Utilization of Depolarization ratio in Atmospheric Aerosol Researches

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GIST University of Hertfordshire UH

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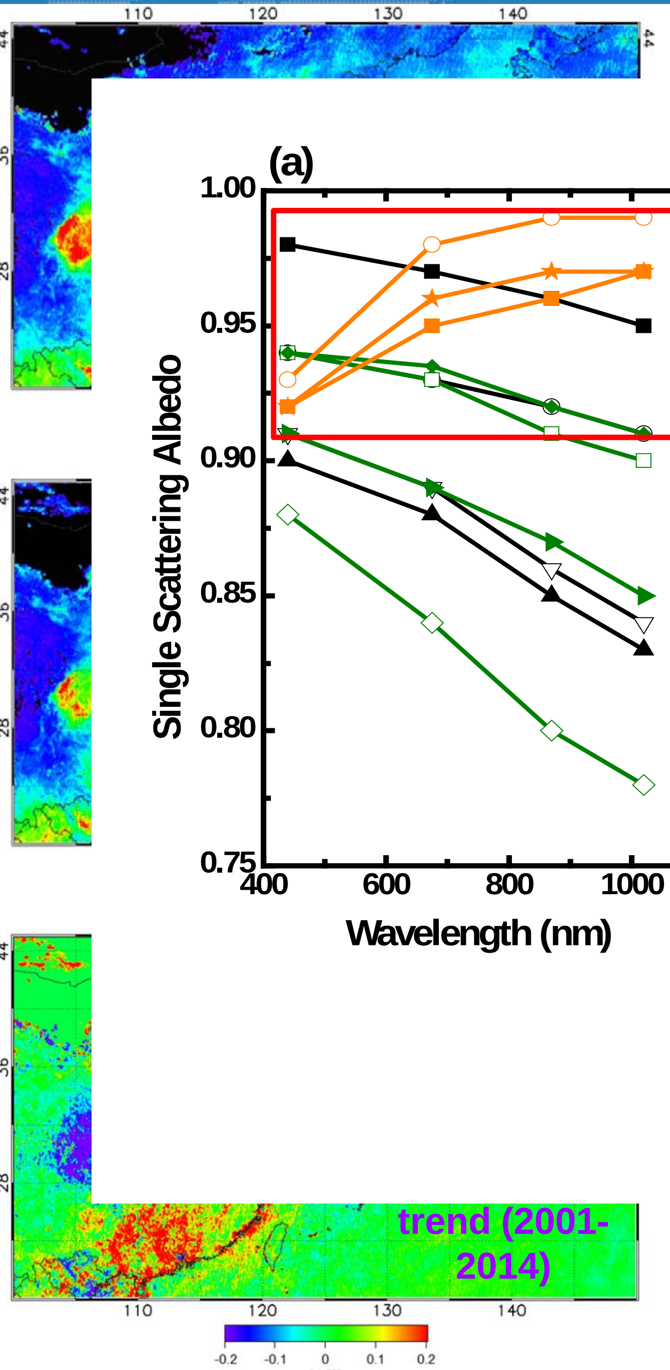
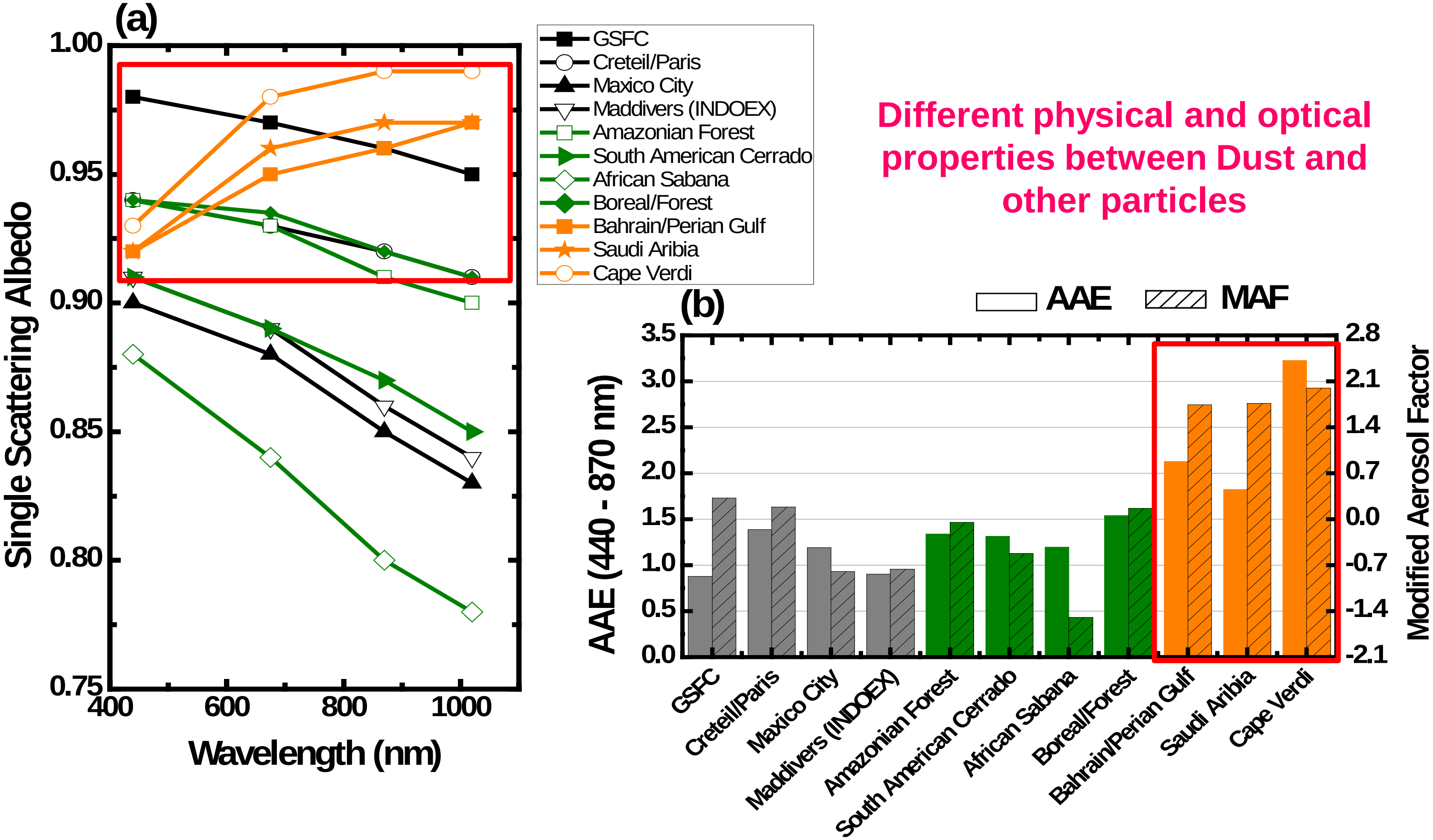




Different physical and optical properties between Dust and other particles

anthropogenic etc), and mixed together.

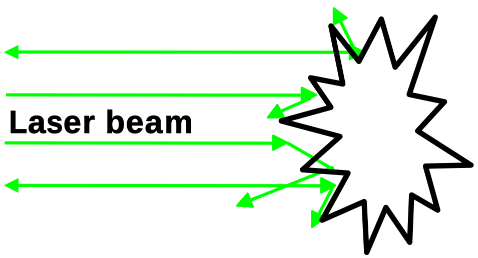
Depolarization Ratio

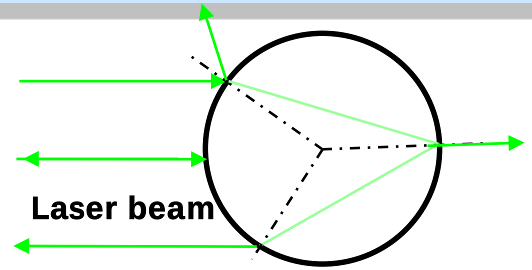
1. Depolarization ratio, definition : $\delta = I_{\perp} / (I_{//} + I_{\perp})$,

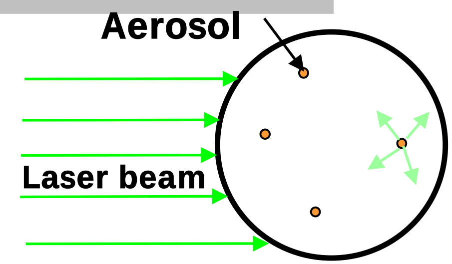
   Initial beam : $I_{//}$ (100 %)

2. The variation parameter of Aerosol Depolarization Ratio(DPR)

   : Shape, Size, Moist, etc







Type **1: Nonspherical particle**

Asian dust : 0.3 ~ 0.35
Saharan dust 0.31
Mixed dust : 0.08~0.2 (Externally)
Cirrus cloud : 0.4
Sea salt : 0.02

Type **2 : Ideal spherical particle**

LPDR = 0

Sulphate : 0.04

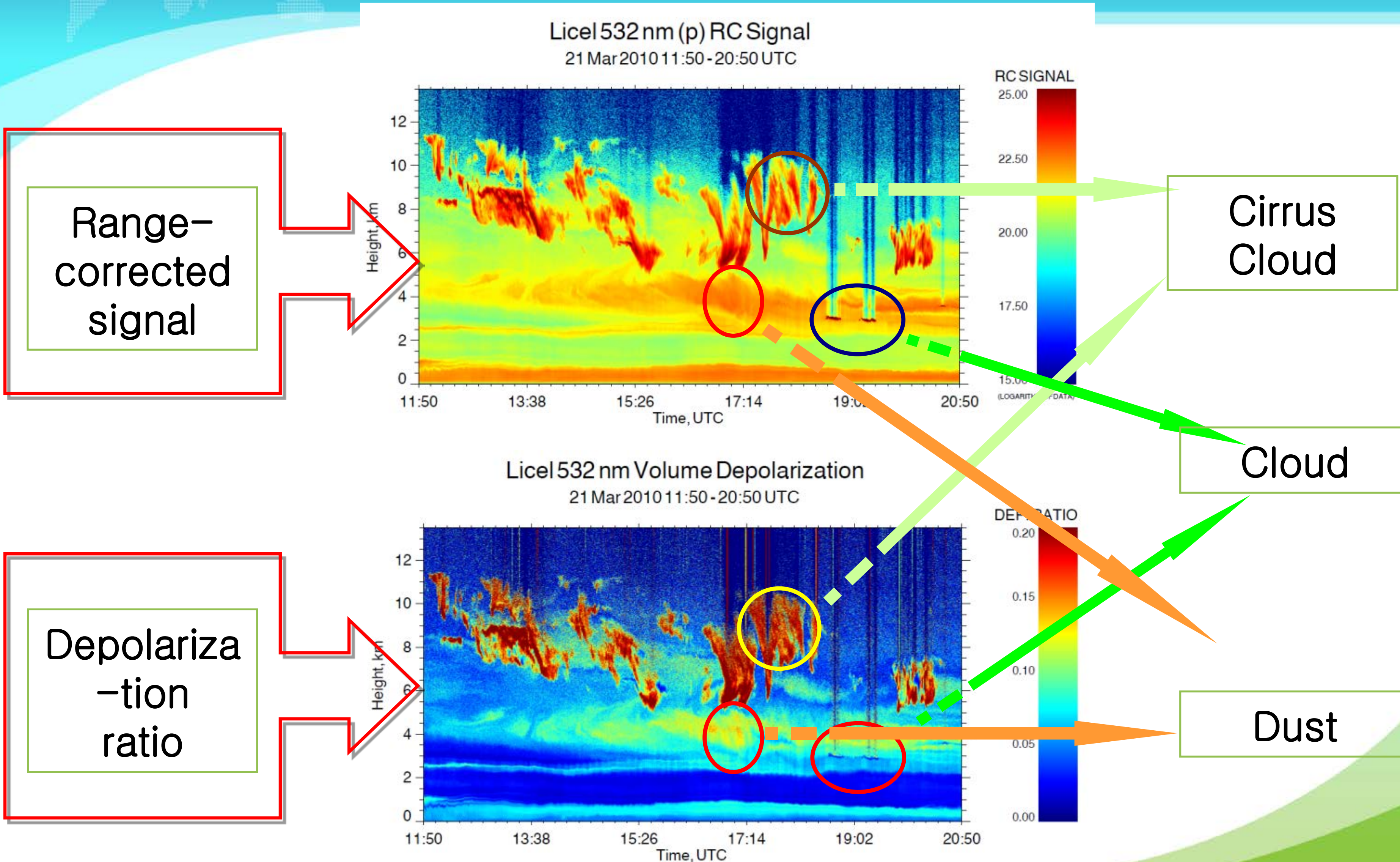
Type 3: Internally mixed aerosol

Hygroscopic aerosol

- LPDR depends on the internal structure

Utilization in Atmospheric Aerosol Researches

Aerosol Type Classification by LPDR



LPDR Value differences by mixing between dust and pollution

Optical properties of aerosol

Pure dust — **Mixed dust** — **Pollutant**

Depolarization ratio (DPR)

Non-spherical particle → Spherical particles

0.35 | 0.3 | 0.2 | 0.08 | 0.02

[Saharan dust :Feudenthaler et al., 2009]
[Asian dust : Iwasaka et al., 2003; Yi et al., 2014]

[Polluted dust : Shimizu et al., 2004;
Chen et al., 2009]

[Crystallized sulphate :
Sassen et al., 1989;
Cooper et al., 1974]

0.33 ← GIST measurements → 0.08

Lidar ratio (LR)

Low light absorption → High light absorption

30 | 50 | 60 | 80

[Saharan dust : De Tomasi et al., 2003][Saharan dust : Mueller et al., 2007]
[Asian dust : Murayama et al., 2004]

38 ← GIST measurements → 83

Ångström exponent (Å)

Larger particle → Smaller particle

0 | 2

[Saharan dust : Eck et al., 1999
Asian dust : Sakai et al., 2002; Chen al., 2007]

[Fine mode, accumulation mode particle
: Eck et al., 1999]

0.38 ← GIST measurements → 1.71

Retrieval of Particle Depolarization Ratio

➤ LIDAR

$$\delta(z) = \frac{S(z)}{P(z) + S(z)}$$

δ : **Volume depolarization ratio**
P : **Initial laser beam**
S : **Depolarized laser beam**

$$\delta_p(z) = \frac{\delta(z)R(z) - \delta_m(z)}{R(z) - 1}$$

δ_p : **Particle depolarization ratio**
$R(z)$: **Scattering ratio**
δ_m : **Depolarization ratio for air (0.014)**

