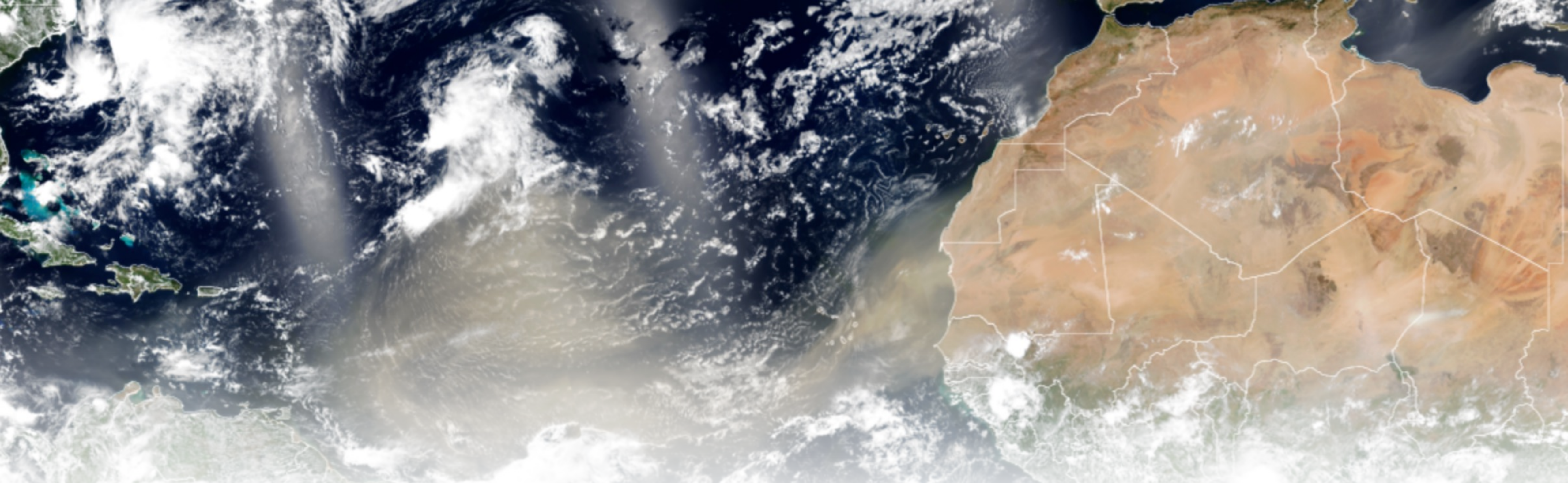

Satellite Monitoring of Dust

Using Measurements at UV – and Visible Wavelengths

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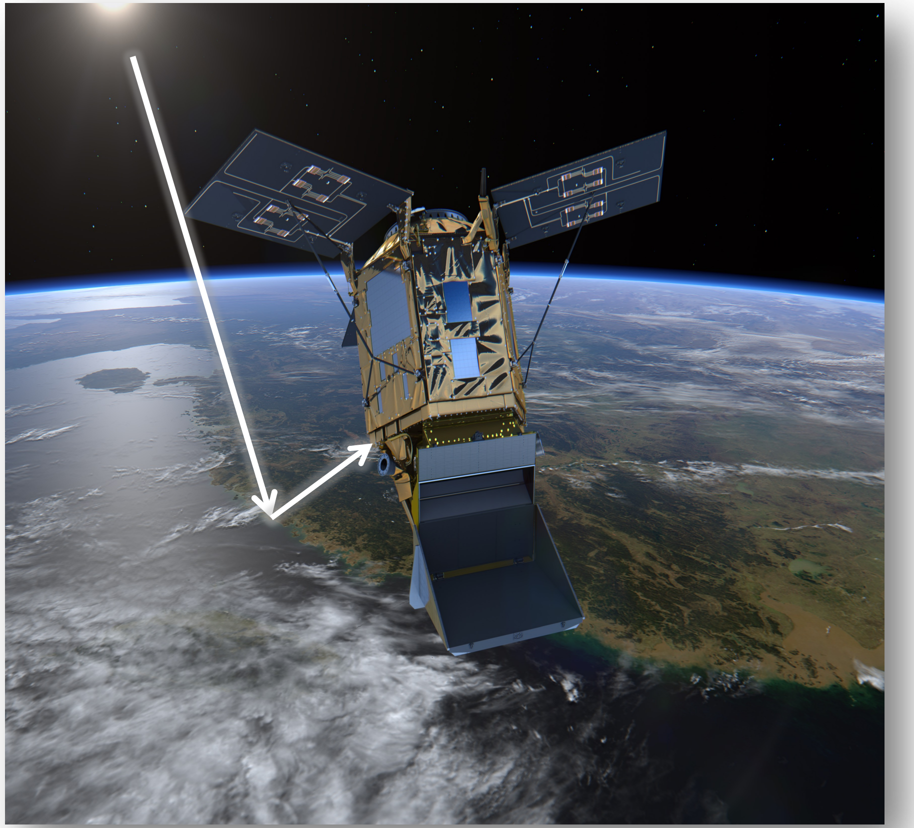
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

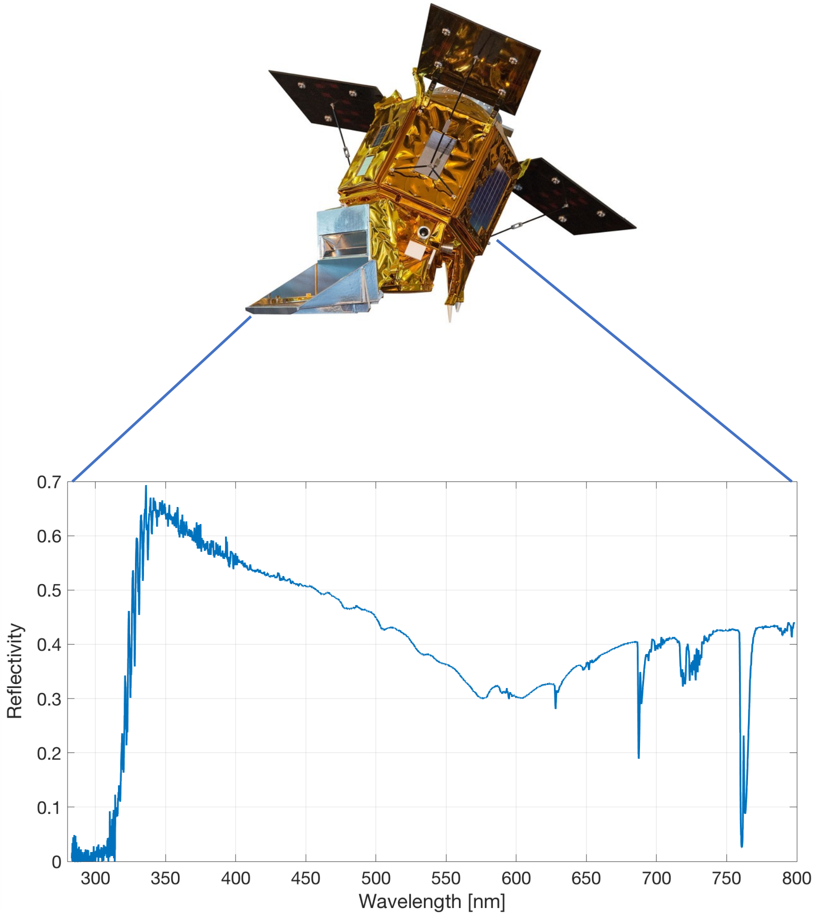
EUMETSAT
AC SAF
ATMOSPHERIC COMPOSITION MONITORING

Contents of the lecture

- Basic principles of passive satellite measurements
- True color RGB images from satellite and RGB composites
- Aerosol Optical Depth
- Absorbing Aerosol Index
- Absorbing Aerosol Height

Basic principle of a passive satellite measurement

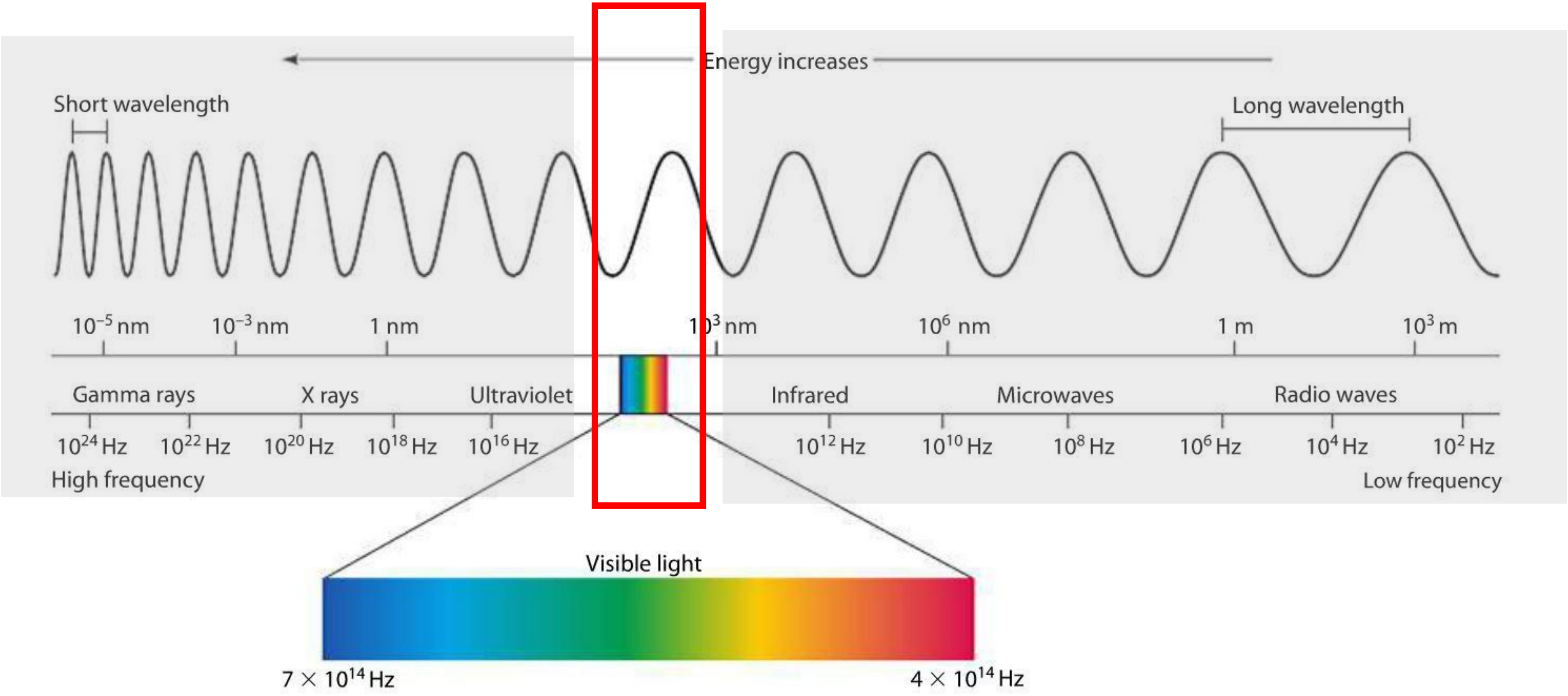




- Passive satellite instruments measure
    - Solar radiation that is reflected back to the space from Earth surface and the atmosphere.
    - Thermal radiation that is emitted from the Earth and the atmosphere

- Satellite observations of atmospheric components are **always indirect:** satellites measure radiation, not e.g. concentrations.

The focus of this lecture: satellite observations at UV – Visible wavelengths

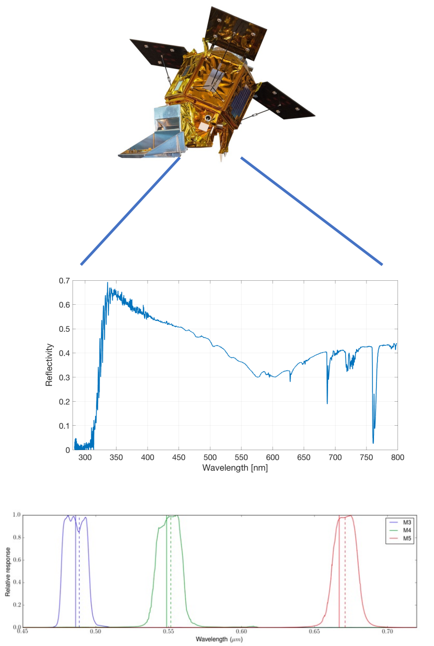


400 nm "VIS" 760 nm

Basic concept of satellite retrievals

- Passive satellite instruments measure reflected radiation at selected wavelengths
- The key is the "fingerprint" that different gases and aerosols leave on the measured radiation

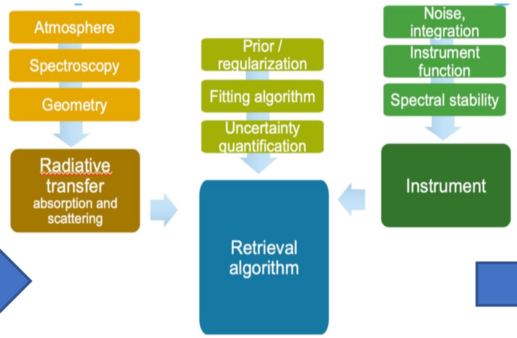
Level 1b data



(Schreirer et al., 2018)

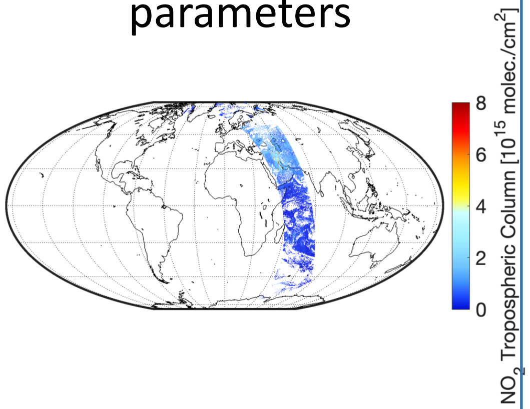
- Products containing geolocated and calibrated spectral radiance and solar irradiance data.

Retrieval algorithm



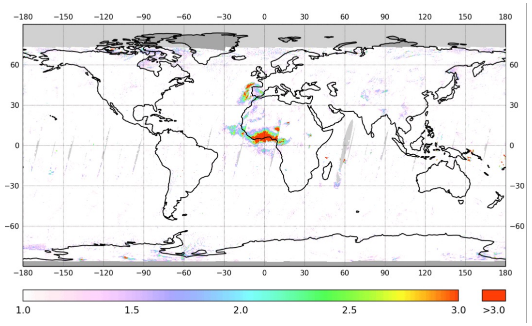
Level 2 data

Atmospheric parameters



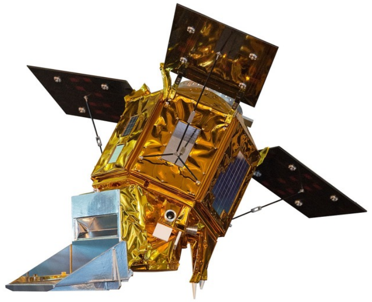
- Atmospheric products retrieved from the L1B product.
- Near real time (NRT) or "offline"
- Use of L2 data requires knowledge, especially on quality filtering

Level 3 data



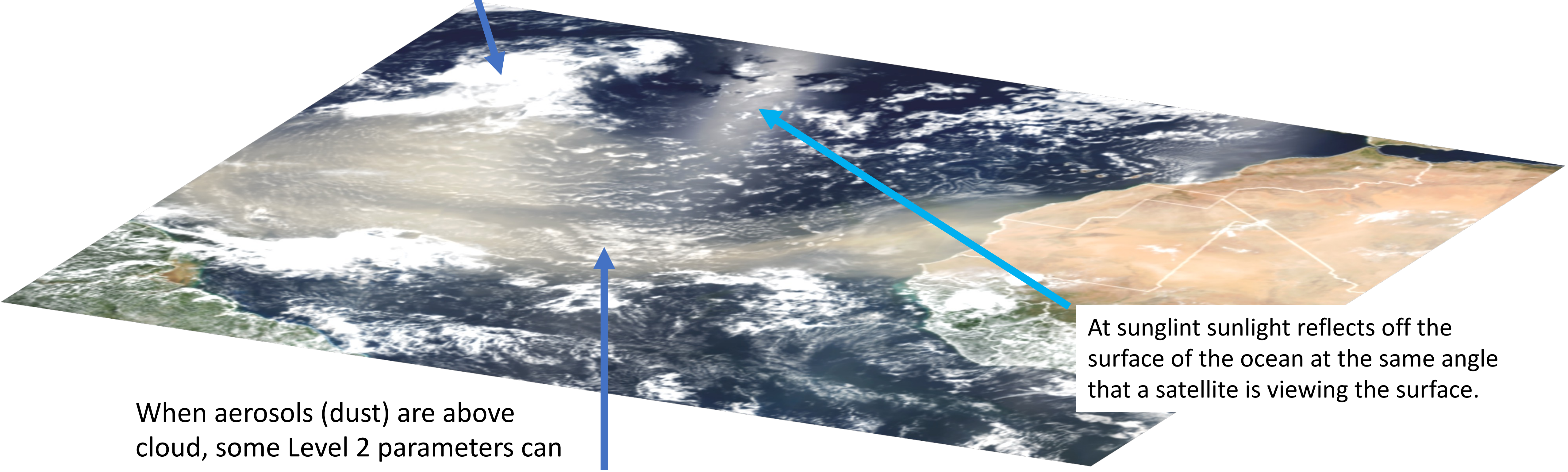
- Data gridded into a regular grid (often global)
- Typically daily or monthly products
- Quality filtered

Passive satellite instrument **can't see below** clouds -> no Level 2 observations



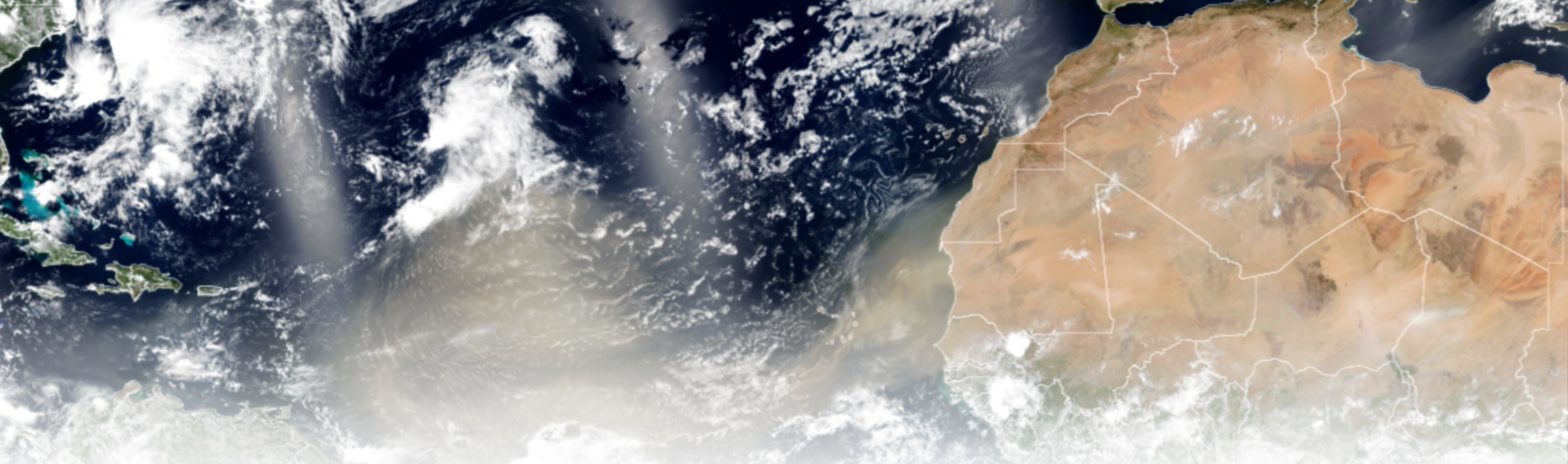
Some limitations of passive satellite aerosol observations:

- Clouds, snow and ice
  - some parameters can be obtained if aerosols above
- Sunglint over ocean
- Lack of solar light during winter time



At sunglint sunlight reflects off the surface of the ocean at the same angle that a satellite is viewing the surface.

