Ratios of Extinction, Mass, Surface Area to Backscatter, and Mass and Surface area to Extinction derived from 30 years of mid latitude OPC measurements

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- Motivation
- The basic equations
- Profiles of temperature, weight fraction, index of refraction
- Profiles of Backscatter, Extinction, Mass, Surface Area
- Profiles of the ratios: E:B, M:B, SFA:B, M:E
- Scatter plots to derive dependencies of E:B, M:B, SFA:B, M:E
- Application to Tskuba Lidar data, from Osamu Uchino at NIES in Japan

The OPC data presented here are publicly available at https://doi.org/10.15786/21534894

Motivation

- E/B ratio - the Lidar ratio
  - Needed for lidar measurement retrievals
  - Can be used to convert lidar profiles to extinction profiles, and aerosol optical depth, e. g. Ridley et al., 2014, GRL, *41,* 7763–7769
- m/B, m/E ratios
  - Allows optical measurements to be used to estimate aerosol mass, useful for estimating aerosol lifetimes in the stratosphere
  - With assumptions integrated profile measurements (a typical lidar data product) can be used to estimate the stratospheric sulfur burden
- s/B, s/E ratios
  - Allows optical measurements to be used to estimate aerosol surface area, important for stratospheric chemistry
  - The bad news these relationships are much less solid than the other ratios

We all know the basic equations for surface area, s, mass, m, extinction, E, and backscatter, B

$$s = \int_0^\infty \pi\, a^2\, dn(a)/da \;\, da,$$

$$m = \int_0^\infty \pi\, a^3\, /6\, dn(a)/da \;\, da,$$

$$E = \int_0^\infty \pi\, a^2\, Q_{ext}(\lambda, m, a)\;\, dn(a)/da \;\, da,$$

$$B = \left[\int_0^\infty \pi\, a^2\, Q_{bks}(\lambda, m, a) \frac{dn(a)}{da}\;\, da\right]/4\pi,$$

for aerosol size distribution dn(a)/da, where a is particle diameter, $Q_{ext/bks}$ the Mie extinction and backscatter cross sections, at wavelength, λ, and particle index of refraction, m.

Aside from the Mie calculations, the tricky part is getting index of refraction, which for sulfate is a function water vapor and temperature as these affect the weight fraction and solution density, both important for m.

But we know how to do this, e.g. Deshler et al., 2019, JGR, *124*(9), 5058–5087

Extinction/backscatter calculations from in situ measurements

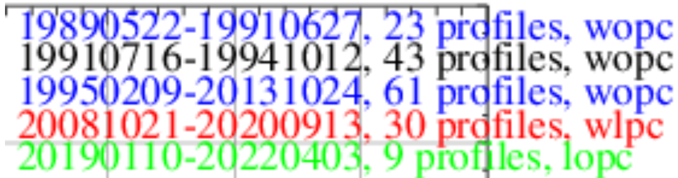
$$\beta_\lambda(m) = \int_0^\infty \pi a^2 \cdot Q(a, \lambda, m) \cdot dn/d\ln(a) \cdot d\ln(a),$$

$Q(a, \lambda, m)$ Is the extinction cross section, with m the index of refraction, the only tricky part of the calculation.

- Calculation of index of refraction, m, requires:
  - Water vapor (assumed) and temperature (measured) profiles
  - Sulfuric acid weight percent = f(wv, T) [Steele and Hamill, 1981]
  - Palmer and Williams [1975] for m(300 K) = f(sulfuric acid weight percent)
  - Lorentz-Lorenz for index of refraction = f(T, density of sulfuric acid, $\rho(T)$)

$$m(T) = \sqrt{\left(\frac{1 + 2A\rho(T)}{1 - A\rho(T)}\right)}, \text{ where } A = \frac{m^2(300) - 1}{[m^2(300) + 2]\rho(300)}$$

