HARMONIA CA21119

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Presentations and discussions of the 2nd Harmonia WG4 Workshop on Industry Engagement Towards Innovative Hardware & Software Products

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1. Introduction

This second Workshop of the Working Group 4 (WG4) was held in Valladolid (Spain), in the facilities of the Group of Atmospheric Optics from the University of Valladolid (GOA-Uva) on 30 June 2026. This meeting brought together 18 participants from different European countries, all attending in person.



This Workshop was organized in line with the main goals of WG4 (Industry engagement towards innovative hardware, software products), which focuses on the creation of a hub among scientists and the industrial sector including instrument and software developers. The main aim is to demonstrate the possibilities of improvements based on synergistic and standardization aspects (WG1 to 2) and also inform on the needs of new technologies towards specific end user goals (WG3). The main tasks within this WG are:

- Identify new value-added products resulting from synergistic approaches. Create an assessment of current measurement uncertainties versus user needs and defining a road map towards future measurement improvements needed.

- Establish a collaboration platform among scientists and instrument manufacturers aiming on instrument hardware improvement, linked with retrieval algorithms, towards improvement of aerosol retrieval accuracy.

- Suggest software, hardware and other aerosol retrieval improvements including low sensors assessment and share the information with major industrial developers inside and outside HARMONIA network.

With these goals in mind, this Workshop included 14 presentations (summarized in the next section) delivered by both scientists from research institutes and representatives from software and instrument manufacturing companies, with the objective of fostering collaboration between these groups and initiating discussions on improving measurement techniques and results.

2. Presentations Summaries

2.1 What We Can Do with All-Sky Cameras and What We Need (by Roberto Román)

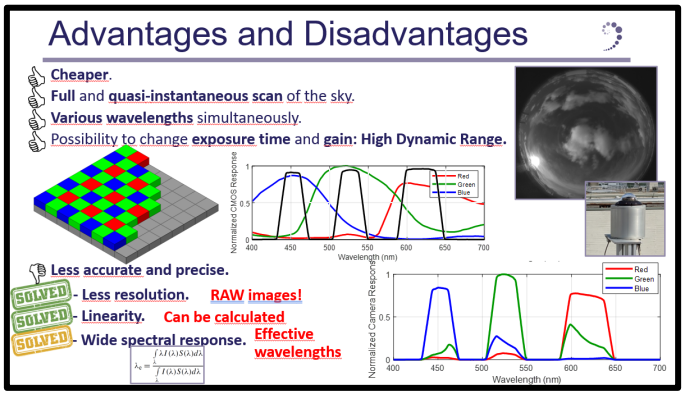
In this presentation Roberto Román from the University of Valladolid introduced the all-sky cameras. This instrument is designed to take photos of the full sky and have been used historically for cloud observations. However, its use is not restricted to this application. During his talk, Roberto Román showed that all-sky cameras are useful also to: retrieve the cloud cover applying neural networks, estimate sky radiances during the day to retrieve aerosol properties using the GRASP code (GRASP-CAM inversion strategy) and estimate star irradiance to calculate night-time AOD by Langley calibration, among others.

Despite all-sky cameras are less accurate and precise than other instruments, most disadvantages can be solved. They also present many advantages like: they are cheaper, they perform a full and quasi-instantaneous scan of the sky, they measure various wavelengths simultaneously, and they allow to change exposure time and gain (High Dynamic Range).

Roberto Román also introduced his latest project, the PRESENTE All-Sky Camera Network, which consist on 20 all-sky cameras OMEA-3C-TF installed around Valladolid. This network is used to conduct stereophotogrammetry of clouds, which allows to obtain maps for cloud base and top heights.

Finally, Roberto exposed the daily problems that affect all-sky cameras. These are mainly related to the presence of birds and to dirty due to dust, rain and bird residuals. Therefore,

cleaning tasks are crucial. In addition, the dome reflections can affect the measurements (they can look like fake clouds); this issue should be corrected.



2.2 Co-Designing All-Sky Camera Networks with the Scientific Community (by Max Aragón)

Max Aragón is part of Wematics, a R&D-native startup in atmospheric sensing, and MINES Paris (PSL). In this presentation Max talked about his work developing all-sky cameras and designing all-sky camera networks.

He highlighted that the main aspects to consider when designing All-Sky Camera Networks are:

- The number of cameras to install.
- The layout of the cameras; i.e., which configuration (location) is better.
- The siting: where to place the cameras, and availability to be installed in buildings.

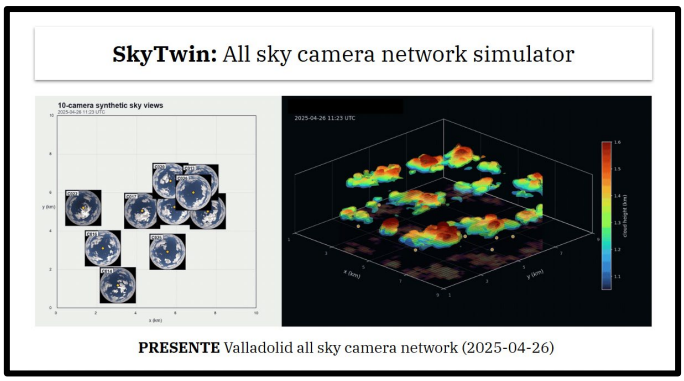
To analyse these aspects Wematics developed SkyTwin, an all-sky camera network simulator that allows to simulate the images that would be observed by all-sky cameras established at certain locations for a simulated cloud evolution. Max showed the simulation obtained for a day in Valladolid considering the PRESENTE all-sky camera network presented by Roberto Román in the previous talk.

This simulator can be used to validate cloud parameters determined by other methods. The differences between the cloud height (or other parameter) retrieved in the simulation and the obtained by other methods can be used to estimate error maps and determine the retrieval need (points with more error); i.e., the points where more cameras are needed to improve the estimations of cloud height (or other parameter).

Another application of the simulator is the estimation of solar irradiance. This way, maps of solar radiation can be obtained emulating the hole radiative transfer.

The main conclusion of this work is that the way the camera networks are designed is very dependent on the desired application of the cameras. In addition, Max highlighted that SkyTwin should be improved to include aerosol scattering.

Finally, Max talked about the all-sky camera prototype they are working on, that consists in a completely autonomous all-sky camera self-powered, self-calibrated, self-cleaned, multispectral and with an edge recognized by AI.



PRESENTE Valladolid all sky camera network (2025-04-26)

2.3 Using Radiance Information from All-Sky Imagers for Simultaneous Multi-Angle Observations of Sky Conditions (by Laurent Sauvage)

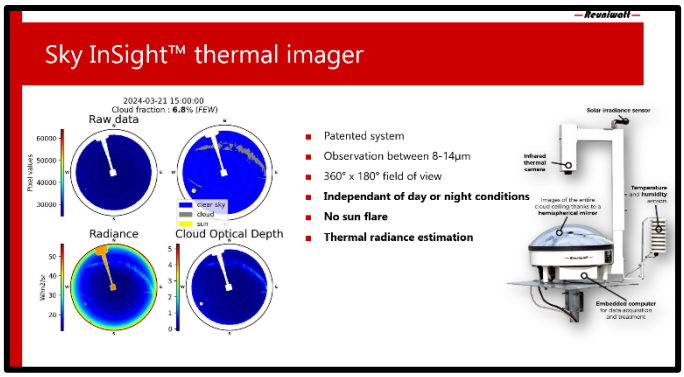
Laurent Sauvage, from Reuniwatt, presented a VIS/TIR sky imaging system designed primarily for cloud observation, though some development has also targeted aerosols. Sky Insight™ is the thermal infrared all-sky imager, and offers 24/7 observations without sun flare, and Sky Cam Vision™ is the visible-range all-sky imager. These instruments are robust to harsh weather, require a low maintenance and are easy to deploy. The imagers are provided with intelligent self-calibrating algorithms for positioning, levelling and mask detection; an automatic geometric calibration is performed following the sun/moon positions. Each system is calibrated in radiance against their “golden” reference systems in Toulouse.

These systems are aimed at the solar energy market and contrail studies, with main applications including solar energy, airport weather monitoring, free-space optical communications, and atmospheric research (including contrails).

The TIR system is particularly useful for cloud coverage, radiance, and cloud optical depth. It is useful for determining cloud structure (cover, height), evolution (speed), and optical properties. Using satellite information, the contrails can be matched to the airplane that produced the contrails, and even detect contrails before they become visible.

One of their key products is contrail optical depth, retrieved using radiative transfer simulations — an important input for validating contrail models, which are currently not very accurate. There are also synergies with ceilometers, pyrheliometers, and CIMEL photometers. They are also working in the determination of cloud base height considering two imagers.

Regarding aerosols, the TIR camera could help detect the impact of large particles on the radiation field, although urban aerosols cannot be characterised with this system. It can therefore be used in scientific research to complement sun photometer observations, particularly for large particles. Reuniwatt expressed interest in establishing a collaboration on AOD retrieval combined with sun photometer data.



2.4 Dust Clouds or Dusty Clouds: Aerosol–Cloud Interactions and Their Impact on Solar Energy Production (by György Varga)

György Varga focused his talk on the impact of Saharan dust on the solar energy production. For this study, he has considered long time series of Saharan dust events occurring in Hungary. Between 1976 and 2026 he identified more than 300 such events, using satellite data and back-trajectory analysis, and has observed an increase in both the frequency and intensity of these events in the last years due to climate change.

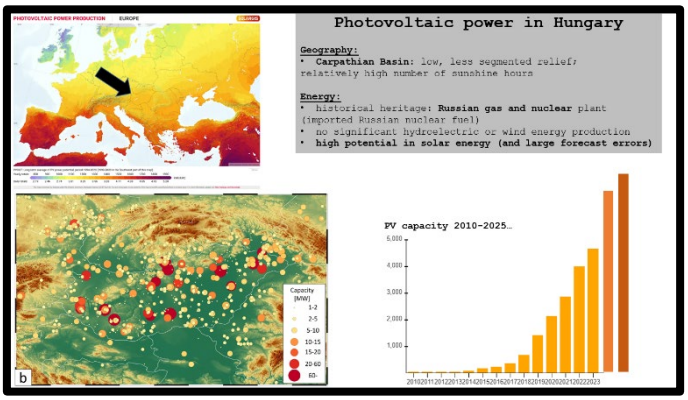
With respect to energy production, György noted that around 28% of Hungary's energy currently comes from solar sources, reflecting the broader photovoltaic (PV) boom seen across Europe in recent years. He also highlighted Hungary's high potential for generating this type of clean energy, but also the limited support of governments to promoting it.

Due to the observed high impact of Saharan dust in Hungary, György has conducted an analysis of the impact of dust in the photovoltaic energy production. For this analysis he studied the PV performance ratio and PV loss. He showed that there was a difference of more than 500 MW between the 24-hour (day-ahead) schedule and the actual photovoltaic

production during some events dust events (causing tens of millions EUR of damage) in 2022, highlighting the discrepancies between modelled/forecast energy output and the actual energy generated. Further, he investigated the indirect effects of dust-induced cirrus on the PV production, which appear to be increasing, and are more frequent in spring.

He concluded that atmospheric dust is very important in PV generation, and forecasting updates must be considered in order to correctly estimate the dust load and include not only the effects of dust deposition in the surface of the panel, but also their direct effects on solar irradiance and indirect effects due to their role in cloud formation.





2.5 Building Sustainable Air Quality Monitoring Networks Using Low-Cost Sensors in Sub-Saharan Africa (by Maurizio Bacci)

Maurizio Bacci, from CNR, shared his group's experience deploying low-cost sensors (LCS) across Sub-Saharan Africa. The main motivation for this work is the current lack of ground-based coverage, which needs to be increased to understand the real climatic situation and to detect local pollution hotspots. In collaboration with a private company, they have developed the AirQino (AQ) Low-Cost Air Quality Stations, which are equipped with sensors for the measurement of gaseous pollutants and particulate matter. These stations have been deployed across different environments — Europe, the Arctic, and Africa; the system proved robust across these harsh environments. Monitoring campaigns have been conducted in three different countries in Africa, covering more than 150 days of observations. The main challenges were related to power supply and data transmission, nonetheless, system downtime remained low, at under 17% across all stations.

Maurizio highlighted the many advantages of low-cost sensor systems especially in remote areas, which include: the robustness of the AQ systems, the low economic impact in the replacement of the system, energy autonomy, simplified maintenance and operation, easy management of saturation by PM and cleaning, feasibility to create a network and identify

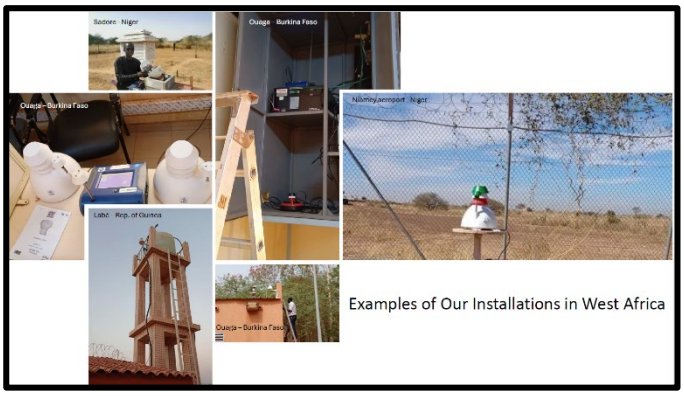
pollution hotspots, they allow an effective transfer of the technical knowledge. It was also highlighted the importance of performing in-situ calibration, under local environmental conditions.

In summary, the operational considerations for designing an effective field campaign strategy include:

- Coincident use of Reference Grade Monitors (RGM) and LCS
- The need to correct for biases (including relative humidity effects and seasonality)
- Recurring logistical challenges — recommendation to use a local site coordinator
- The need to improve data transmission (e.g. local SIM cards)
- The need to maintain a backup of all collected data

They also recommended establishing protocols for co-location and calibration and highlighted the potential of AI to improve system performance, underlining the strong social relevance of these systems.





2.6 Low-Cost Complementary Aerosol Observations in North Africa: From Capacity Building to Dust Early Warning Applications (by Africa Barreto)

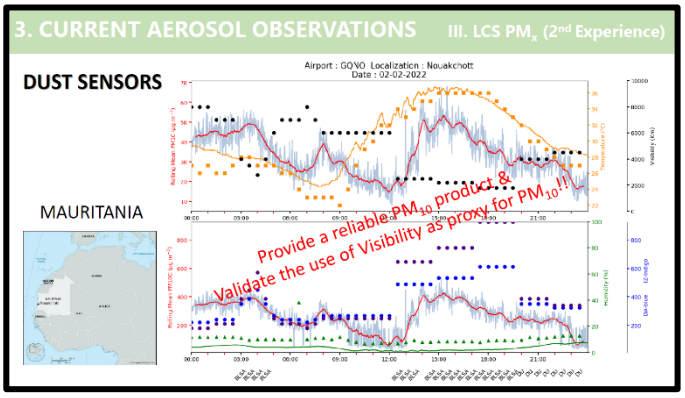
This presentation provided an overview of the current status of aerosol observations across North Africa and the Middle East, emphasising the importance of these regions as major sources of mineral dust and highlighting the significant gaps that still exist in atmospheric monitoring networks. It showed that many countries lack adequate observational infrastructure and, in some cases, even air quality regulations, limiting their ability to monitor dust events and assess their impacts on health and climate.

África Barreto reviewed several international initiatives led by the World Meteorological Organization (WMO) to strengthen dust observation capabilities and early warning systems. These included the Sand and Dust Storm Warning Advisory and Assessment System (SDS-

WAS) and the Barcelona Dust Regional Center, which provide operational forecasts, monitoring products, and warning services based on numerical models such as MONARCH. In addition, collaborative projects such as CREWS, MAC-CLIMA, and KADI were presented as key examples of capacity-building efforts through personnel training, instrument deployment, and the development of observation infrastructures across Africa.

Finally, the presentation highlighted recent progress in capacity building through the implementation of low-cost aerosol observing systems, including handheld Calitoo sun photometers and low-cost particulate matter sensors. Results from several pilot projects demonstrated the successful calibration and validation of these instruments, including the use of artificial intelligence techniques to improve measurement quality. These initiatives are helping to expand aerosol monitoring networks across Africa, providing valuable observations for model evaluation, enhancing dust early warning systems, and strengthening local capacity for atmospheric composition monitoring.





2.7 A zenith looking radiometer (ZEN-R52) for the retrieval of aerosol properties (by Sara Herrero-Anta)

In this talk, Sara Herrero-Anta presented a methodology to retrieve aerosol properties using only measurements from a zenith looking radiometer (ZEN-R52). This instrument is robust, does not have moving parts and is less expensive than other instruments used to monitor aerosols, like the CE318 sunphotometers from AERONET. Therefore, it can be useful to increase the spatial coverage of aerosols monitoring, especially in remote areas.

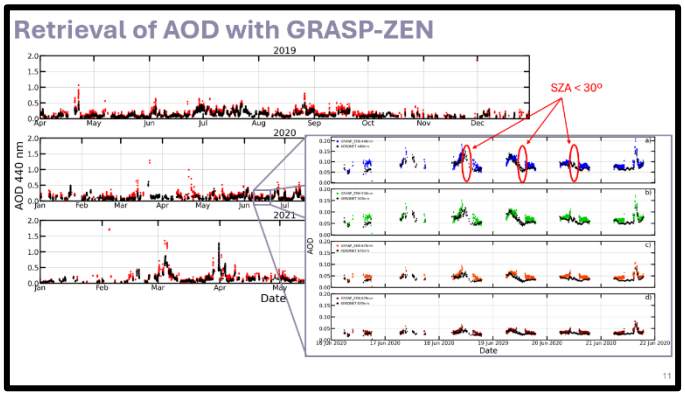
In the presentation, she showed that, at the wavelengths measured by the ZEN-R52 (440, 500, 675 and 870 nm), the zenith sky radiances are sensitive to the load and type of aerosol. Therefore, they are useful to retrieve information about the aerosols. To this end, it has been developed an inversion strategy in GRASP, called GRASP-ZEN, to retrieve aerosol properties from the ZEN-R52 measurements. Due to the limited number of measurements provided by this instrument, the inversion strategy considers the method *models* from GRASP, which

considers pre-defined aerosol types. Because of this, the inversion strategy is limited to extensive aerosol properties like AOD and volume concentration (VC) for total, coarse and fine modes.

The performance of the inversion strategy was evaluated conducting a synthetic study for several artificial aerosol scenarios. This study showed that GRASP-ZEN overestimates the AOD and VC but shows a good precision for these parameters. Finally, a comparison of the AOD and VC obtained with GRASP-ZEN with respect reference values obtained by a co-located CE318 sunphotometer showed a good agreement, with similar temporal evolution and high precision with respect to the reference values.

Some design problems of the instrument were also highlighted, like the intromission of stray light for low solar zenith angles, and a high uncertainty of the radiance measured at longer wavelengths, which constitute the main source of error of the retrieval.





2.8 Low-Cost Handheld Photometry for Expanding Aerosol Observations: Capabilities, Limitations and Integration Challenges (by Frédéric Bouchar)

The representatives of the French company Tenum, Frédéric Bouchard and Stéphane Villeneuve, presented their low-cost handheld sun photometer, Calitoo. The company provides instrumentation and services to Airbus and CNES and supports educational activities within the GLOBE programme.

They outlined the system's advances and limitations: it is low-cost, durable (lasting more than 10 years), easy to use, comes with dedicated software, and can be transported in the pocket to any place in the world. However, the system presents a lower precision compared to reference-grade monitors in low (AOD<0.1) and high (AOD>0.5) aerosol loads and only measures at three wavelengths. In addition, calibration can be an issue, as it must be renewed periodically and is not automatic, requiring human intervention, which limits the

ability to build large datasets. Calitoo can be calibrated through intercomparison with AERONET or via the Langley method (which requires a high-altitude site); the accompanying software supports this calibration process.

2.9 Handheld Photometers within Hybrid Aerosol Observing Ecosystems: Applications and Field Experiences (by Stéphane Villeneuve)

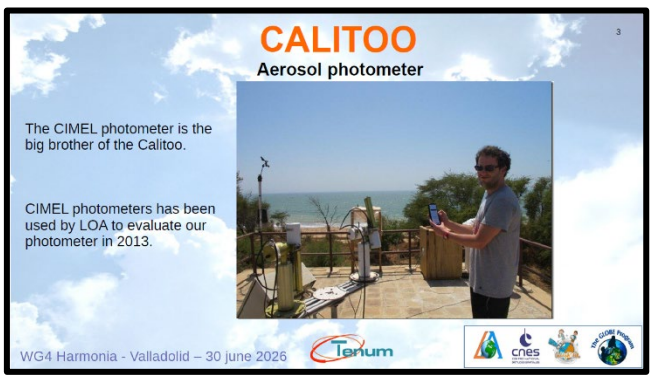
In this second presentation, Frédéric Bouchard and Stéphane Villeneuve focused in the close relationship between Calitoo & CIMEL sunphotometer and the new exploration of possible uses of the Calitoo. The Calitoo has grown together with the CIMEL sunphotometer in LOA, which has been used to evaluate and calibrate the Calitoo.

They emphasised the important educational support of the Calitoo. The company provides teaching materials for students aged 10–11 to help them use the Calitoo, including exercises that also reinforce topics such as decimal numbers. It has also been used in a group of schools, building a local network of Calitoo managed by these young scientists. Calitoo and the PC software are also used by older students to study aerosols, and has been even be used in the International Earth Science Olympiads; this proves that their offer is very flexible across educational levels.

Other products related to Calitoo include Calibot (a robotic platform for automated measurements, no longer manufactured) and Calimir (a waterproof version). Although Calibot is discontinued, Tenum noted they could still support the community in enabling automated Calitoo measurements on a solar tracker, controlled via USB commands. They also presented Calinet, an online database developed jointly by LOA and ICARE/AERIS.

The presenters were asked by the audience asked why the 500 nm band — typically used in climate studies — was not included in the selected filters. Tenum acknowledged the feedback and indicated they may adjust the spectral bands, with an IR prototype possibly available soon in collaboration with LOA.



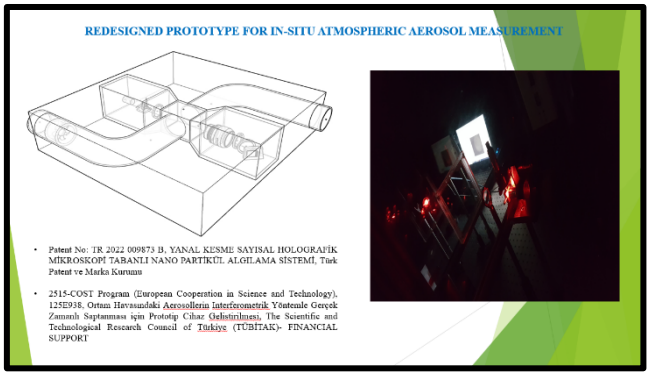


2.10 Real-Time Aerosol Detection by Interferometric System: Development of a Prototype Device (by Gülhan Kaya)

In this talk, Gülhan Ustabaş Kaya presented a holographic microscopy system prototype for aerosol detection — a portable optical instrument capable of remotely detect aerosol particles across a range of sizes. It offers a cost-effective and versatile alternative to photometers in real-time ground-level aerosol detection.

The operating principle of the instrument is based on the lateral shearing digital holographic microscopy (LS-DHM) which involves illuminating aerosol particles with a controlled laser. The resulting holograms are recorded and numerically reconstructed to obtain unwrapped phase maps in 3D, which are then binarized in 2D images that are used for the particle detection and analysis. Some test and determination of aerosol concentrations with this prototype have already been carried out, monitoring continuously over time for different humidity conditions. Gülhan also talked about the problem of the duplicate (twin image) in the registered hologram, which they solve to enable the formation of the effective interference area. In addition, they have improved modulation depth and supressed high-frequency speckle noise.

The system prototype for in-situ atmospheric aerosol measurement has been patented and preliminarily validated against AERONET observations. Further validation will be carried out in the next stages of prototype development, which include the comparison against satellite measurements and analysed by statistical methods. This will be useful to determine how effectively satellite-based AOD products represent ground-based observations. In addition, they need to stablish the sampling flow rate that better results produce and the calibration procedure. Finally, they want to study the effects of environmental parameters, including wind speed, ambient temperature, relative humidity, and atmospheric pressure on the results obtained, and quantify the effects of ambient environmental conditions on AOD measurements.



2.11 Automatic Ship-Based Photometers for Enhanced Aerosol Characterization over the Open Ocean: Towards a Global Network (by Benjamín Torres)

In this presentation, Benjamín presented the adapted system that has been developed to automatically measure aerosol properties onboard ships. The main motivation is the lack of sunphotometer measurements over the oceans. This is a problem for satellite validation over the oceans, since leaves observational gaps and little characterization of aerosol properties in these areas.

To increase the coverage over the oceans, the LOA (Laboratoire d'Optique Atmosphérique - Université de Lille) team has been working on an adapted shipborne CIMEL 318-T from AERONET. This instrument has been adapted to the movement of the ship (heading, pitching and rolling), to the hazard conditions, and has a special firmware (continuous tracking of the sun during sun triplets). It is fully compatible with AERONET and produces AOD data in level 0 (raw data), level 1 (sun/clouds) and level 1.5 (cloud-screening and perfect track). Radiance measurements are also performed and used for the retrieval of aerosol properties, but they are not corrected from boat movement. However, it is proposed a quality control based on the standard deviation and the mean values of the pitching and rolling angles during the measurements.

Since 2021 several campaigns onboard different vessels have been conducted. This has allowed to record a great amount of AOD data. During these campaigns several aerosol episodes have been identified for which some inversion retrievals have been performed. This way, information about the volume size distribution and the single scattering albedo has also been obtained. The values obtained are consistent with previous works conducted in the same areas, showing the importance and quality of this new approach.





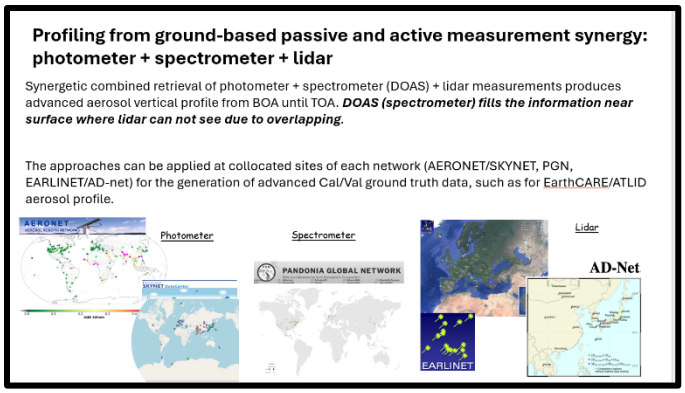
2.12 Aerosol Profiling through bottom-to-top Atmosphere from the Synergetic Observations of Sun-Sky Photometer, Spectrometer and Lidar/Ceilometer (by Masahiro Momoi)

The retrieval of aerosol properties is very complex due to their high variability and different properties. Because of this many kinds of observations are desired for their study. In this talk Masahiro Momoi focused on the improvements and differences observed in the retrieval of the aerosol vertical profile when combining different instrumentation.

For this retrieval Masahiro combines a sunphotometer from AERONET, which mainly provides information about aerosols, a pandora spectrometer, which provides information about gases and is more sensitive to vertical profiles near the surface, and a lidar o ceilometer, which provides vertical resolution mainly in the lower atmosphere. This combination allows to retrieve aerosol and gas vertical concentration profiles with good resolution even near the surface, where the sunphotometer + lidar combination is limited. This retrieval can be done using the GRASP code, that has been updated to incorporate DOAS measurements, expanding the functionality of gas calculation to allow gas vertical profile retrieval.

In the presentation Masahiro showed the vertical aerosol concentration that is obtained when considering different pair of combinations of these three instruments for the retrieval, at the AERONET Warsaw site. It is observed that the best vertical resolution is obtained when combining the three instruments. He highlighted that if instead of a ceilometer we use a lidar with 3 channels and polarization we can even retrieve trace gases profiles. With all, this synergetic retrieval has been demonstrated, but a validation is needed and is being planned at LOA.



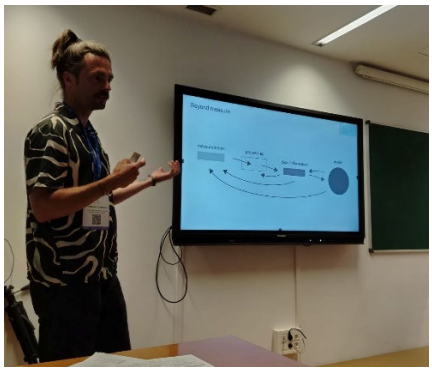


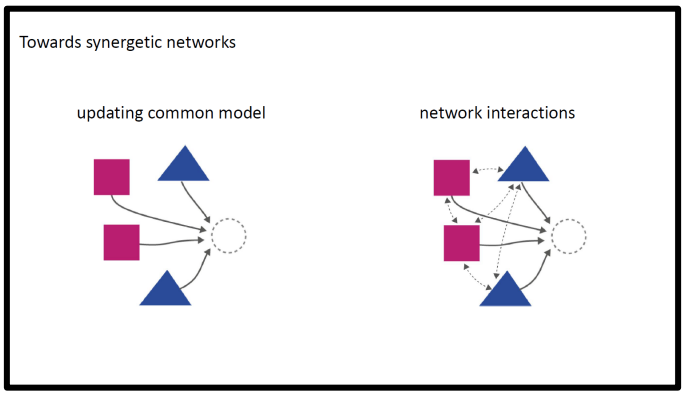
2.13 Measurements within the Pandonia Global Network (by Axel Kreuter)

In this talk Axel Kreuter introduced the Pandonia Global Network (PGN) — a fiducial reference network of 215 instruments designed to be processed homogeneously and to provide near-real-time observations — and its standard instrument, the Pandora Spectrometer System. He focused the presentation on the innovation in hardware and software within the global community.

Axel also discussed how measurements are processed and used as ground truth, either as reference measurements or as the basis for developing atmospheric models. With this context, Axel raised the issue of subjectivity in current atmospheric monitoring practices, noting that simply compiling observations from different instruments and methodologies to build a final climate model is not necessarily the most objective approach.

He discussed the need to reconcile models and measurements in a more objective way, concluding that the field should move towards a synergetic network of co-located, multi-instrument observations that actively interact with one another in order to update a common model.





2.14 Mindset and Strategy of a Private Company in the Atmospheric Research Field (by David Fuertes)

David Fuertes, from GRASP-Earth, presented the perspective of a company founded to create synergies between different instruments and techniques. Rather than focusing on a single method or instrument, the company's strategy has been to build a system capable of integrating different instruments and techniques. Their current objective is to manage their own reference instruments and integrate their measurements within the same ecosystem to treat them as a whole.

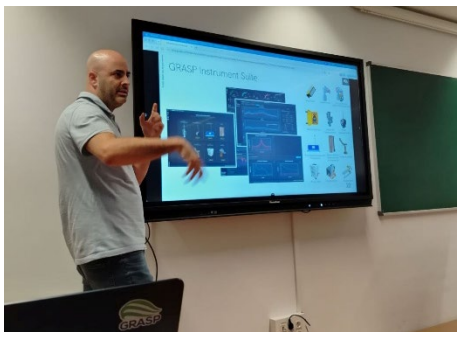
During his talk, David shared his experience in building and growing his company. A good starting point for their philosophy is their motto “In principle, yes”, which reflects their openness to new ideas and collaborations.

From his point of view, some key ideas to keep in mind when building a company are:

- Have an ambitious plan that motivates people to follow you.
- Do not forget your essence; stay true to your values.
- Look for results and share them with others (through publications, new developments, etc.).
- Surround yourself with people who want to dream and innovate.
- Be open to any collaboration.
- Enjoy what you do.
- Try to find balance in every aspect.

These principles are also the guidelines to follow when presenting a company to new investors and banks: mission, vision, and values.

Finally, David provided an overview of GRASP’s history, highlighting its main achievements, the growth of the team, and the expanding community using GRASP technologies.



3. Main topics of the workshop, Issues discussed & Aspects for improvement

This meeting was structured around several complementary topics, all of which can be considered combined approaches for aerosol observations, including low-cost instrumentation, practical applications, emerging technologies, and synergistic techniques. Together, they constitute a very interesting set of tools that perfectly complement those presented during our previous WG4 meeting in Davos. This reflects an

important idea: reference-grade monitors alone are not able to address all the challenges that today's aerosol observing systems face.

The first session introduced All-Sky Cameras, covering both the scientific perspective and the manufacturer's point of view. This technique clearly emerges as a powerful complement to Sun-Moon-Sky photometers within the current climate observing system.

