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Long-term trend of aerosol composition retrieved from CALIOP and MODIS observations

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Introduction

Long-term changes in aerosols

- Aerosols have a significant impact on the climate change.
- Radiative forcing depends on the aerosol composition.
- Aerosol composition has been changing over time.
- It is essential to observe long-term changes in aerosol composition.

This study

- MODIS provides the columnar optical properties. CALIOP observes the vertical profiles.
- We developed a synergistic method to retrieve aerosol composition from CALIOP and MODIS observations.
- Long-term trends of aerosol composition from 2007 to 2021 are investigated.

Aerosol changes in Japan over 30 years

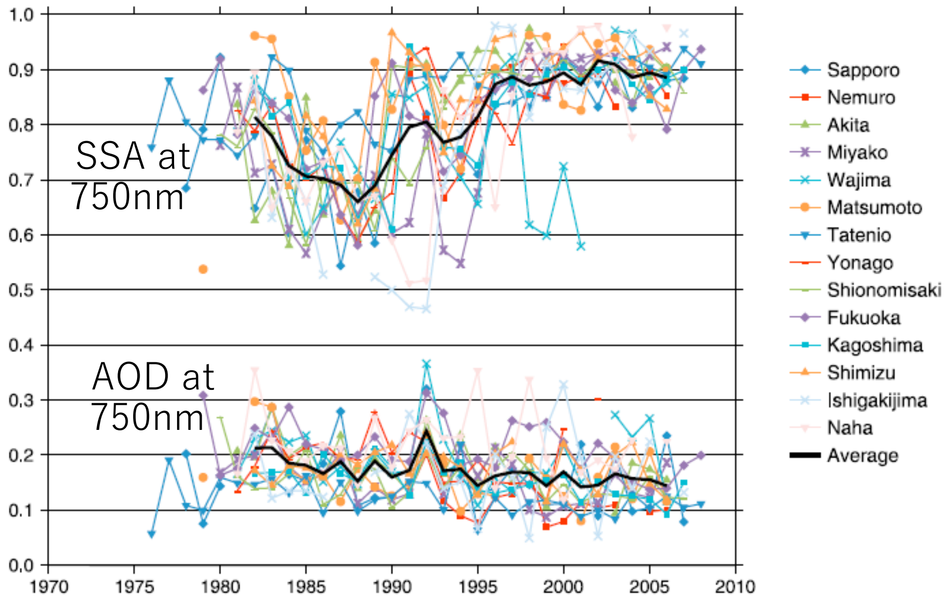


Figure 4. Annual means of AOD (lower lines) and SSA (upper lines) at 0.75 μm at the 14 sites (colored lines). The bold lines are the averages among the sites, calculated when data were available from at least 10 sites.

Kudo et al. 2012, JGR

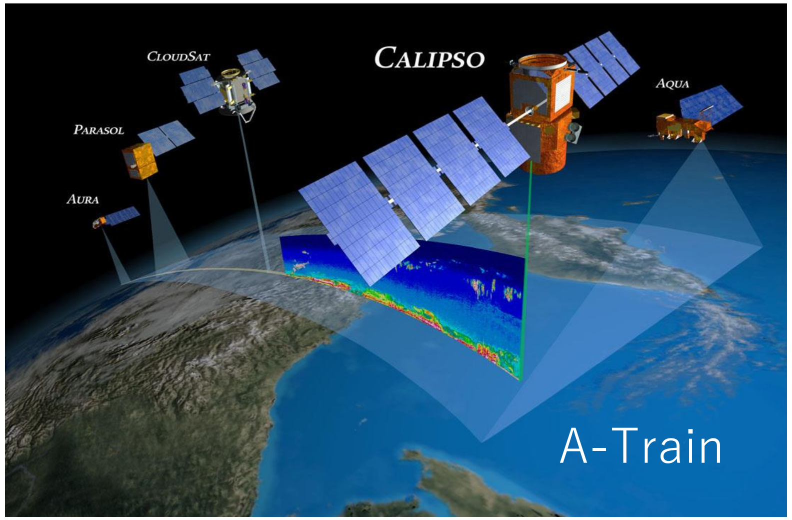
CALIOP and MODIS observations

CALIPSO/CALIOP Version 4

- Attenuated backscatter coefficients at 532 and 1064 nm.
- Total (Volume) depolarization ratio at 532 nm.
- Vertical Feature Mask (layer classification information of clear air, tropospheric and stratospheric aerosols) for eliminating the cloud-contaminated data.

Aqua/MODIS Collection 6

- Radiances at band 1 (620-670 nm) and 2 (841-876 nm).
- Cloud mask to remove the cloud-contaminated data.
- Surface albedo (MCD43C3) for the forward calculation of MODIS.

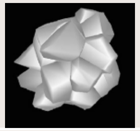


Matched-up data set

- Clear-sky matched-up data set was created for the retrieval.
- Horizontal resolution along the track is 1 km.
- Vertical resolution is 120 m for the altitudes from -0.5 to 20.2 km, and 180 m for the altitudes from 20.2 to 30.1 km.
- Cloud-free MODIS data at the nearest pixel within a 10-km range from the near-nadir measurements of CALIOP was selected.

Aerosol composition

Assuming that aerosols consist of four components, which have different sizes and light-absorbing characteristics.

Component		Shape Depolarization ratio (532nm)	Radius (μm)	SSA (532nm)	Refractive index	Hygroscopic growth
Water-soluble (WS)	External mixture of Sulfate, Nitrate, Organic, others. (Hess 1999)	Sphere 0.0	～0.10 μm	～0.96	Hess 1998	Hess 1998
Light-absorbing (LA)	Internal mixture of BC and WS. Core-Gray shell model (Kahnert 2013) 	Sphere 0.0	～0.10 μm	～0.44	WS: Hess 1998 BC: Chang 1990	Only for WS of shell Hess 1998
Dust (DS)	Desert dust 	Voronoi aggregate (Ishimoto 2010) 0.49	～2.0 μm	～0.91	Asian dust (Aoki 2005)	-
Sea-salt (SS)	Salt in seawater	Sphere 0.0	～2.0 μm	1.00	Hess 1998	Hess 1998

