InterComparison and Evaluation of Aerosol Optical Depths from four Reanalyses using AERONET data for climate studies

Peng Xian[1], Jeffrey S. Reid[1], Melanie Ades[2], Angela Benedetti[2], Peter R. Colarco[3], Arlindo da Silva[3], Tom F. Eck[3, 4], Johannes Flemming[2], Edward Hyer[1], Zak Kipling[2], Samuel Rémy[5], Tsuyoshi Thomas Sekiyama[6], Taichu Tanaka[7], Keiya Yumimoto[8] and Jianglong Zhang[9]

[1]Naval Research Laboratory, Monterey, CA, USA.
[2]European Centre for Medium-Range Weather Forecasts, Reading, UK.
[3]NASA Goddard Space Flight Center, Greenbelt, MD, USA.
[4]University of Maryland Baltimore County, Baltimore, MD, USA
[5]HYGEOS, Lille, France
[6]Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
[7]Information Infrastructure Department, Japan Meteorological Agency, Tokyo, Japan
[8]Research Institute for Applied Mechanics, Kyushu University, Kasuga, Japan
[9]Department of Atmospheric Sciences, University of North Dakota, Grand Forks, ND

Acknowledge: data providers from the remote sensing community.

U.S. NAVAL RESEARCH LABORATORY

Four global full-species and long-record aerosol reanalyses

	Organization	Meterology	Resolution lat x lon	DA metho	Assimilated obs.	Species	Anthro. & Biogenic Emission	BB Emissions	Available time	reference
CAMSRA	ECMWF	Inline ERA5	0.7 x 0.7	4D-Var	DAQ MODIS PMAp	BC, OM, Sulfate Dust, Sea Salt	MACCity (trend: ACCMIP + RCP8.5), monthly VOC	GFAS	2003-present	Inness et al., 2019
MERRA-2	NASA	Inline MERRA-2	0.5 x 0.6	2D-Var +LDE	Neural Net MODIS, MISR, AVHRR, AERONET	BC, OC, Sulfate Dust, Sea Salt	EDGAR V4.1, AeroCom Phase II	GFED before 2009, QFED after 2009	1980-present	Randles et al., 2017
NAAPS-RA	NRL	Offline NOGAPS/NAVGEM	1 x 1	2D-Var	DAQ MODIS, MISR	BB smoke, Dust, Sea Salt, ABF	MACCity, BOND POET, monthly SOA	FLAMBE	2003-present	Lynch et al., 2016
JRAero	JMA	Inline	1.1 x 1.1	2D-Var	DAQ MODIS	BC, OC, Sulfate Dust, Sea Salt	MACCity	GFAS	2011-present	Yumimoto et al., 2017
MRC	-	-	1 x 1	-	-	BB smoke, Dust, Sea Salt, ABF	-	-	2003-present	this work

* CAMSRA: Copernicus Atmosphere Monitoring Service ReAnalysis
MERRA-2: Modern-Era Retrospective Analysis for Research and Applications, version 2
JRAero: Japanese Reanalysis for Aerosol
NAAPS-RA: Navy Aerosol Analysis and Prediction System ReAnalysis

- https://acp.copernicus.org/articles/24/6385/2024/

Data and Methods

Data used in this study:

- Remote Sensing :
  - AERONET V3L2 (Giles et al, 2019) with Spectral Deconvolution Algorithm (SDA, O'Neill et al. 2001, 2003)
  - MODIS v6 550nm products: derived L3 DT, DB AOD, Data-Assimilation-quality AODs
- Aerosol Reanalyses:
  - ECMWF CAMSRA speciated AOD at 550 nm (Inness et al. 2019)
  - JMA JRAero speciated AOD at 550 nm (Yumimoto et al., 2017); 2011-2019.
  - NRL NAAPS-RA speciated AOD at 550 nm (Lynch et al. 2016)
  - NASA MERRA2 speciated AOD at 550 nm (Randles et al. 2017)
  - Multi-Reanalysis-Consensus based on the three/four RAs.

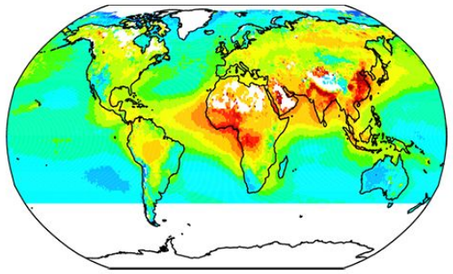
Method:

- The 550 nm AOD was employed as the benchmark parameter for this study.
- Use fine mode (FM) and coarse mode (CM) AOD derived from AERONET with SDA.
- The species of interest: biomass burning (BB) smoke, anthropogenic and biogenic fine aerosols (ABF) in NAAPS, and its equivalent of sulfate for MERRA-2, CAMSRA and JRAero, dust and sea salt aerosols.
- Sum of OA/OC+BC was used to approximate BB smoke from CAMSRA, MERRA-2 and JRAero.