Moving to applications, we discussed the importance of accurate aerosol forecasts and the assessment of both the direct and indirect aerosol effects for solar energy applications.

Several low-cost sensors were then presented, highlighting their potential to extend the spatial coverage of existing observation networks. We also learned from the experience of two European institutions working to expand PM measurements in key mineral dust source regions across Africa. These presentations emphasized the major societal and public health impacts of dust and sand storms (as well as air pollution in general) on a global scale. Providing timely and reliable information to society is essential for anticipating these events and supporting efficient Early Warning Systems.

Other low-cost instruments, such as the ZEN radiometer and the Calitoo handheld photometer, also demonstrated their potential to complement reference photometers such as the Cimel, particularly in remote locations where deploying more sophisticated instrumentation is challenging.

Regarding emerging technologies, we were introduced to an interferometric aerosol monitor as an alternative approach for in situ aerosol measurements. In addition, a modified Cimel instrument designed for shipborne observations was presented. This represents a significant achievement, involving not only an innovative system to compensate for ship motion but also the development of dedicated QA/QC protocols specifically adapted to the marine environment.

Finally, synergistic approaches played a central role throughout the meeting. By combining different measurement techniques, these approaches can provide additional products that cannot be retrieved by individual instruments alone while also compensating for the limitations inherent to each method. The idea is moving towards a synergistic network of co-located multi-instrument observations, something like a hybrid measurement ecosystem ;)

All these developments are particularly relevant in the context of HARMONIA, where they could play a key role in the future co-design of the next generation of aerosol observing systems, helping to:

- improve global observational coverage;

- strengthen the integration of observations with models and satellite information; and
- enhance societal relevance and better address end-user needs.

This session prompted a broader reflection, echoed in follow-up discussion, on how to frame industry talks (Tenum/Calitoo and similar low-cost manufacturers) in future editions of the WG4 meeting so that they contribute more directly to HARMONIA's objectives, rather than reading as commercial or purely technical presentations. Five themes were identified as a more useful structure for these sessions:

- Observational gap: which concrete gap does the instrument address — e.g. lack of AOD coverage in North Africa, the practical impossibility of deploying dense Cimel/AERONET-type networks, mobile or citizen-science measurement needs, capacity building — framing the instrument as part of a wider observational strategy rather than a standalone low-cost gadget.
- Quality and traceability: an open, honest discussion of calibration approach, temporal stability, expected uncertainty, comparisons against AERONET/Cimel, known limitations, and environmental sensitivities — since low-cost should not be equated with low-science.
- Complementarity rather than replacement: the value such instruments add without substituting reference-grade instrumentation — e.g. spatial densification, intensive campaigns, maritime observations, regional satellite validation, extreme events, gap-filling, and support to PV forecasting.
- Integration with GRASP and hybrid platforms: how the instrument's data (formats, APIs, metadata, automation) can feed into synergistic, multi-platform retrievals alongside lidar, satellite, and other observing systems, rather than being considered only as a hardware product
- Future roadmap: manufacturer plans for miniaturisation, autonomy, automated AI-based QC, multi-spectral capability, connectivity/cloud integration, and cost reduction, as a basis for dialogue between industry and the scientific community

The suggested core message for this type of session is that the aerosol observing ecosystem of the future will likely rely not on a single perfect instrument, but on the intelligent integration of complementary, scalable and accessible technologies capable of filling the major observational gaps that persist globally (North Africa, oceans, remote and resource-limited regions) — in line with WG4's industry-engagement objective and WG3's focus on end-user applicability.

Beyond the specific outcomes of each talk, the discussion held around this meeting reinforced a broader framing that is worth carrying forward, both as a synthesis of this workshop and as guidance for how future WG4 sessions are presented and structured.

Major observational gaps remain, particularly over North Africa, oceans, remote areas and resource-limited regions — precisely the regions that matter most for dust transport, climate forcing, air quality and PV production. Reference networks such as ACTRIS and AERONET remain essential but cannot resolve this spatial problem alone, since they are costly, limited in density and complex to maintain; this is exactly why complementary, portable, low-cost and autonomous observing platforms are needed.

The challenge ahead is no longer only about measurement accuracy, but about integration: the future of aerosol observing will most likely not rely on a single perfect instrument, but on the intelligent combination of multiple, partial observations — satellites, lidar, photometers, all-sky cameras, PM sensors, shipborne systems and radiative measurements — brought together through frameworks such as GRASP.

At the same time, low-cost does not mean low-science: the scientific usefulness of these systems depends on calibration, quality control, uncertainty characterisation, harmonisation and metadata, and this discussion should remain honest and rigorous rather than purely promotional. Ultimately, the value of meetings like this one lies in building bridges between science, industry and end users — moving beyond companies simply showcasing products, towards genuine co-design informed by user needs, scientific priorities and operational applicability.

In short: this meeting was not about replacing reference instrumentation, but about understanding how complementary, emerging and more accessible technologies can strengthen the global aerosol observing system and help address the observational gaps that still limit both science and its applications — building, together, the next generation of aerosol observing systems.

4. Workshop presentations

HARMONIA
International network for harmonization of atmospheric aerosol retrievals from ground based photometers

What We Can Do with All-Sky Cameras and What We Need

Roberto Román (roberto.roman@uva.es)
Group of Atmospheric Optics (GOA)
University of Valladolid (Spain)

2nd Workshop WG4 HARMONIA – June 2026

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
Funded by the European Union

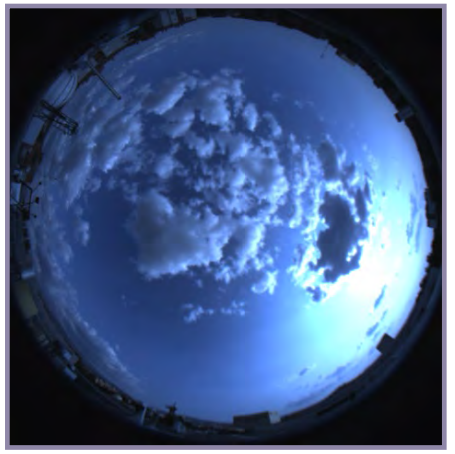
All-Sky Cameras

Devices to take photos of the full sky.



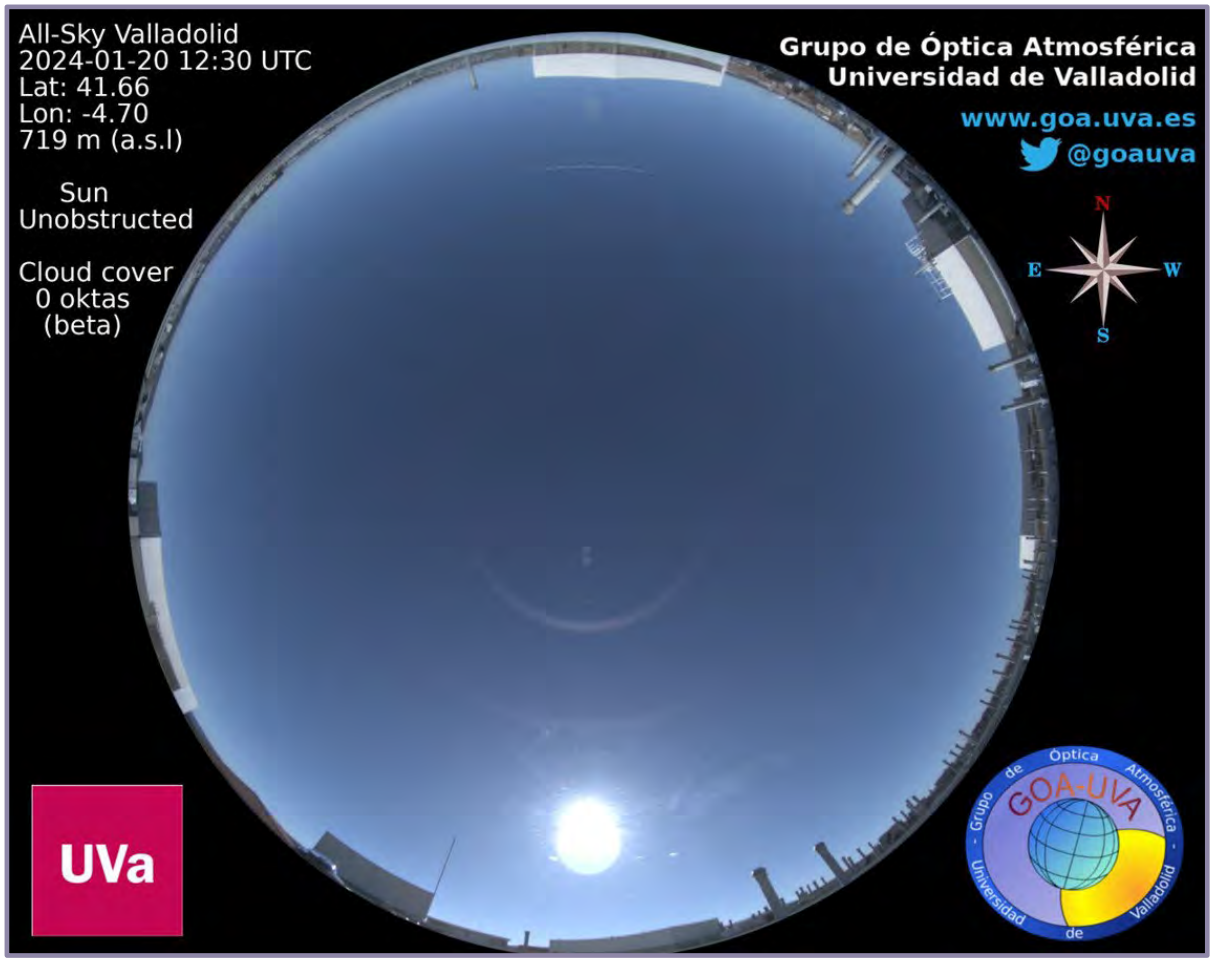


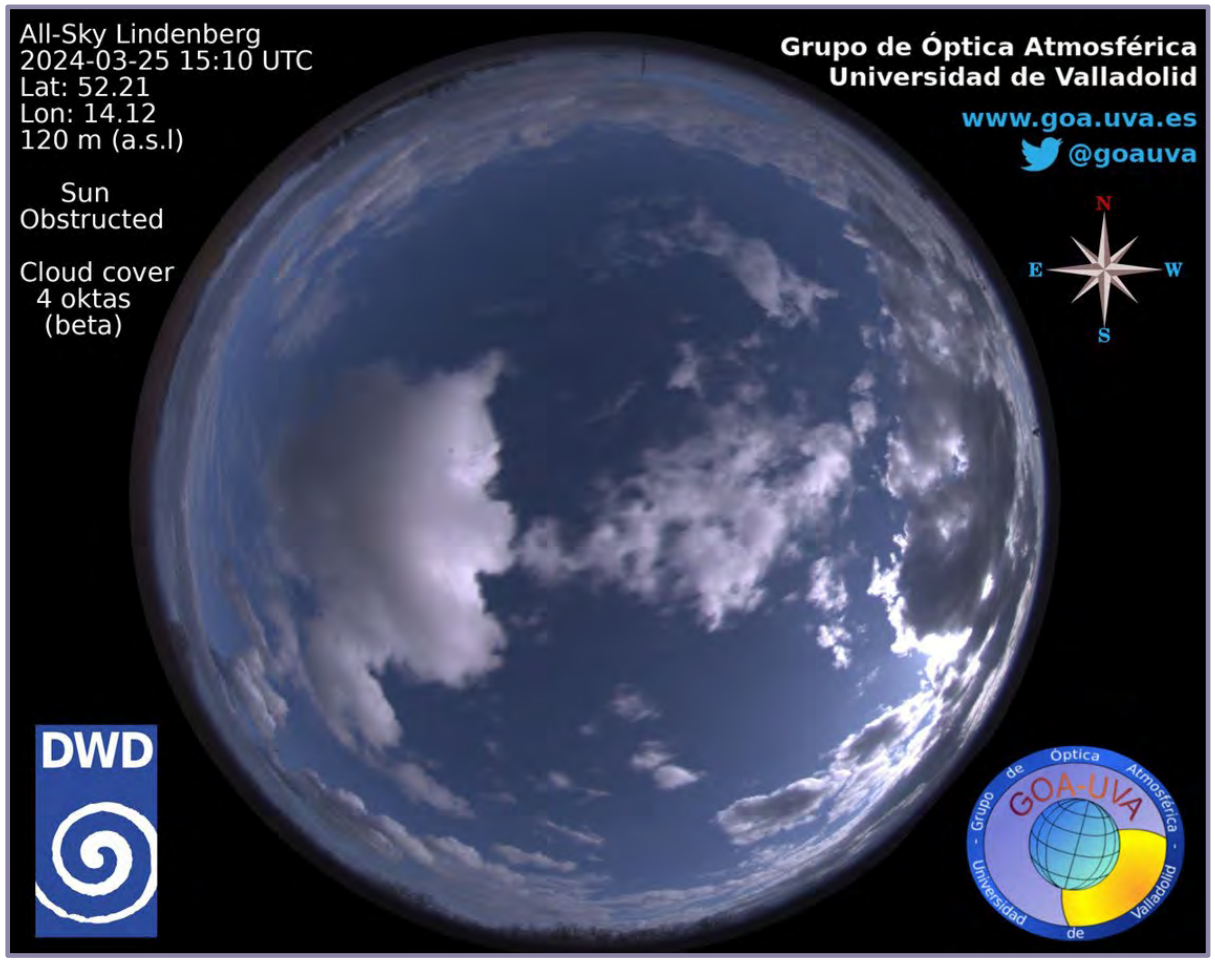


All-Sky Cameras

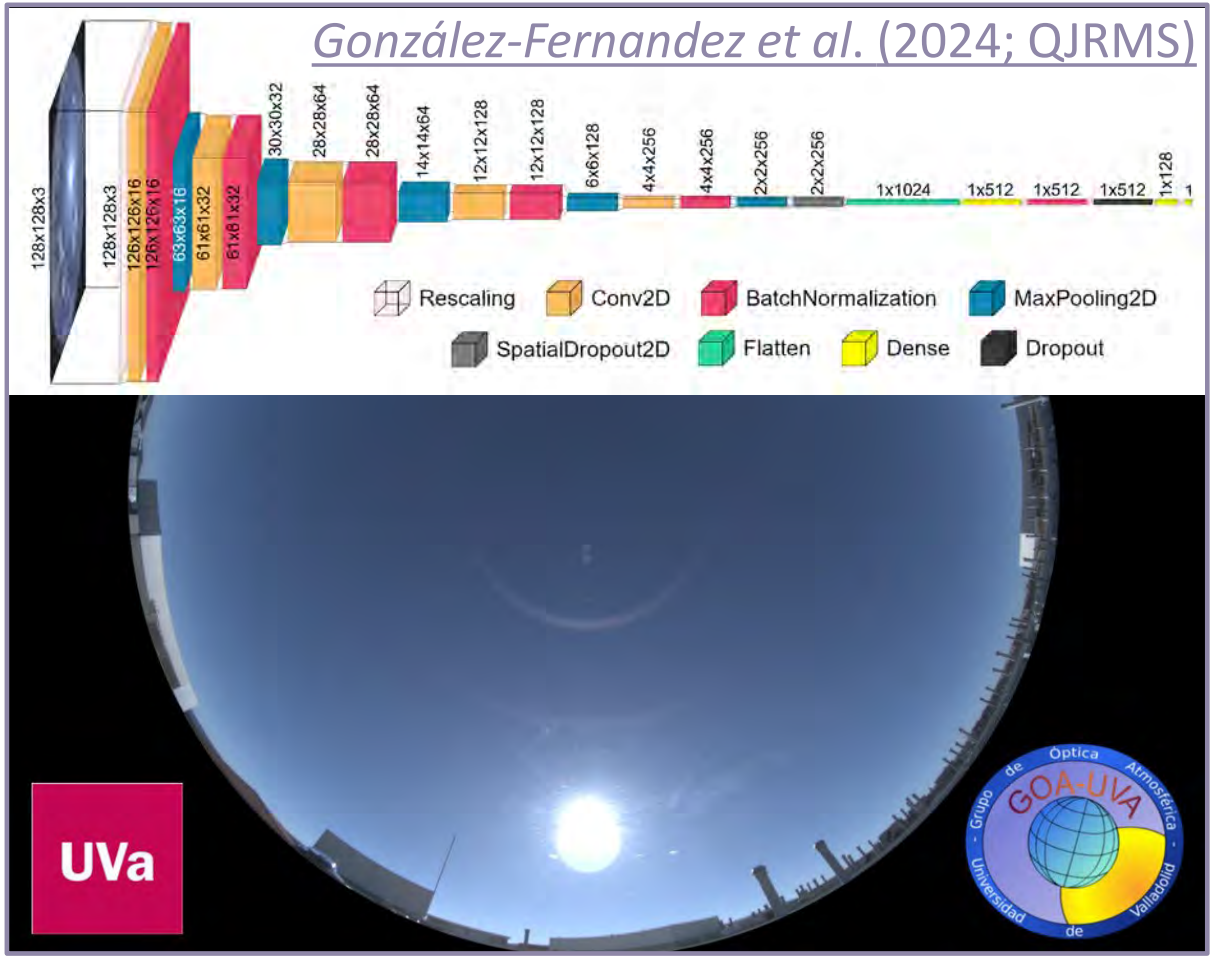
Cloud cover and segmentation.

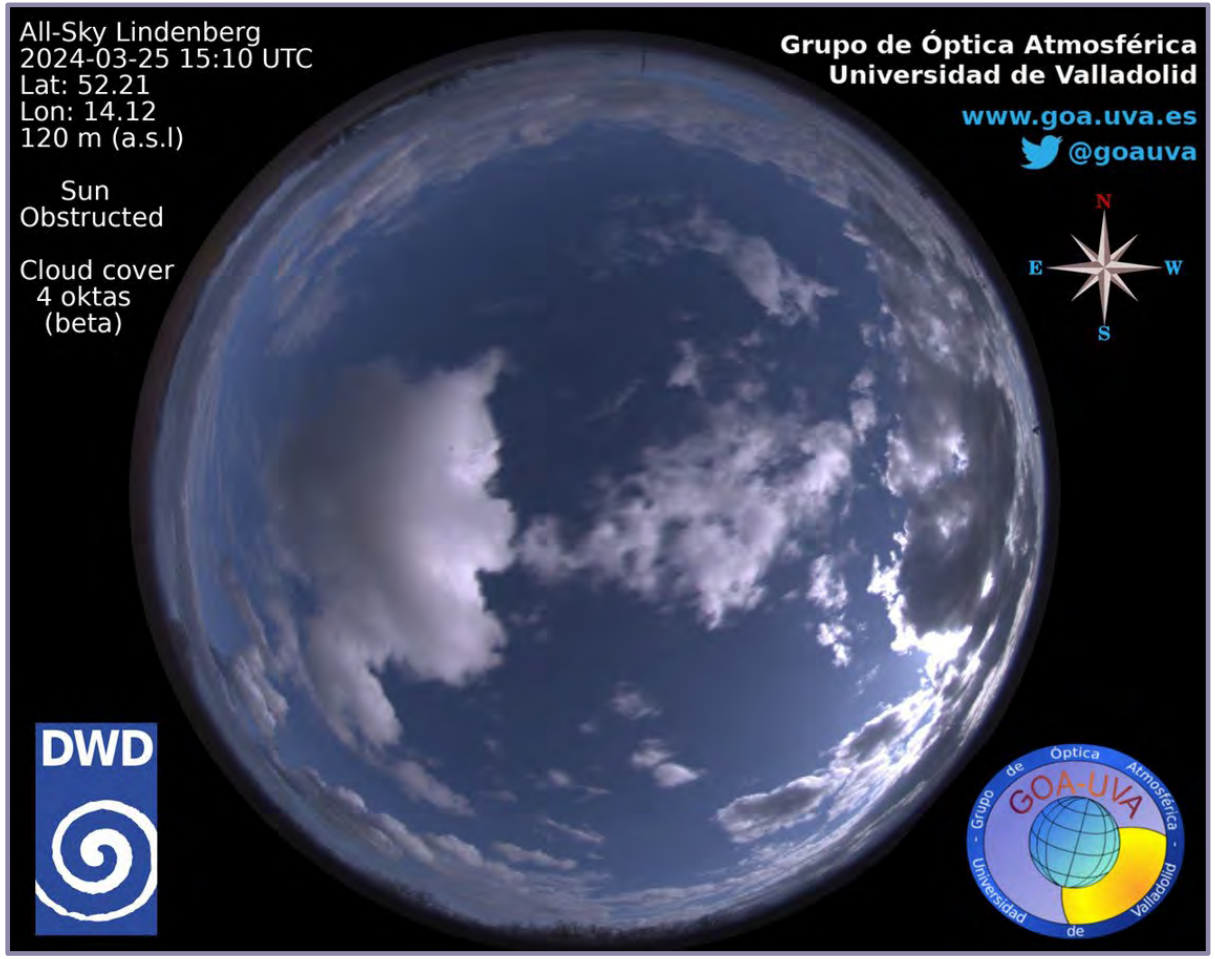




All-Sky Cameras

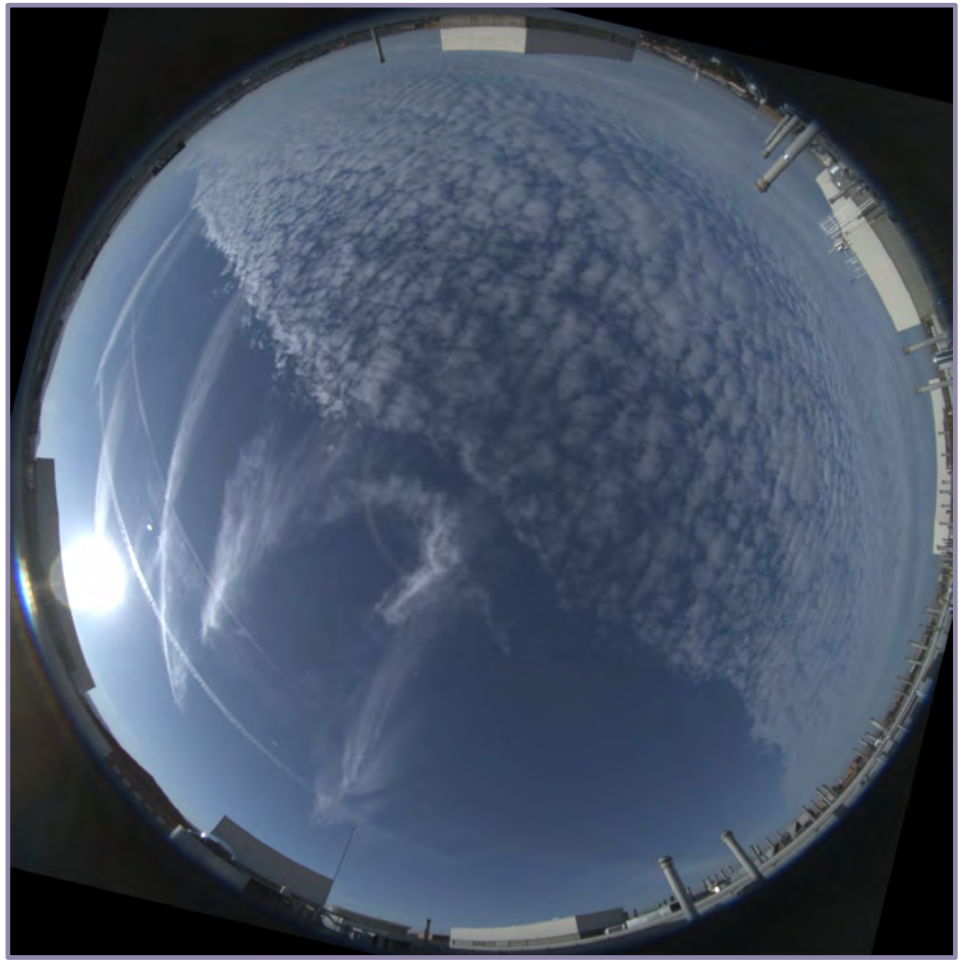
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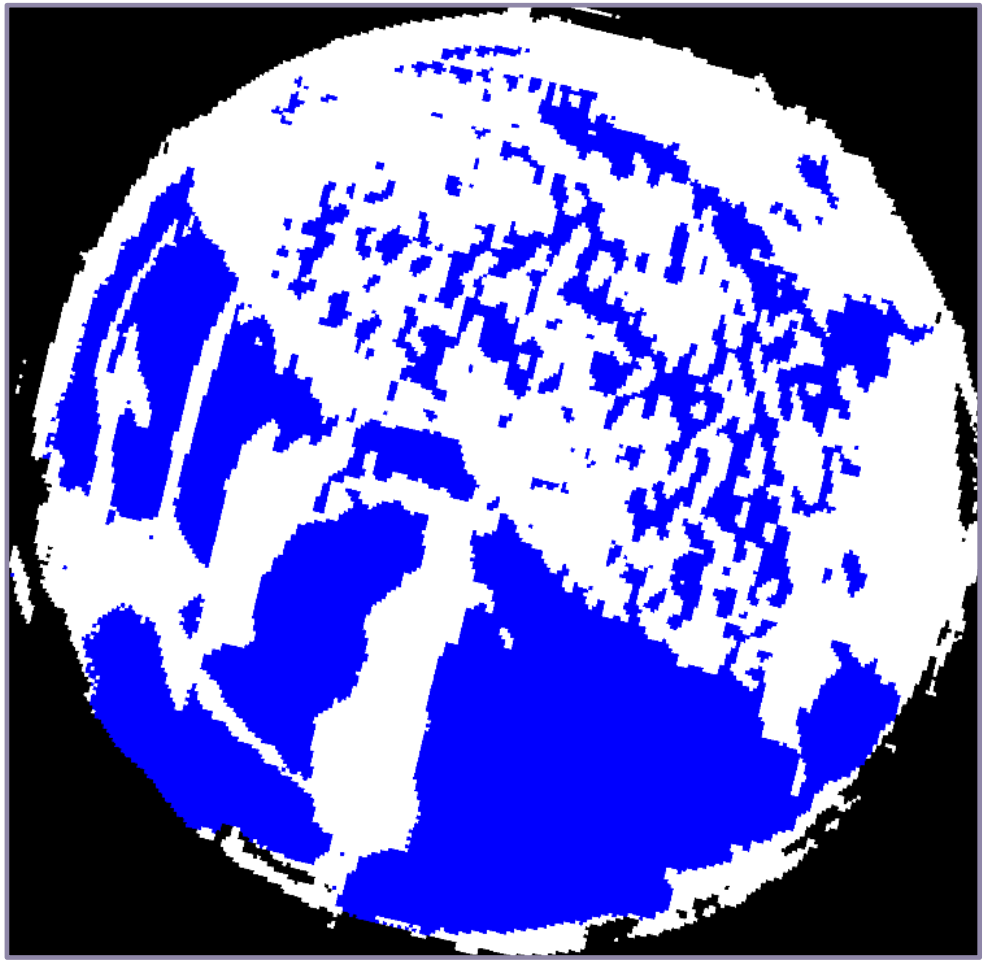




All-Sky Cameras

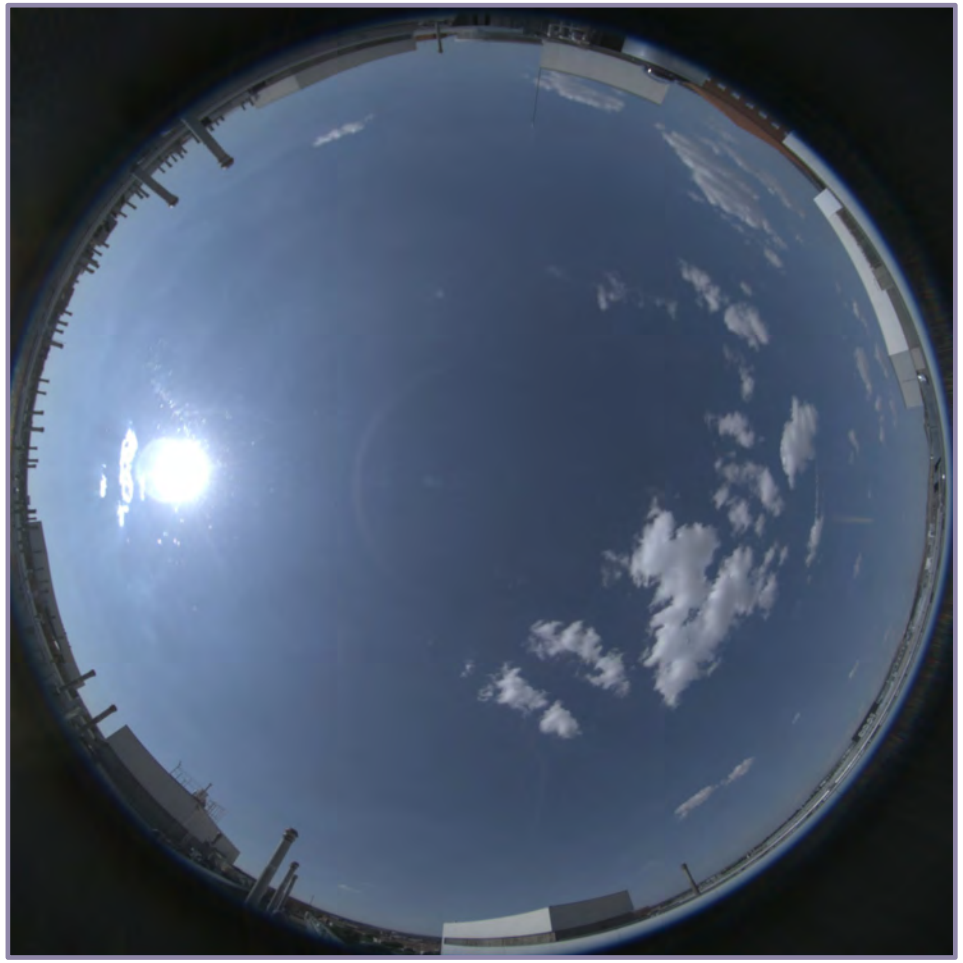
Cloud cover and segmentation.

