Modeling and observational studies of aerosols and some criterion trace gas pollutants over Africa

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Outline

- Background
- How good are recent satellite-based sensors in capturing the air pollution in Africa? Do models agree with satellites?
    - Aerosol; Ozone; CO; NO_2 and HCHO
- Did the progress made in Satellite Observations so far translate into Air Quality Monitoring?
- Summary and Recommendations

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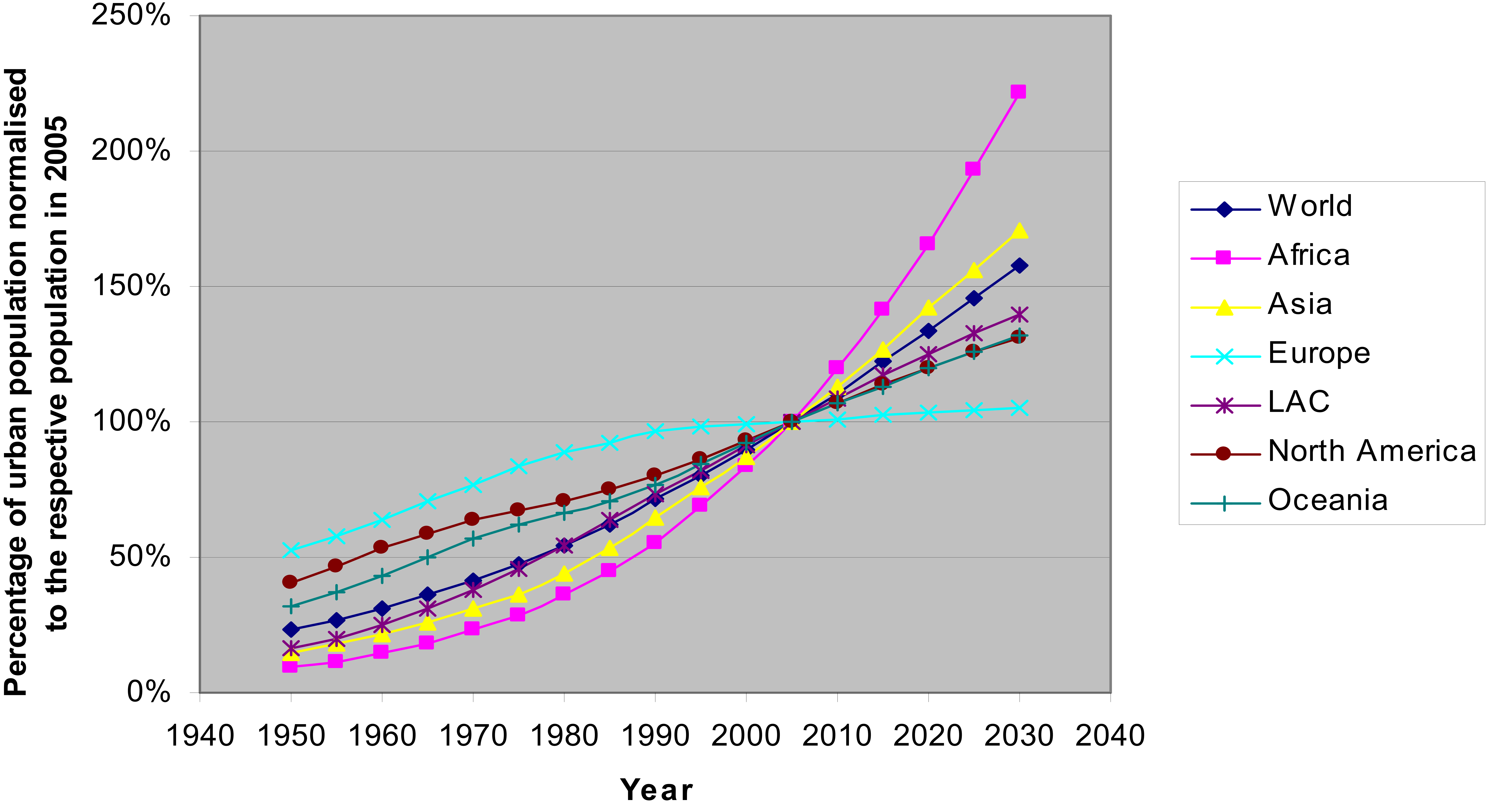
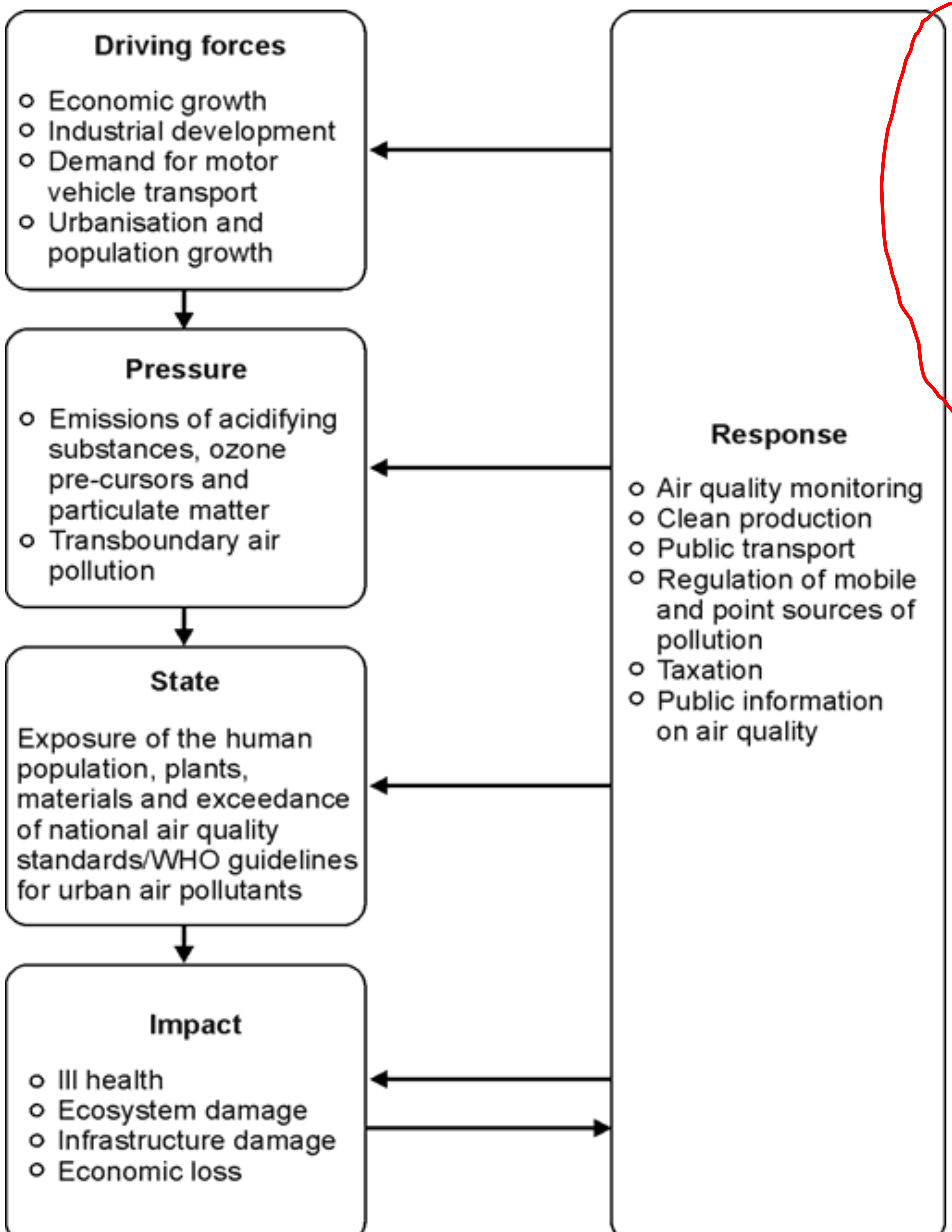
Back ground: Population Increase and Air Pollution



Source: World Bank

Back ground: Population Increase and Air Pollution



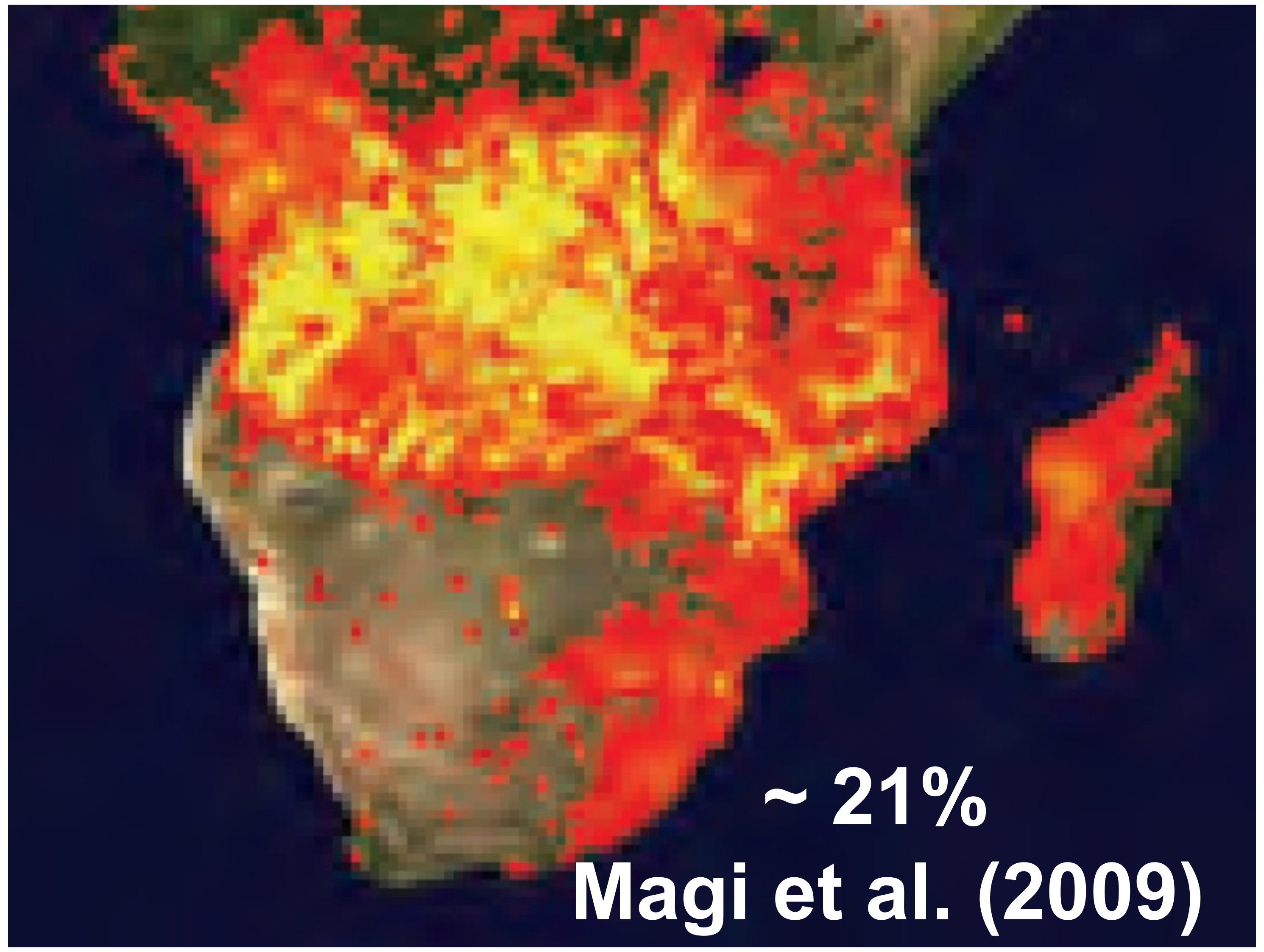
Difficult to quantify in Africa due to lack of/sparse in-situ monitoring infrastructure

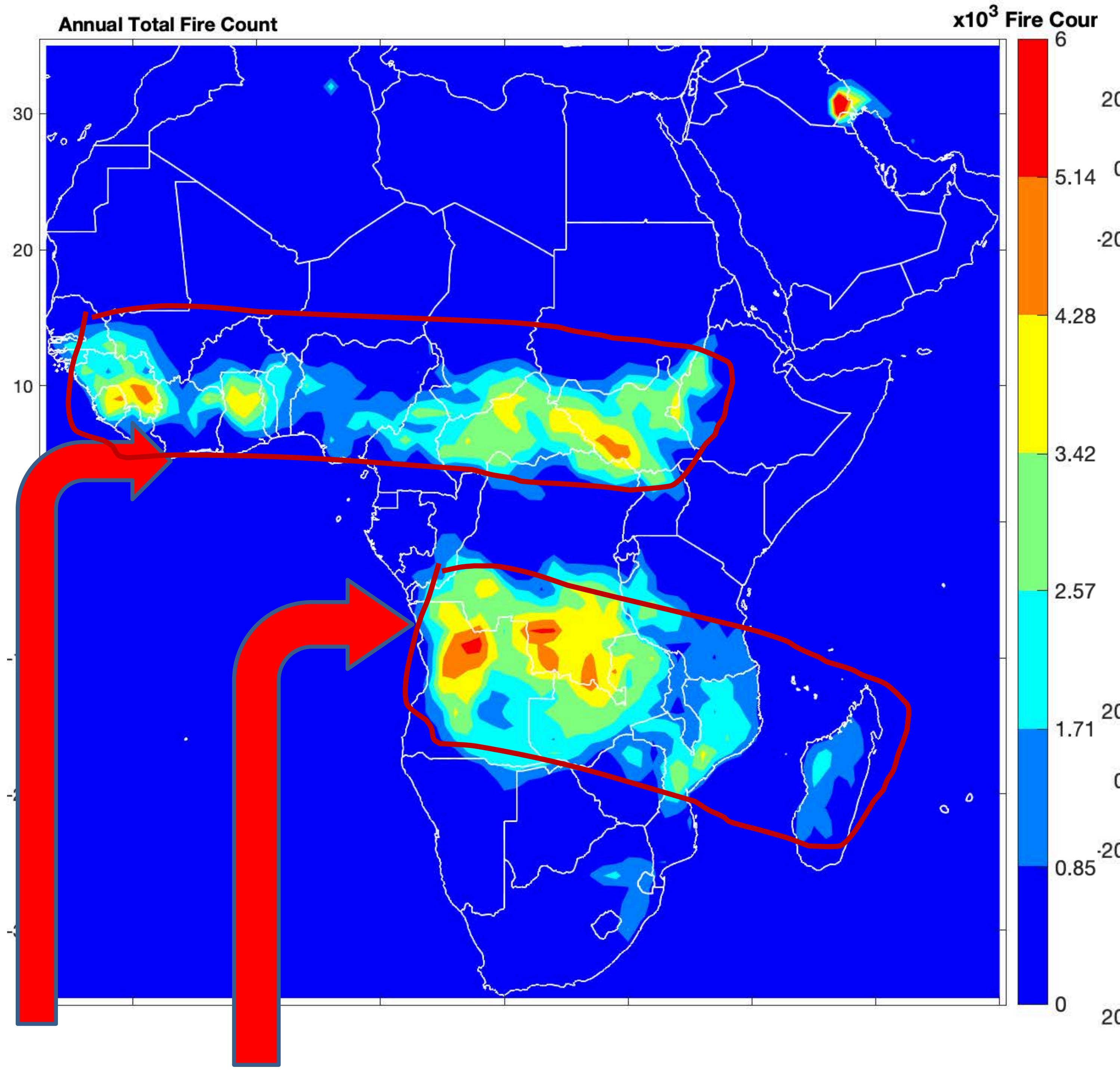
- Rapidly growing vehicle fleets;
- The growth of two-wheelers;
- Vehicles in cities of Sub Saharan Africa are badly maintained and of an elevated age (mean age ~14 years);
- Insufficient infrastructure-re-suspended dust emissions;
- Quality of petroleum products;
- Industrial plants (mostly old using obsolete technologies).
- forest fires of natural origin and windblown dust.
- Open burning of solid waste and agricultural burning

The Driving forces – Pressures – State – Impacts – Responses (DPSIR) framework developed by the European Environmental Agency) used by The Clean Air Initiative in Sub-Saharan African Cities (CAI-SSA), the United Nations Environment Programme (UNEP) and the Air Pollution Information Network Africa (APINA).