When aerosols (dust) are above cloud, some Level 2 parameters can be retrieved

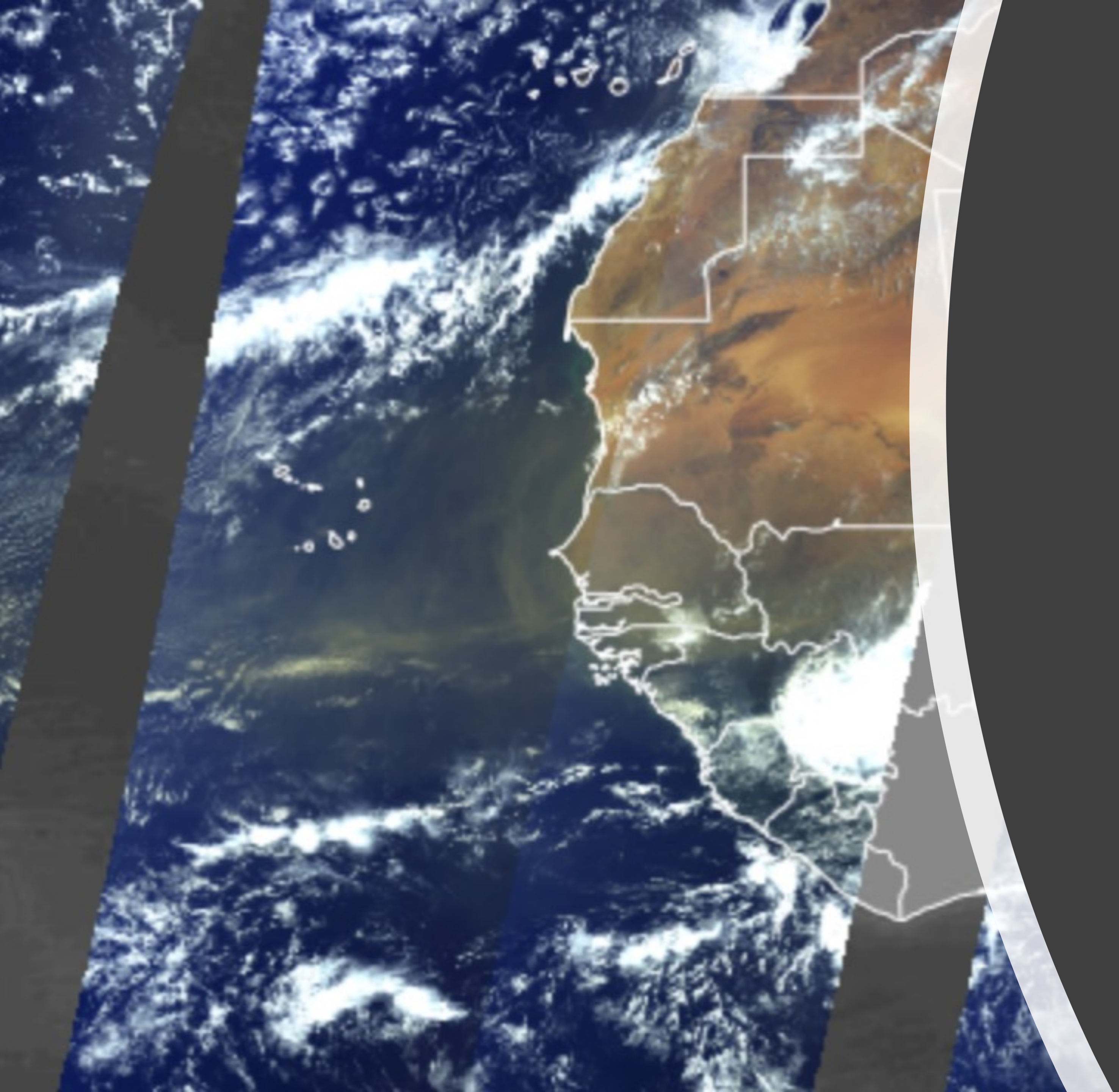


(Passive) satellite observation of dust at UV / VIS

True color RGB
Dust color composites
Dust indexes

Aerosol Optical Depth at VIS

Absorbing Aerosol Index at UV
Absorbing Aerosol Height



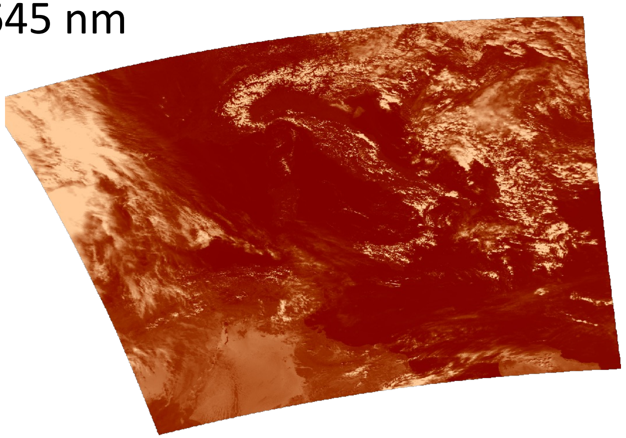
True color RGB images

RGB “True color” images

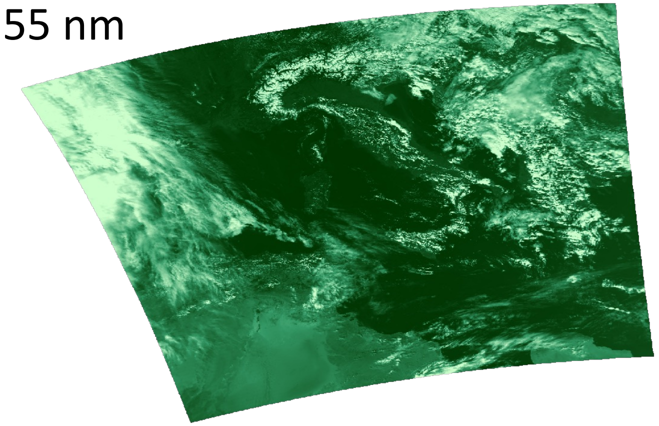
- RGB image composite is a technique to display the color imagery by using the property of the three primary colors of the light.
- RGB image from satellite observations is created from (calibrated) radiances, i.e. Level 1 data.
- To create proper RGB images from satellite data, some enhancement factors etc. might be needed.

Example: MODIS

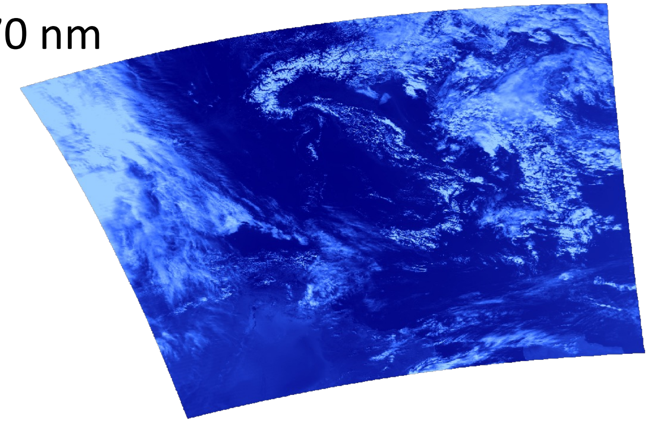
645 nm

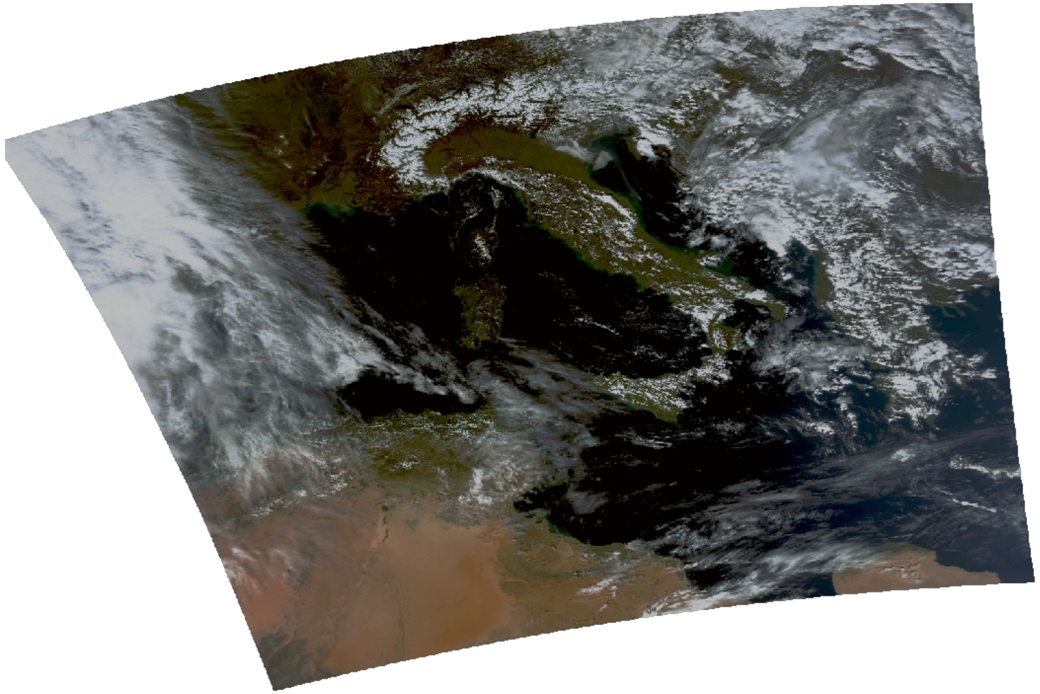


555 nm



470 nm



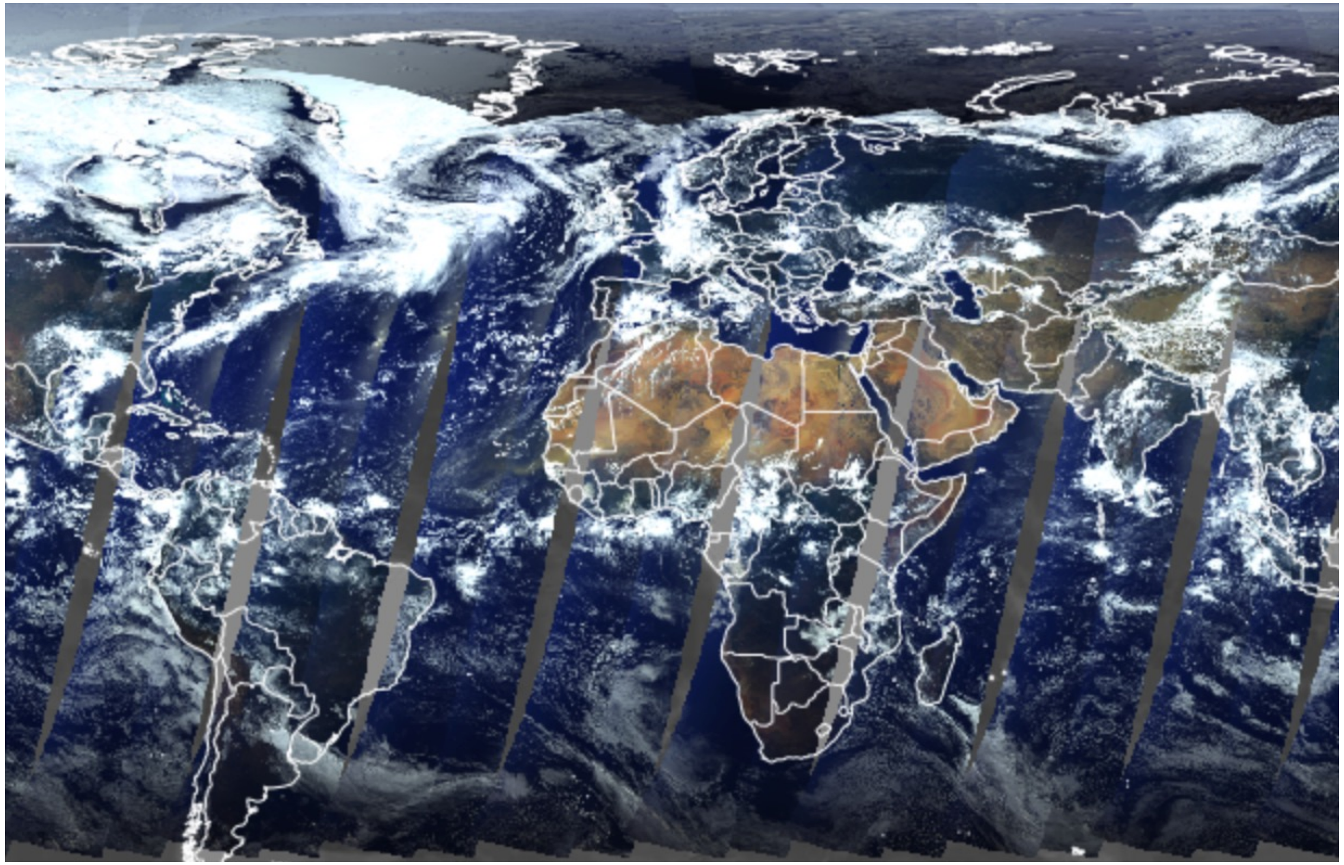


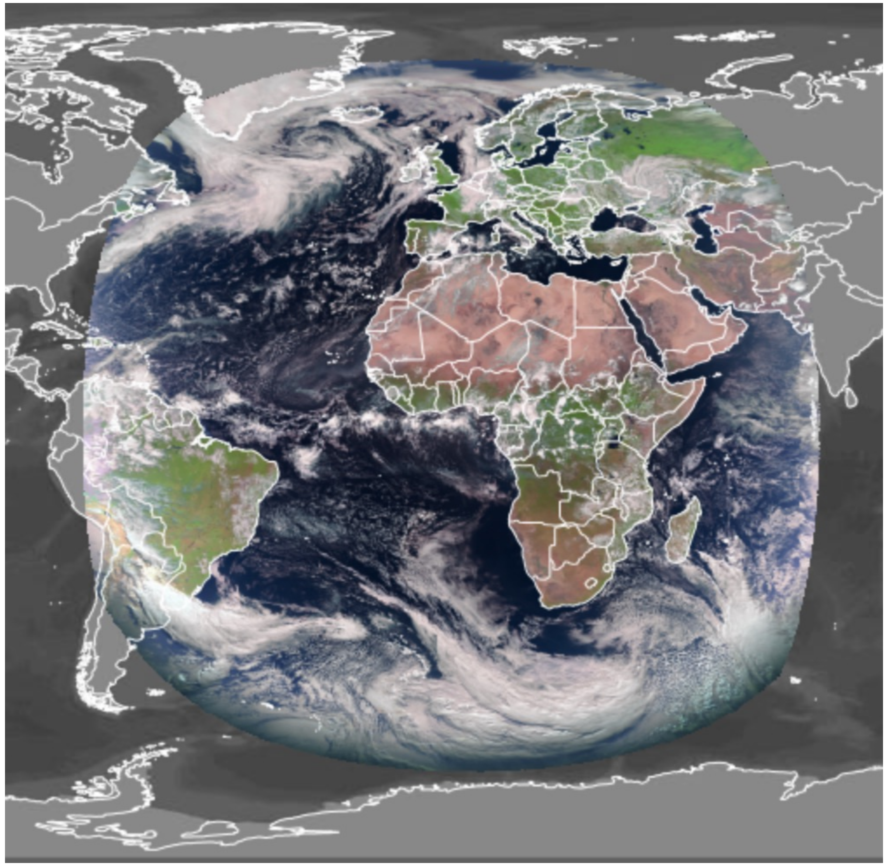
Polar orbiting satellite:
Sentinel-3 OLCI

- Observations about once per day / location at about same local time.
- Global coverage

Geostationary satellite:
MSG Seviri

- Observations every 15 minutes during daytime (true color RGB based on solar channels)
- Covers only restricted area

