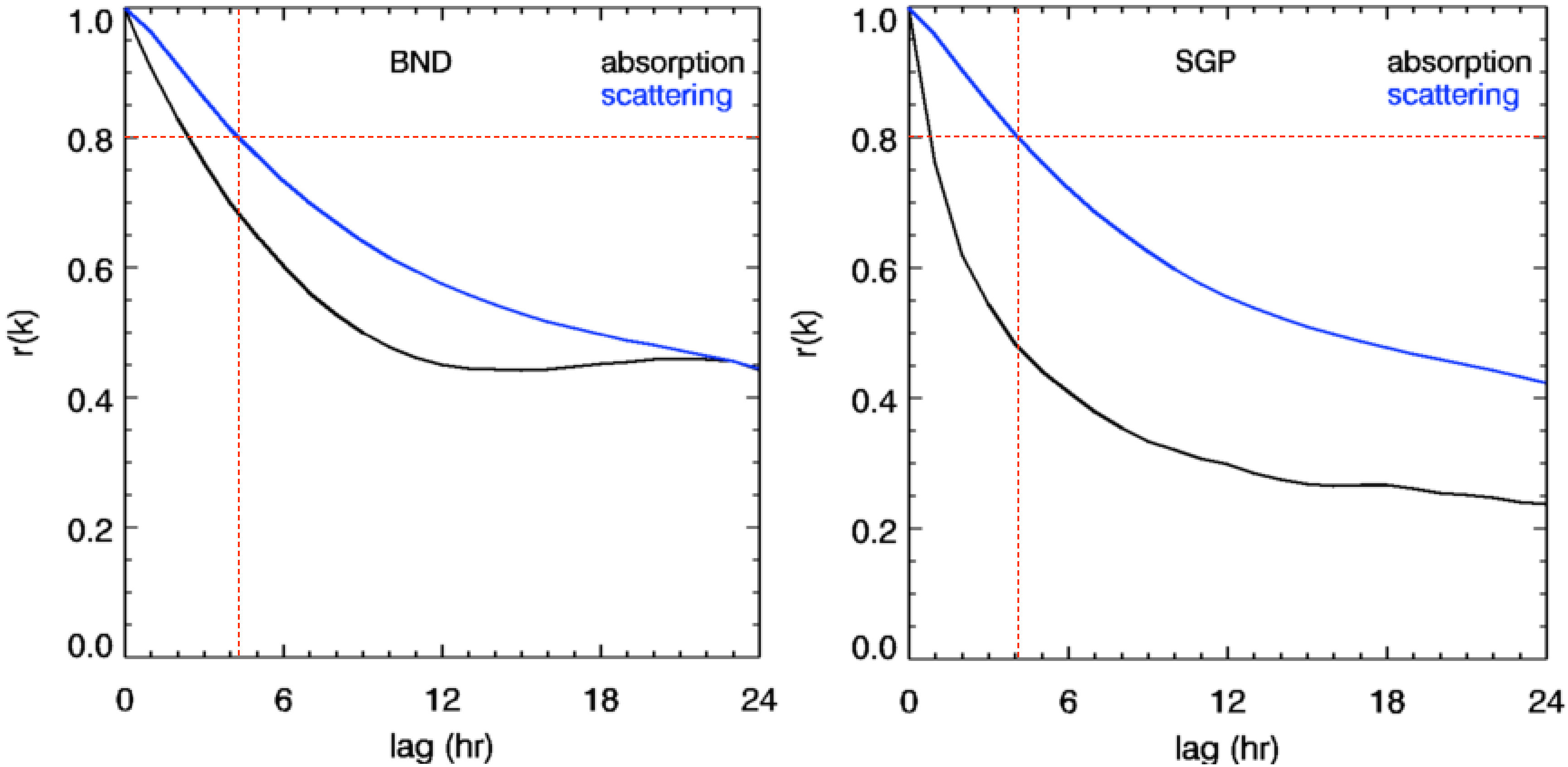
Scientific Objectives

- To obtain a statistically-significant data set of the vertical distribution of aerosol properties.
- To relate these properties to those measured by identical instruments at the surface
  - When can surface measurements be used to estimate column properties?
- To contribute to the verification of aerosol remote sensing retrieval algorithms.



A-Train satellite overpass tracks in the vicinity of the AAO base of operations. Overpasses along each track occur approx. twice per month.

How close do measurement times need to be?



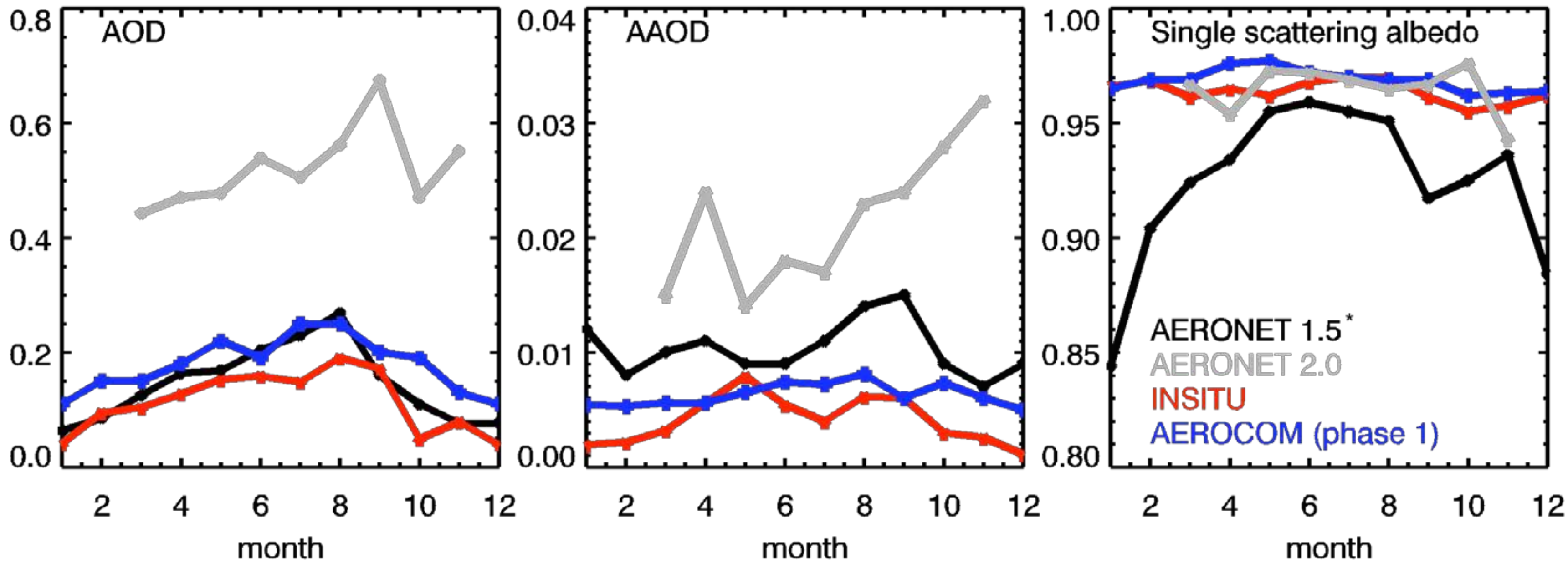
- Lag-autocorrelation analysis of surface measurements determines time window
- Scattering well correlated (r(k)>0.8) out to 4 hr lag
- Absorption less correlated than scattering
- AERONET vs. in-situ comparison time window chosen as ±3-hr based on this analysis