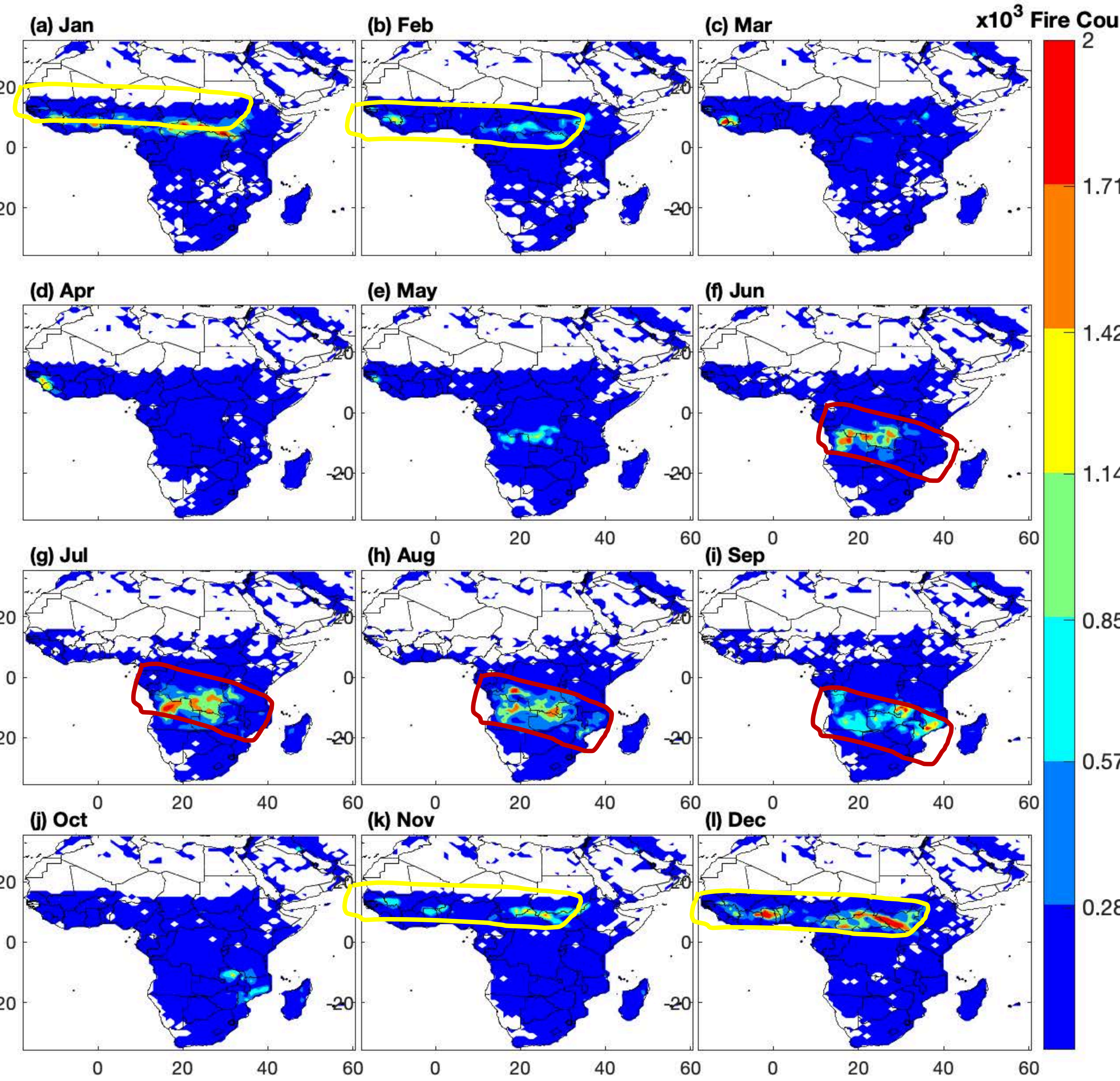
Source: World Bank

Back ground: Natural and Anthropogenic Sources-Biomass Burning

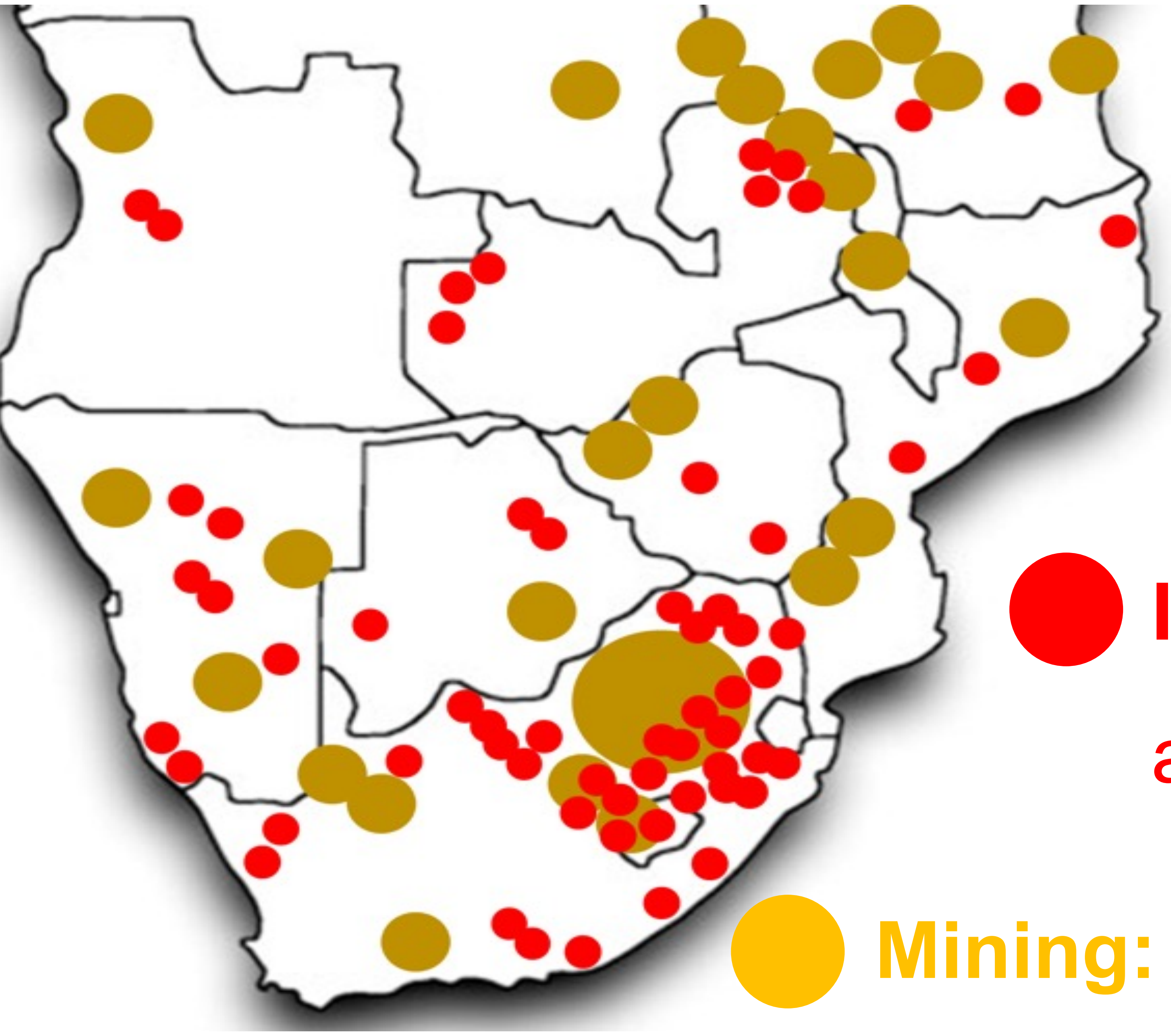




Annual total fire counts are mainly located along 5-12°N during Northern Hemisphere and along 5 to 20°S during Southern Hemisphere winters



MODIS fire count shows frequent biomass burning over summer latitude band of ITCZ. The frequent fires are observed over South Sudan and adjoining SW Ethiopia, central African Republic and northern DRC from November of the previous year to February of the following year-likely attributed to burning of seasonal vegetations



Industries: Coal based electrical power and fuel production, refineries…..

Mining: Gold, Iron, Copper, Magnesium, Diamond…..

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Back ground: Southern Africa-Dust Sources

Etosha Pans

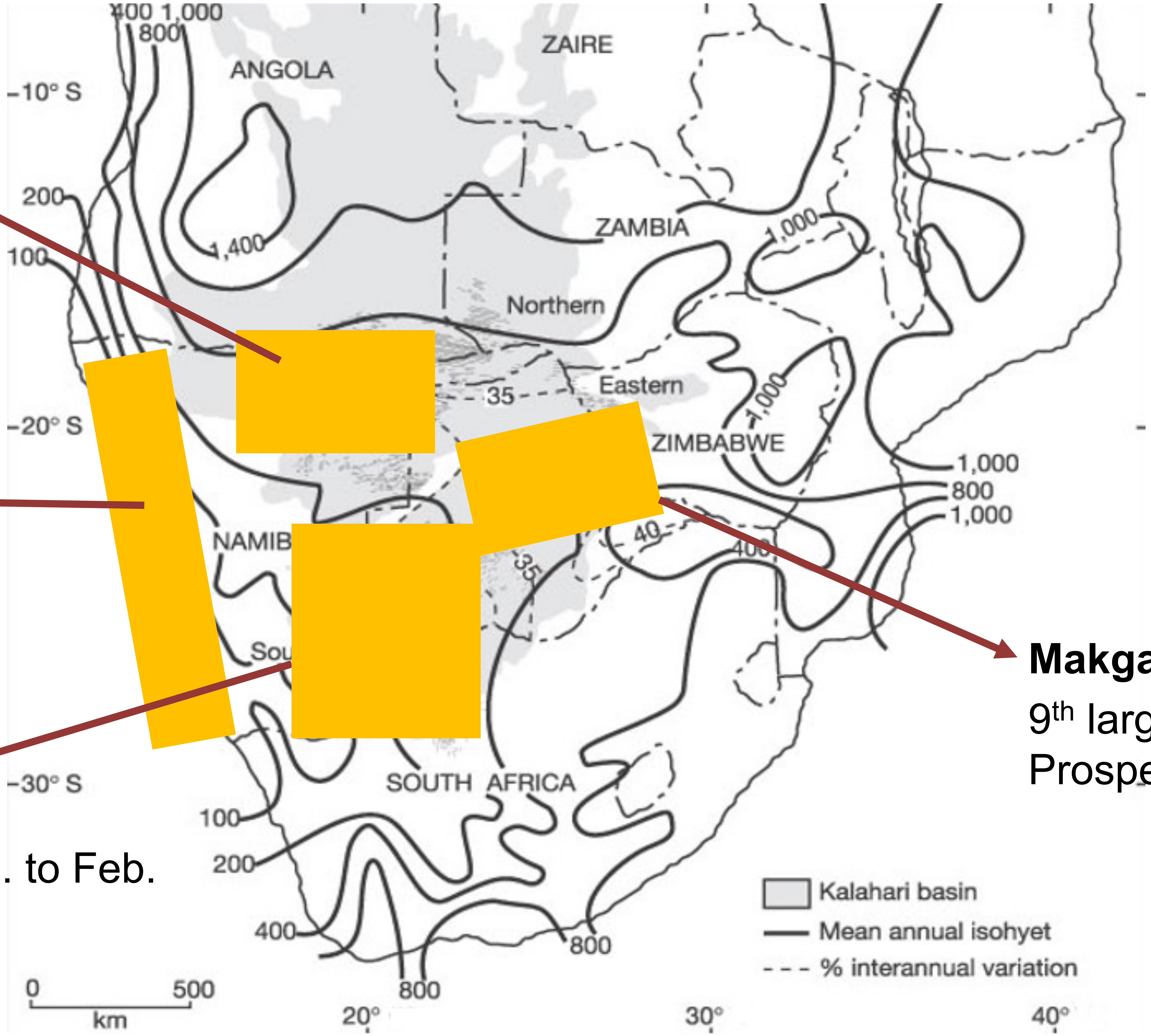
7th largest dust source
Washington et al. (2003)

Namib Desert

Active in most seasons
Ginoux et al. (2012)

Kalahari desert

Relatively strong from Sep. to Feb.
Ginoux et al. (2012)
Vickery et al. (2013)



Makgadikgadi pans

9th largest dust source
Prospero et al. (2002)

Back ground: General Circulation governing transport of dust and BB aerosols and trace pollutants over Southern Africa

Tyson et al. (1996), Piketh et al. (1999)

- The General Circulation is largely influenced by subtropical high pressure systems throughout the year
- This semi permanent anticyclonic circulation undergoes seasonal changes- Stronger in summer and spring than winter and autumn.
- Also exhibits spatial shifts

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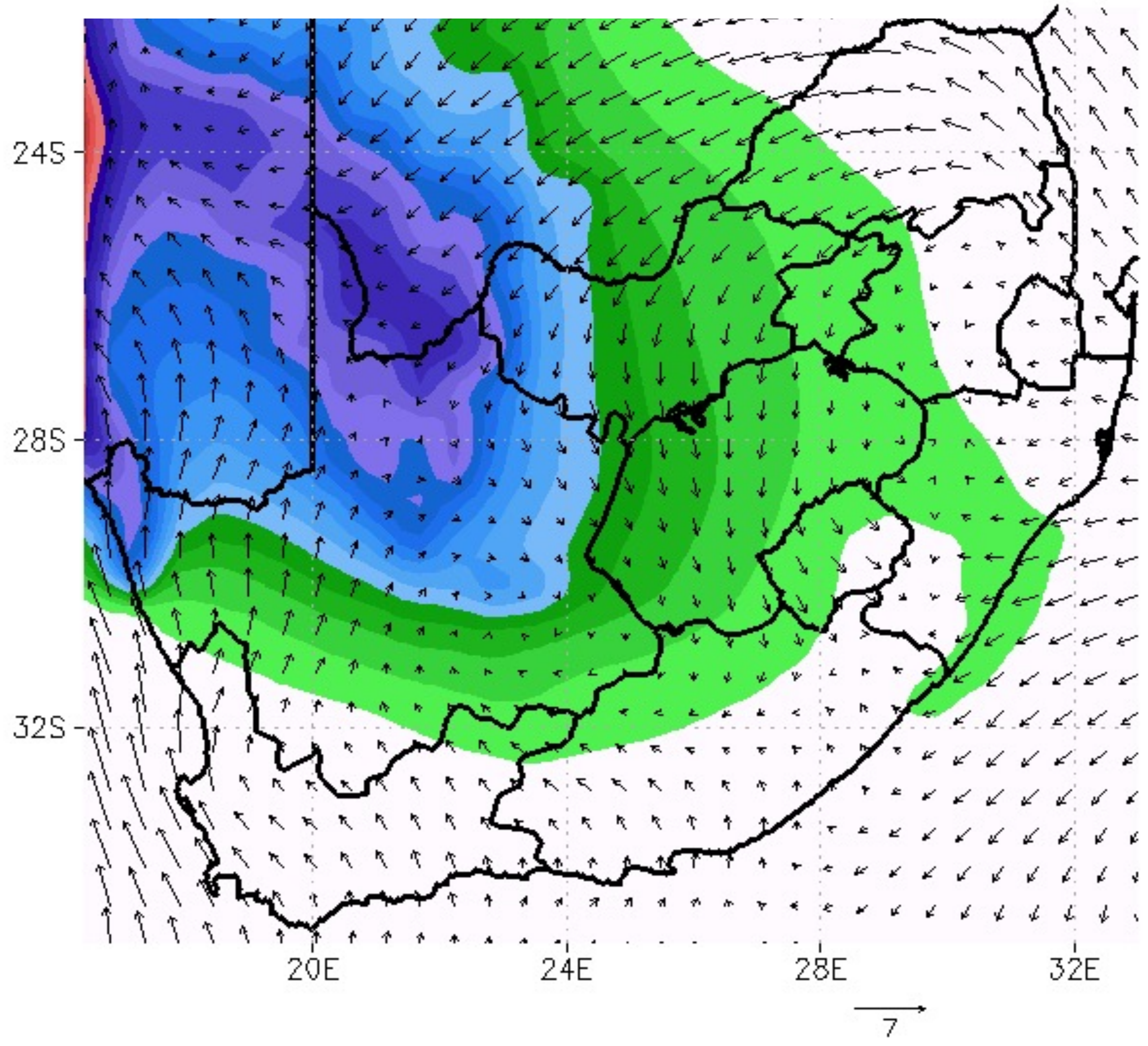
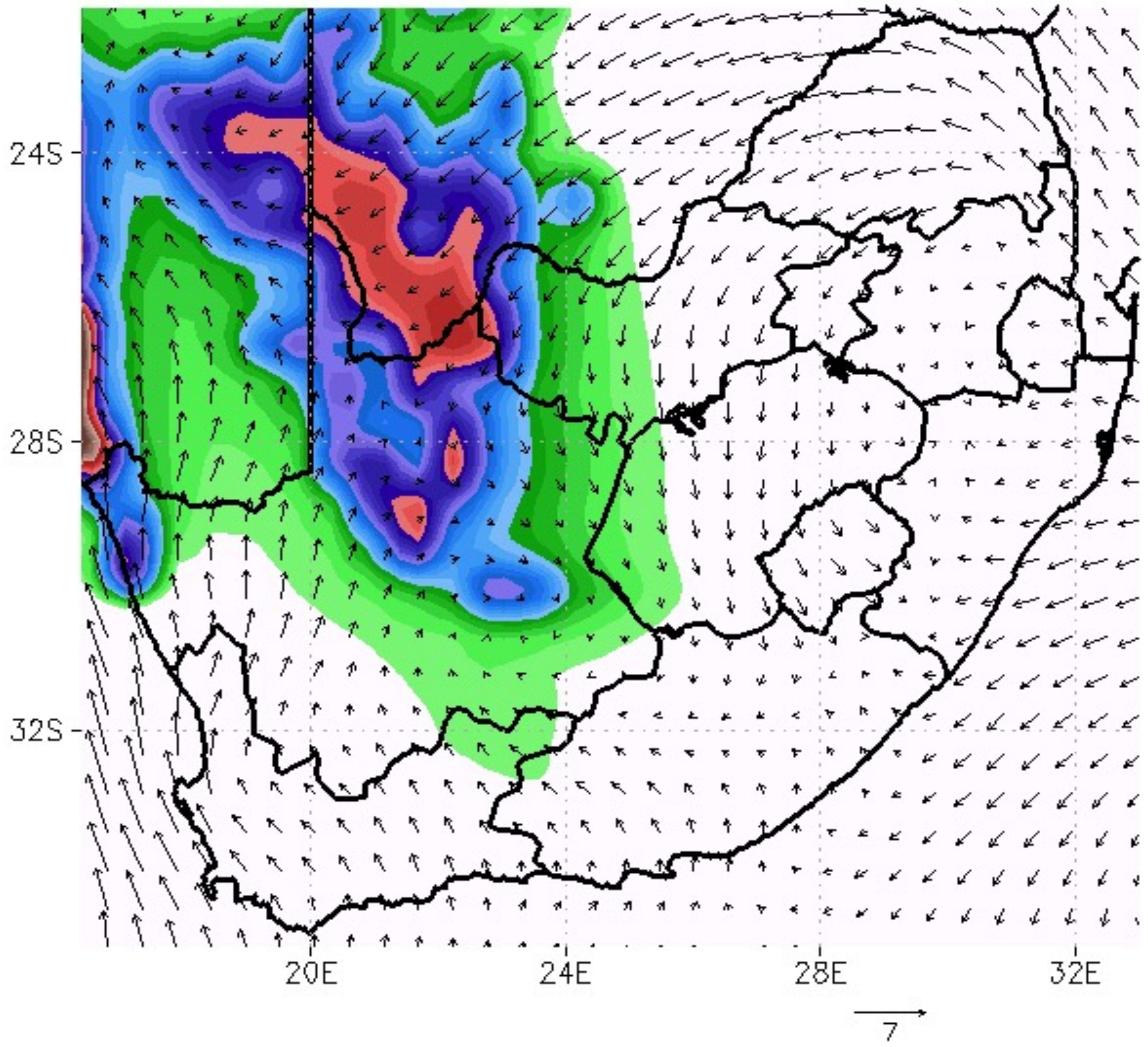
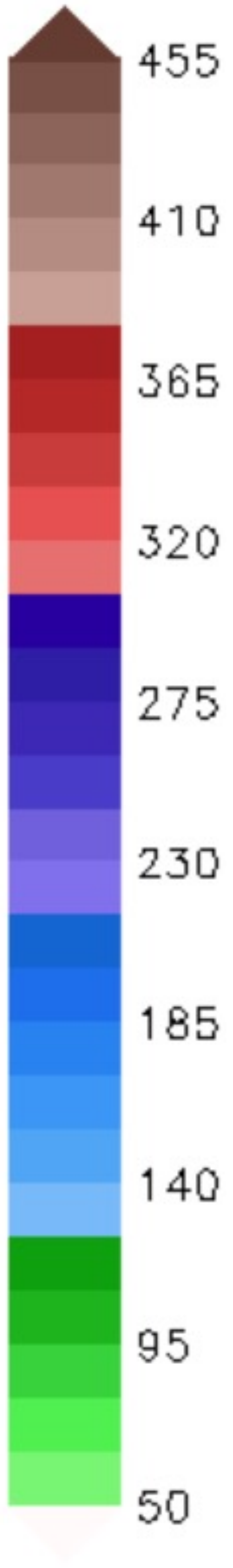
Back ground: Dust column burden over Southern Africa







❑Maximum: 270 mg/m^2 (0.01–2.5µm – NDJF) 440 mg/m^2 (2.5–20µm – ASO)

❑Minimum: MJJ (dust load reduced by about ~ 45% relative to the maximum)

❑ South and Eastern parts of Southern Africa has low dust column burden during NDJF & ASO

- Tesfaye et al. (2014): Int. J. Climatol., 35 (2014), pp. 3515-3539, 10.1002/joc.4225
- Tesfaye et al. (2015):J. Arid Environ, 10.1016/j.jaridenv.2014.11.002
- Tesfaye et al. (2016): J. Atmos. Sol.-Terres. Phys., 10.1016/j.jastp.2016.02.013