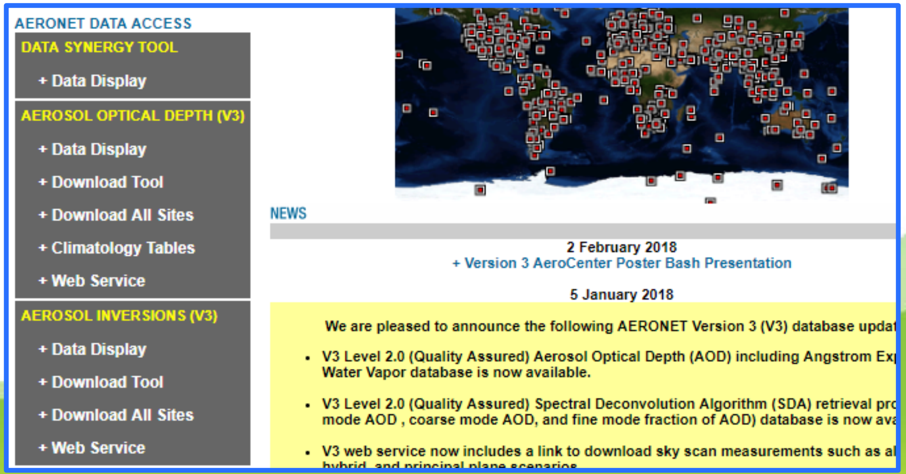
➤ Sunphotometer

$$\delta_p(\lambda) = \frac{1 - F_{22}(\lambda, 180°)/F_{11}(\lambda, 180°)}{1 + F_{22}(\lambda, 180°)/F_{11}(\lambda, 180°)} \times 100\,(\%)$$

F11 and F22 (Müller scattering matrices) :
computed from the retrieved complex refractive indices and particle size distributions

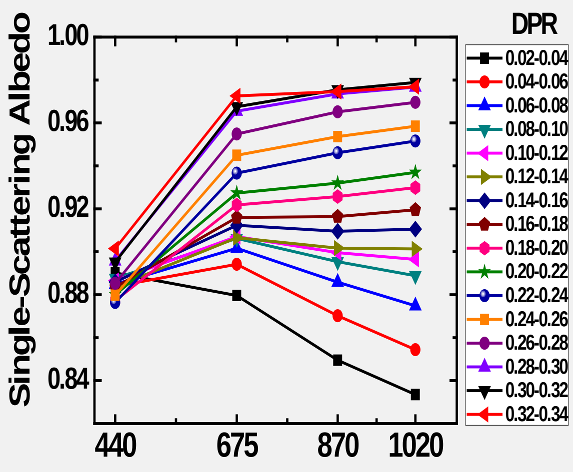
(Dubovik., 2006: JGR)

- AERONET Version 3 data released on January 2018
- Linear Particle Depolarization ratio (LPDR) and Lidar ratio at 440, 675, 870 and 1020 nm are included in Version 3 Inversion data

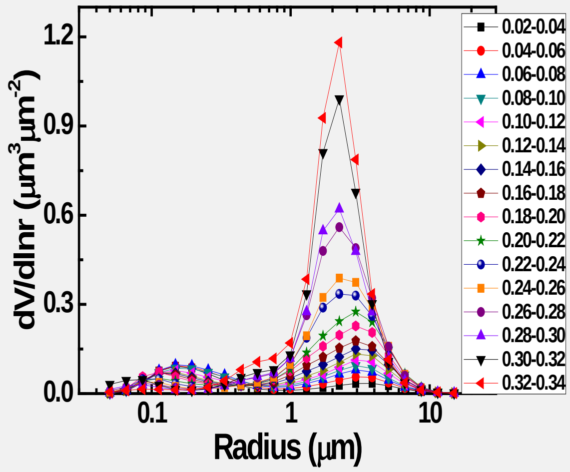


Variation of Optical Parameter (Beijing)

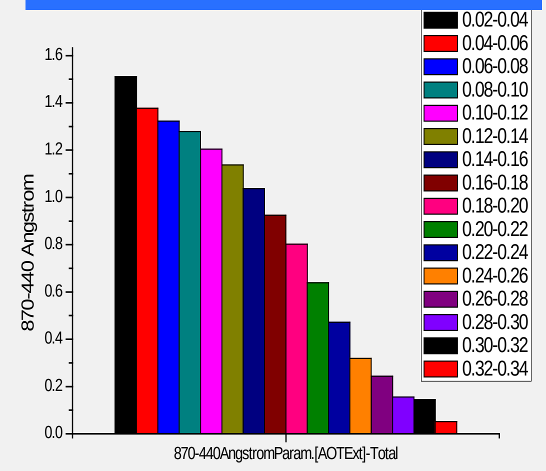
Single-Scattering Albedo



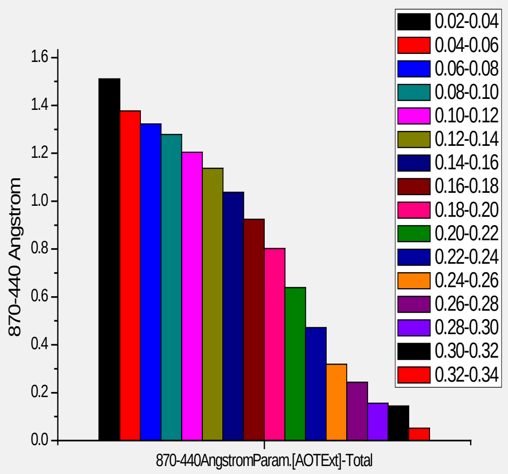
Size distribution



Fine-mode Fraction



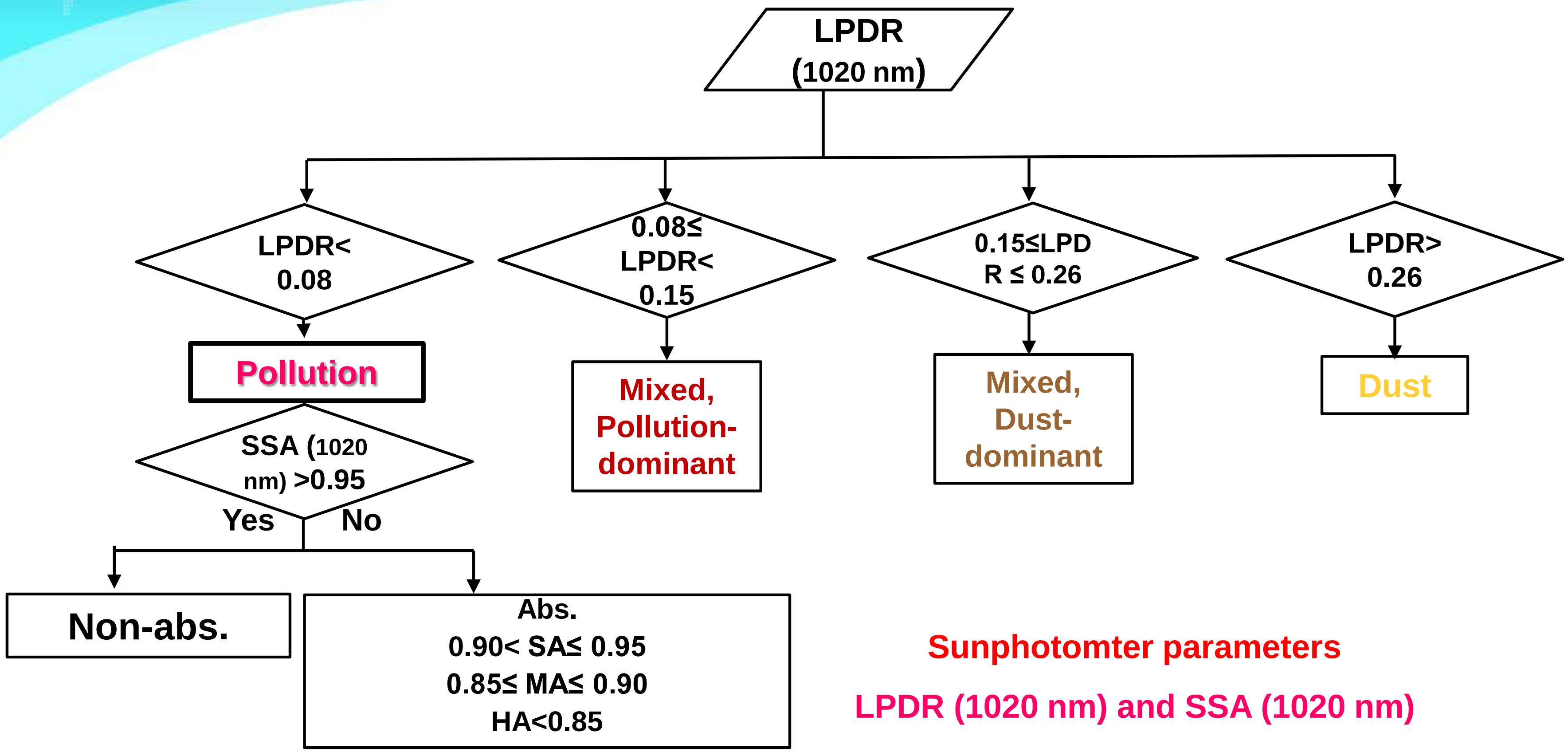
Ångström Exponent (440-870 nm)



Utilization of Depolarization ratio in Atmospheric Aerosol Researches

1. **Aerosol Type Classification** → What are the major aerosol types? (Dust, Dust-dominant mixed, Pollution-dominant mixed, Pollution)
2. **Aerosol Type Separation**: Total AOD = Dust AOD + fine-mode Pollution AOD + Coarse-mode Pollution AOD
3. **Retrieval of Black Carbon** related Absorption AOD (AAOD)

Flowchart of the aerosol classification algorithm

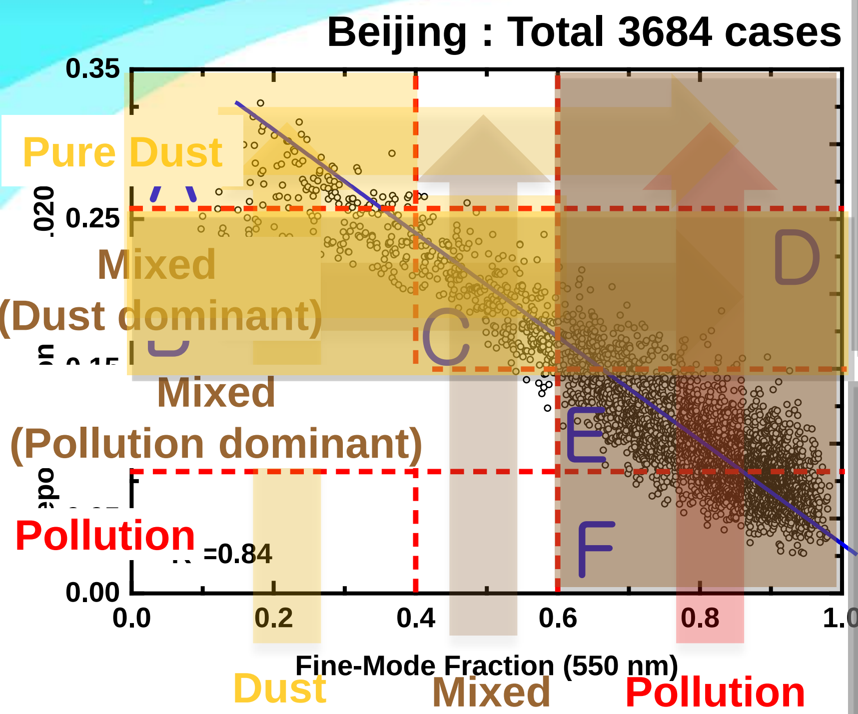


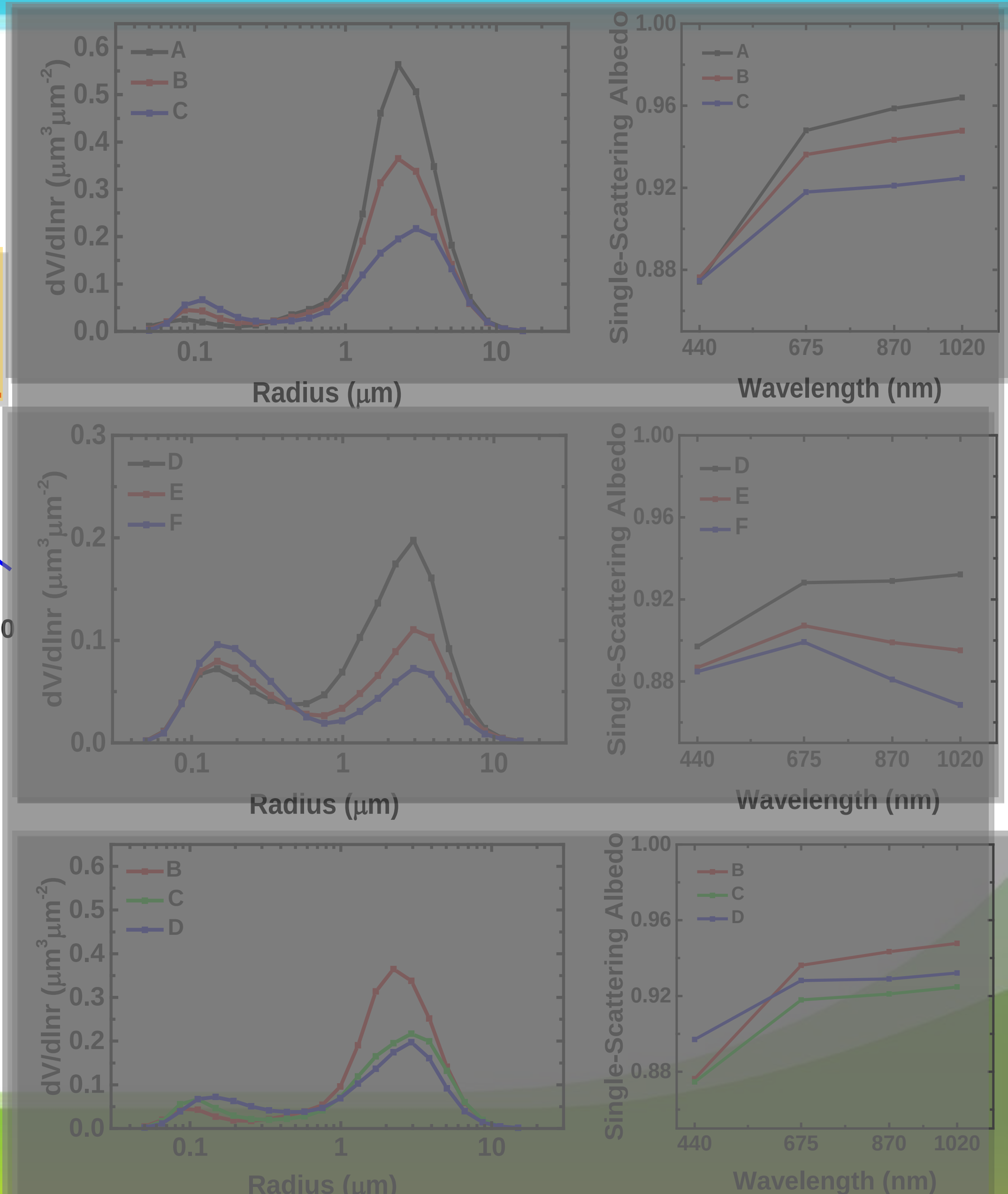
Sunphotomter parameters

LPDR (1020 nm) and SSA (1020 nm)

- **Dust aerosols (LPDR to be greater than 0.26)**
- **Dust-dominant (0.15 ≤ LPDR ≤ 0.26)**
- **Pollution-dominant (0.08 ≤ LPDR <0.15)**
- **Pollution aerosols (LPDR to be less than 0.08)**
- **The HA, MA, SA, and NA represent highly-absorbing, moderately-absorbing, slightly-absorbing, and non-absorbing aerosols, respectively**