Statistical Comparisons

- Much more data is available for comparisons if we look at the entire record from AERONET, all in-situ profiles, and the long-term surface measurements
- Model results can also be included in the statistical comparisons
- Keep in mind the limitations of these comparisons, as the different data sets are not directly matched in time

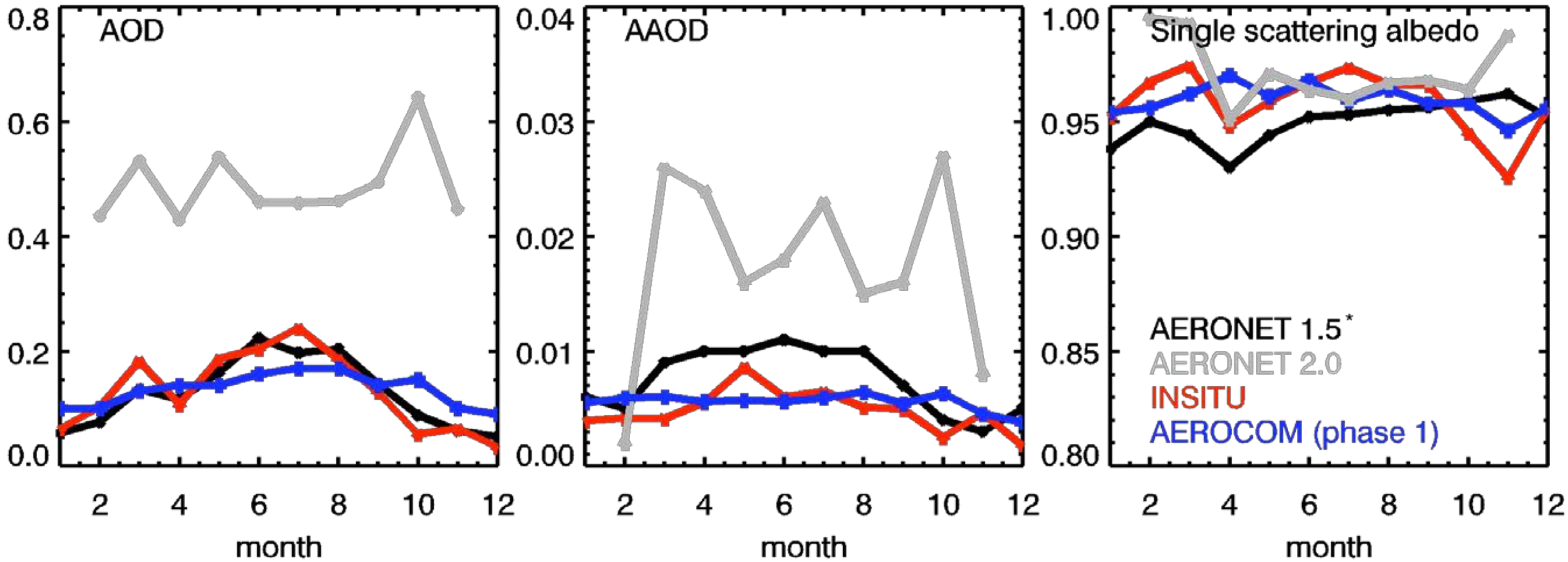
Do we see similar patterns in annual cycles and systematic variability?

Monthly comparisons at BND



- AERONET Level 2.0 AOD and AAOD are much higher than in-situ, model, and Level 1.5* results, as expected
- In-situ AOD and AAOD tends to be lower than AeroCom models
- AERONET Level 2.0 SSA agrees well with in-situ and model results, while Level 1.5* values are much lower (c.f., direct comparisons)

Monthly comparisons at SGP



- As at BND, monthly AOD and AAOD look reasonably close, although AERONET Level 1.5* AAOD tends to be higher than models and in-situ
- As at BND, AERONET Level 1.5* SSA retrievals are lower than Level 2.0 retrievals for all months

Results from both sites suggest that AERONET Level 1.5* retrievals are biased towards more absorption

Literature review of direct matchups

- Multiple studies compare AERONET SSA (or AAOD) with in-situ measurements
- Few of these are suitable for evaluating the accuracy of the AERONET retrievals, which requires complete in-situ profiles matching the AERONET retrievals in space and time
- Other than the BND and SGP measurements, only one direct AAOD comparison study has been published (Corrigan et al., 2008, Maldives). Its 13 profiles showed AERONET-AAOD averaged 20% greater than INSITU-AAOD
- Multiple, direct, column-average SSA comparisons (total 13 profiles) have been published previously.
  - 10 profiles show AERONET-SSA < INSITU-SSA
  - 3 profiles show AERONET-SSA > INSITU-SSA

Most direct matchups show that AERONET retrievals yield more absorption than in-situ measurements

Model comparisons with BC at surface

- There are many long-term measurements of black carbon at surface monitoring sites, some beginning in the 1980's
- These measurements, particularly in the early years, were made with optical techniques that have poorly-understood artifacts.
- Koch et al (2009) compared AeroCom models for 2000 with surface data, and reported *"In regions other than Asia, most models are biased high compared to surface concentration measurements."*
- The surface data were not included in the "Bounding BC" assessment

Do the surface measurements provide any support for the up-scaling of model results?