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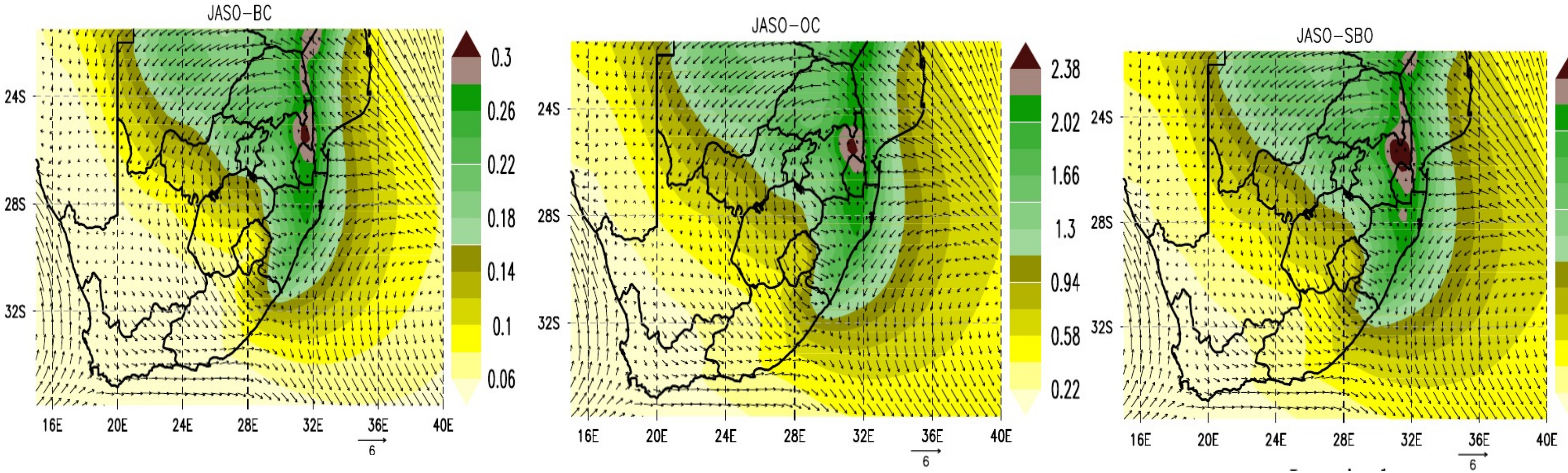
Back ground: Biomass Burning Aerosols Column burden (shaded, mg/m^2)



- BC, OC and total (sulfate + BC + OC: SBO) aerosol dominates Northeast and eastern Southern Africa which are the wettest parts of southern Africa during NDJF & Source SBO
- Anticyclonic air circulation prevents SBO transport to Southwestern part of the region
- Sugarcane farming and refineries in NE South Africa-Common practice to burn sugar cane field before harvesting

- Tesfaye et al. (2014): Int. J. Climatol., 35 (2014), pp. 3515-3539, 10.1002/joc.4225
- Tesfaye et al. (2014): *Meteorol Atmos Phys* 125, 177–195, 10.1007/s00703-014-0328-2
- Tesfaye et al. (2016): J. Atmos. Sol.-Terres. Phys., 10.1016/j.jastp.2016.02.013

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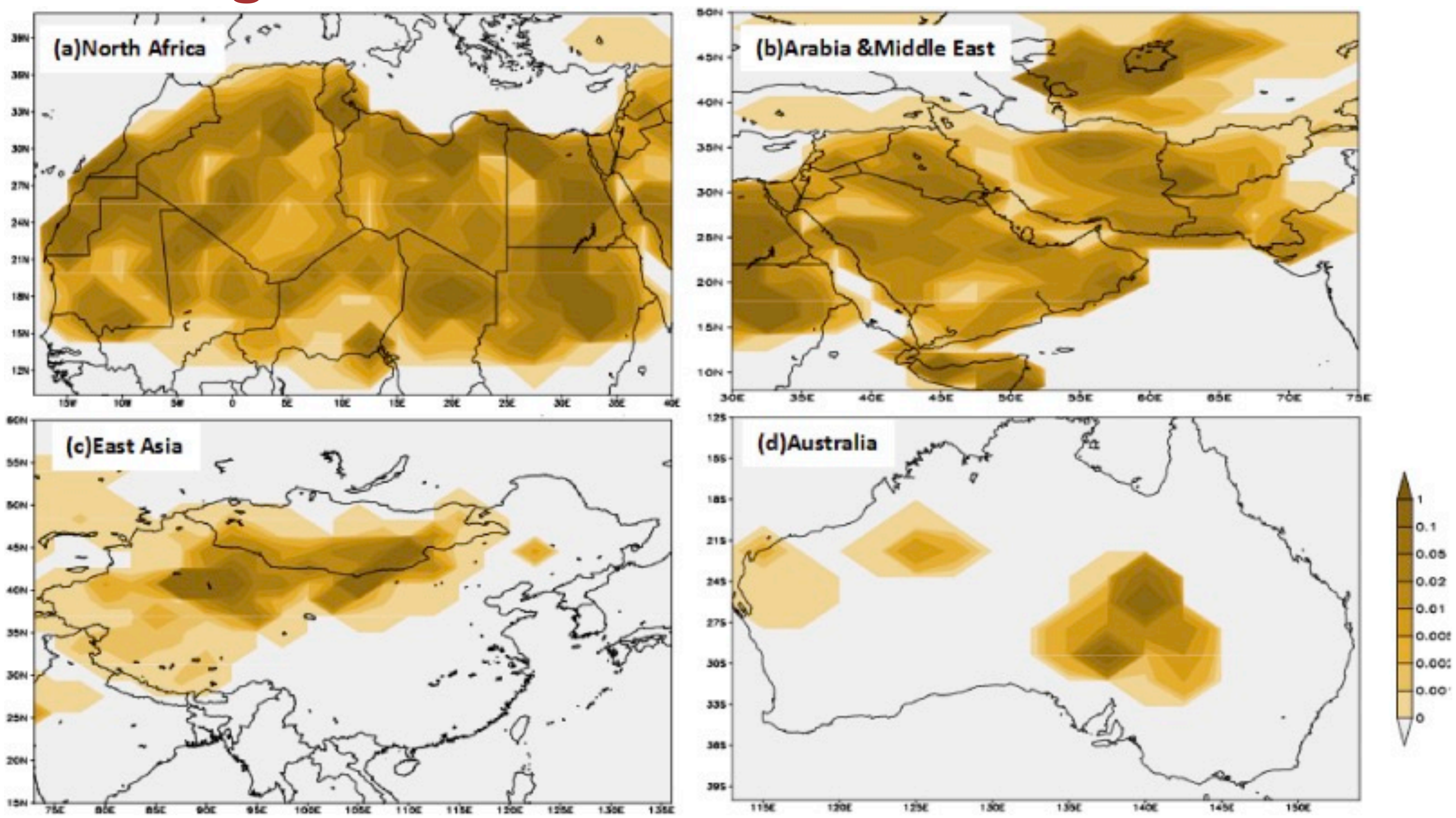
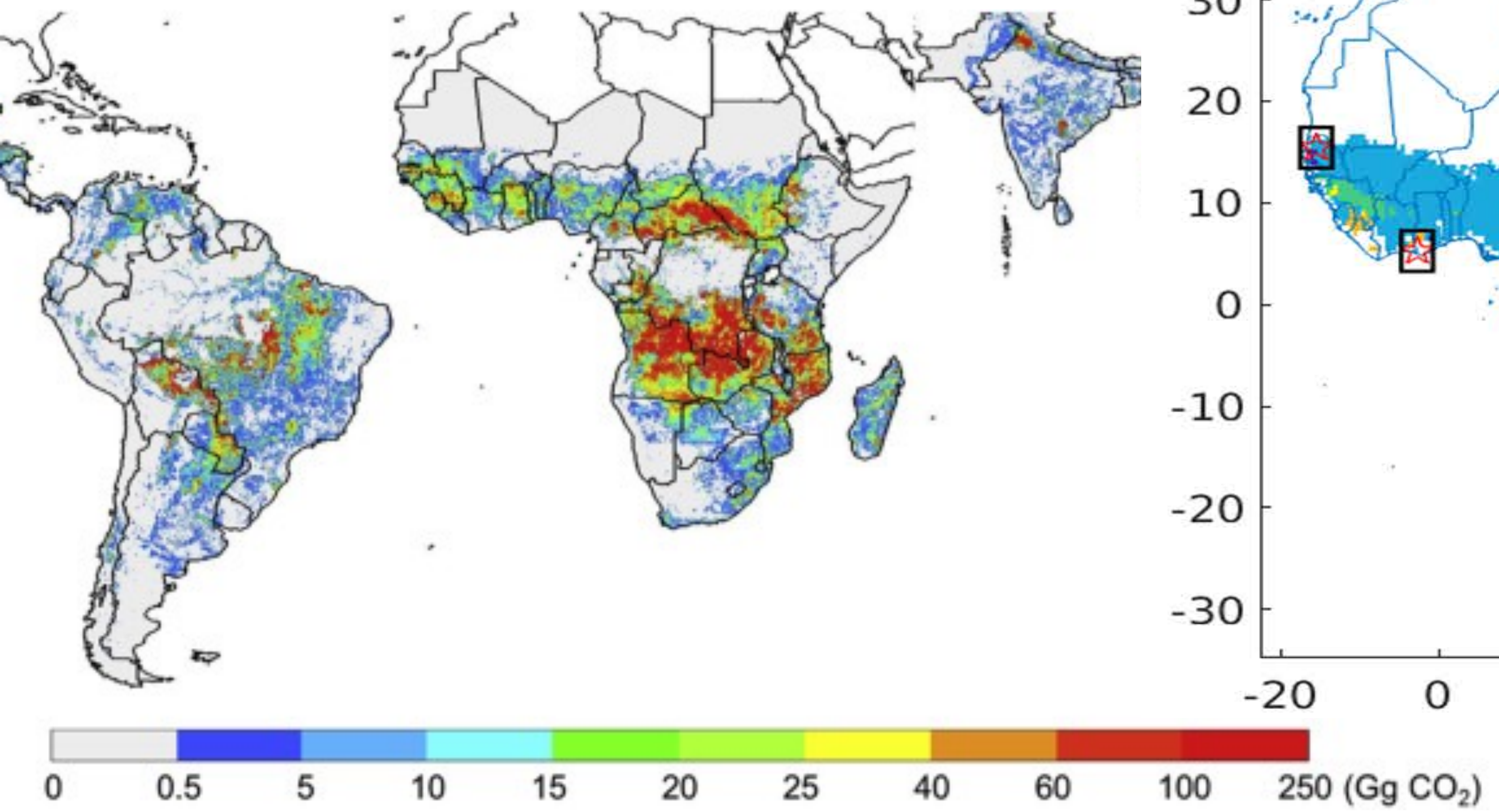
Back ground: Annual dust emission (kg m^{-2} a^{-1}) over North Africa and other regions

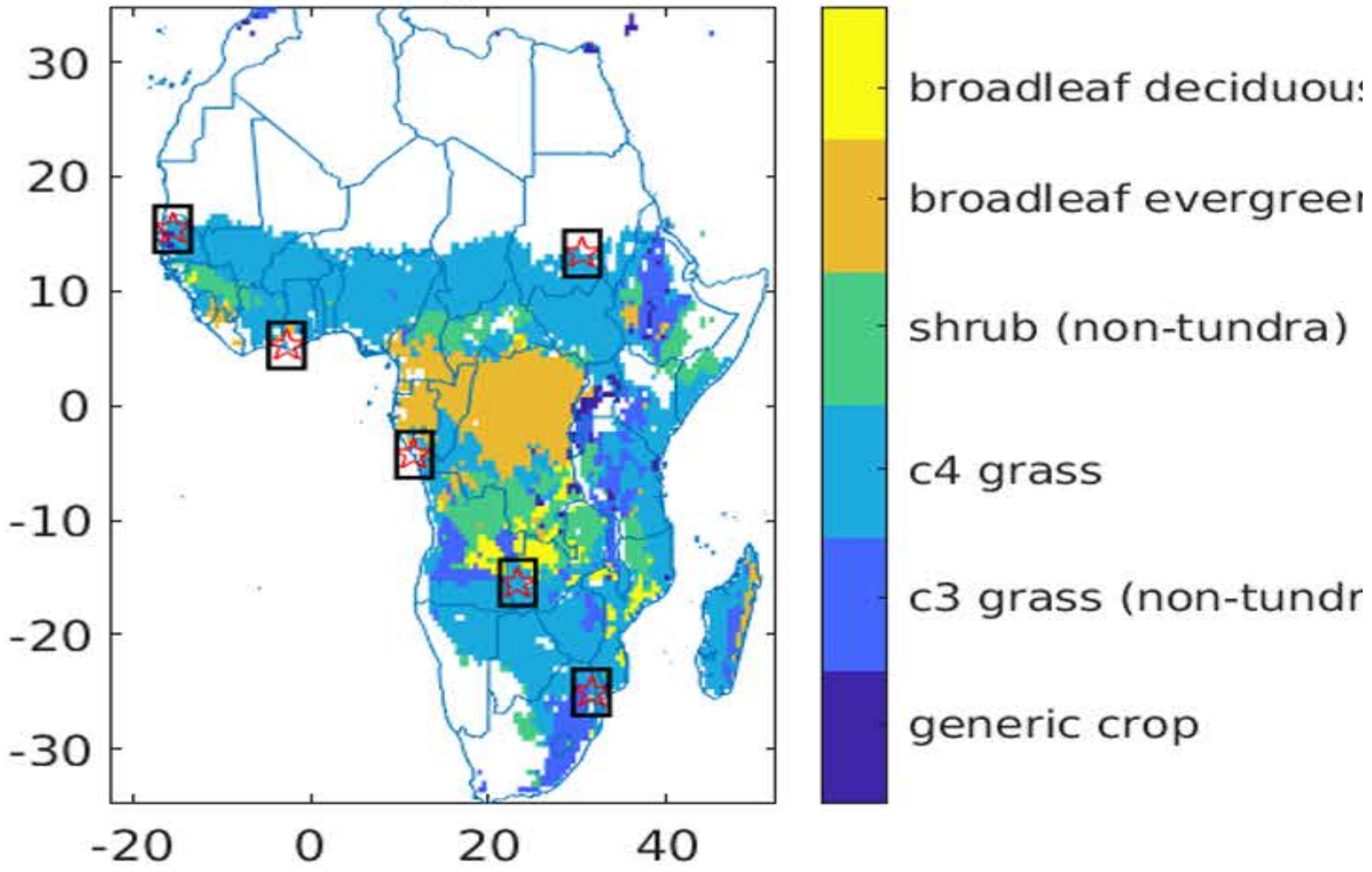


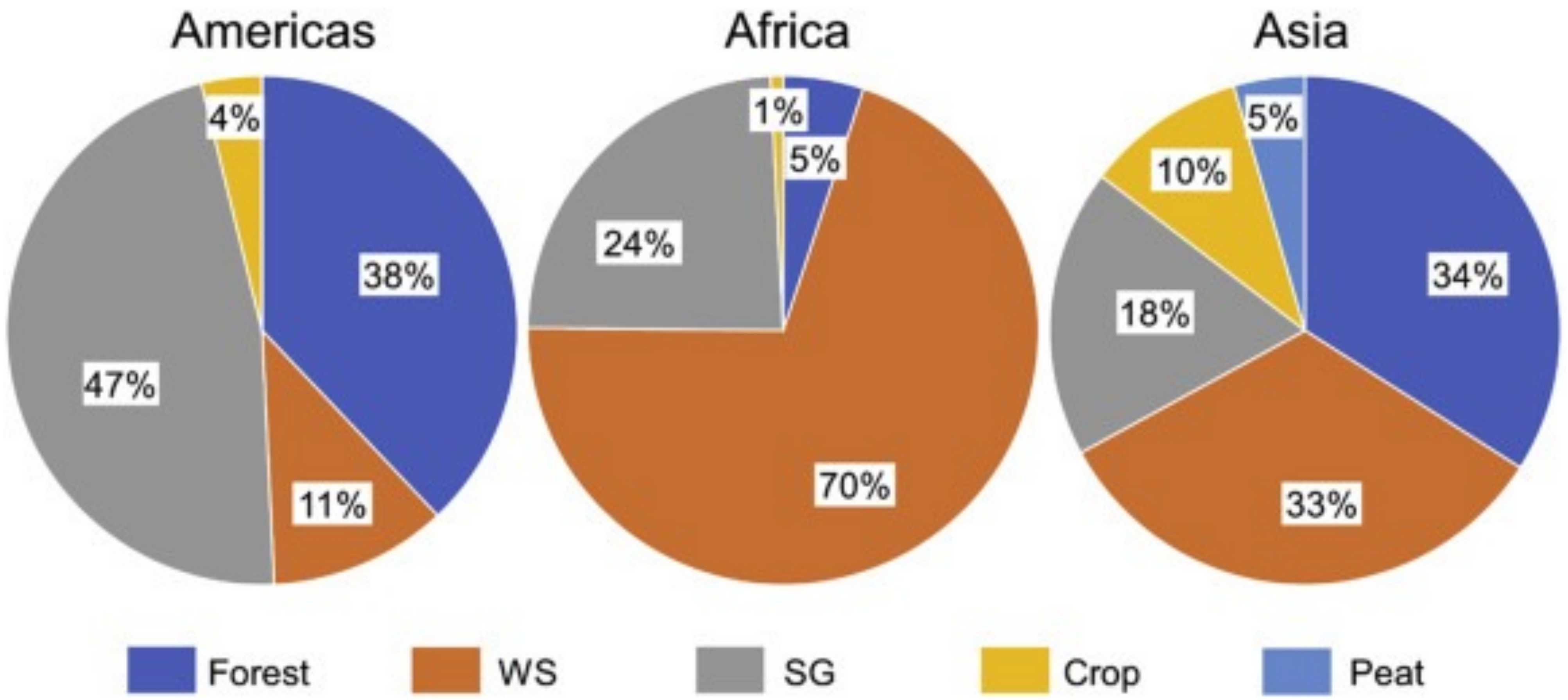
- Distribution of annual dust emissions in four source areas **(taken from Xiong et al. (2020)**
- Global climate model CAM 5.1 (Community Atmosphere Model, version 5.1) simulations revealed that North Africa, the Arabian Peninsula and the Middle East, East Asia, and Australia respectively account for 60%, 18%, 12%, and 2.5% of the global dust aerosol emission.

- **Xiong et al. (2020), J. Atmos. Sol.-Terres. Phys., 10.1016/j.jastp.2020.105415**
- **Ntwali and Chen (2018), J. Atmos. Environ., 10.1016/j.atmosenv.2018.03.054**

Back ground: Biomass Burning Emission over Africa and other regions







Top-Left: Averaged annual Biomass Burning (BB) CO_2 emissions (0.1° × 0.1°) from five land types in tropical continents during 2001–2017. Source: Shi et al. (2020).