Comparison Between LPDR and FMF





Aerosol type classification by size information

- Pollution (FMF > 0.6)
- Dust (FMF < 0.4)
- Mixture (between 0.4 and 0.6)

FMF at 550 nm
(Lee et al., 2010)

Linear Particle Depolarization Ratio (LPDR) from different desert regions

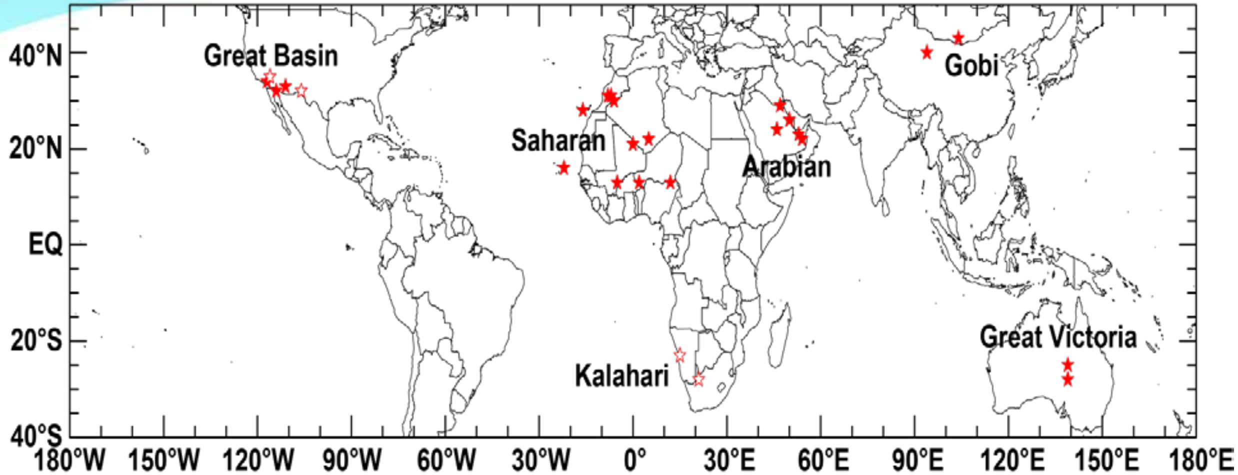
$$R = \frac{(\delta_a - \delta_2)(1+\delta_1)}{(\delta_1 - \delta_2)(1+\delta_a)}$$

R : Dust ratio (0 ~ 1)
δ_1 : 0.32, assumed value for pure dust
δ_2 : 0.02, pure pollution
→ Empirical data by long-term lidar measurements

[Shimizu et al. (2004), Tesche et al. (2009), Noh et al. (2014)]

- The contribution of dust to a mixed dust plumes could be retrieved with depolarization ratio.
- Dust ratio relies on knowing of depolarization ratio for different aerosol types in their pure form.
- LPDR for pure dust could be varied according to desert source.

AERONET DATA SELECTION



Gobi (3) : Dalanzadgad, Dunhuang, Dunhuang_LZU

Arabian (5) : Hamin, Mezaira, Solar Village, Bahrain, Shagaya Park

Saharan (10) : IER_Cinzana, Capo Verde, DMN Maine Soroa, Banizoumbou, Bord Badji Mokhtar, Tamamrasset, Izanam Quarzazate, Oukaimeden, Ras El Ain, Saada

Kalahari (2) : Gobabeb, Uprington

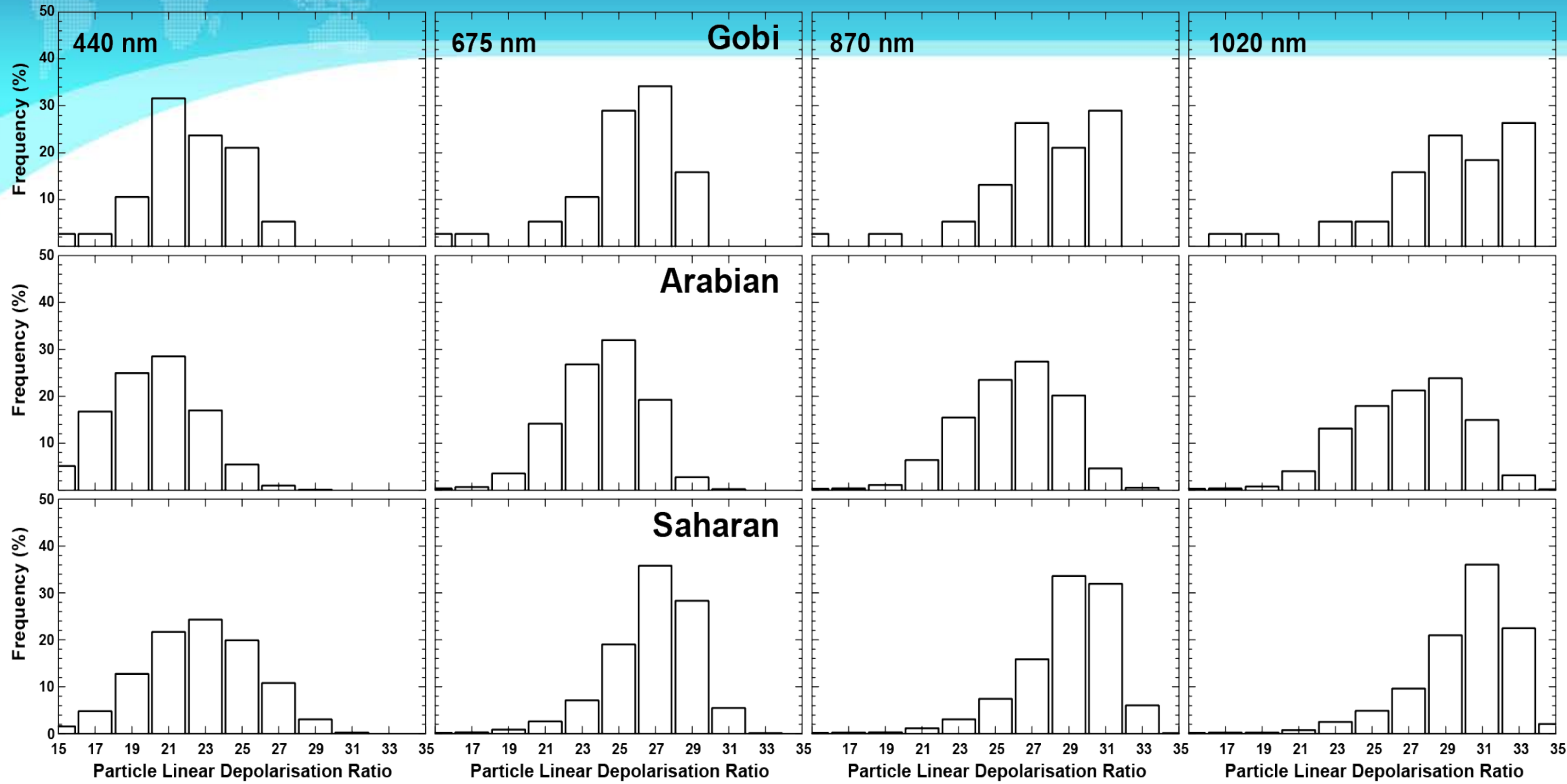
Great Basin (5) : Yuma, Maricopa, White Sands, Roger Dry Lake, Goldstone

Great Victoria (2) : Tinga Tingana, Birdsville

Data Filtering for pure dust : A.E < 0.4, FMF < 10%

- **AERONET ver. 3 lv 2.0 data including LPDR and LRs recently released.**
- **We report the LPDR and LRs provided from AERONET observations representative for different desert in order to investigate the LPDR for pure dust.**
- **Reliable LPDR for pure dust -> Reliable Dust ratio could be retrieved!**

Statistics of LPDRs at desert around the world

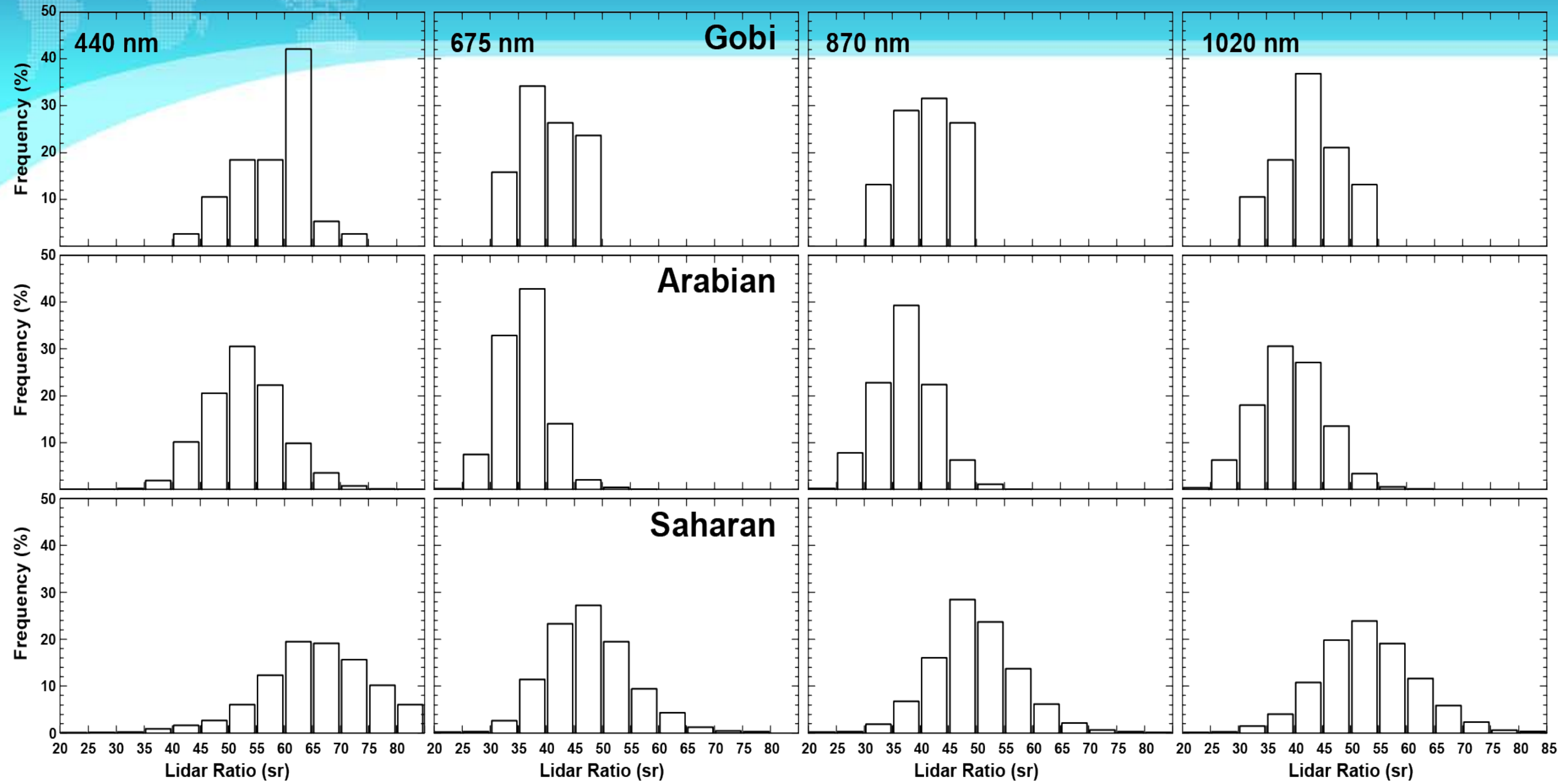


Regions	Gobi	Arabian	Saharan	Great Basin	Great Victoria
N	38(26%*)	3556(55%)	7228(59%)	7(25%)	16(36%)
δ_{440}	0.23±0.03	0.21±0.03	0.24±0.03	0.22±0.03	0.19±0.02
δ_{675}	0.26±0.03	0.25±0.03	0.28±0.03	0.26±0.02	0.24±0.02
δ_{870}	0.29±0.03	0.27±0.03	0.30±0.03	0.27±0.02	0.28±0.03
δ_{1020}	0.30±0.04	0.28±0.03	0.31±0.03	0.28±0.02	0.27±0.02

* % denotes the ratio of pure dust from observation cases

[Shin et al., ACP 2018]

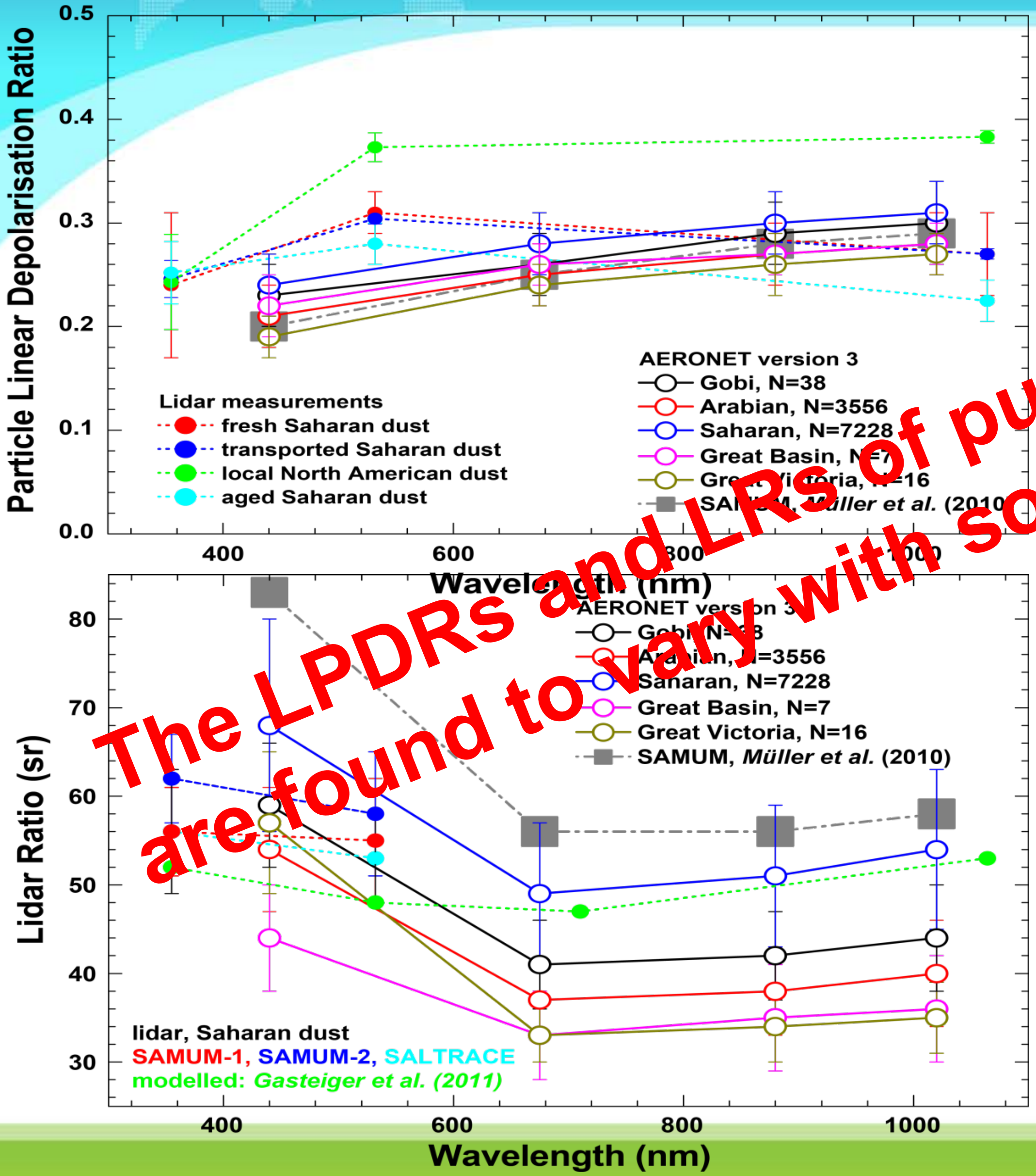
Statistics of Lidar Ratio(LR)s at desert around the world



Regions	Gobi	Arabian	Saharan	Great Basin	Great Victoria
N	38(26%)	3556(55%)	7228(59%)	7(25%)	16(36%)
S_{440}	59±7	54±7	68±12	44±6	57±8
S_{675}	41±5	37±4	49±8	33±5	33±3
S_{870}	42±5	38±5	51±8	35±6	34±4
S_{1020}	44±6	40±6	54±9	36±6	35±4

[Shin et al., ACP 2018]

Spectral variation of LPDRs and LRs



The LPDRs and LRs of pure mineral dust are found to vary with source regions !