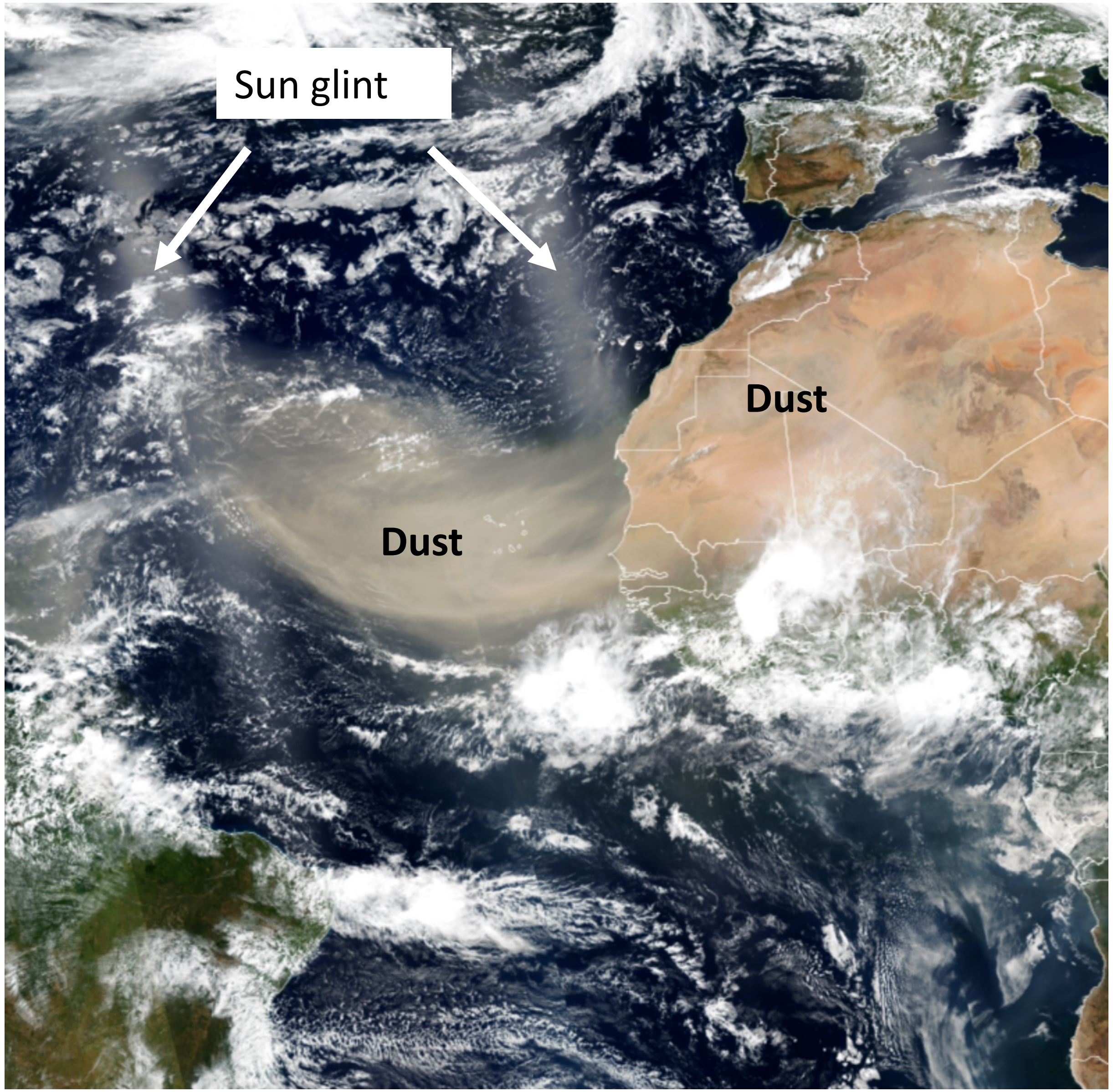


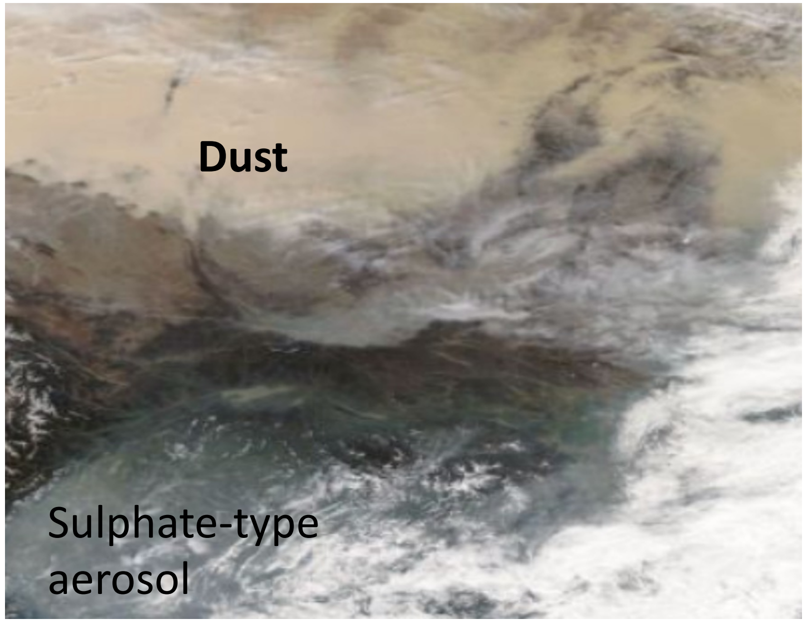


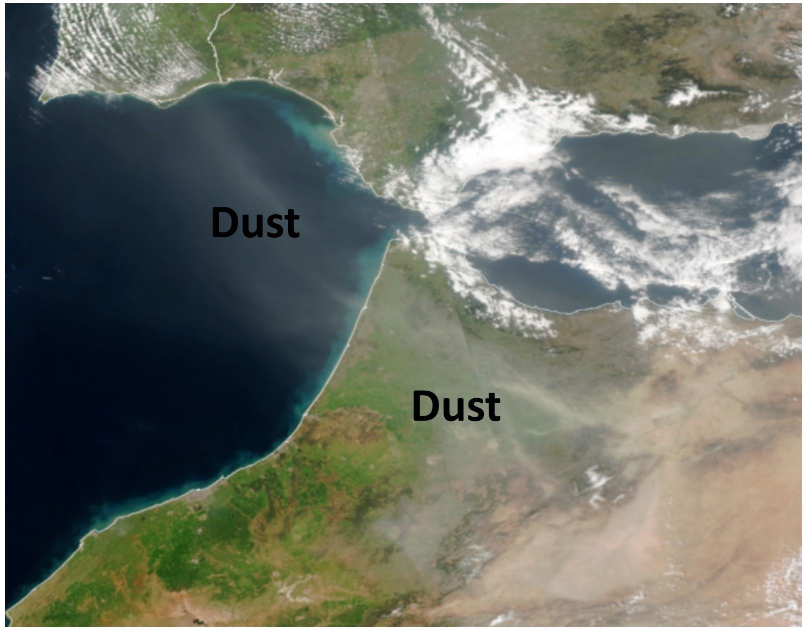
Dust in RGB images

Polar orbiting satellites

Observation time always at about same local time (sun synchronous)





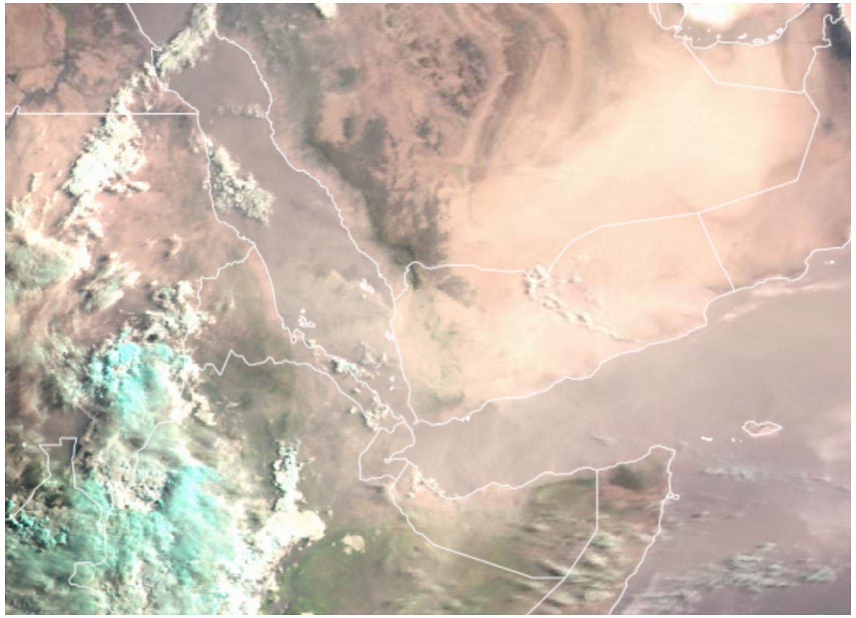


Dust in RGB images
Geostationary satellite

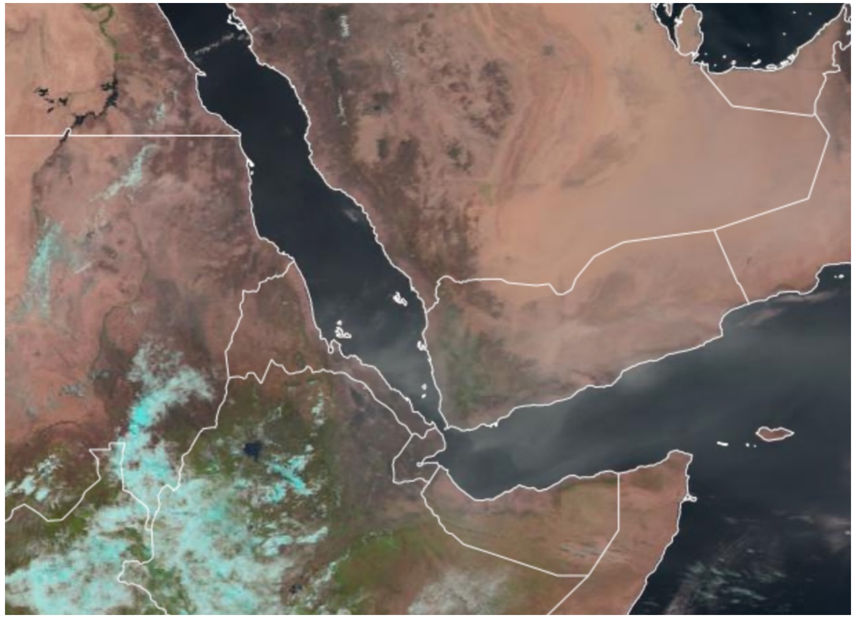
Example: MSG Seviri RGB True color product

Observation time changes -> solar angle change

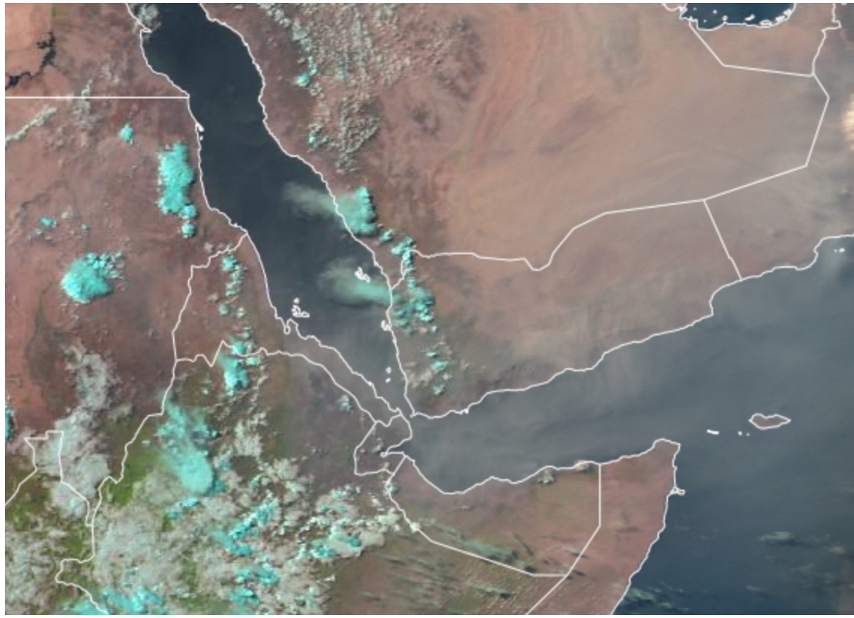
"Early morning"

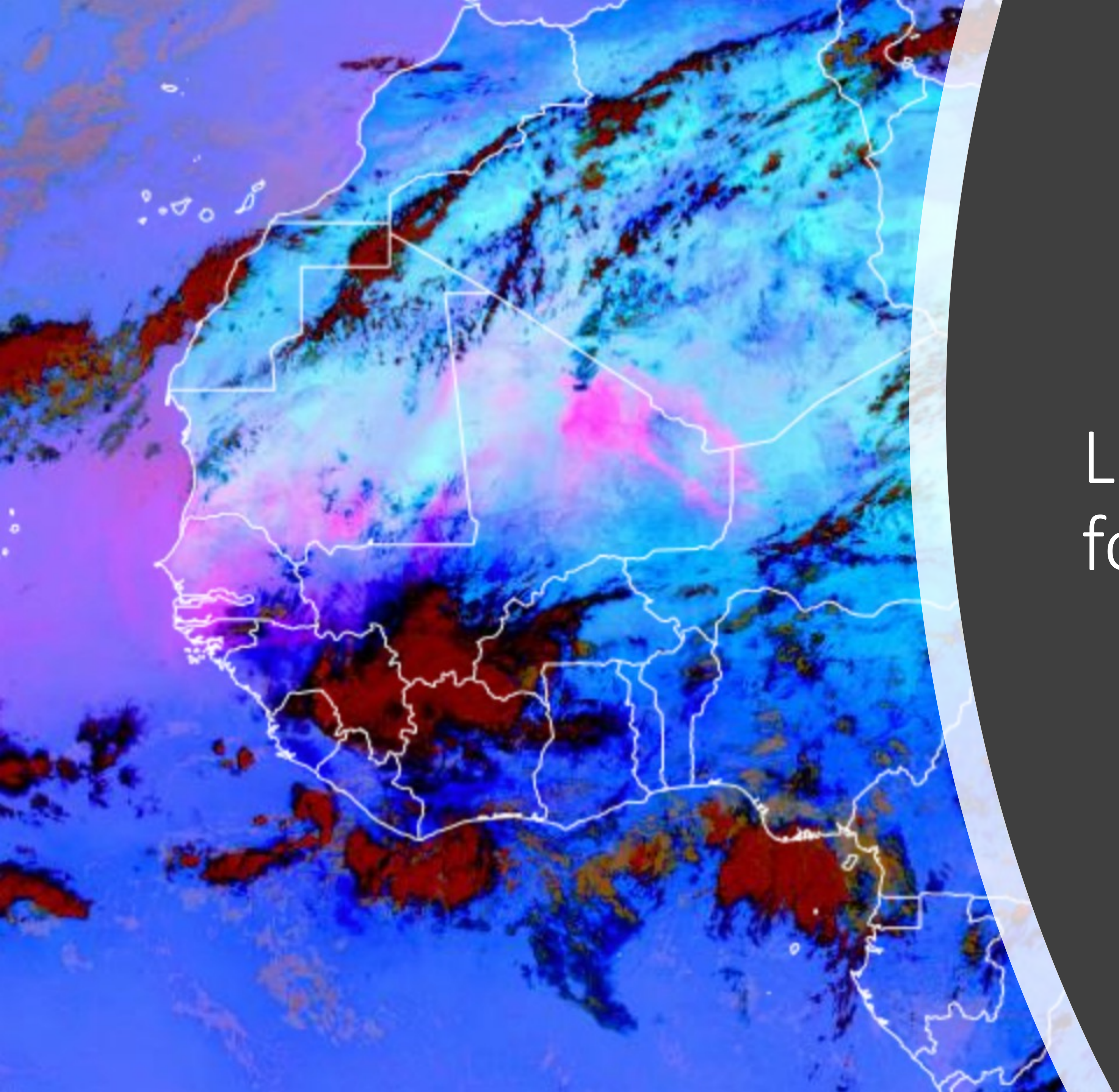


"Close to noon"



"Late afternoon"

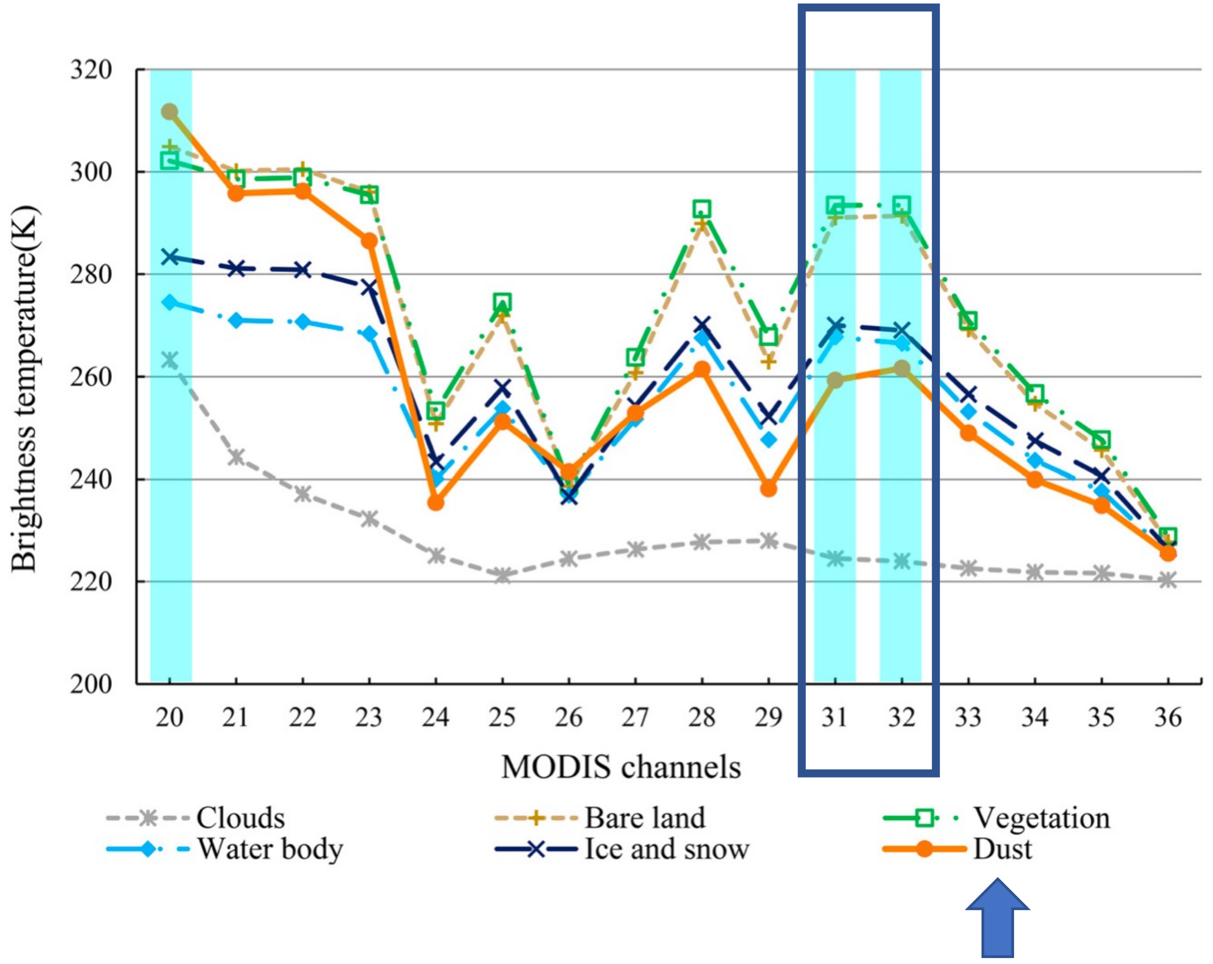




Level 1 RGB composites for dust monitoring

Dust composites using thermal channels

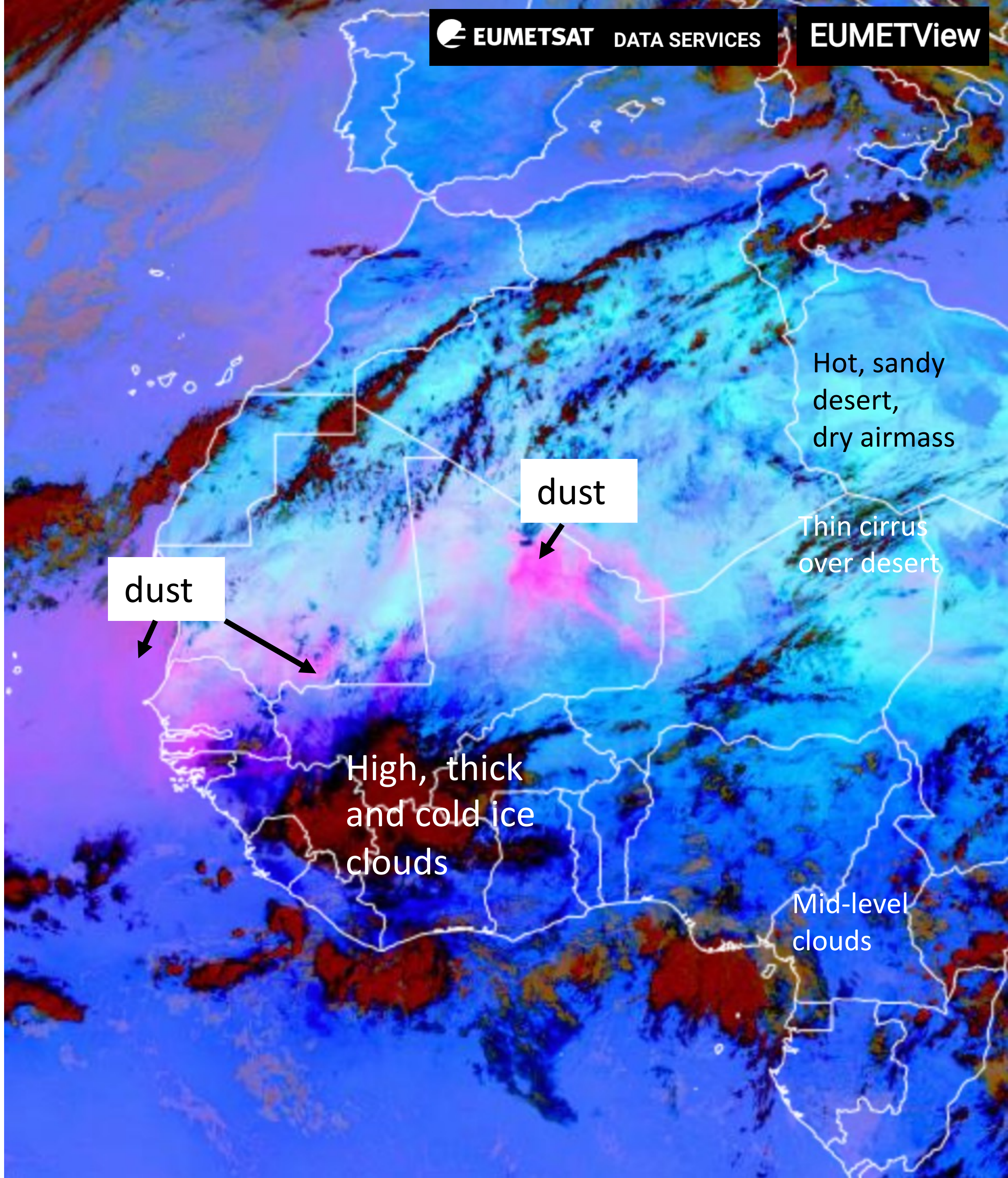
- Based on spectral characteristics of dust in thermal channels
- Typically these indexes are obtained by very simple “band calculations”