Aoki 2005, https://doi.org/10.2151/jmsj.83A.315
Hess 1998, https://doi.org/10.1175/15200477(1998)079<0831:OPOAAC>2.0.CO;2
Ishimoto 2010, ttps://doi.org/10.1016/j.jqsrt.2010.06.018
Kahnert 2013, https://doi.org/10.1364/OE.21.007974

CALIOP-MODIS retrieval

State vector $\boldsymbol{x}$
- Dry volume concentrations of WS, LA, DS, SS
- Dry median radii of fine (WS, LA) and coarse (DS) particles

Forward models $\boldsymbol{y}(\boldsymbol{x})$
- Aerosol optical property
- CALIOP observations
- MODIS observations

A priori constraints $\boldsymbol{y}_a(\boldsymbol{x})$
- Smoothness of vertical profiles of WS, LA, DS, SS
- Similarity of vertical profiles of WS and LA
- $AOD_{LA} < AOD_{WS}$
- A priori distributions of fine (WS, LA) and coarse (DS) median radii

Iteration by Gauss-Newton method and a line search with Armijo rule (Kudo 2016)

$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + \alpha \boldsymbol{d}$

Objective function

Observations $\boldsymbol{y}^{obs}$
- CALIOP observations
- MODIS observations

Convergence

Optimized $\boldsymbol{x}$

Output
- AOD, SSA, etc. of total aerosols
- AOD and extinction coefficients of WS, LA, DS, SS

$$f(\boldsymbol{x}) = \frac{1}{2}\left(\boldsymbol{y}^{obs} - \boldsymbol{y}(\boldsymbol{x})\right)^T (\boldsymbol{W}^2)^{-1}\left(\boldsymbol{y}^{obs} - \boldsymbol{y}(\boldsymbol{x})\right) + \frac{1}{2}\boldsymbol{y}_a(\boldsymbol{x})^T(\boldsymbol{W}_a^2)^{-1}\boldsymbol{y}_a(\boldsymbol{x})$$

Aerosol optical property
- Lognormal size distribution.
- Median radii of WS and LA is same.
- Median radius of SS is estimated by the parameterization using ocean surface wind speed (Erickson 1988)
- Hygroscopic growth depending on relative humidity for WS, Shell of LA, and SS (Hess 1998)
- WS, LA, DS over land. WS, LA, DS, SS over ocean.

CALIOP
- Lidar equation

MODIS
- Vector RTM, PSTAR (Ota 2010)

- Smoothness of vertical profile

$$y_a(\boldsymbol{x}) = \ln\left(V_{dry}(z_{i-1})\right) - 2\ln\left(V_{dry}(z_i)\right) + \ln\left(V_{dry}(z_{i+1})\right)$$

- Similarity of vertical profiles of WS, LA

$$y_a(\boldsymbol{x}) = \ln\left(V_{dry,LA}(z_i)/V_{dry,LA}(z_{i+1})\right) - \ln\left(V_{dry,WS}(z_i)/V_{dry,WS}(z_{i+1})\right)$$

- $\tau_{LA} < \tau_{WS}$

$$y_a(\boldsymbol{x}) = -\ln(1 - \tau_{LA}/\tau_{WS})$$

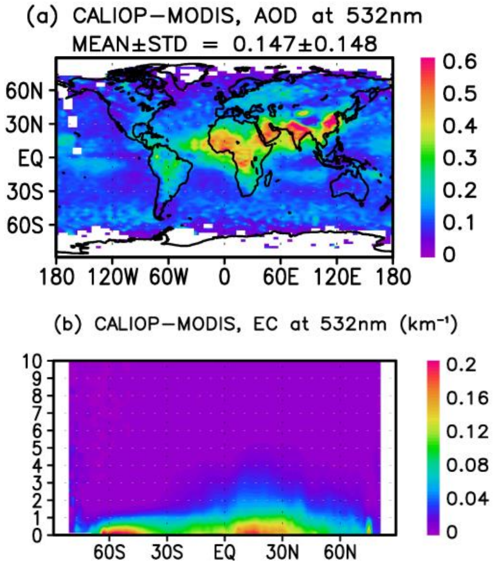
- A priori values of median radii

$$y_a(\boldsymbol{x}) = \ln\left(r_{fine/coarse}\right) - \ln\left(r_{fine/coarse}^{a\ priori}\right)$$

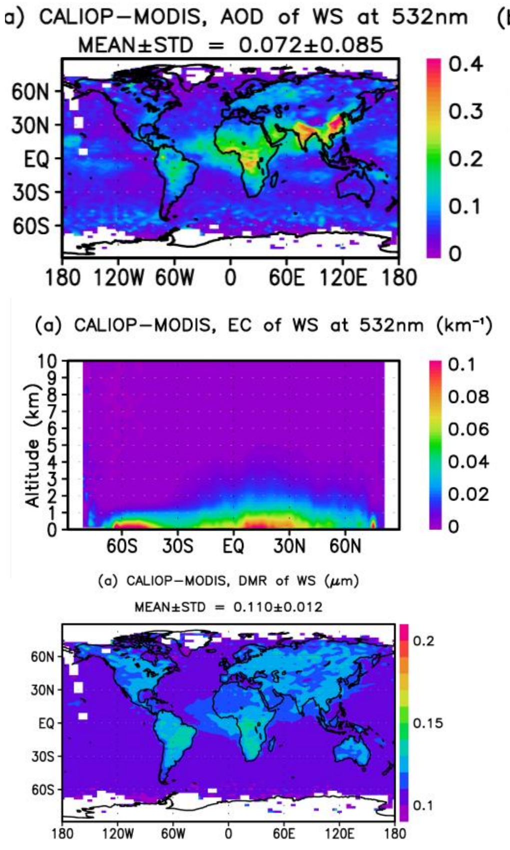
Kudo 2016, https://doi.org/10.5194/amt-9-3223-2016
Erickson 1988, https://doi.org/10.1029/JC093iC11p14079
Ota 2010, https://doi.org/10.1016/j.jqsrt.2009.11.021