In-situ vs. modelled equivalent BC at surface

SGP

BND

Skeie et al, ACP, 2011

- **Oslo CTM2 model (Skeie et al., 2011) for 2001-2008**
- **Model does not show a pronounced low bias when compared to in-situ measurements**
- **Model shows much lower range of values**
- **Note the log-scales**

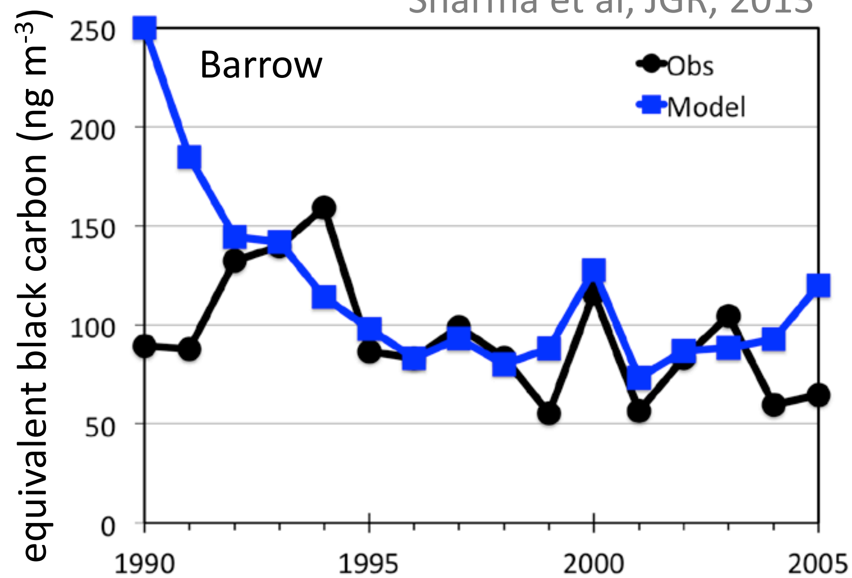
Need to repeat for other sites/models

NIES (Canada) model ⇒ reproduces long-term, wintertime-average trend at Barrow, Alaska

Skeie et al, ACP, 2011

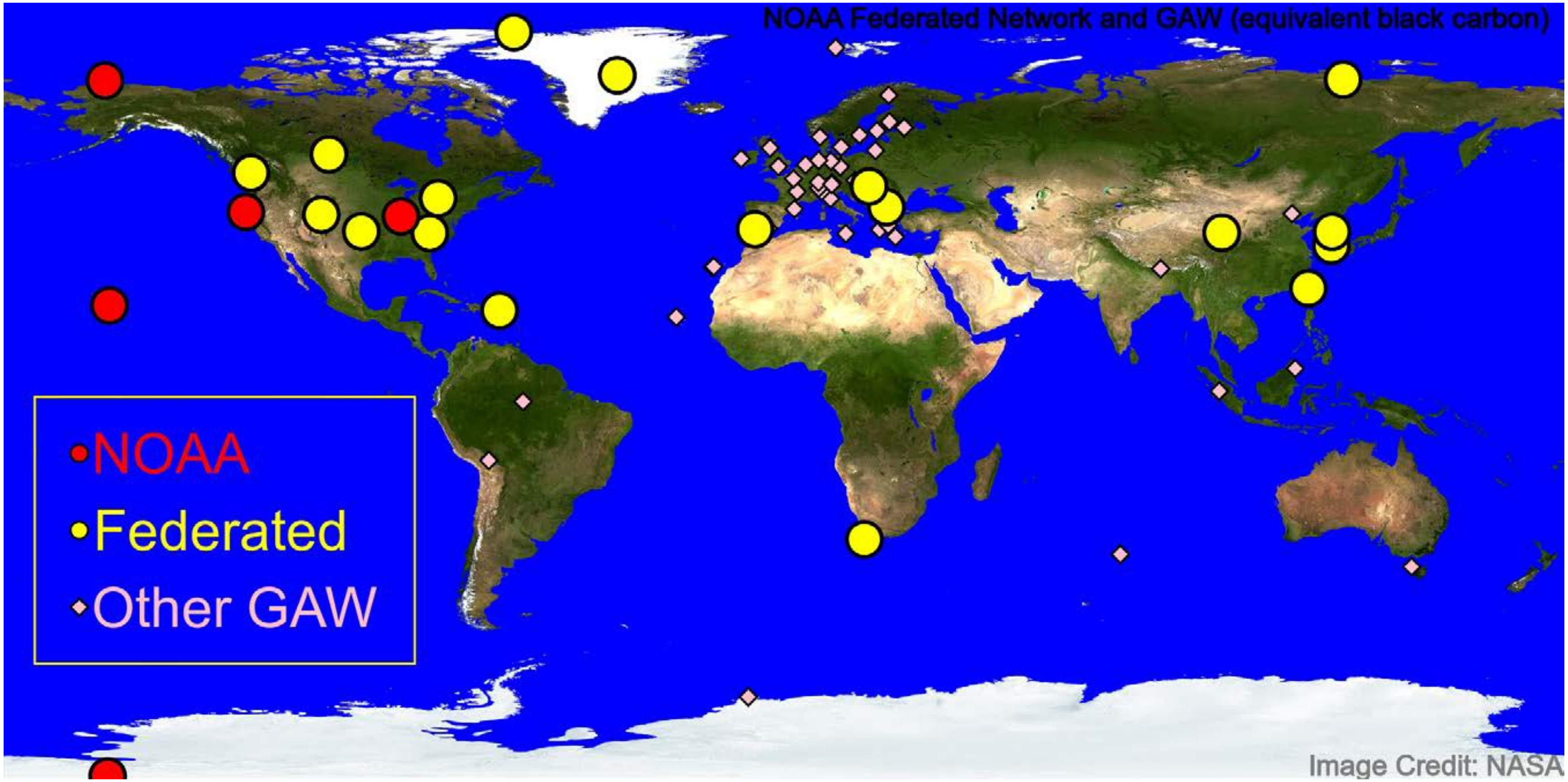
Model
equivalent black carbon (ng m^{-3})