- ✓ **The spectral LRs show much stronger regional variation than PLDRs due to differences in the mineralogical composition of the dust particles for each desert, whereas LPDR more likely depends on the morphology of dust particles.**
- ✓ **Findings provide reference values in order to classify mineral dust aerosols from the mixed dust plumes as well as to separate aerosol-type.**

[Shin et al., ACP 2018]

BC related AAOD retrieval with AERONET observation data

❖ Suggested Methodology

$$R_D = \frac{(\delta_a - \delta_2)(1+\delta_1)}{(\delta_1 - \delta_2)(1+\delta_a)}$$

R_D : Dust ratio (0 ~ 1)
δ_1 : 0.30, assumed value for pure dust
δ_2 : 0.02, pure pollution
→ Empirical data by long-term lidar measurements

We refer PLDR at 1020 nm obtained from AERONET V3 inversion product for pure dust from each desert source (Gobi ; 0.30, Saharan ; 0.31, Shin et al., 2018, ACP)

$$R_{nd} = 1 - R_d$$

: Non-dust ratio

Dust ratio and non-dust ratio obtained from using PDLR refer to the lidar observations in the backscatter direction and allow for inferring the dust-related BSC as:

$$\beta_d = \beta \cdot R_d$$

: Backscatter coefficient by DUST

$$AOD = \alpha \cdot h$$

α: Extinction coefficient

$$LidarRatio(S) = \frac{\alpha}{\beta}$$

$$AOD_d = S_d \cdot \beta_d \cdot h$$

: DUST AOD

BC related AAOD retrieval with AERONET observation data

❖ Suggested Methodology

$$AOD_d = AOD \times R_d \times \frac{S_d}{S}$$

We refer LR at 1020 nm obtained from AERONET V3 inversion product for pure dust from each desert source (Gobi ; 44 sr, Saharan ; 54 sr, Shin et al., 2018, ACP)

$$AOD_{nd} = AOD - AOD_d$$ **: NON DUST AOD**

Convert the 1020-nm AOD to other wavelength λ with Ånström exponent for dust (AE_dust) = 0.06 ± 0.21

(Tesche et al., 2009)

$$AOD_{d,\lambda} = AOD_{d,1020nm} \times \left(\frac{1020nm}{\lambda}\right)^{AE\_dust}$$

$$AOD_{nd,\lambda} = AOD_{\lambda} - AOD_{d,\lambda}$$

BC related AAOD retrieval with AERONET observation data

❖ Suggested Methodology

Extinction-related dust ratio factor χ

$$\chi_{d,\lambda} = \frac{AOD_{d,\lambda}}{AOD_{\lambda}} = R_d \frac{S_d}{S}$$

$$\chi_{nd,\lambda} = \frac{AOD_{nd,\lambda}}{AOD_{\lambda}} = 1 - R_d \frac{S_d}{S}$$

Total SSA could be considered to be the results of mixing the SSA of dust and non-dust particles following the mixing rule:

$$\omega_{\lambda} = \chi_{d,\lambda}\omega_{d,\lambda} + \chi_{nd,\lambda}\omega_{nd,\lambda}$$

$$\omega_{nd,\lambda} = \frac{\omega_{\lambda} - \chi_{d,\lambda} \cdot \omega_{d,\lambda}}{\chi_{nd,\lambda}}$$

BC related AAOD retrieval with AERONET observation data

❖ **Suggested Methodology**

$$\omega_{nd,\lambda} = \frac{\omega_{\lambda} - \chi_{d,\lambda} \cdot \omega_{d,\lambda}}{\chi_{nd,\lambda}}$$

***Note that SSA for pure dust particles is taken from previous studies**

Non-dust fraction to AAOD :

$$AAOD_{nd,\lambda} = (1 - \omega_{nd,\lambda}) \cdot AOD_{nd,\lambda}$$

****We can assume that the light-absorbing features of the non-dust of the aerosol plume are caused primarily by Black carbon, but BC is not an ideal light absorber (i.e., $\omega_{bc} \neq 0$)**

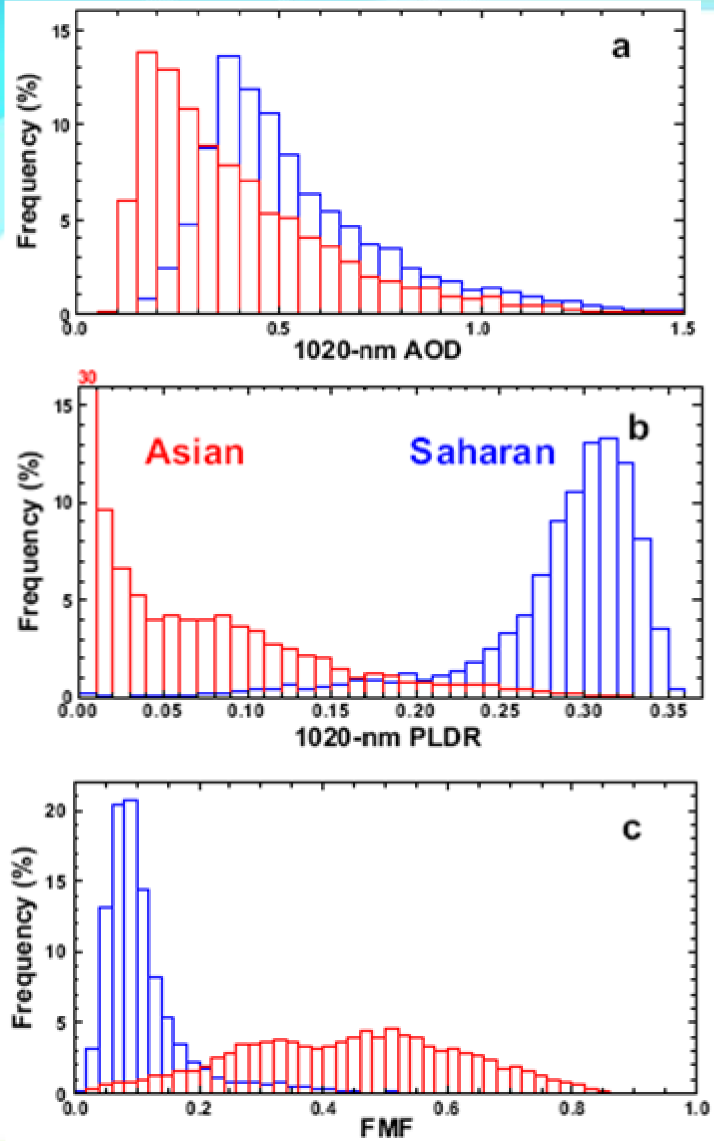
BC-related AAOD :

$$AAOD_{BC,\lambda} = AOD_{nd,\lambda} \cdot (1 - \omega_{nd,\lambda})(1 - \omega_{BC,\lambda}) = AAOD_{nd,\lambda}(1 - \omega_{BC,\lambda})$$

*****Note that SSA for Black carbon is taken from previous studies (0.10. – 0.28 for fresh BC, Bond and Bergstrom (2006))**

BC related AAOD retrieval with AERONET observation data

❖ Overview of the optical properties in Saharan and Asian desert



- Comparably similar features in the histogram of AOD

- Clear differences in the LPDR and FMF

- The two regions allows for assessing the methodology we suggested in situation;

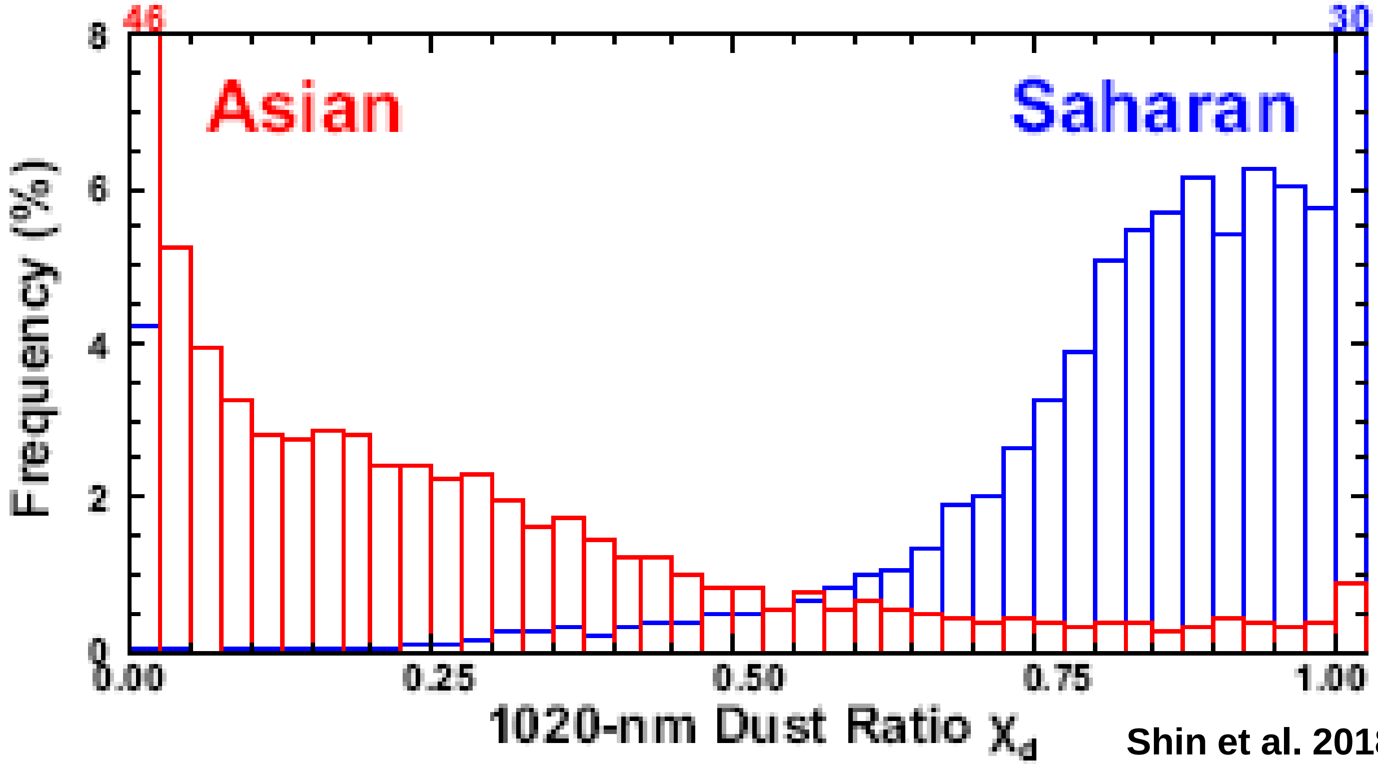
- Dominated by mineral dust (Saharan)

- Dusty mixture with a broad range of dust/non-dust mixing ratios (Asian)

Station	Location	Period	N	AOD_{1020}	δ_{1020}	FMF
Beijing	39.98 °N, 116.38 °E	2001–2018	2713	0.45 ± 0.29	0.06 ± 0.07	0.42 ± 0.17
Gwangju_GIST	35.23 °N, 126.84 °E	2004–2018	956	0.25 ± 0.12	0.06 ± 0.07	0.51 ± 0.19
XiangHe	39.75 °N, 116.96 °E	2001–2018	4300	0.41 ± 0.25	0.06 ± 0.07	0.44 ± 0.18
combined Asian		2001–2018	7969	0.41 ± 0.26	0.06 ± 0.07	0.44 ± 0.18
Banizoumbou	13.55 °N, 2.67 °E	1995–2018	4217	0.60 ± 0.31	0.29 ± 0.05	0.11 ± 0.08
Capo_Verde	16.73 °N, 22.94 °W	1994–2018	1689	0.55 ± 0.25	0.30 ± 0.05	0.09 ± 0.04
Dakar	14.39 °N, 16.96 °W	1996–2018	4118	0.54 ± 0.28	0.28 ± 0.06	0.12 ± 0.08
combined Saharan		1994–2018	10024	0.57 ± 0.29	0.29 ± 0.05	0.11 ± 0.07

BC related AAOD retrieval with AERONET observation data

❖ **Dust ratios in Saharan and Asian desert**



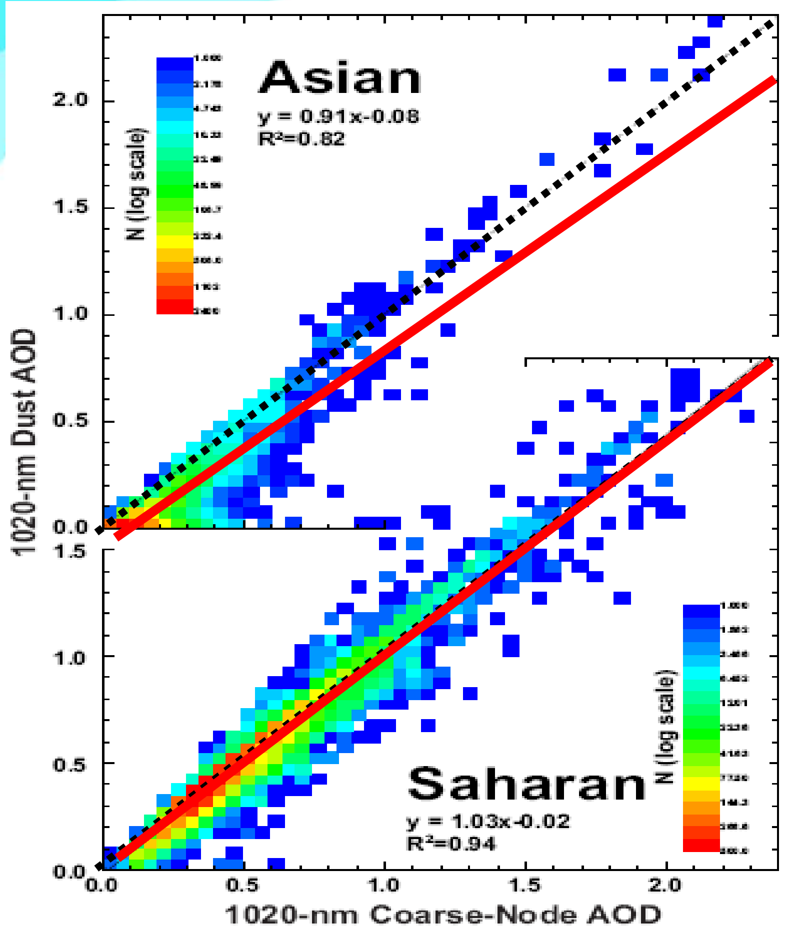
Shin et al. 2018, AMT (in review)

<Histograms of Dust ratio for the considered AERONET stations affected by Saharan (Blue) and Asian dust (red)>

- Distribution of Dust ratio confirms the first impression provided by overview of optical properties in two regions regarding the different impact of mineral dust !!