$\rho(T)$, is calculated from Luo et al. (1996),

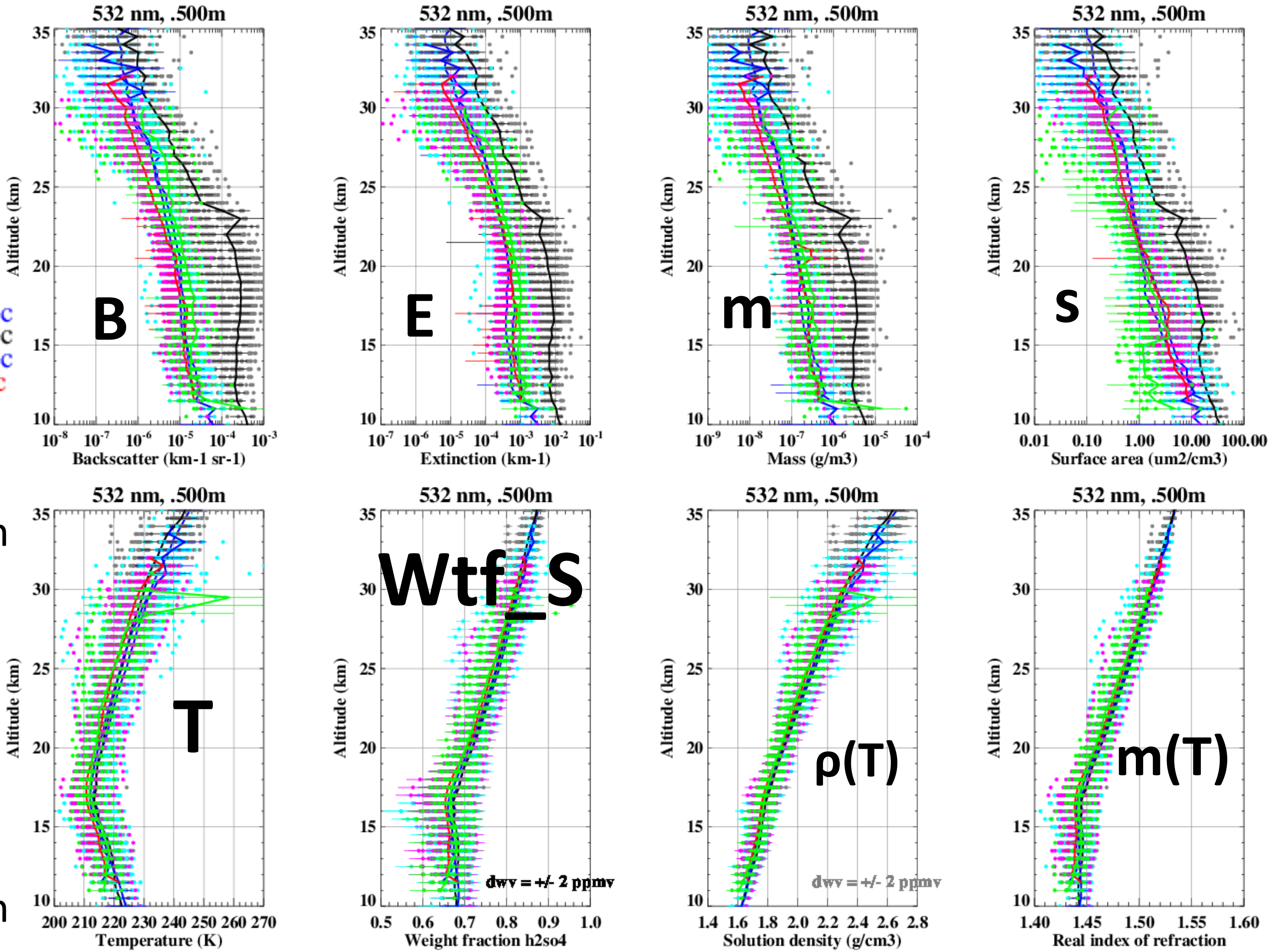


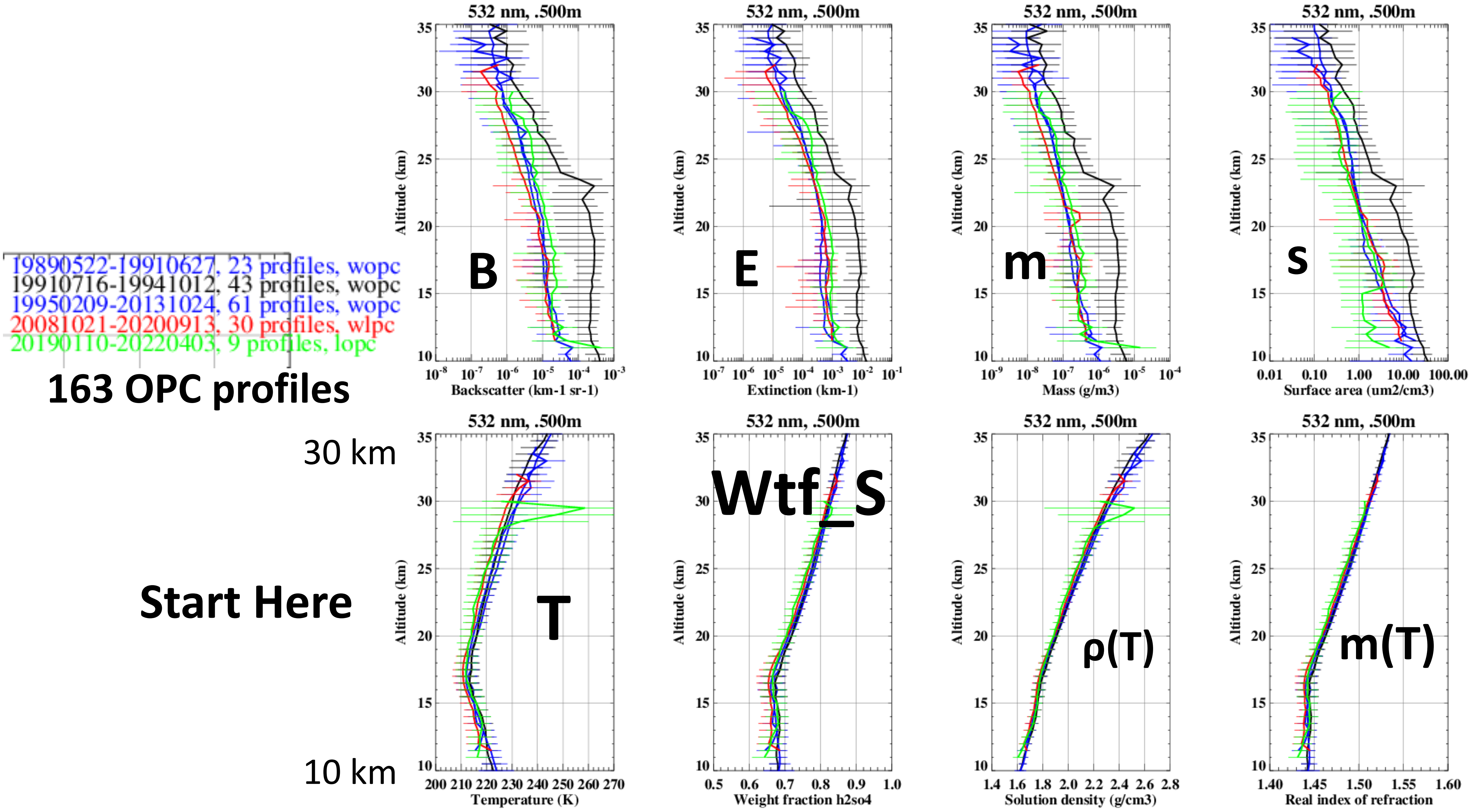
163 OPC profiles

30 km

Start Here

10 km





532 nm, .500m
B
E
m
S
19890522-19910627, 23 profiles, wopc
19910716-19941012, 43 profiles, wopc
19950209-20131024, 61 profiles, wopc
20081021-20200913, 30 profiles, wlpc
20190110-20220403, 9 profiles, lopc
163 OPC profiles
Altitude (km)
Backscatter (km-1 sr-1)
Extinction (km-1)
Mass (g/m3)
Surface area (um2/cm3)
30 km
10 km
Start Here
T
Wtf_S
ρ(T)
m(T)
Temperature (K)
Weight fraction h2so4
Solution density (g/cm3)
Real index of refraction