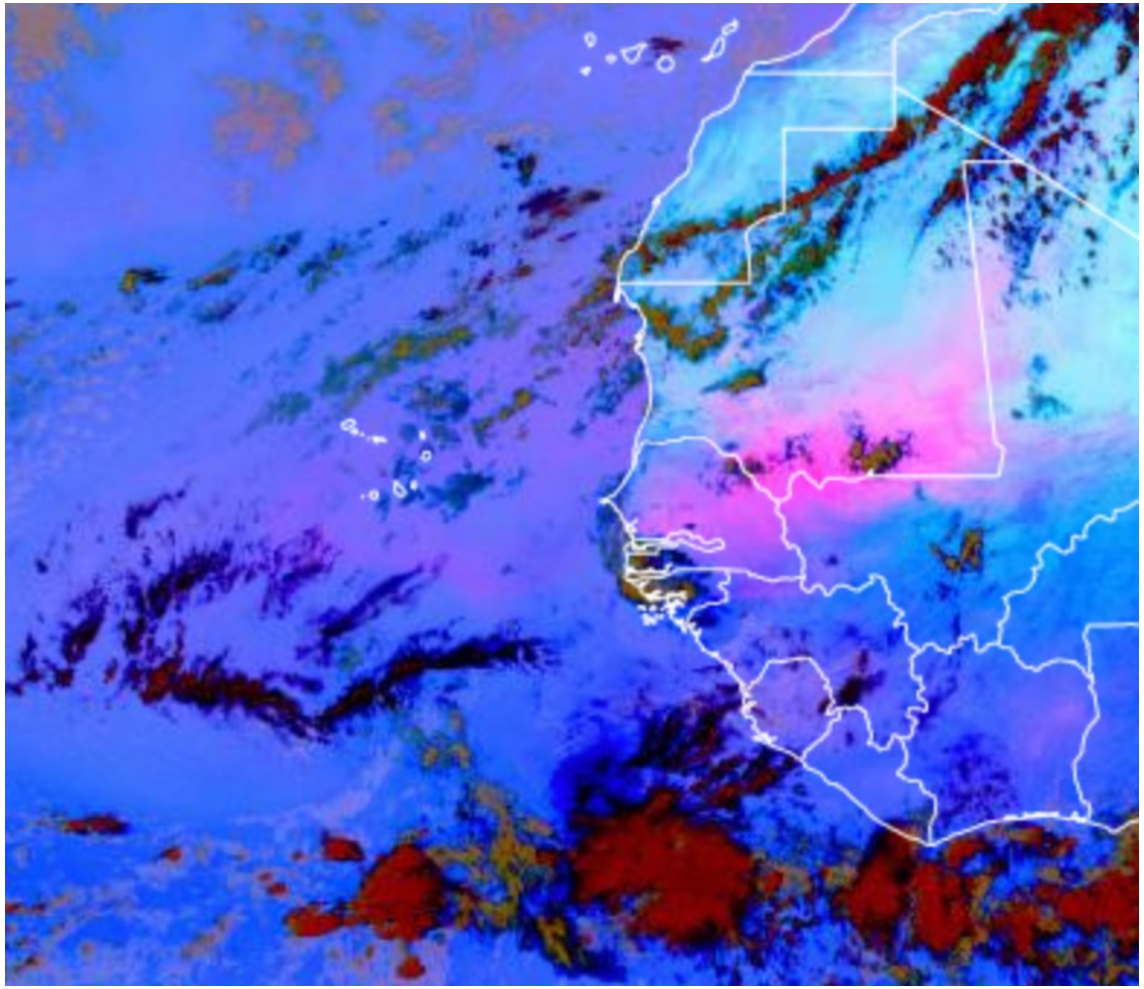
From Yue et al. *Int. J. Appl. Earth Obs. Geoinf, 57,* 166–176, 2017

MSG Seviri Dust RGB composite product

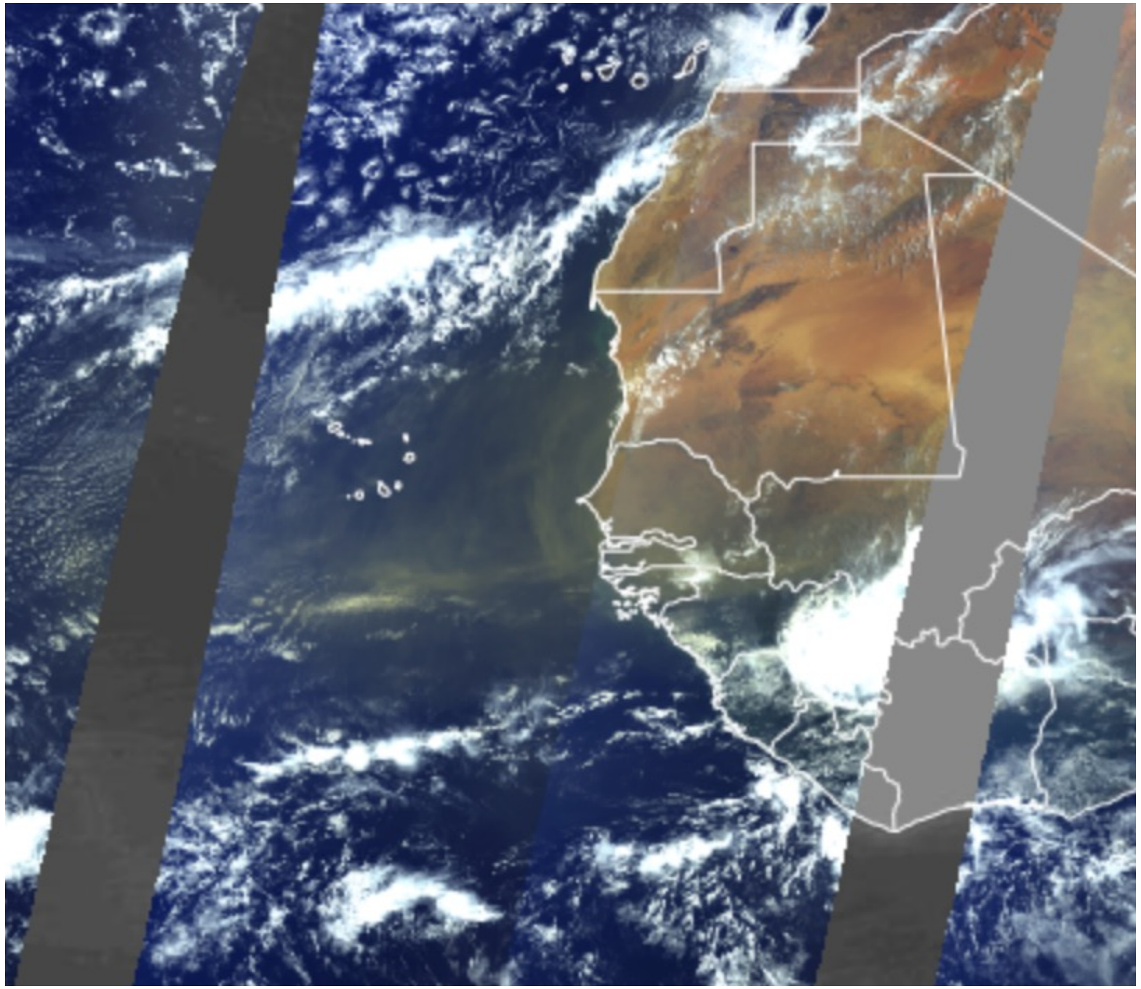
- Based on combining measurements from three different ***infrared*** channels:
  - Red: IR12 – IR10.8
  - Green: IR10.8-IR8.7
  - Blue: IR10.8
- Benefits:
  - Available night and day at 15 min temporal resolution near real time
  - Easy and quick to use in EUMETSAT online services
  - Additional info on cirrus clouds or dry/humid air masses
- Limitations:
  - Dust RGB doesn’t indicate the concentration or height of the dust plume
  - Color shades can vary, interpretation not always straightforward
  - Thin or low level dust over ocean difficult to detect
  - For more detailed analysis with dust RGB recommended to use other satellite products
- Interpretation (roughly):
  - **Pink/violet :** Dust
  - **Orange/brown**: thick high/mid-level clouds
  - **Black**/ **dark green**: thin cirrus

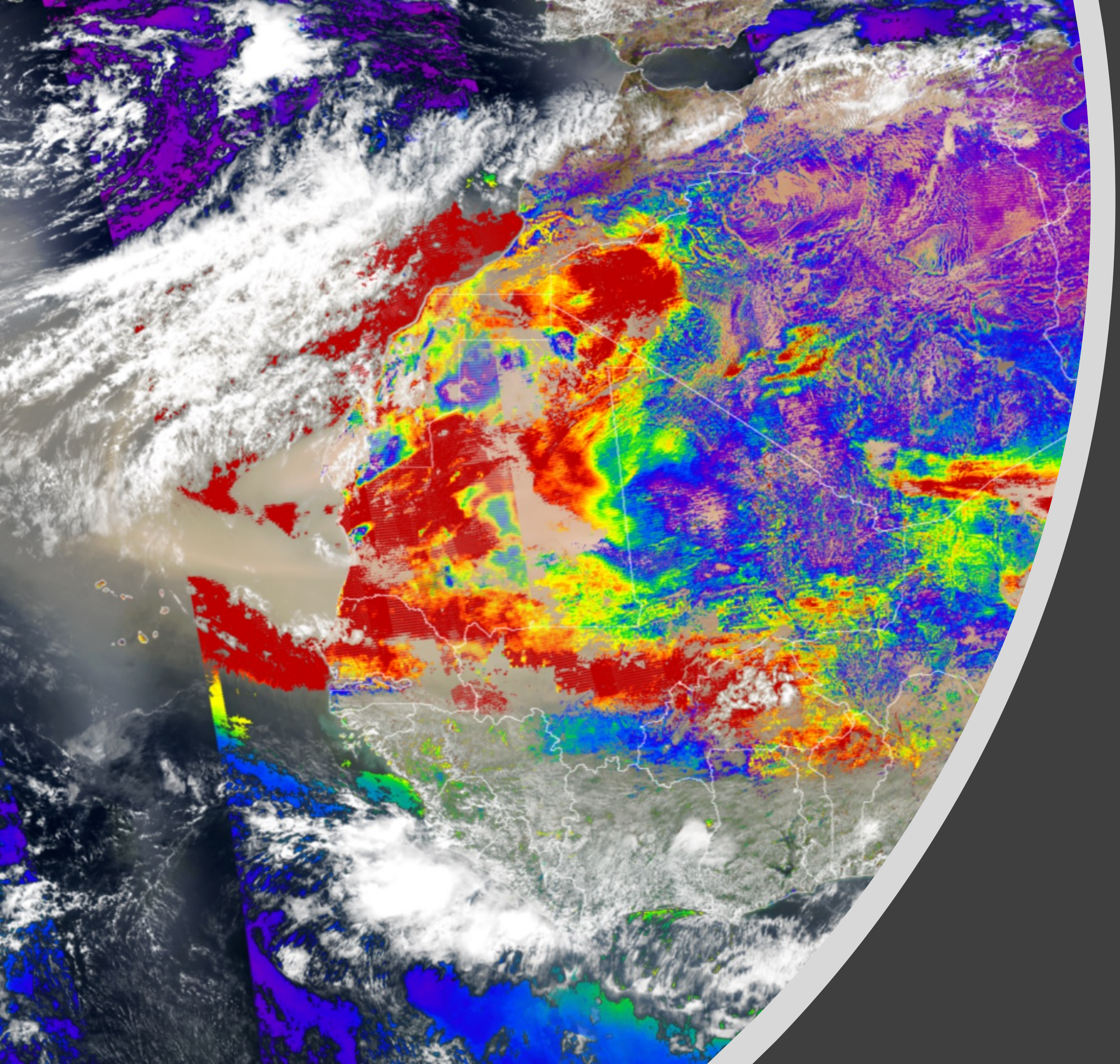


MSG Dust RGB 5.6.2021 (12 UTC)



Sentinel-3 OLCI RGB 5.6.2021

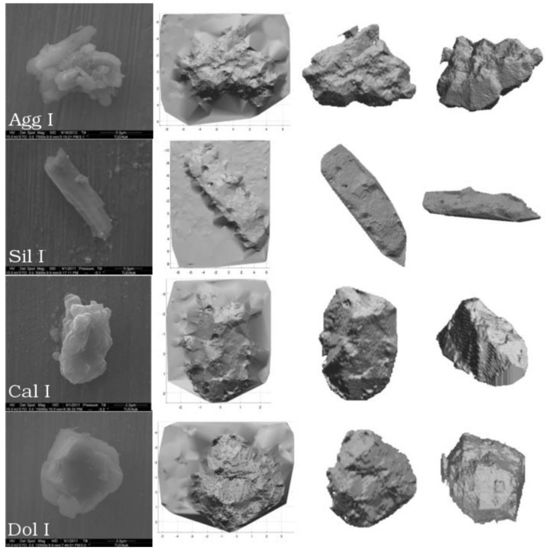




Aerosol Optical Depth

Aerosol optical properties

- The way how incident radiation interacts with aerosol particles depends on
  - wavelength of the radiation
  - aerosol size
  - aersol shape
  - aerosol chemical composition, defined by the complex refractive index m=n+ik
- Extinction = scattering + absorption



(Lindqvist et al., 2014)

Scattering cross section	Absorption cross section	Single scattering albedo

$$C_{sca}$$

- Hypothetical area that is needed to collect the scattered amount of power from the incident radiation

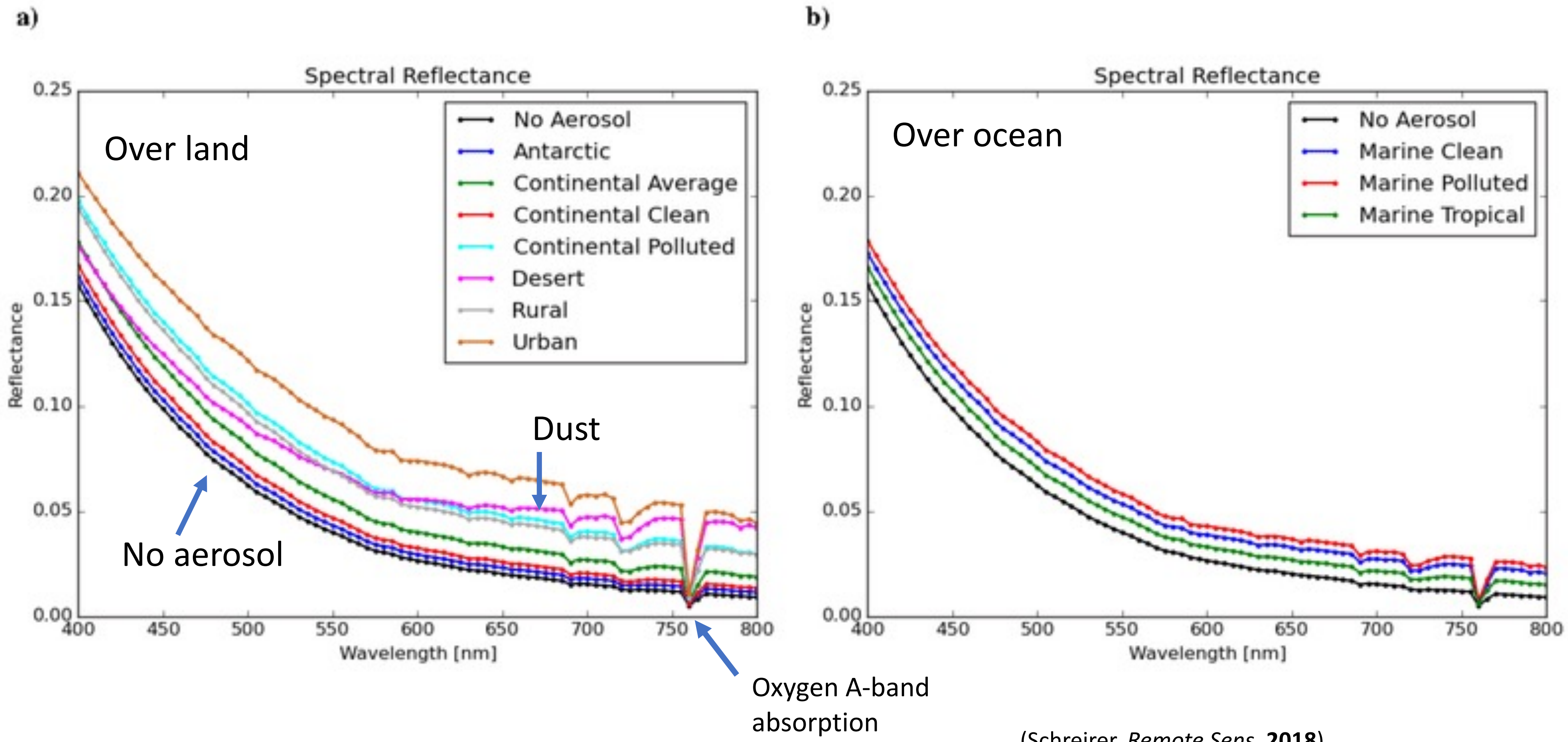
$$C_{abs}$$

Hypothetical area that is needed to collect the absorbed amount of power from the incident radiation

$$SSA = \frac{C_{sca}}{(C_{sca} + C_{abs})}$$

(Extinction cross section $C_{ext} = C_{sca} + C_{abs}$)

How aerosols affect radiation at VIS?