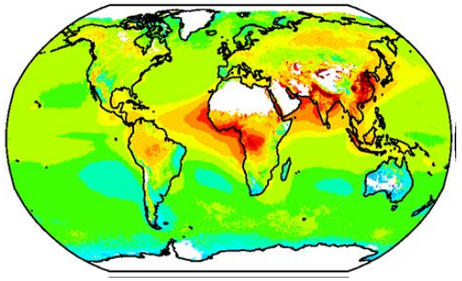
Note: Total, dust and sea salt AODs are trackable variables as all the RAs have these species.
While fine mode species are less trackable as they are defined differently in the RAs.

Annual mean total AOD climatology (2003-2019, except for 2011-2019 from JRAero)

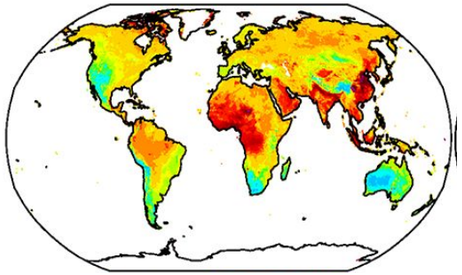
MODIS DA-quality



MODIS-DT

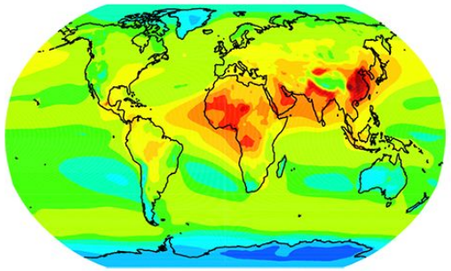


MODIS-DB

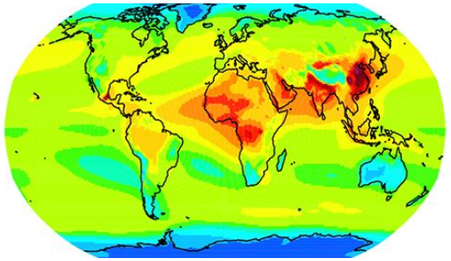


White-colored area means no available data

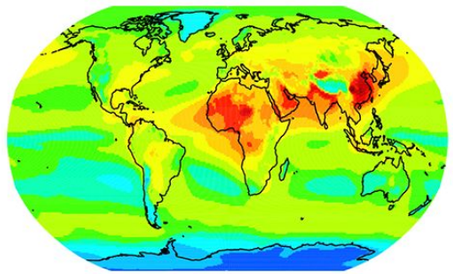
Multi-RA-Consensus (MRC)