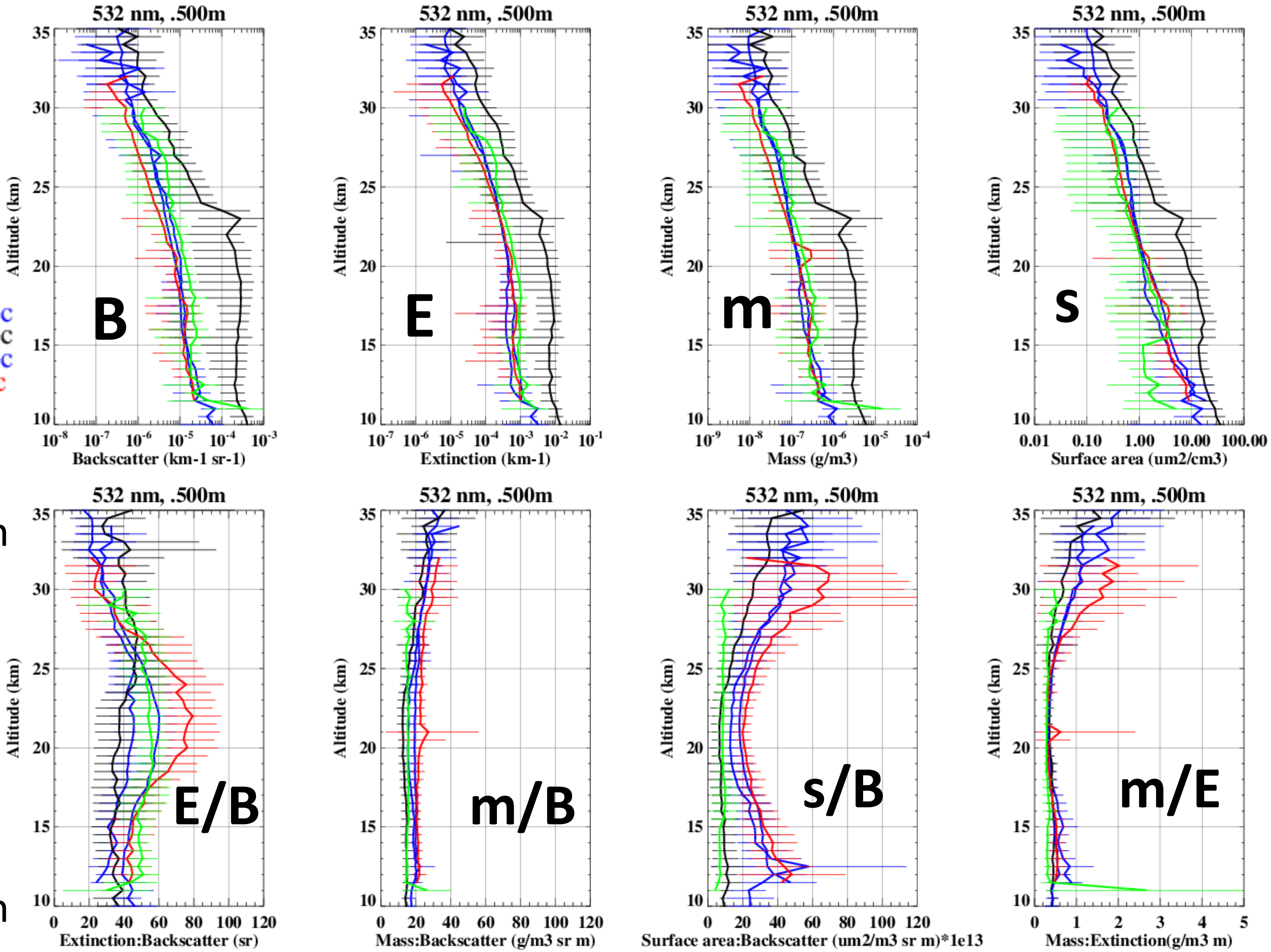
Now Here

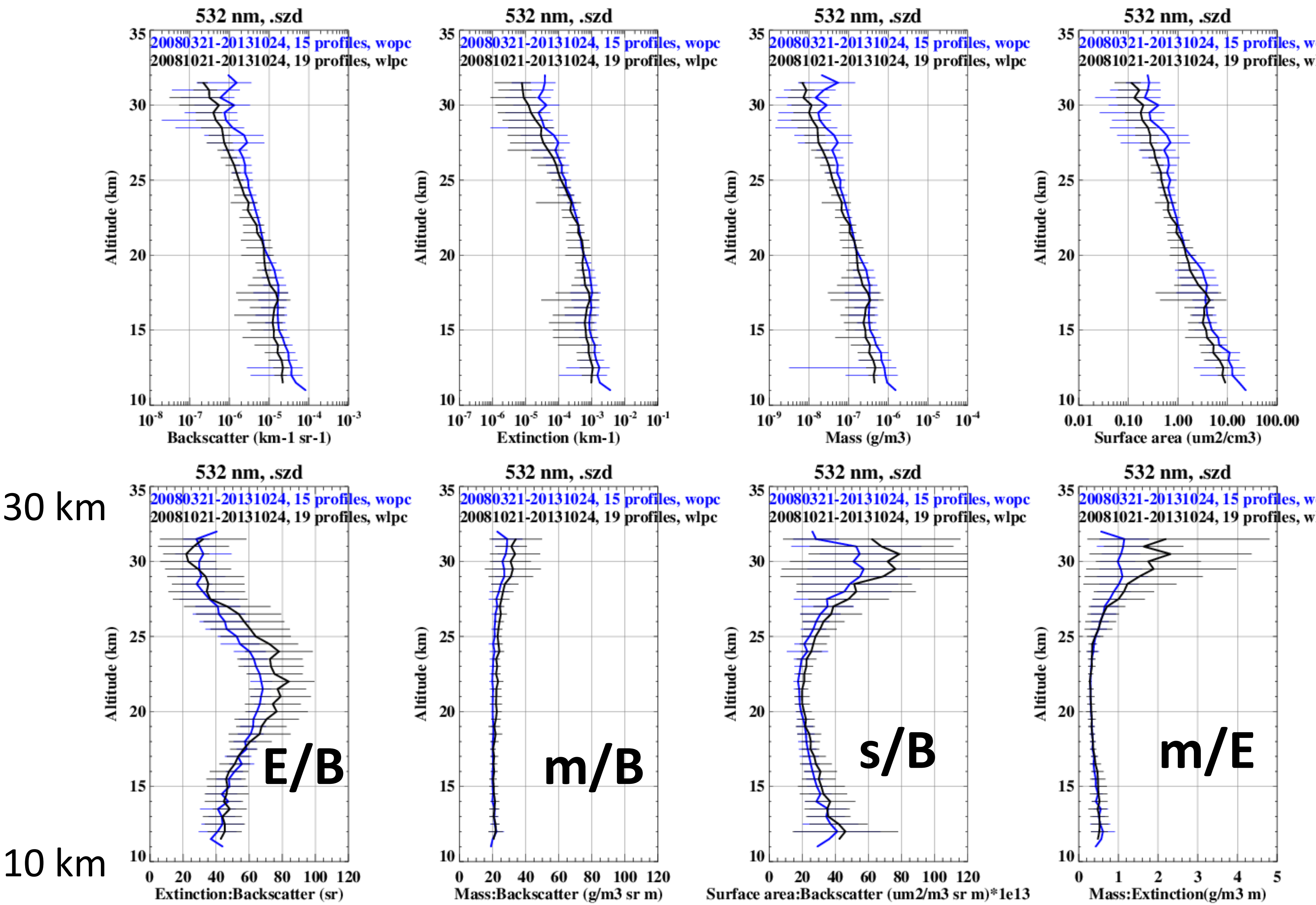
19890522-19910627, 23 profiles, wopc
19910716-19941012, 43 profiles, wopc
19950209-20131024, 61 profiles, wopc
20081021-20200913, 30 profiles, wlpc
20190110-20220403, 9 profiles, lopc