Result in 2010

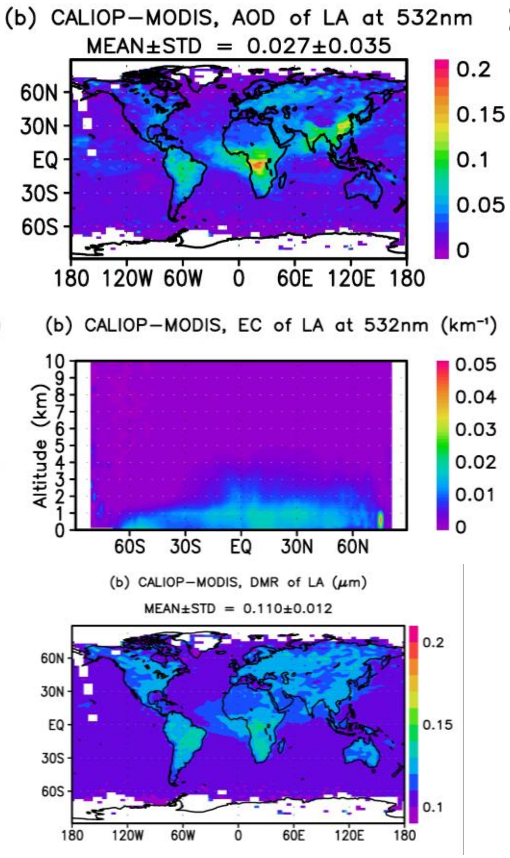
Total
AOD = 0.147 ± 0.148



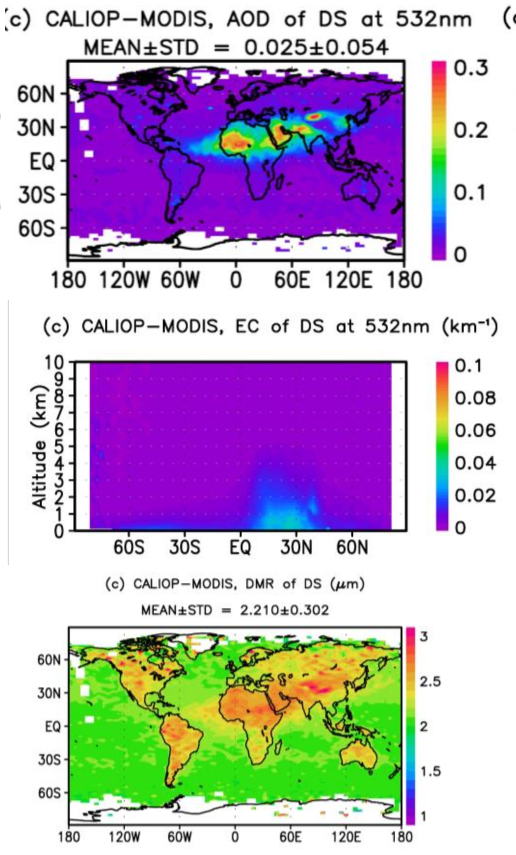
WS
AOD = 0.072 ± 0.085
R_{dry} = 0.110 ± 0.012 μm



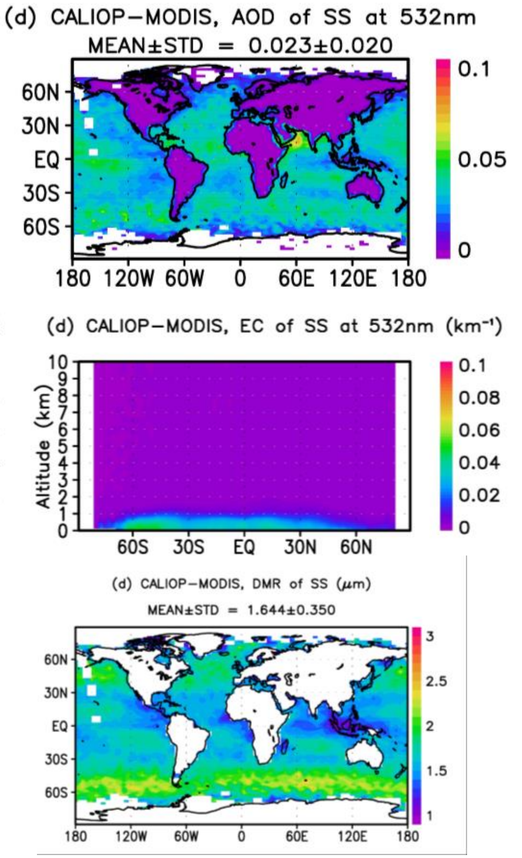
LA
AOD = 0.027 ± 0.035
R_{dry} = 0.110 ± 0.012 μm



DS
AOD = 0.025 ± 0.054
R_{dry} = 2.210 ± 0.302 μm



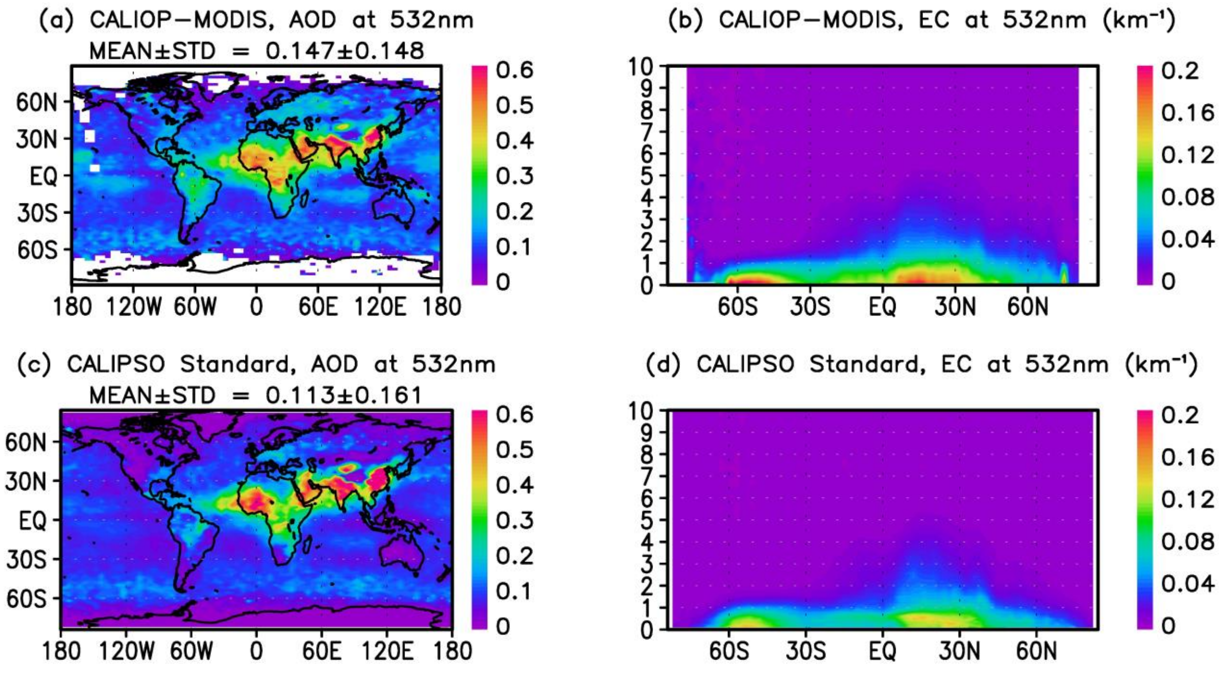
SS
AOD = 0.023 ± 0.020
R_{dry} = 1.644 ± 0.350 μm