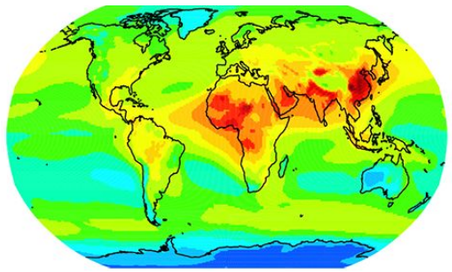
CAMSRA



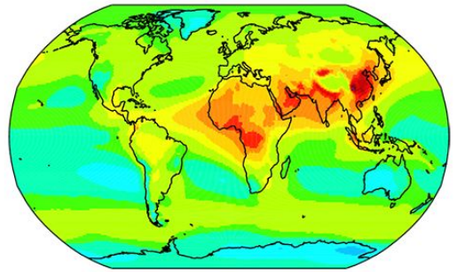
MERRA-2



NAAPS-RAv1



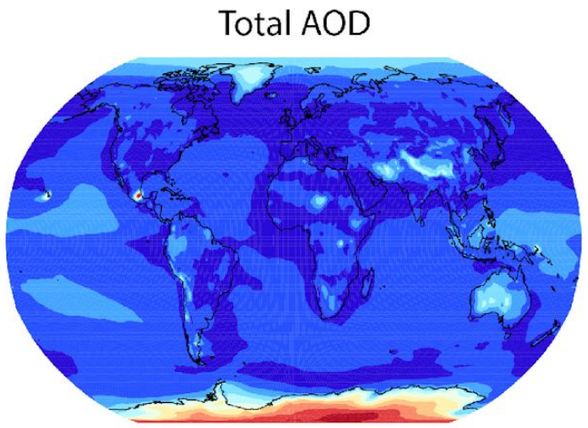
JRAero



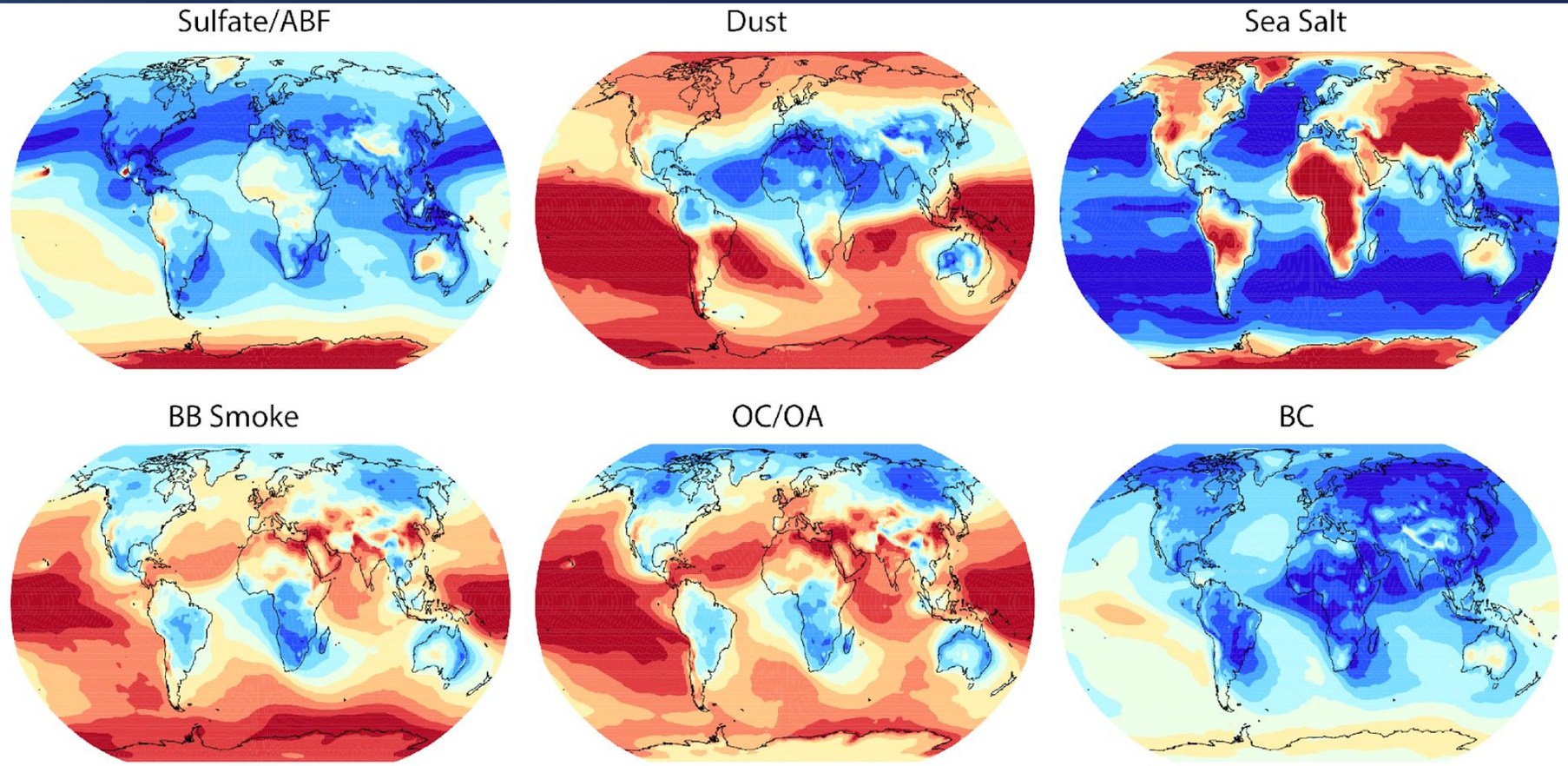
- In general, very similar spatial AOD distribution patterns and AOD magnitude among the reanalyses and MODIS for the annual-mean (for all four seasons, see paper).
- More divergence among the reanalyses in regions with little satellite observation (e.g. bright desert, snow/ice-covered, high-cloud-coverage and polar regions).
- The divergence in total AOD climatology among the RAs is comparable to or even smaller than the divergence observed in the MODIS products.