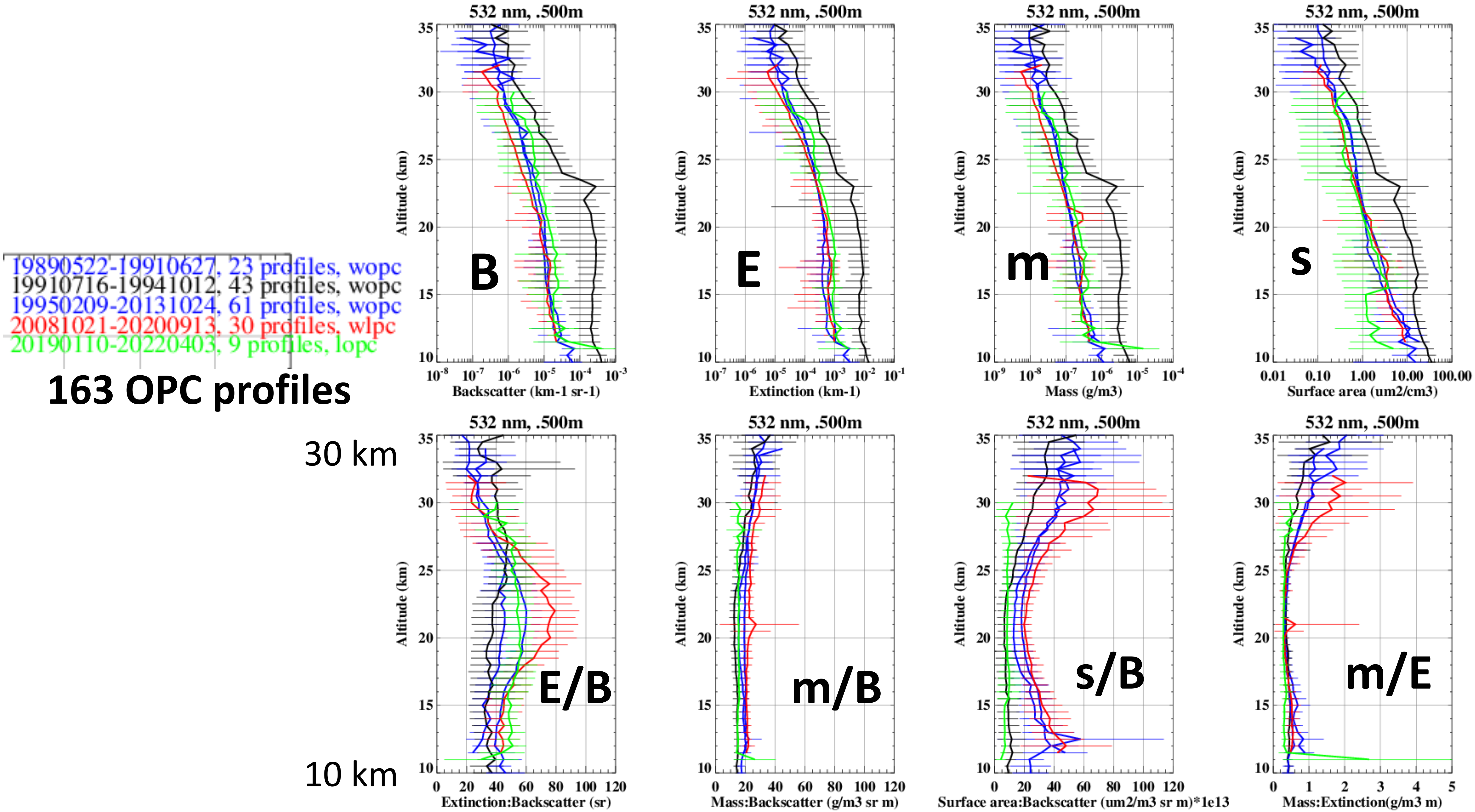
163 OPC profiles

30 km

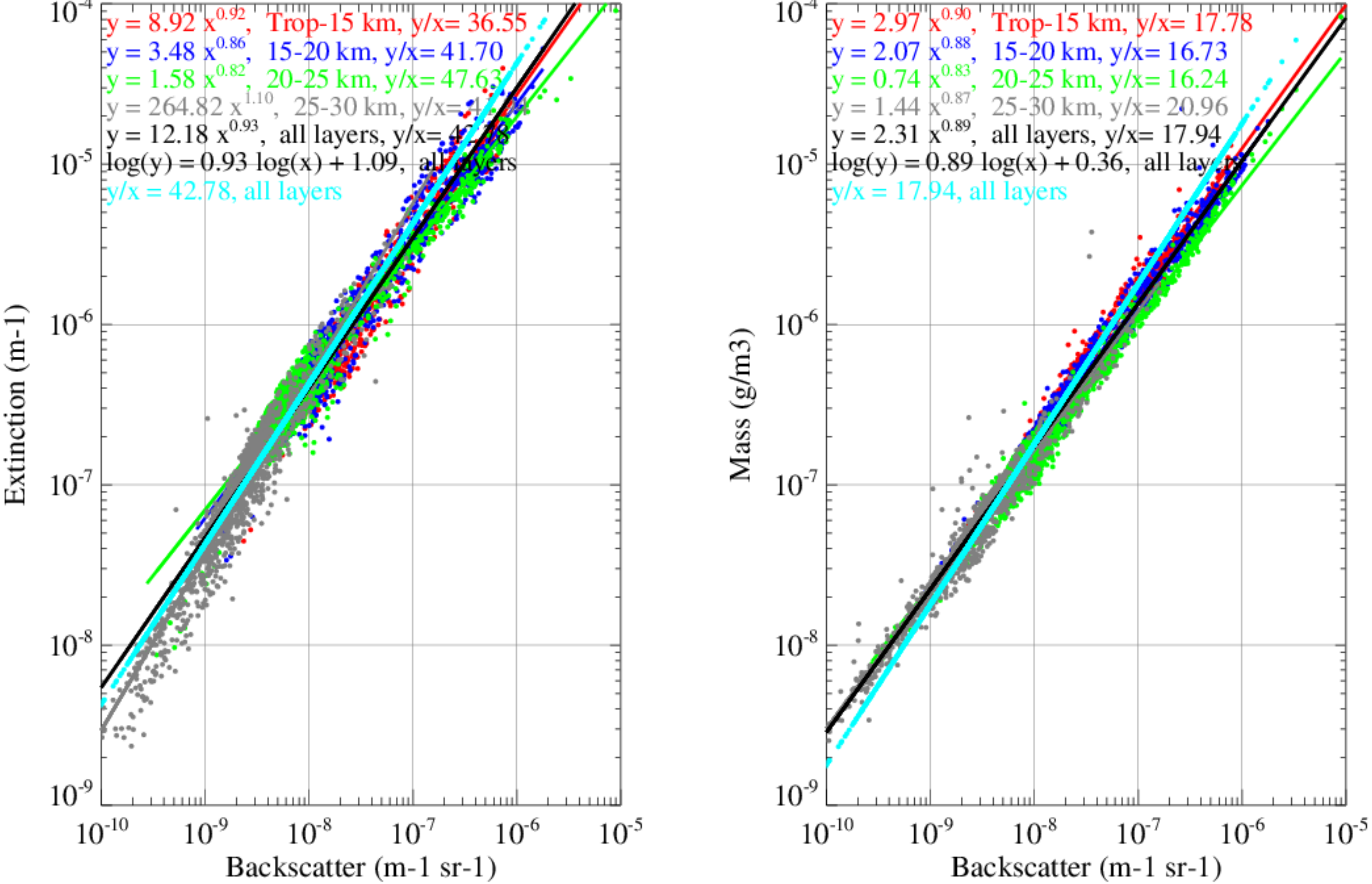
10 km

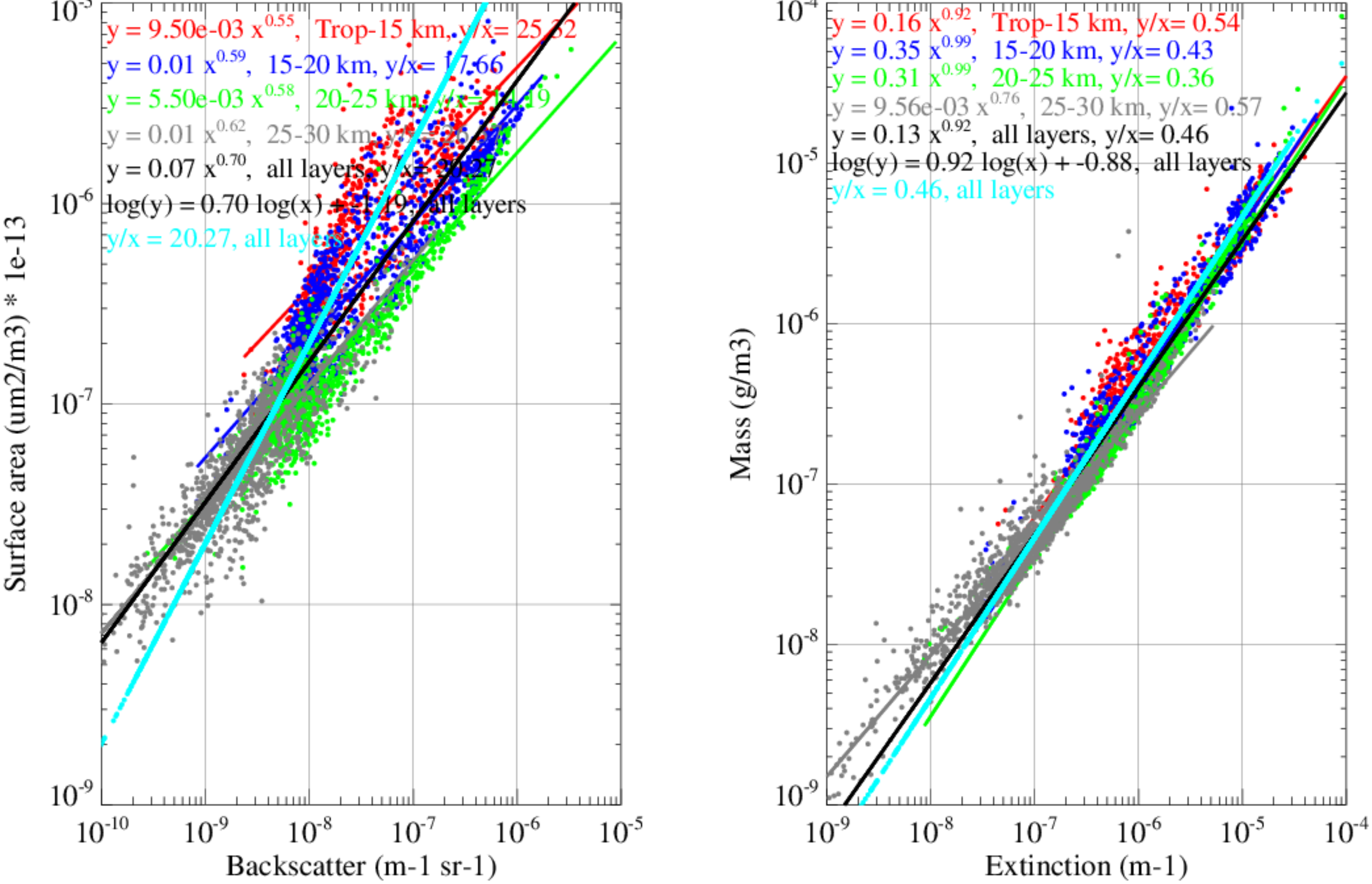



532 nm, .szd
20080321-20131024, 15 profiles, wopc
20081021-20131024, 19 profiles, wlpc
Altitude (km)
Backscatter (km-1 sr-1)
Extinction (km-1)
Mass (g/m3)
Surface area (um2/cm3)
30 km
10 km
E/B
m/B
s/B
m/E
Extinction:Backscatter (sr)
Mass:Backscatter (g/m3 sr m)
Surface area:Backscatter (um2/m3 sr m)*1e13
Mass:Extinction(g/m3 m)