(Schreirer, *Remote Sens.* **2018**)

- Typical charachteristic of dust: relatively high affect also at longer wavelengths

Aerosol optical depth (AOD)

- Also known as aerosol optical thickness (AOT)
- AOD is *related to the amount* of (optically active) aerosols in the total atmospheric column.
- Retrieved from satellite- and ground-based remote sensing instruments
- Extinction coefficient:

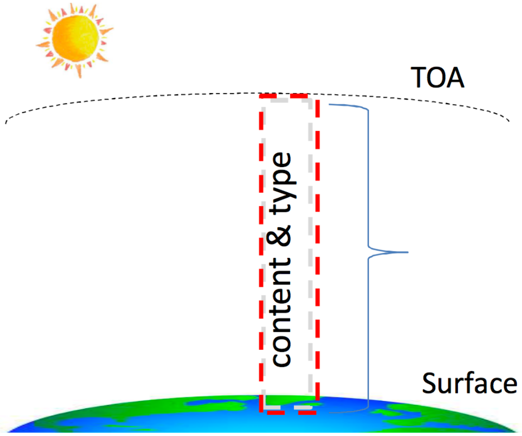
$$\beta_e = \beta_a + \beta_s$$ units of inverse length [m^{-1}]

$$\beta_e = \int C_{ext}(D_p) N(D_p)\, dD_p$$

Extinction cross section

Particle number concentration

AOD [unitless]



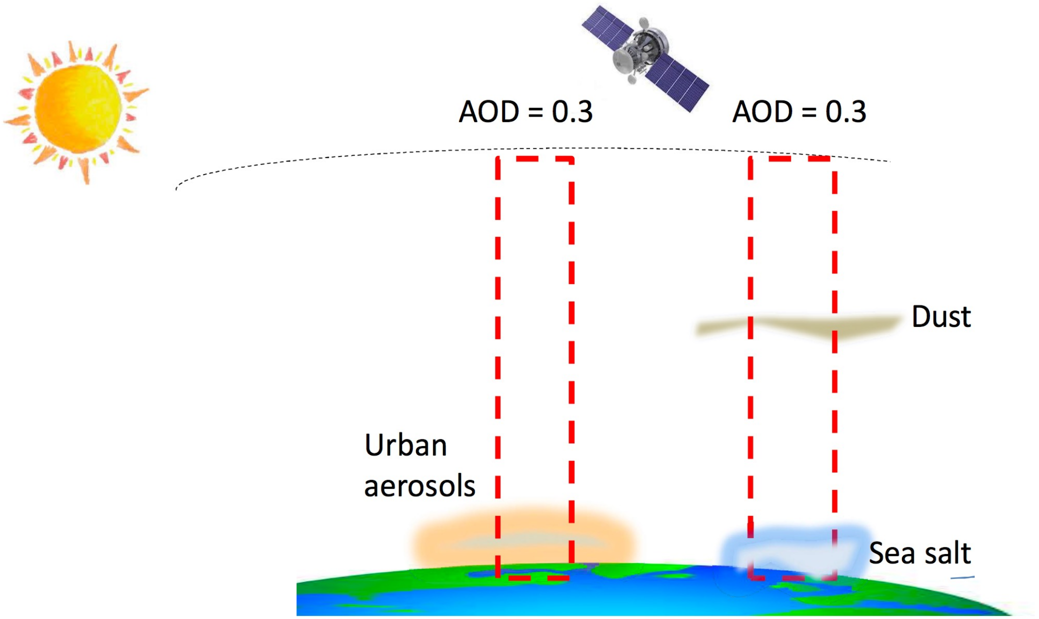
AOD is defined as the sum of aerosol extinction at all atmospheric levels, from surface up to the top of the atmosphere

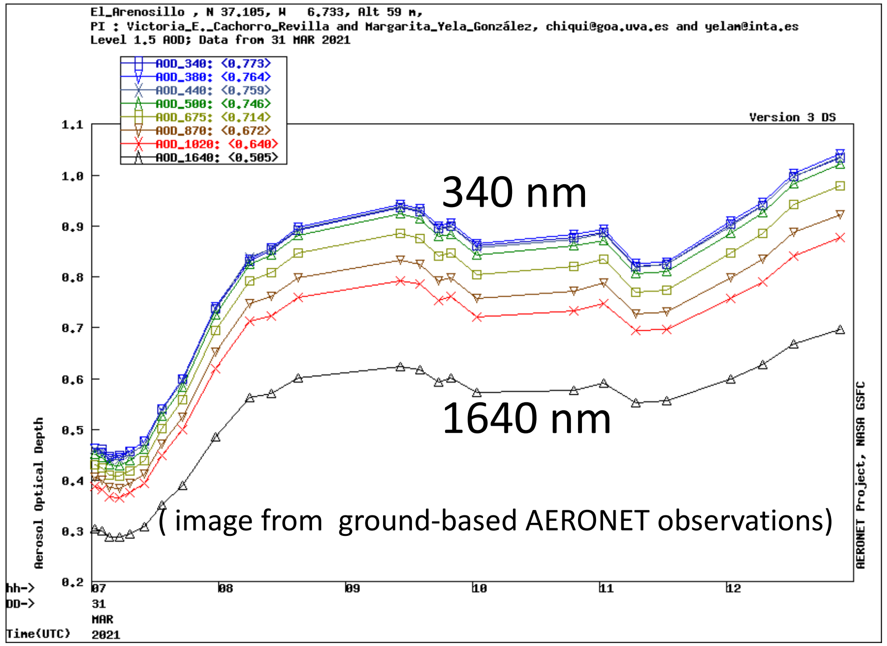
$$AOD = \int_{surf}^{TOA} \beta_e(s)\, ds$$

- AOD is **wavelength dependent**, often satellite products provide AOD at 550 nm

- AOD doesn’t tell aerosol type, but with spectral information on AOD some rough estimations about aerosol type can be made
    - Typical for dust cases is elevated AOD at longer wavelengths

- AOD from passive satellite instruments doesn’t indicate what is the vertical distribution of aerosols
    - “same” AOD can be obtained for very different cases





Basic concept of AOD retrievals

$$\rho_\lambda^{\mathrm{TOA}}(\tau,\theta_0,\theta,\varphi) = \rho_\lambda^{a}(\tau,\theta_0,\theta,\varphi) + \frac{T_\lambda(\tau,\theta_0)\,T_\lambda(\tau,\theta)\rho_\lambda^{s}}{1 - s_\lambda(\tau)\rho_\lambda^{s}}$$

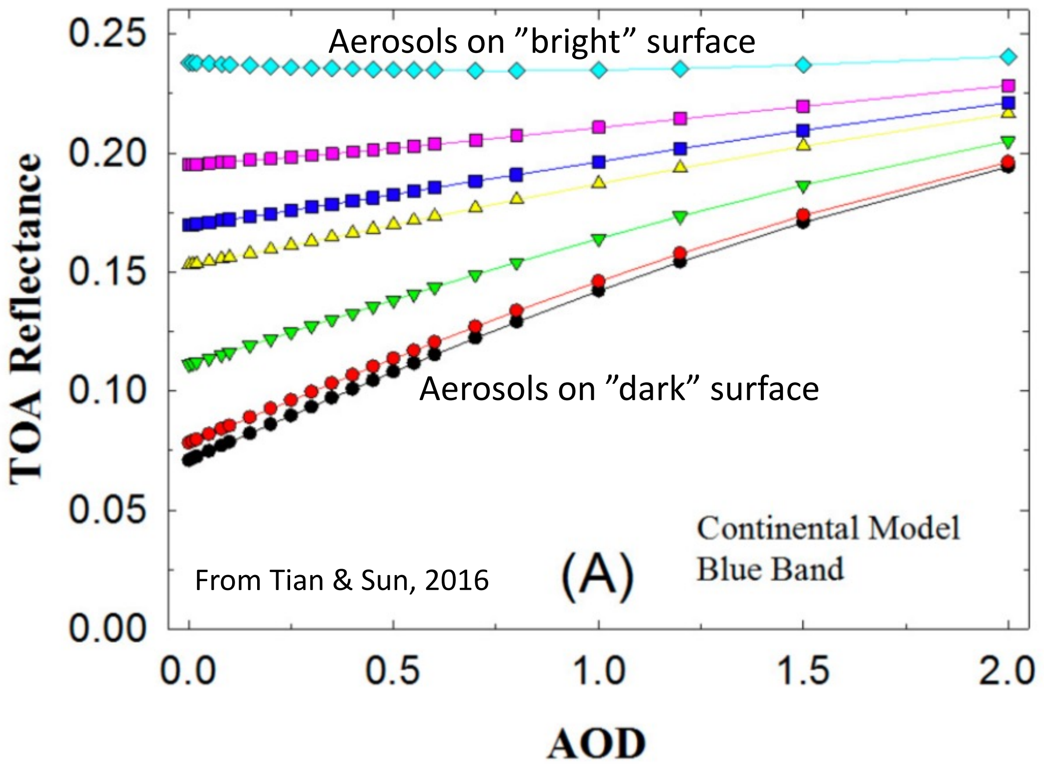
Reflectance at TOA measured by satellite

Atmospheric path reflectance:
- aerosols
- molecules

Surface contribution

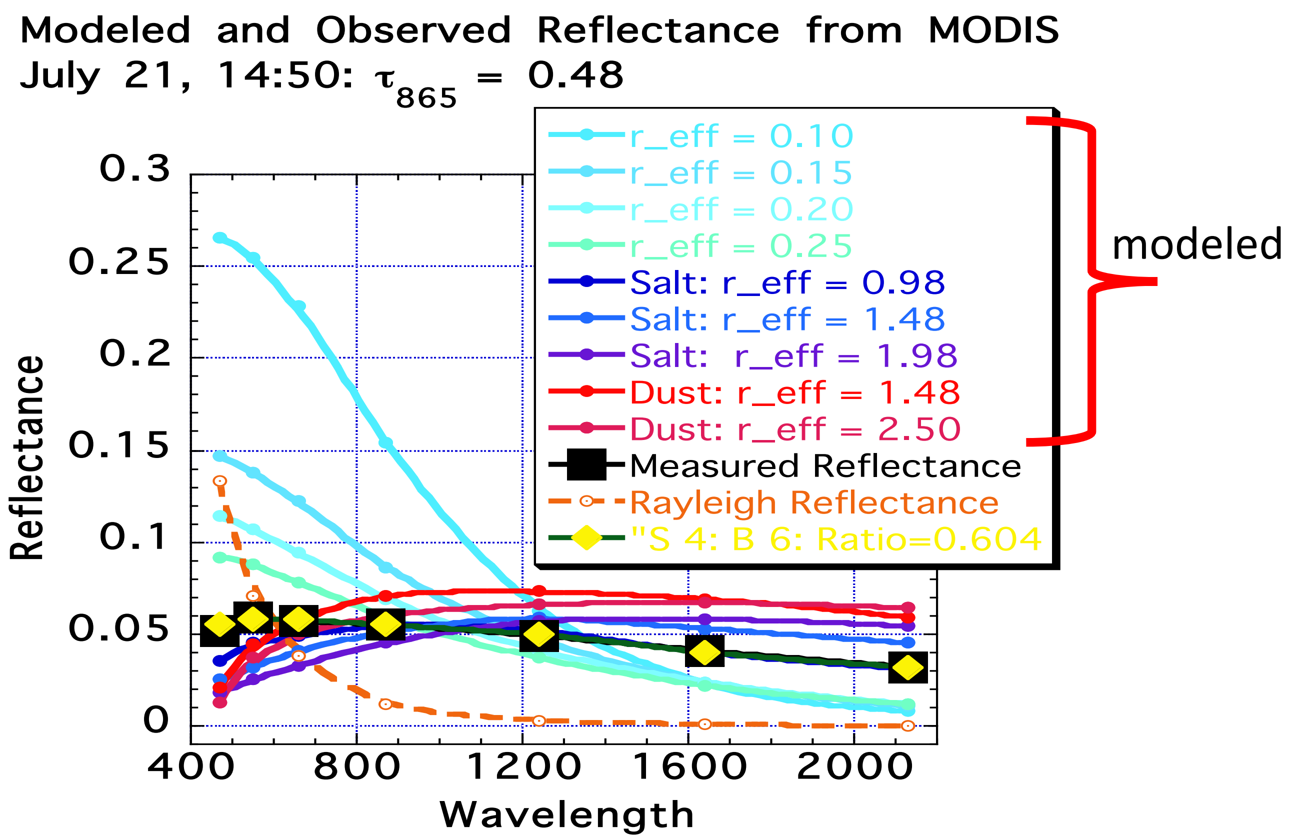
- Aim: to separate the **aerosol contribution** from the measured TOA reflectance:
  - **Cloudscreening -> very important step in the retrieval**
  - Surface contribution (can be also retrieved simultaneously with aerosols)
  - Rayleigh correction

Aerosols + surface



Basic concept of AOD retrievals

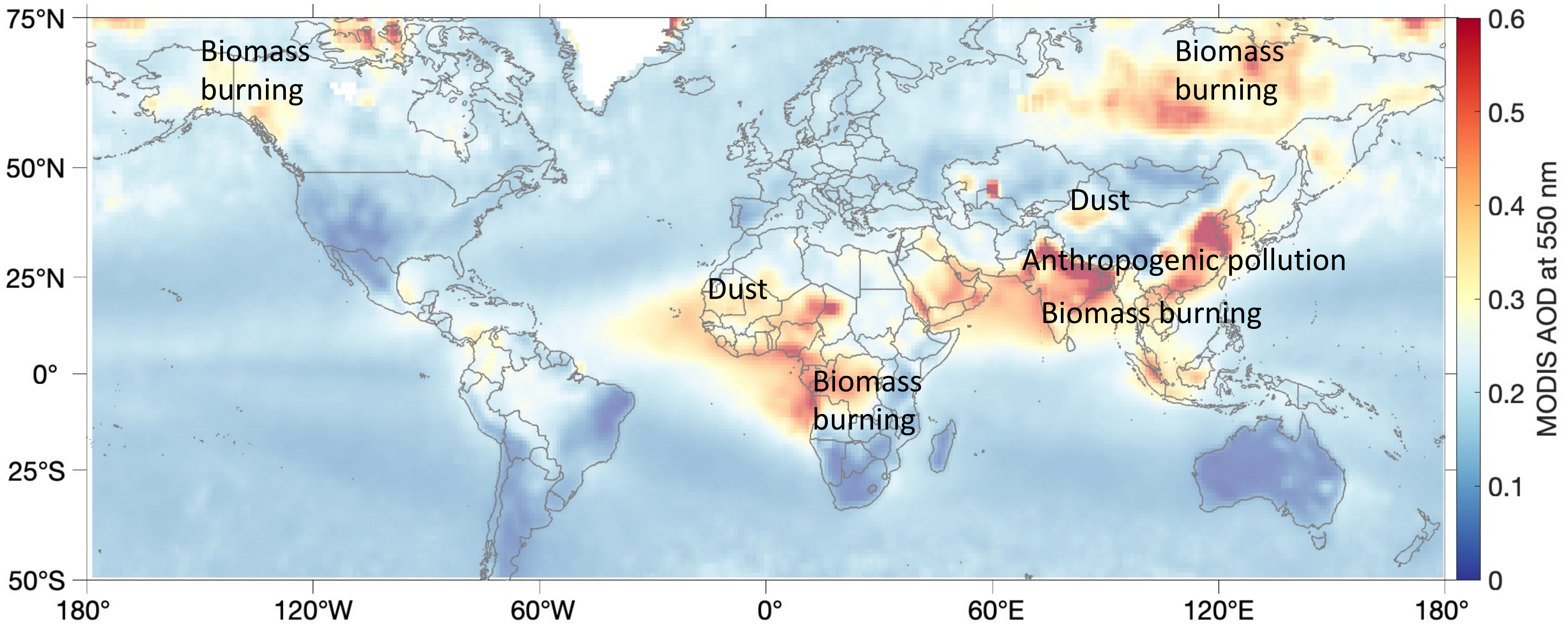
- Two typical components of a retrieval:
  - (Pre-computed) radiative transfer **model** calculations of **TOA reflectance** for various aerosol scenarios
  - Measured **TOA reflectance from the satellite**
- For cloud free pixels: select the "aerosol scenario" that minimises the difference between modeled and measured TOA reflectances
  → AOD at selected wavelengths



(Levy, 2007)

Satellite AOD is available from several instruments (and wavelengths), e.g.:

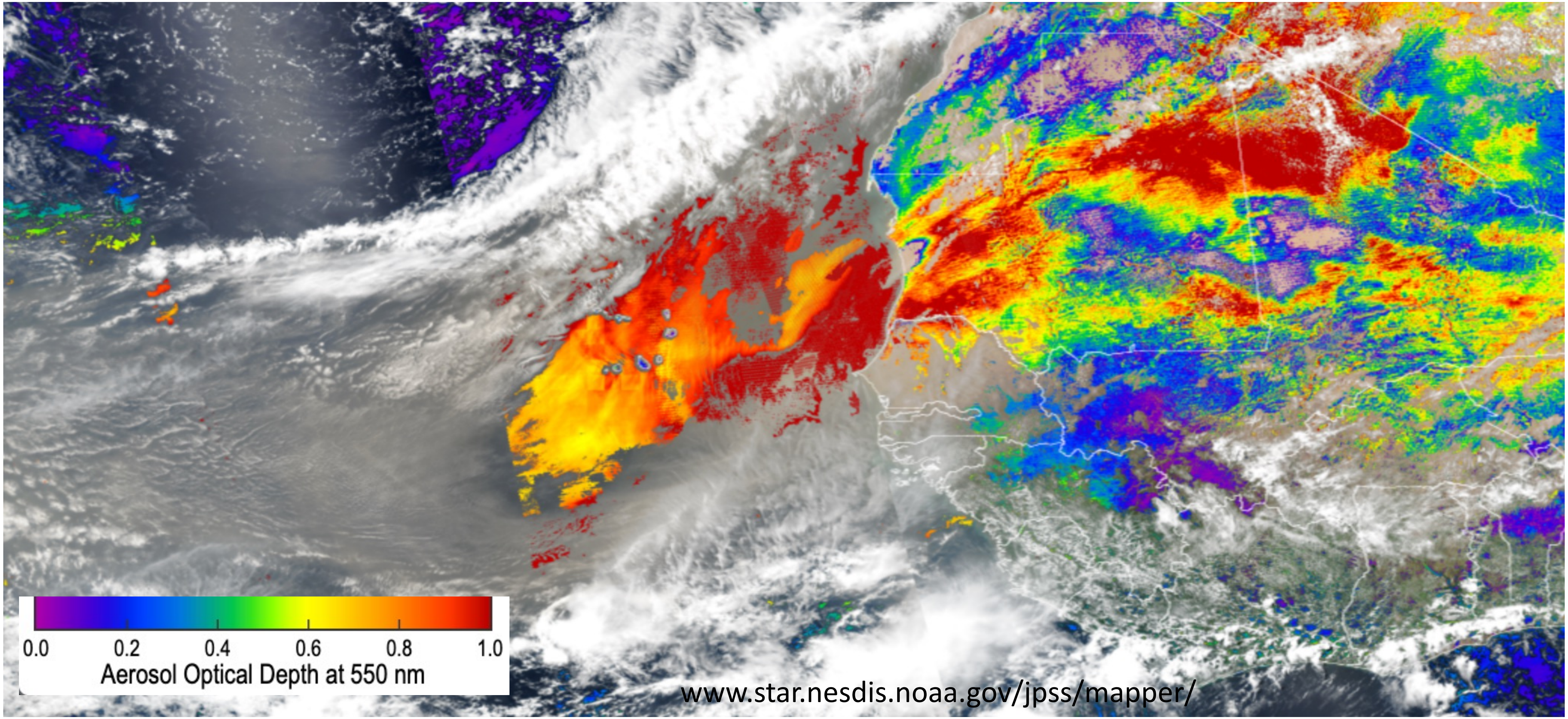
- OLCI, SLSTR (Sentinel 3), AATSR (Envisat, until 2012)
- E.g. MODIS (Aqua, Terra), MISR (Terra), VIIRS (Suomi NPP, NOAA 20), SeaWIFS,
- Multi-instrument products such as PMAp (combining information from GOME-2, AVHRR, IASI)



MODIS Terra 2019 / Deep Blue Algorithm

AOD at 550 from VIIRS instrument 7.6.2021

- AOD is not retrieved for cloudy pixels
  - thickest parts of dust plumes can be interpreted as clouds -> AOD is not provided
- AOD is not provided at sunglint