BC related AAOD retrieval with AERONET observation data

❖Coarse mode AOD vs Dust AOD



Shin et al. 2018, AMT (in review)

<2nd histograms of 1020-nm coarse-mode AOD provided from AERONET and dust AOD at 1020 nm retrieved from the method we suggested>

- Asian stations : coarse mode AOD tends to overestimate the contribution of mineral dust to AOD.

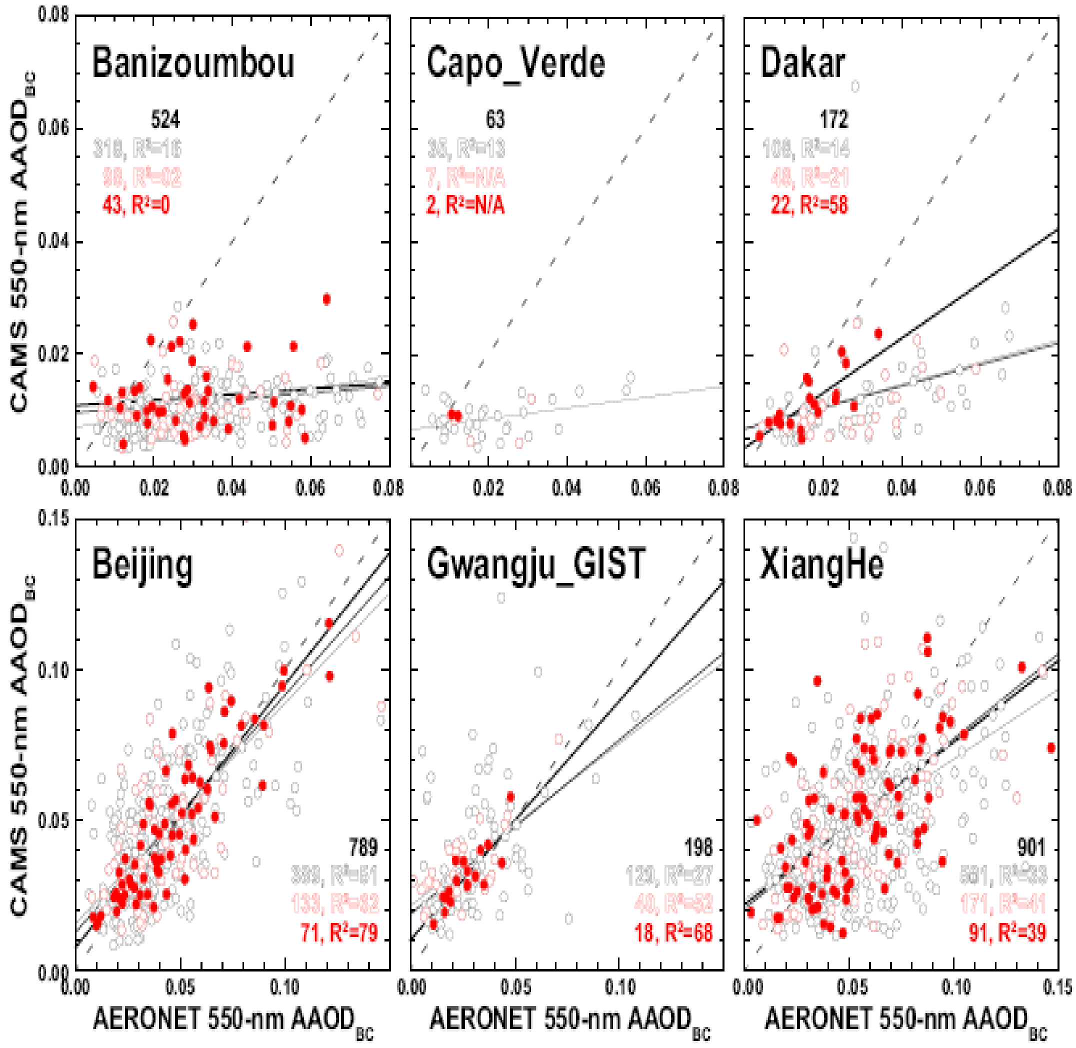
- Saharan stations : coarse mode AOD is found to be suitable proxy for dust AOD.

- Coarse mode AOD and dust AOD cannot necessarily be considered as synonymous !

- Needs to be kept in mind when using AERONET coarse mode AOD in the calibration/validation of spaceborne remote-sensing observations. (Particularly for locations with high occurrence rate of complex aerosol mixture)

BC related AAOD retrieval with AERONET observation data

❖ Comparison of AAODbc with CAMS model



- **Asian sites : Slopes of the linear fit that are reasonably close to the 1:1 line**

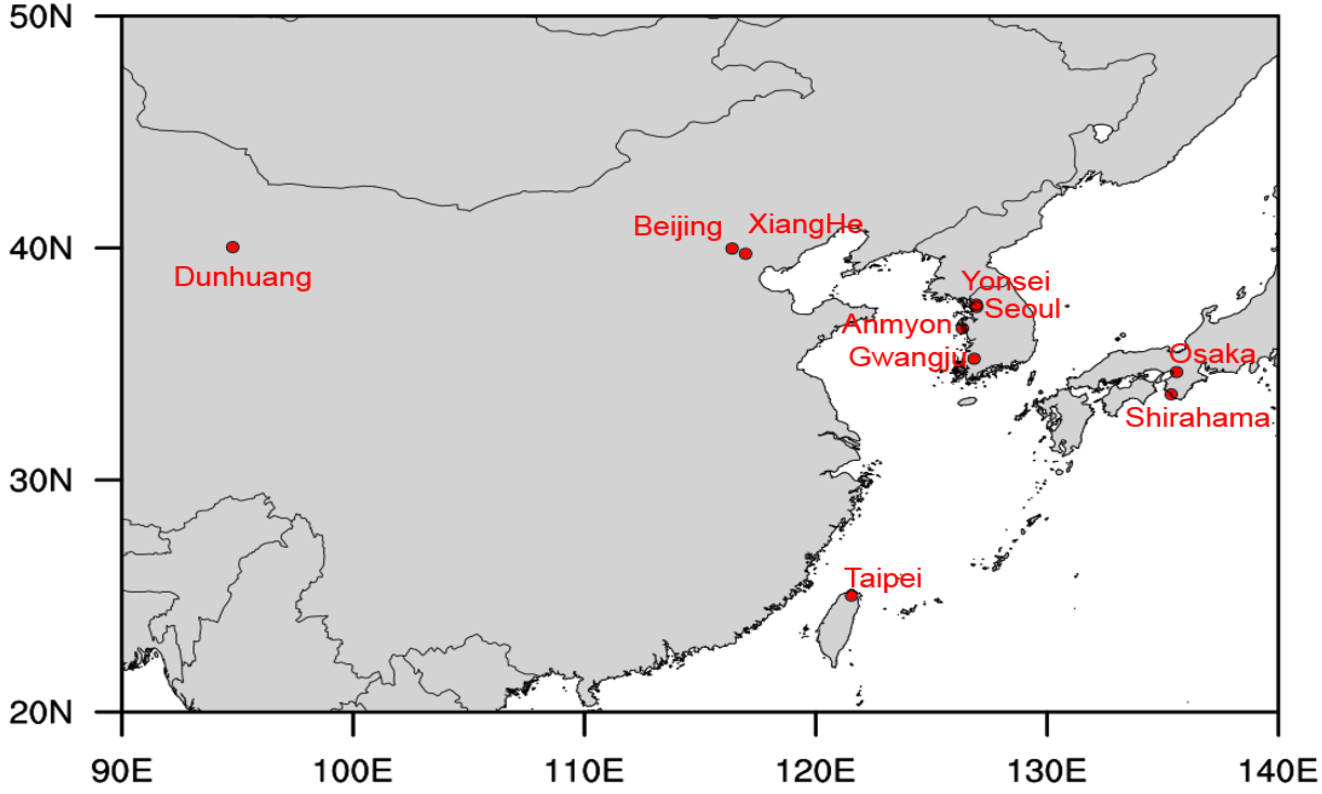
- **Saharan sites : CAMS AAODbc is strongly underestimating the contribution of BC in mixed Saharan dust plume**

(Best resemblance found in Dakar, where local pollution has a much stronger effect on aerosol composition than the other Saharan sites)

AAODbc we derived is more likely to describe aerosol absorption in anthropogenic pollution than in biomass-burning !

Shin et al. 2018, AMT (in review)

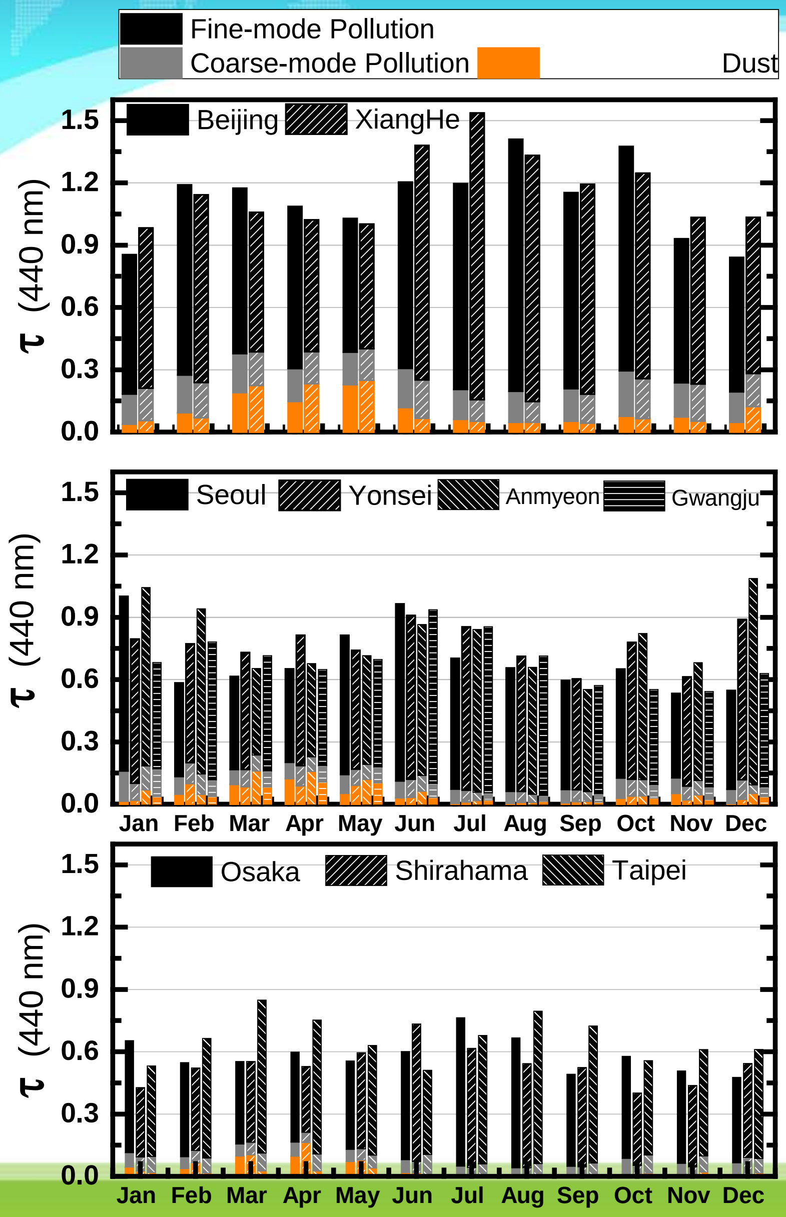
Aerosol Type Separation (DUST, Fine-, Coarse-mode Pollution)

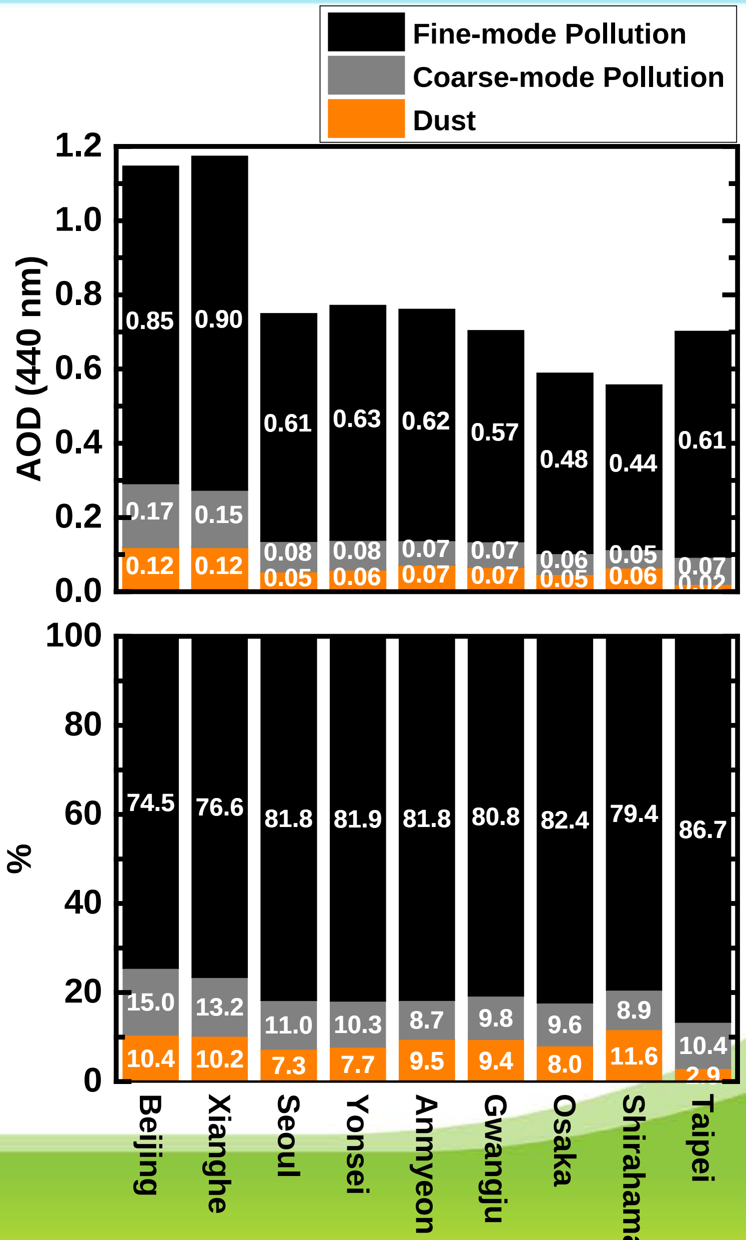


The sites are selected as

1. **Represent the optical properties of atmospheric aerosols generated in Northeast Asia region**
2. **Can show variation of aerosol optical characteristics due to mixing between dust and anthropogenic aerosol during long-range transport.**
3. **The presence of long-term observation data was one of the important considerations in selection of the sites.**