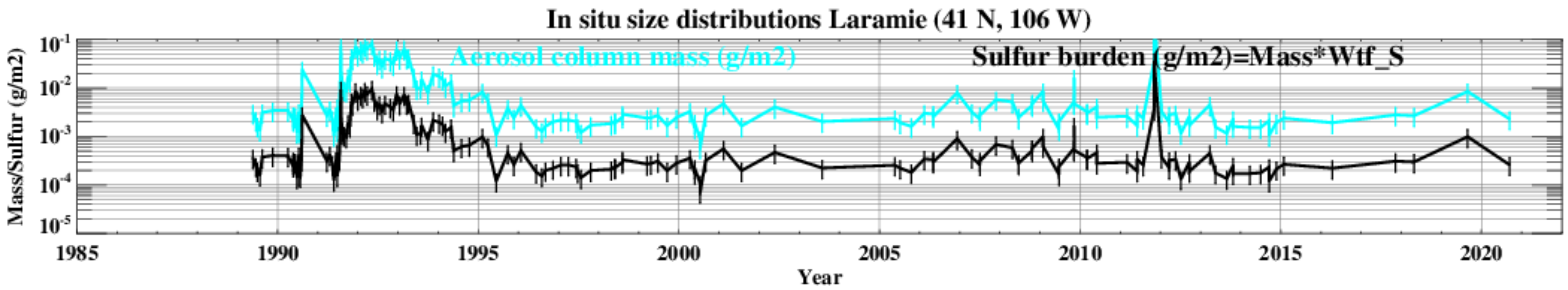


19890522-19910627, 23 profiles, wopc
19910716-19941012, 43 profiles, wopc
19950209-20131024, 61 profiles, wopc
20081021-20200913, 30 profiles, wlpc
20190110-20220403, 9 profiles, lopc
163 OPC profiles
30 km
10 km
532 nm, .500m
Altitude (km)
B
Backscatter (km-1 sr-1)
E
Extinction (km-1)
m
Mass (g/m3)
s
Surface area (um2/cm3)
E/B
Extinction:Backscatter (sr)
m/B
Mass:Backscatter (g/m3 sr m)
s/B
Surface area:Backscatter (um2/m3 sr m)*1e13
m/E
Mass:Extinction(g/m3 m)