Top-Middle: Vegetation types from the terrestrial biosphere model SiBCASA . Source: Mengistu et al. (2021)

Top-Right: Contributions of the five major land types (forest, woody savanna/shrubland (WS), savanna/grassland (SG), crop residue, and peatland) to annual BB CO_2 emissions in three tropical continents during 2001–2017. Source: Shi et al. (2020)

- ❑ Natural and human induced BB contributes to high emissions in tropical continents (Shi et al., 2015).
- ❑ According to the Global Fire Emissions Database v4.1s (GFED4.1s), approximately 84% of the global mean carbon emissions from BB during the period of 1997–2016 emanates from tropical regions (23.5°N to 23.5°S) (van der Werf et al., 2017).

- Shi et al. (2020): J. Cleaner Production, 10.1016/j.jclepro.2020.122511
- Shi et al. (2015): Environ. Sci. Technol., 49, pp. 10806-10814
- van der Werf et al. (2017): Earth Syst. Sci. Data, 9 (2017), pp. 697-720
- Mengistu et al. (2021): Biogeosciences, 18, 2843-2857,10.5194/bg-18-2843-2021

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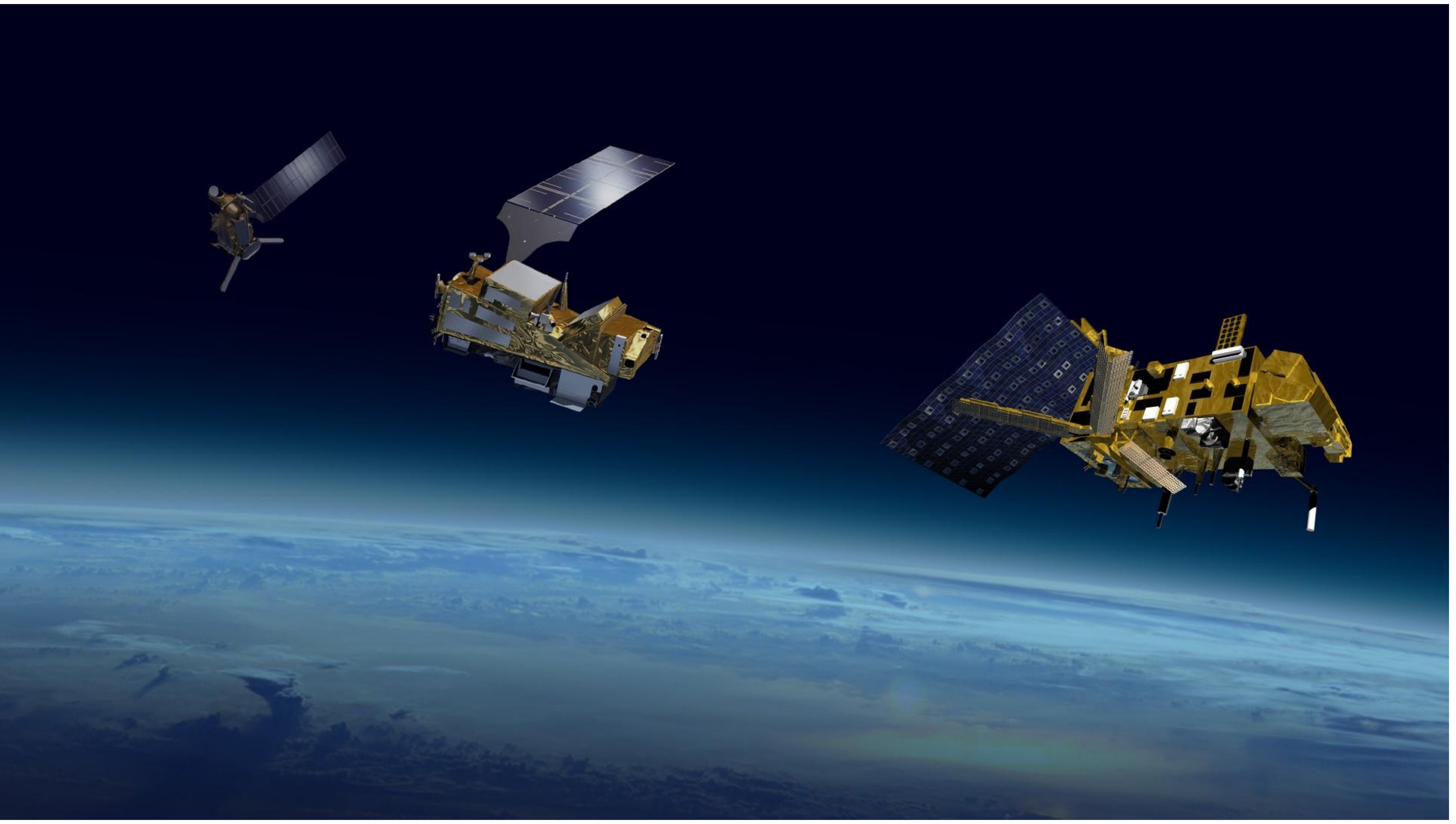
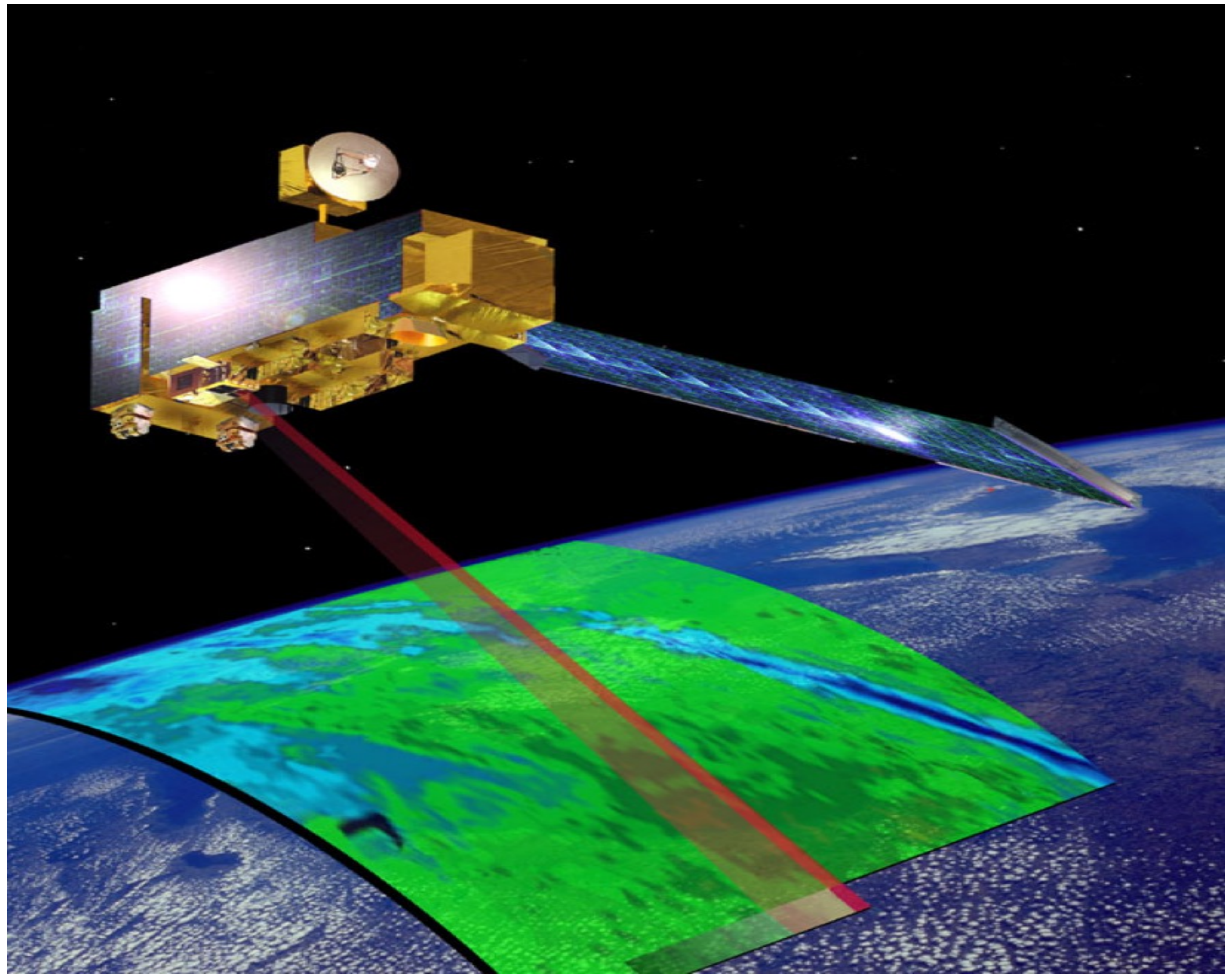
How good are recent satellite-based sensors in capturing the air pollution in Africa?



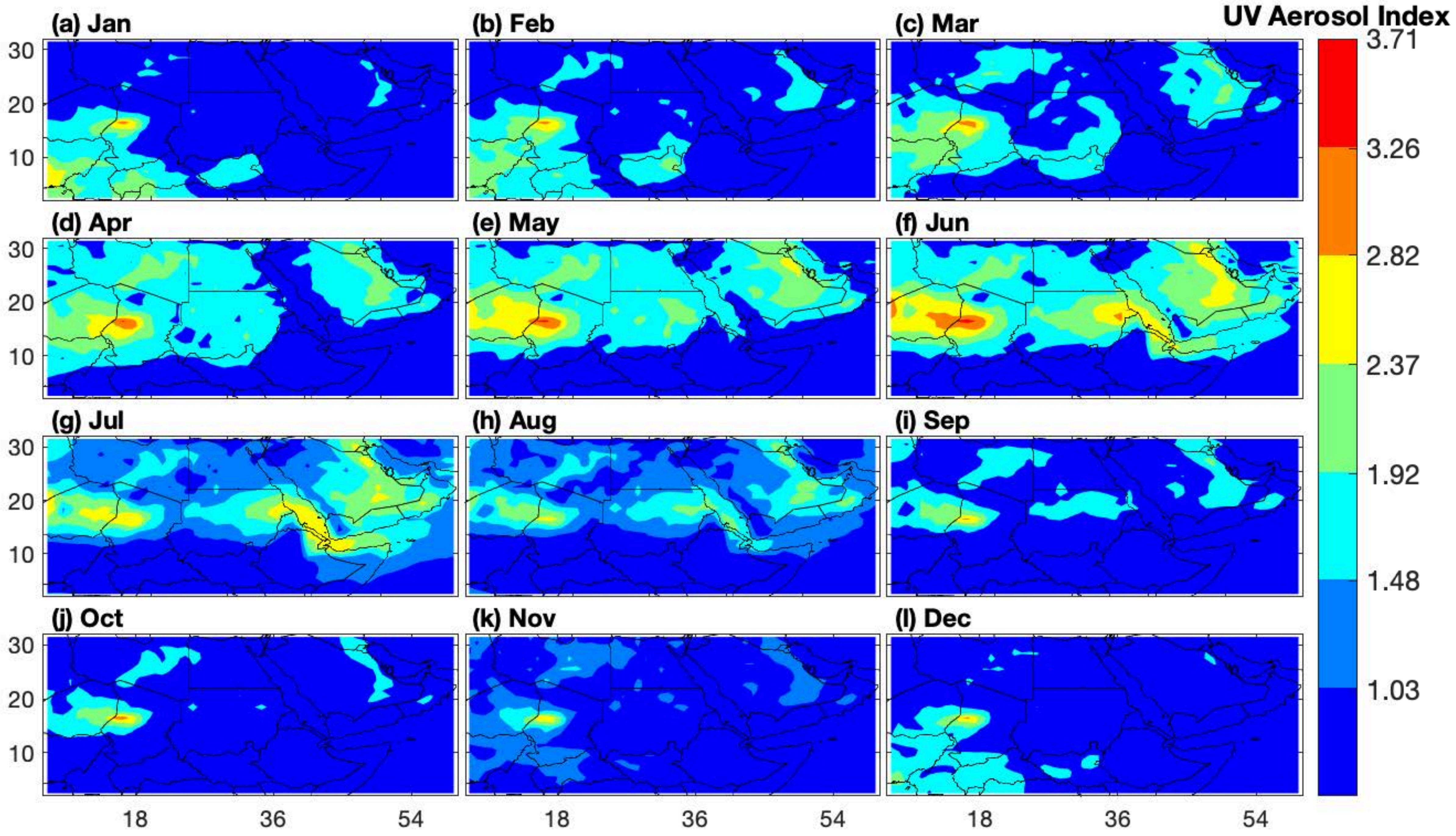
Metop Series A to C are able to provide Aerosol Column Density, lower tropospheric Ozone Column

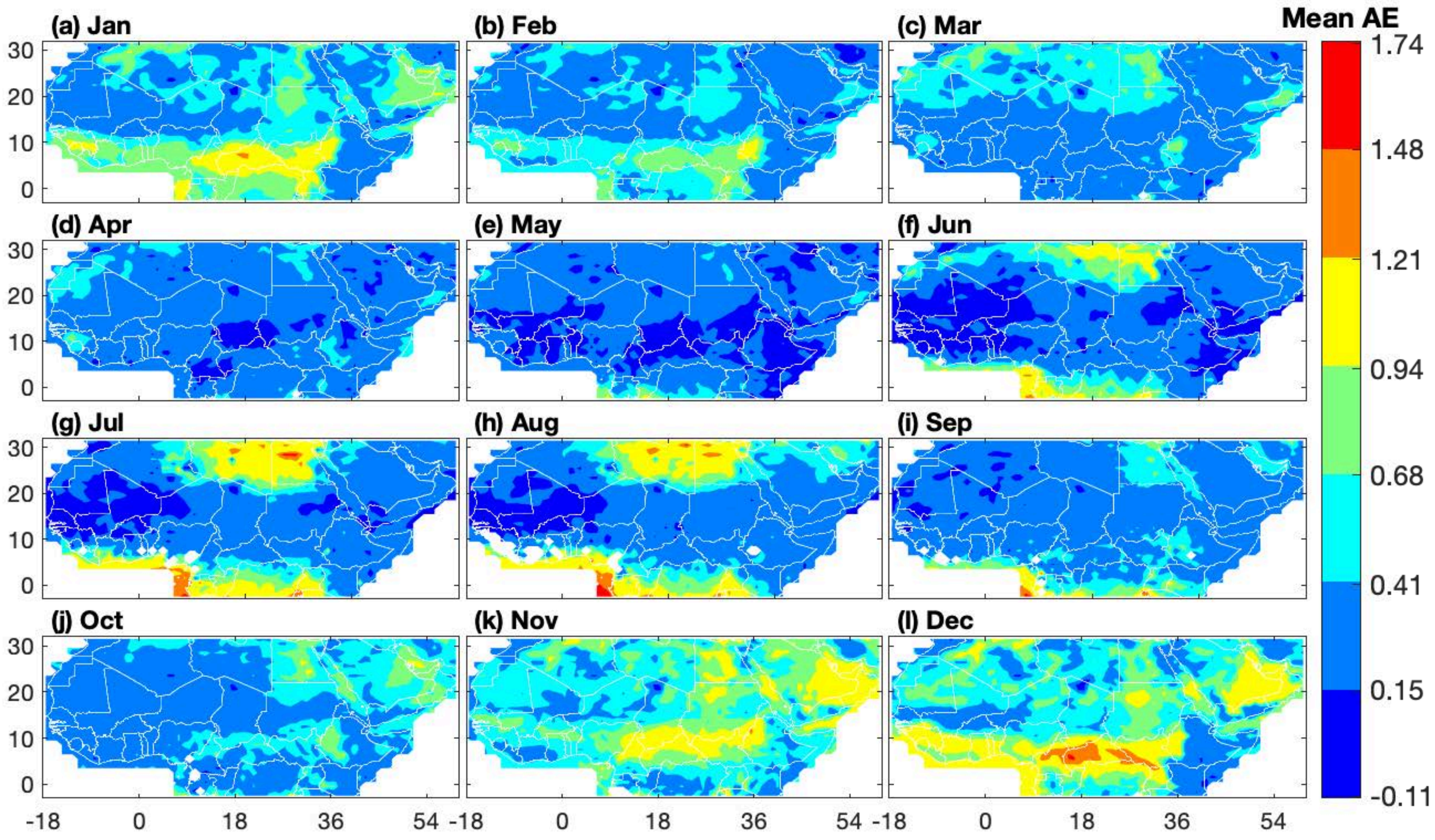


MOPITT (Measurement of pollution in the troposphere) sensor provide tropospheric CO Column

OMI-Ozone monitoring Instrument provides Ozone, NO_2, HCHO, UV Aerosol Index

How good are recent satellite-based sensors in capturing air pollution in Africa: Aerosol