U.S. NAVAL RESEARCH LABORATORY

Diversity of speciated AOD among the four reanalyses



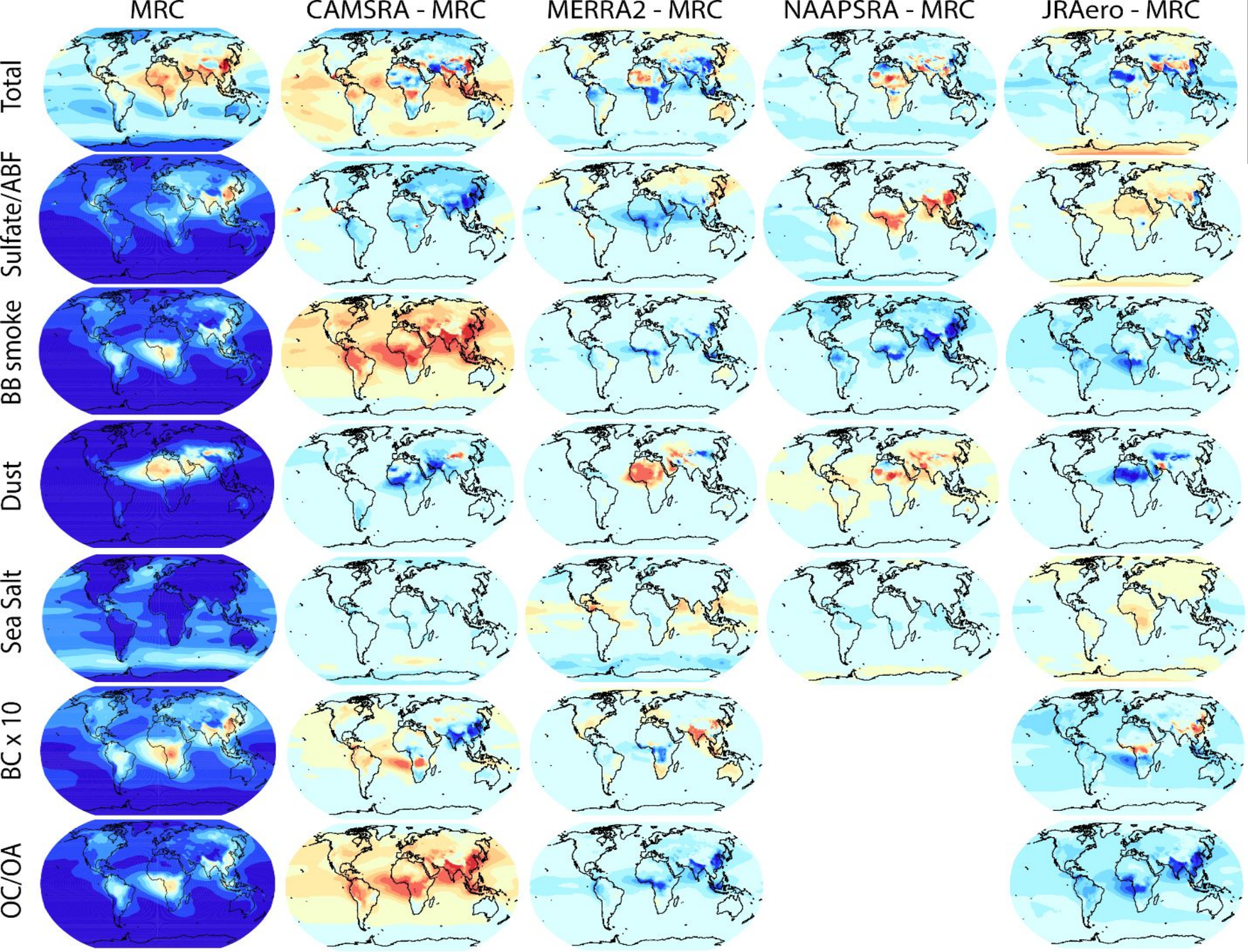
Note: Total, dust and sea salt AODs are trackable variables as all the RAs have these species. While fine mode species are less trackable as they are defined differently in the RAs.



Relative spread (ratio of standard deviation of the reanalyses AOD to the mean)