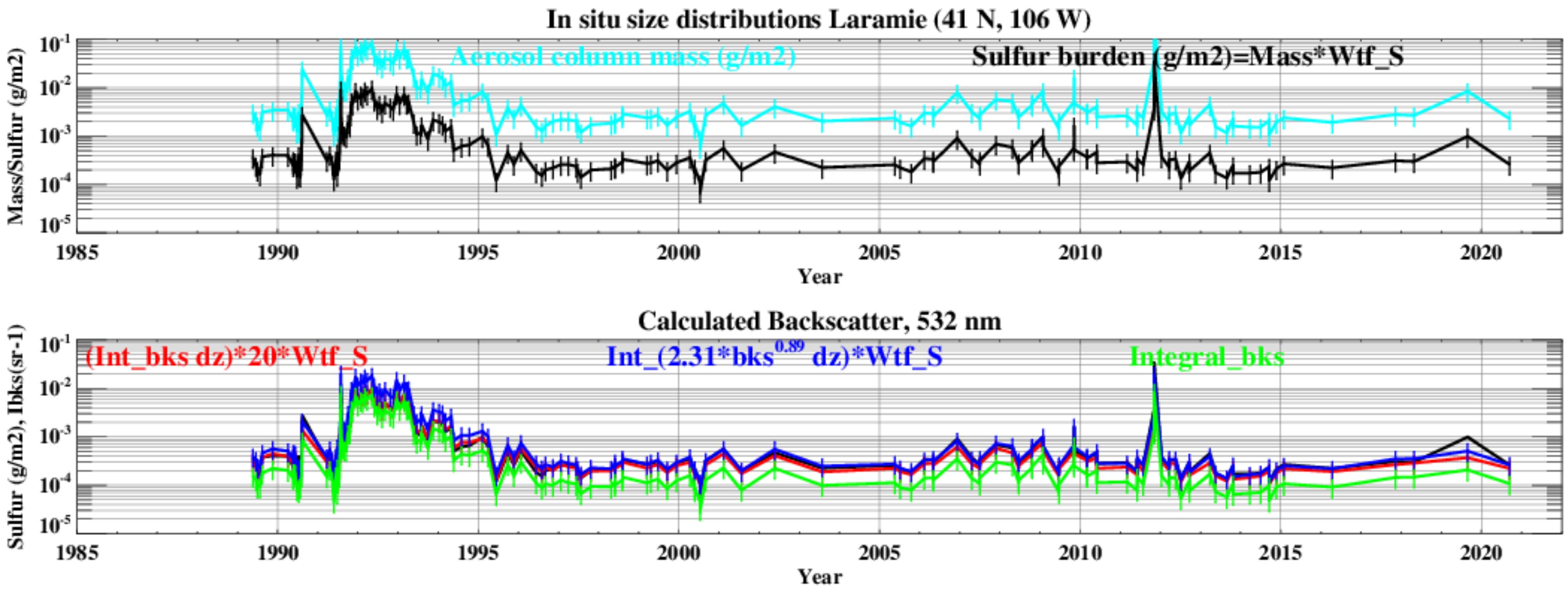

y = 8.92 x^0.92, Trop-15 km, y/x= 36.55
y = 3.48 x^0.86, 15-20 km, y/x= 41.70
y = 1.58 x^0.82, 20-25 km, y/x= 47.63
y = 264.82 x^1.10, 25-30 km
y = 12.18 x^0.93, all layers
log(y) = 0.93 log(x) + 1.09
y/x = 42.78, all layers
Extinction (m-1)
Backscatter (m-1 sr-1)
y = 2.97 x^0.90, Trop-15 km, y/x= 17.78
y = 2.07 x^0.88, 15-20 km, y/x= 16.73
y = 0.74 x^0.83, 20-25 km, y/x= 16.24
y = 1.44 x^0.87, 25-30 km, y/x= 20.96
y = 2.31 x^0.89, all layers, y/x= 17.94
log(y) = 0.89 log(x) + 0.36
y/x = 17.94, all layers
Mass (g/m3)
Backscatter (m-1 sr-1)