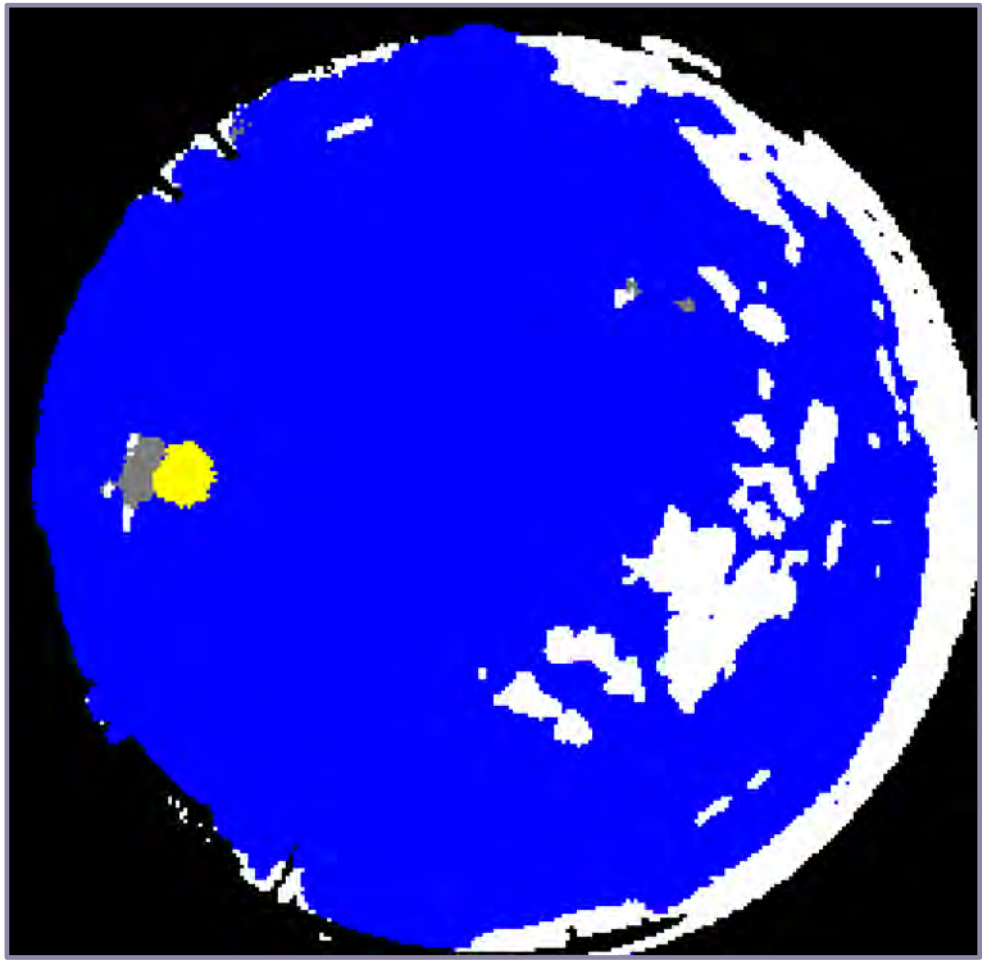




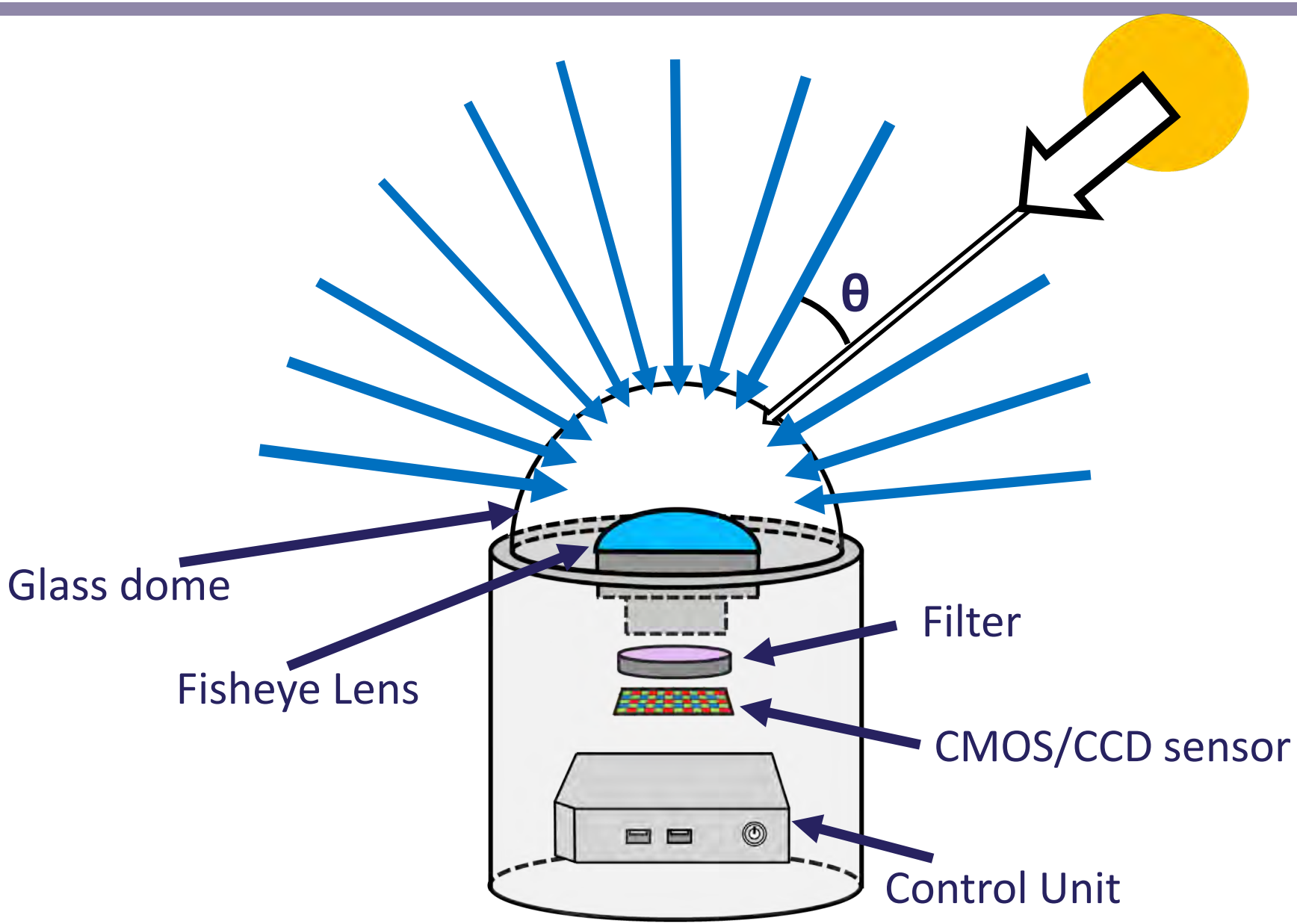
All-Sky Cameras

Cloud cover and segmentation.

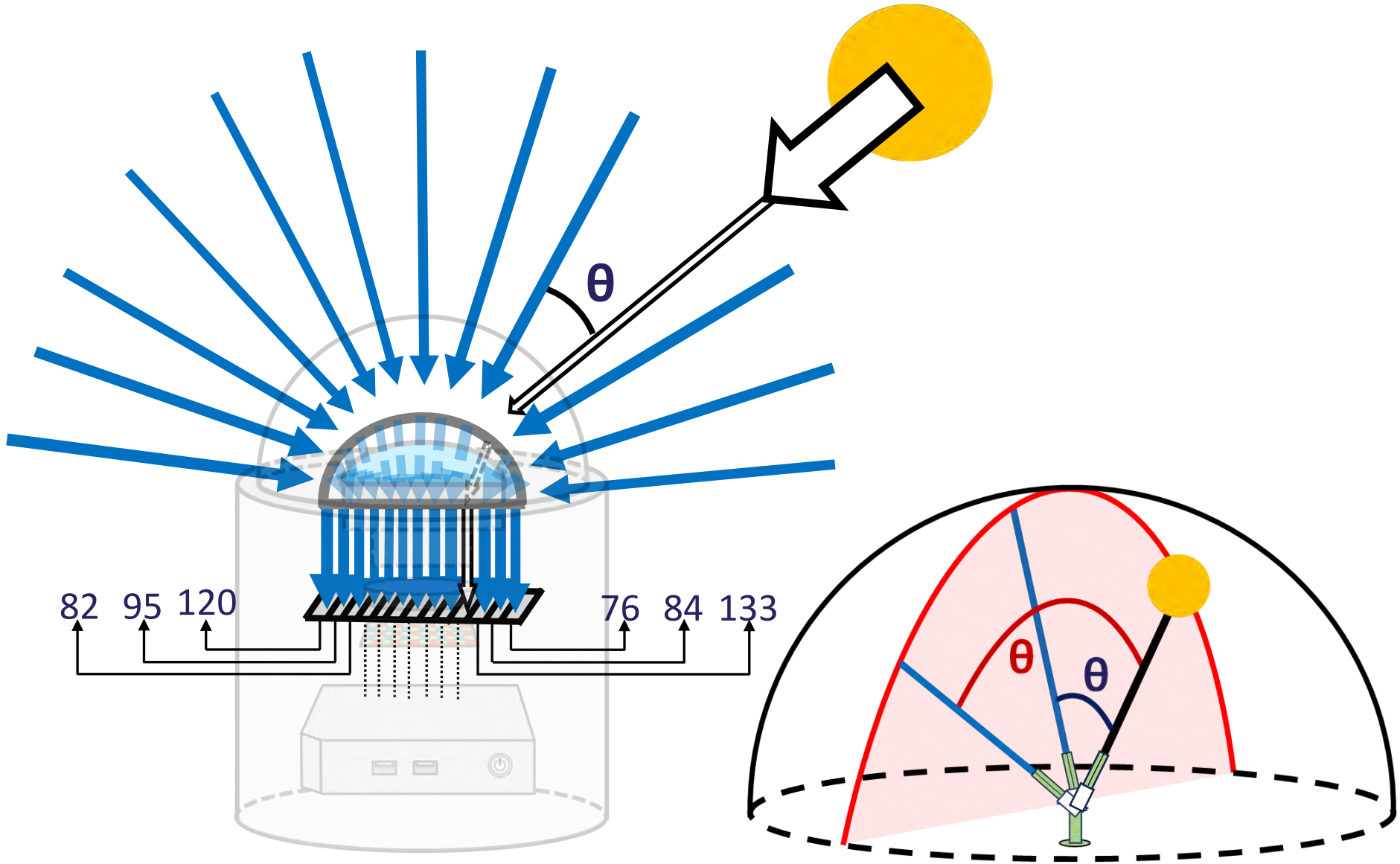




All-Sky Cameras

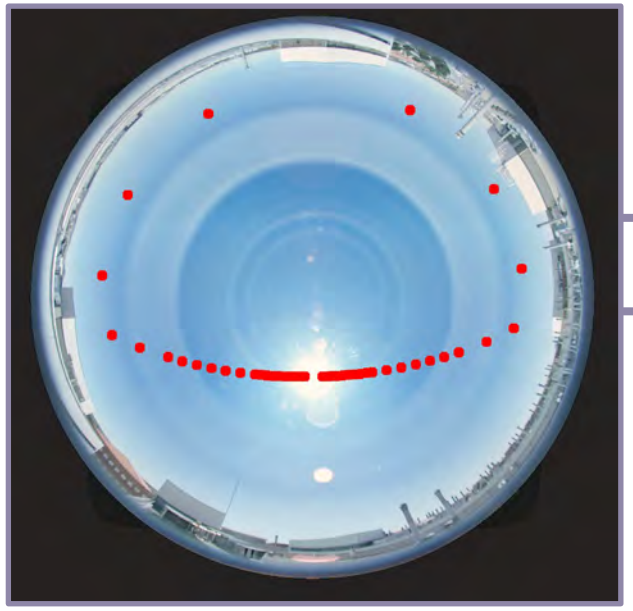


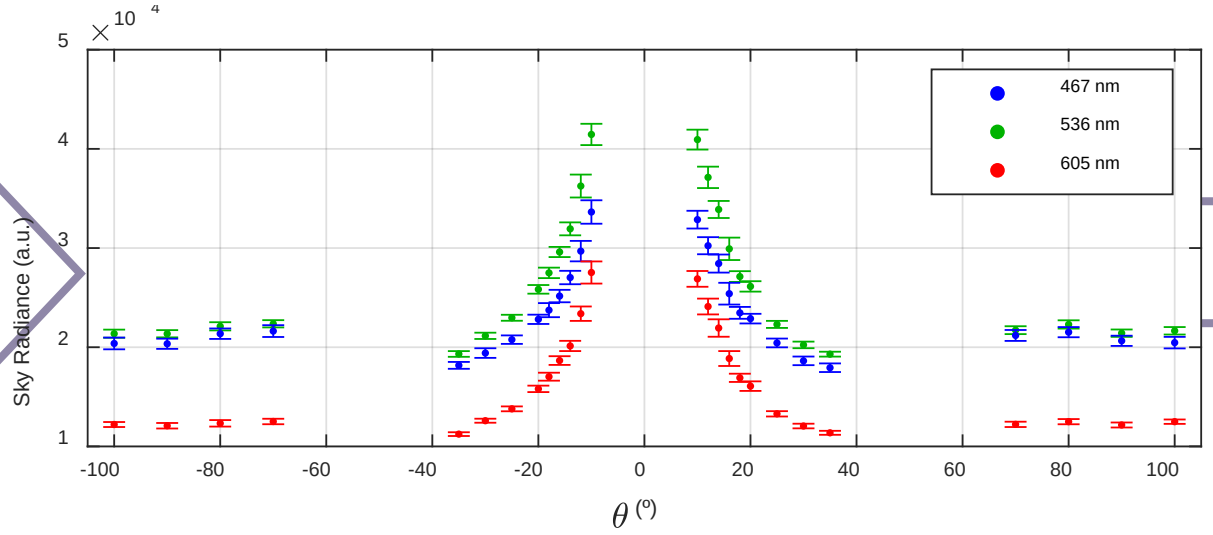
Sky Radiance



Sky Radiance and Aerosols

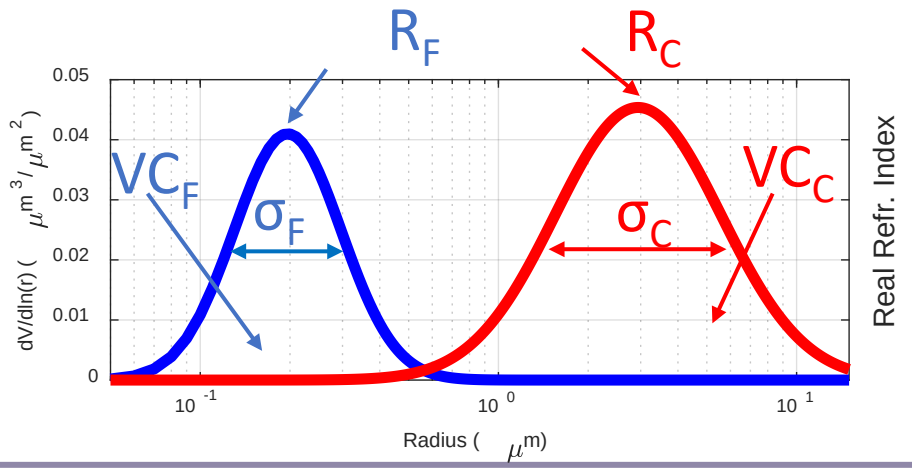
Estimate sky radiances and use them to retrieve **aerosol** properties (GRASP-CAM).

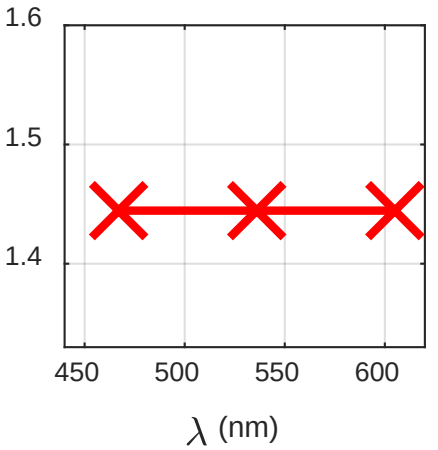


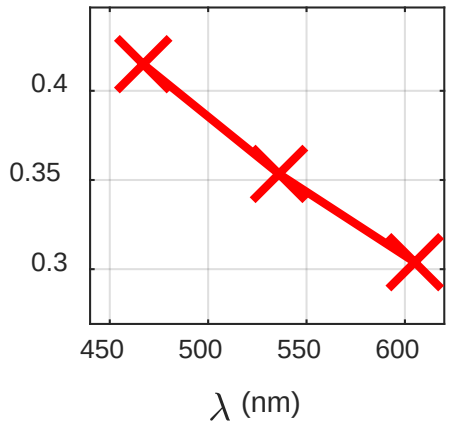


GRASP

Output





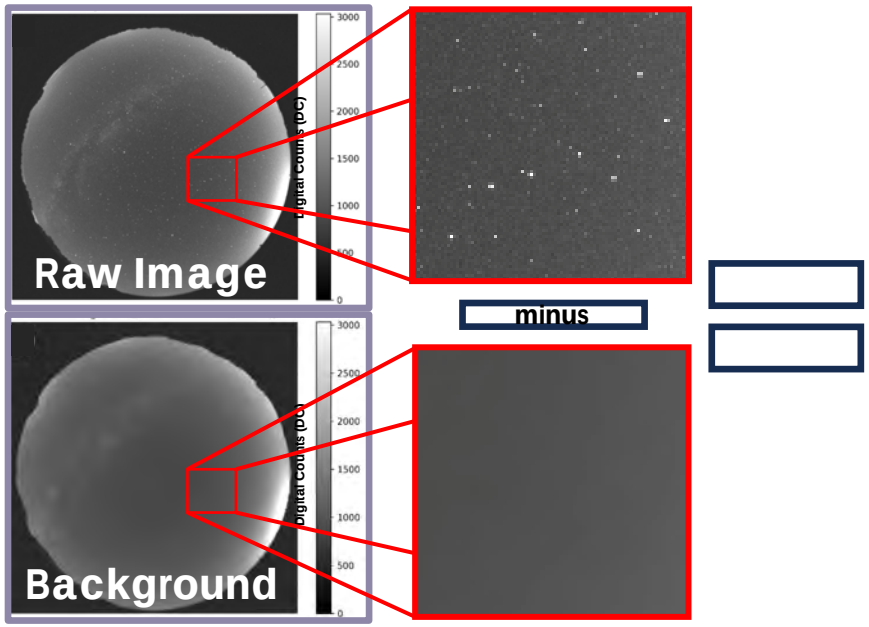


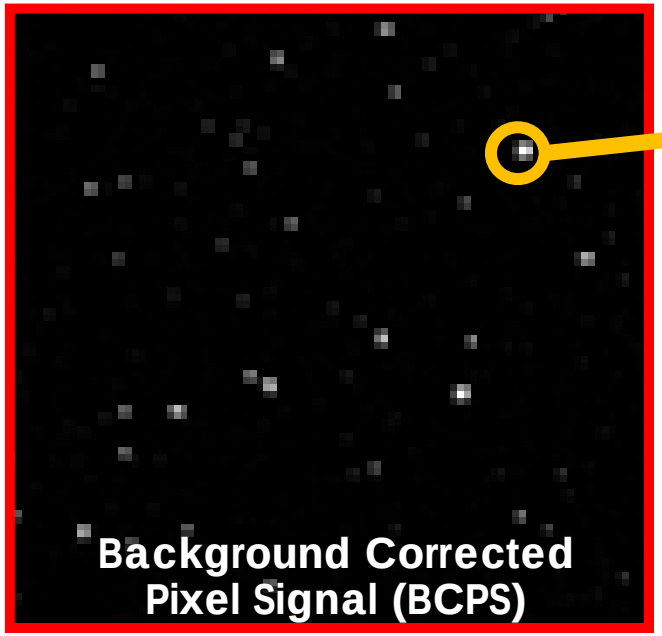
Antuña-Sánchez et al. (2021; AMT)

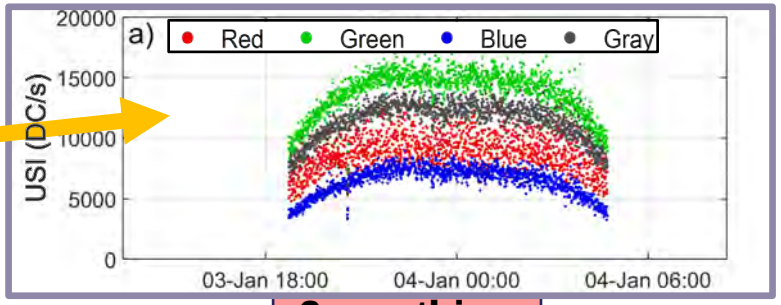
Román et al. (2022; AMT)

Sky Radiance and Aerosols

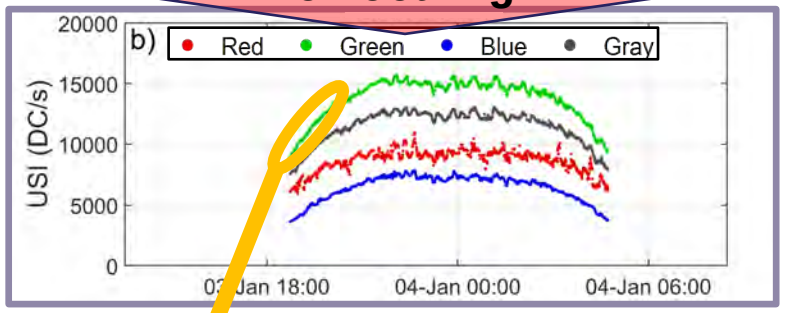
To estimate star irradiance and calculate **night-time AOD** by Langley calibration.



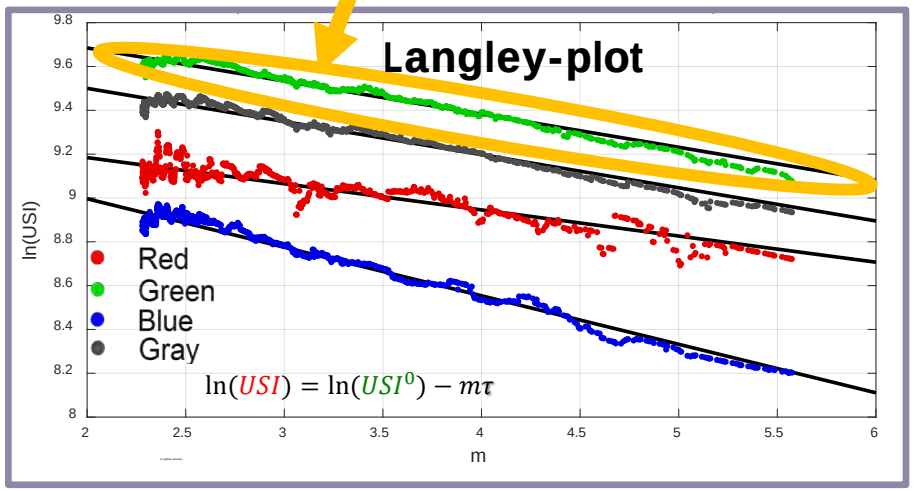




Smoothing

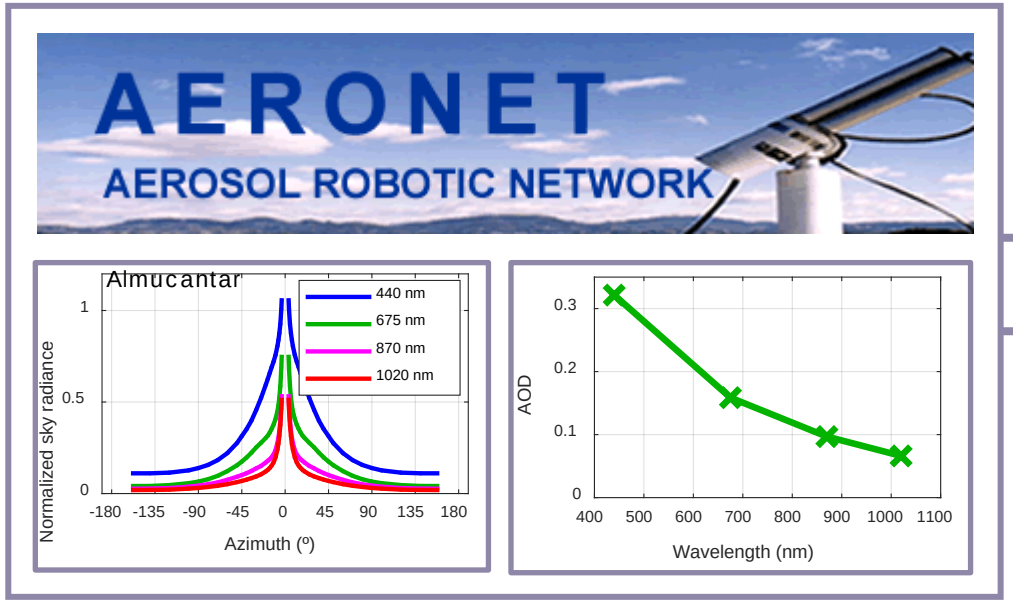


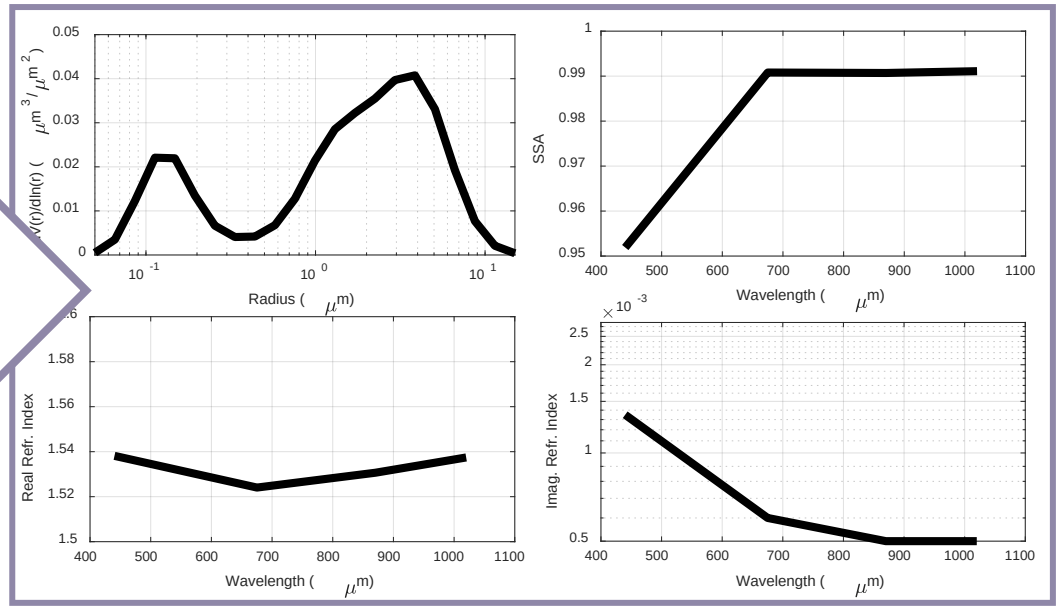
Uncalibrated star irradiance (USI) is extracted from images which background is removed. USI values are smoothed and used for Langleys for calibration factors that are used to convert USI in aerosol optical depth (AOD). *Román et al.* (2025; AMT)

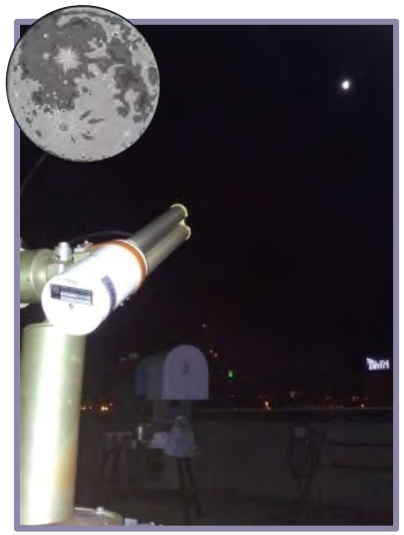


Sky Radiance and Aerosols









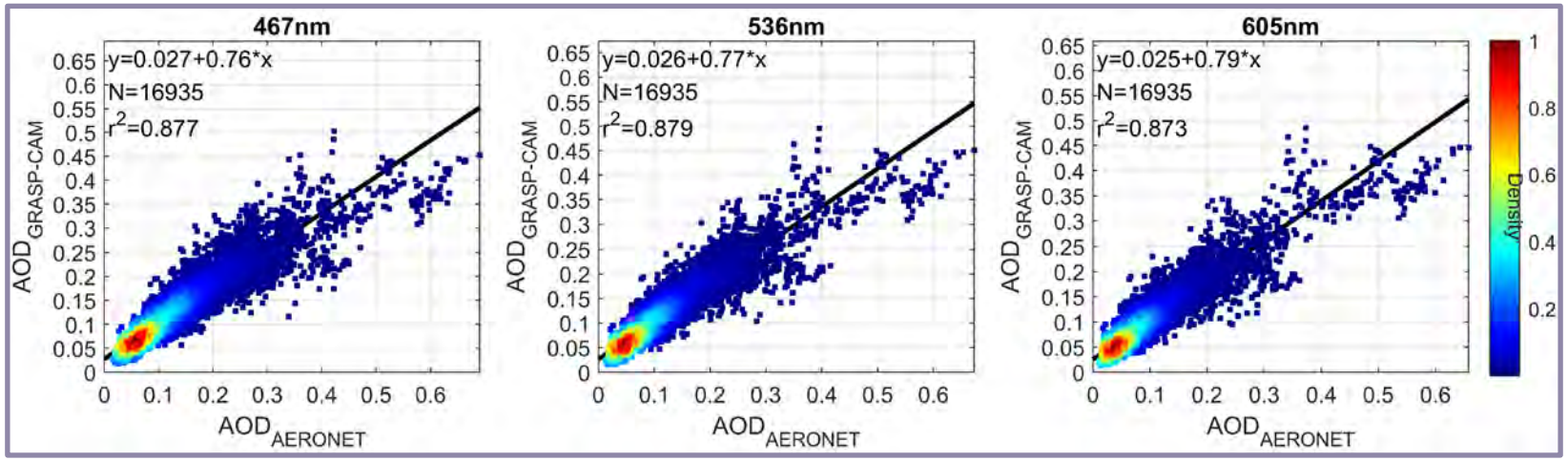
Photometers:

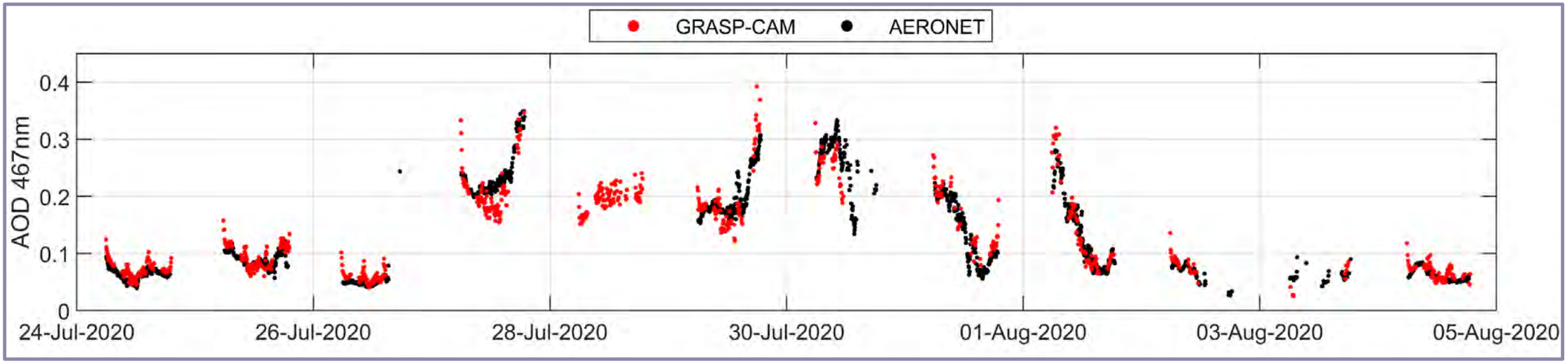
- **accurate** and **precise** measurements (absolute values, well calibrated)
- **Expensive**, **scan** angle by angle and λ by λ (**time consumption**)
- Scan **only various sky angles**.
- Night-time just with **Moon** and between **first and third quarter**.

Daytime Aerosols

Daytime AOD from **camera (GRASP-CAM) correlates well** with **photometer**.

This method estimates AOD values with a **precision** around **0.02-0.03**.

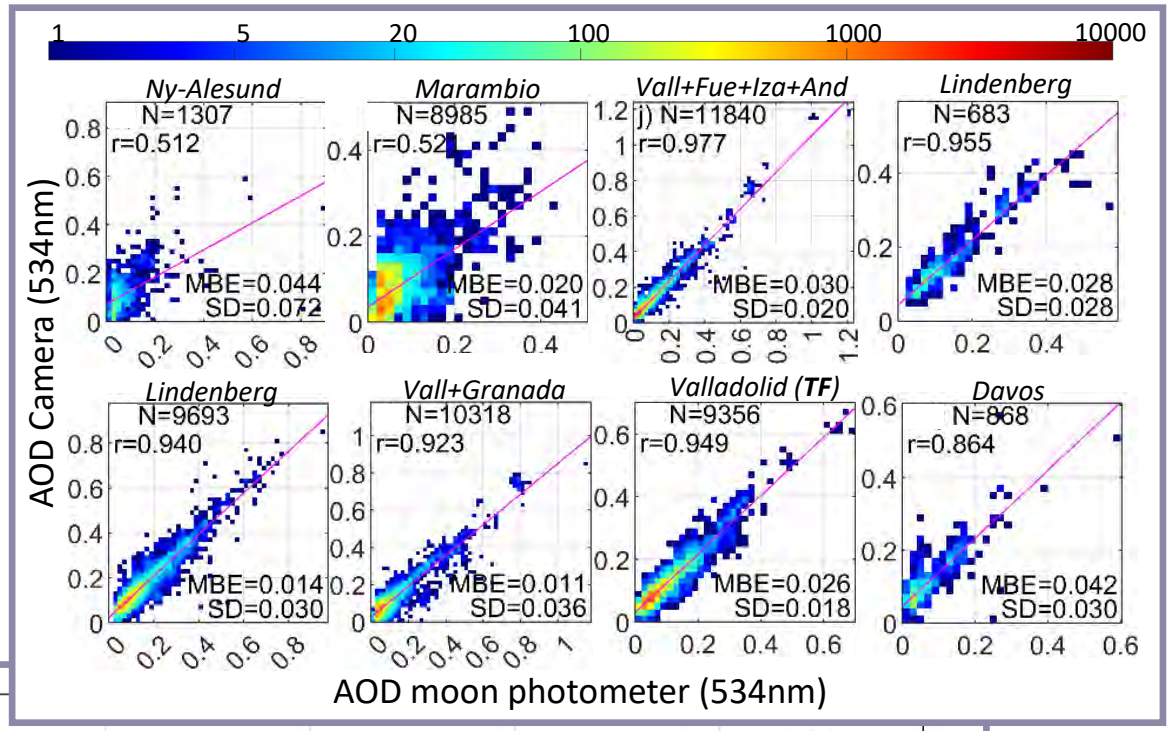


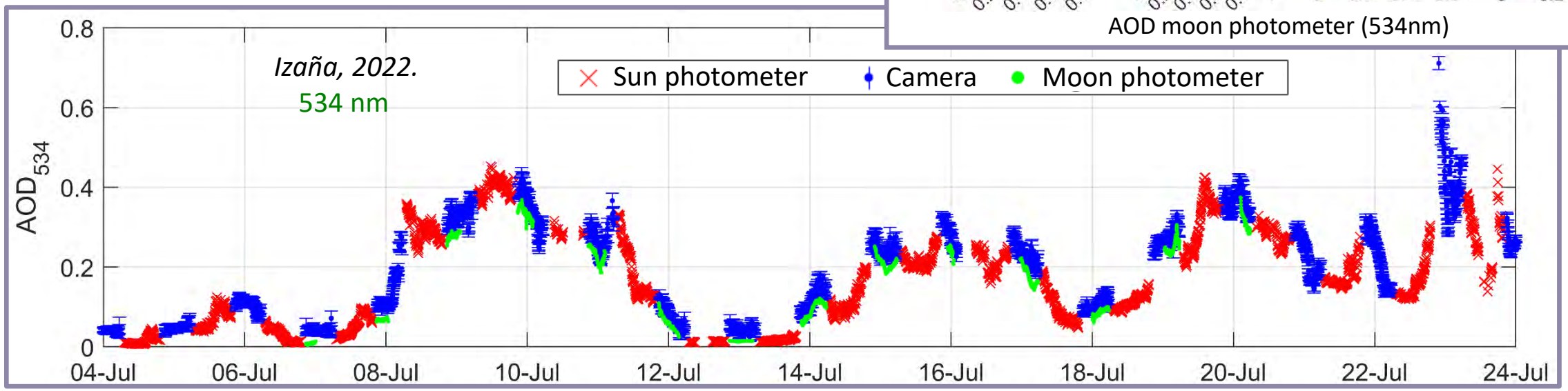


Night-time Aerosols

AOD at night-time from **camera correlates well** with **photometer** AOD in most of the studied locations.