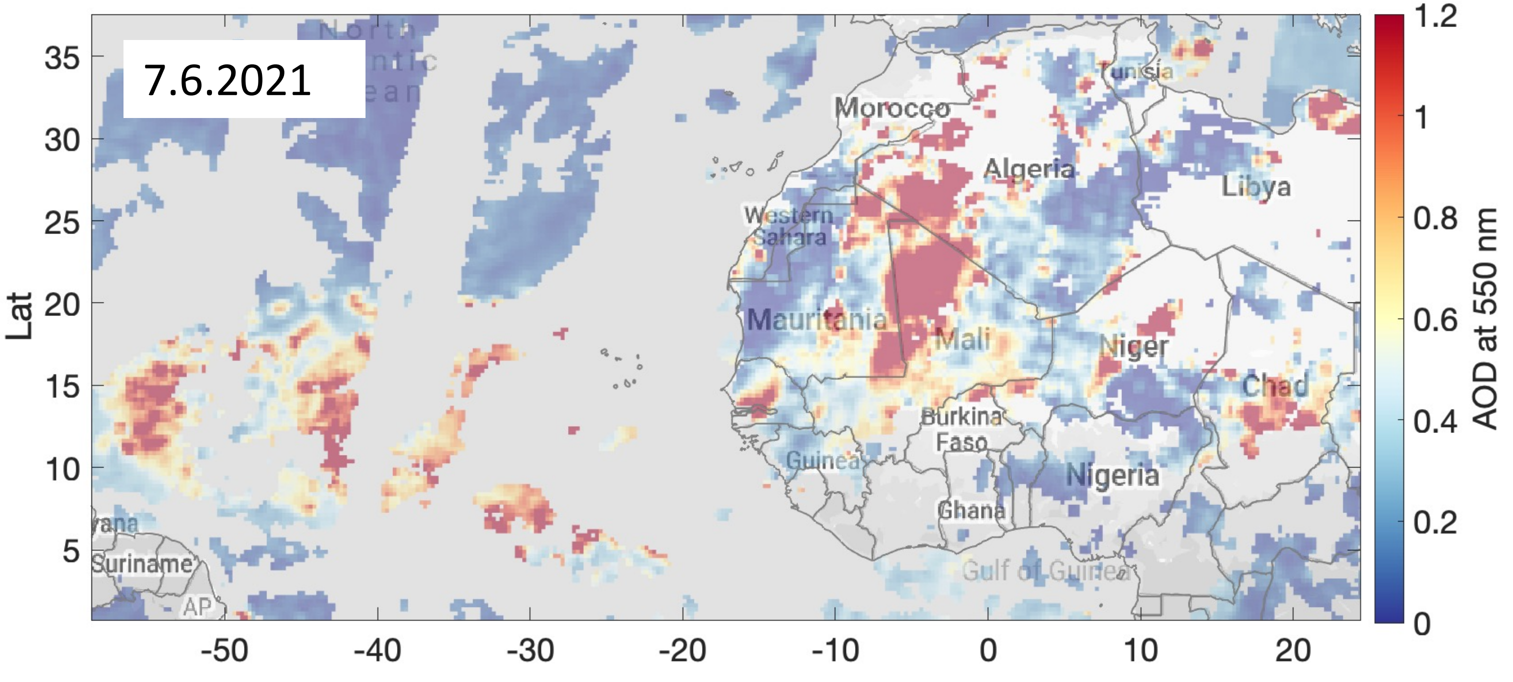


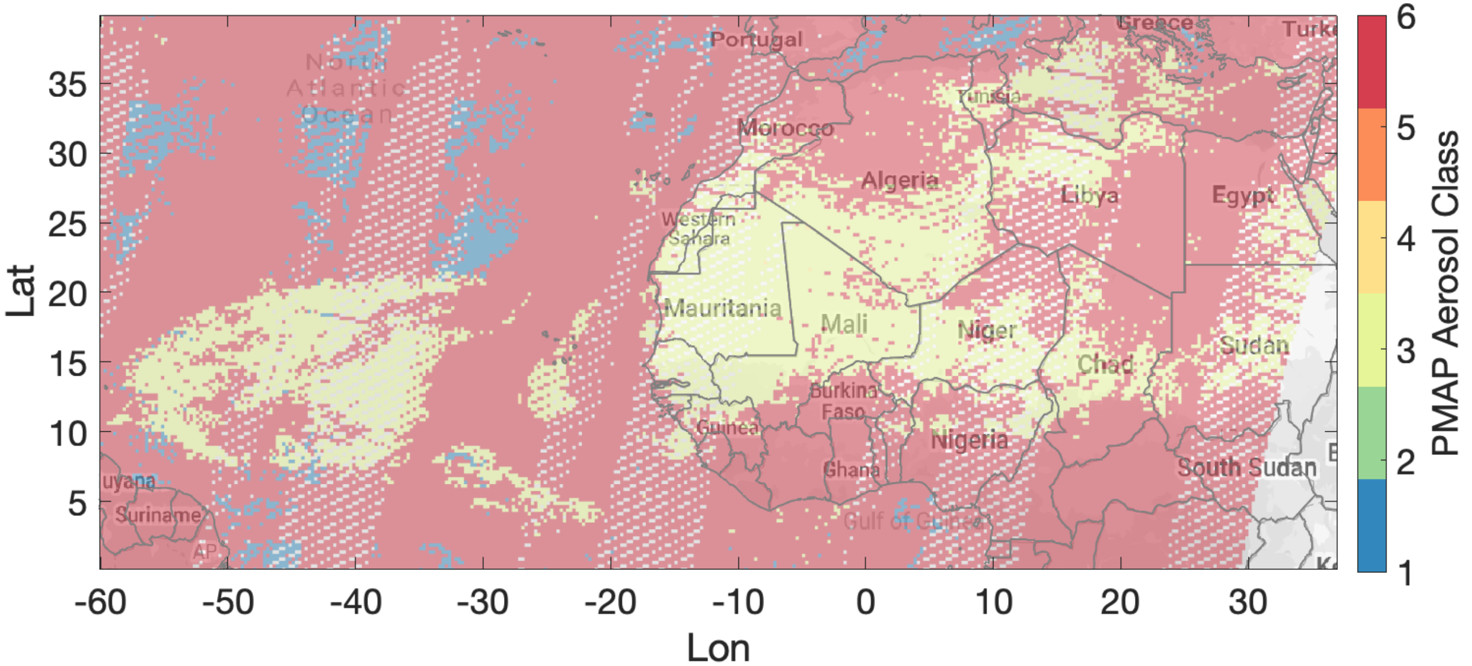
Polar Multi-sensor Aerosol optical properties product (PMAp)

- AOD product by EUMETSAT
  - Operational
  - Climate Data Record
- Uses multi-instrument approach; GOME-2, IASI, AVHRR onboard Metop-A, B, and C satellites
- Provides aerosol classification including dust

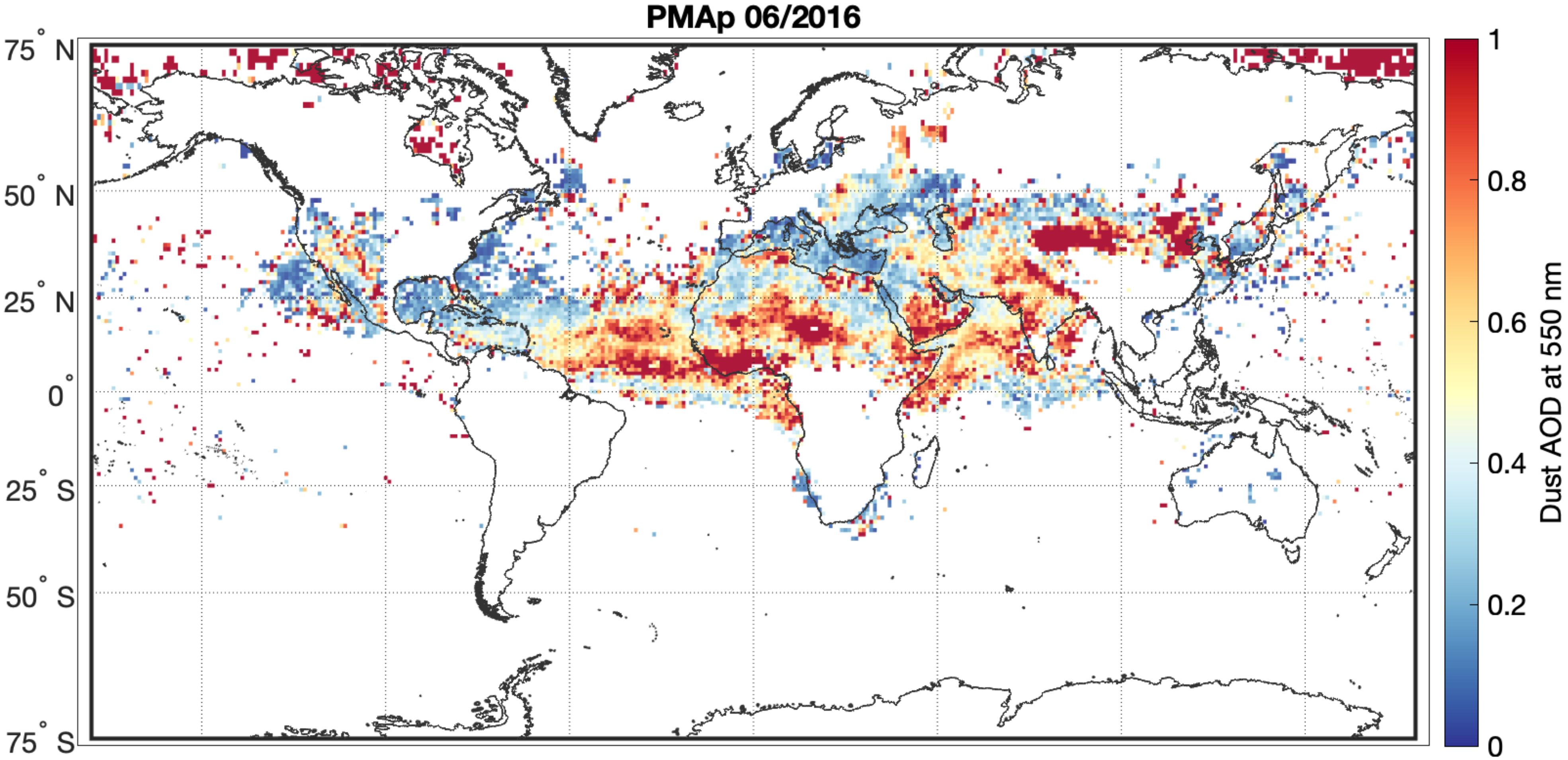
PMAP Aerosol classification

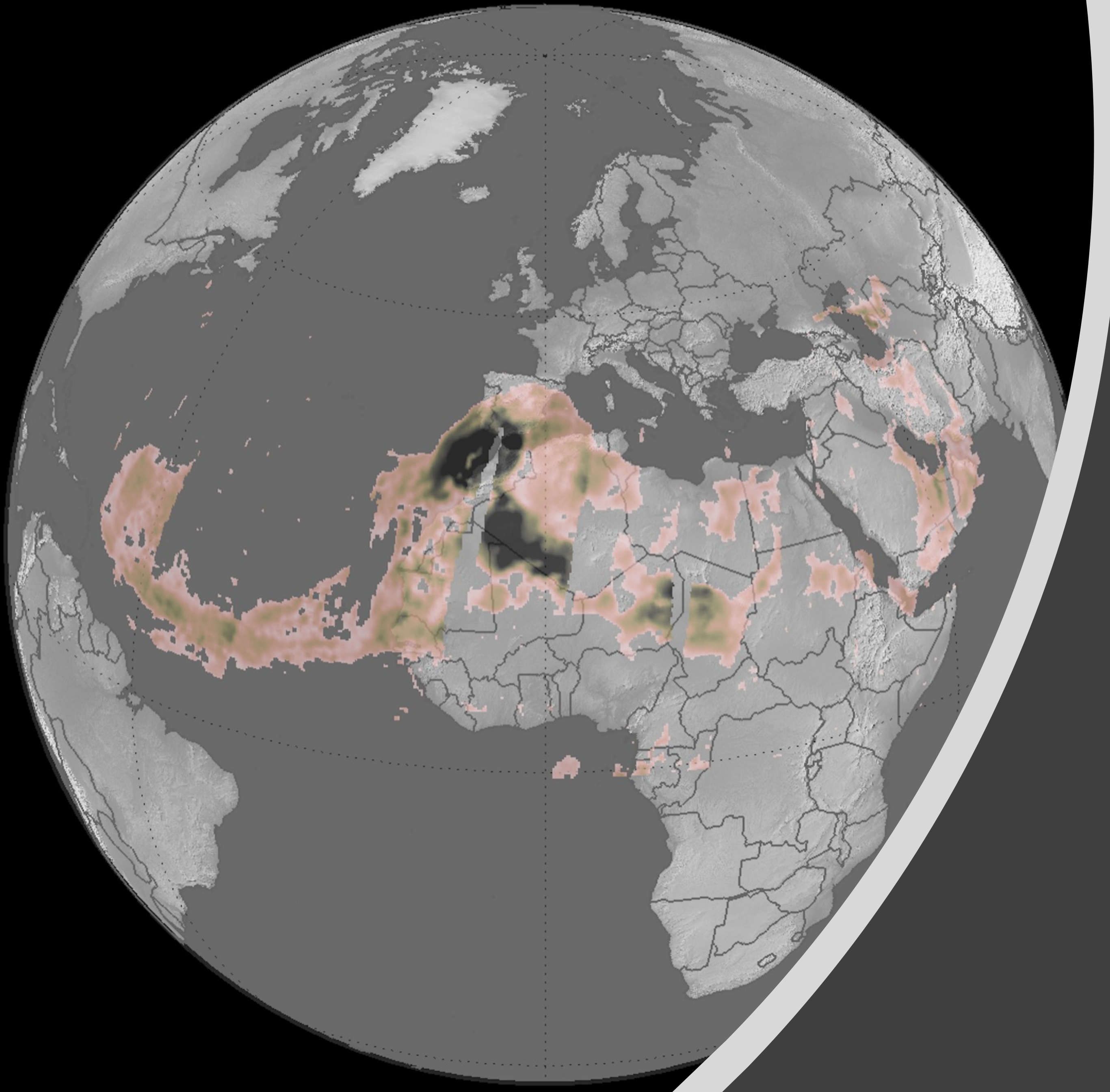
1=Coarse mode (ocean)
3= Dust
6= in this image including PMAP classes 10, 11, 15, aerosol cont. cloud, no class.





Example of PMAp Climate Data Record Dust AOD at 550 nm (Metop-B)





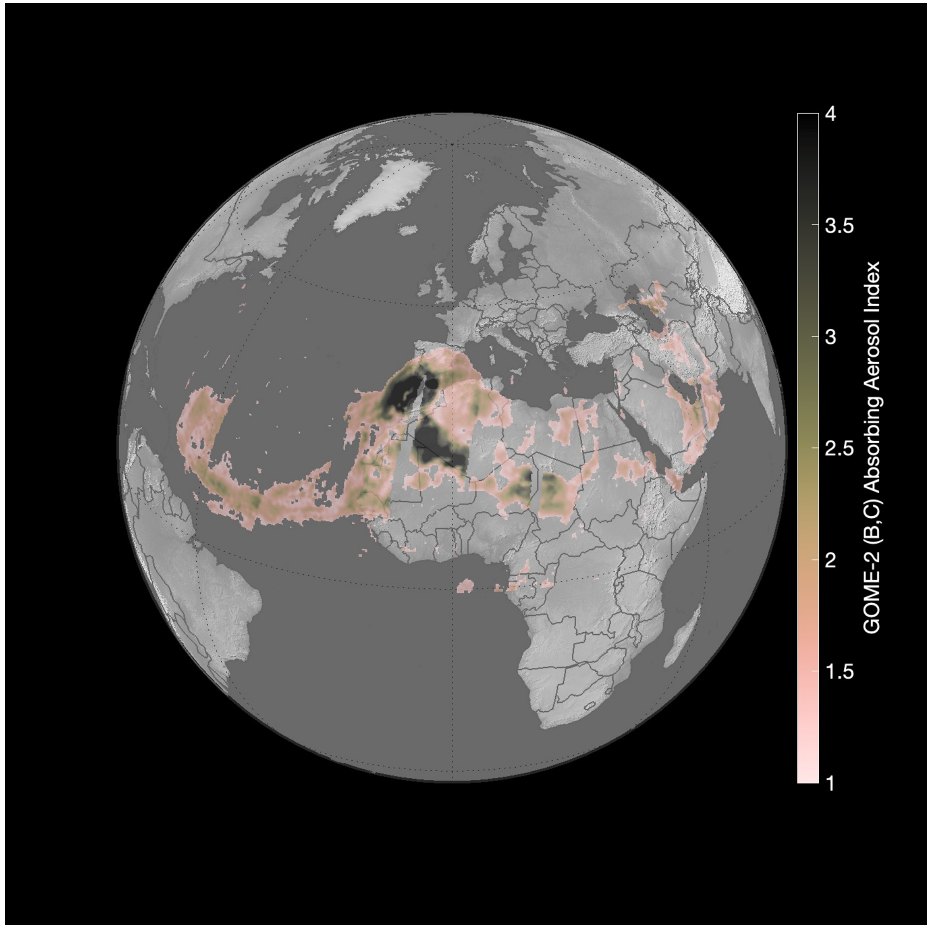
Absorbing Aerosol Index

Absorbing Aerosol Index (AAI)

- AAI, also referred as UVAI or AI is an **index** that indicates the presence of absorbing aerosols (**dust,** smoke, volcanic ash)

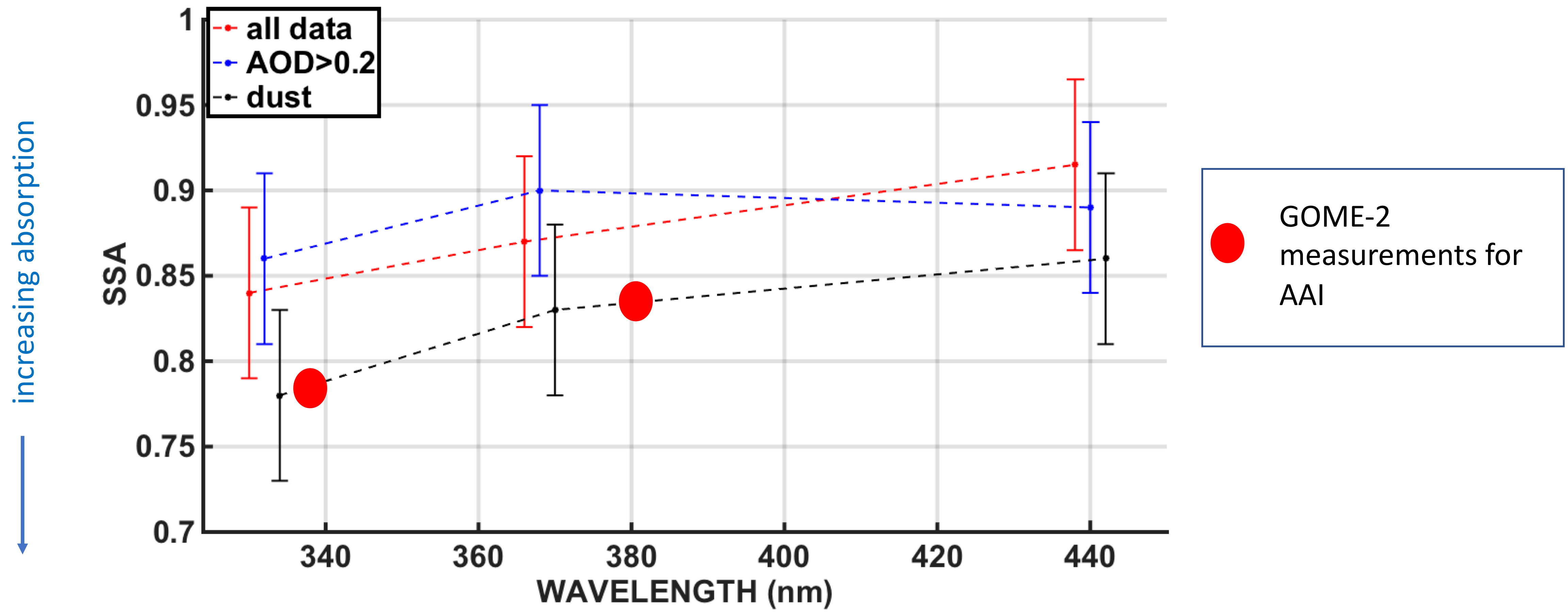
- AAI separates the spectral contrast at two UV wavelengths caused by aerosol extinction from that of other effects (e.g. molec. scattering)

- Can be obtained also for cloudy scenes, where aerosols are on top of clouds.