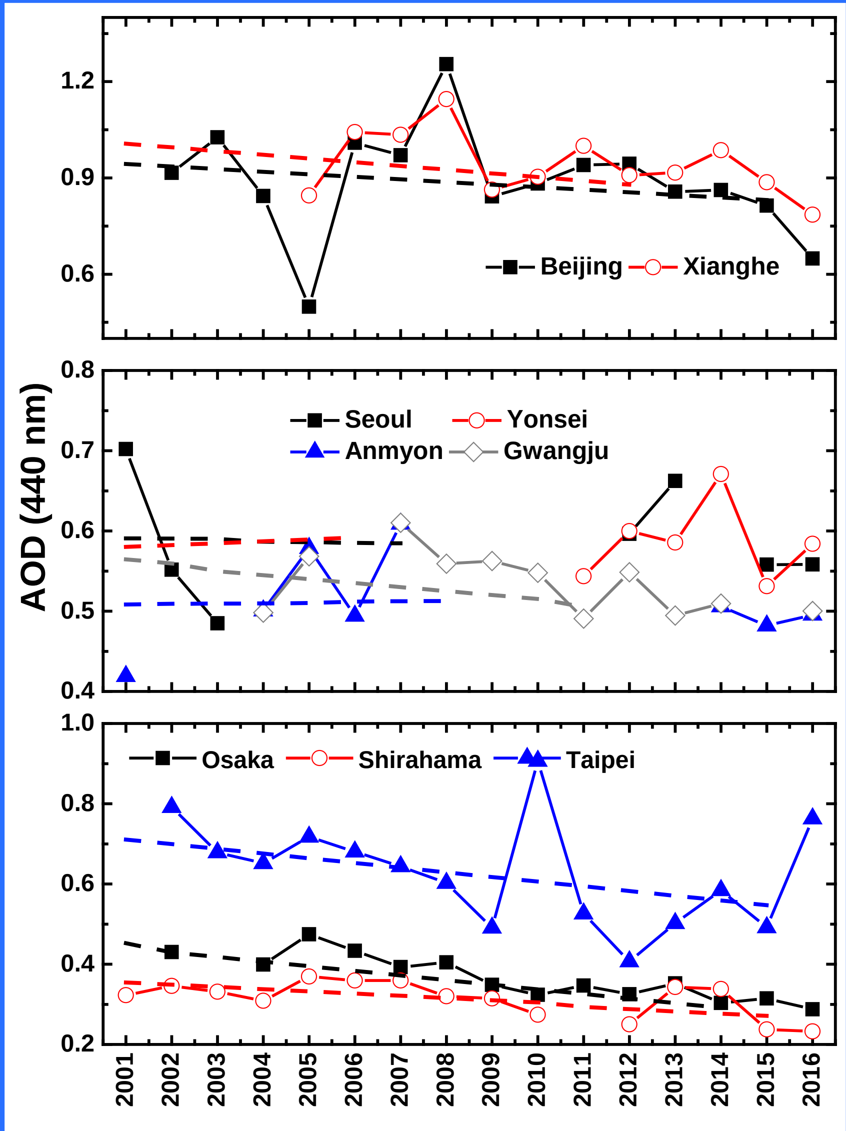
Aerosol Type Separation (DUST, Fine-, Coarse-mode Pollution)



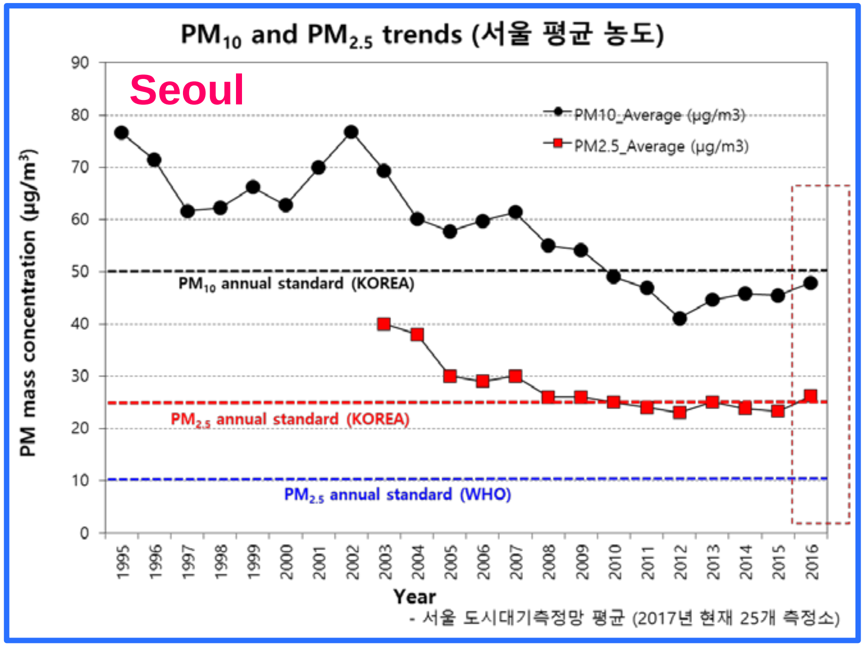


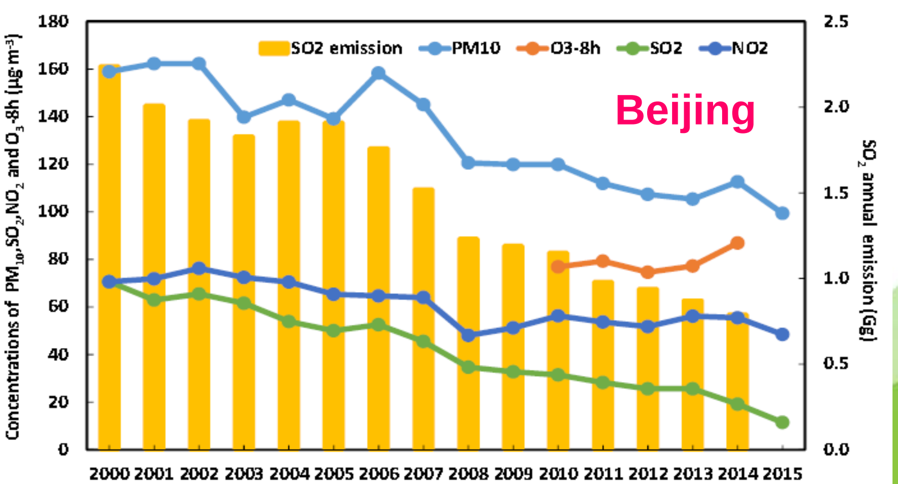
Annual AOD Variation (2001-2016)

AOD by AERONET Sunphotometer



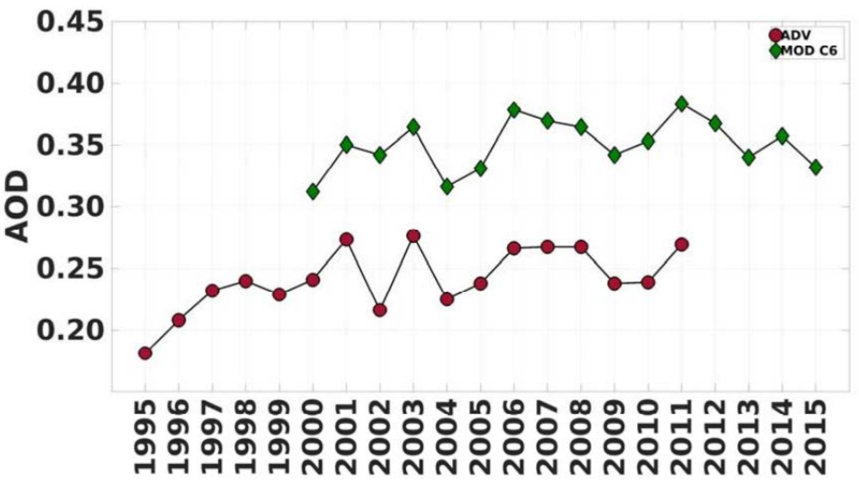
PM Concentration in Asia (Seoul, Beijing)



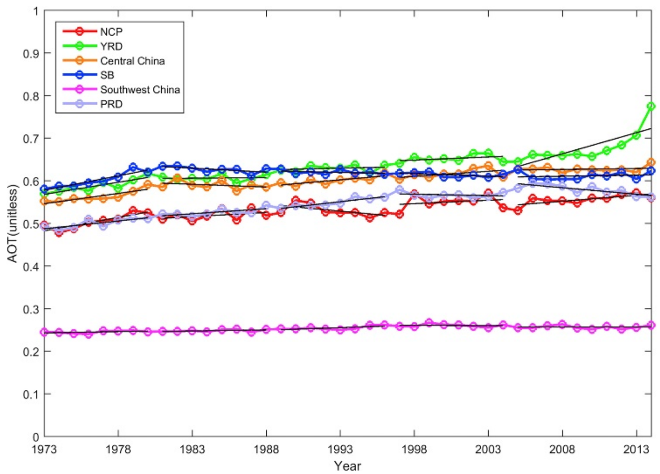


Annual variation of main pollutants in Beijing (Lang et al., 2017, AAQR)

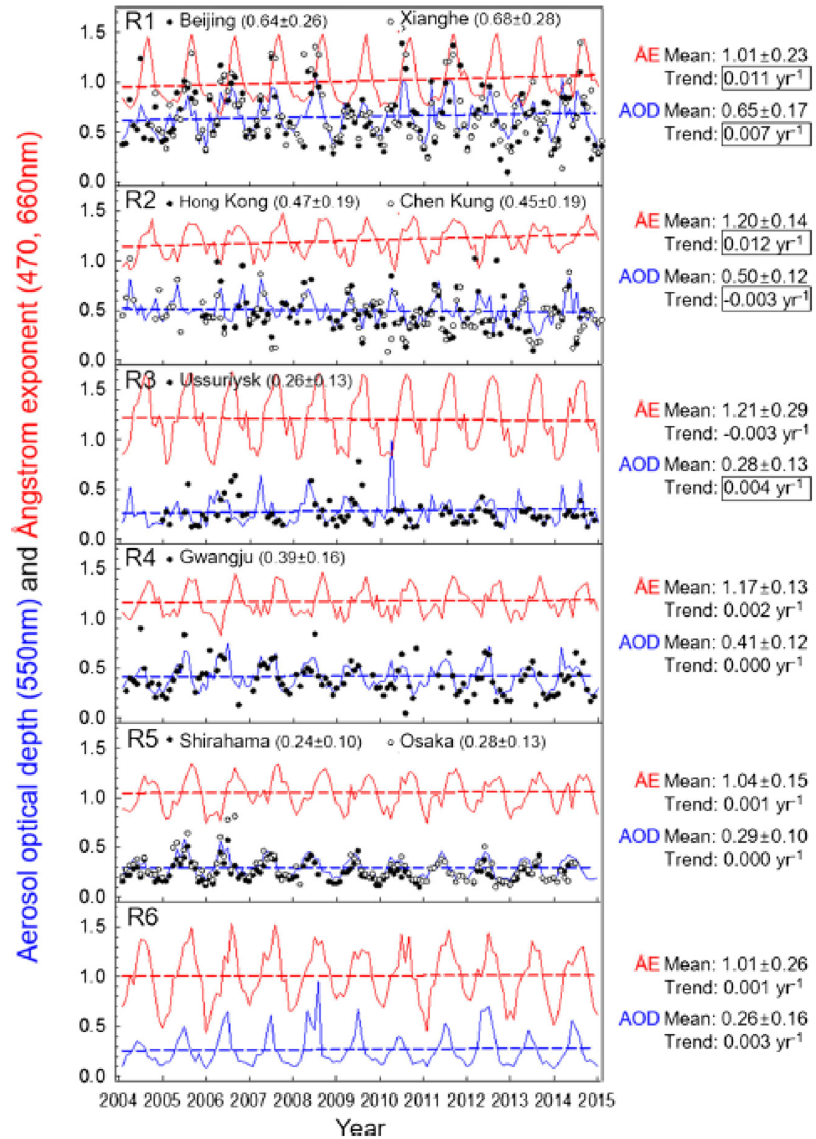
Annual AOD Variation (2001-2016) – other researches



[Leeuw et al., 2017: Atmos. Chem. Phys.]



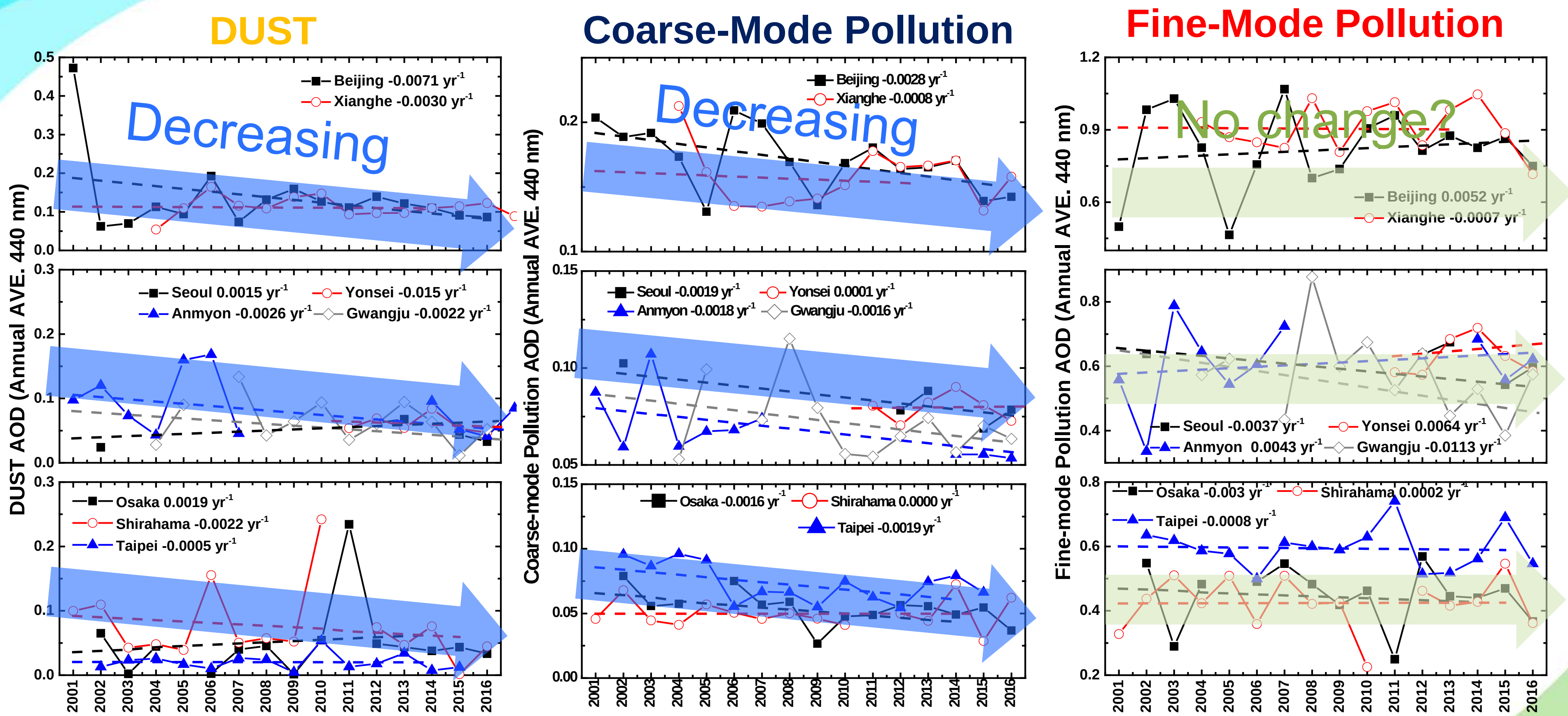
[Zhang et al., 2017: Atmos. Environ.]