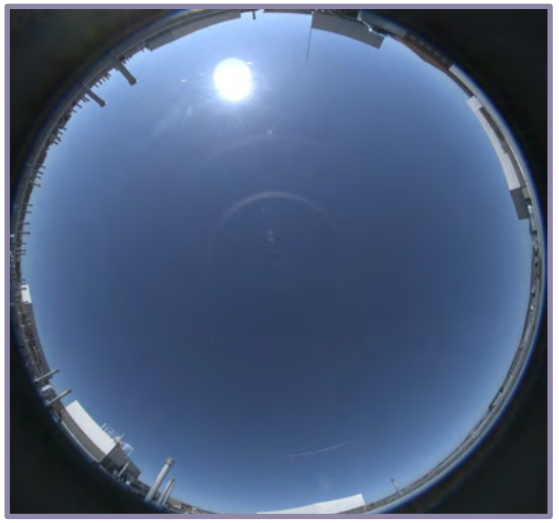
This method **overestimates** AOD values about **0.02** (MBE) with a **precision** around **0.03-0.04** (SD).

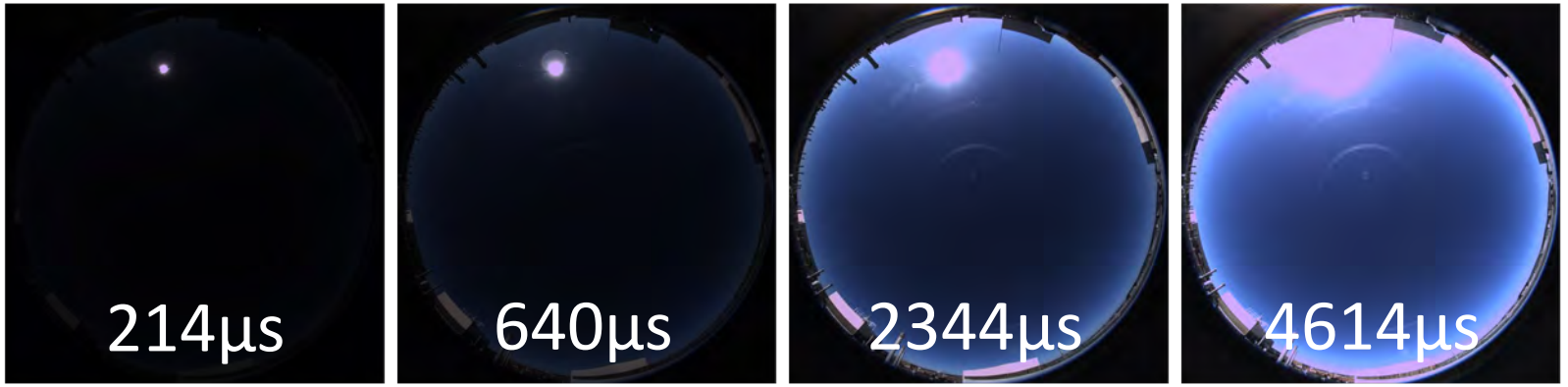




Advantages and Disadvantages

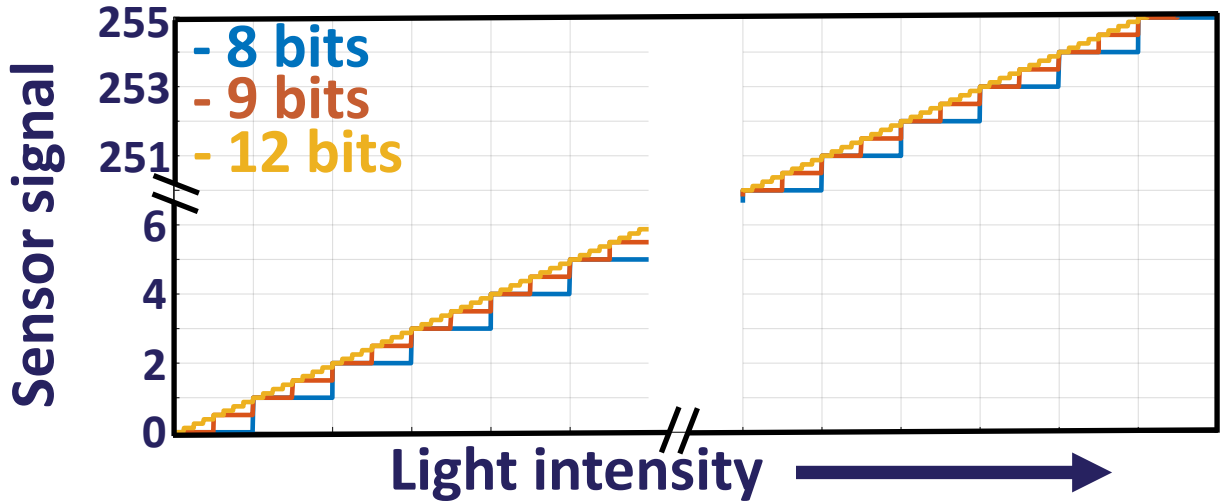
- **Cheaper**.
- **Full** and **quasi-instantaneous scan** of the sky.
- **Various wavelengths** simultaniously.
- Possibility to change **exposure time** and **gain: High Dynamic Range.**





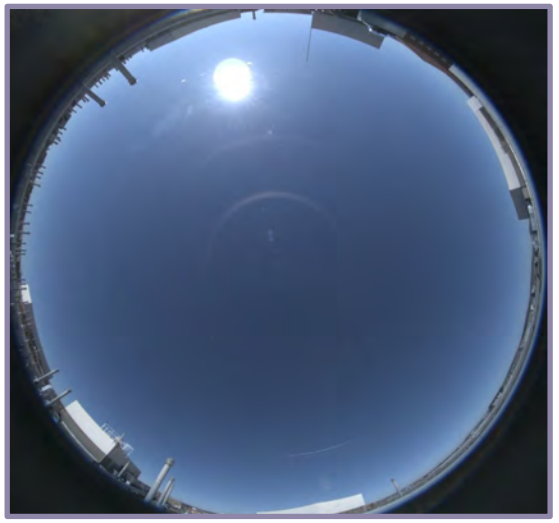
- **Less accurate and precise.**
- **Less resolution.** **RAW images!**

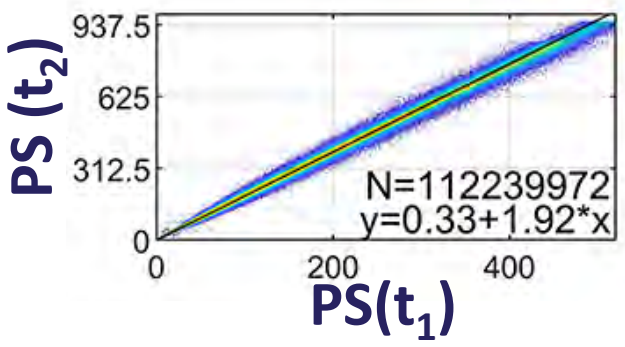
SOLVED

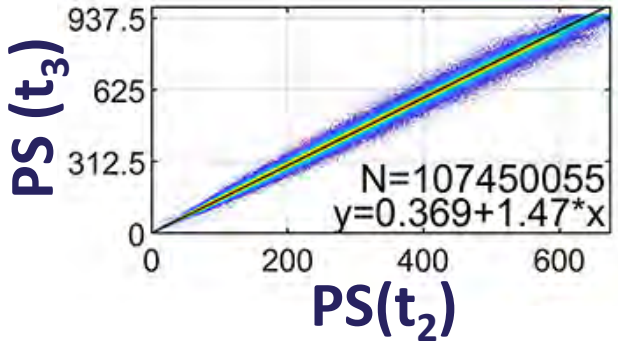


Advantages and Disadvantages

- **Cheaper**.
- **Full** and **quasi-instantaneous scan** of the sky.
- **Various wavelengths** simultaniously.
- Possibility to change **exposure time** and **gain: High Dynamic Range.**



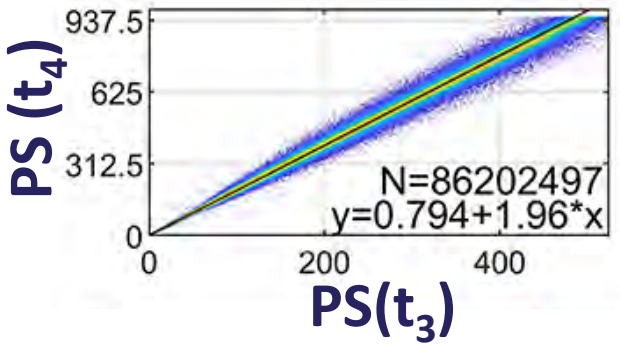


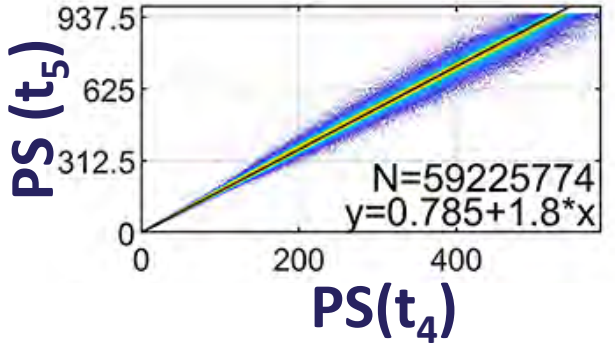


- **Less accurate and precise.**

SOLVED - **Less resolution.** **RAW images!**

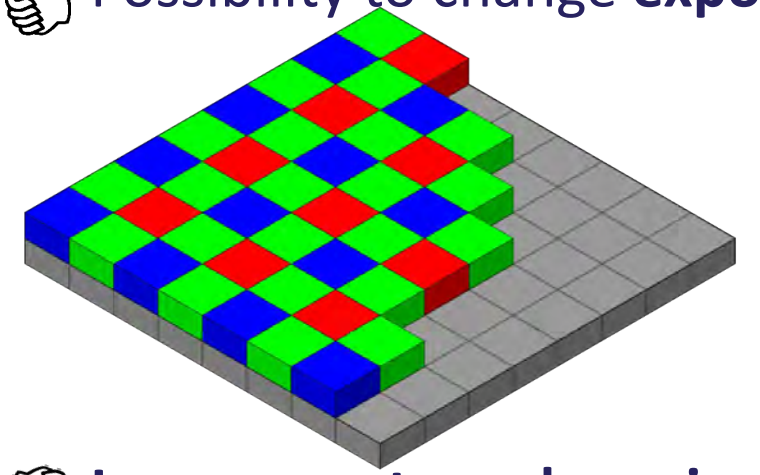
SOLVED - **Linearity.** **Can be calculated**

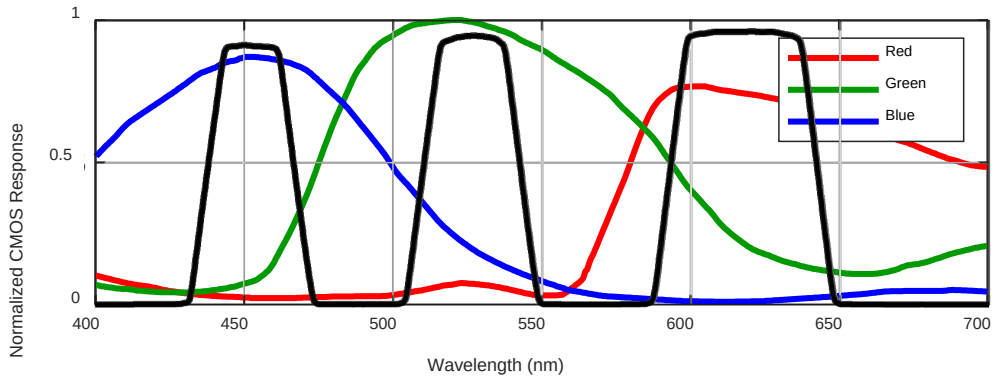


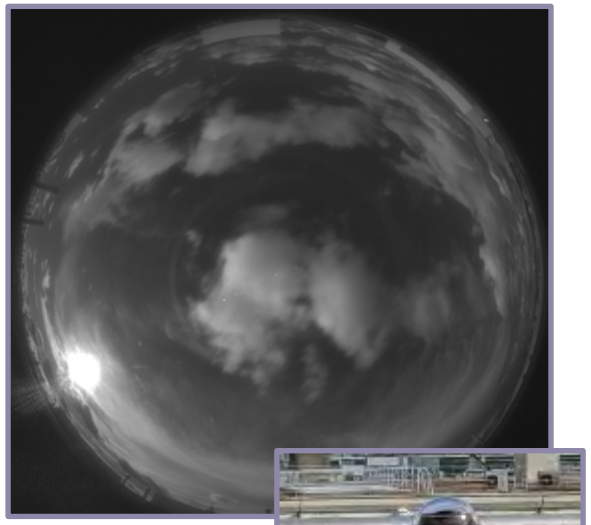


Advantages and Disadvantages

- **Cheaper**.
- **Full** and **quasi-instantaneous scan** of the sky.
- **Various wavelengths** simultaniously.
- Possibility to change **exposure time** and **gain: High Dynamic Range.**









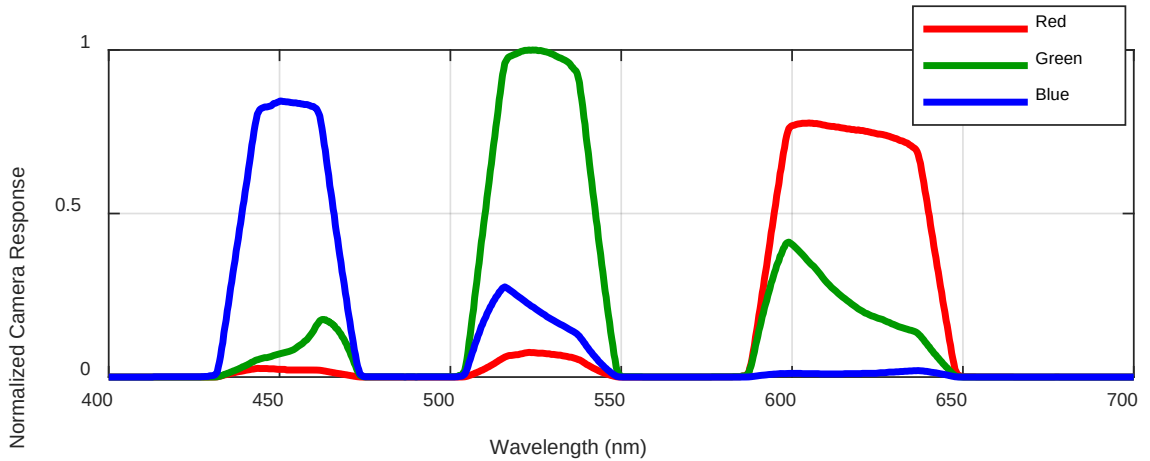
- **Less accurate and precise.**

SOLVED - **Less resolution.** **RAW images!**

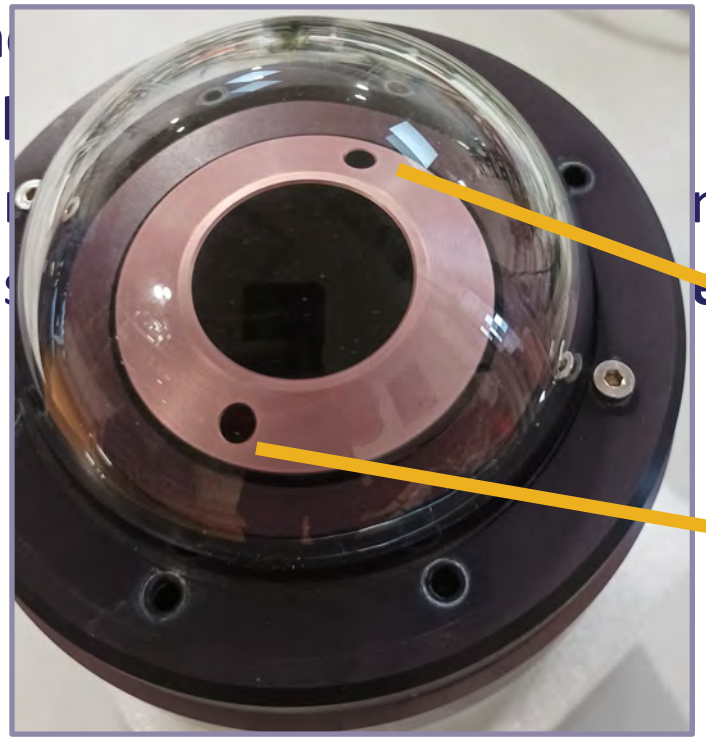
SOLVED - **Linearity.** **Can be calculated**

SOLVED - **Wide spectral response.** **Effective wavelengths**

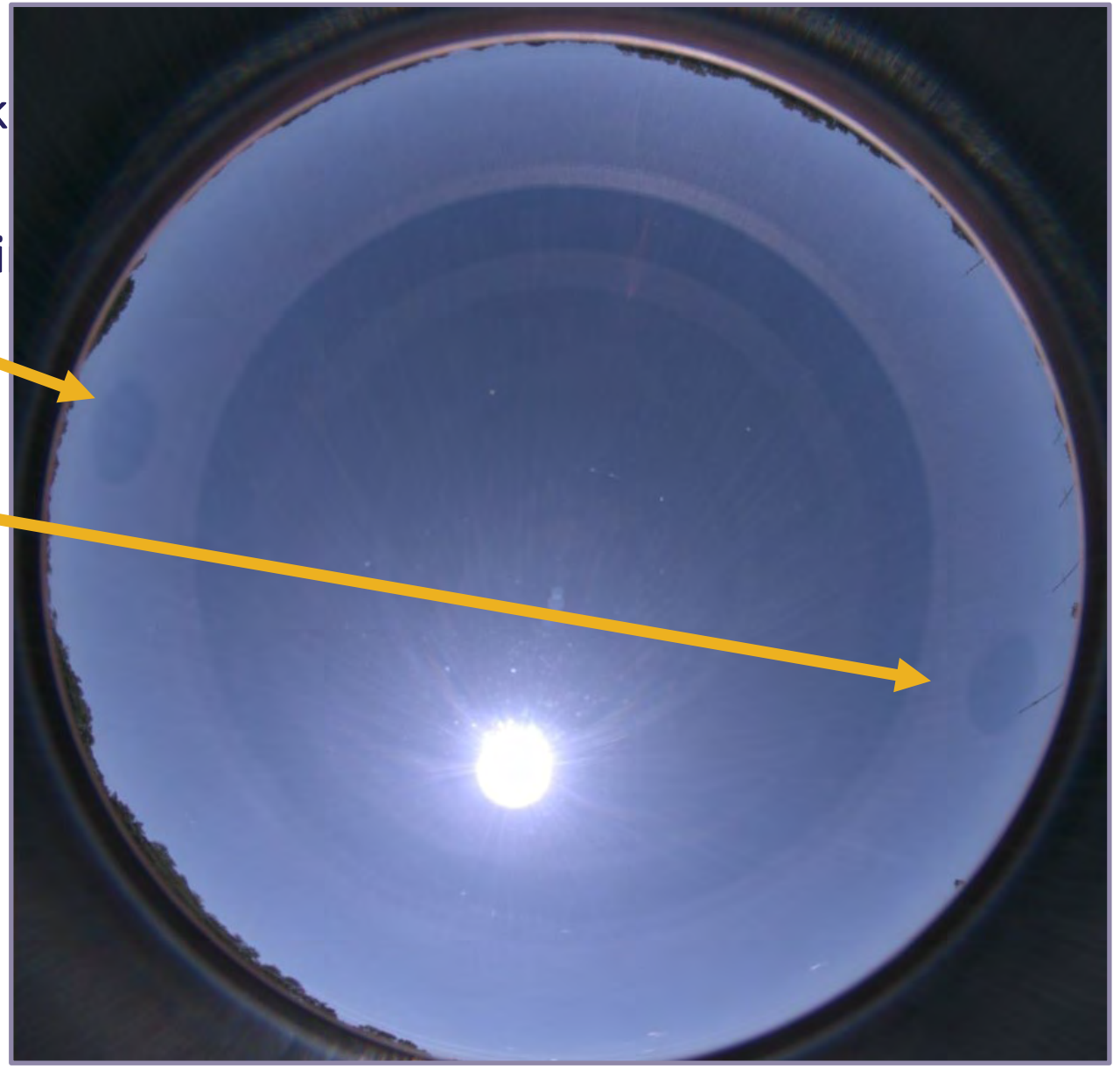
$$\lambda_e = \frac{\int_\lambda \lambda I(\lambda) S(\lambda) d\lambda}{\int_\lambda I(\lambda) S(\lambda) d\lambda}$$



Advantages and Disadvantages



- Ch
- Ful **scan** of the sk
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- Pos **time** and **gai**

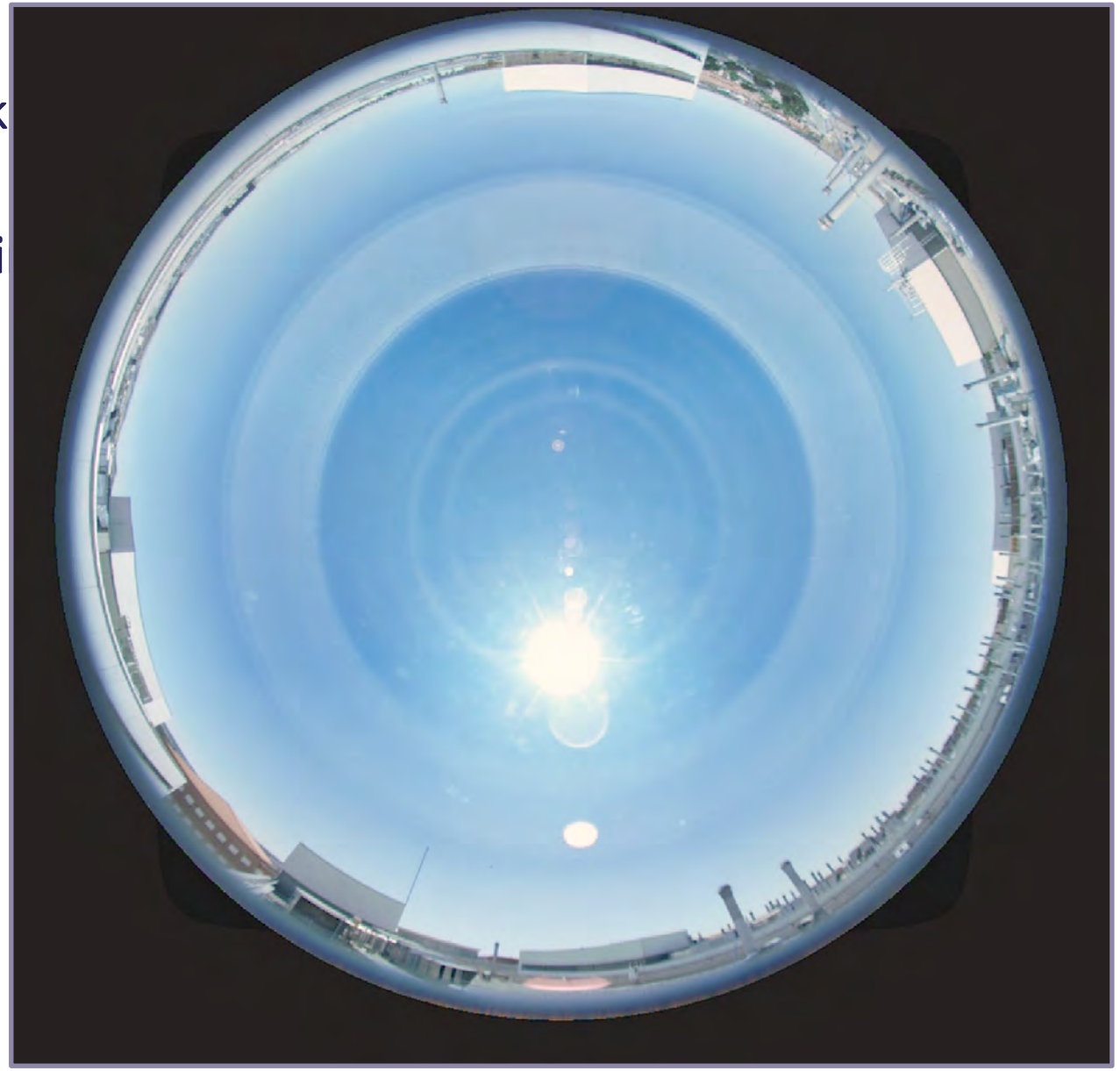


- Less accurate and precise.
  - Less resolution. **RAW images!** SOLVED
  - Linearity. **Can be calculated** SOLVED
  - Wide spectral response. **Effective wavelengths** SOLVED
  - Reflections in the dome.

Advantages and Disadvantages



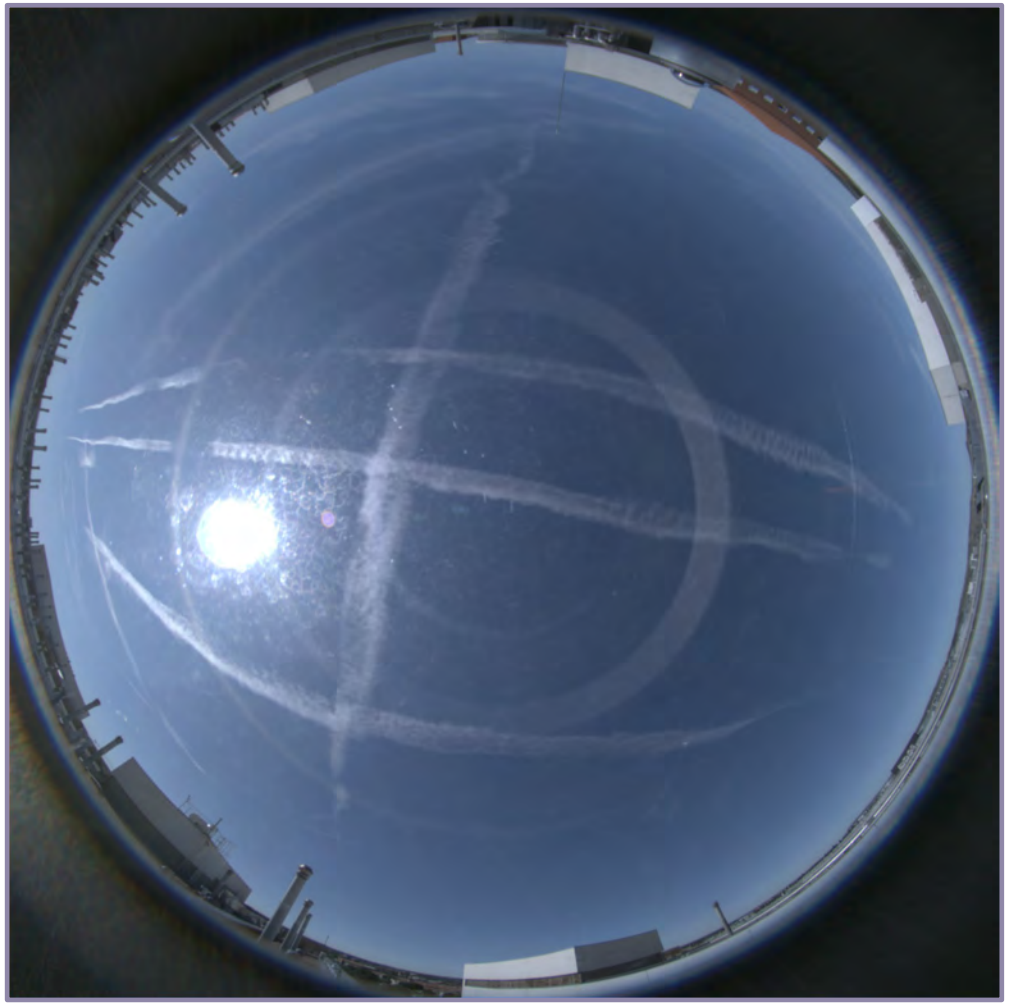
- Ch
- Ful **scan** of the sk
- Va niously.
- Pos **e time** and **gai**

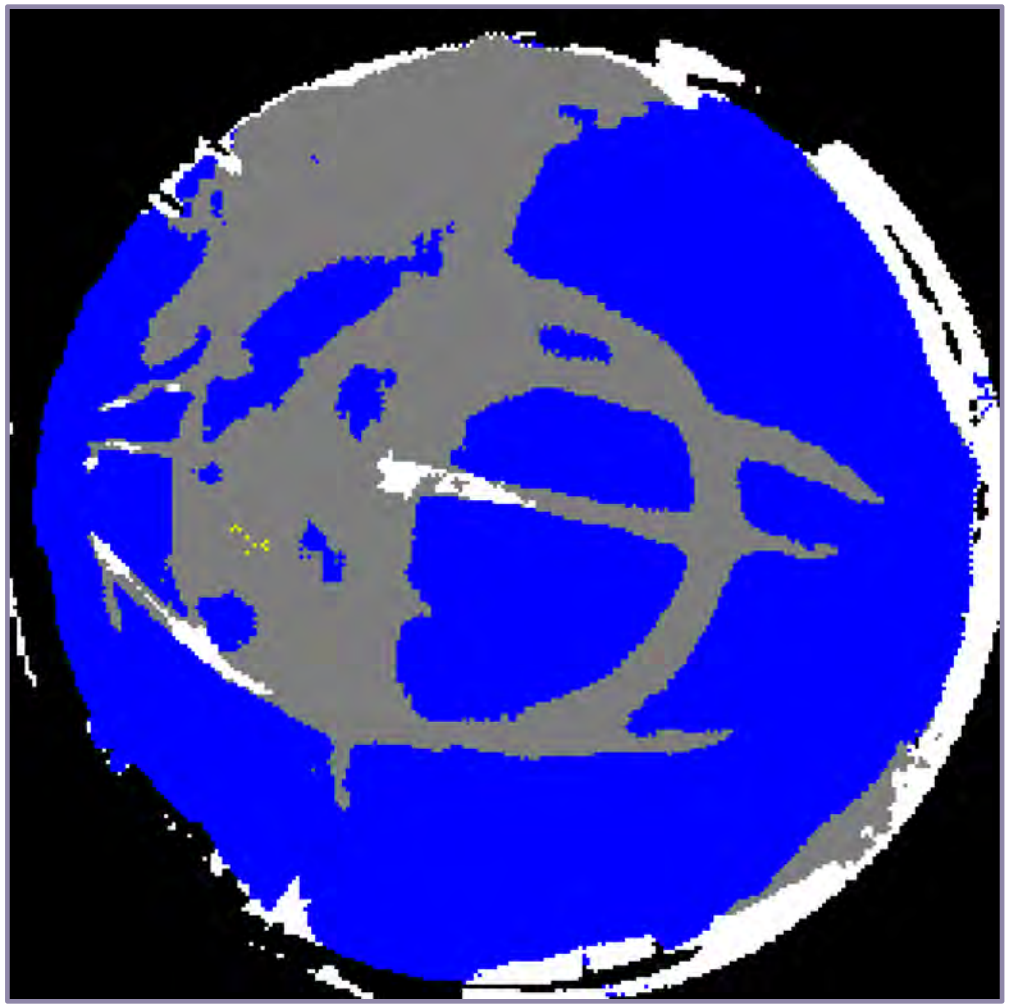


- **Less accurate and precise.**
  - **Less resolution.** **RAW images!** (SOLVED)
  - **Linearity.** **Can be calculated** (SOLVED)
  - **Wider spectral response.** **Effective wavelengths** (SOLVED)
  - **Reflections in the dome.**

Dome Reflections

Dome reflections can be misinterpreted as cloud.