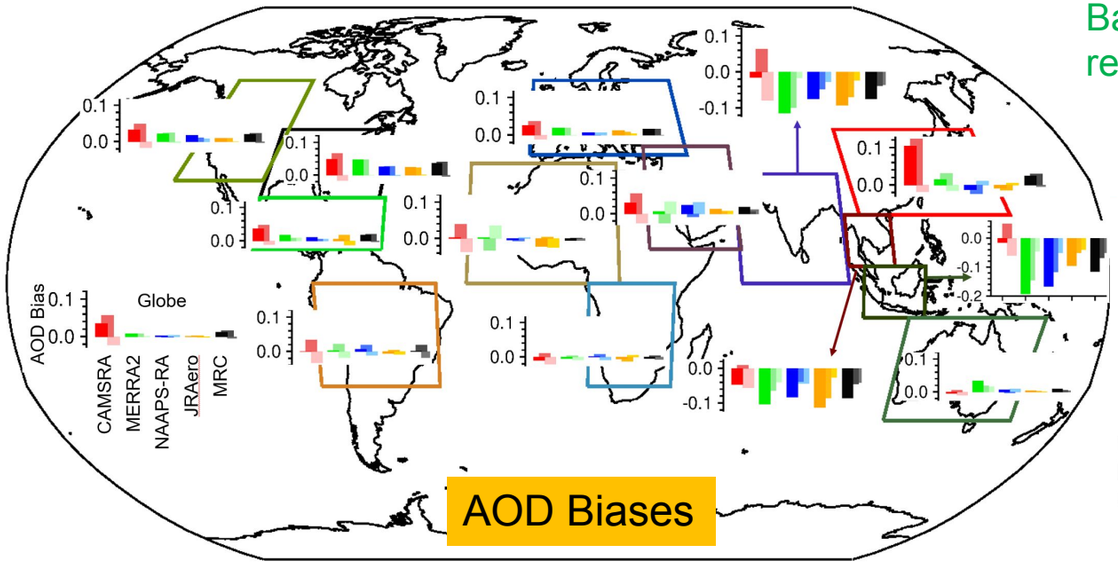
- Small for total AOD (except for polar regions and a few hotspots),
- But can be large for speciated AODs, especially in regions remote to aerosol sources.

Differences in annual mean total and speciated AODs

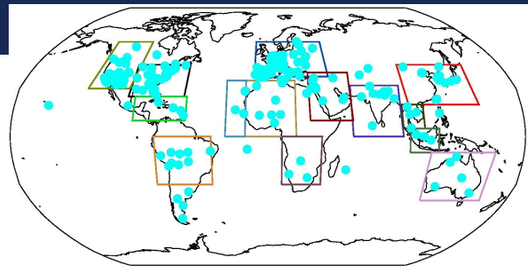


- CAMSRA is higher than the other three RAs in smoke/OA AOD, and total AOD in general.
- For dust AOD, MERRA-2 is relatively higher over north Africa and Arabian Peninsula and NAAPS-RA is relatively higher over most regions, including oceanic areas, while CAMSRA and JRAero are relatively lower over most regions except around Gobi desert for CAMSRA and Iran for JRAero.
- NAAPS-RA ABF AOD is higher than sulfate AOD in other RAs in some regions. This is expected as ABF in NAAPS-RA includes biogenic and anthropogenic primary and secondary aerosols besides sulfate.
- JRAero sea salt AOD is relatively higher over most continents, which is probably unphysical.

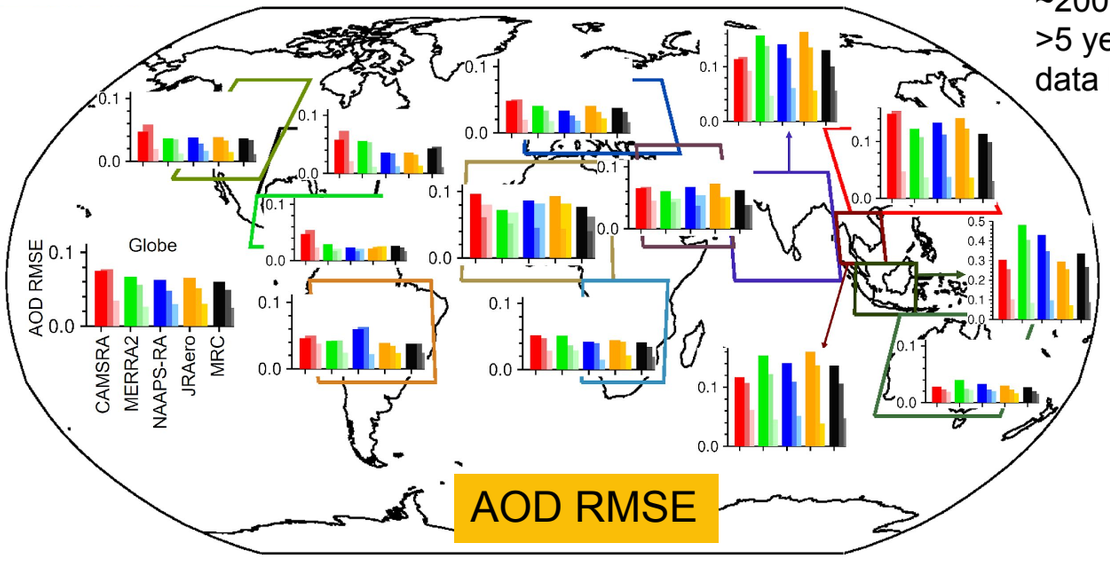
Verification of total, FM, CM AODs with AERONET regionally