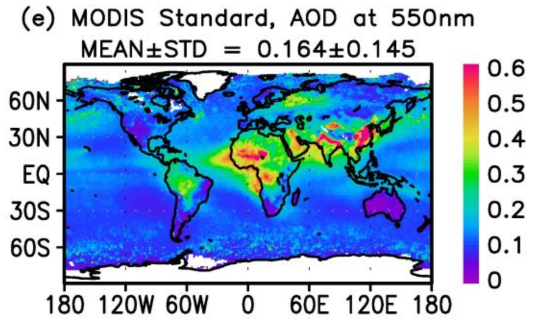


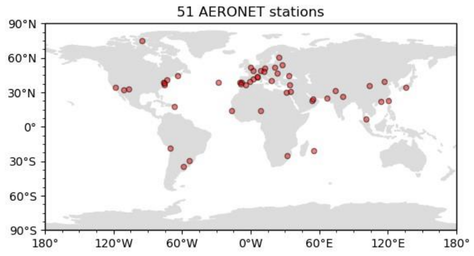
Upper: AOD at 532 nm
Middle: Zonal mean of extinction coefficient at 532 nm
Lower: Dry median radius

Comparison with NASA products

Comparison with CALIPSO and MODIS L3 products



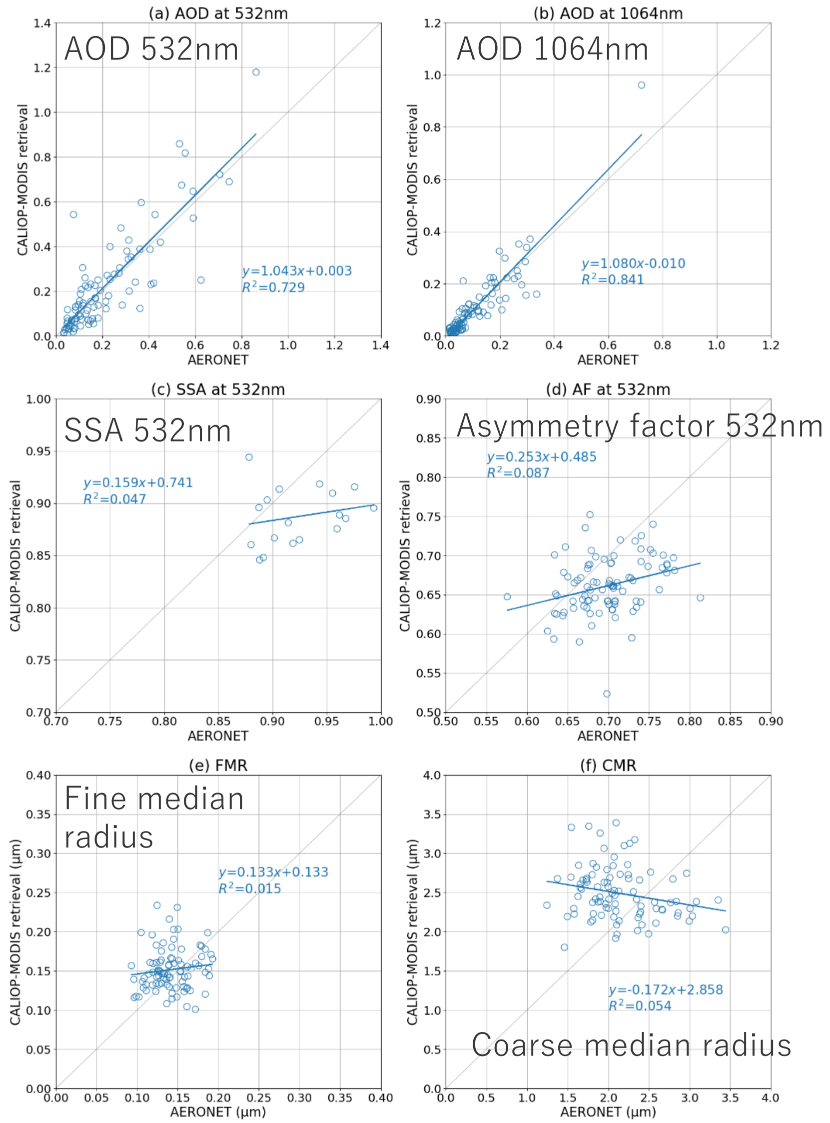




Coincidence criteria:

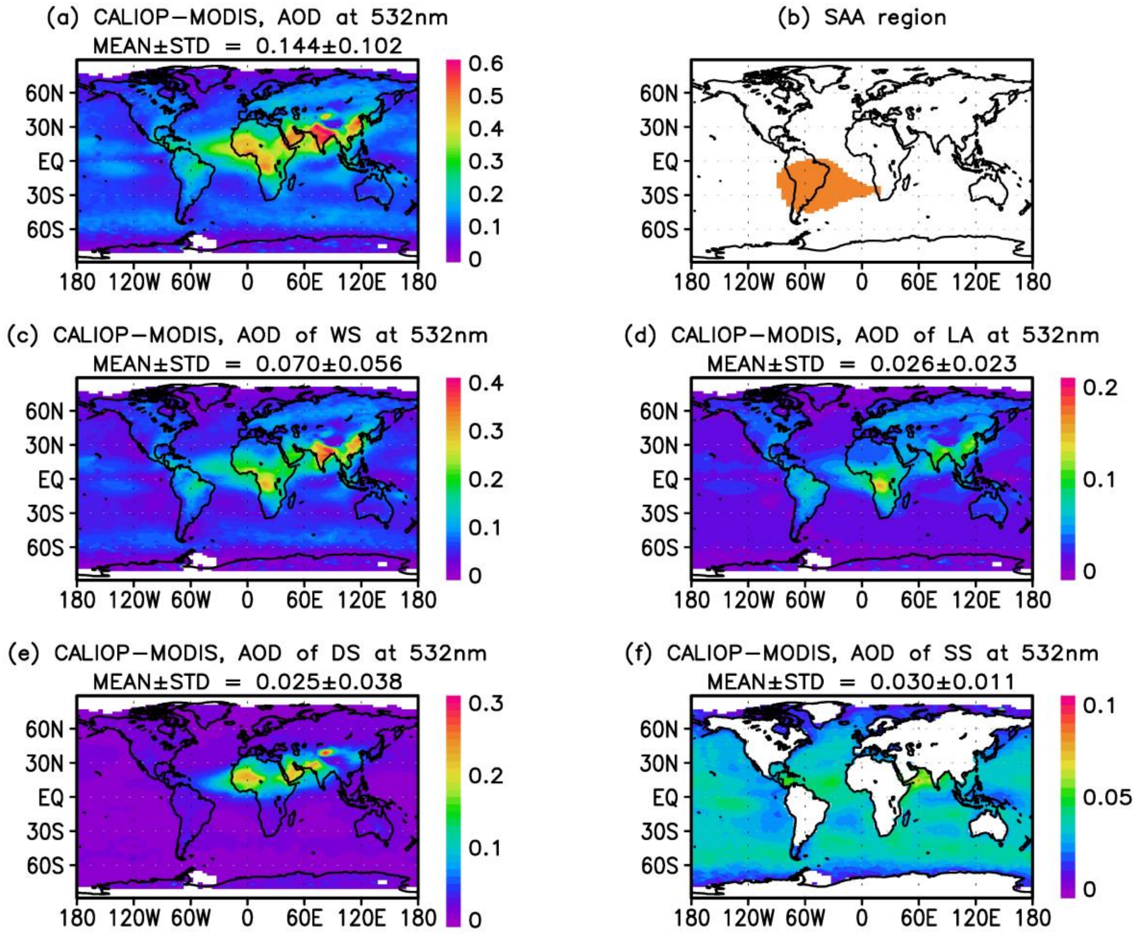
- ±2 hours
- Within a 40-km radius of an AERONET site
- ± 100m of an AERONET site elevation

Comparison with AERONET

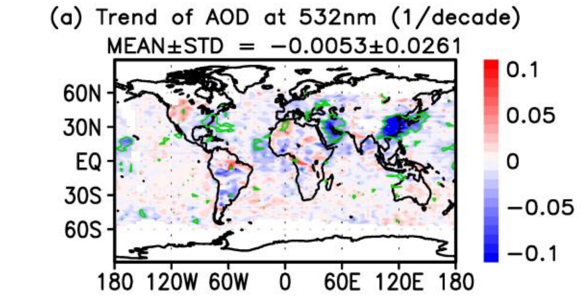


Long-term trend in 2007-2021

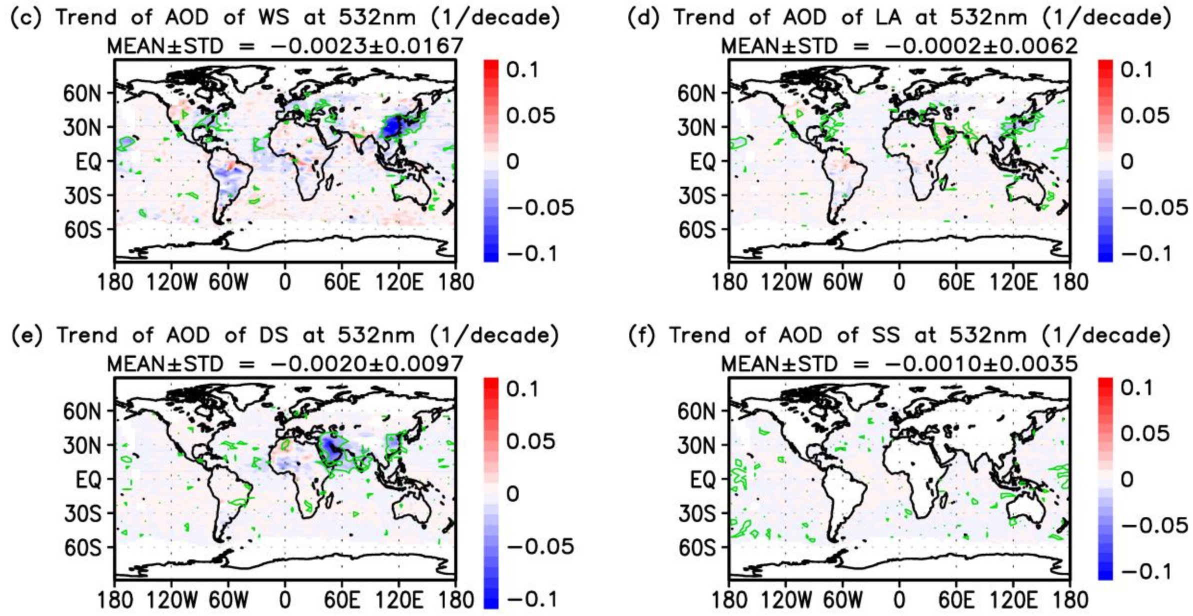
Means



Linea trend (1/decade)