Sharma et al, JGR, 2013



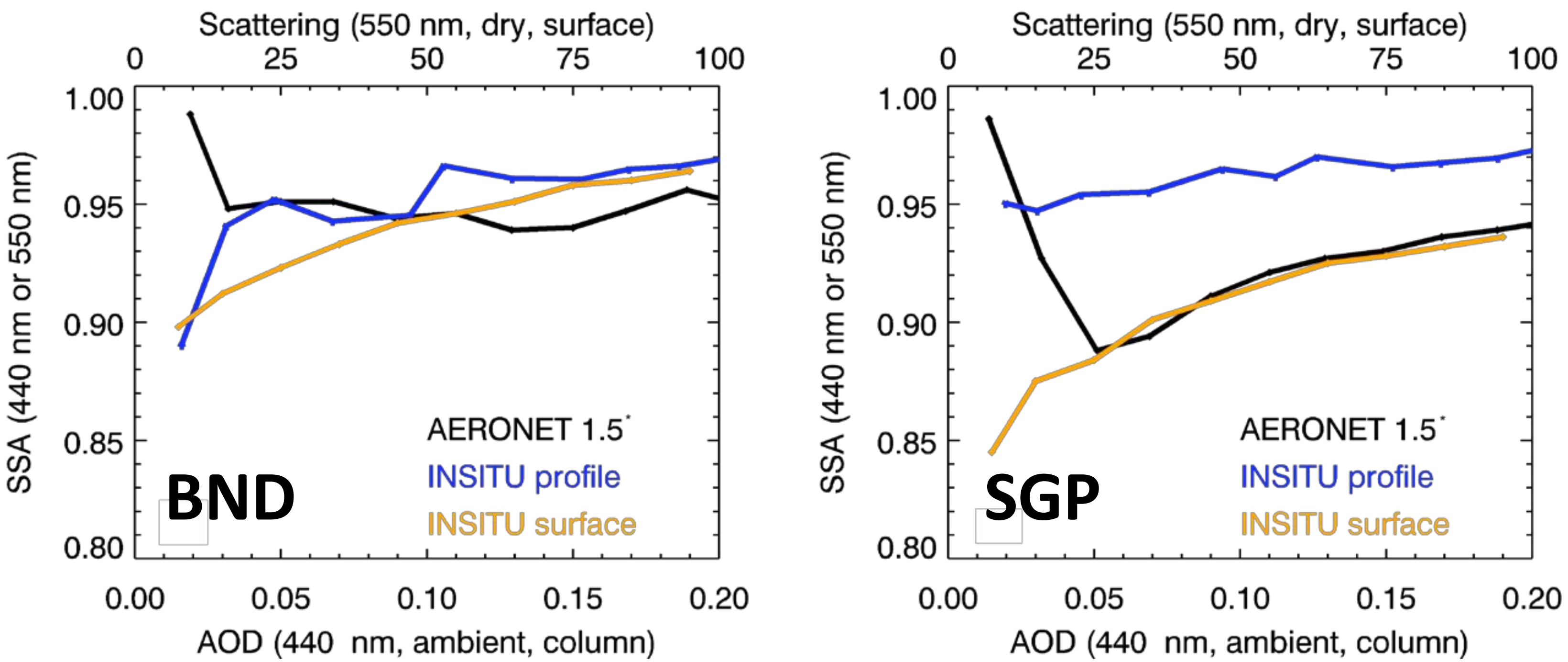
⇐ Oslo CTM2 model is biased low and has less variability than observations (monthly averages, 2001-2008)

Many GAW sites measure BC



Sites shown participate in WMO Global Atmosphere Watch and are listed in GAW metadata as measuring “black carbon” or light absorption coefficient