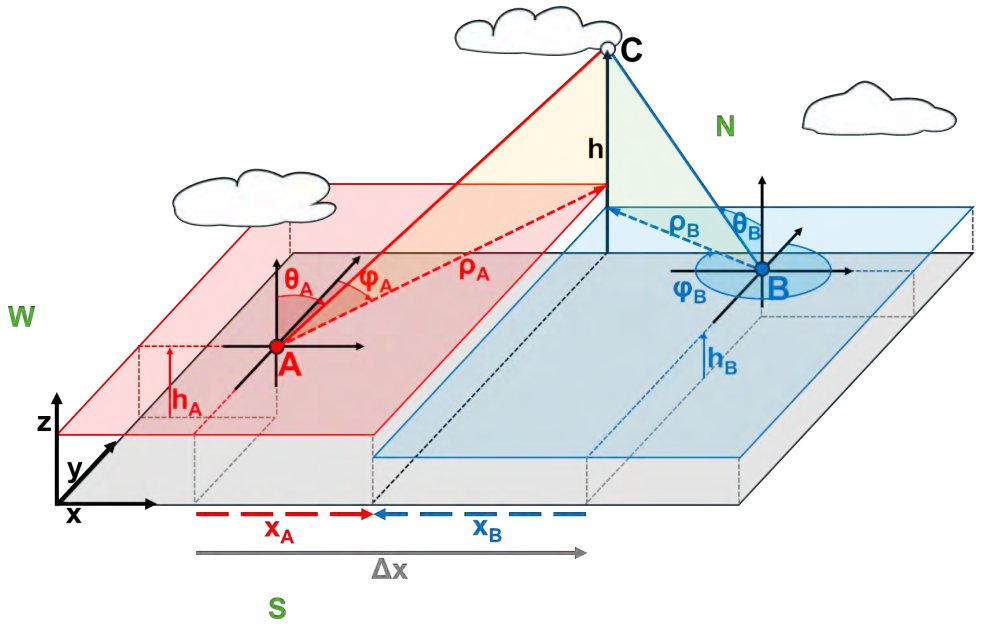
3D Cloud reconstruction

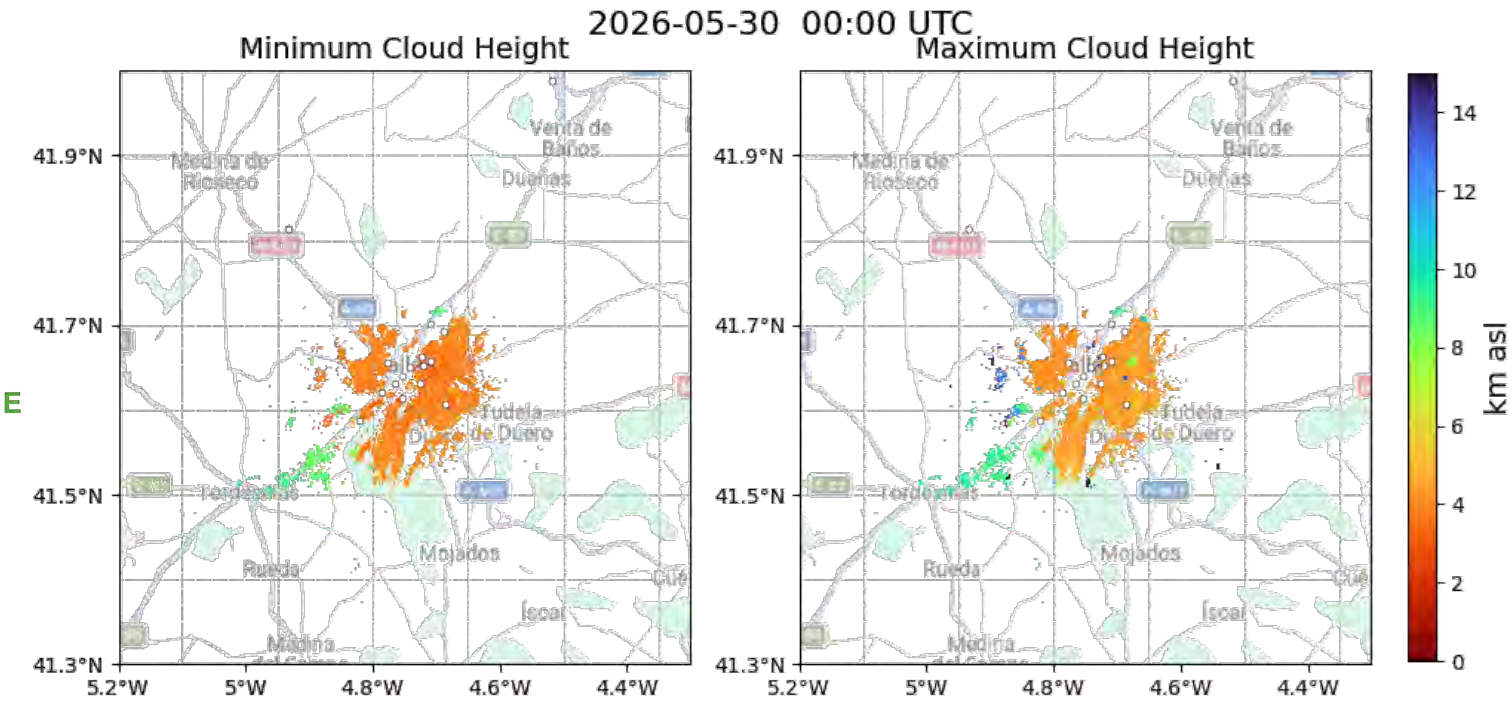


<u>20 all-sky cameras</u> (OMEA-3C-TF) over **Valladolid**

- **Stereophotogrammetry** of clouds.
- <u>Maps</u> of **cloud base** (CBH) and **top** (CTH) **heights**.
- <u>Dome reflections</u> can create <u>fake clouds</u>!!

<u>Herrero del Barrio et al. (2026; AMT)</u>





Birds

Need to **prevent** the **presence of birds** like pigeons in the dome.



Birds

Options: **Plastic decoy birds** (crows) used to scare away other birds.





Birds

Options: **Shiny reflective strips** and streamers.





Birds

Options: **Reflective wind spinners** that move with the wind.

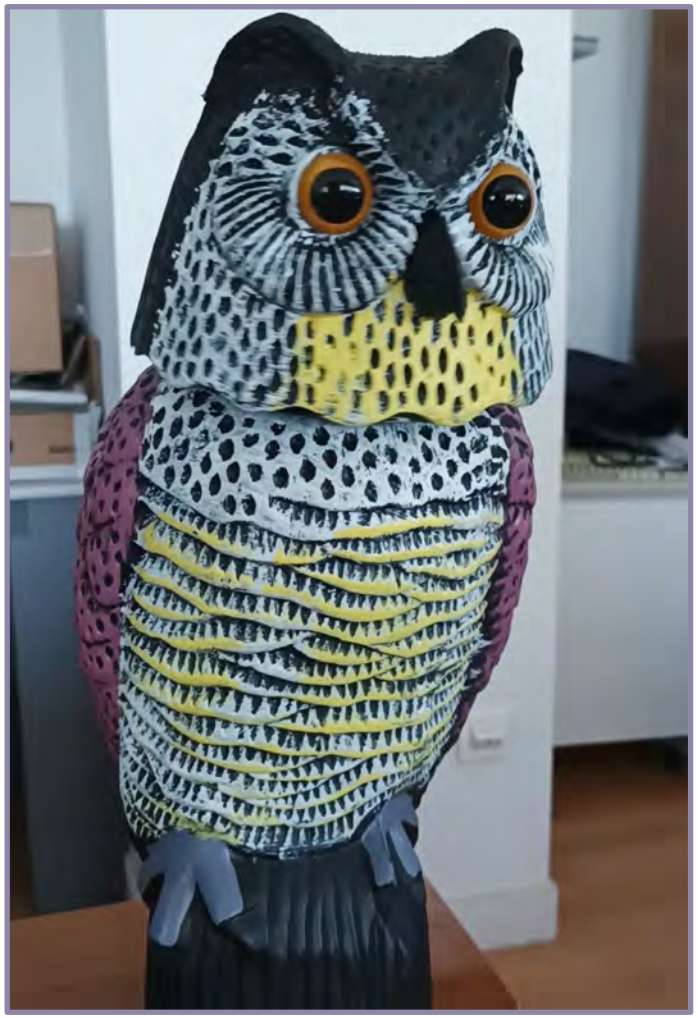




Birds

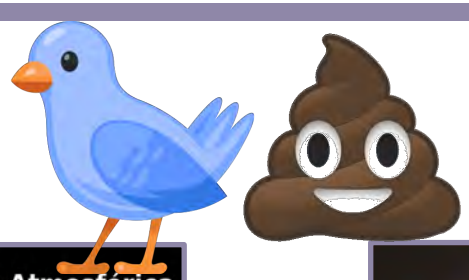
Options: **A decoy owl** with a wind-activated **rotating head.**



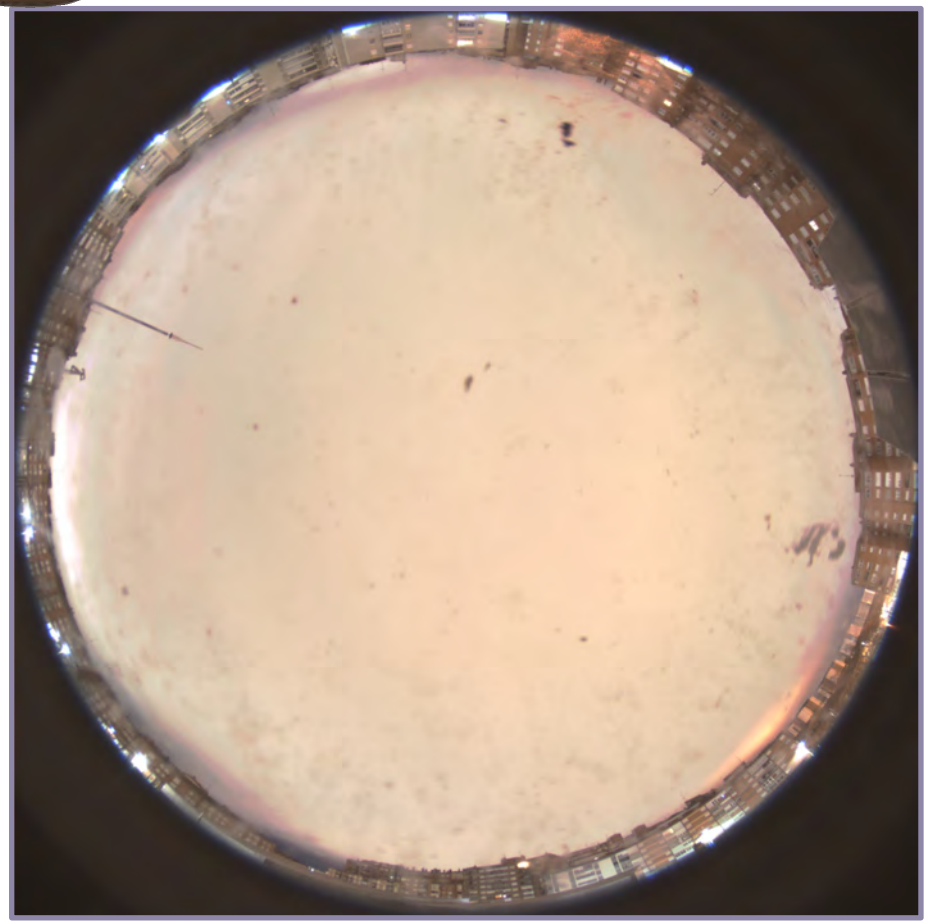


Dirt

The main problem:

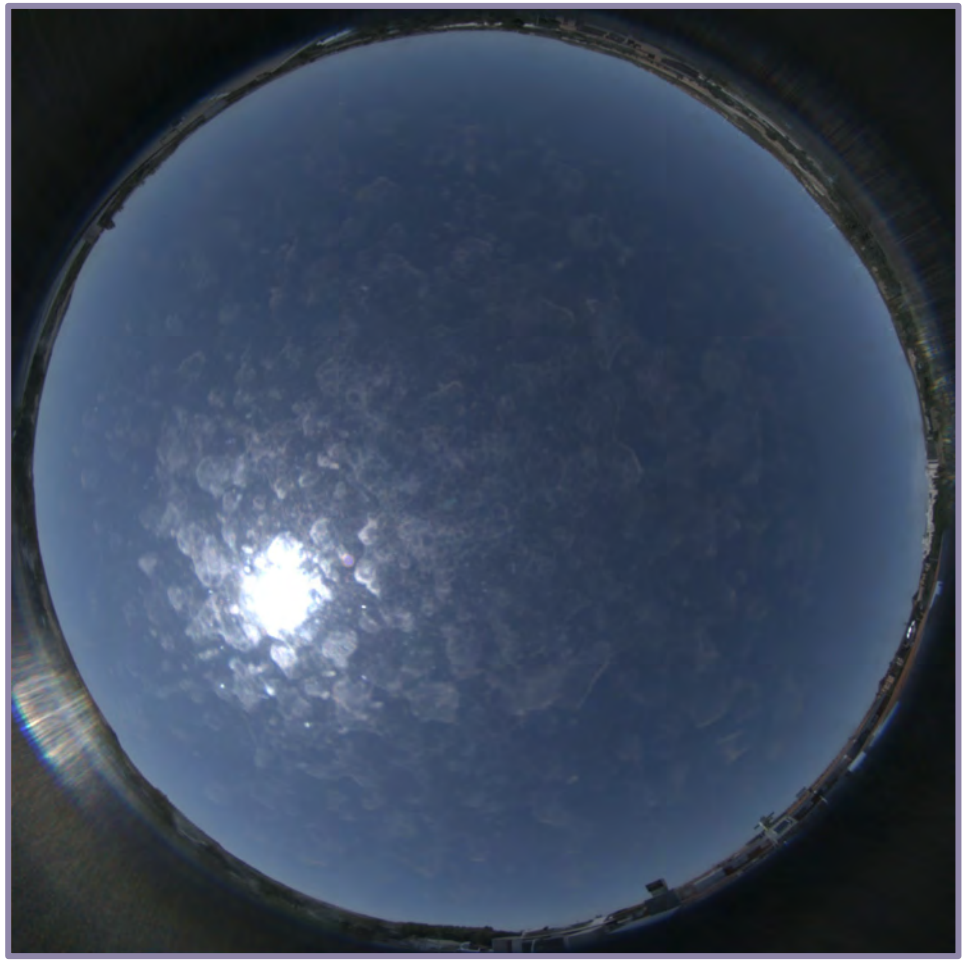


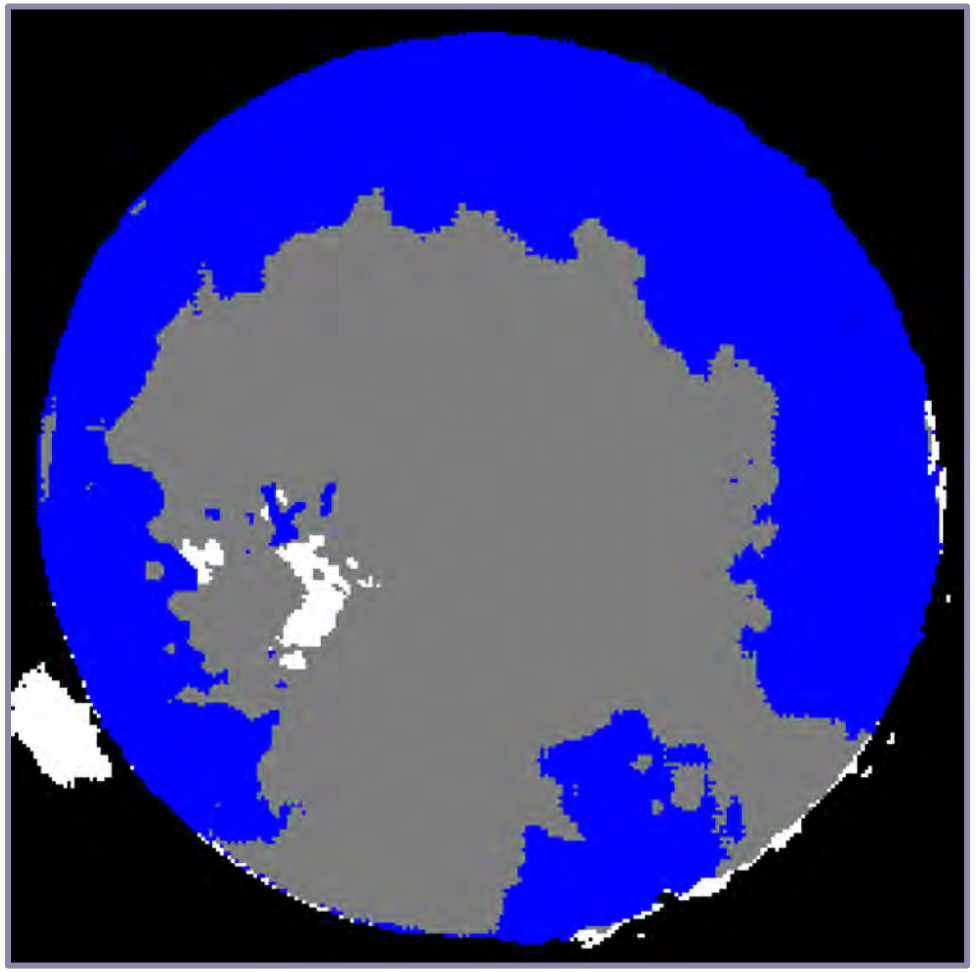




Cleaning

Animals (birds, spyders…), **dust** and **rain** (heating system needed). Cleaning tasks are crucial.





Geometric Calibration

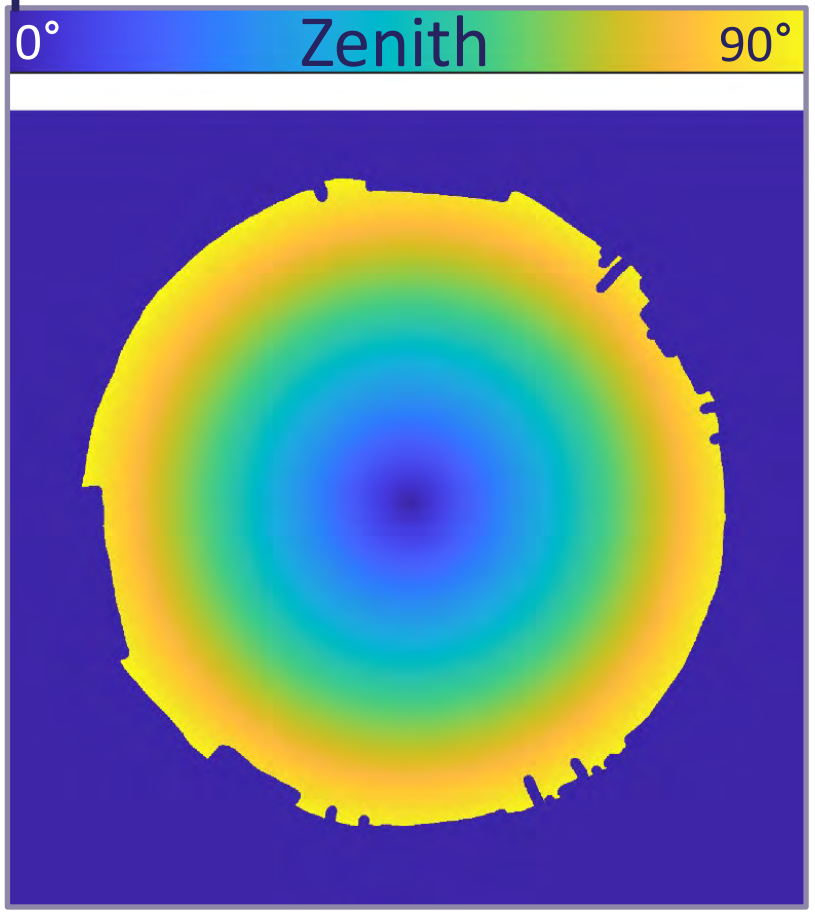
If we want to locate any direction (almucantar, …) or body (stars, Moon, …) in the images, we need to know the **zenith** and **azimuth** of each pixel.

ORION APP



https://goa.uva.es/orion-app/

Antuña-Sánchez et al. (2022; PlosOne)





Summarize

All-sky cameras can be used for **multiple applications** (aerosols, clouds, solar energy, northern lights, fireballs…).

The needs vary with the application but **in any case is better**:

- To allow the **control** of all parameters like **exposure time** or **ISO**.
- To **capture and store raw images**, preferably with high depth resolution (at least 12-14 bits).
- The **pixel signal** should be preferably **linear**.
- To have a **narrower spectral response**.
- To **avoid dome reflections** (reducing the dome size?).
- To **keep birds** and other animals **away**.
- To keep the **dome clean** (could be automatic?).

Thank you!

This material is based upon work from COST HARMONIA, CA21119, supported by COST (European Cooperation in Science and Technology).

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.

Roberto Román
roberto.roman@uva.es



Funded by the European Union

June 30, 2026

HARMONIA

Co-designing all-sky camera networks

Industry engagement towards innovative hardware, software products





Max Aragón

Wematics CEO & Mines Paris PSL PhD student

Contents

01 OUR TEAM & BACKGROUND

02 ALL SKY CAMERA SIMULATOR

03 CO-DESIGN USE CASES

04 AUTONOMOUS HARDWARE



Wematics: R&D-native startup in atmospheric sensing



Max Aragon
Chief Executive Officer
`PhD in atmospheric physics`



Paul Matteschk
Chief Technology Officer
`PhD in autonomous robotics`



Quentin Paletta
Chief Intelligence Officer
`PhD in AI weather forecasting`



Jose Gomez
Chief Platform Officer
`PhD in geoinformatics`



Paul Rousseau
Chief Operating Officer
`MA in deep tech & innovation`

We have done research on Earth observation, solar radiation, and atmospheric modelling at:

PARIS LODRON UNIVERSITÄT SALZBURG
MINES PARIS | PSL
TECHNISCHE UNIVERSITÄT DRESDEN
DLR Deutsches Zentrum für Luft- und Raumfahrt
UNIVERSITY OF CAMBRIDGE
esa European Space Agency
WAGENINGEN UNIVERSITY & RESEARCH
ETH zürich
UNIVERSITY OF HELSINKI
Hochschule Bonn-Rhein-Sieg University of Applied Sciences
iea International Energy Agency



2020



2022



2024

Why to design all-sky camera networks?



- **Count:** How many sky cameras? 6 or 4?
- **Layout:** Which camera network arrangement?
- **Siting:** Where to place new cameras?

WEMATICS
WEATHER INFORMATICS

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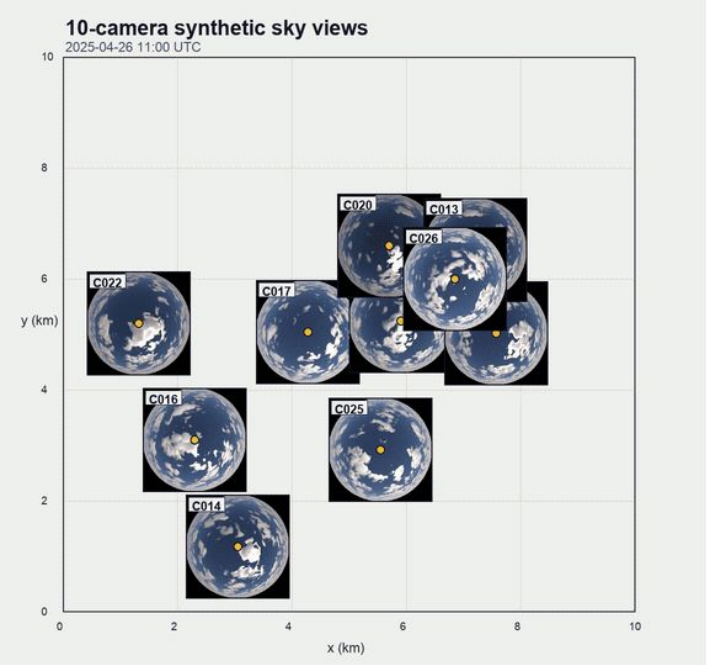
WEMATICS
WEATHER INFORMATICS

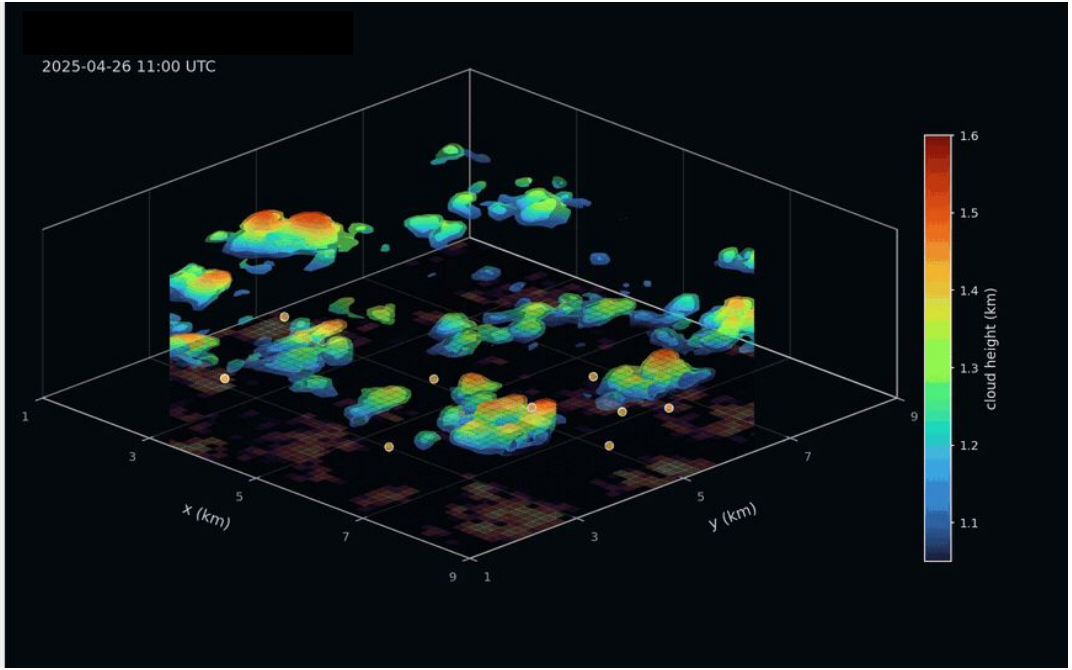
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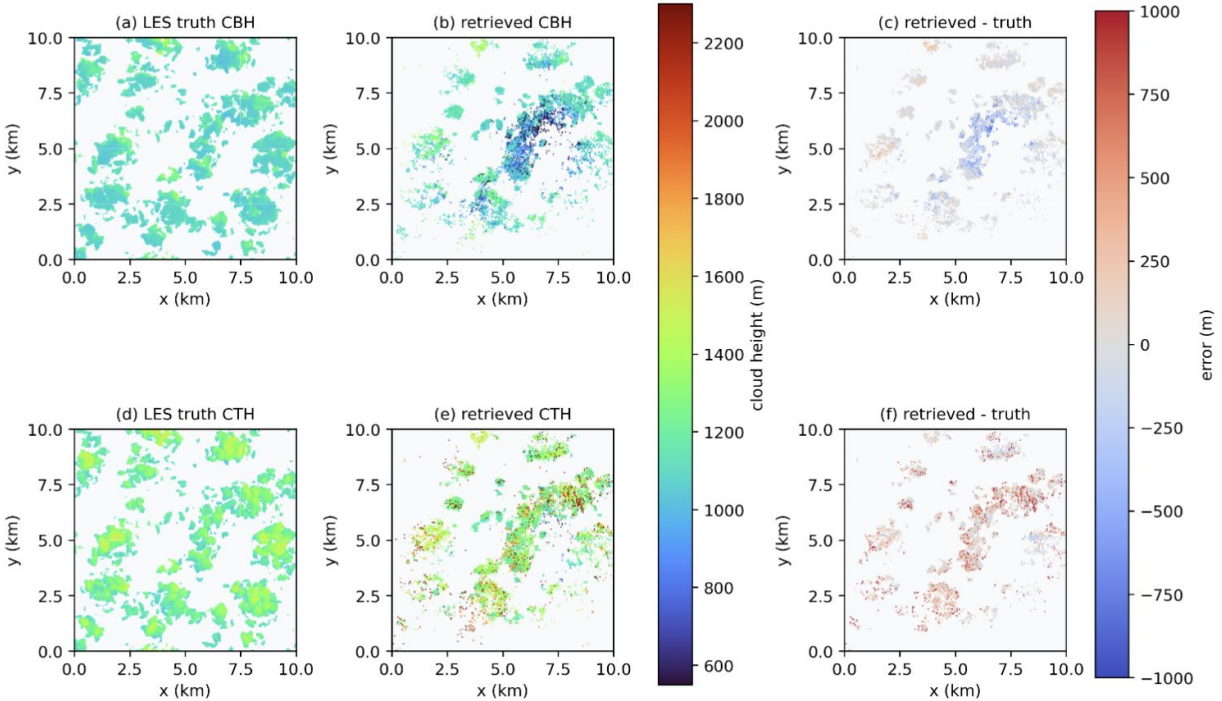
SkyTwin: All sky camera network simulator





PRESENTE Valladolid all sky camera network (2025-04-26)

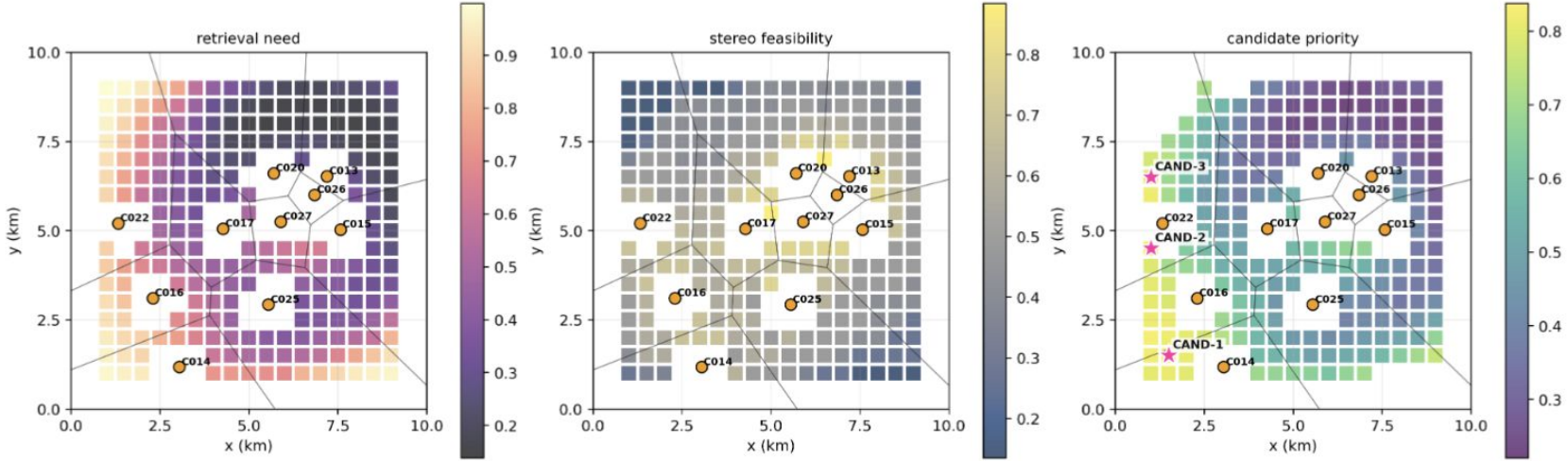
Application #1: Cloud height validation and siting