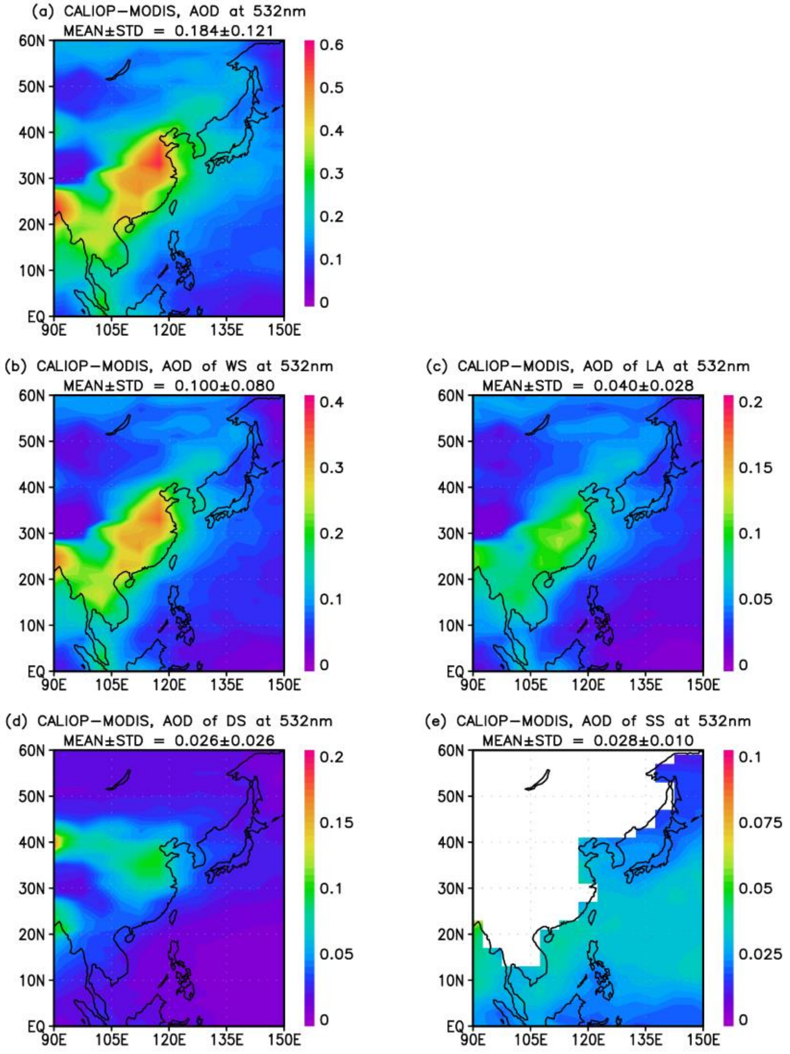


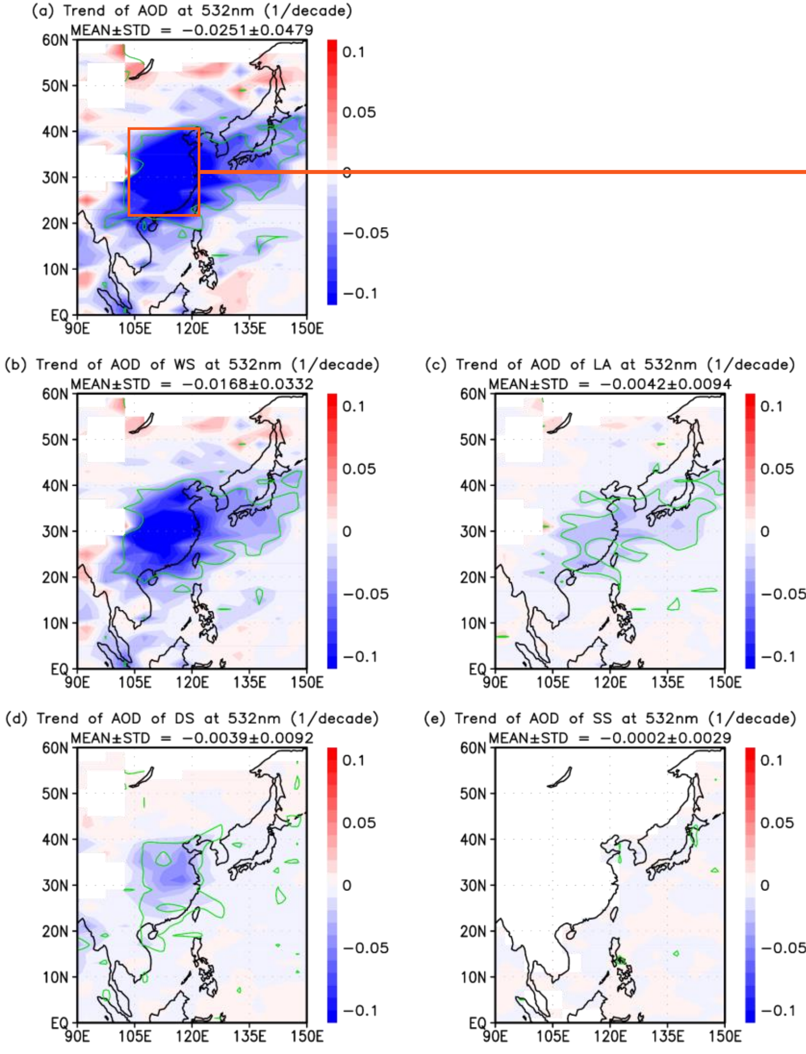
Green contour indicates statistically significant trend determined by t-test.

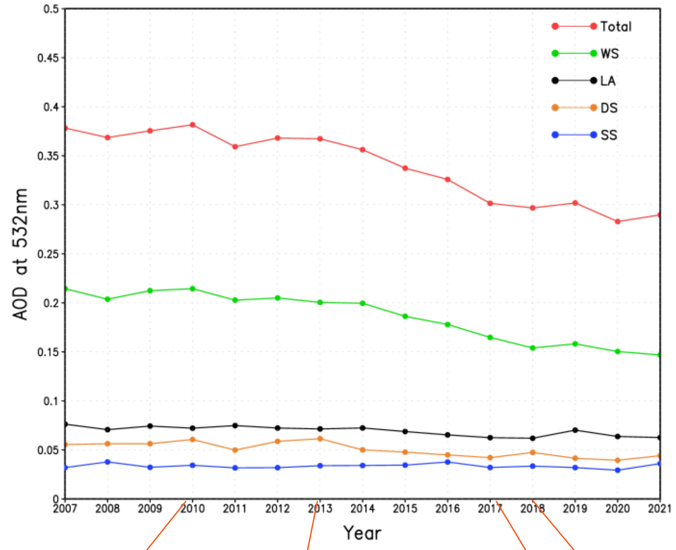


SAA (South Atlantic Anomaly) is an area where Earth's inner Van Allen radiation belt comes closest to Earth's surface. This exposes satellites to higher-than-usual levels of ionizing radiation. Since 2016, the influences to CALIOP measurements has been remarkable. Therefore, the data for SAA region after 2017 was not used.