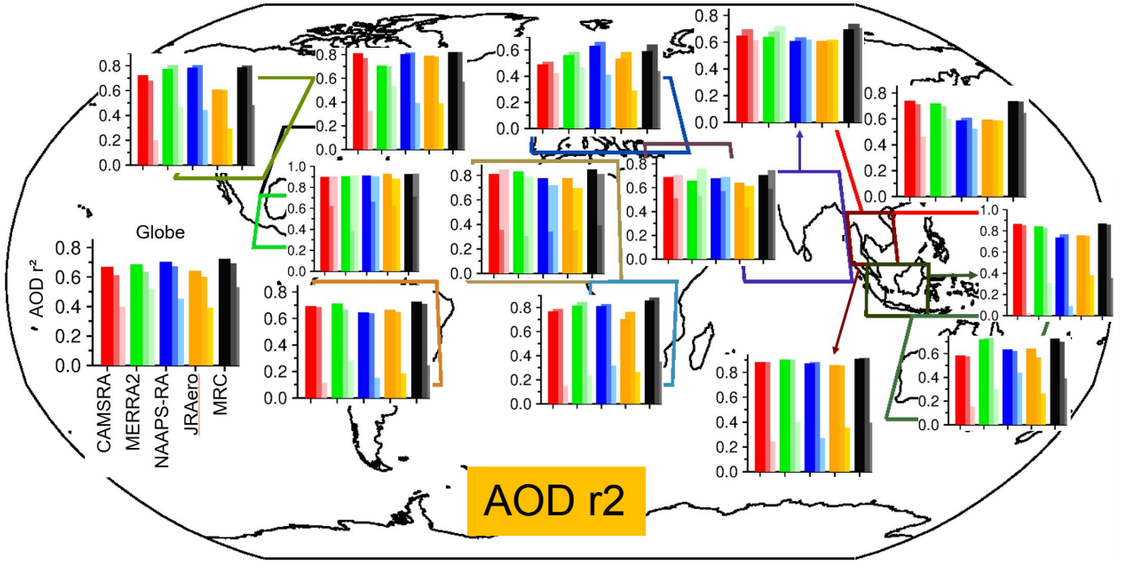


Bars in the bar group from left to right represent total, FM, CM in similar color.



~200 AERONET sites with >5 year and >1000 daily data between 2011-2019.