Cloud height validation for **shallow cumulus clouds** based on a multi-view stereo retrieval algorithm (*)

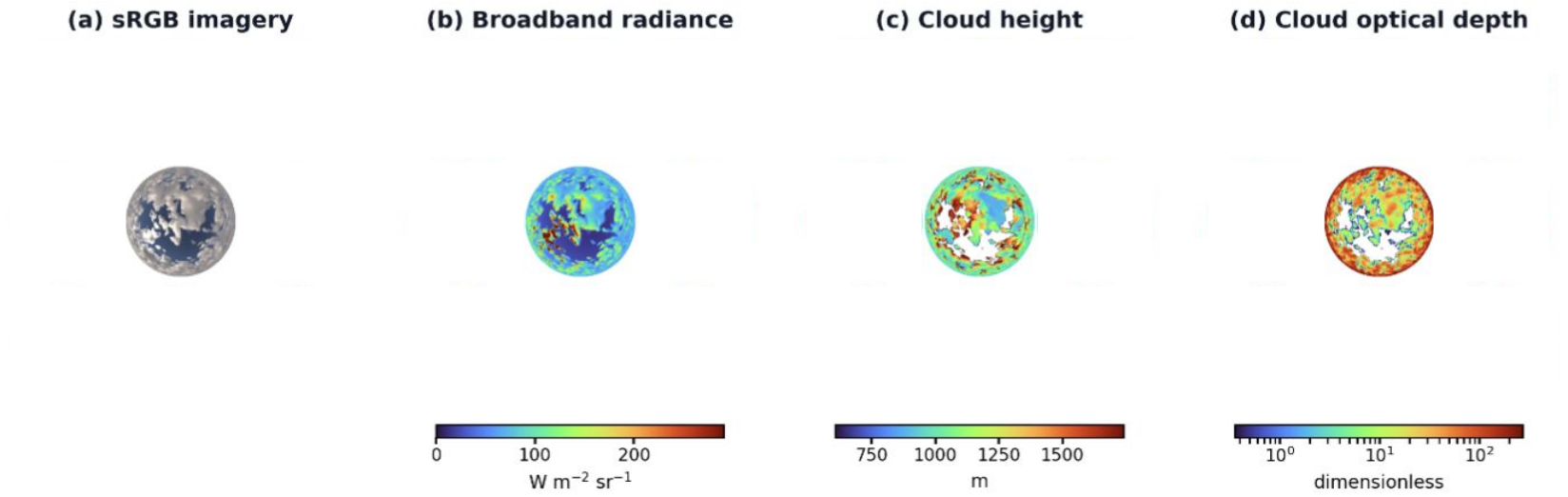
* *Herrero del Barrio, C., et al.: Cloud height mapping using multi simultaneous sky images from an all-sky camera network, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-2694, 2026.*

Application #1: Cloud height validation and siting



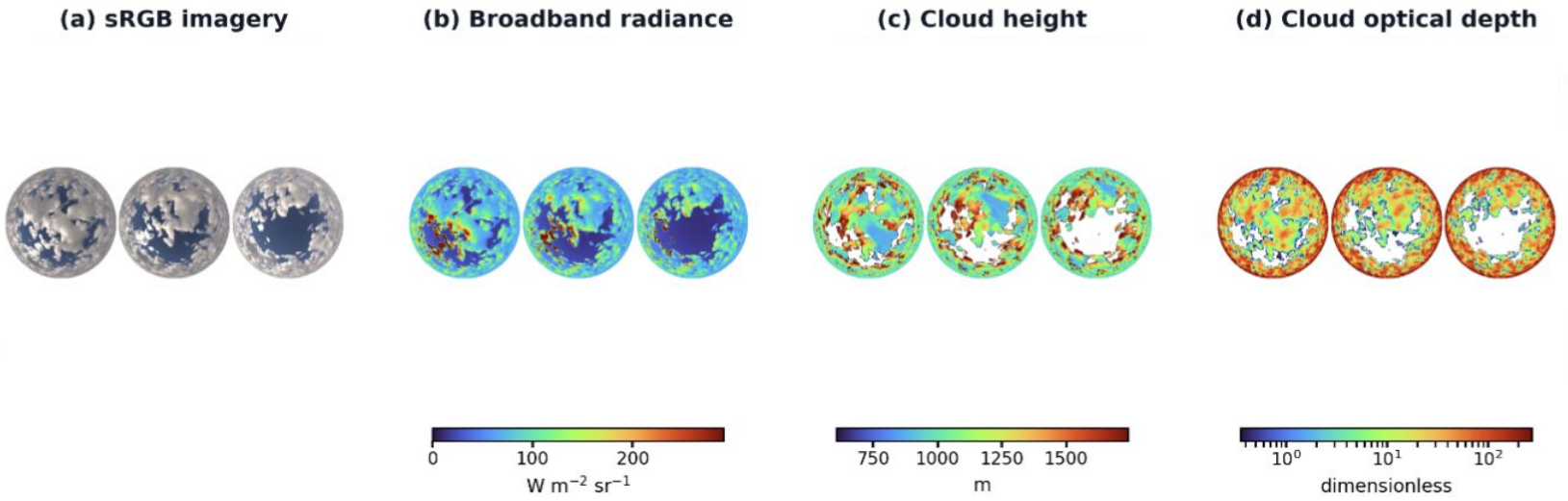
Where to place new cameras to improve cloud height estimation?

Application #2: Data-driven solar irradiance estimation



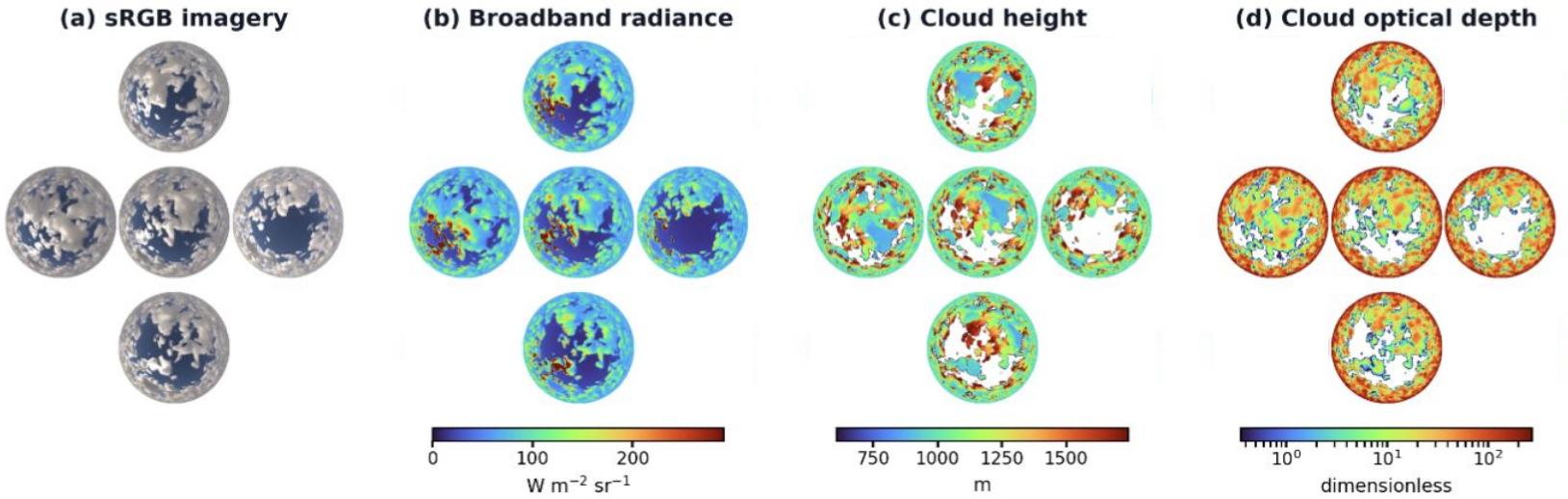
What's the value of added views and physical priors for solar irradiance?

Application #2: Data-driven solar irradiance estimation



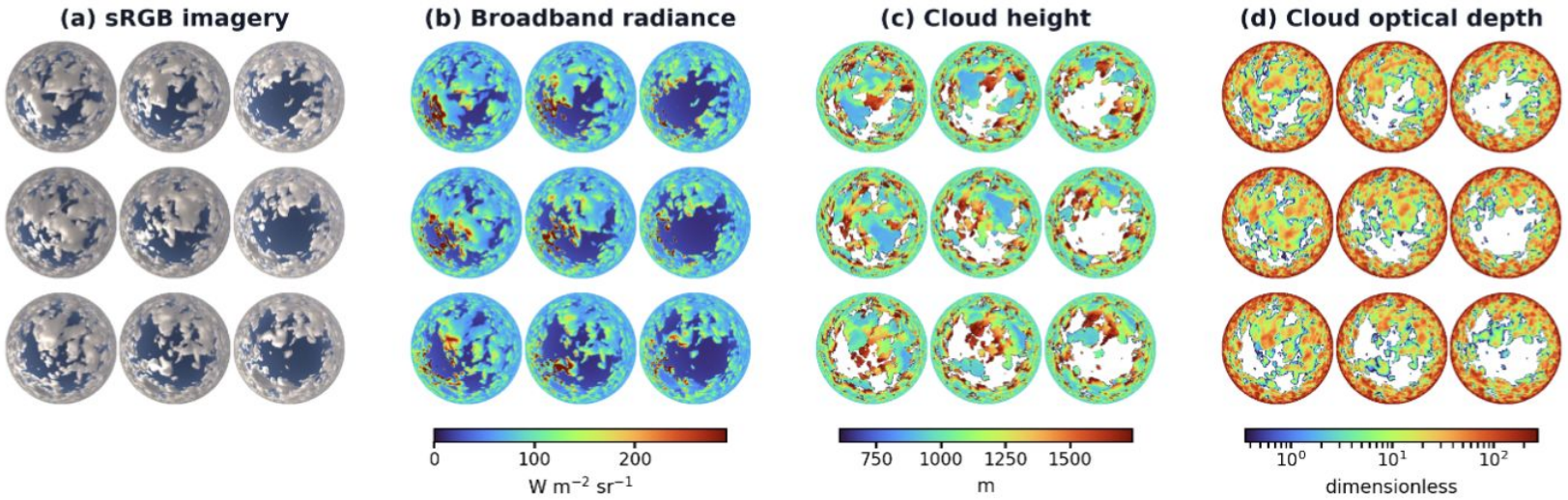
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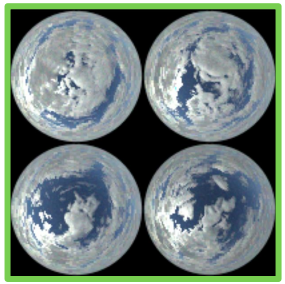
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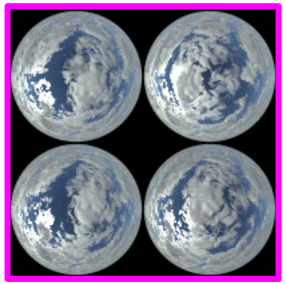
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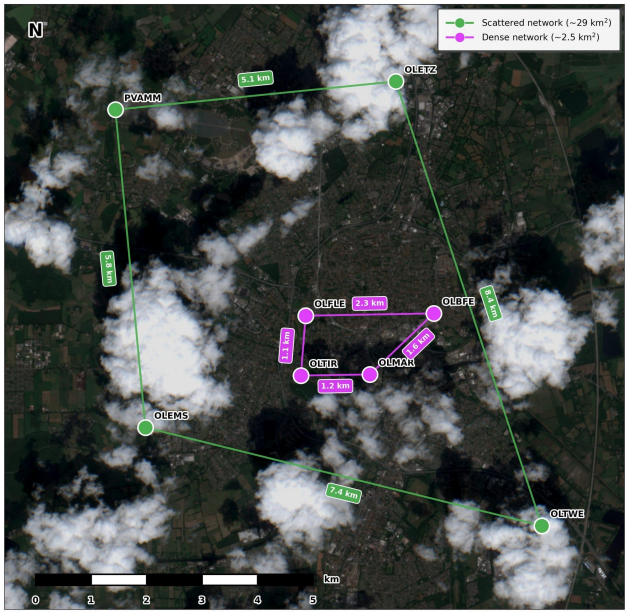
Application #3: Data-driven solar irradiance estimation

Scattered



Dense





Surface solar irradiance field emulation using multi-view imagery

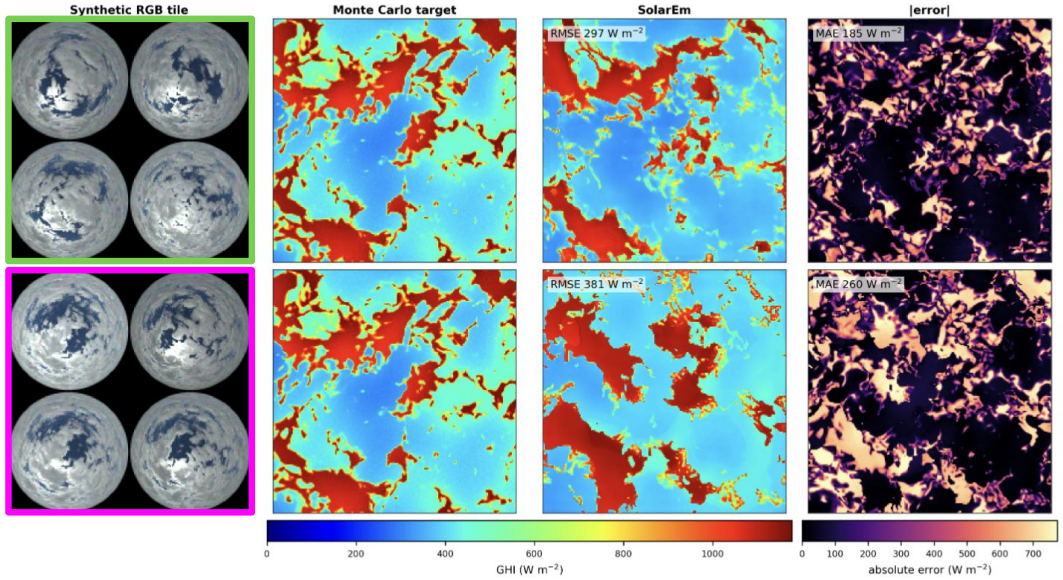
Aragon Cerecedes., et al (2026). Spatial solar irradiance emulation of Monte Carlo ray tracing with multi-view all-sky imagery: EGU26-13181. Abstract from EGU General Assembly 2026, Vienna, Austria. https://doi.org/10.5194/egusphere-egu26-13181

Which layout produces more accurate surface solar irradiance fields?

Application #3: Data-driven solar irradiance estimation

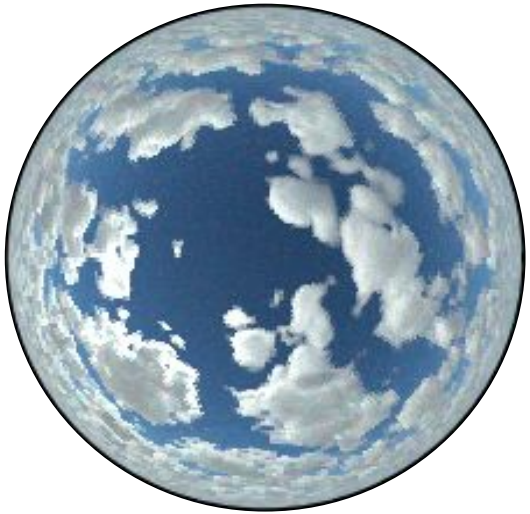
Scattered

Dense

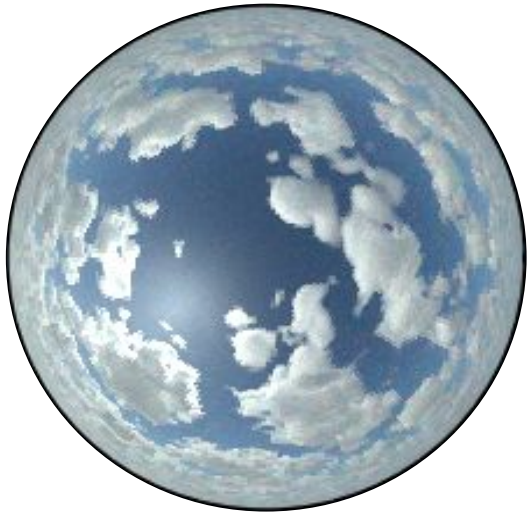


Which layout produces more accurate surface solar irradiance fields?

What's next? Improve **SkyTwin** realism

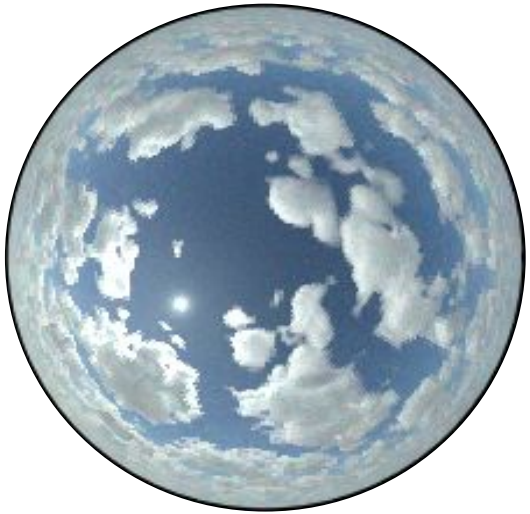


No aerosols



Aerosols
(simple scattering)

Henyey Greenstein



Aerosols
(complex scattering)

Double Henyey Greenstein

Hardware? all-sky cameras for autonomous operations



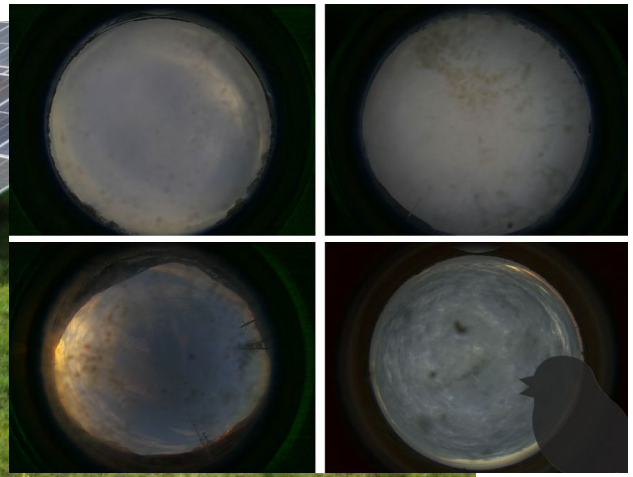


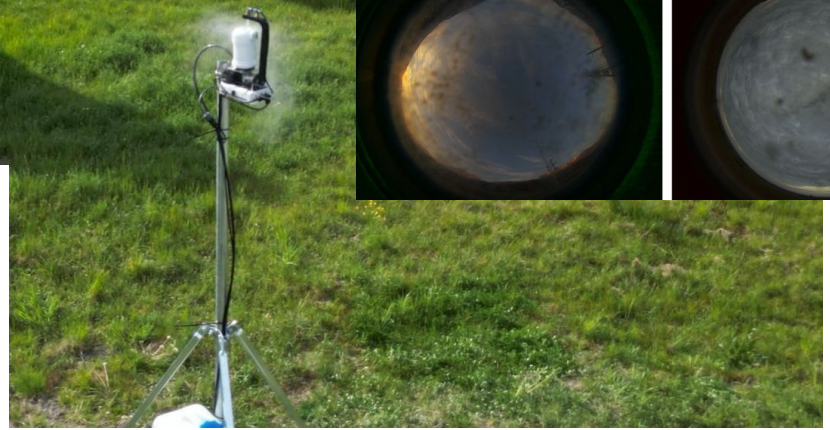
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Hardware? all-sky cameras for autonomous operations







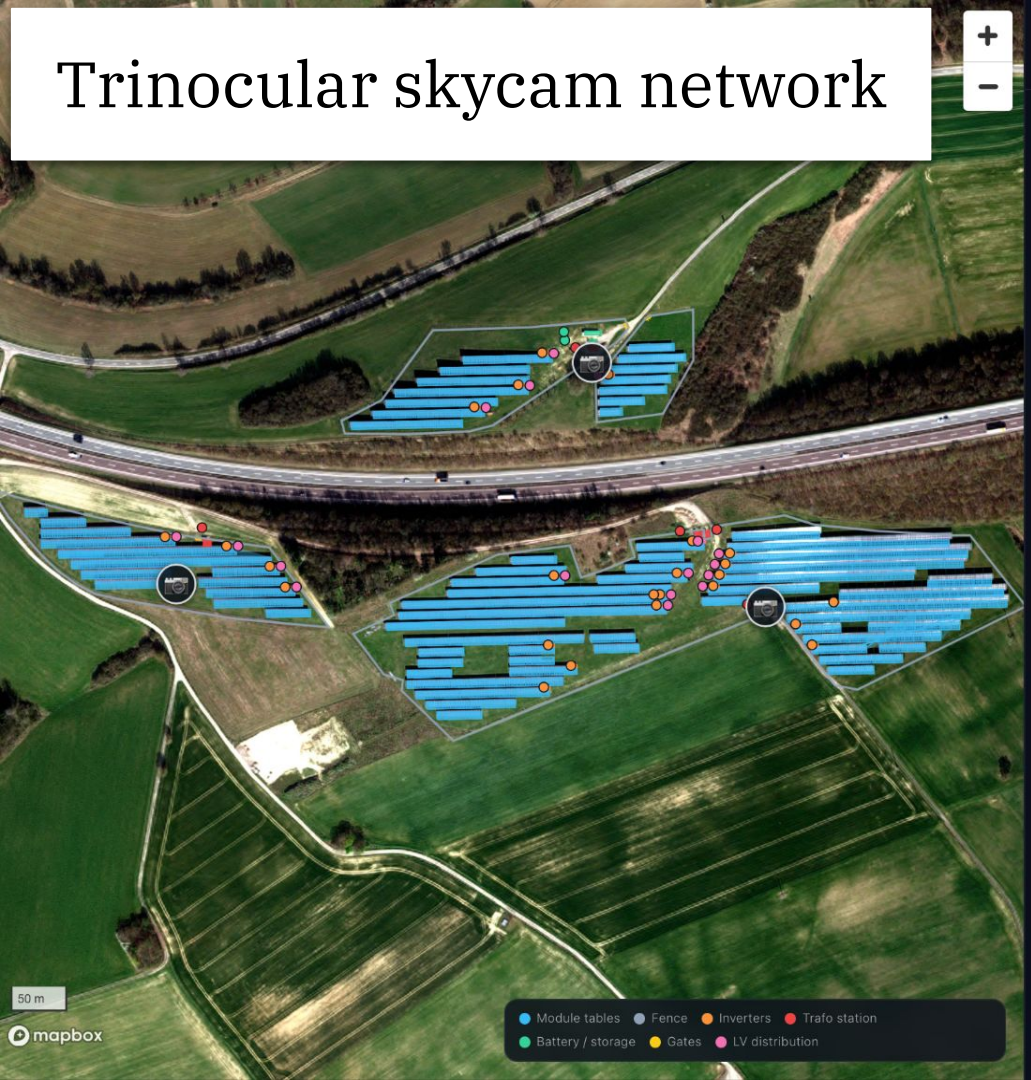


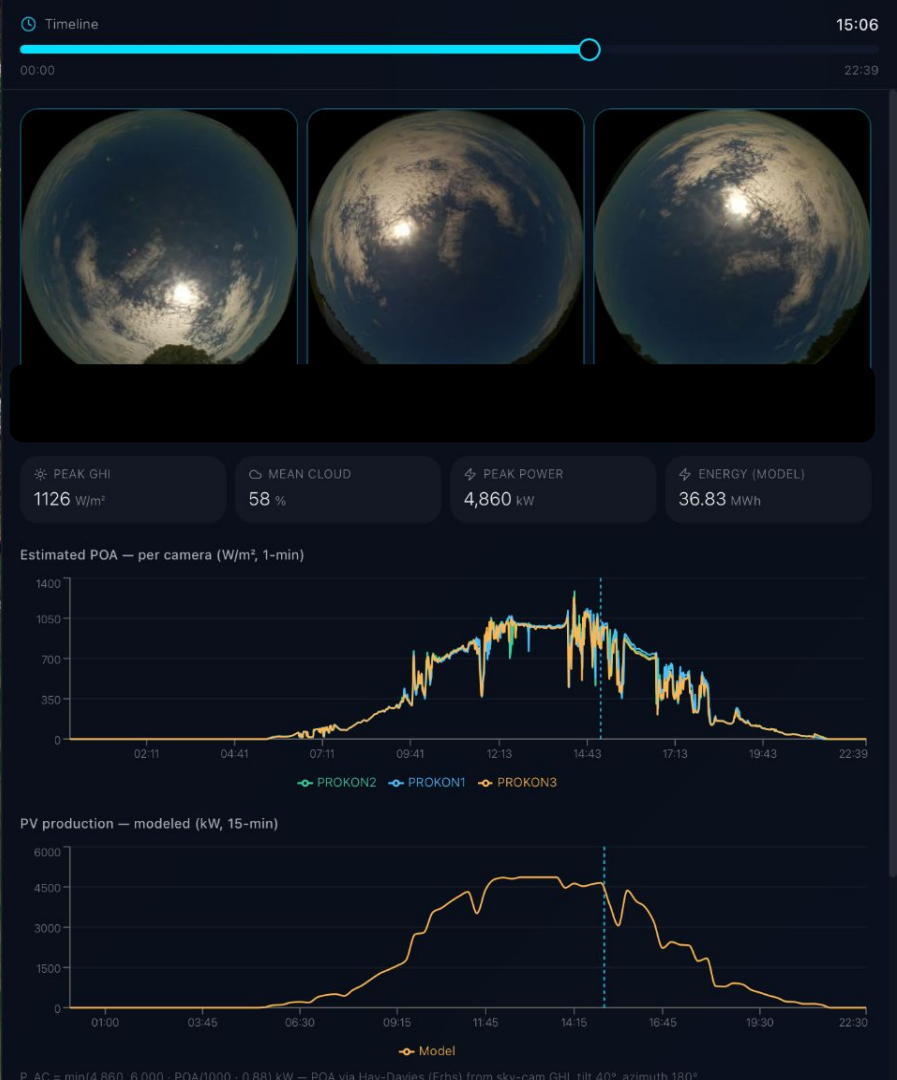




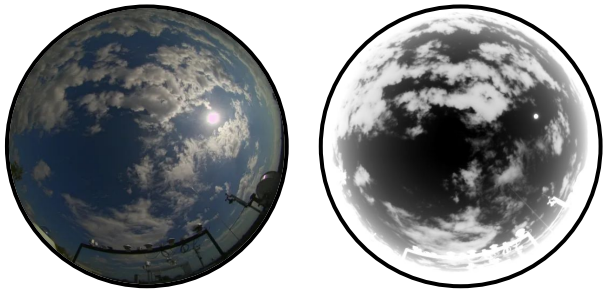
WEMATICS
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Trinocular skycam network





Latest innovation: Dual visible/thermal all sky camera





In summary:

- Self-powering
- Self-calibration
- Self-cleaning
- Multispectral
- Edge-AI

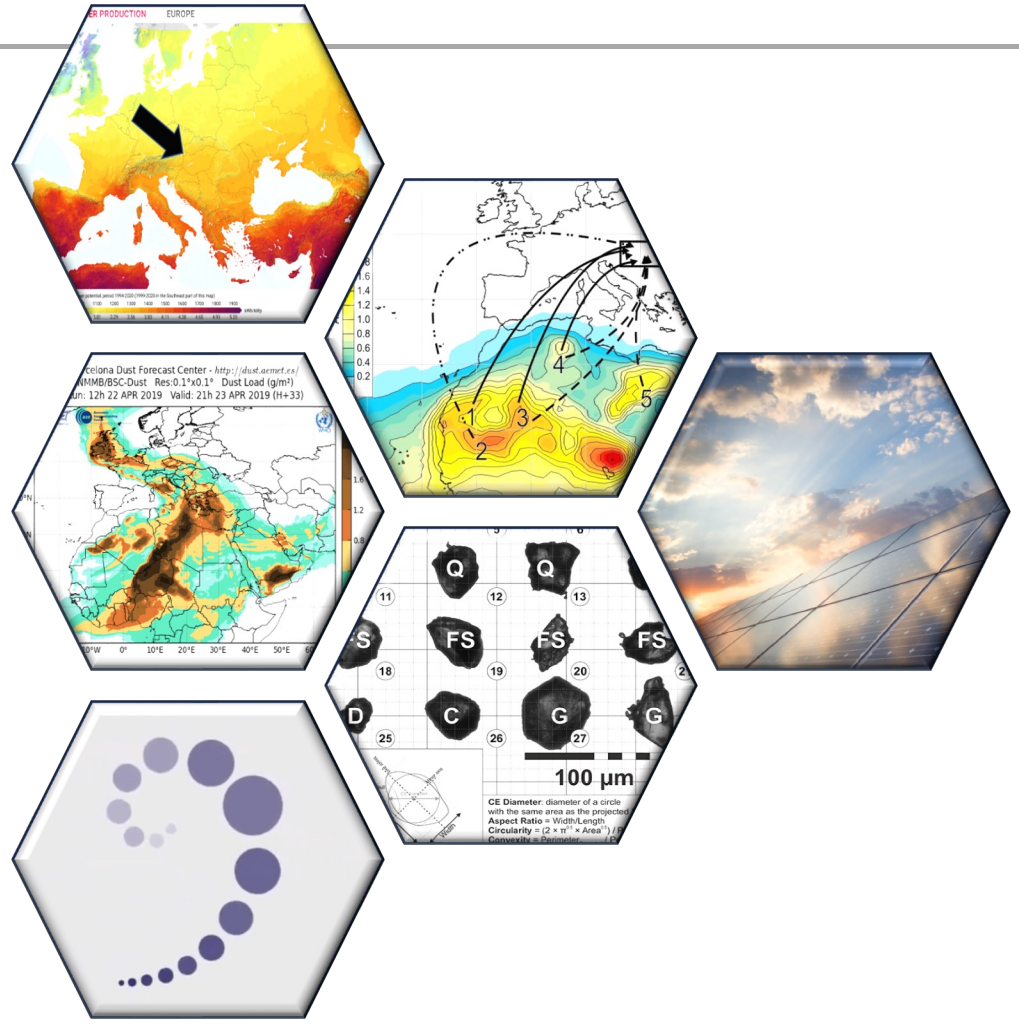
HARMONIA

Thank you

max@wematics.com





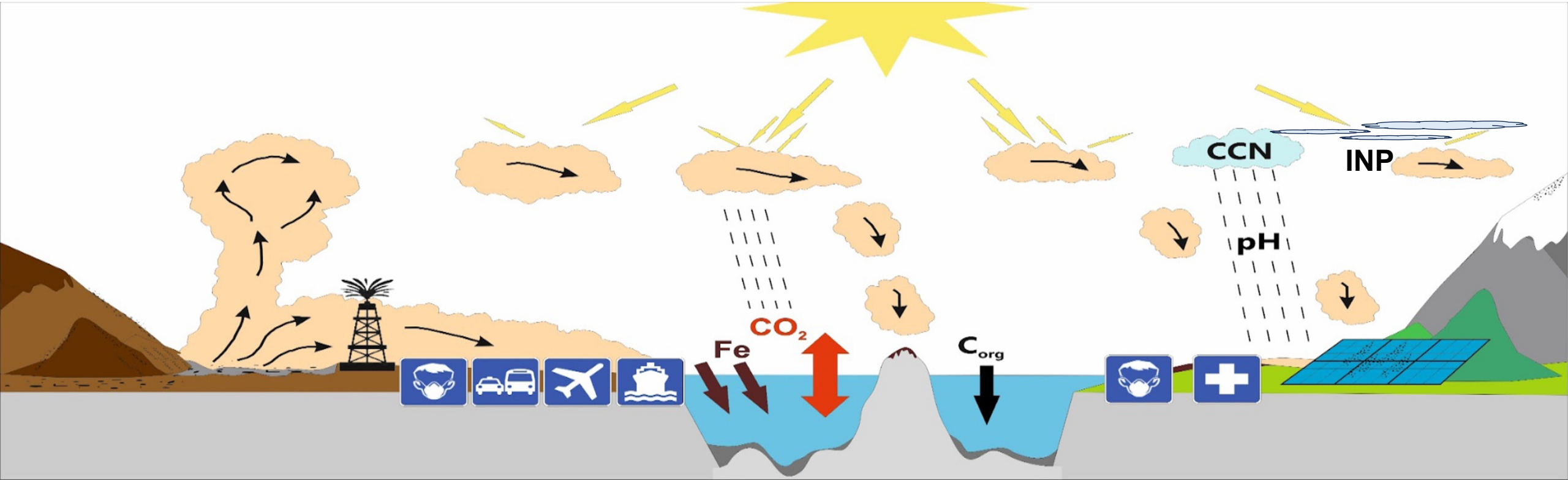


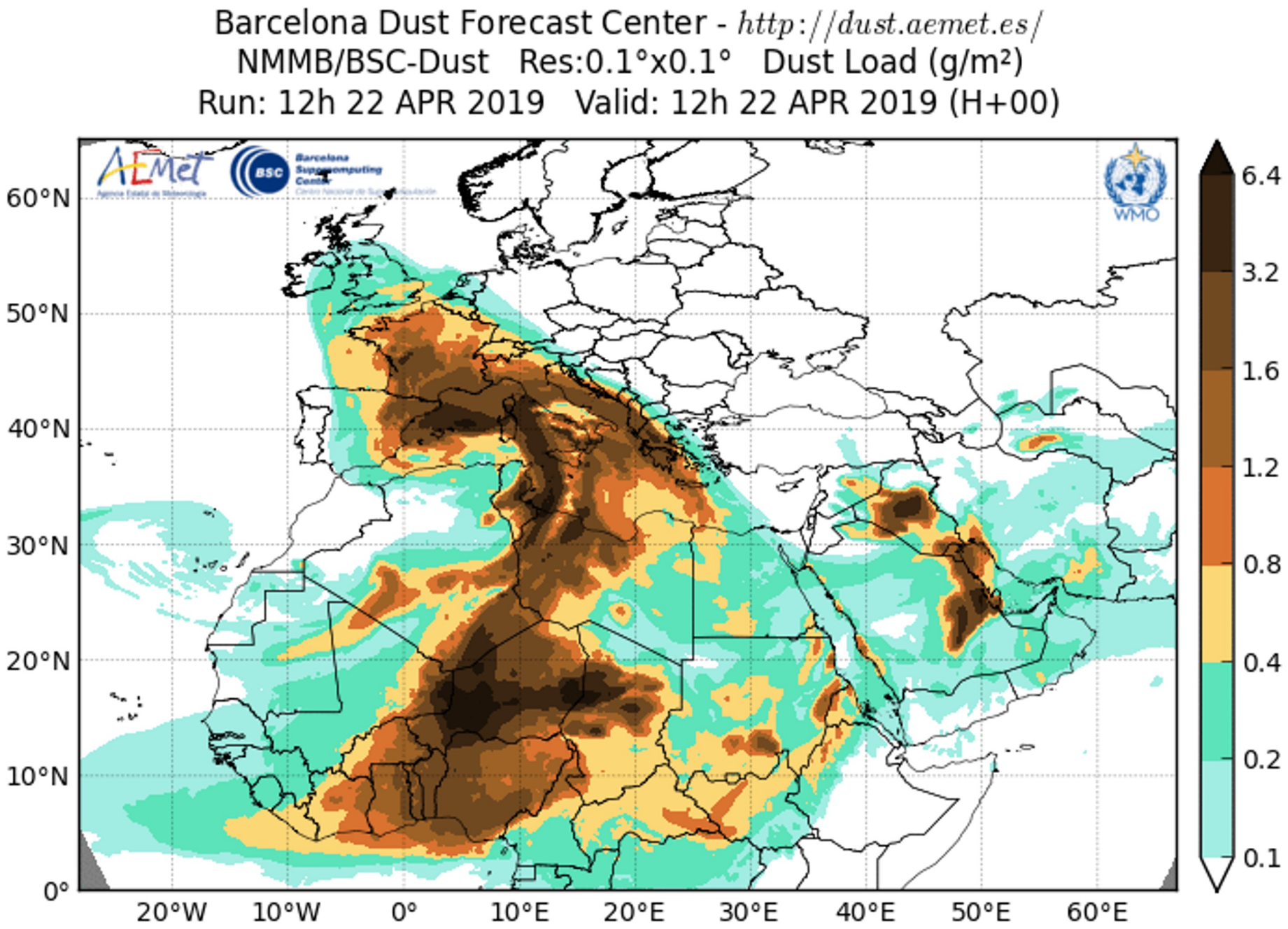
Dust Clouds or Dusty Clouds: Aerosol–Cloud Interactions and Their Impact on Solar Energy Production

György Varga
varga.gyorgy@csfk.org

Why is dust (so) important?