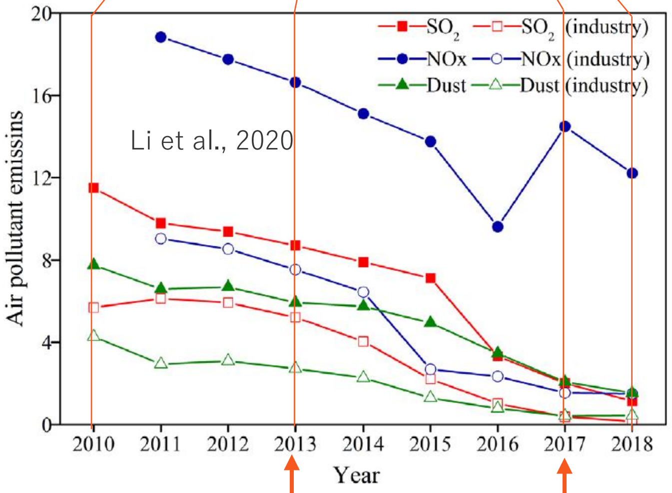
Trend in East Asia





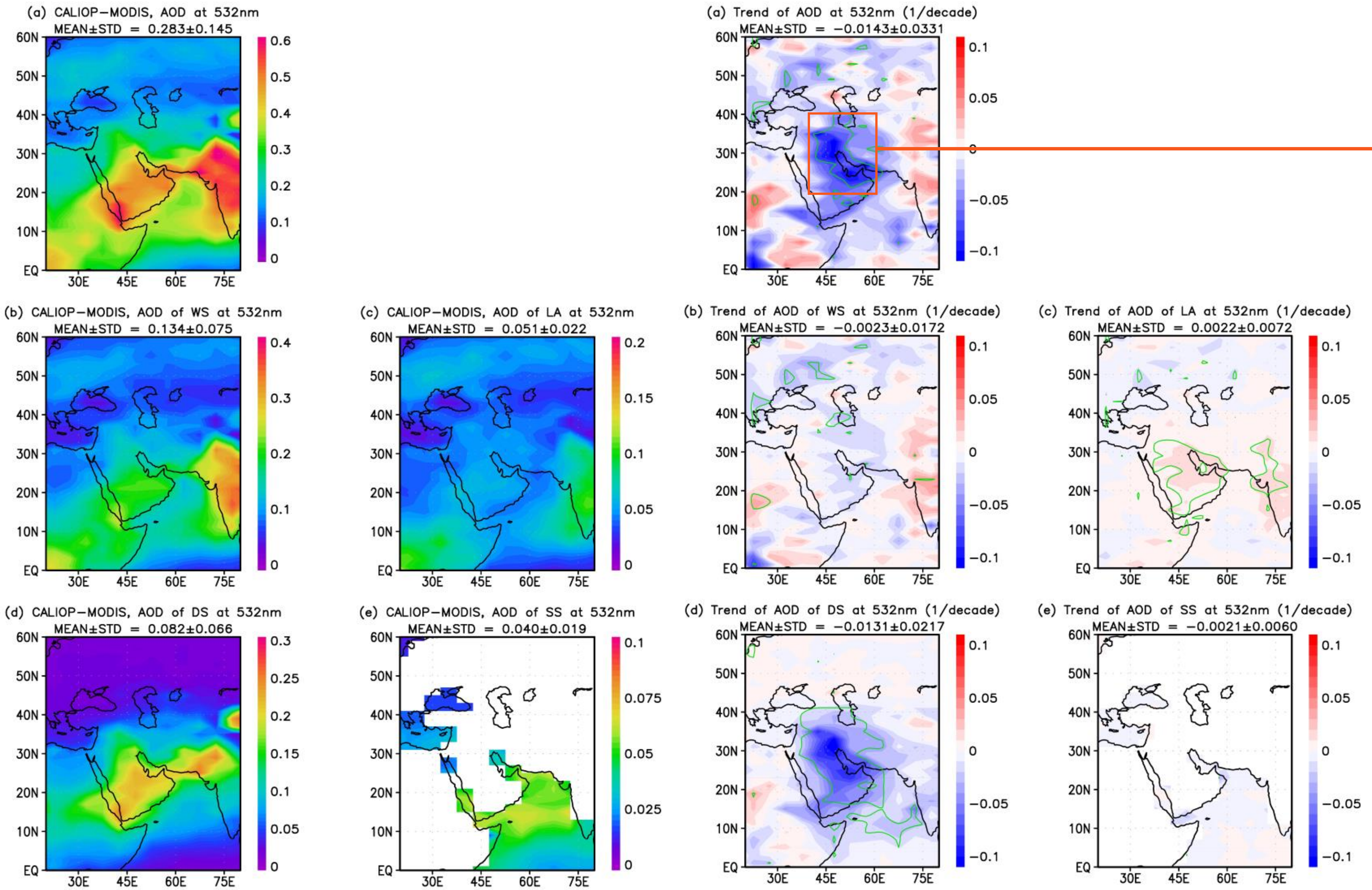


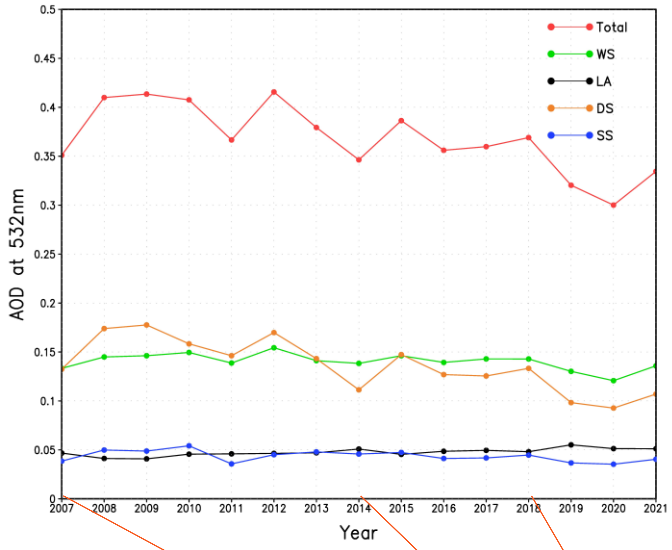
Emissions in Beijing, China



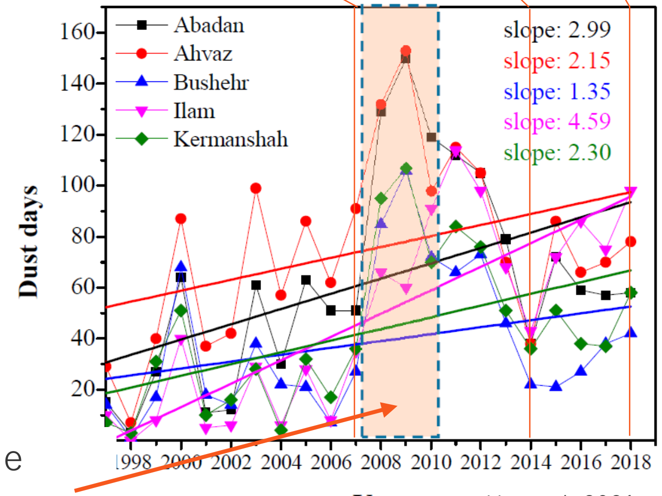
2013: Air Pollution Prevention and Control Action Plan
2017: Action Plan for Comprehensive Control of Atmospheric Pollution in Autumn and Winter of Beijing-Tianjin-Hebei region

Trend in West Asia





Dust days observed at meteorological stations in Iran



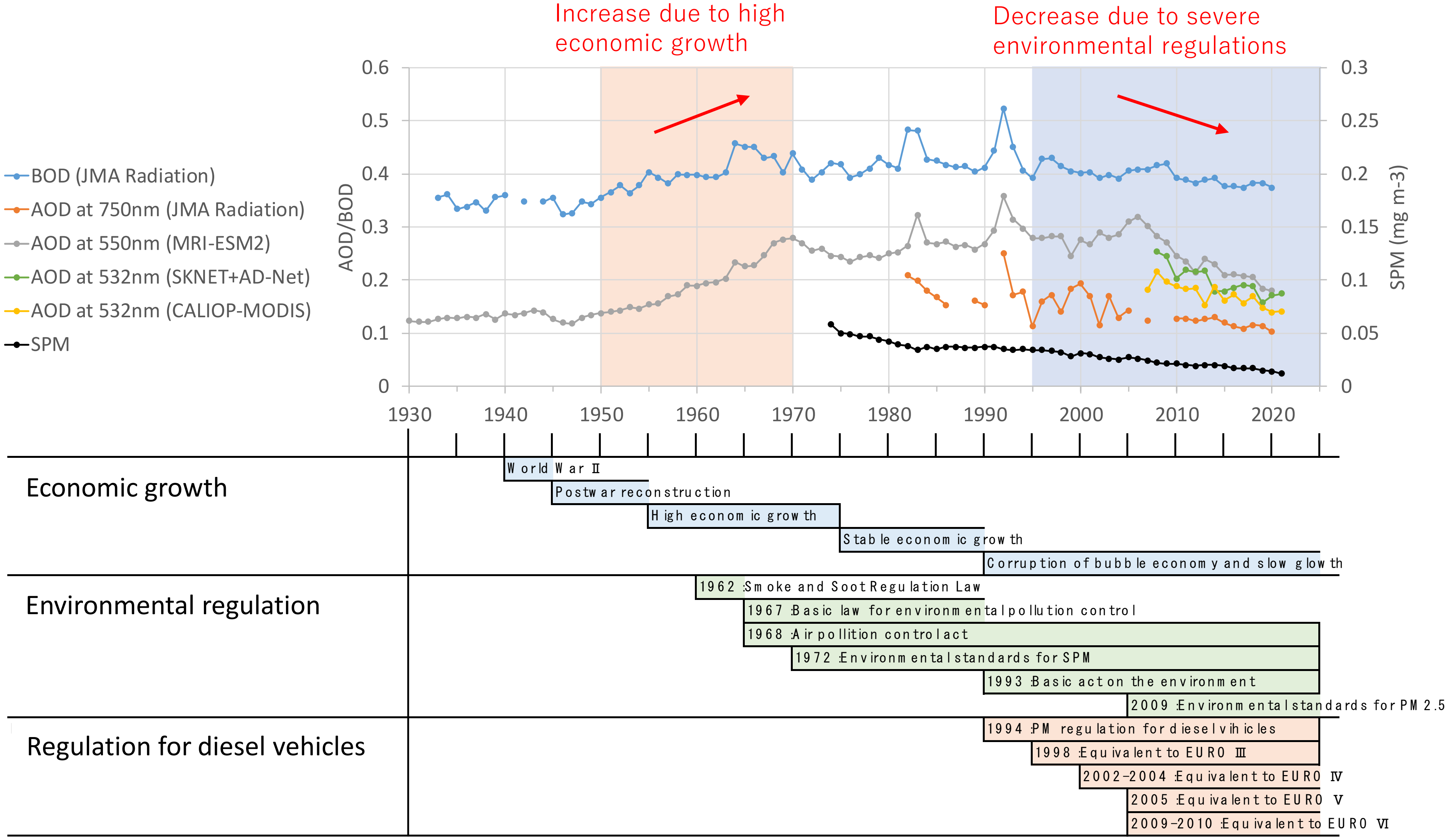
Hamzeh 2021

Due to drought in the fertile crescent

Historical change in Japan

We are investigating various long-term data in Japan.

- Broad band Optical Depth derived from transmittance observed by Pyrheliometer (JMA Web page).
- AOD (750nm) from Pyrheliometer and pyranometer (Direct and diffuse radiation) (Kudo 2010).
- AOD, SSA, etc., from SKYNET and AD-Net (Kudo 2016)
- AOD, SSA, etc., from CALIOP-MODIS (Kudo 2023).
- SPM (Ministry of Environment)
- MRI-ESM2 (Earth system model, Yukimoto 2019)



Summary and Future plan

CALIOP-MODIS

- CALIOP-MODIS synergistic retrieval method was developed. The results are consistent with other products and studies.

EarthCARE

- We are developing an application to ATLID and MSI onboard EarthCARE. ATLID is a HSRL at 355 nm. Lidar ratio derived from HSRL is related to SSA. We expect that the retrieval of SSA and LA is improved.

AOS

- We will develop an application to the combination of multi-angle polarimeter and lidar of AOS-Sky.