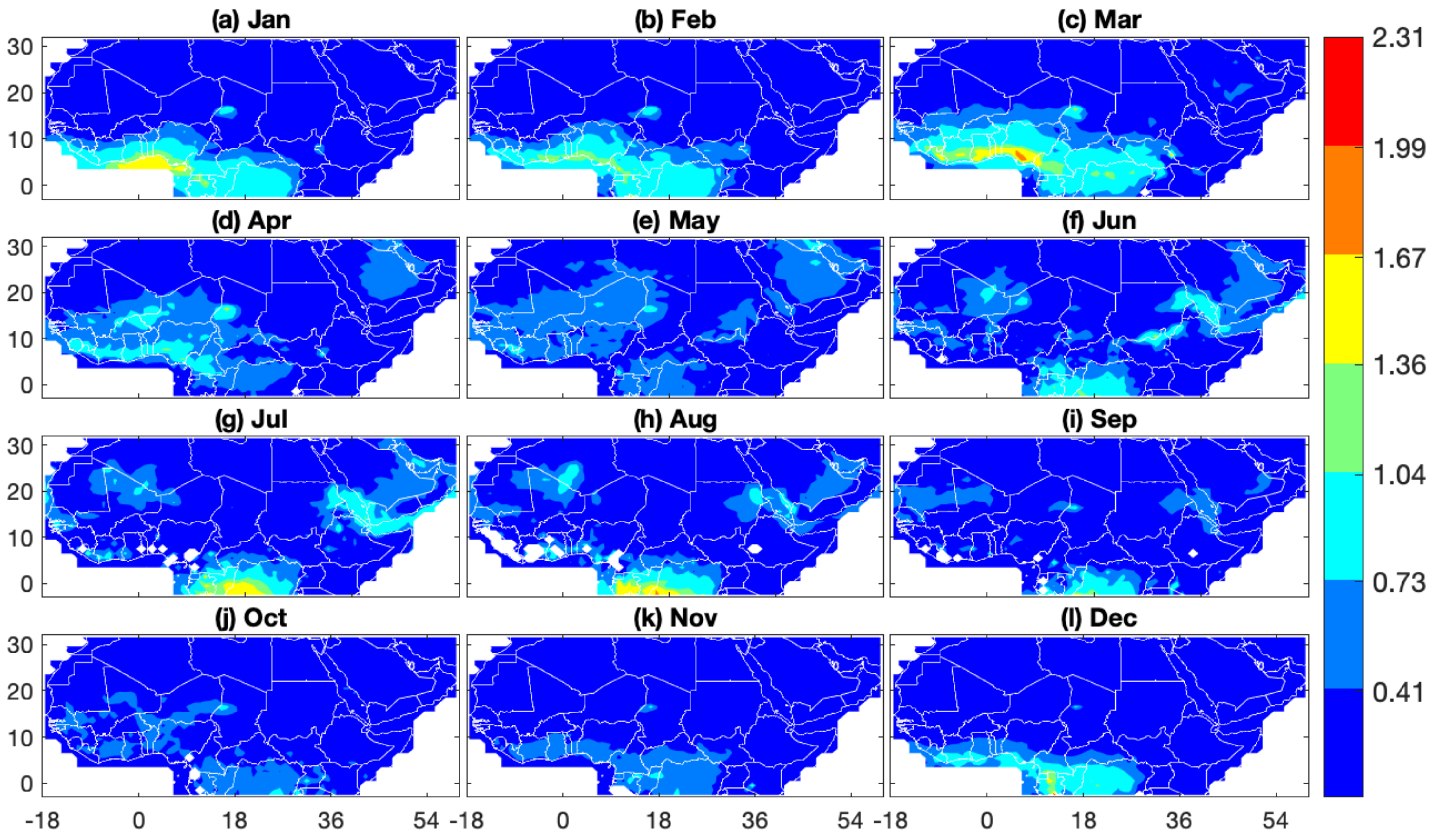


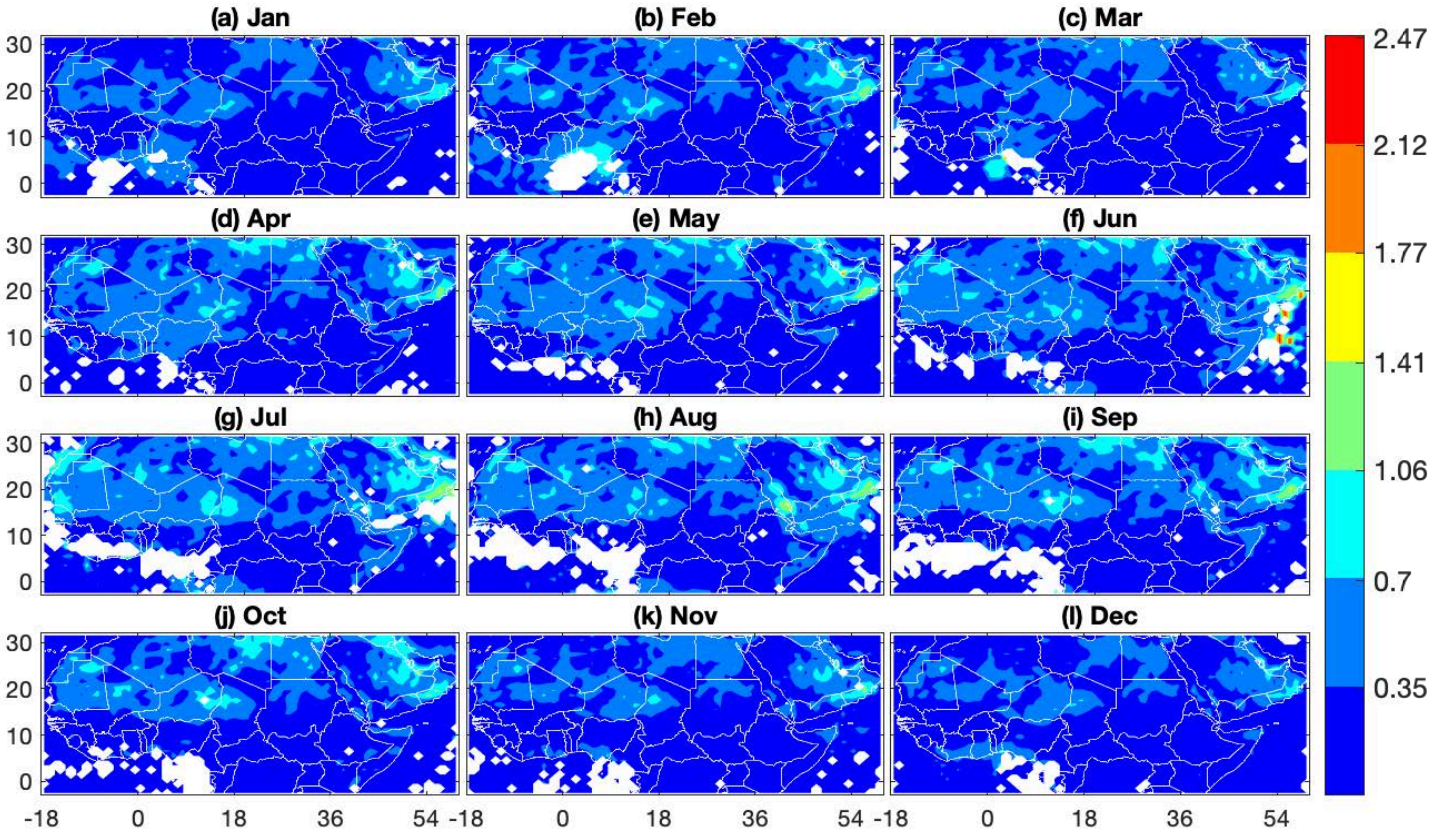


- The **Aerosol Index** derived from OMI indicates the presence of **UV**-absorbing **aerosols** such as dust and soot
- The index captured the dust belt over western Africa extending well into middle east.
- The intense dust belt follows the westerly low level flow during summer

- Angstrom Exponent calculated from AOD measurements at 670 & 865 nm provided by POLDER-PARSOL-GRASP Instrument
- AE<0.7-> Dust Aerosol; AE>1.2->Biomass Burning Aerosol; 0.7<=AE<=1.2-> Mixed Aerosols (**Ntwali and Chen, 2018**)
- The intense dust belt follows the westerly low level flow during summer

How good are recent satellite-based sensors in capturing air pollution in Africa: Aerosol

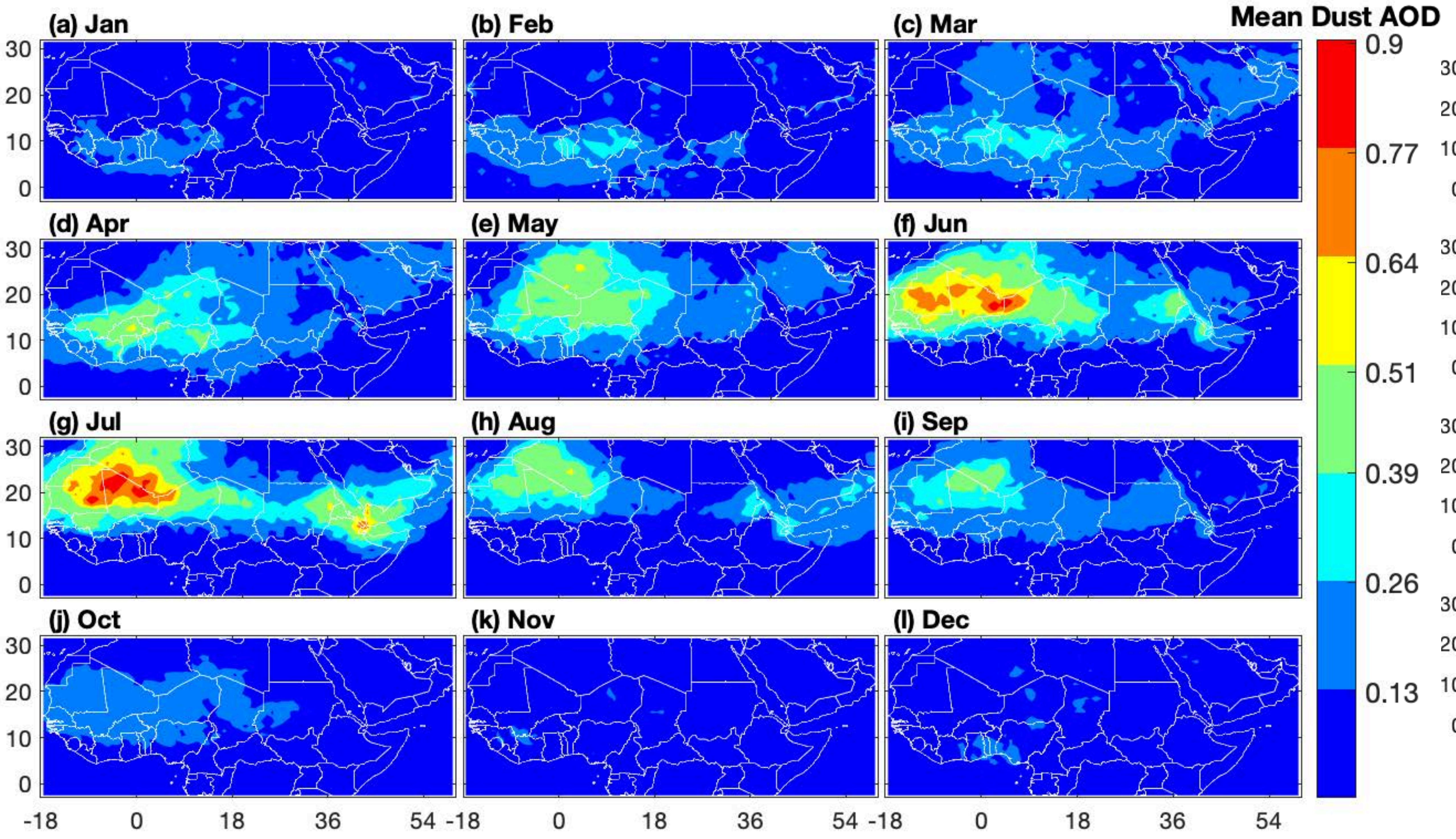


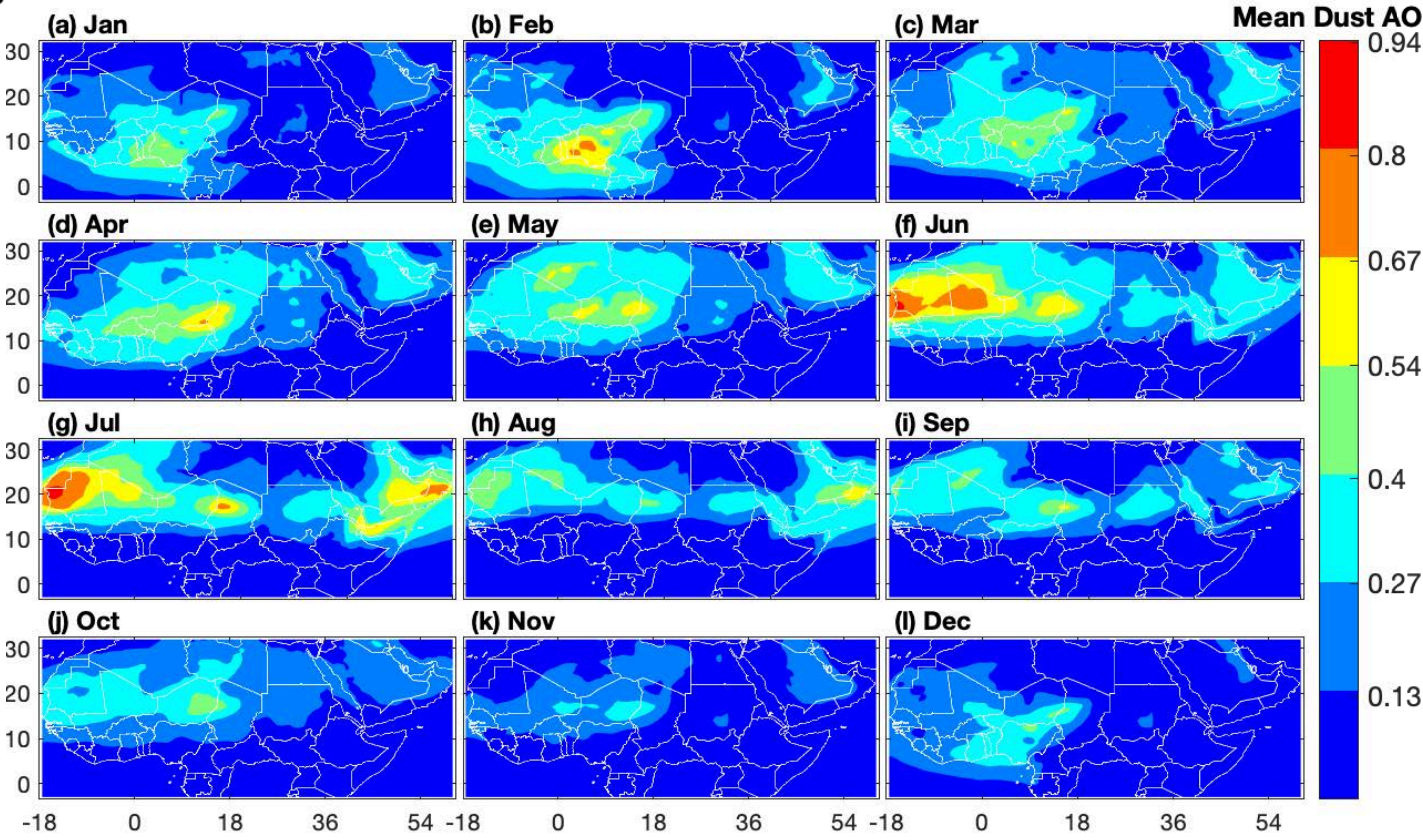


- **PARASOL** (**Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar**) carried an instrument called POLDER which studied the radiative and microphysical properties of clouds and aerosols
- AOD at 550 nm over West and East Africa

- The **SENTINEL-3** Ocean and Land Colour Instrument (**OLCI**)
- AOD at 550 nm is different from GRASP PARASOL product
- Despite data gaps, it captured similar spatial pattern as OMI UV AEROSOL index

How good are recent satellite-based sensors in capturing air pollution in Africa: Comparison with models

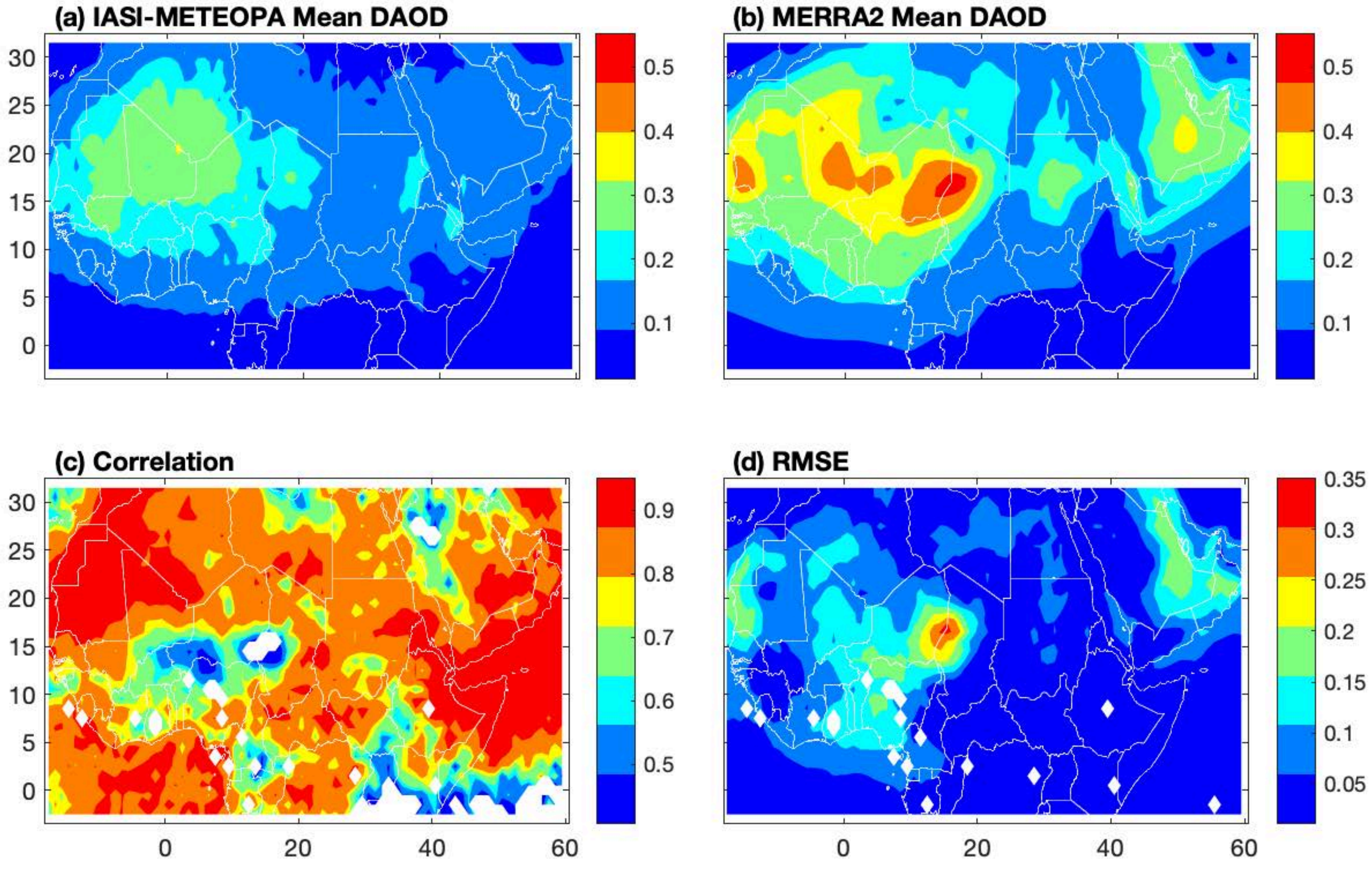




- Top-left: IASI-METOPA dust AOD at 550 nm over West and East Africa latitude
- AOD picks in June and July

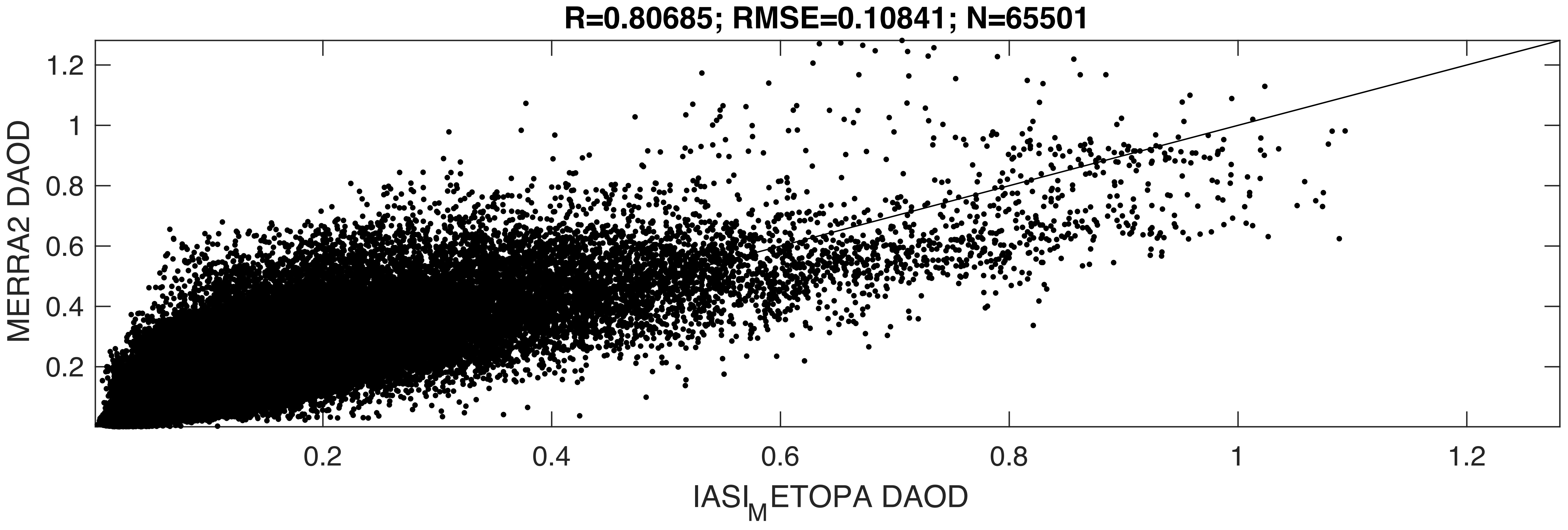
- Top-right: MERRA-2 dust AOD at 550 nm
- The MERRA-2 model AOD peaks during both June and July