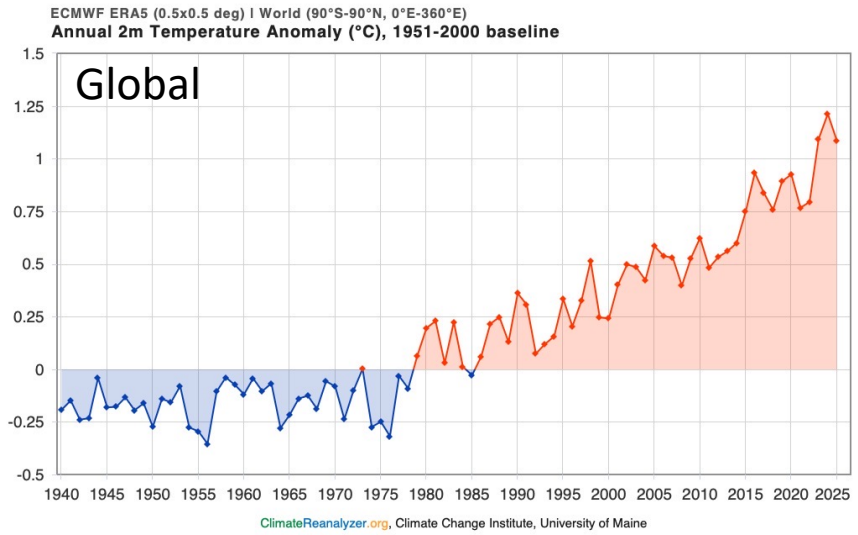
- annual global mineral dust emission: **1-3 billion tons** (50-70% from the Sahara)
- direct and indirect effects on **climate system**
- other **environmental influences** (pH; terra rossa-formation; carbon cycle, etc.)
- **proxy** for past environmental changes (aeolian dust deposits)
- **human health and economic** effects

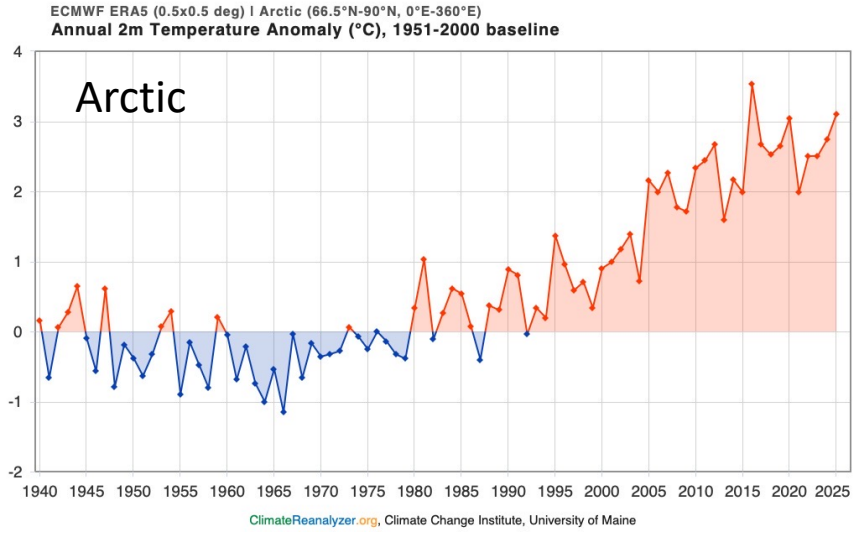


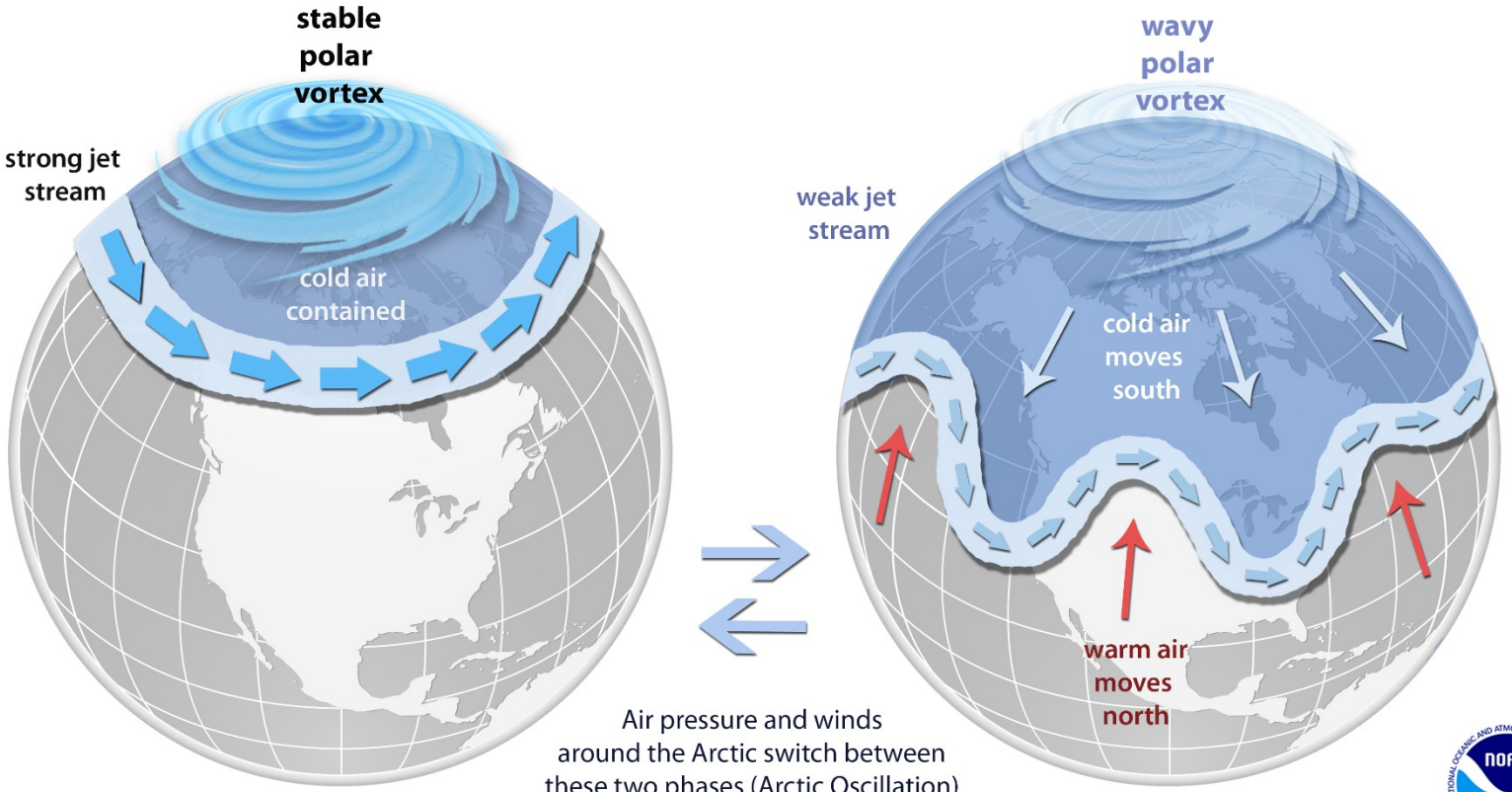

Barcelona Dust Forecast Center - http://dust.aemet.es/
NMMB/BSC-Dust Res:0.1°x0.1° Dust Load (g/m²)
Run: 12h 22 APR 2019 Valid: 12h 22 APR 2019 (H+00)
60°N
50°N
40°N
30°N
20°N
10°N
0°
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
60°E
6.4
3.2
1.6
1.2
0.8
0.4
0.2
0.1

The Science Behind the Polar Vortex

The polar vortex is a large area of low pressure and cold air surrounding the Earth's North and South poles. The term vortex refers to the counterclockwise flow of air that helps keep the colder air close to the poles (left globe). Often during winter in the Northern Hemisphere, the polar vortex will become less stable and expand, sending cold Arctic air southward over the United States with the jet stream (right globe). The polar vortex is nothing new — in fact, it's thought that the term first appeared in an 1853 issue of E. Littell's *Living Age*.



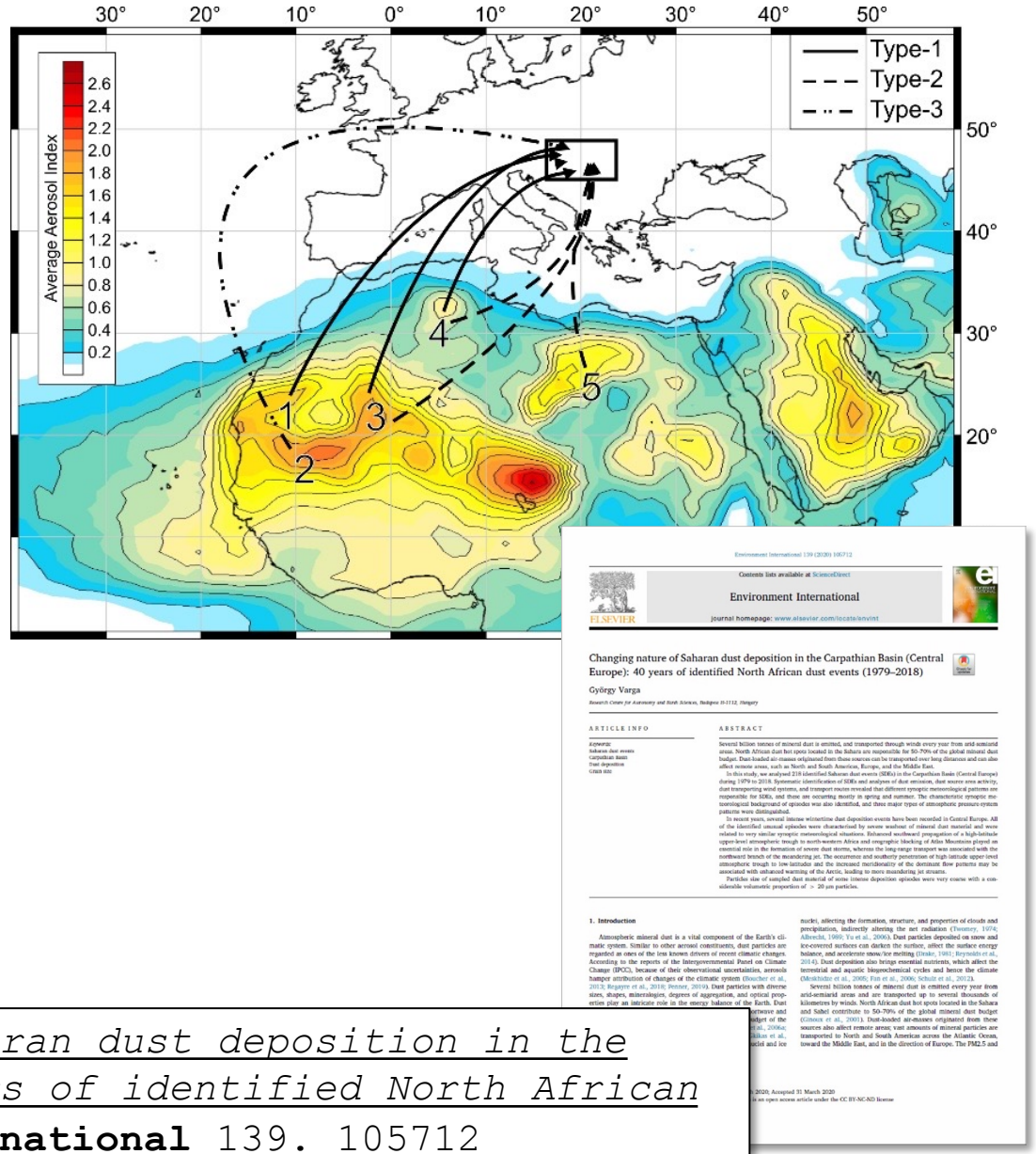




Air pressure and winds around the Arctic switch between these two phases (Arctic Oscillation) and contribute to winter weather patterns.

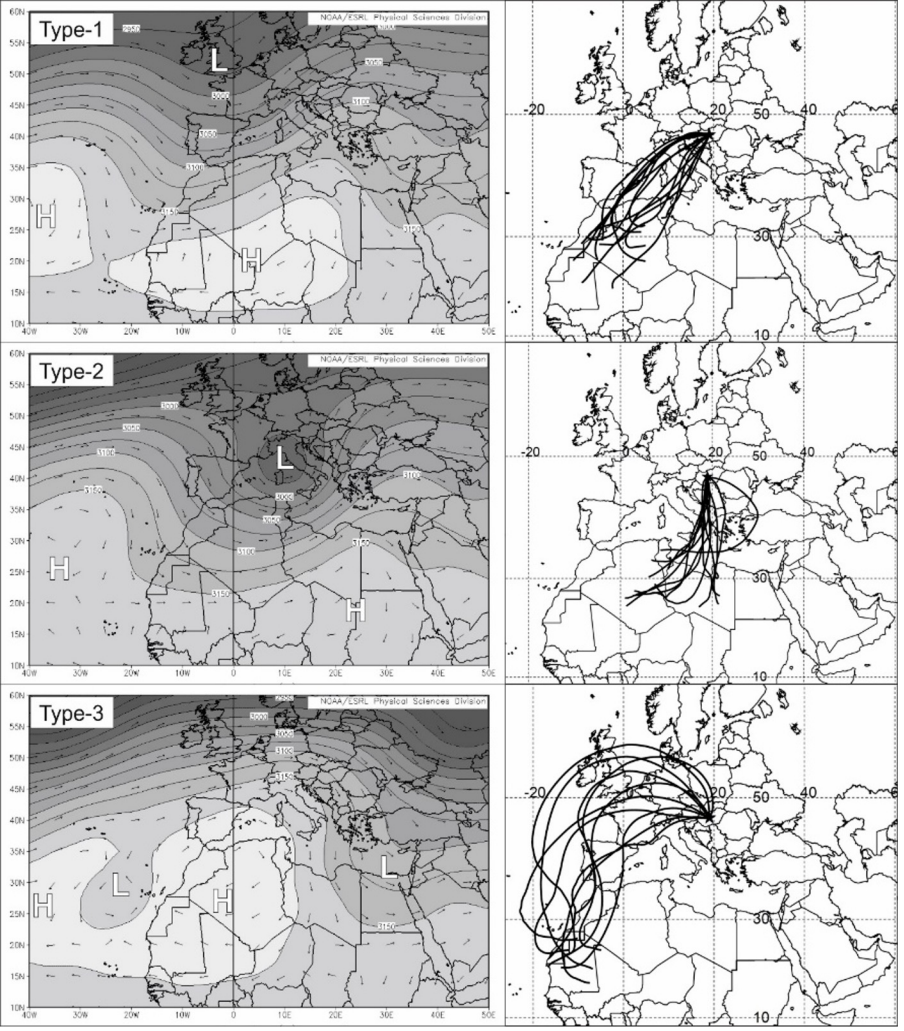
Saharan dust events in Hungary

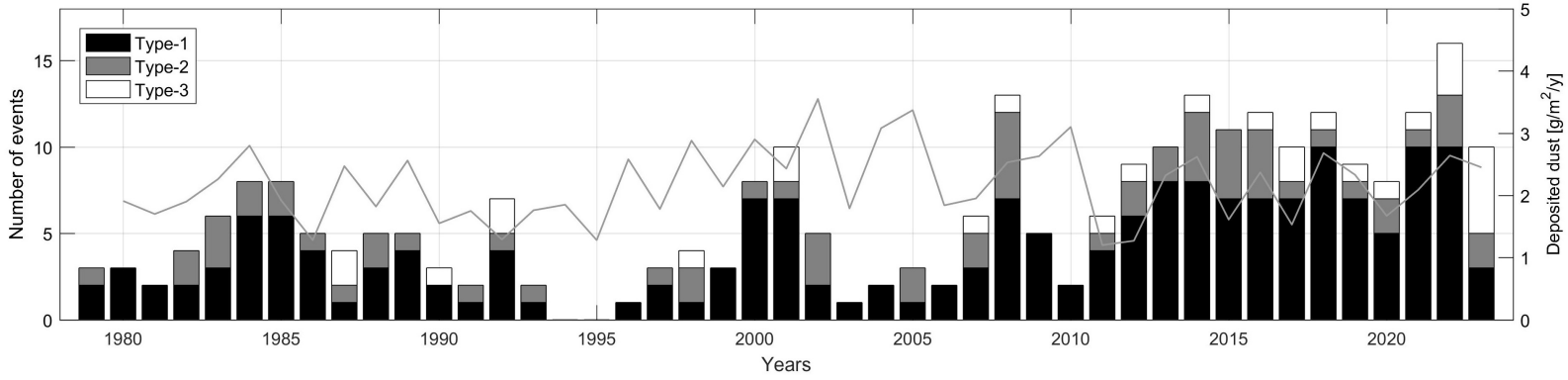
- **300+ Saharan dust events** were identified **between 1979 and 2026** (NASA TOMS and OMI Aerosol Index) by **satellite observations**
- BSC DREAM8b v1.0 and v2.0 **numerical dust simulations** show similar frequency of dust events
- HYSPLIT **backwards-trajectories** were applied to confirm the Saharan origin
- 700 hPa geopotential height, zonal and meridional wind vectors were used to determine different types of **synoptic meteorological patterns** of Saharan dust events (SDEs)
- summarized **dry and wet deposition data** of the five available dust size-bins of the NASA's MERRA-2 were applied to estimate dust deposition

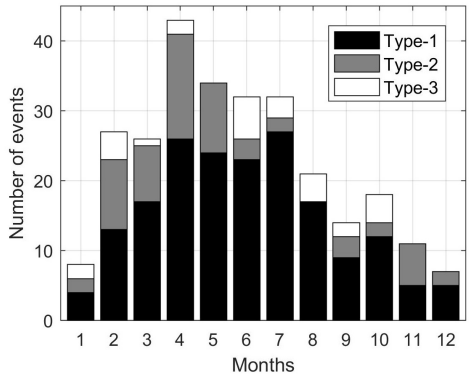


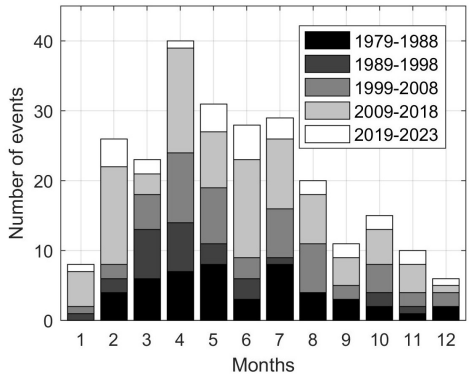
Varga, Gy. (2020). *Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018).* **Environment International** 139. 105712

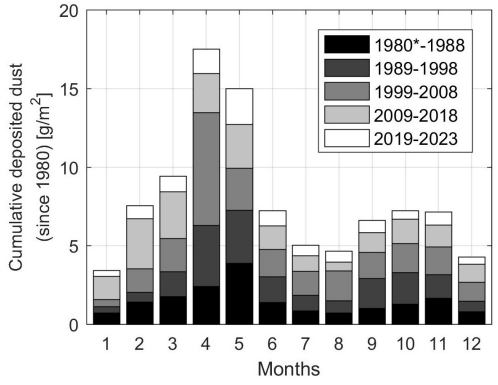
Saharan dust events in Hungary











Decade	SDEs				Deposition [g/m^2]							
	Events	Type-1	Type-2	Type-3	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON
1979–1988	48	32(66.7%)	14(29.2%)	2(4.2%)	6(12.5%)	21(43.8%)	15(31.3%)	15(12.5%)	2.1	0.3(15.8%)	1.0(47.1%)	0.3(16.6%)	0.4(20.6%)
1989–1998	27	16(59.3%)	7(25.9%)	4(14.8%)	3(11.1%)	17(63.0%)	4(14.8%)	3(11.1%)	1.9	0.2(8.3%)	0.8(43.8%)	0.4(18.5%)	0.6(29.4%)
1999–2008	53	35(66.0%)	14(26.4%)	4(7.6%)	4(8.2%)	20(40.8%)	17(34.7%)	8(16.3%)	2.6	0.4(15.9%)	1.2(44.9%)	0.5(18.7%)	0.5(20.5%)
2009–2018	90	64(71.1%)	19(21.1%)	7(7.8%)	16(18.8%)	26(30.6%)	30(35.3%)	13(15.3%)	2.1	0.5(24.9%)	0.8(40.0%)	0.3(15.0%)	0.4(20.0%)
Full period	218	147(67.4%)	54(24.8%)	17(7.8%)	29(13.9%)	84(40.2%)	66(31.6%)	30(14.4%)	2.2	0.3(16.2%)	1.0(44.1%)	0.4(17.3%)	0.5(22.4%)

Environment International 139 (2020) 105712

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018)

György Varga

Research Centre for Astronomy and Earth Sciences, Budapest H-1112, Hungary

HUNGARIAN GEOGRAPHICAL BULLETIN

Current Archives About

Home / Archives / Vol. 72 No. 4 (2023) / Articles

Increasing frequency and changing nature of Saharan dust events in the Carpathian Basin (2019–2023) – the new norm

Atmos. Chem. Phys., 24, 4083–4104, 2024
https://doi.org/10.5194/acp-24-4083-2024
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Atmospheric Chemistry and Physics

Open Access

Sharp increase in Saharan dust intrusions over the western Euro-Mediterranean in February–March 2020–2022 and associated atmospheric circulation

Emilio Cuevas-Agulló[1,☆], David Barriopedro[2], Rosa Delia García[1,3], Silvia Alonso-Pérez[4,5], Juan Jesús González-Alemán[6], Ernest Werner[7], David Suárez[8], Juan José Bustos[1], Gerardo García-Castrillo[7], Omaira García[1], África Barreto[1], and Sara Basart[9,a]

Atmos. Chem. Phys., 24, 12031–12053, 2024
https://doi.org/10.5194/acp-24-12031-2024
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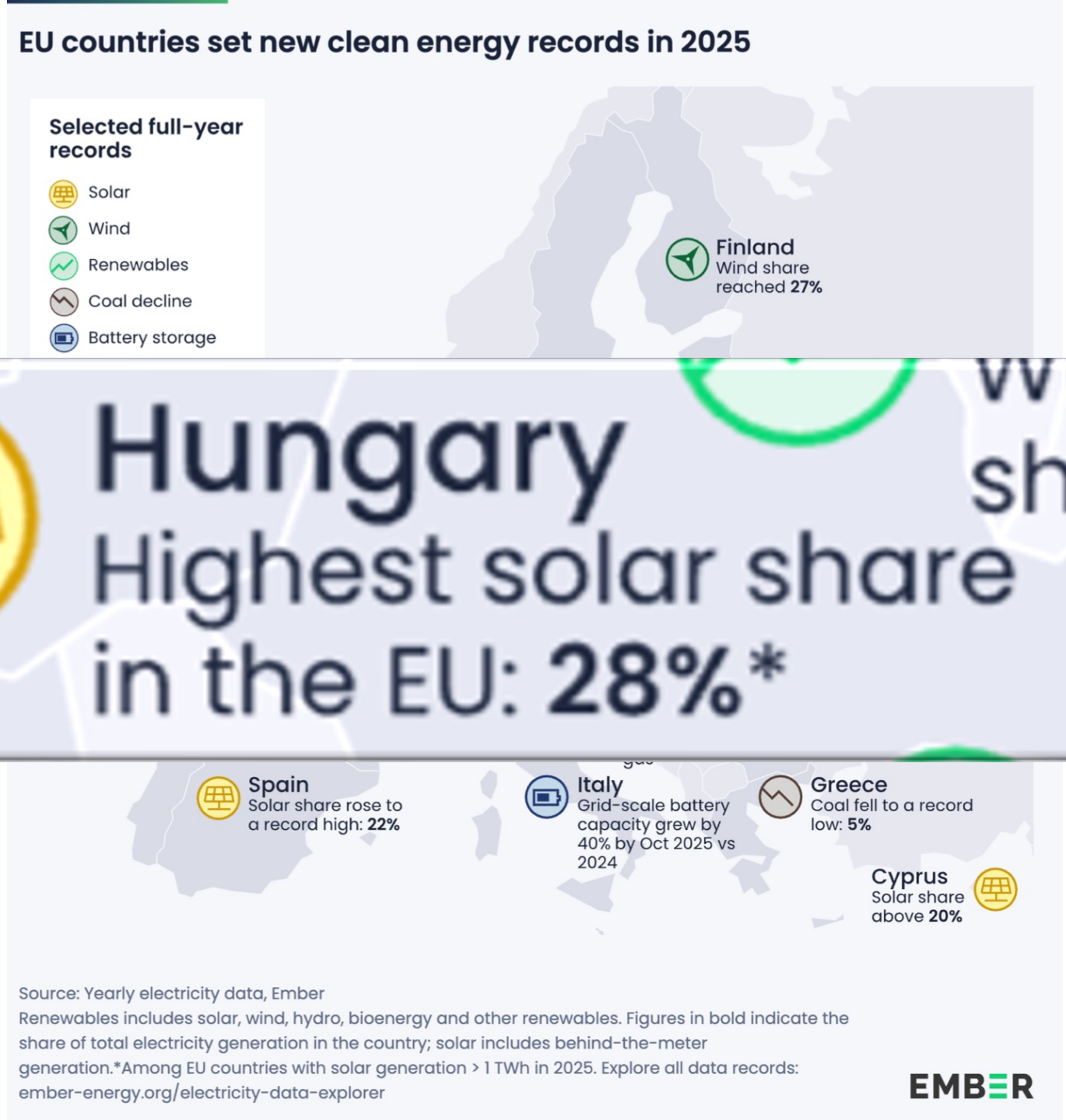
Atmospheric Chemistry and Physics

Open Access

EGU

Extreme Saharan dust events expand northward over the Atlantic and Europe, prompting record-breaking PM_{10} and $PM_{2.5}$ episodes