[Nam et al., 2017: Air Qual. Atmos. Health]

Aerosol Type Separation (DUST, Fine-, Coarse-mode Pollution)

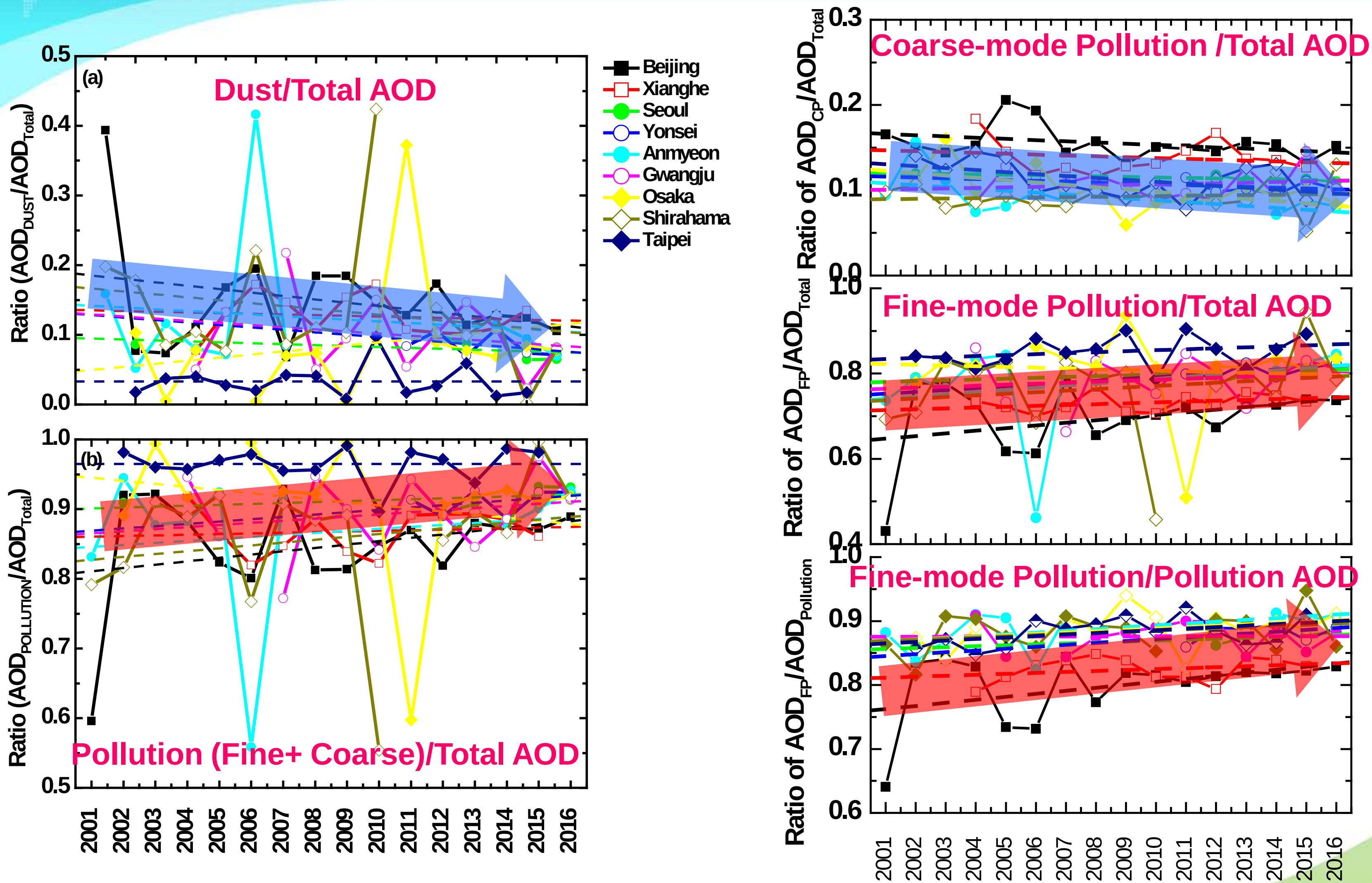
Annual AOD variation according to Aerosol types



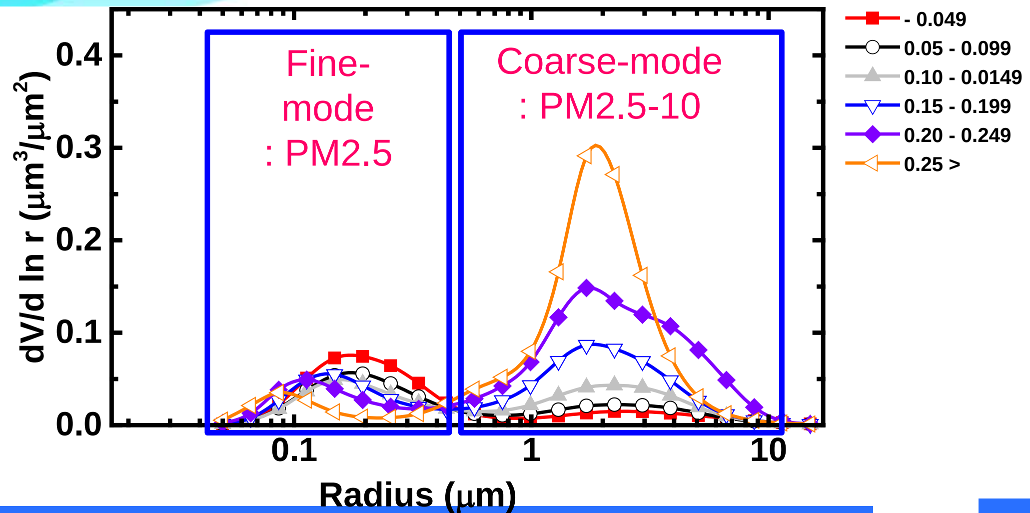
- Different annual trend according to Aerosol types
- Dust and Coarse-mode pollution show decreasing trend
- Fine-mode pollution shows increasing trend

Aerosol Type Separation (DUST, Fine-, Coarse-mode Pollution)

Annual variation of Ratio



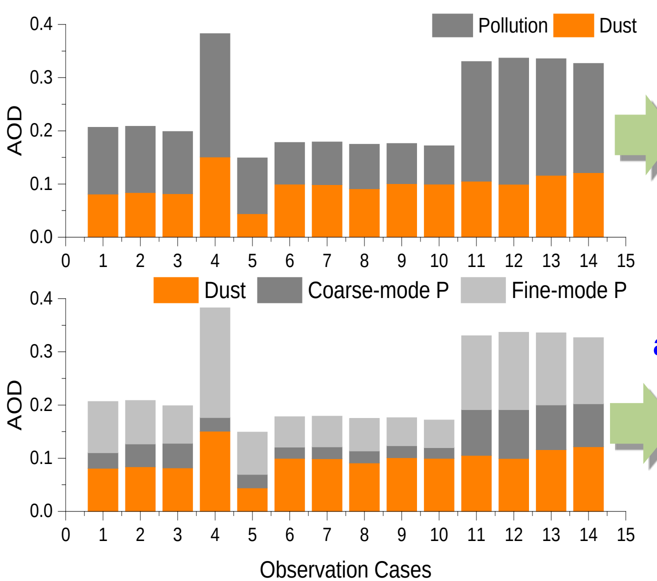
Aerosol Separation as Asian dust, PM10, PM2.5



Mass Extinction Efficiency

Asian dust: 0.2 ~ 1.1 m^2/g,
Sulfate: 6 ~ 8 m^2/g,
Biomass: 2.6 m^2/g,
Urban particle: 4.5 ~ 7.1 m^2/g

Separation of Aerosol Concentration

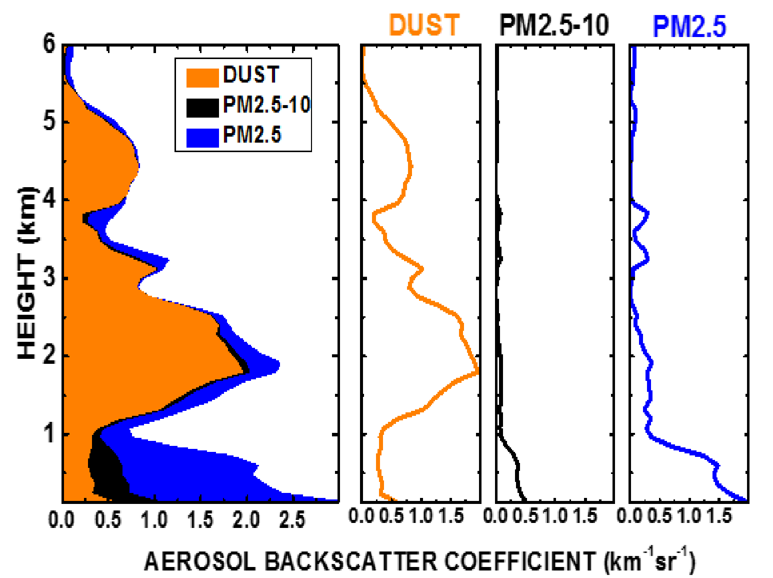


Dust and Pollution particle using only Dust ratio

Separation as Dust, PM10 and PM2.5 using Dust ratio & Size distribution

PM2.5 = Fine-mode pollution
PM2.5-10 = Dust+Coarse-mode Pollution

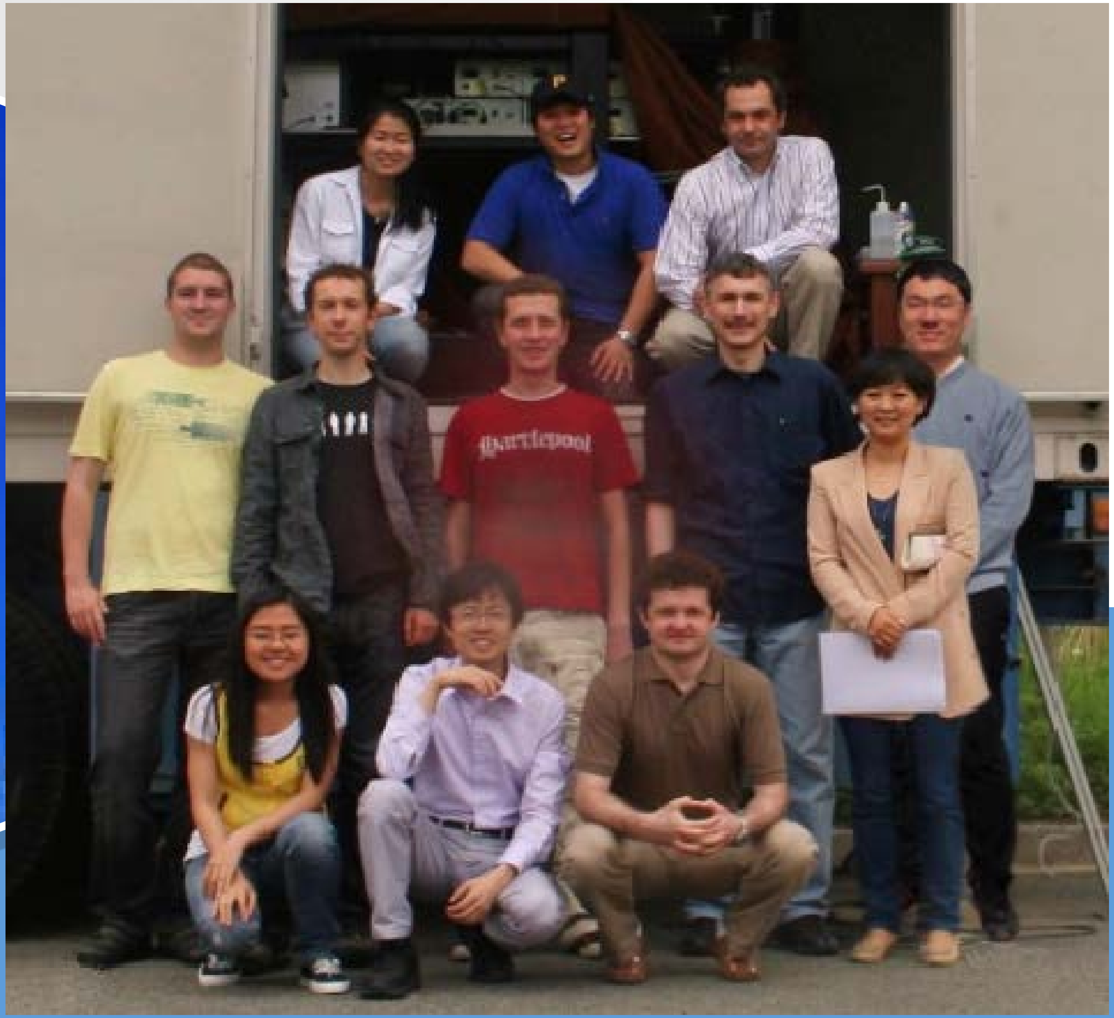
Vertical Separation Data



Summary

- We found that coarse and fine mode AOD cannot always be considered as synonymous with the AOD related to dust and non-dust aerosol, respectively
- We note that our methodology is the first to enable such a differentiation solely on products provided by AERONET.
- We consider the presented methodology as a useful tool for a more detailed calibration and validation of spaceborne remote-sensing observations and aerosol dispersion modeling with AERONET measurements.
- It will be particularly valuable at locations with a frequent occurence of complex mixture of dust and anthropogenic pollution.
- Aerosol type separation results can give an answer on why the annual AOD variations do not show a declining trend.
- Our methodology can be usefully utilize to retrieve PM mass concentration from AOD of remote sensing measurements.