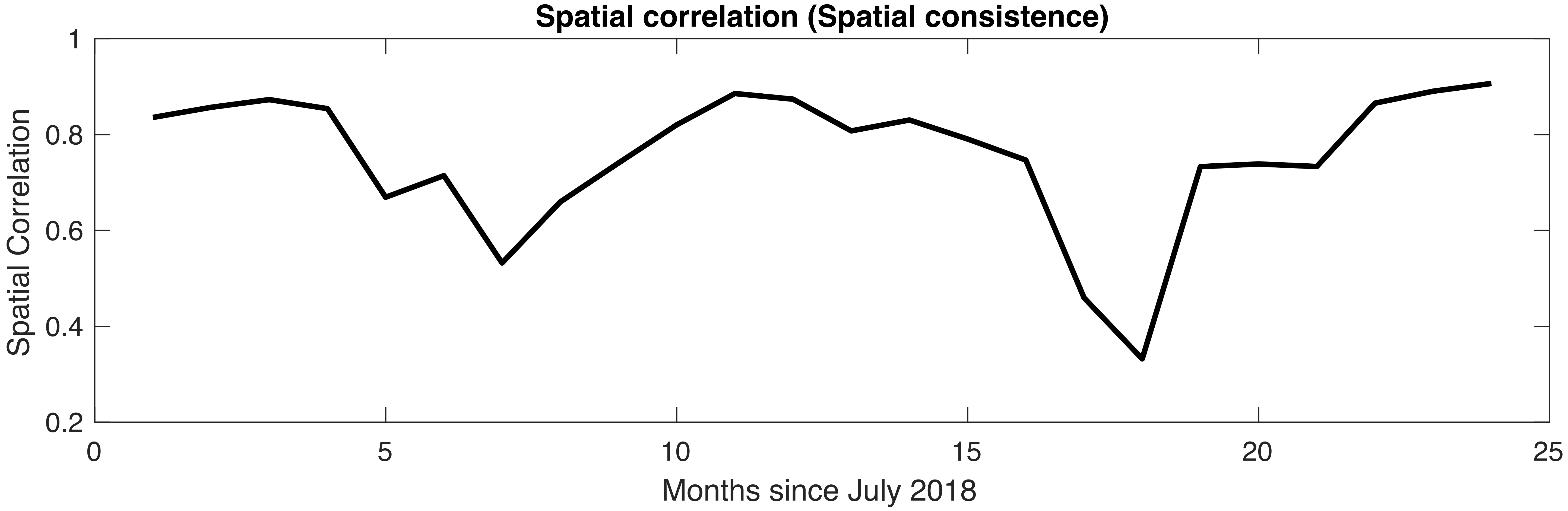
How good are recent satellite-based sensors in capturing air pollution in Africa: Aerosol



- The model has captured the spatial pattern except over middle east; however, the phase of AOD variation is good.
- The model also missed the magnitude of AOD due to dust over West Africa which is reflected in both correlation and RMSE over the region
- There is also a relatively weaker correlation over SW Ethiopia and South Sudan where the fire counts are high

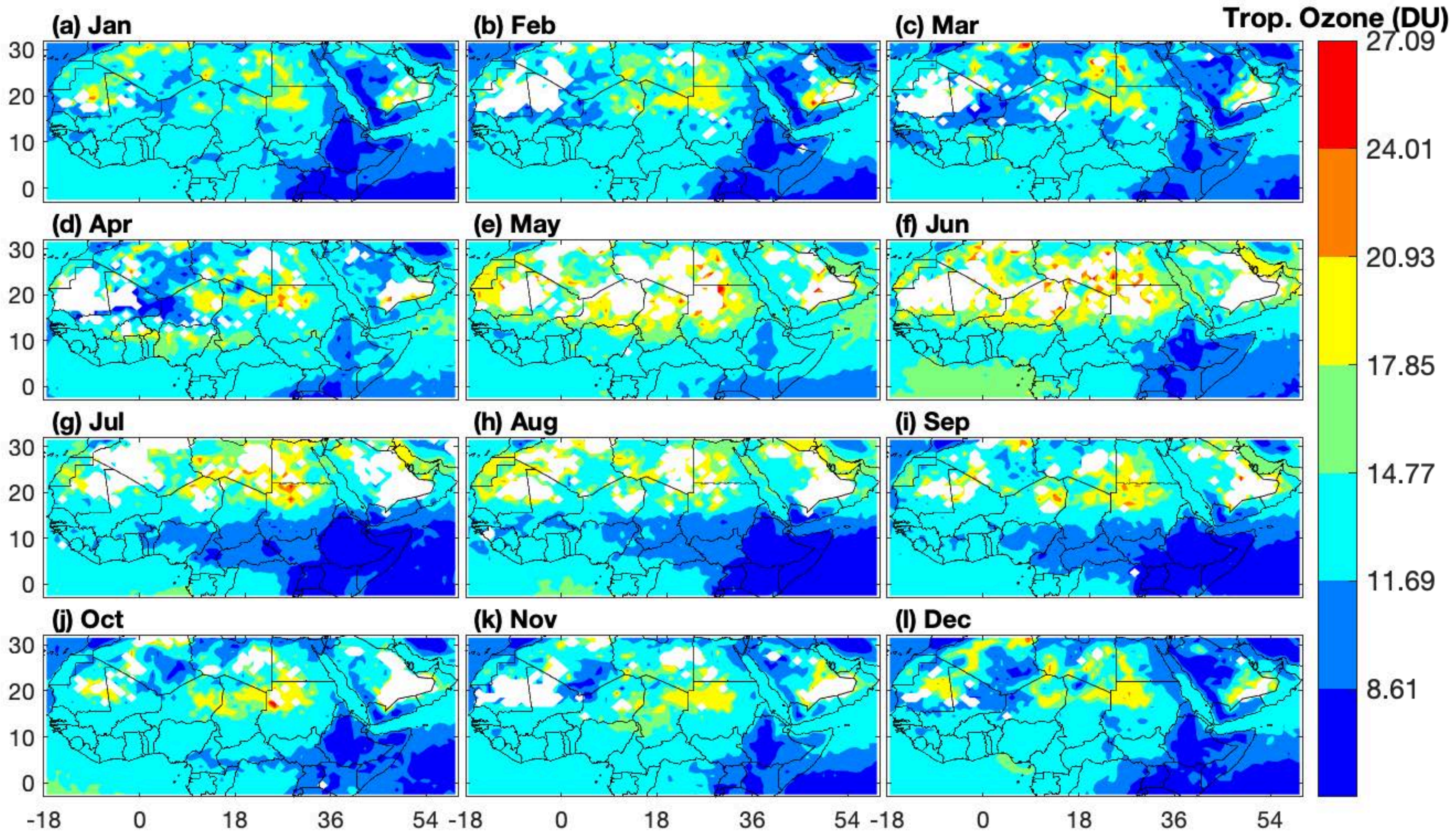
How good are recent satellite-based sensors in capturing air pollution in Africa: Aerosol

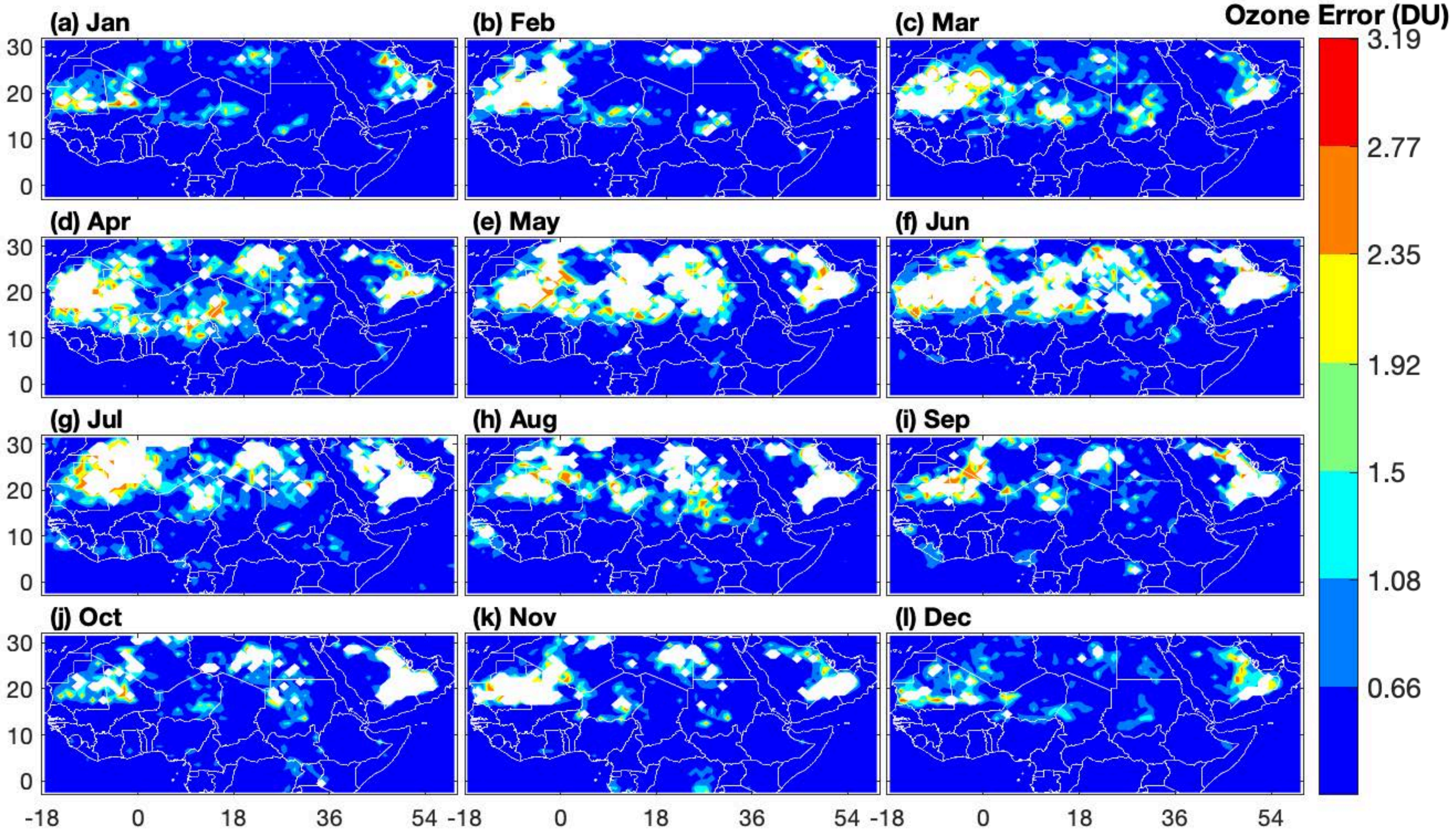




- MERRA2 has high bias at the lower ends of dust AOD.
- The model exhibit lower spatial consistence during winter months over the region with lowest in January

How good are recent satellite-based sensors in capturing air pollution in Africa: Ozone

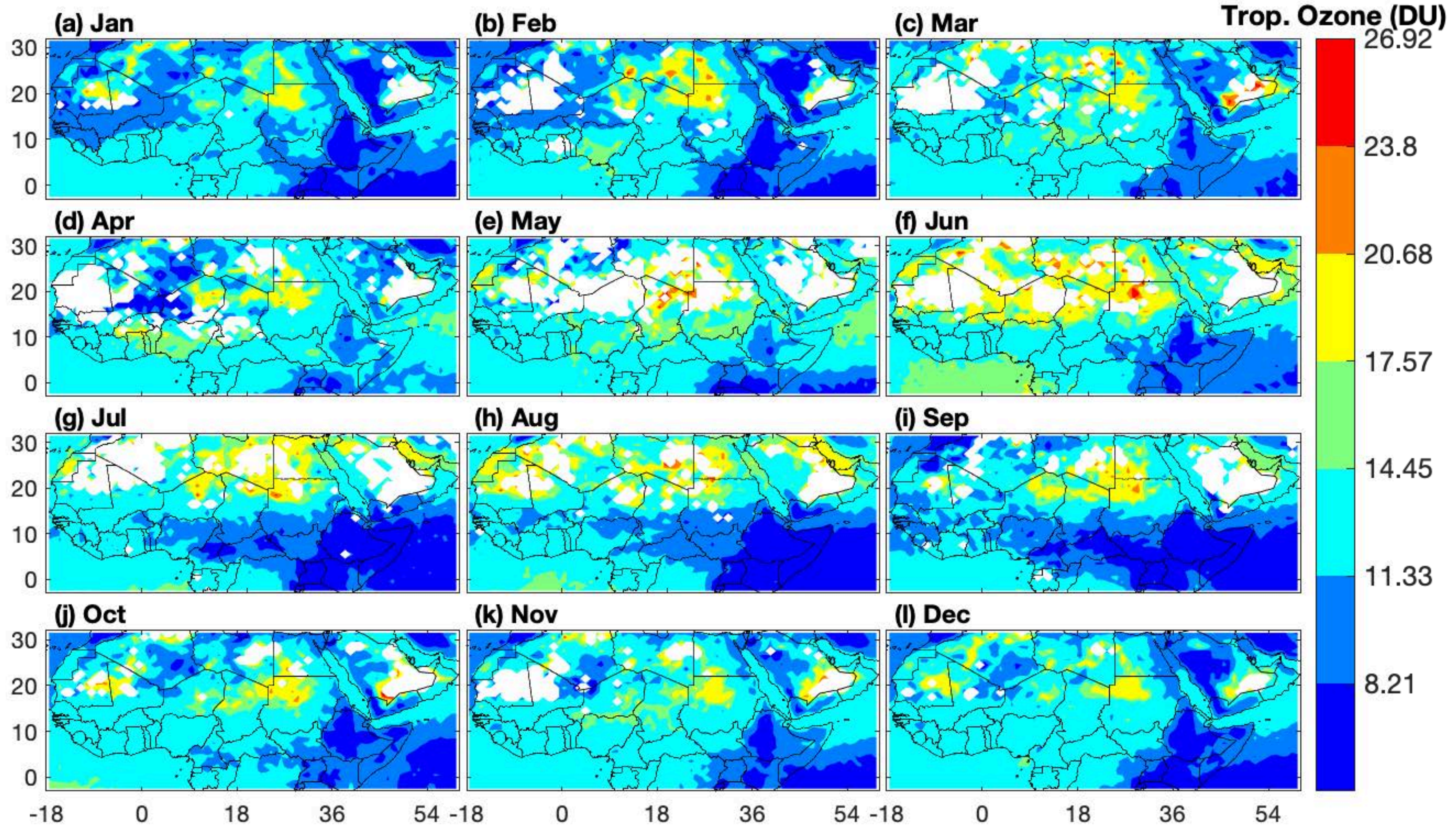


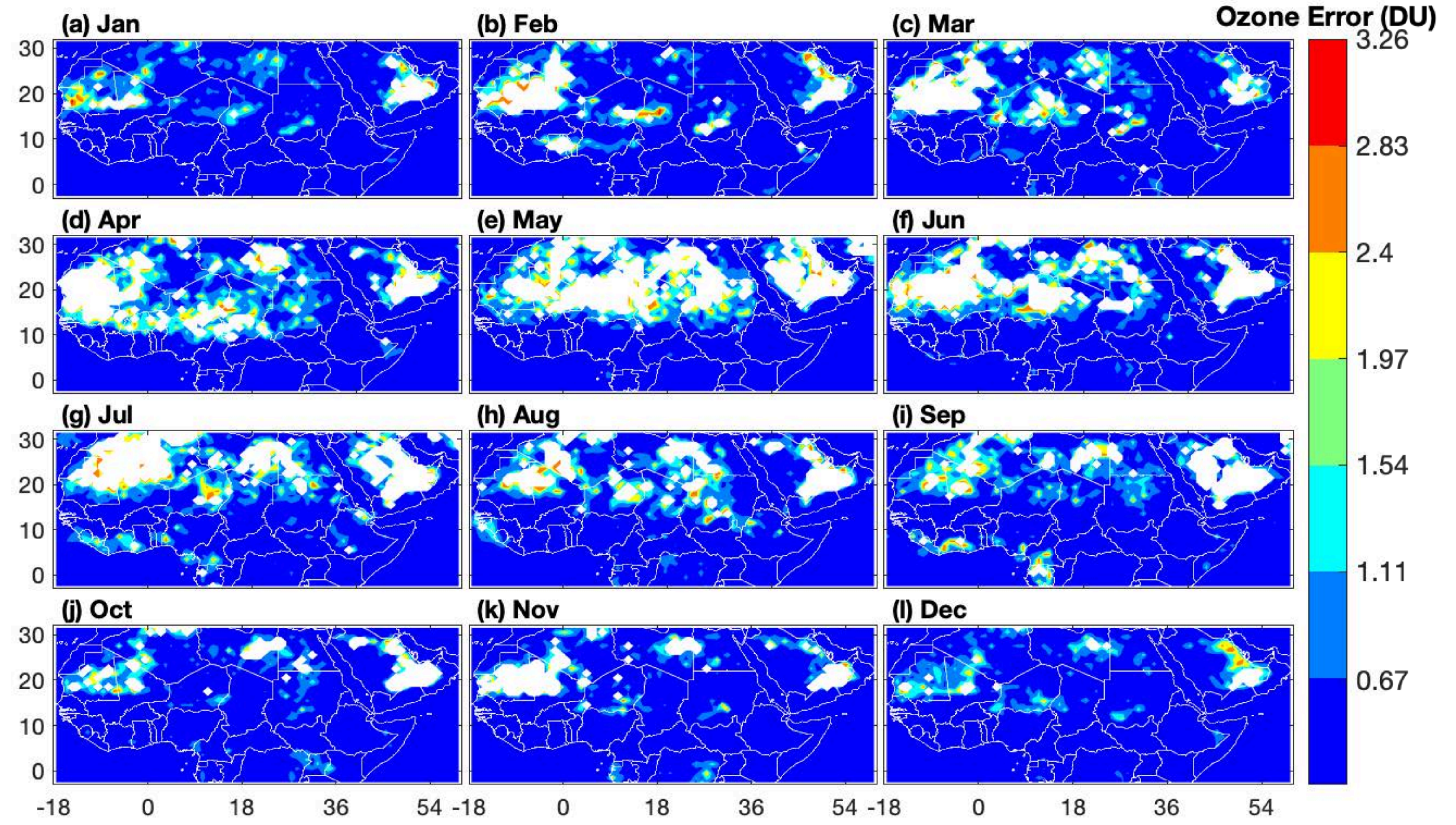


- Left: IASI-IR-METOPA lower tropospheric Ozone;
- Right: IASI-IR-METOPA lower Tropospheric Retrieval Error

- Most of hot spot of enhanced ozone is over the Sahel and northern Africa
- No clear seasonal pattern
- The highlands of Eastern Africa is mostly clean.