AAI is a good tracer for dust, smoke and ash plumes

Dust "fingerprint" at UV wavelengths



Mean single scattering albedo measured at Athens for 2009-2014
(Raptis et al., 2018)

Absorbing Aerosol Index

$$AAI = -100 \cdot \left[log_{10}\left(\frac{R_{340}}{R_{380}}\right)^{meas} - log_{10}\left(\frac{R_{340}}{R_{380}}\right)^{sim} \right]$$

Radiance at TOA measured by the satellite
-> Real atmosphere including aerosol contribution

Modeled TOA radiance for aerosol-free atmosphere

- Incl. Rayleigh scattering and absorption, and
- surface reflection and absorption.

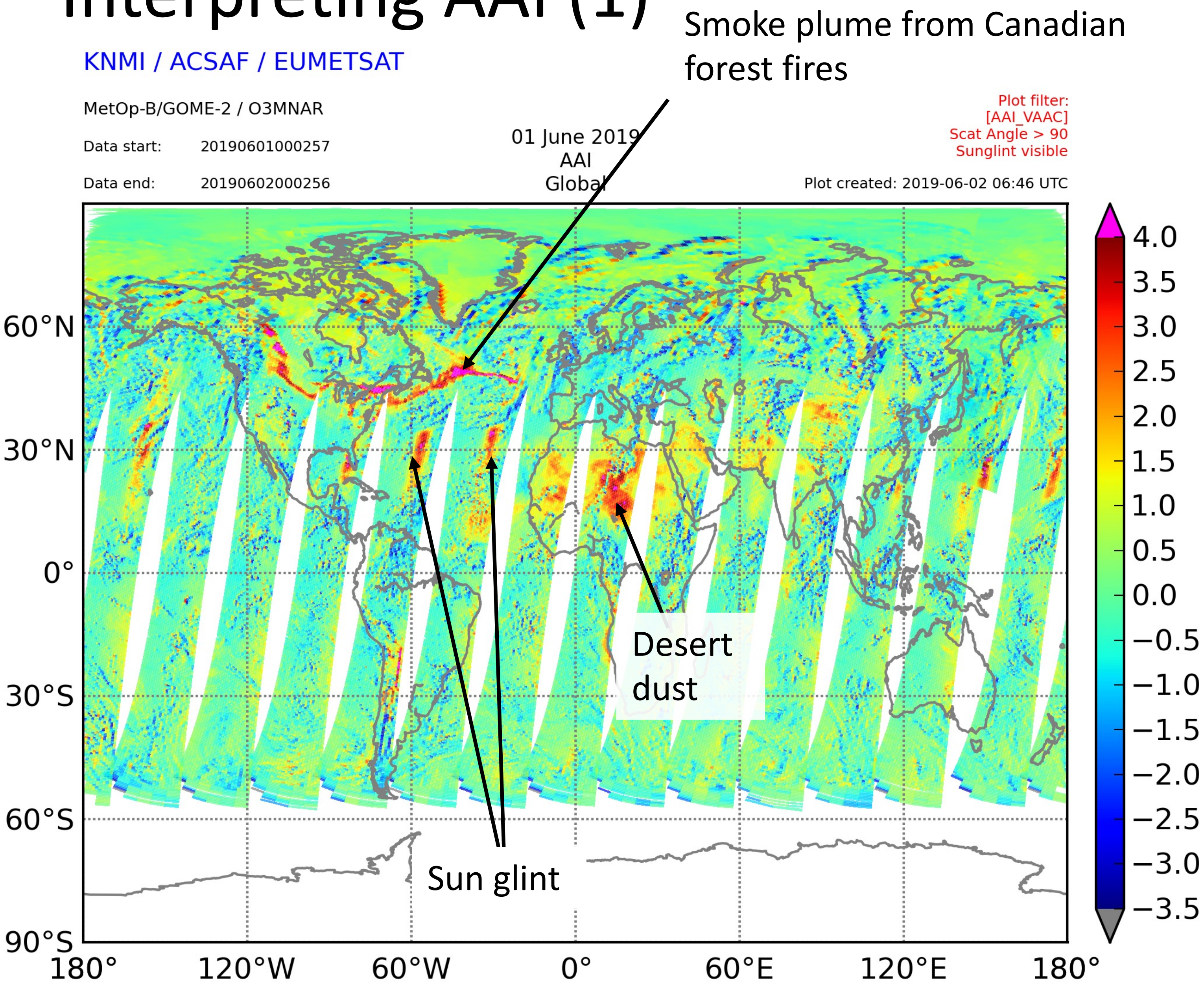
- AAI is defined from reflectance pairs measured at two different wavelengths.
  - E.g. 340 nm & 380 nm
- The surface albedo for the Rayleigh atmosphere calculation for the reference wavelength is chosen so that

$R_{meas}(380)=R_{sim}(A_{ler}, 380)$

Assuming that surface albedo is constant between the two wavelengths

$$AAI = 100 \cdot log_{10}\left(\frac{R_{sim}(340)}{R_{meas}(340)}\right)$$

Interpreting AAI (1)



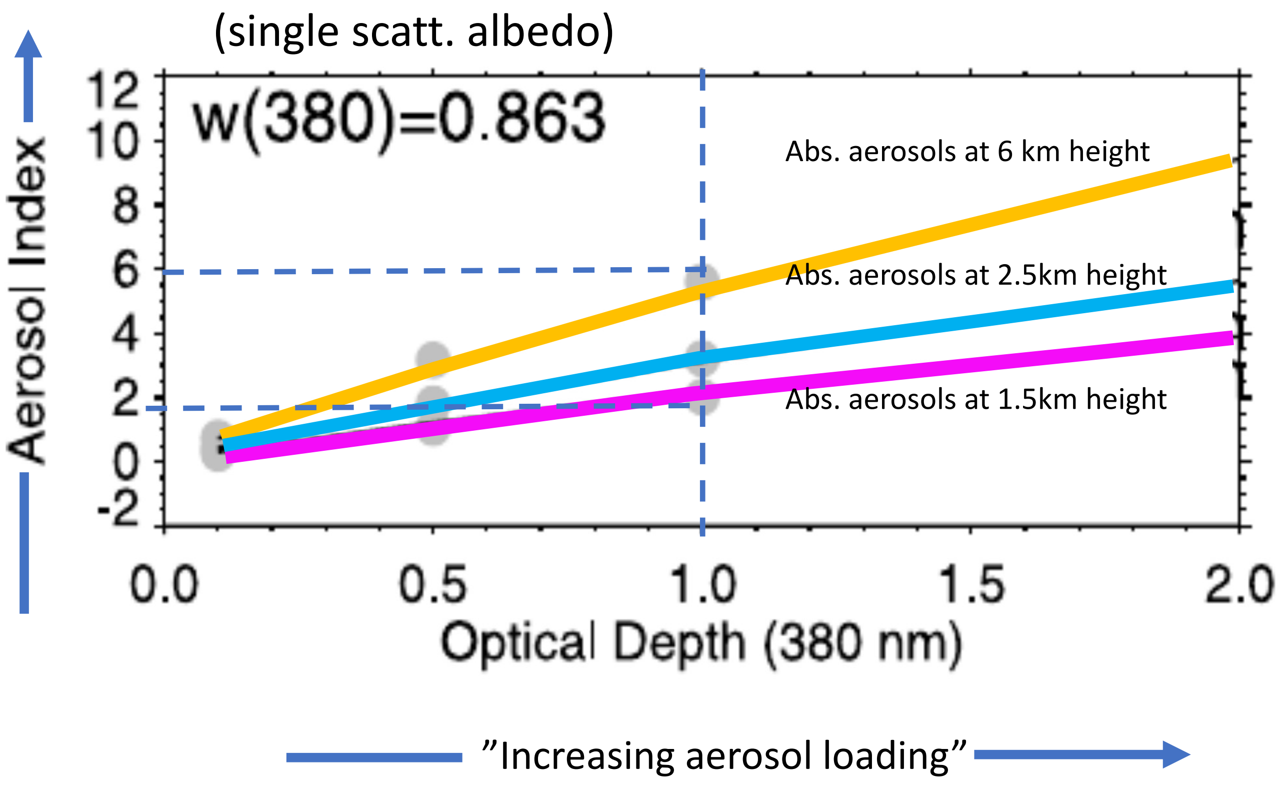
- **Positive AAI values** indicate **presence of absorbing aerosols**
  - For clouds (or scattering aerosols) AAI is close to zero or negative
  - Sunglint over ocean causes positive values but that is artifact, and should be filtered out from the data.
- For abosorbing aerosol plumes typically AAI > 1.0
  - Background slightly positive

Interpreting AAI (2)

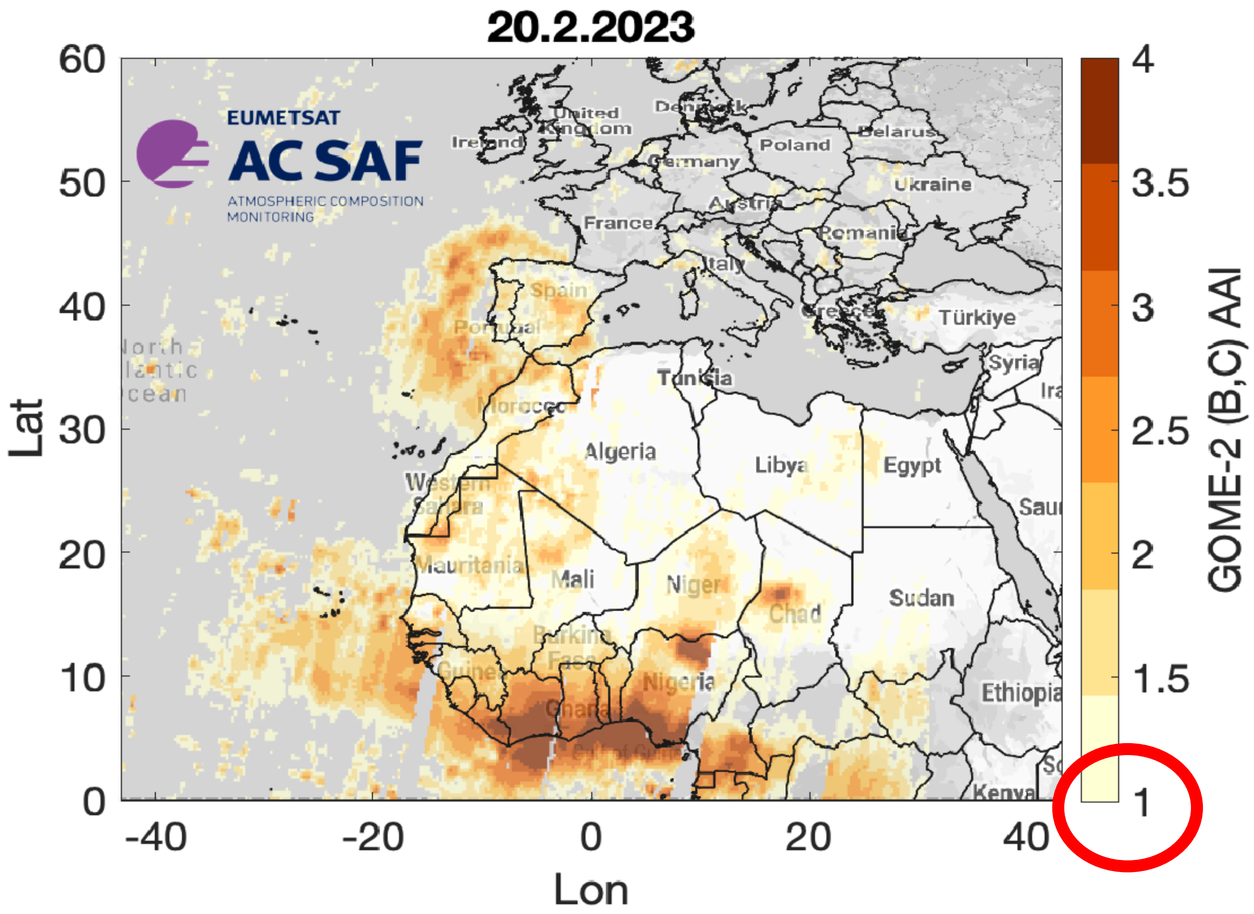
- AAI is a function of many parameters, and cannot be used as direct measure of aerosol amount.
  - AAI depends e.g. on aerosol type (SSA), aerosol amount (AOD), height of the aerosol layer.
  - AAI values are not necessarily comparable from case to case

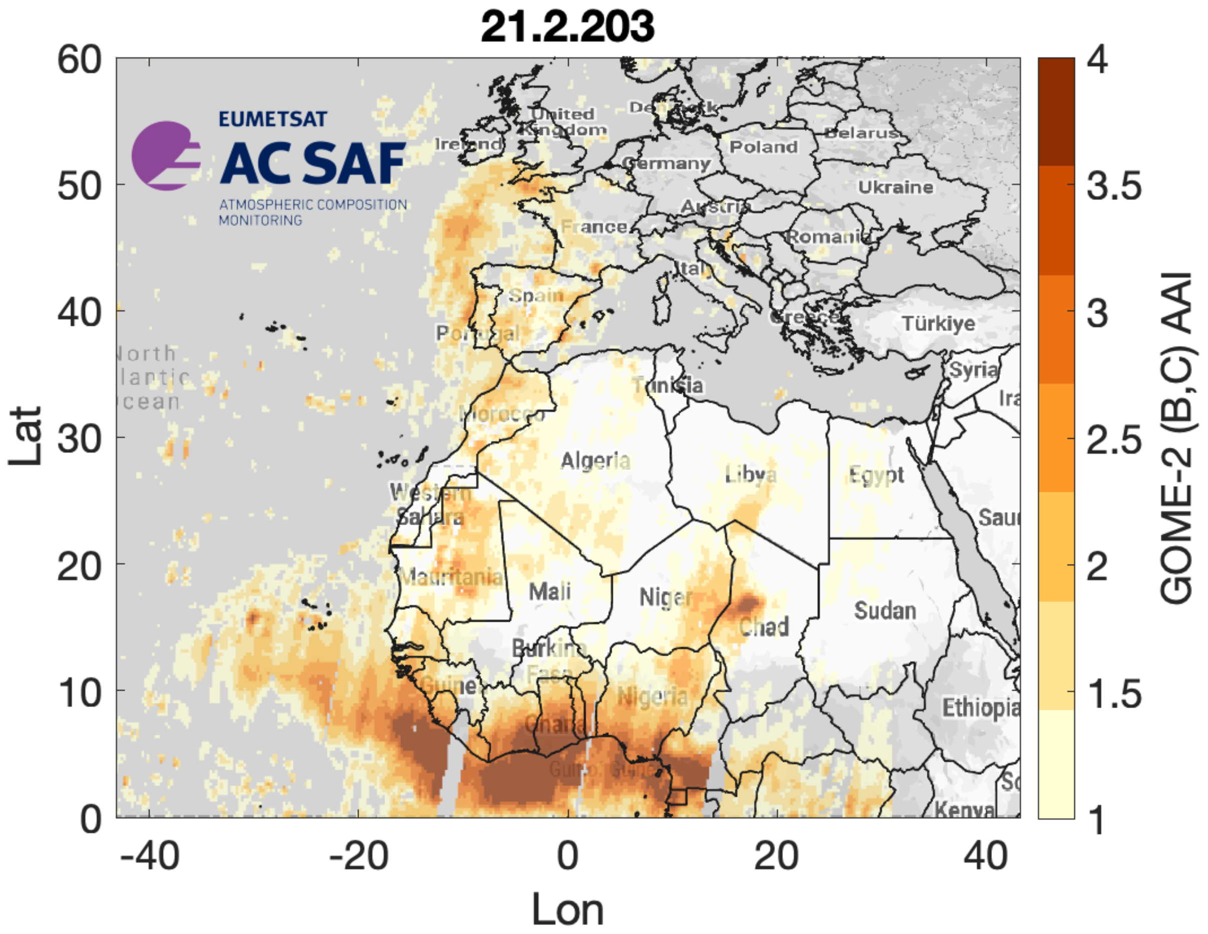
- Not a "direct" measure of aerosol loading

- With **AAI you typically see an elevated plume**
  - For assessing air quality at the surface, additional information (model, in situ, lidar) is recommended.

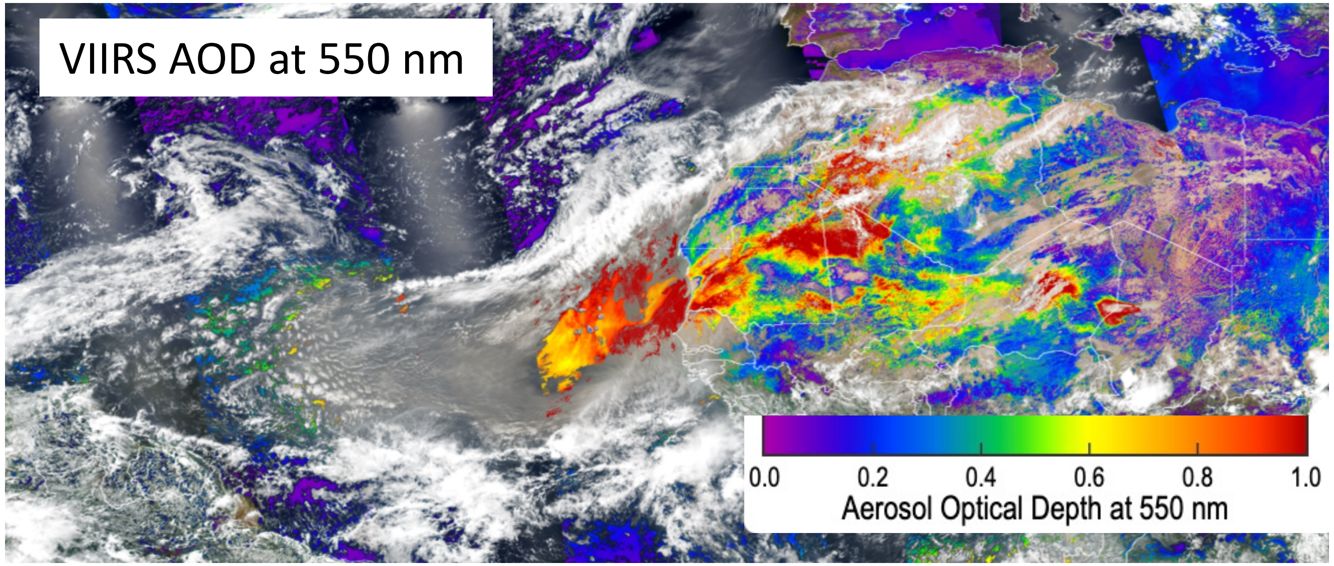


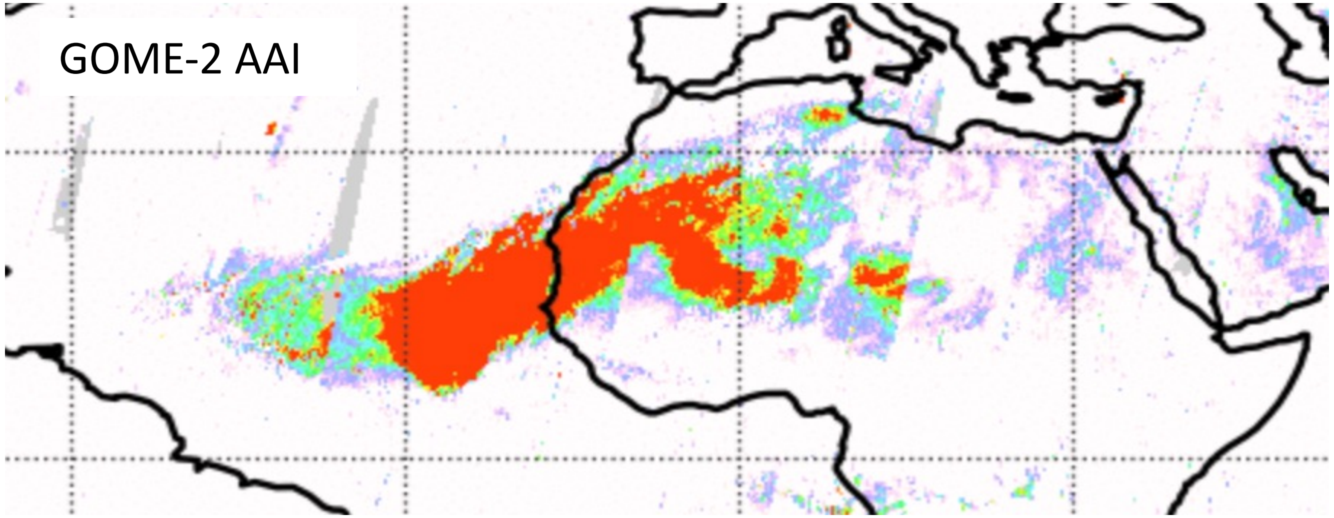
From: Ginoux & Torres, JGR, 2003


20.2.2023
EUMETSAT
AC SAF
ATMOSPHERIC COMPOSITION MONITORING
Lat
Lon
GOME-2 (B,C) AAI
60
50
40
30
20
10
0
-40
-20
0
20
40
4
3.5
3
2.5
2
1.5
1