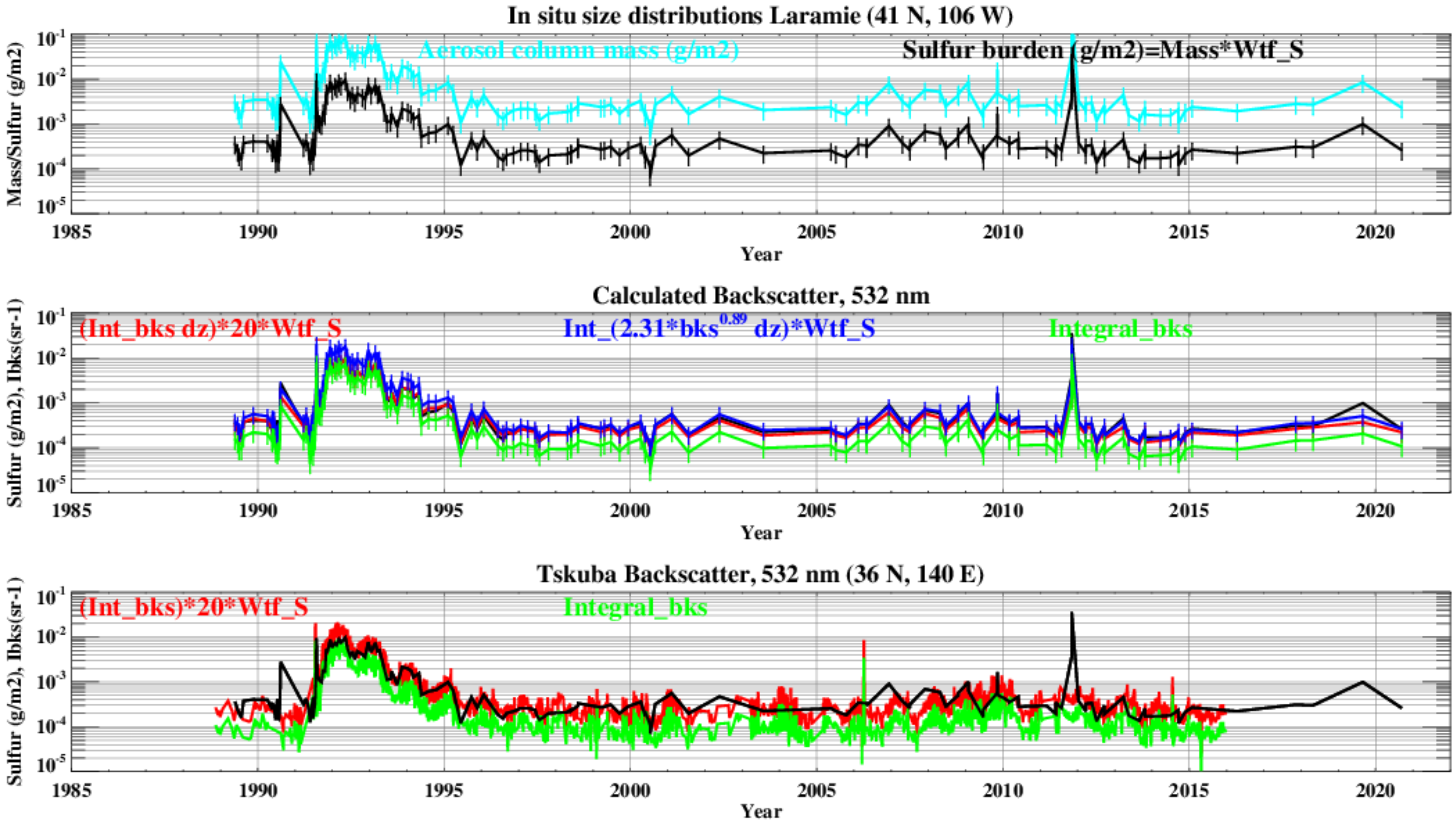


y = 9.50e-03 x^0.55, Trop-15 km, y/x= 25.32
y = 0.01 x^0.59, 15-20 km, y/x= 17.66
y = 5.50e-03 x^0.58, 20-25 km
y = 0.01 x^0.62, 25-30 km
y = 0.07 x^0.70, all layers, y/x= 20.27
log(y) = 0.70 log(x) + -1.19, all layers
y/x = 20.27, all layers
Surface area (um2/m3) * 1e-13
Backscatter (m-1 sr-1)
y = 0.16 x^0.92, Trop-15 km, y/x= 0.54
y = 0.35 x^0.99, 15-20 km, y/x= 0.43
y = 0.31 x^0.99, 20-25 km, y/x= 0.36
y = 9.56e-03 x^0.76, 25-30 km, y/x= 0.57
y = 0.13 x^0.92, all layers, y/x= 0.46
log(y) = 0.92 log(x) + -0.88, all layers
y/x = 0.46, all layers
Mass (g/m3)
Extinction (m-1)