How good are recent satellite-based sensors in capturing air pollution in Africa: Ozone

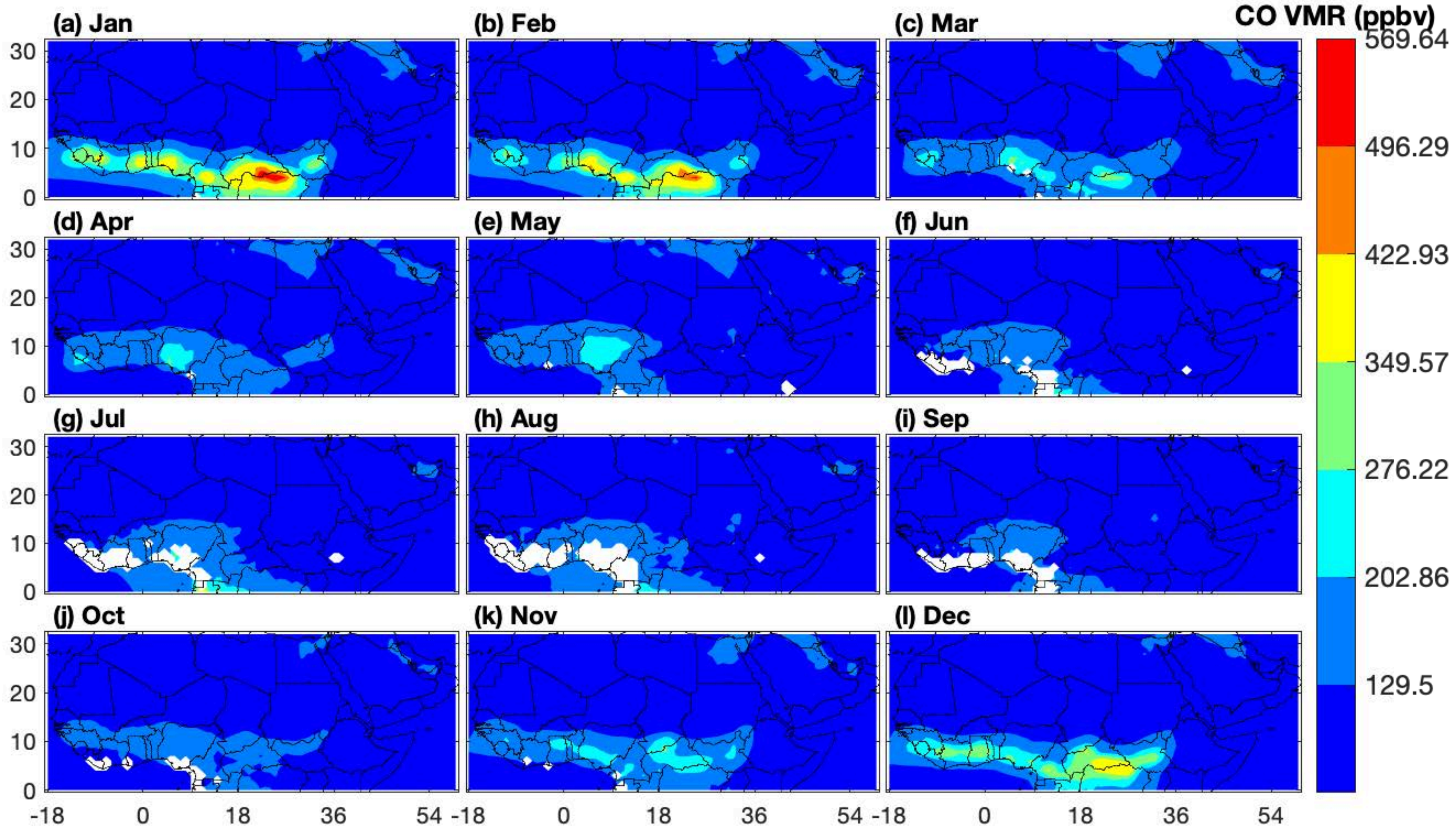


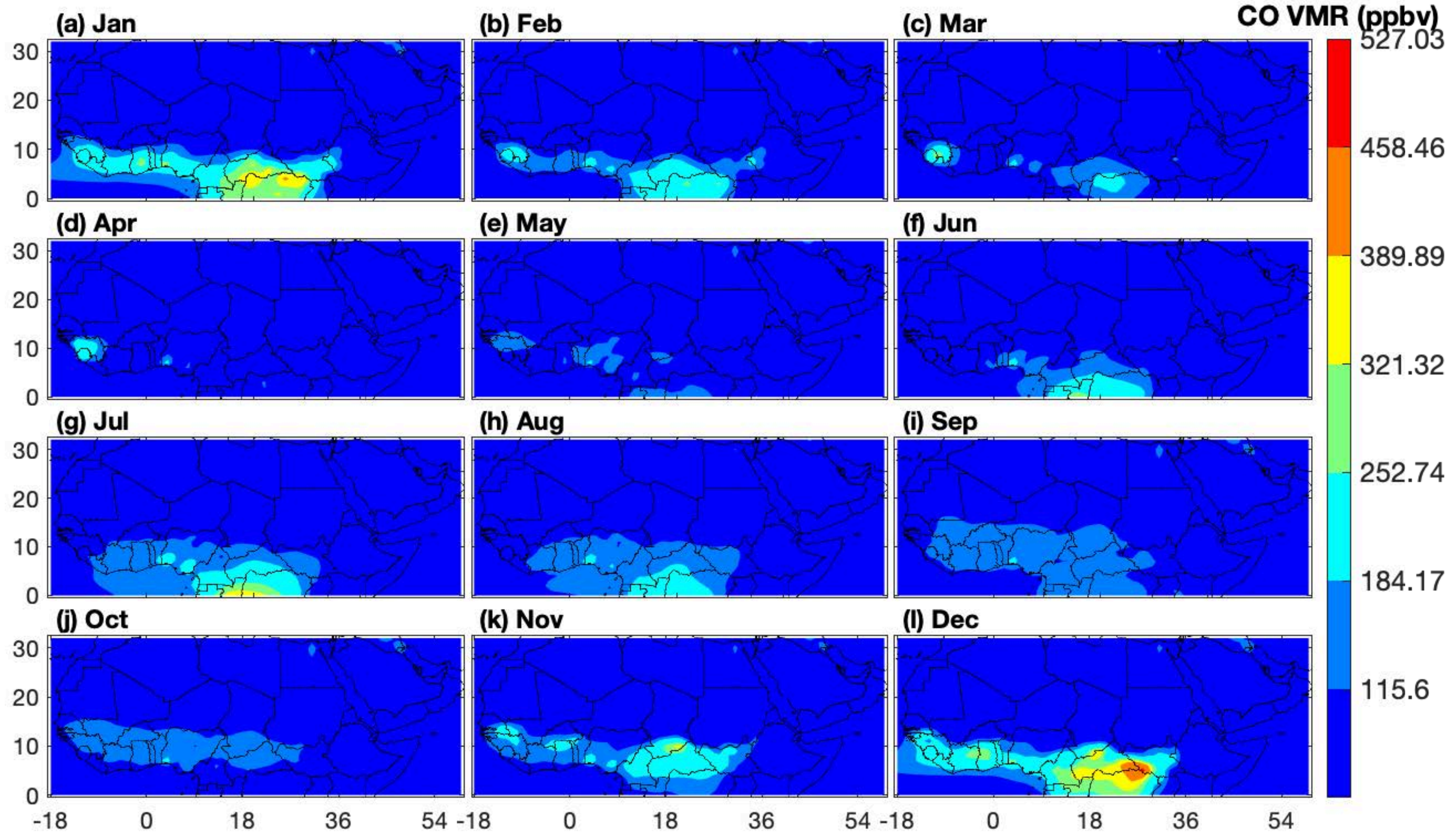


- Left: IASI-IR-METOPB lower tropospheric Ozone;
- Right: IASI-IR-METOPB lower Tropospheric Retrieval Error

- Similar lower tropospheric Ozone distribution as IASI-IR METOPA over West and Eastern Africa latitude;
- Lower Tropospheric Ozone Retrieval Error is proportional to the density
- Enhanced ozone over the Sahel and northern Africa might be partly attributed to mixing through large Planetary waves

How good are recent satellite-based sensors in capturing air pollution in Africa: CO

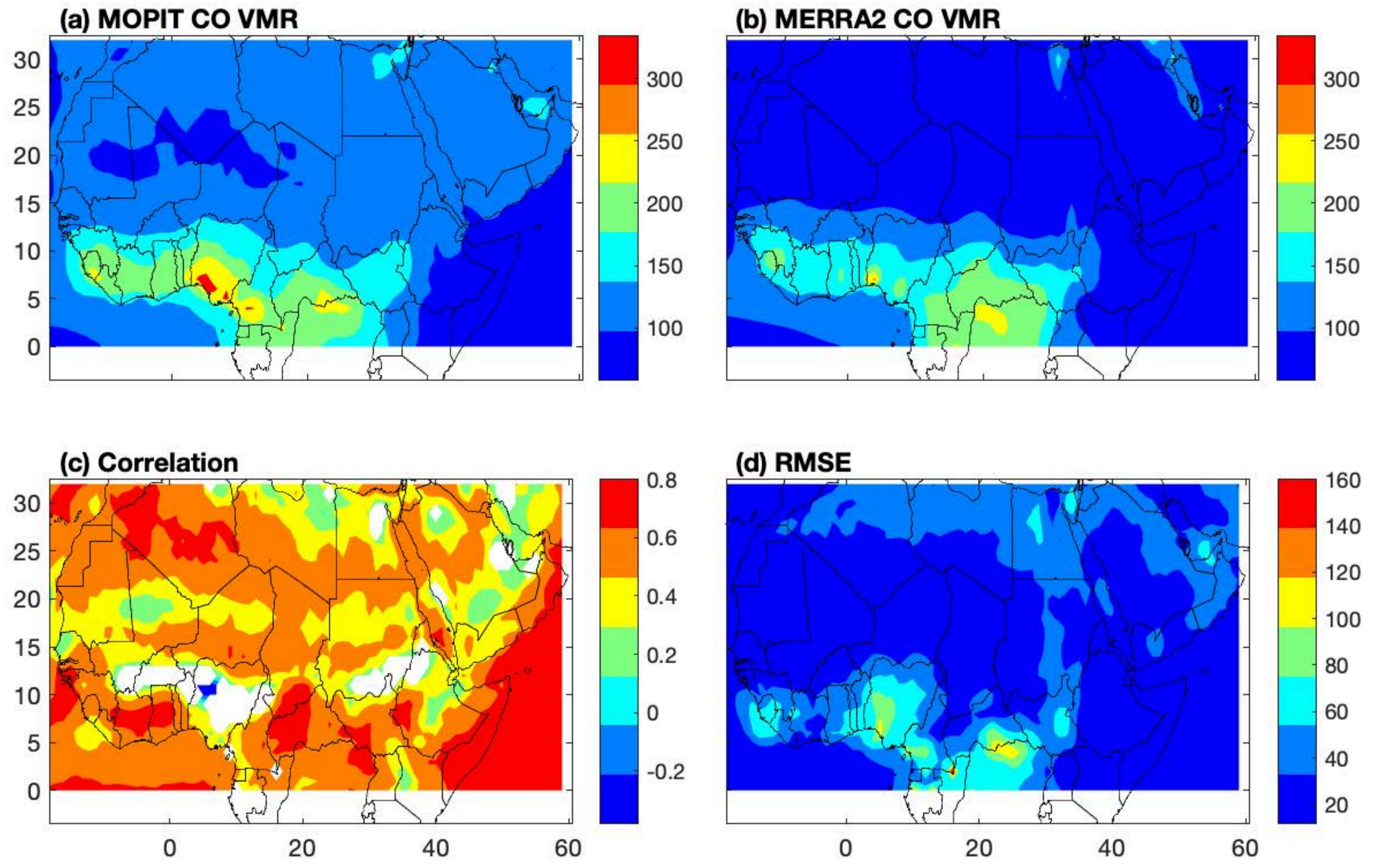


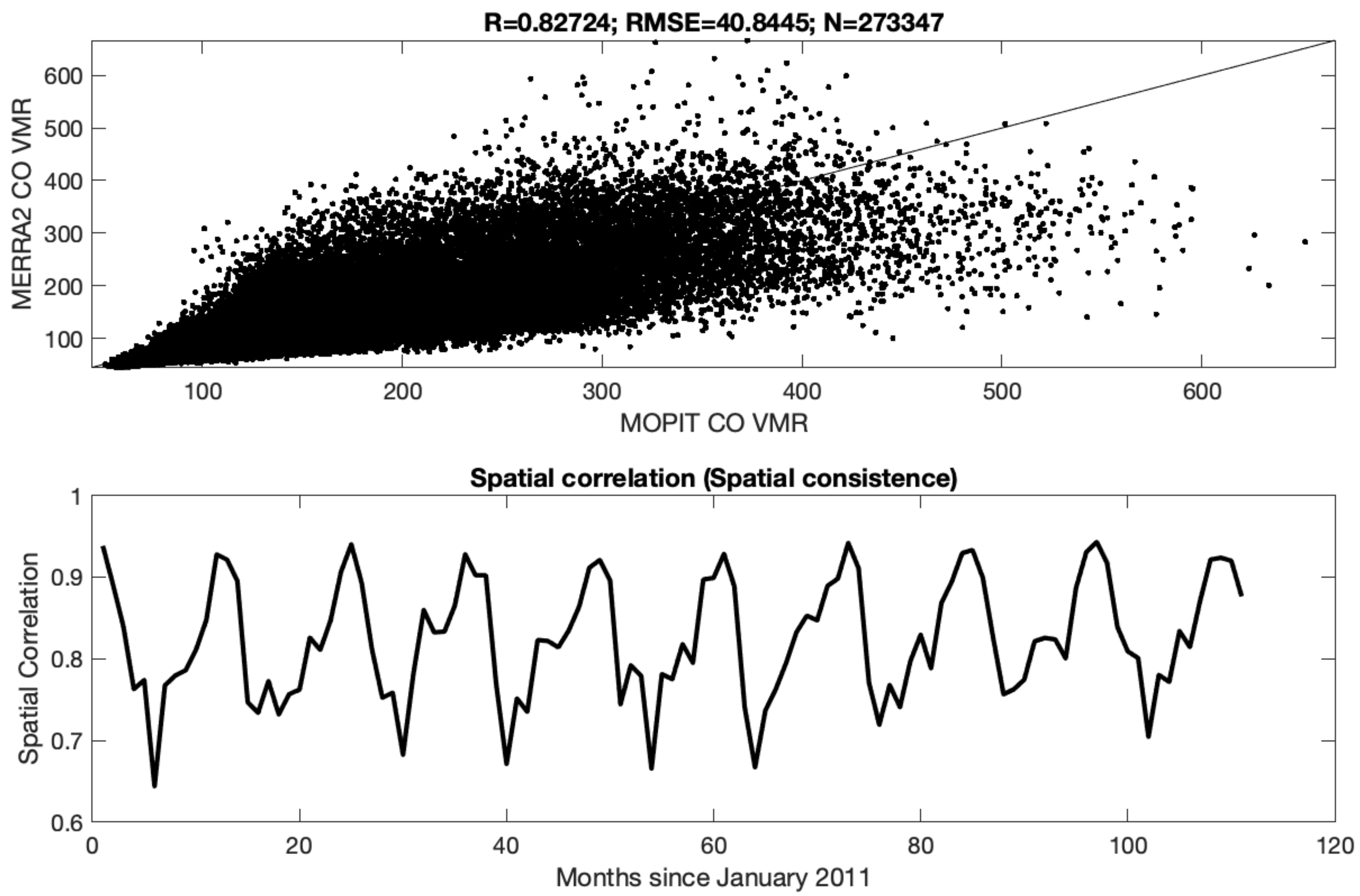


- Left: MOPITT tropospheric CO VMR;
- Right: MERRA-2 Tropospheric CO VMR

- Tropospheric CO VMR observed by MOPITT is well captured by MERRA-2 model
- Peak in austral winter season in both observation and model
- Dominant vegetation in this area is mostly C4 grass and shrubs

How good are recent satellite-based sensors in capturing air pollution in Africa: CO