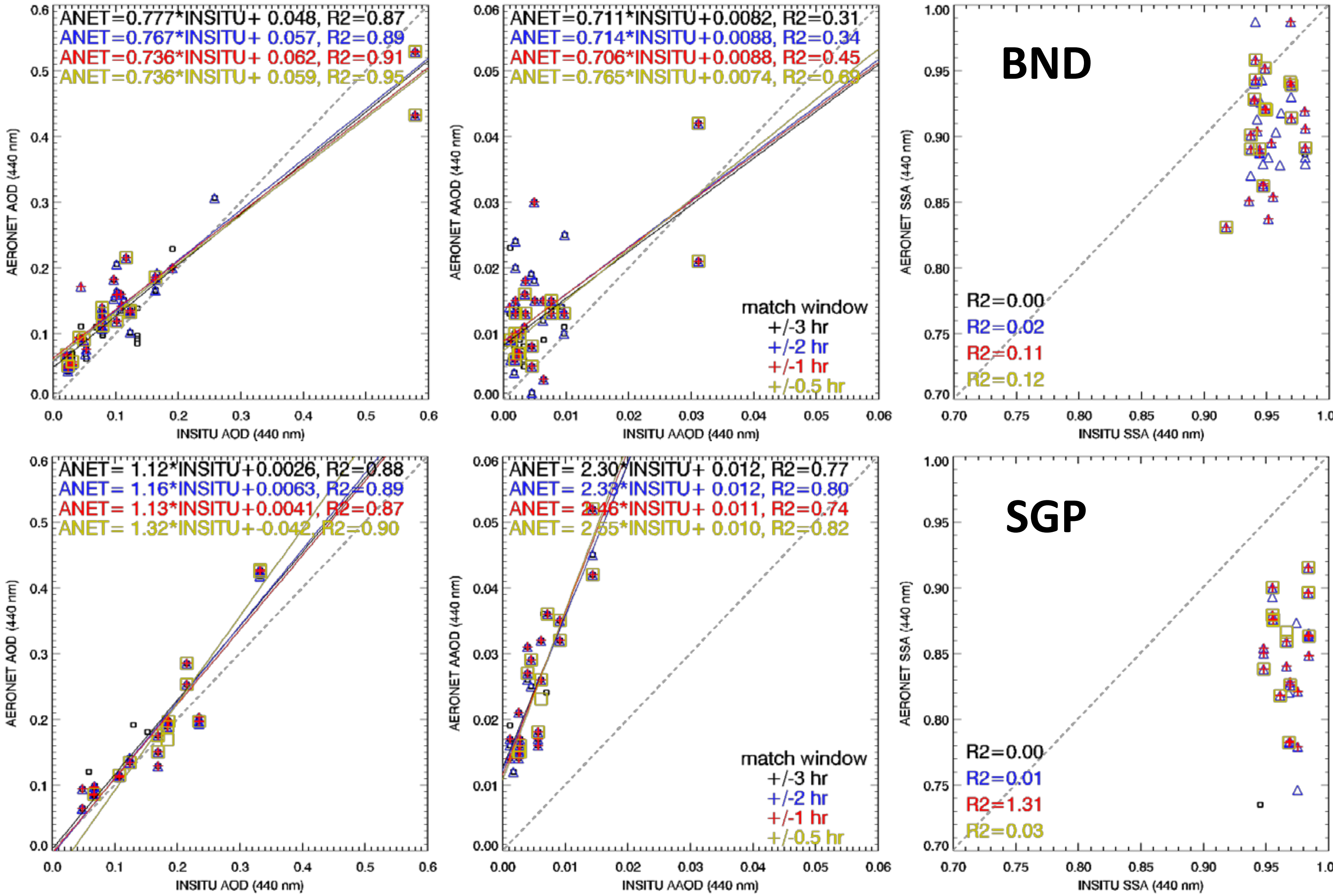
Dependence of SSA on AOD



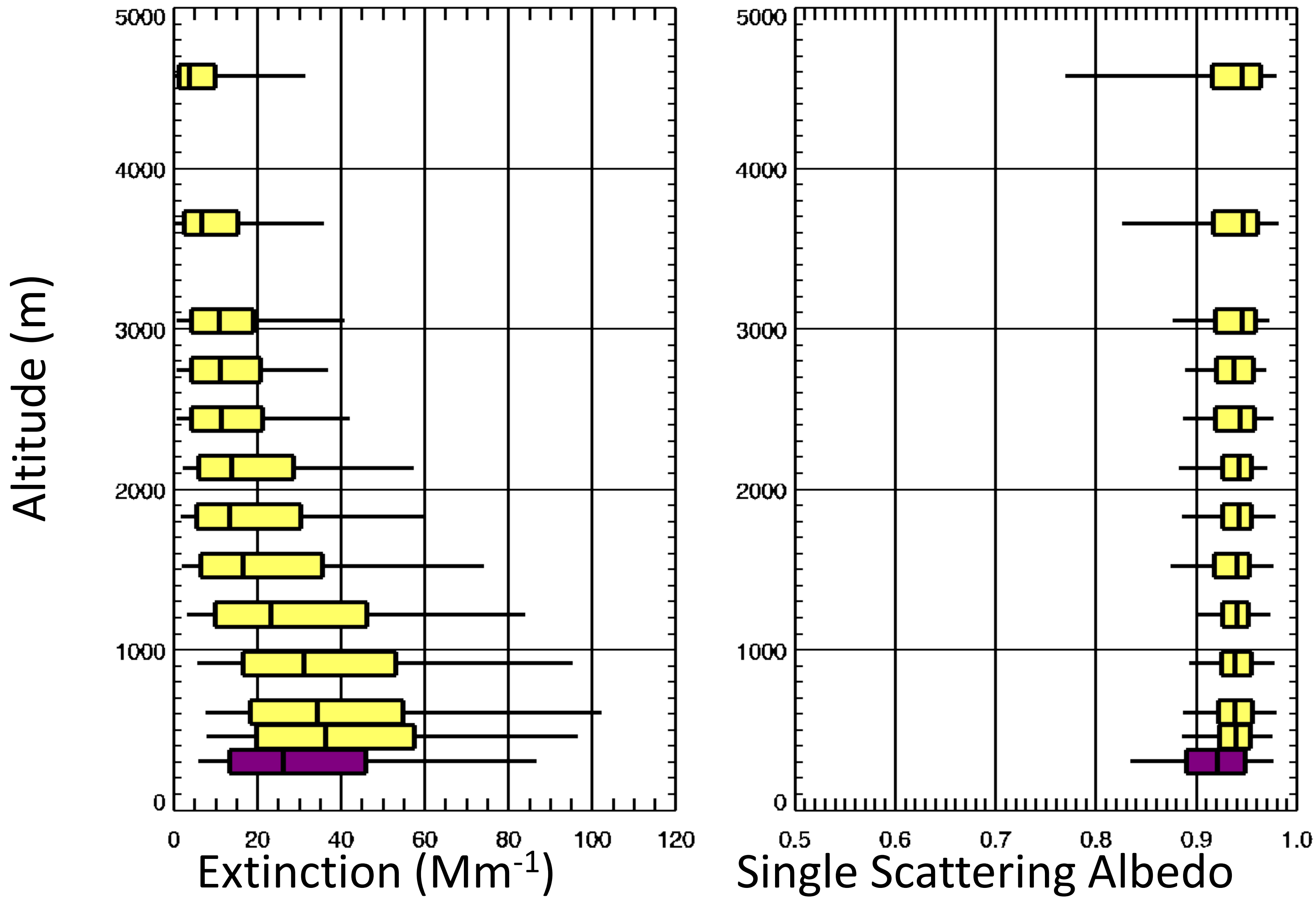
Comparisons with long-term data show similar patterns, except

- **AERONET SSA values are lower than in-situ profiles**
- **AERONET SSA values at the lowest AOD values diverge**
  - Problem with retrievals in cleanest conditions?