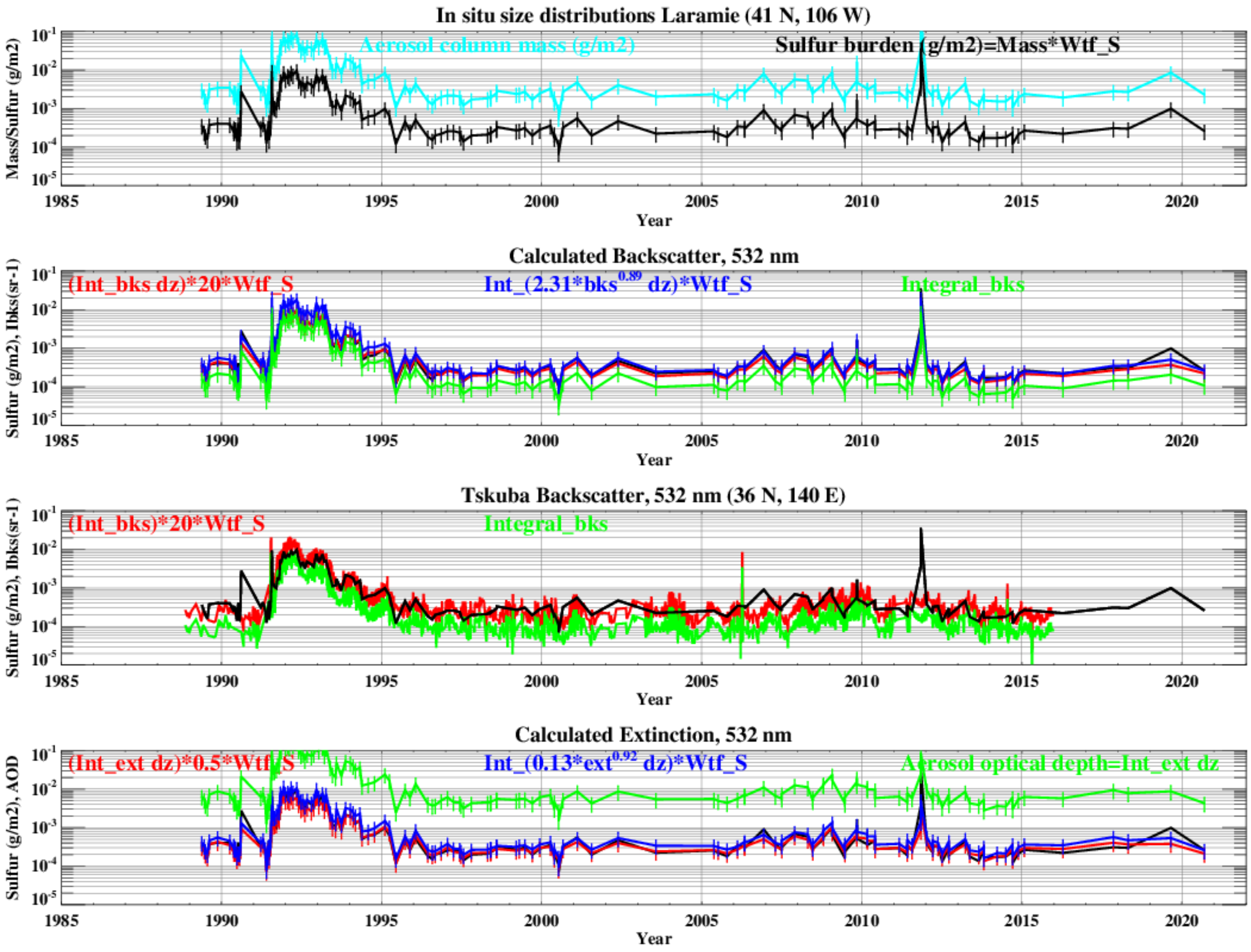


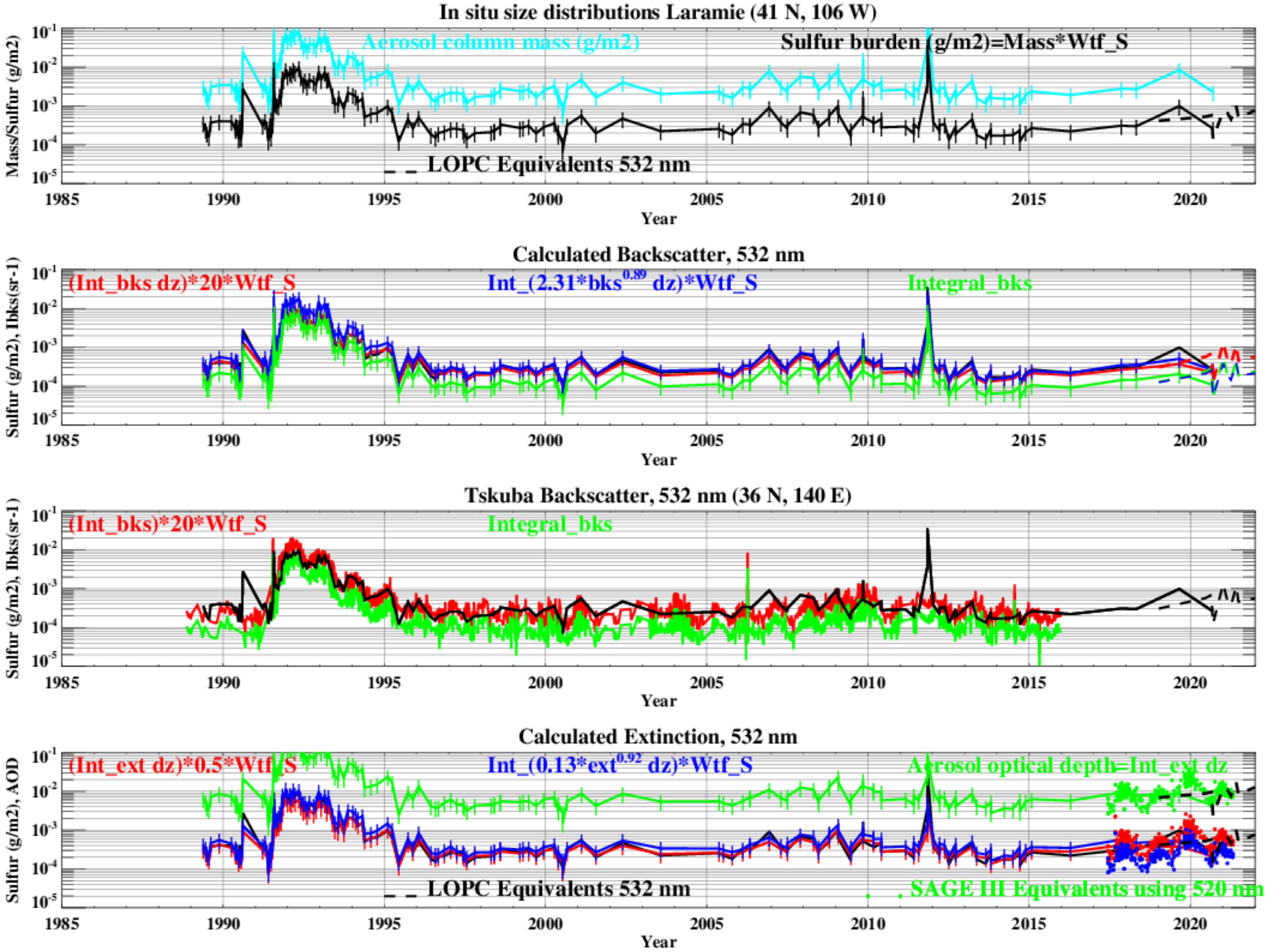
In situ size distributions Laramie (41 N, 106 W)
Aerosol column mass (g/m2)
Sulfur burden (g/m2)=Mass*Wtf_S
Mass/Sulfur (g/m2)
10-1
10-2
10-3
10-4
10-5
1985
1990
1995
2000
2005
2010
2015
2020
Year


In situ size distributions Laramie (41 N, 106 W)
Aerosol column mass (g/m2)
Sulfur burden (g/m2)=Mass*Wtf_S
Mass/Sulfur (g/m2)
Year
Calculated Backscatter, 532 nm
(Int_bks dz)*20*Wtf_S
Int_(2.31*bks^0.89 dz)*Wtf_S
Integral_bks
Sulfur (g/m2), Ibks(sr-1)
Year



In situ size distributions Laramie (41 N, 106 W)
Aerosol column mass (g/m2)
Sulfur burden (g/m2)=Mass*Wtf_S
Mass/Sulfur (g/m2)
Year
Calculated Backscatter, 532 nm
(Int_bks dz)*20*Wtf_S
Int_(2.31*bks^0.89 dz)*Wtf_S
Integral_bks
Sulfur (g/m2), Ibks(sr-1)
Year
Tskuba Backscatter, 532 nm (36 N, 140 E)
(Int_bks)*20*Wtf_S
Integral_bks
Sulfur (g/m2), Ibks(sr-1)
Year


In situ size distributions Laramie (41 N, 106 W)
Aerosol column mass (g/m2)
Sulfur burden (g/m2)=Mass*Wtf_S
Mass/Sulfur (g/m2)
Year
Calculated Backscatter, 532 nm
(Int_bks dz)*20*Wtf_S
Int_(2.31*bks^0.89 dz)*Wtf_S
Integral_bks
Sulfur (g/m2), Ibks(sr-1)
Year
Tskuba Backscatter, 532 nm (36 N, 140 E)
(Int_bks)*20*Wtf_S
Integral_bks
Sulfur (g/m2), Ibks(sr-1)
Year
Calculated Extinction, 532 nm
(Int_ext dz)*0.5*Wtf_S
Int_(0.13*ext^0.92 dz)*Wtf_S
Aerosol optical depth=Int_ext dz
Sulfur (g/m2), AOD
Year



In situ size distributions Laramie (41 N, 106 W)
Aerosol column mass (g/m2)
Sulfur burden (g/m2)=Mass*Wtf_S
LOPC Equivalents 532 nm
Mass/Sulfur (g/m2)
Year
Calculated Backscatter, 532 nm
(Int_bks dz)*20*Wtf_S
Int_(2.31*bks^0.89 dz)*Wtf_S
Integral_bks
Sulfur (g/m2), Ibks(sr-1)
Tskuba Backscatter, 532 nm (36 N, 140 E)
(Int_bks)*20*Wtf_S
Integral_bks
Calculated Extinction, 532 nm
(Int_ext dz)*0.5*Wtf_S
Int_(0.13*ext^0.92 dz)*Wtf_S
Aerosol optical depth=Int_ext dz
LOPC Equivalents 532 nm
SAGE III Equivalents using 520 nm
Sulfur (g/m2), AOD

Conclusions

- Distribution moments (backscatter, extinction, mass, surface area) from three generations of OPCs are consistent, outside of large geophysical events, across 30 years of measurements.
- Ratios of these moments provide extinction or mass from backscatter measurements, or mass from extinction measurements.
- These relationships are reasonably tight in spite of altitude and temporal dependencies, and can often be approximated with a simple ratio.
- Relationships to surface area are much more variable. This is likely due to the dependence of surface area on smaller particles which don't contribute significantly to the optical quantities.
- Application of the mass:backscatter ratio to Tskuba lidar data showed surprisingly good correspondence of aerosol sulfur burden estimates between the Wyoming (OPC) and Japanese (Lidar) measurements, both in magnitude and temporally.
- These OPC data are publicly available at https://doi.org/10.15786/21534894