Thank you for your listening



Depolarization comparison : Lidar & Sunphotometer

LIDAR Depolarization Ratio (Vertical resolved data) ⟶ Column-integrated value

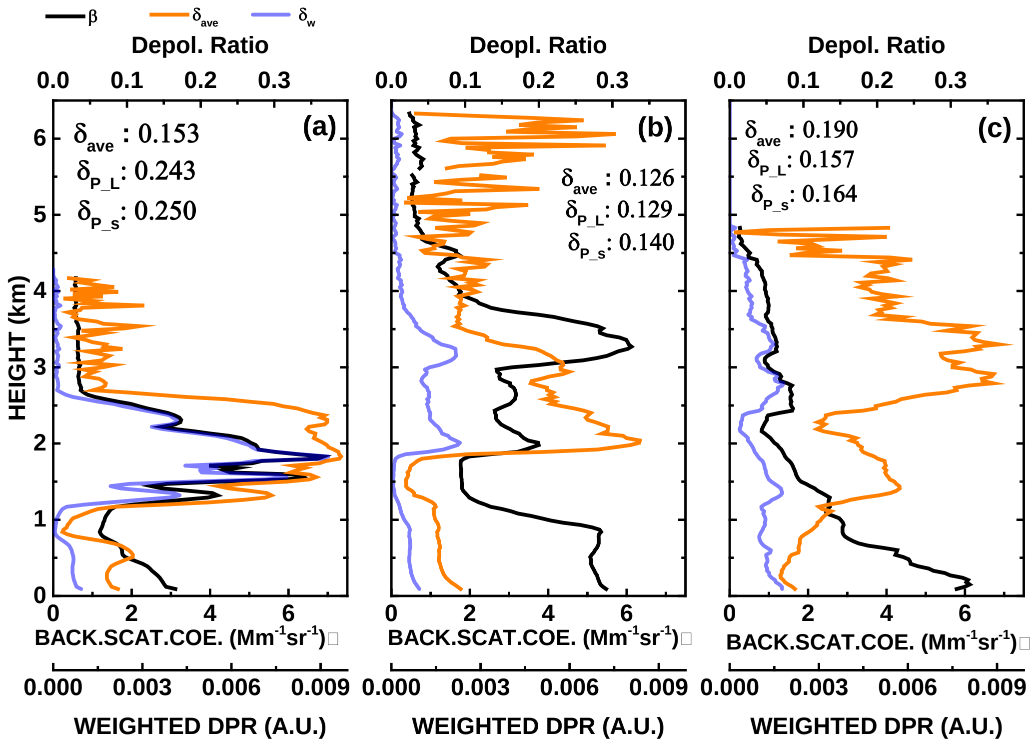
Column-integrated DPR (δ_{P_L})

$$\delta_{P\_L} = \int_0^z \delta_P(z)W(z)dz$$

$W(z)$ **: Weight factor**

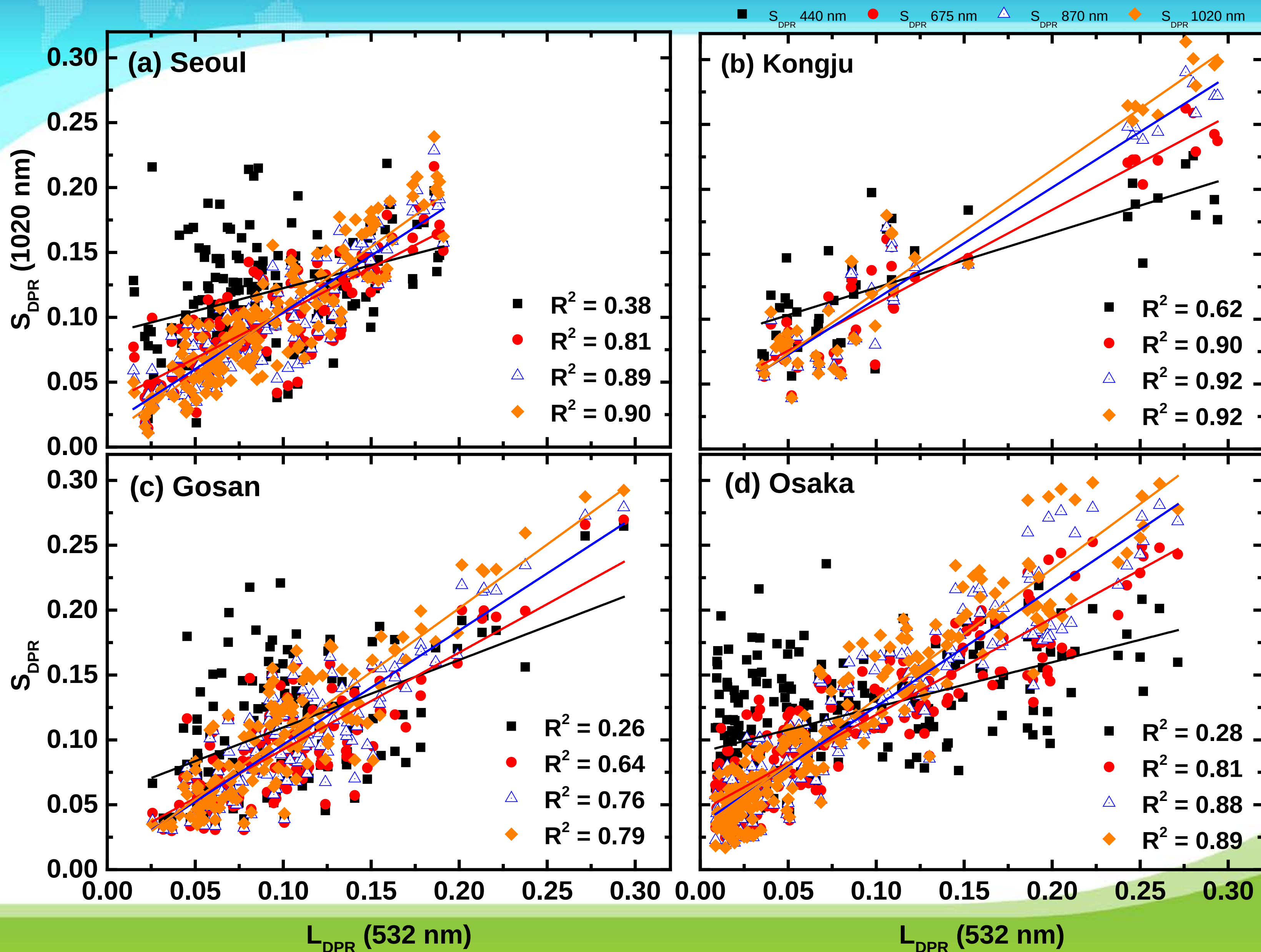
$$W(z) = \frac{\beta_a(z)}{\int_0^z \beta_a(z)dz}$$

β_a**: aerosol backscatter coefficient (LIDAR data)**



- Case I : High value of δ and high value of β
- Case II : Two aerosol layers, high value of only at above layer
- Case III : low value of β and high value of δ

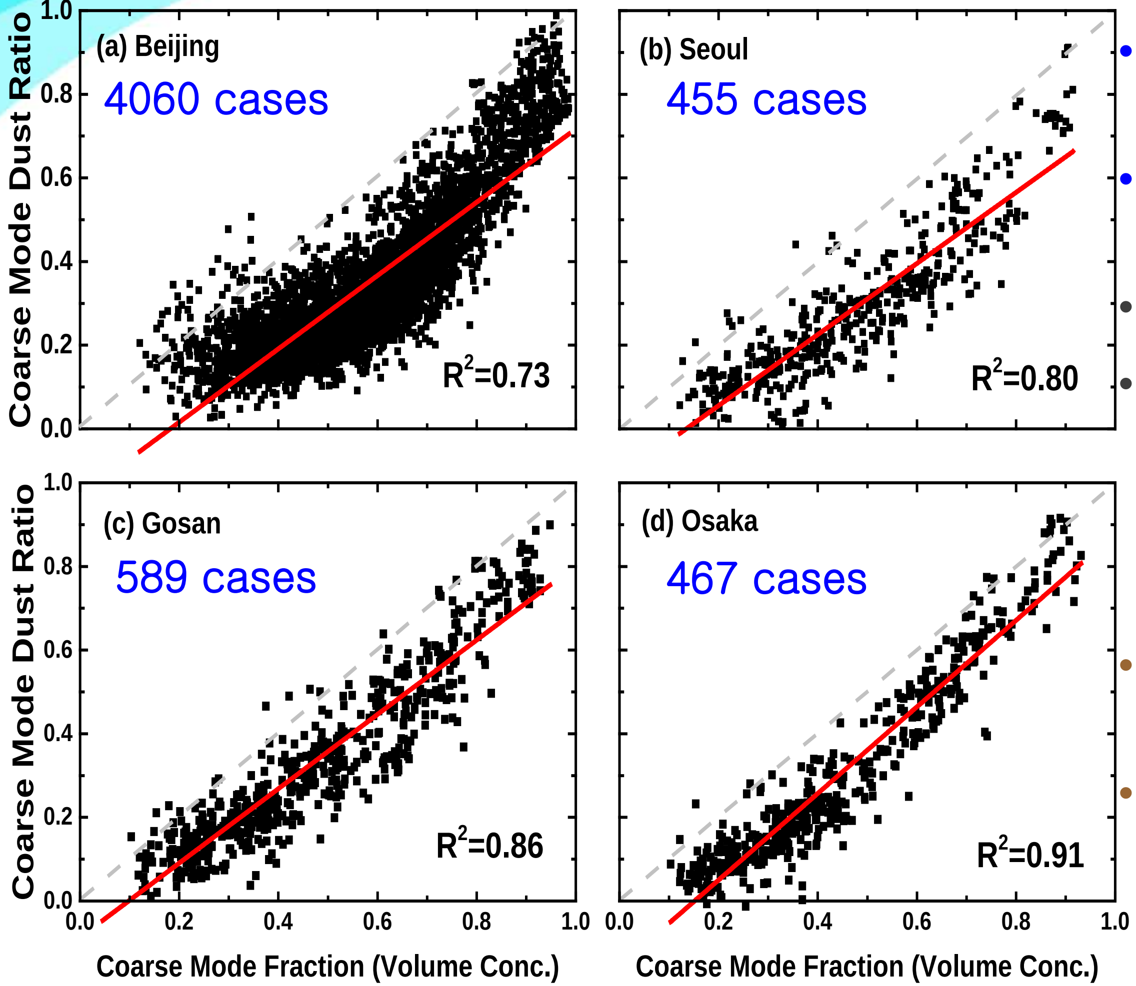
Depolarization comparison : Lidar & Sunphotometer



[Noh et al., 2017 (ACP)]

Comparison between Dust ratio and Coarse-mode fraction

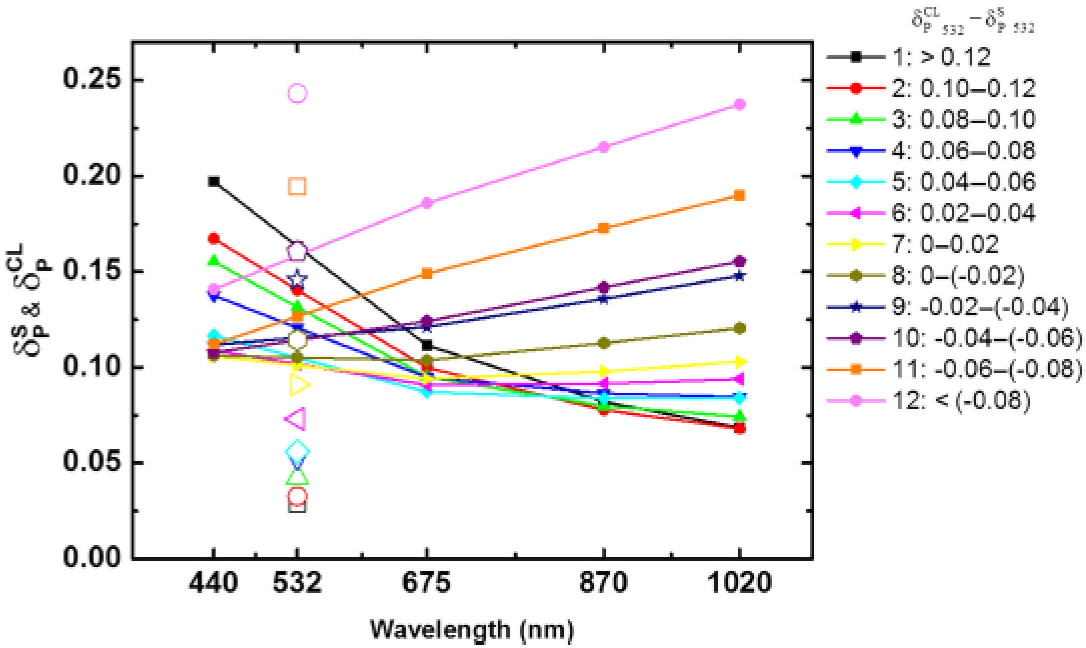
Total 5561 cases

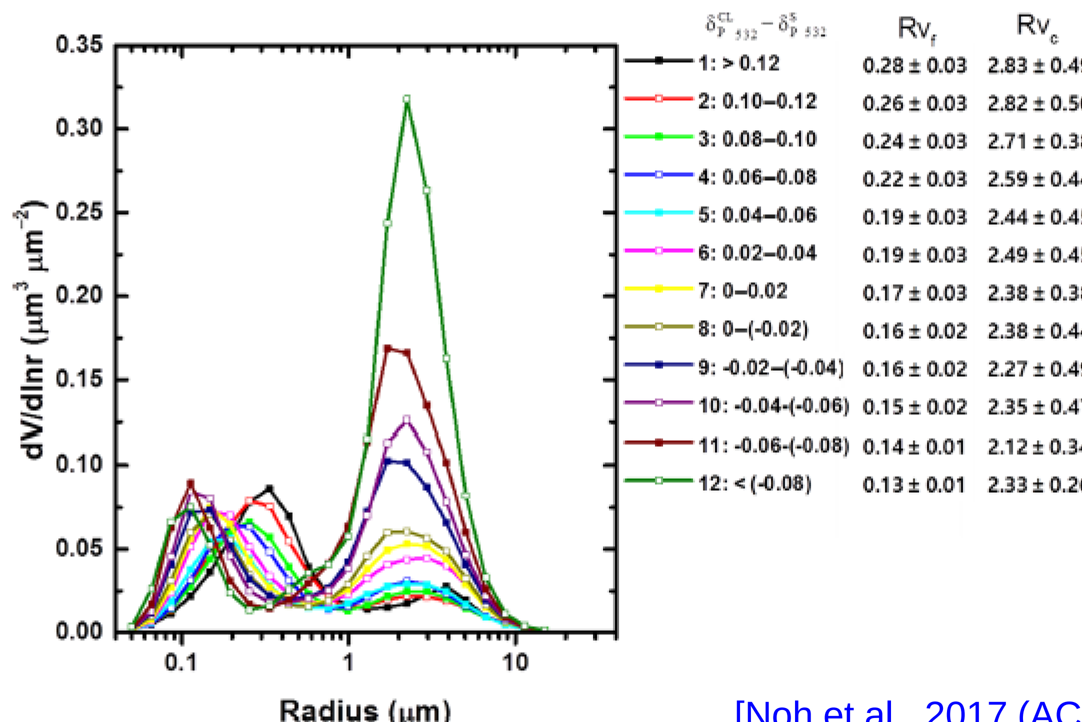


Year 2001 ~ 2016

- **Dust ratio (R_D) : the ratio of dust particle to pollution particles**
- **Coarse-mode fraction (CMF) : only related to particle size**
- **CMF is higher 10 – 20 % than R_D**
- **CMF and R_D show similar value at Dunhuang**

- **All coarse-mode particle is not dust particle**
- **Size parameter has high uncertainty to classify aerosol type**





[Noh et al., 2017 (ACP)]