Sensitivity to width of match window

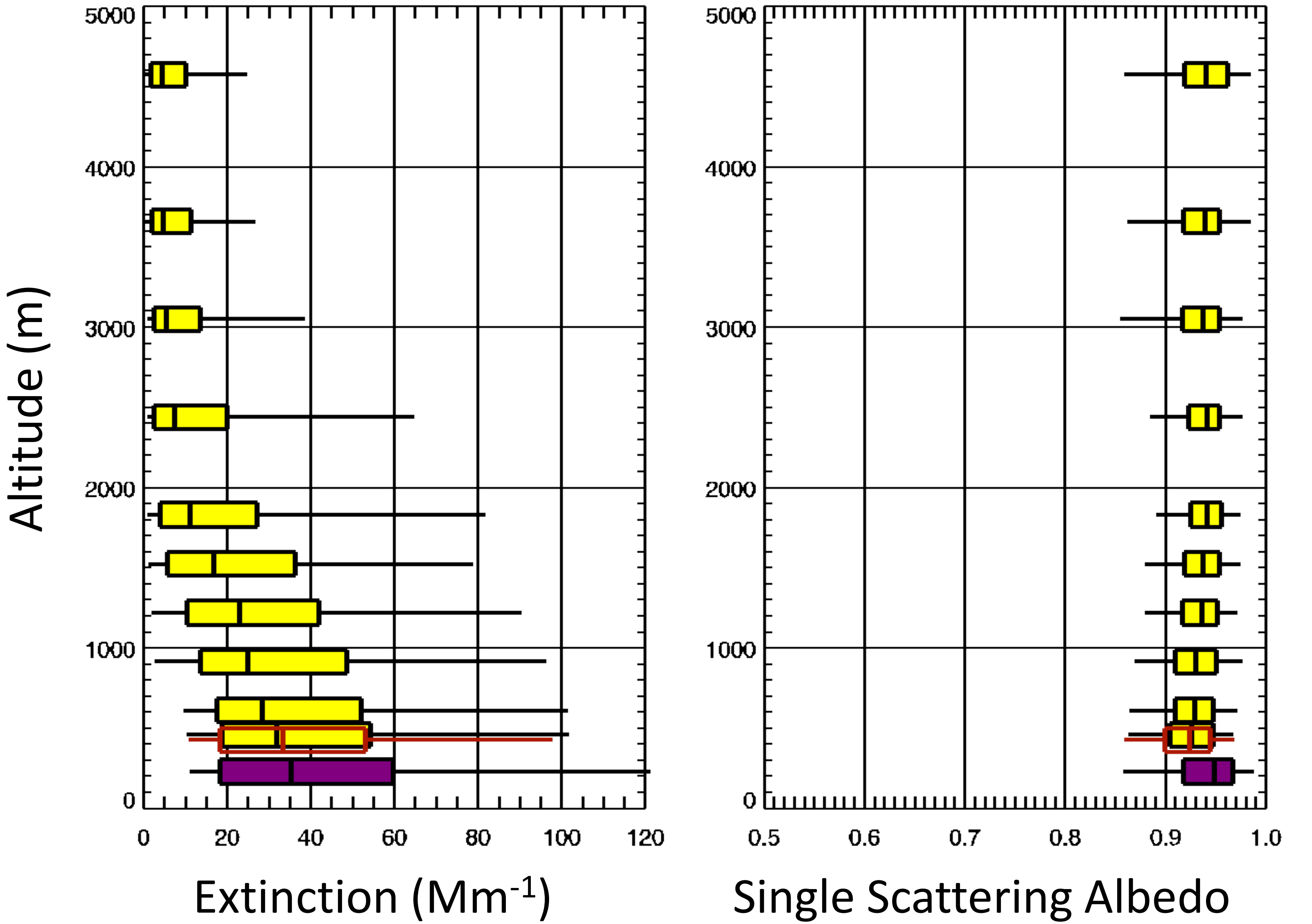


SGP - Surface vs. Aloft (7μm)