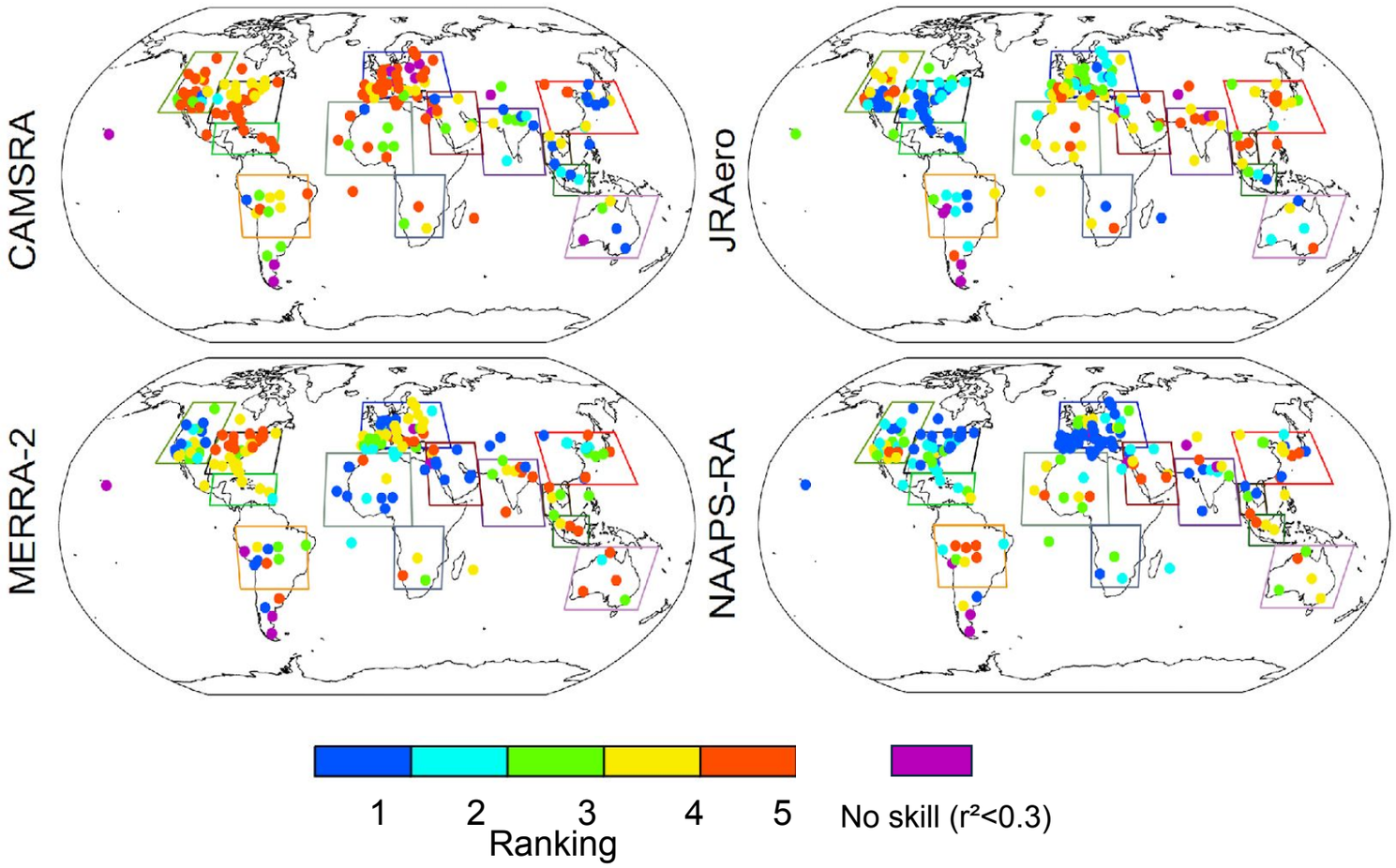




- There are some regional similarity in RA performance due to the nature of regional aerosols.
- Each RA exhibits its own unique regional strengths.

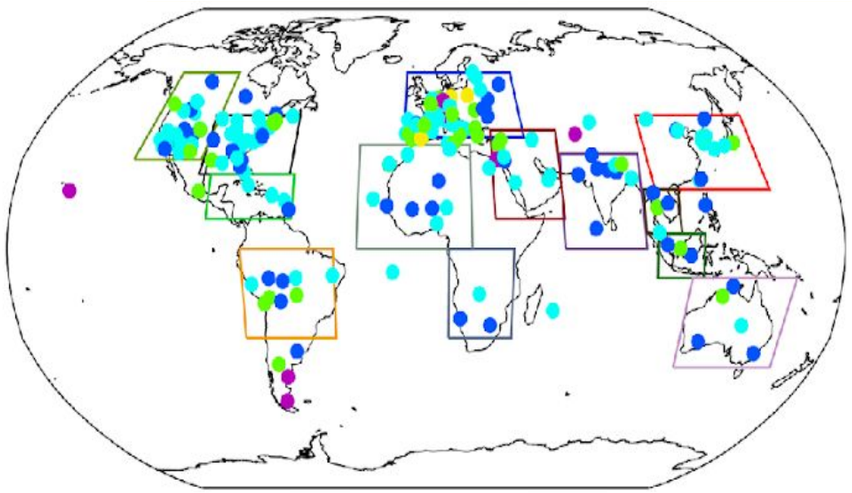
Ranking of the RAs in terms of monthly AOD RMSE/r²