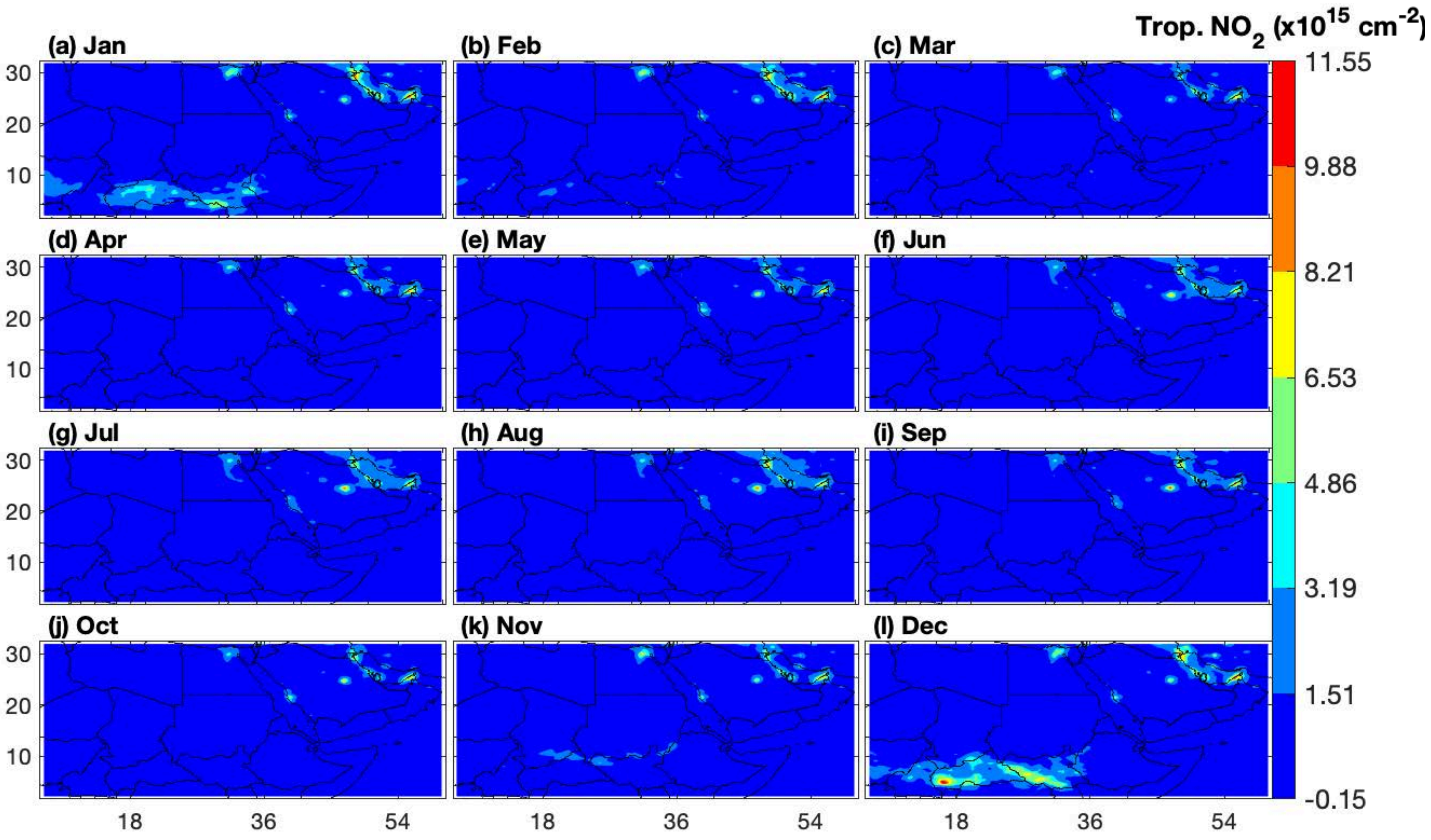


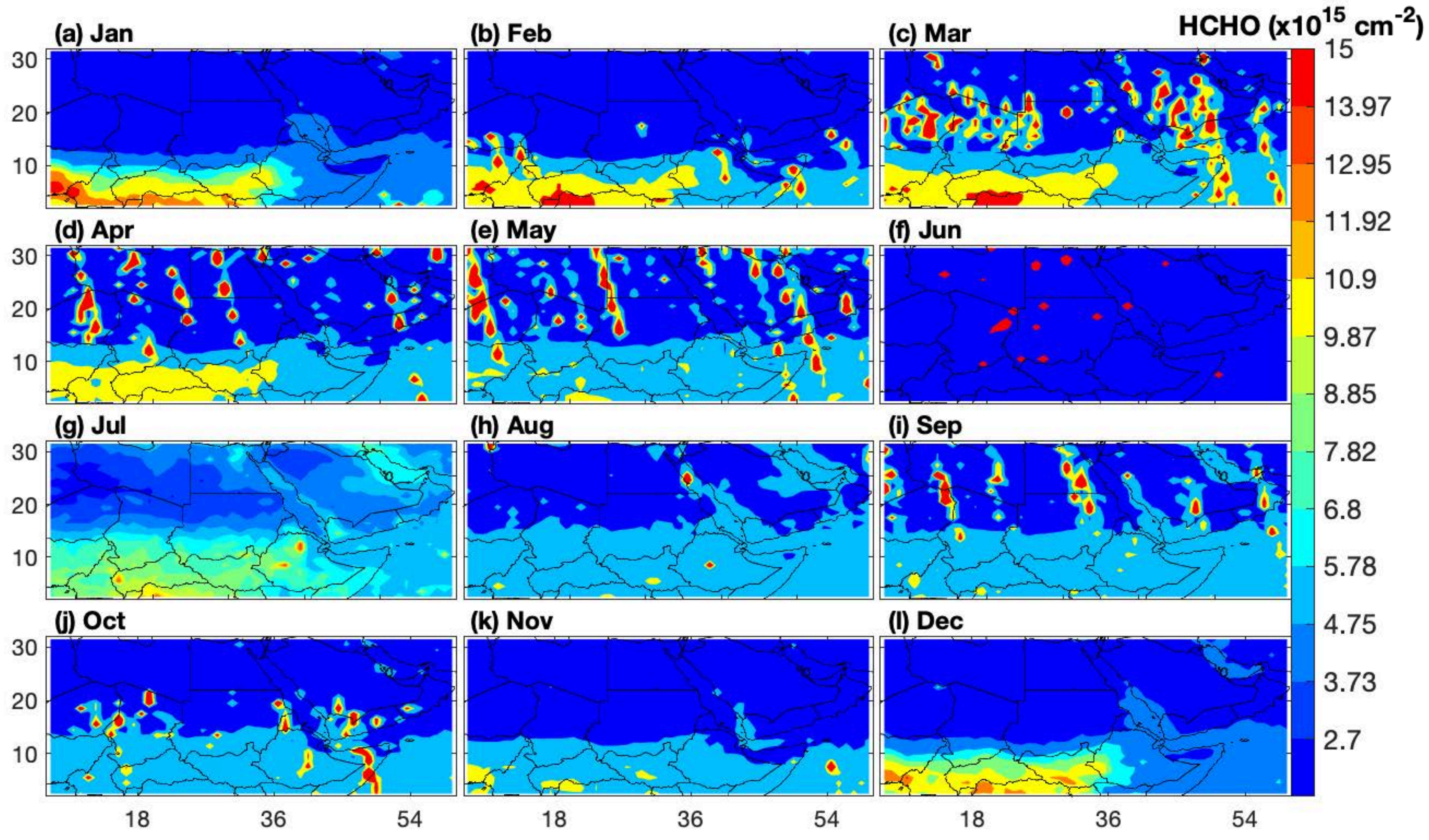


- Left: Mean CO VMR, correlation and RMSE of MERRA2 with respect to MOPITT observations;
- Right: Scatter plot between the two data sets and spatial model consistence in capturing MOPITT observations

- MERRA2 exhibits low bias at the high ends of MOPITT CO VMR;
- The performance of the model over the region is season dependent: Good during dry season & strong emission; weak during wet season & low emission.

How good are recent satellite-based sensors in capturing air pollution in Africa: NO_2 & HCHO



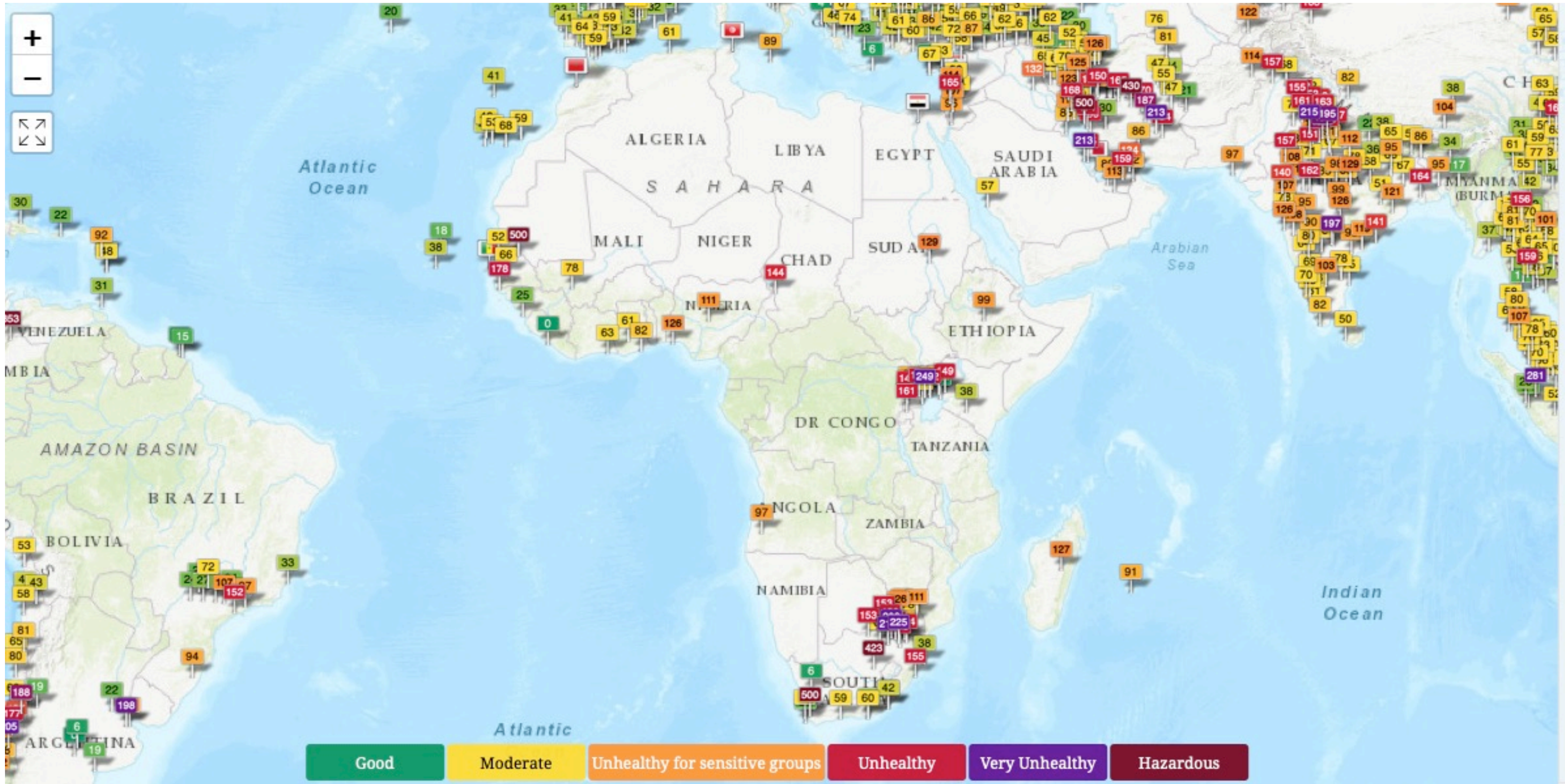


- Left: Tropospheric OMI NO_2 column density
- Right: Tropospheric OMI HCHO column density

- Enhanced tropospheric NO_2 is observed by OMI during December and January months over Africa
- Enhanced HCHO has both biogenic sources (e.g. peak in July) and BB (December, Jan-April)

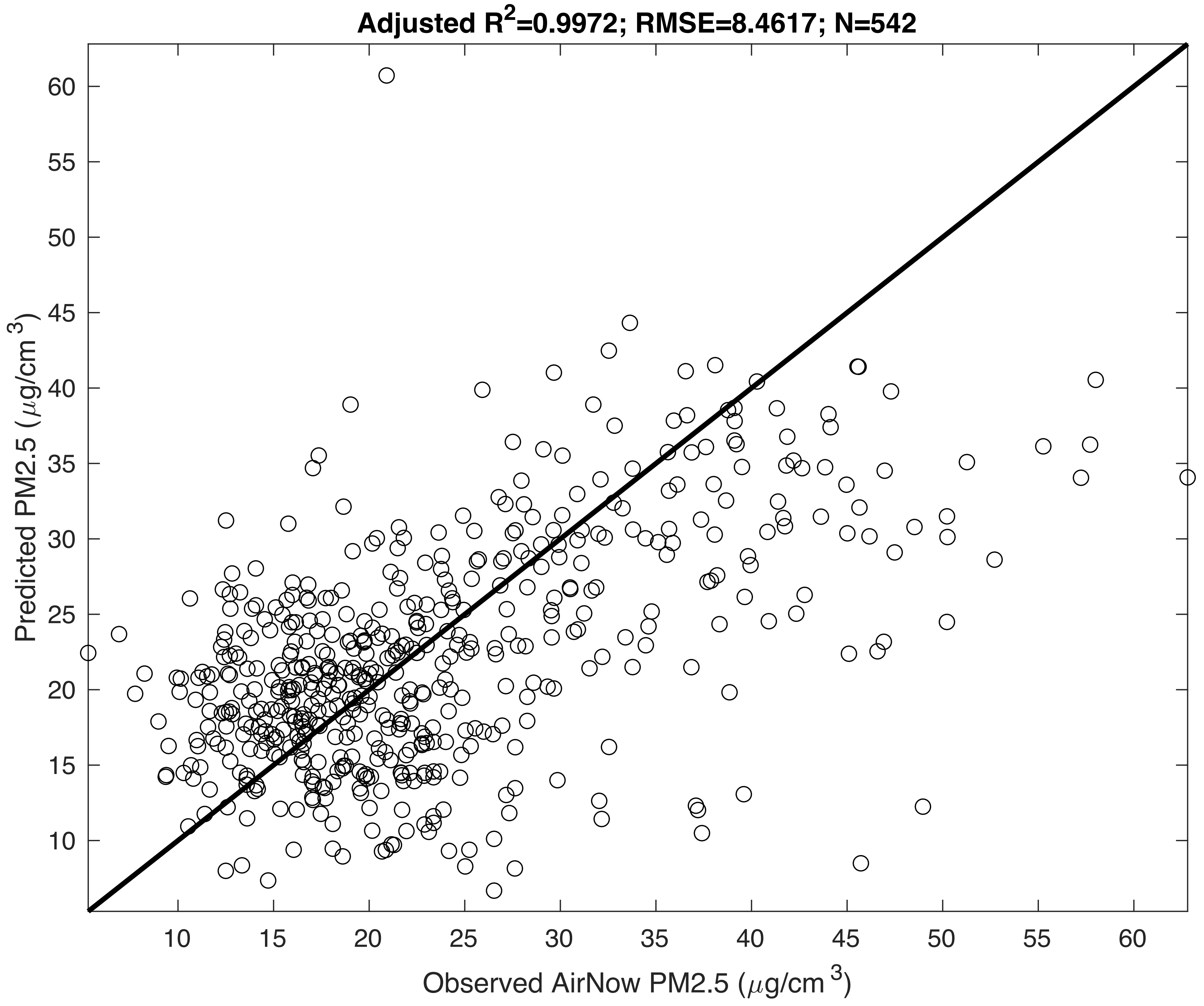
Did the progress made in Satellite Observations translate into Air Quality Monitoring?

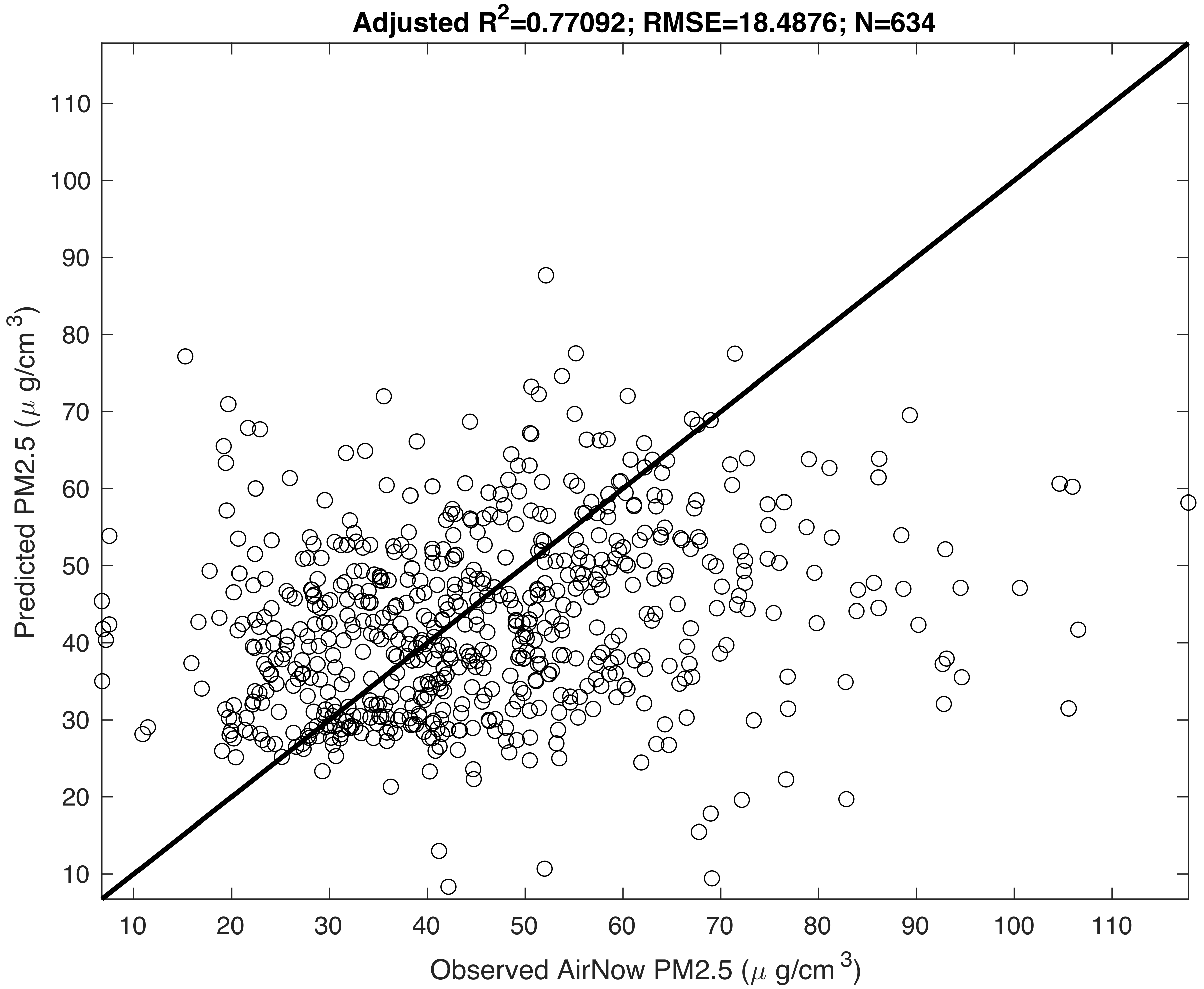
- Source: Aqicn.org



- Despite deteriorating air quality in Africa as a result of population growth and urbanization, not much is invested in in-situ observations leaving data and knowledge gaps;
- The satellite observations are still not capable of monitoring at Urban scale;
- There are efforts to translate satellite AOD observations into estimate of surface PM2.5 in conjunction with the use of data from surface meteorology in nonlinear regression models, land use regression models etc but with limited success and scope.

Did the progress in Satellite Observations translate into Air Quality Monitoring?





- **Left: Observed versus predicted PM at Addis Ababa Air Port; Right: At Kuwait City**
- The model is based on observed MODIS AOD and Surface Meteorological Observations (Temperature, Relative Humidity and Wind Speed).
- The difference between the two sites is the PM2.5 load. The model performance is excellent for low AOD in both sites and fails for PM2.5 exceeding 70 microgram per cubic meter. Therefore, the performance of such model is limited when the urban site is highly polluted.

Ongoing efforts: Four-way collaboration between BIUST, NCAT, Appalachian State and Addis Ababa Universities

- **Left:** Group Photo; **Middle:** Early Morning Measurements by BIUST group and **Right:** Early Morning Measurement by IRES visiting students
- Handheld Sunphotometer is homemade by Dr. Jim Group at Appalachian State Univ. through funding from IRES

Ongoing efforts: Four-way collaborations between BIUST, NCAT and Applachian State and Addis Ababa universities

PurpleAir Aerosol sensor at BIUST
Funded by IRES project (PI: S. Bililign)

Fully equipped Automatic weather Station that hosted PurpleAir Aerosol sensor

Summary and Outlook

- ❑ While substantial progress has been made in the use of satellite in air quality monitoring at regional scale, it is still a challenge to use them for local air quality monitoring.
- ❑ Satellites and models are in relatively good agreement in capturing large scale emissions.
- ❑ Efforts should continue to improve observational infrastructure and model skill to fill data and knowledge gaps over Africa

Mining

Agricultural and construction

Acknowledgements

- ❑ **Satellite data are obtained from NASA through its platform EARTHDATA and from EUMETSAT.**

- ❑ **Meteorological data is obtained from Copernicus Climate Services**

- ❑ **PM2.5 data is obtained from AirNow which is a partnership of the U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration (NOAA), National Park Service, NASA, Centers for Disease Control, and tribal, state, and local air quality agencies**

- ❑ **PurpleAir installations in Ethiopia and Botswana are funded by NRF through IRES project**