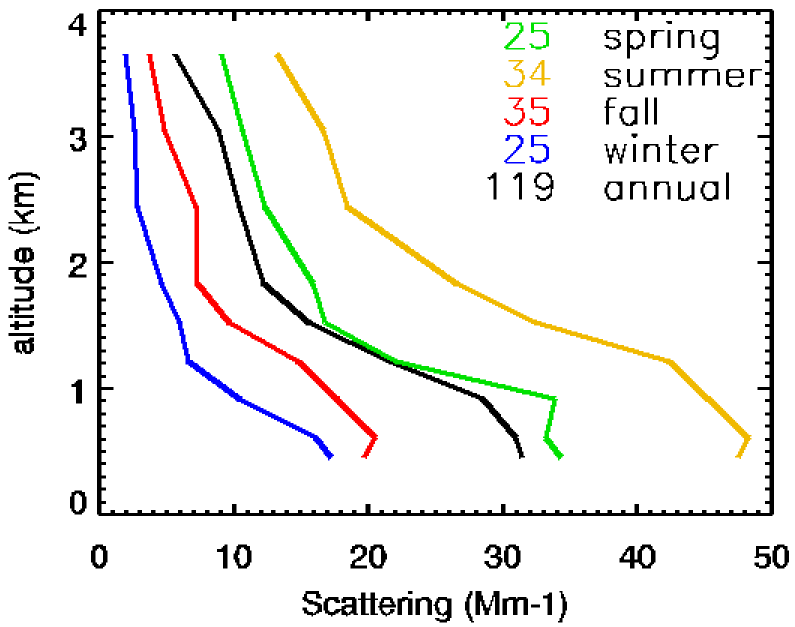


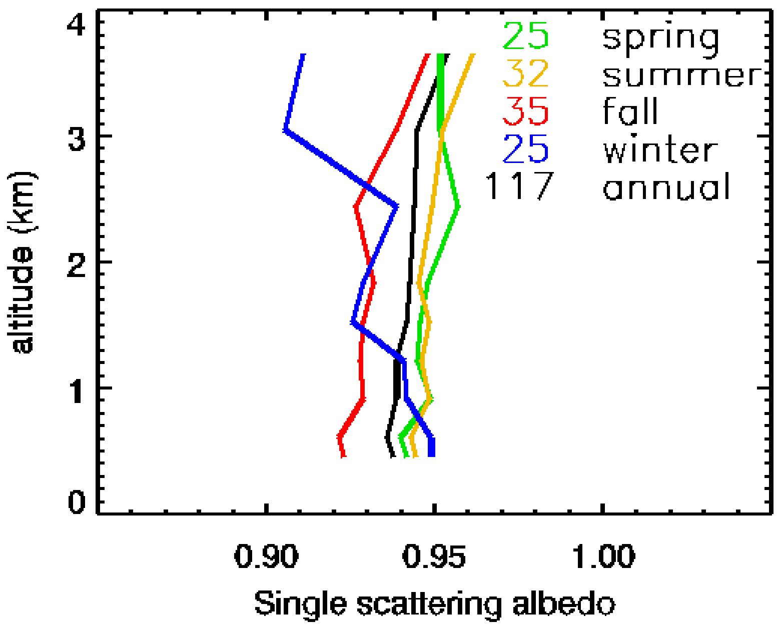
Data from 2005-2007 (new inlet, Cessna206)

BND- Surface vs. Aloft (7μm)



SGP - Seasonal Profiles (sub7μm inlet)



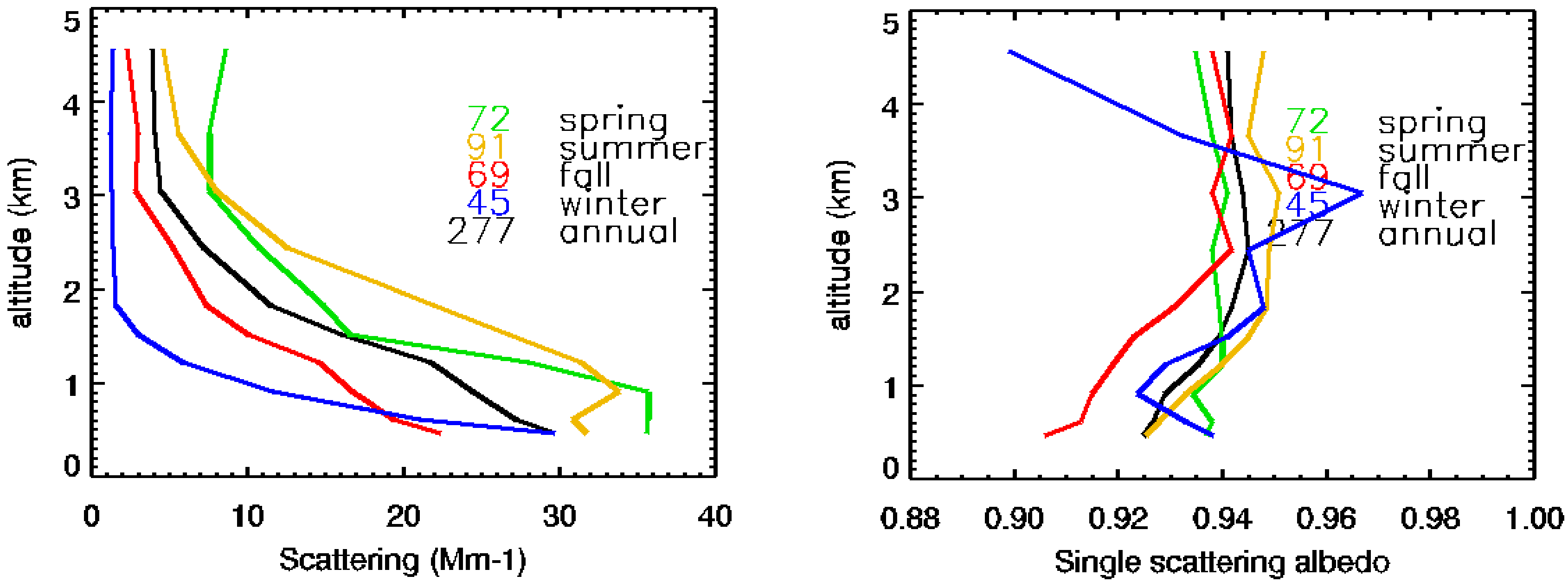


Scattering decreases with altitude, SSA relatively constant

Spring/summer tens to have greatest amounts of aerosol
Winter tends to have the least amount of aerosol

Fall/winter tend to have the lowest single-scattering albedo

BND – Seasonal Profiles (sub7μm inlet)