Ranking of RMSE of total AOD



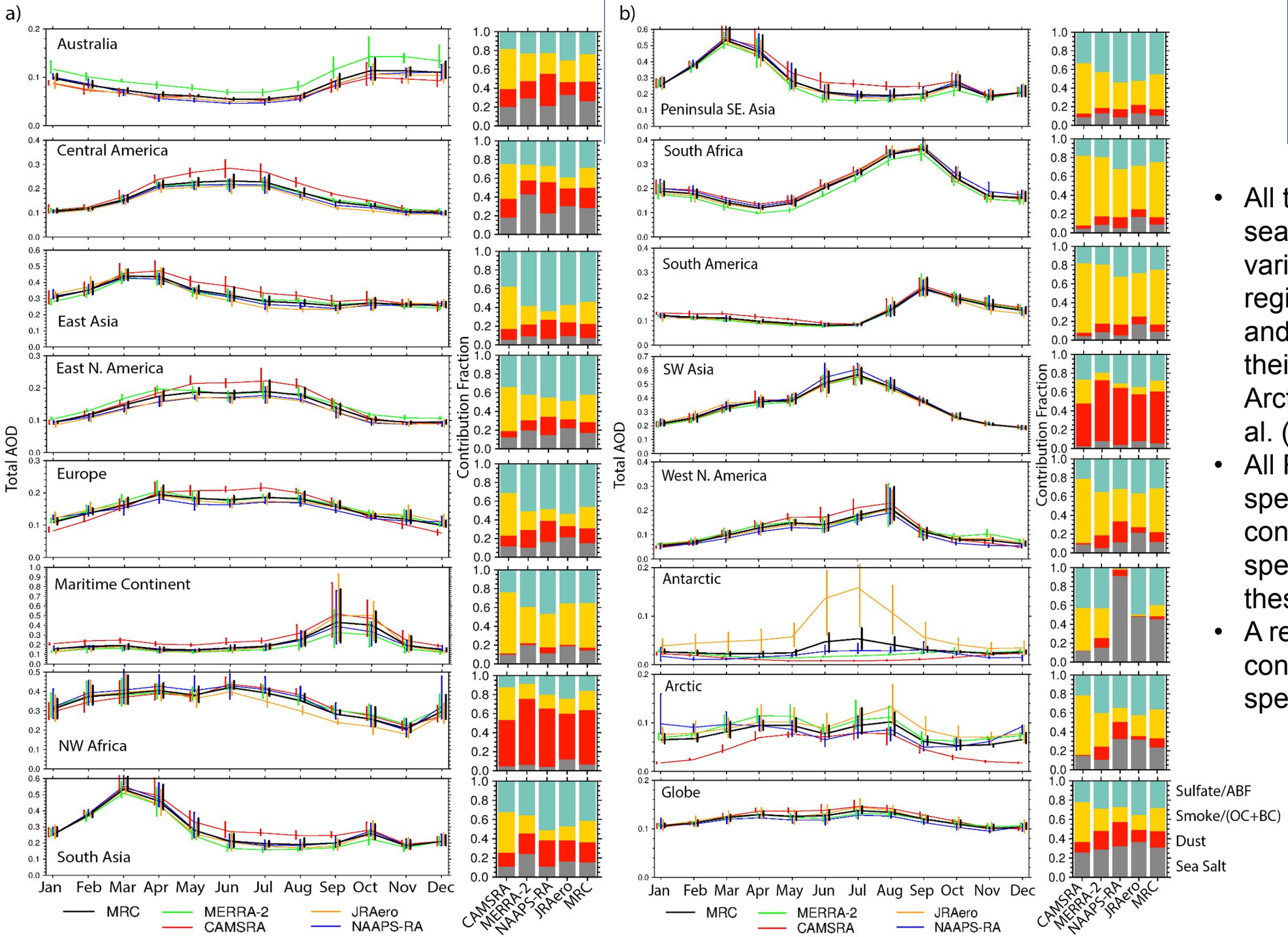
- Specifically, CAMSRA performs better in South and Southeast Asia.
- MERRA-2 excels in in African and Arabian Peninsula dust regions.
- NAAPS-RA shows relatively better performance over Europe and East CONUS
- JRAero performs relatively better over South North America and the Caribbeans.

Ranking of MRC R² of total AOD



- AOD RMSE/r2 of the MRC is not always the lowest/highest, but it is relatively low/high globally.
- MRC ranks often the 1st or 2nd w.r.t. RMSE and r².
- Consensus wins because of its averaging of independent models.
- Consistent with the result of the ICAP-MME paper (Xian, et al., 2019).
- Challenging sites identified.

Seasonality of regional AOD



- All the RAs exhibit a similar seasonality and interannual variability of total AOD for all regions, except for the Antarctic and Arctic, particularly during their winter seasons. For specific Arctic performances, see Xian et al. (ACP 2022a,b).
- All RAs have the same dominant species for most regions, but the contributions from different species can be quite different in these RAs.
- A result of fact that total AOD is constrained through DA, while speciated AODs are not.

Summary on aerosol reanalyses intercomparison

- **AERONET data served as a golden standard for RA AOD evaluations. Thank you, AERONET!**
- Global distribution and magnitude of total AOD demonstrate a high level of similarity among all four RAs.
- The relative spread of speciatedAODs, however, is considerably larger than that of total AOD. CAMSRA consistently yields higher values for biomass burning (BB) smoke or OA AOD in comparison to other RAs.
- The diversity of speciated AODs in regions remote to aerosol sources are extremely large, implying different efficiencies in removal during long-range transport.
- The seasonality and interannual variability of total AOD in the 16 regions under study, with the exception of the Antarctic and Arctic, demonstrate a high degree of similarity across the various RAs.
- The dominant species of aerosols are consistent across most regions in all RAs, but the relative contributions from individual species can vary significantly. Over remote oceans or the polar regions, dominant species vary.
- Each RA exhibits its own unique regional strengths based on AERONET verification.
- The MRC is not always the top-rated performer in terms of RMSE, bias and correlation of modal AODs for a given site or region. However, the MRC generally performs relatively well, ranking first or second regionally and first globally among all the RA, especially for correlation and RMSE.
- Provided reference information for future aerosol reanalyses
- https://acp.copernicus.org/articles/24/6385/2024/

Acknowledgement: ONR for supporting the development of NAAPS-RA and this work.
NASA IDS program for supporting the Arctic RA intercomparison.