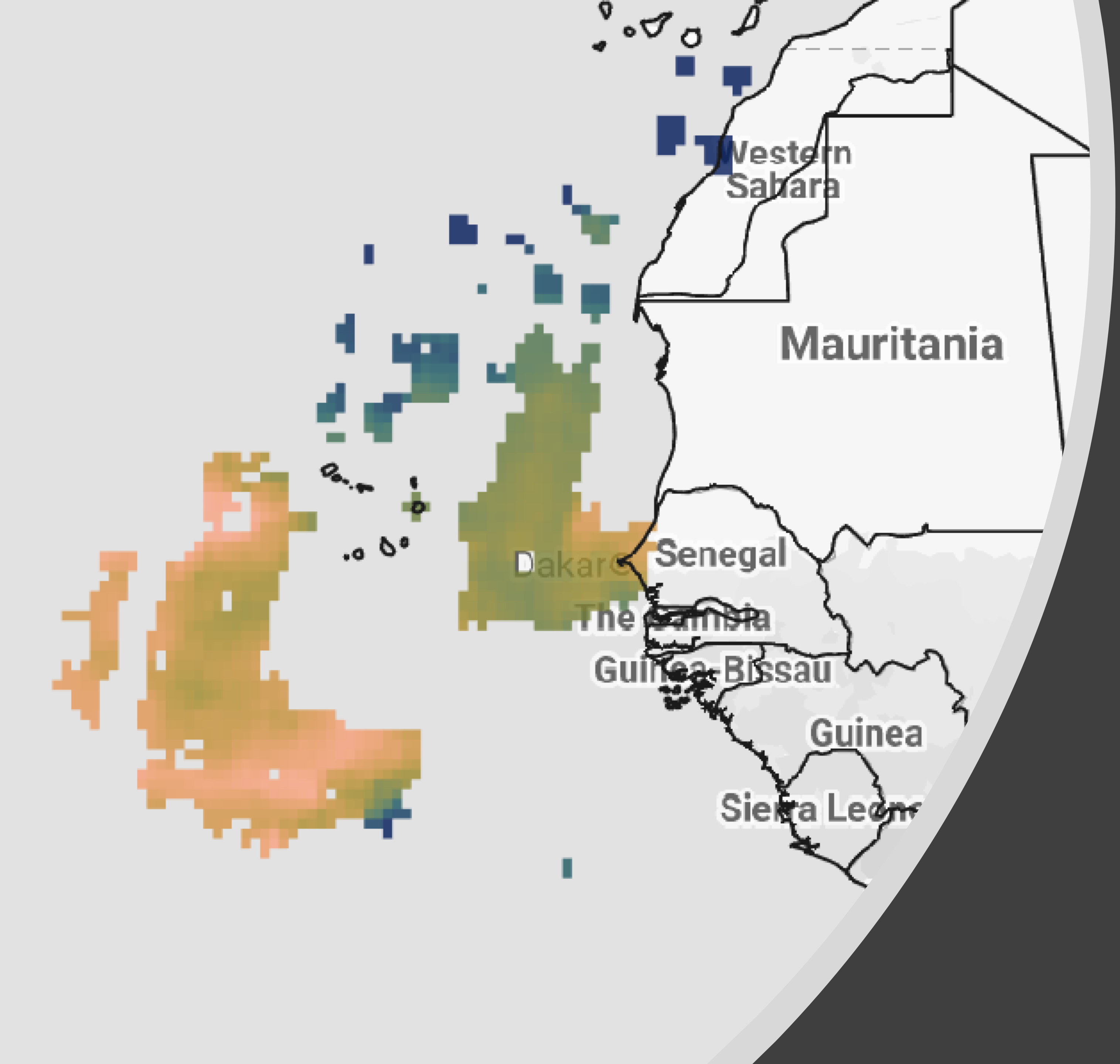

21.2.203
EUMETSAT
AC SAF
ATMOSPHERIC COMPOSITION MONITORING
Lat
Lon
GOME-2 (B,C) AAI
60
50
40
30
20
10
0
-40
-20
0
20
40
4
3.5
3
2.5
2
1.5
1

Comparison of GOME-2 AAI and VIIRS AOD 7.6.2021



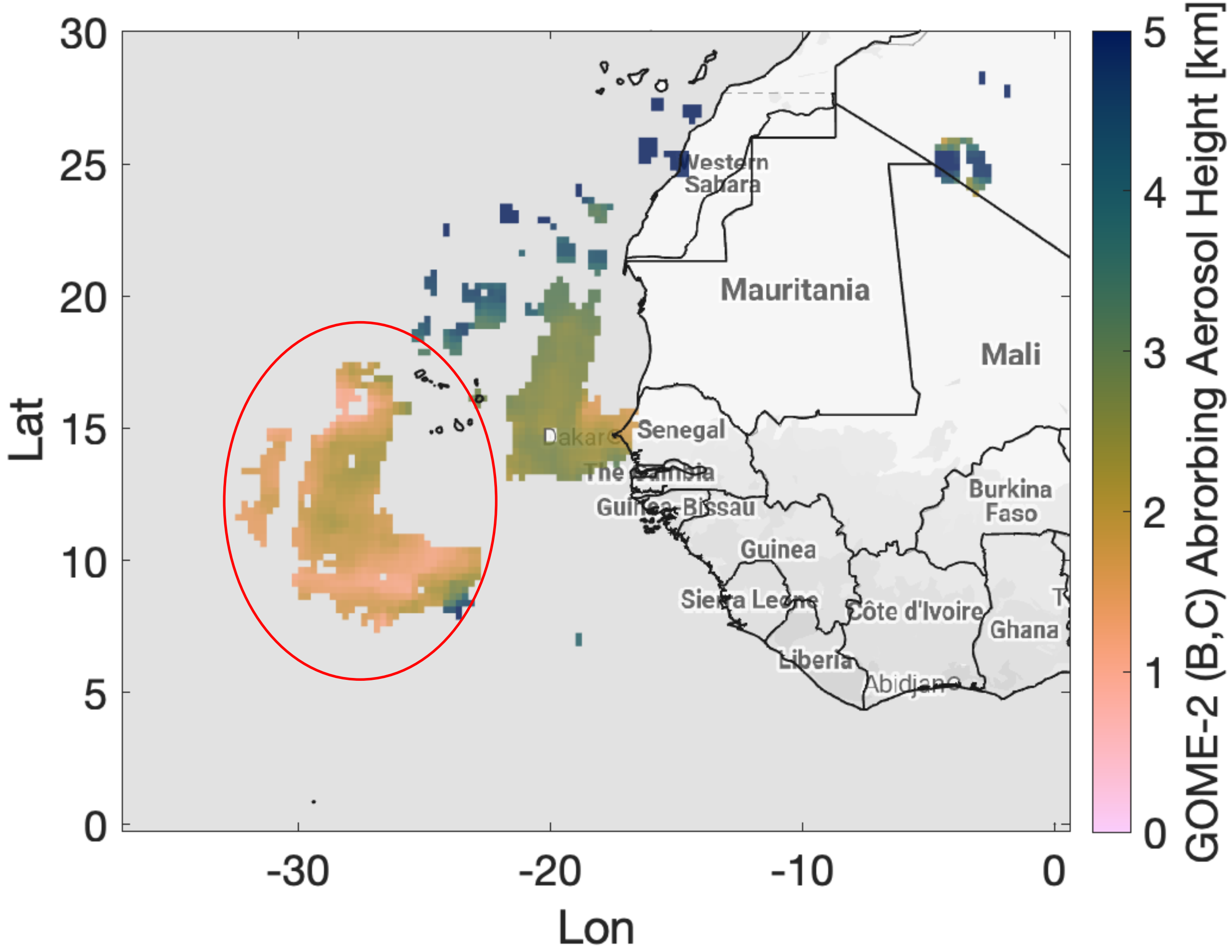


- Combining information from AOD and AAI can give more detailed view on the dust plume
- **AOD** gives more detailed info on **spatial variation of total aerosol loading.**
- AOD "misses" parts of the plume, due to cloudy/ partly cloudy scenes or "too thick" dust
- **AAI** gives more complete view **of the extent of the plume, also for cloudy/partly cloudy scenes**, but does not directly indicate the amount of aerosols.



Absorbing Aerosol Height

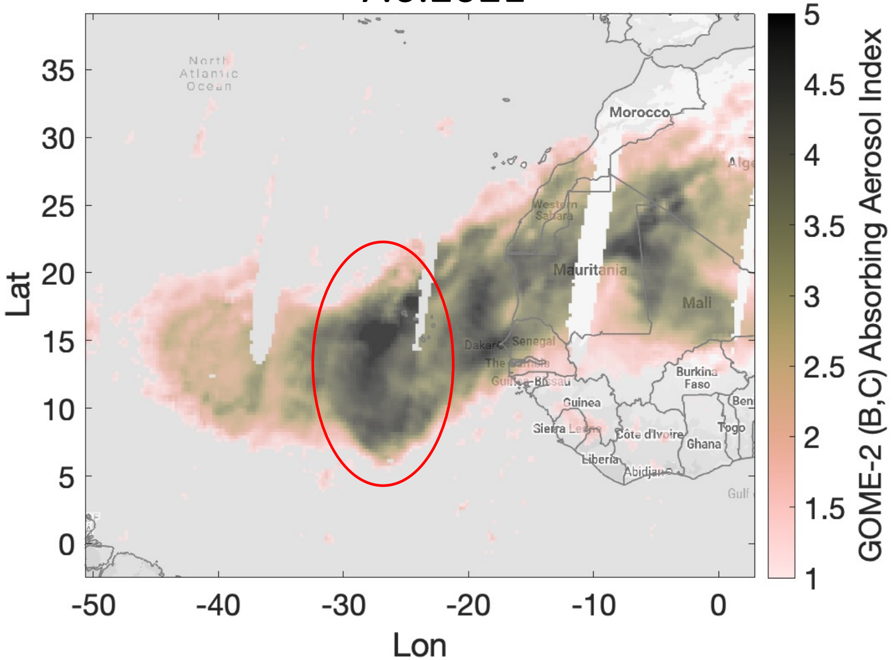
Absorbing Aerosol Height
7.6.2021



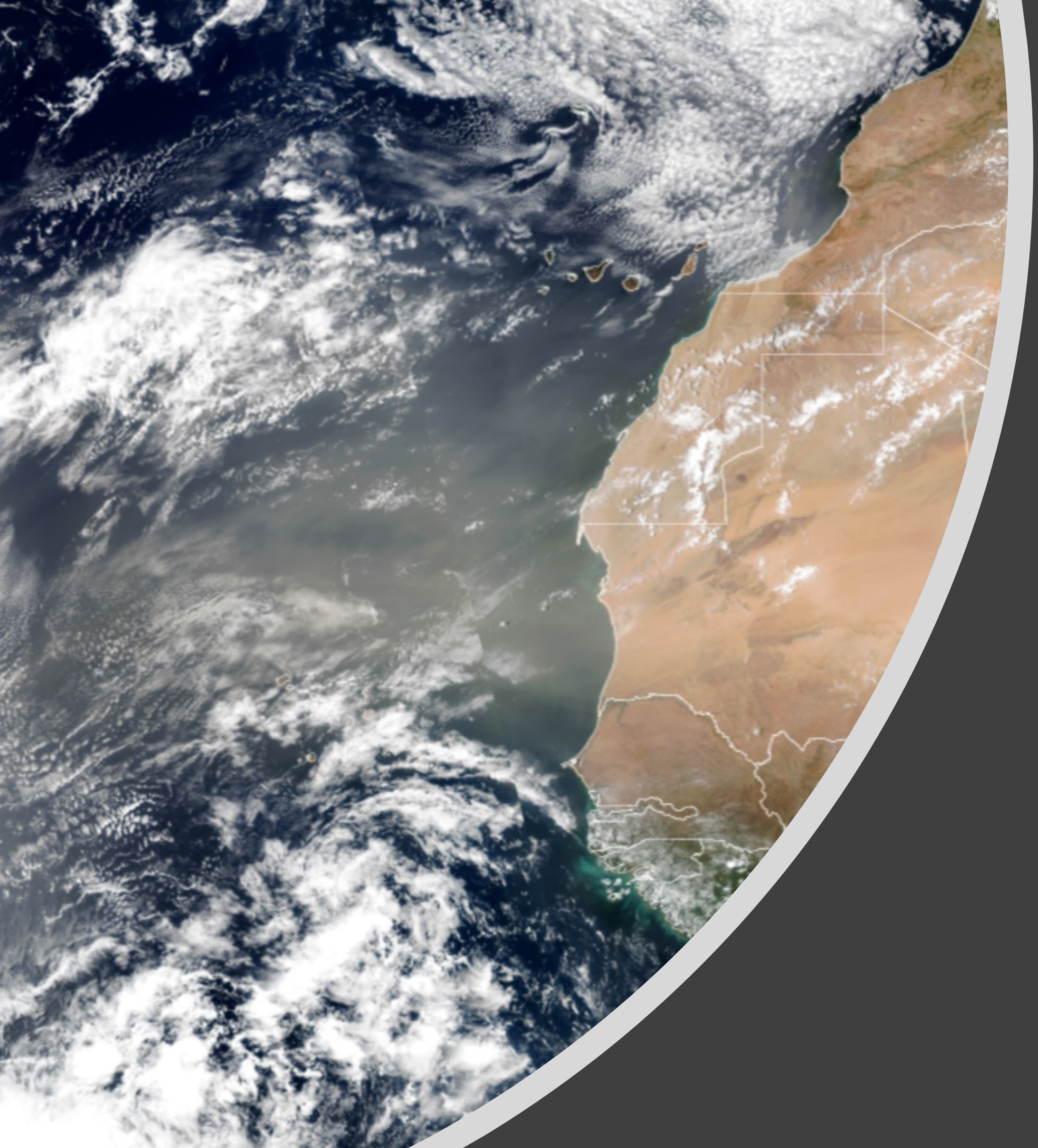
Absobing Aerosol Height

- High quality AAH can be retrieved only for pixels where AAI is high enough (>4)
- Typically AAH is retrieved only parts of the plume

Absorbing Aerosol Index
7.6.2021



EUMETSAT
AC SAF
ATMOSPHERIC COMPOSITION MONITORING



Take home messages

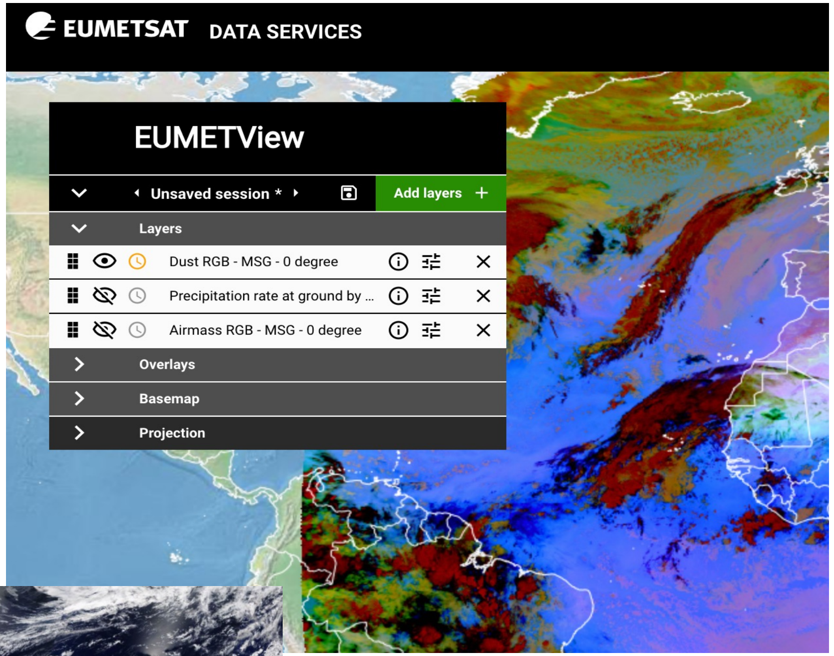
- Passive satellite observations provide various parameters for monitoring dust events
- True color RGB and RGB composite images are available at several web-based services in near real time
  - Easy to use but interpretation not always straightforward
- Aerosol optical depth provides an estimate on aerosol loading of all aerosol types
- Absorbing Aerosol Index indicates the presence of absorbing aerosols (elevated plumes), including dust
- Absorbing Aerosol Height gives an estimate on the height of an absorbing aerosol layer, when the signal is ”strong” enough
- Comprehensive view on dust episodes can be obtained by combining observations of RGB, AOD, AAI and AAH!

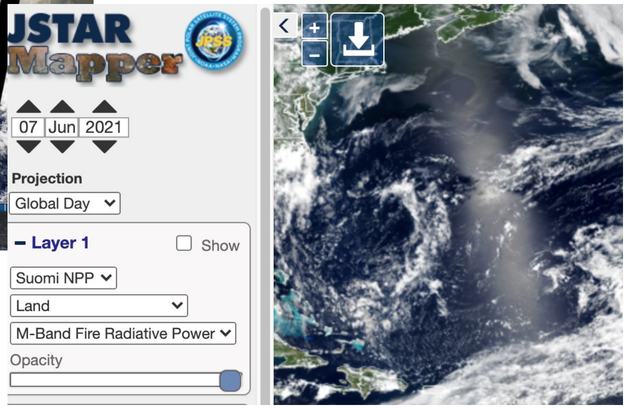
Resources where to obtain RGB and composite images (near real time):

- **EUMETVIEW by EUMETSAT**
  - https://view.eumetsat.int/
  - MSG true color and RGB Dust composites
  - OLCI true color RGB

- **NOAA JSTAR Mapper**
  - https://www.star.nesdis.noaa.gov/jpss/mapper/
  - VIIRS True color RGB

- **NASA World View**
  - https://worldview.earthdata.nasa.gov/
  - MODIS, VIIRS True color RGB





Resources to obtain aerosol observations

Web services for viewing data (no data download or processing needed):

- MODIS AOD, OMI & OMPS AAI: https://worldview.earthdata.nasa.gov/
- VIIRS AOD & TROPOMI AAI: https://www.star.nesdis.noaa.gov/jpss/mapper/
- GOME-2, OMI & TROPOMI AAI: https://sacs.aeronomie.be/nrt/index.php

Actual data download examples (incomplete list)

- PMAP AOD: EUMETSAT EO portal, **https://eoportal.eumetsat.int/**
- MODIS AOD: Nasa Earthdata services, https://ladsweb.modaps.eosdis.nasa.gov/
- GOME-2 AAI and AAH: AC SAF data portal, **https://safserver.fmi.fi/index.html**