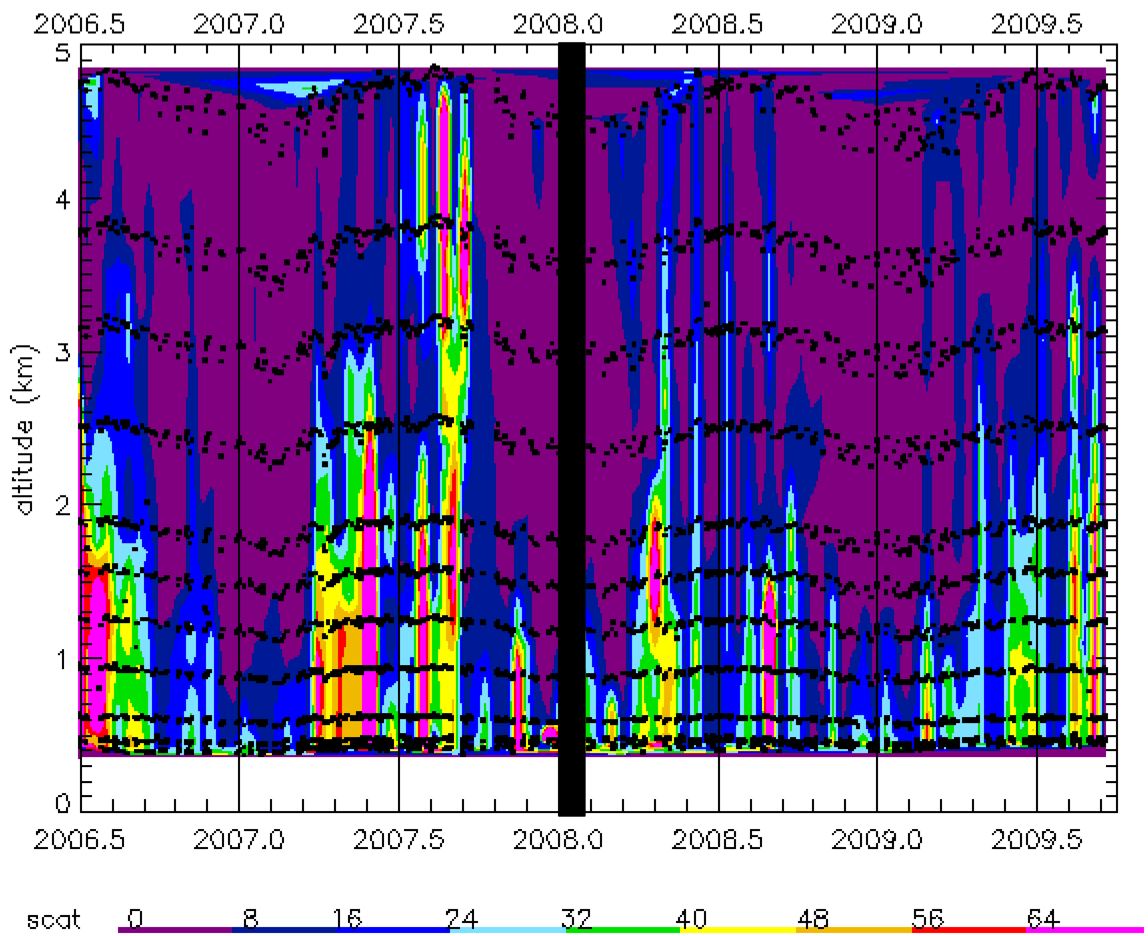


Scattering decreases with altitude, SSA relatively constant

Spring/summer tend to have greatest amounts of aerosol
Winter tends to have the least amount of aerosol

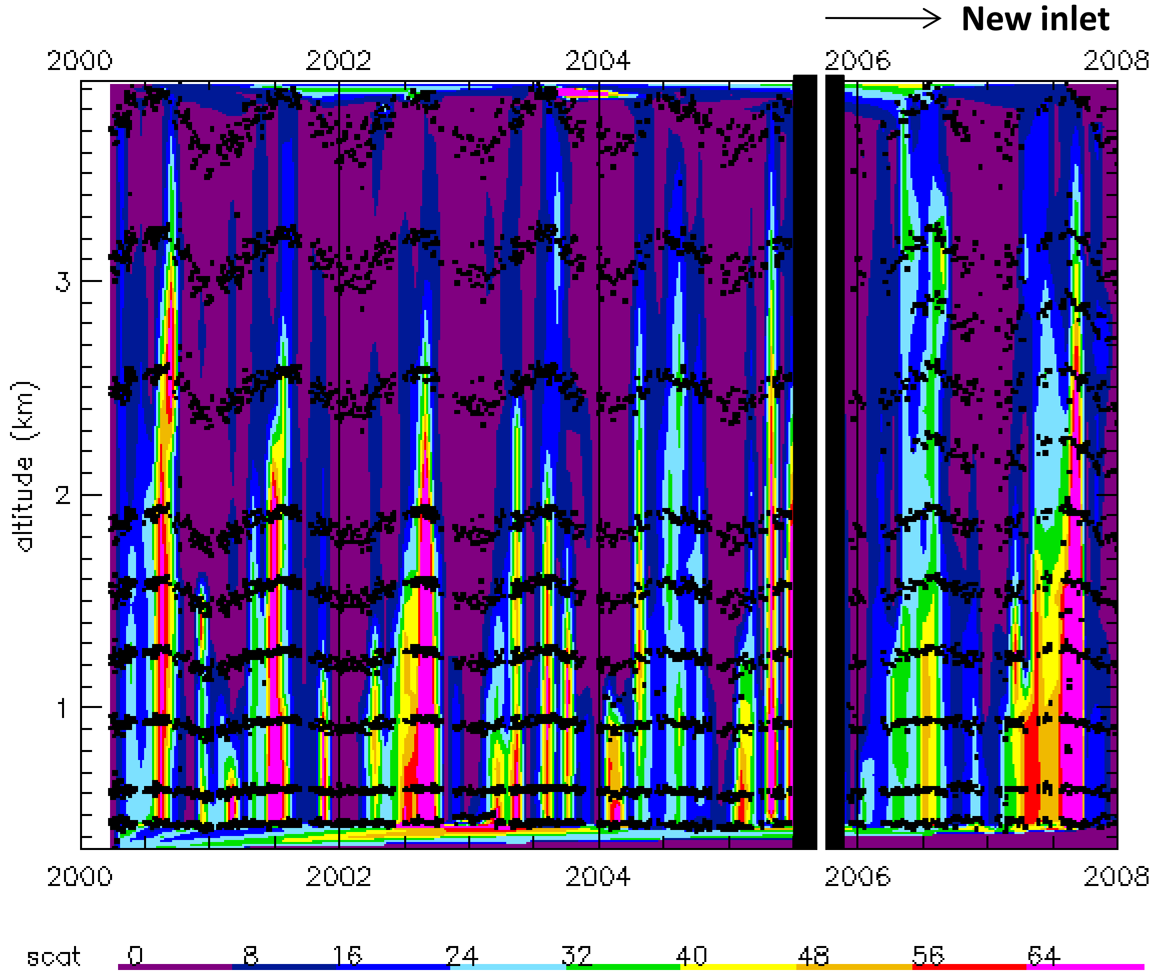
Fall tends to have the lowest single-scattering albedo

BND - scattering as f(z,t)



Strong seasonality in scattering – more aerosol and at higher altitudes in summer. Less aerosol, confined to <1500m during winter

SGP – scattering as f(z,t)



Strong seasonality in scattering – more aerosol and at higher altitudes in summer.
Less aerosol, confined to <1500m during winter
Effect of inlet change not as noticeable on scattering...