Sergio Rodríguez and Jessica López-Darias



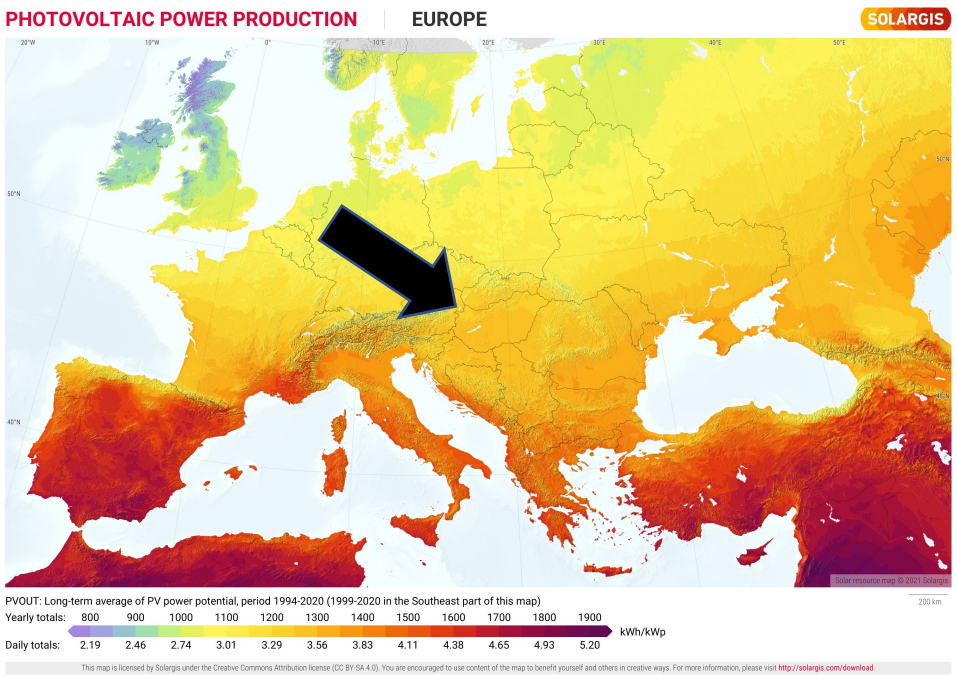
Photovoltaic power in Hungary

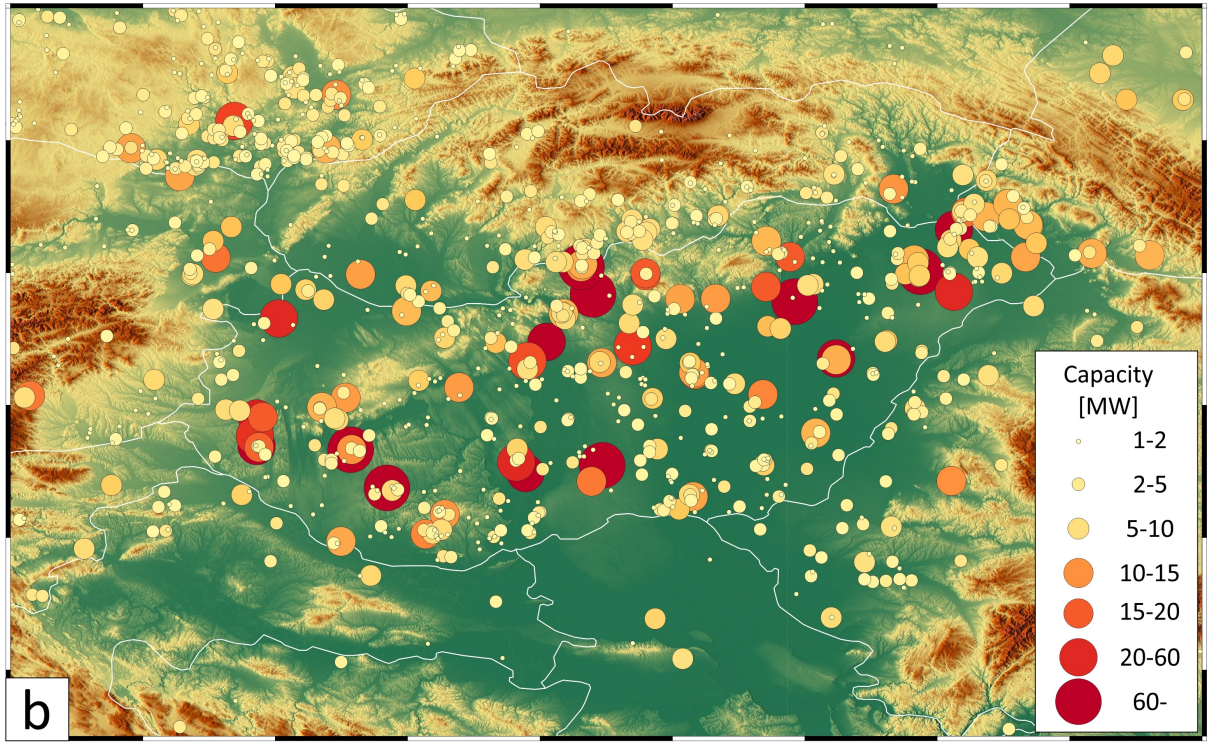
Geography:

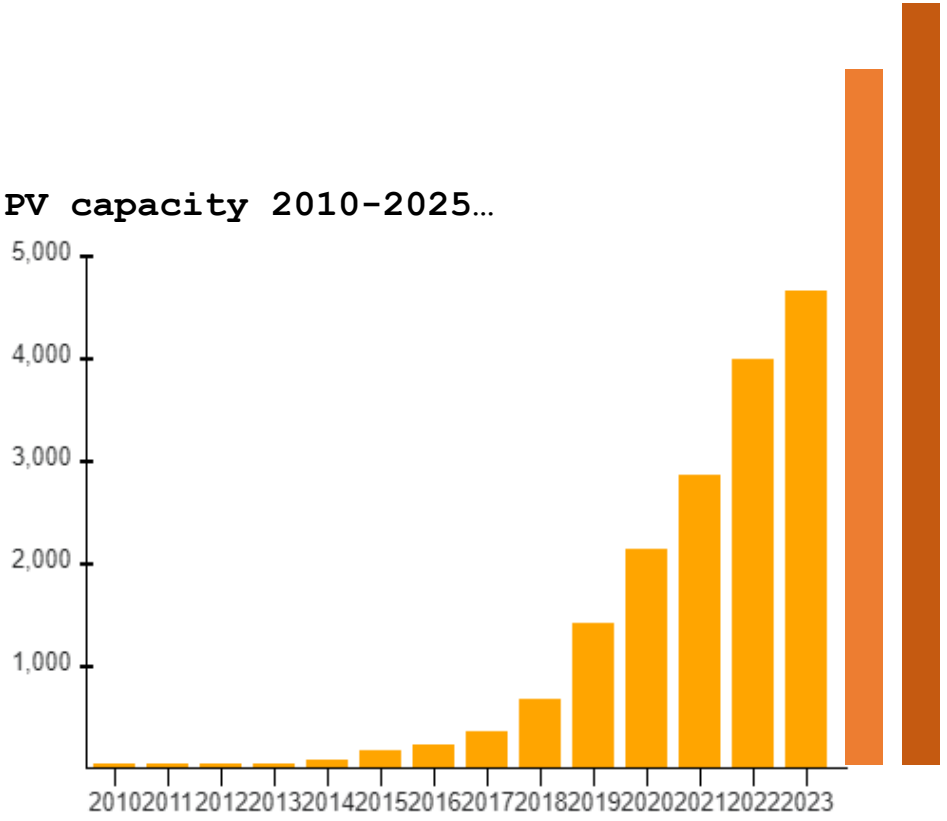
- **Carpathian Basin:** low, less segmented relief; relatively high number of sunshine hours

Energy:

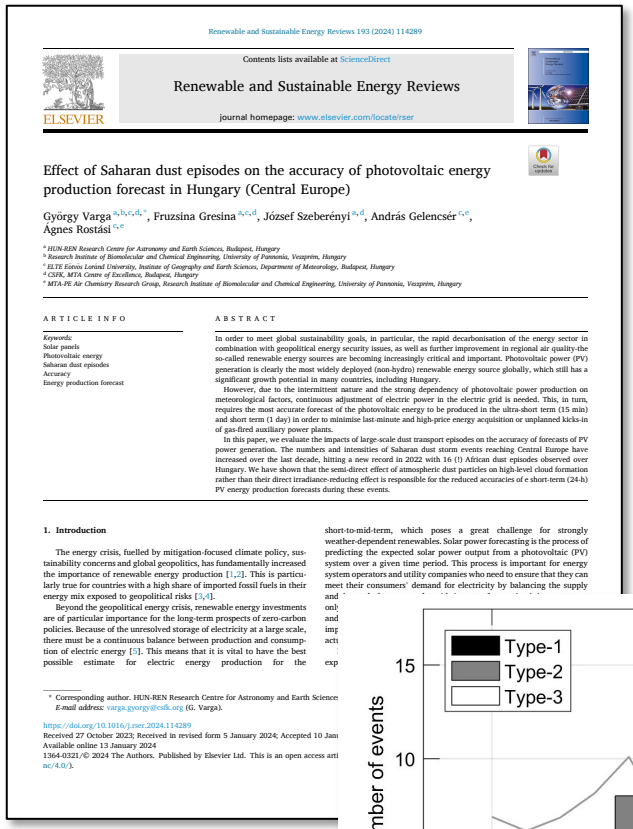
- historical heritage: **Russian gas and nuclear** plant (imported Russian nuclear fuel)
- no significant hydroelectric or wind energy production
- **high potential in solar energy (and large forecast errors)**







Saharan dust and photovoltaic energy production



Renewable and Sustainable Energy Reviews 193 (2024) 114289

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Effect of Saharan dust episodes on the accuracy of photovoltaic energy production forecast in Hungary (Central Europe)

György Varga [a,b,c,d,*], Fruzsina Gresina [a,c,d], József Szeberényi [a,d], András Gelencsér [c,e], Ágnes Rostási [c,e]

[a] HUN-REN Research Centre for Astronomy and Earth Sciences, Budapest, Hungary
[b] Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary
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ARTICLE INFO

Keywords:
Solar panels
Photovoltaic energy
Saharan dust episodes
Accuracy
Energy production forecast

ABSTRACT

In order to meet global sustainability goals, in particular, the rapid decarbonisation of the energy sector in combination with geopolitical energy security issues, as well as further improvement in regional air quality-the so-called renewable energy sources are becoming increasingly critical and important. Photovoltaic power (PV) generation is clearly the most widely deployed (non-hydro) renewable energy source globally, which still has a significant growth potential in many countries, including Hungary.

However, due to the intermittent nature and the strong dependency of photovoltaic power production on meteorological factors, continuous adjustment of electric power in the electric grid is needed. This, in turn, requires the most accurate forecast of the photovoltaic energy to be produced in the ultra-short term (15 min) and short term (1 day) in order to minimise last-minute and high-price energy acquisition or unplanned kicks-in of gas-fired auxiliary power plants.

In this paper, we evaluate the impacts of large-scale dust transport episodes on the accuracy of forecasts of PV power generation. The numbers and intensities of Saharan dust storm events reaching Central Europe have increased over the last decade, hitting a new record in 2022 with 16 (!) African dust episodes observed over Hungary. We have shown that the semi-direct effect of atmospheric dust particles on high-level cloud formation rather than their direct irradiance-reducing effect is responsible for the reduced accuracies of e short-term (24-h) PV energy production forecasts during these events.

1. Introduction

The energy crisis, fuelled by mitigation-focused climate policy, sustainability concerns and global geopolitics, has fundamentally increased the importance of renewable energy production [1,2]. This is particularly true for countries with a high share of imported fossil fuels in their energy mix exposed to geopolitical risks [3,4].

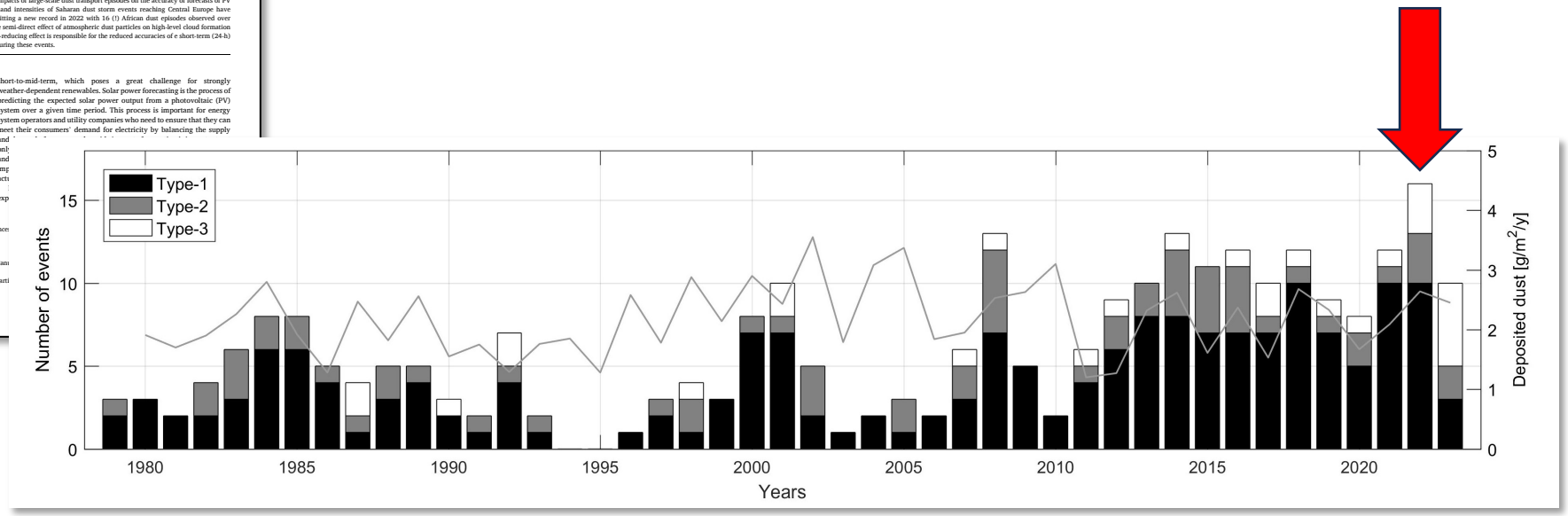
Beyond the geopolitical energy crisis, renewable energy investments are of particular importance for the long-term prospects of zero-carbon policies. Because of the unresolved storage of electricity at a large scale, there must be a continuous balance between production and consumption of electric energy [5]. This means that it is vital to have the best possible estimate for electric energy production for the short-to-mid-term, which poses a great challenge for strongly weather-dependent renewables. Solar power forecasting is the process of predicting the expected solar power output from a photovoltaic (PV) system over a given time period. This process is important for energy system operators and utility companies who need to ensure that they can meet their consumers' demand for electricity by balancing the supply and

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Received 27 October 2023; Received in revised form 5 January 2024; Accepted 10 Jan
Available online 13 January 2024
1364-0321/© 2024 The Authors. Published by Elsevier Ltd. This is an open access arti
nc/4.0/).

Using data for the year **2022,** we examined the link between Saharan dust storm events and PV energy generation

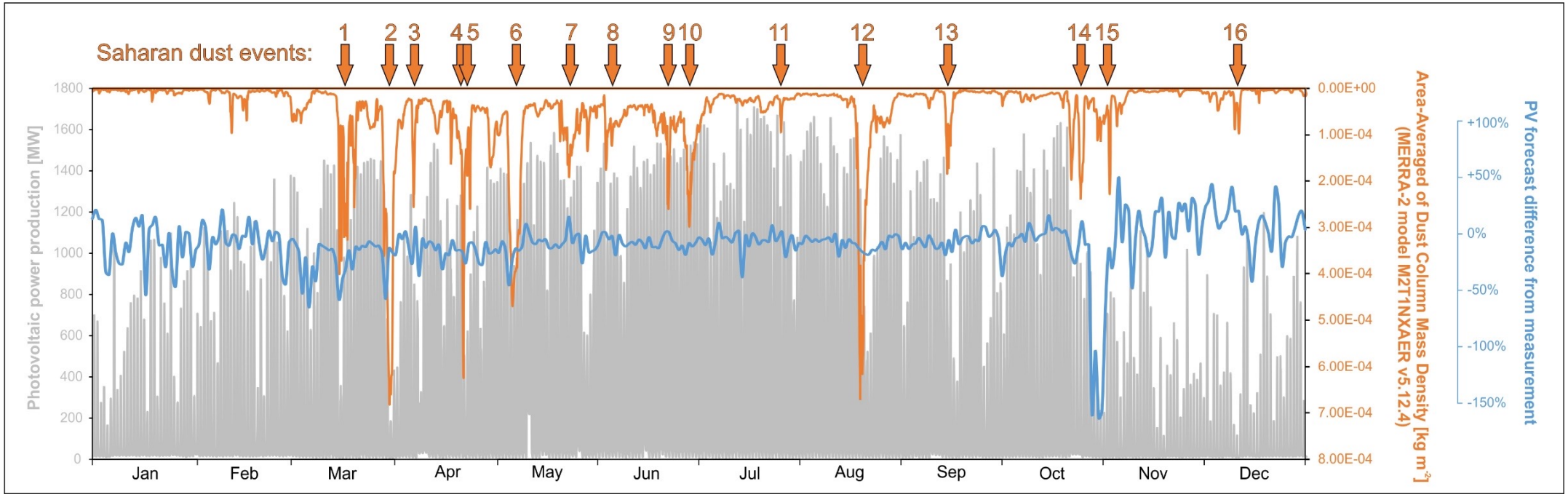
In 2022, Hungary was affected by **16 (!) Saharan dust events**



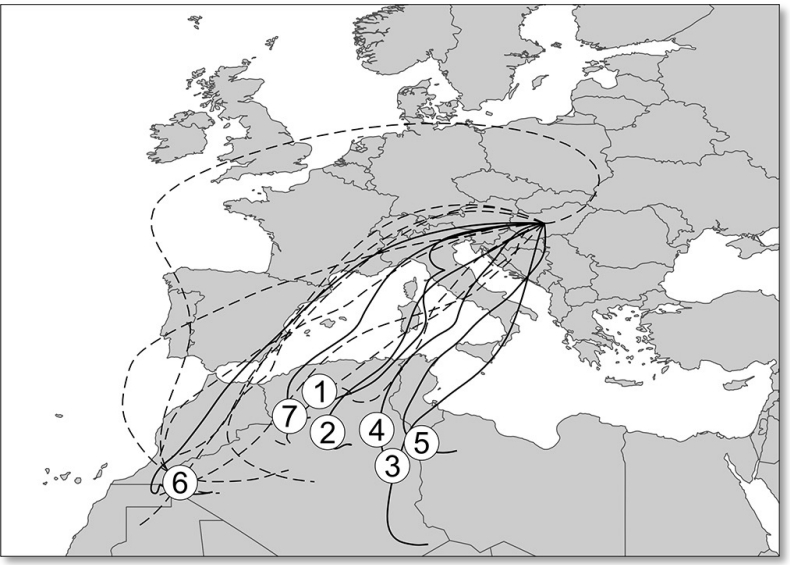
Varga, Gy., Gresina, F., Szeberényi, J., Gelencsér, A., Rostási, Á. (2024). Effect of Saharan dust episodes on the accuracy of photovoltaic energy production forecast in Hungary (Central Europe). **Renewable and Sustainable Energy Reviews** 193. 114289

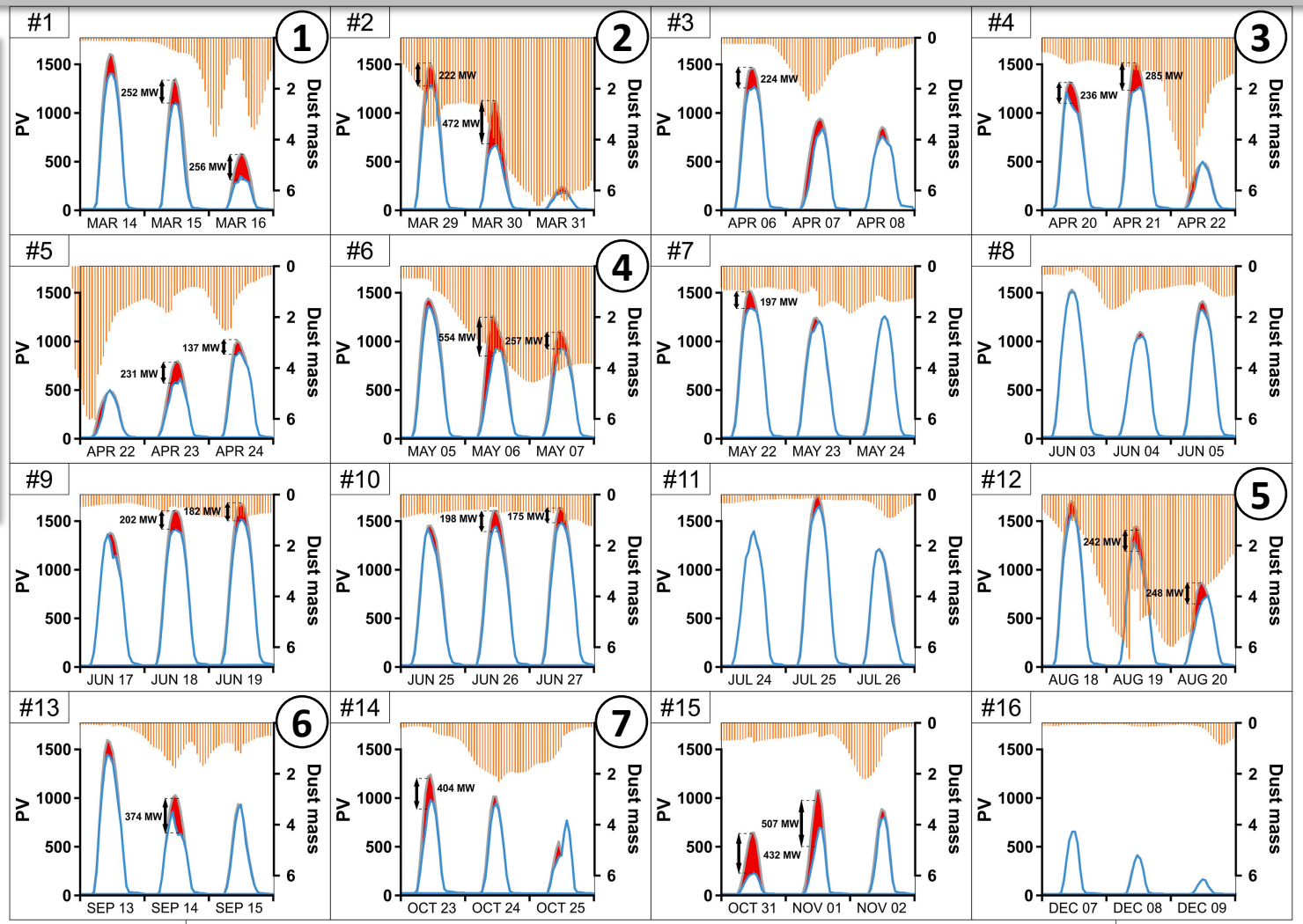
Saharan dust and photovoltaic energy production

According to the system operator (MAVIR), there was a difference of more than **500 MW between the 24-hour (day-ahead) schedule and the actual photovoltaic production** during some events (causing tens of millions EUR of damage).

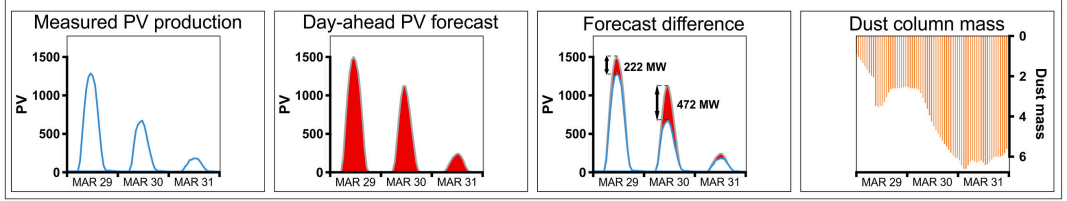


Saharan dust and photovoltaic energy production





LEGEND



Saharan dust and photovoltaic energy production (2019-2023)

Renewable and Sustainable Energy Reviews 212 (2025) 115446

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Desert dust and photovoltaic energy forecasts: Lessons from 46 Saharan dust events in Hungary (Central Europe)

György Varga [a,b,c,*], Fruzsina Gresina [a,c], András Gelencsér [b,d], Adrienn Csávics [a,c], Ágnes Rostási [b,d]

[a] HUN-REN Research Centre for Astronomy and Earth Sciences, Budapest, Hungary
[b] Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary
[c] ELTE Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Meteorology, Budapest, Hungary
[d] MTA-PE Air Chemistry Research Group, Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary

ABSTRACT

Accurate forecasts are essential for generating weather-dependent renewable energy due to supply security requirements and economic reasons. These forecasts rely on various environmental factors, which are uncertainly parameterised and influenced by climate change.

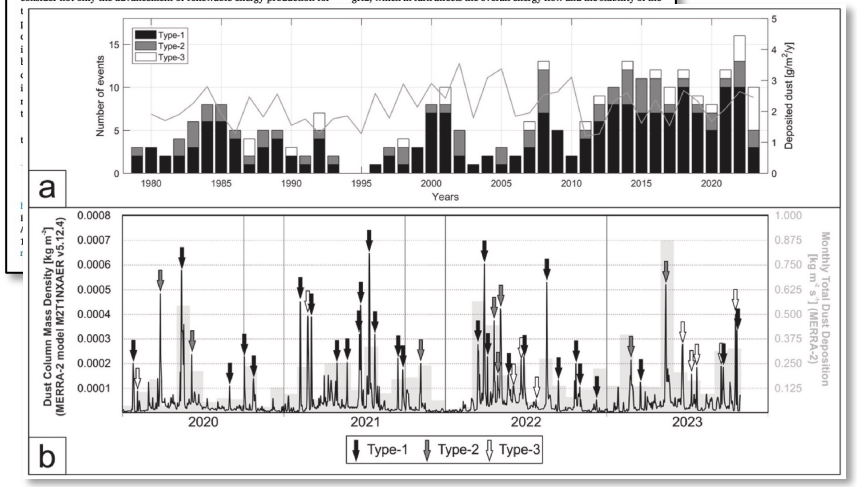
The area discussed, Hungary, is particularly exposed to such uncertainties in photovoltaic (PV) power generation due to the very rapid PV penetration in the country's energy-mix even in a global context, and the growing impact of one of the most uncertain factors (more frequent dust events) in the forecasting.

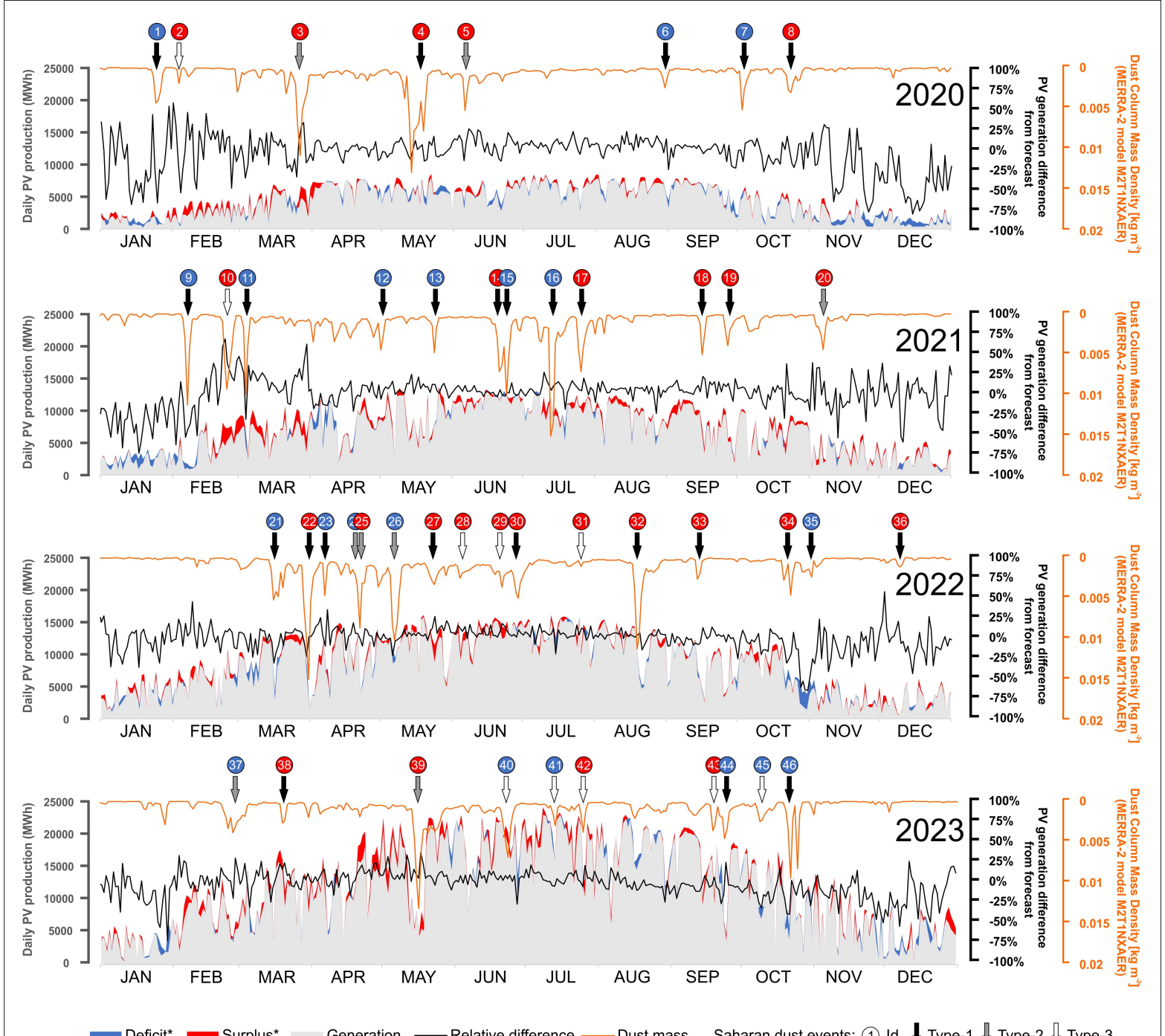
PV production, forecast and 46 identified Saharan dust storm events (SDEs) for 2020–2023 are presented. The indirect effects of dust on irradiance and PV production and forecast errors were quantified. Scheduled values in both directions (deficit and surplus) deviated, typically towards overestimation. During dust storm events, the deviation of both signs was larger than during non-dust states.

The effect of unforeseen cloud cover was dominant on deficit days, while on surplus days with flatter PV production curves, the decreasing cloud cover and potentially the more diurnally prolonged effect of scattered radiation of dusty atmosphere could have caused the excess production. In addition to the direct radiative reduction effect of dust and the role of warm advection in atmospheric physics, the indirect effect of dust in cloud formation processes was identified as the main reason. On deficit days, more extensive cirrus cover caused the outage, while on days with higher irradiance than expected, cirrus with lower radiative forcing replaced the predicted stratus cover.

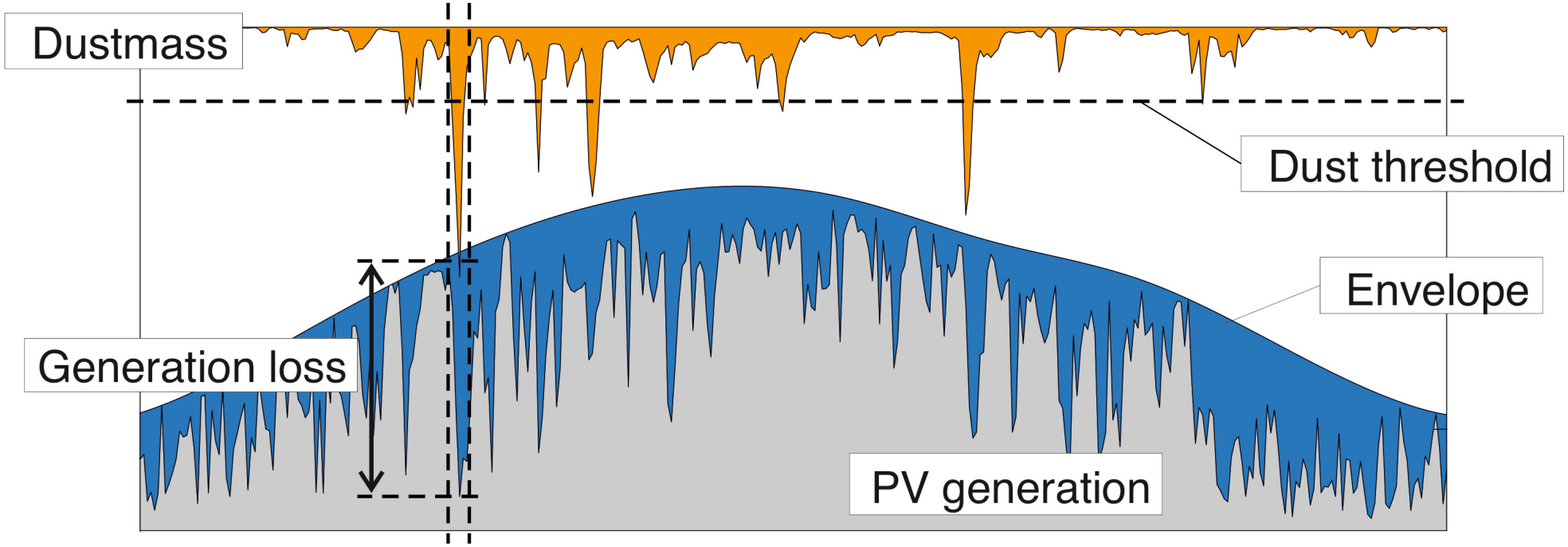
1. Introduction

In the context of accelerating climate change, the contemporary energy crisis, sustainability targets and decarbonisation efforts have placed considerable emphasis on producing-renewable energy [1–3]. In light of the prevailing geopolitical circumstances, it is imperative to consider not only the advancement of renewable energy production for and consumption. As (electric) energy cannot be stored in a sustainable way at scale [5–7], accurate scheduling of short- and mid-term energy production is needed to guarantee the stable and efficient operation of the grid [6]. The impact of desert dust on solar energy is crucial for daily market operations and for public or commercial entities. It influences the amount of energy produced and its integration into the electricity grid, which in turn affects the overall energy flow and the stability of the





Saharan dust and photovoltaic energy production



Data acquisition

PV generation and capacity (ENTSO-E, MEKH)
Dust column mass (MERRA-2)
Cirrus cloud properties (MODIS)
Surface irradiance (CAMS)

Data preprocessing

Aggregation and averaging
PV performance ration calculation
PV production envelope

Event stratification

Dust-affected days
Cirrus conditions
Seasonal segmentation

Mediation modeling

Linear analysis	Quadratic analysis
Dust → Cirrus → PV	Non-linear effects

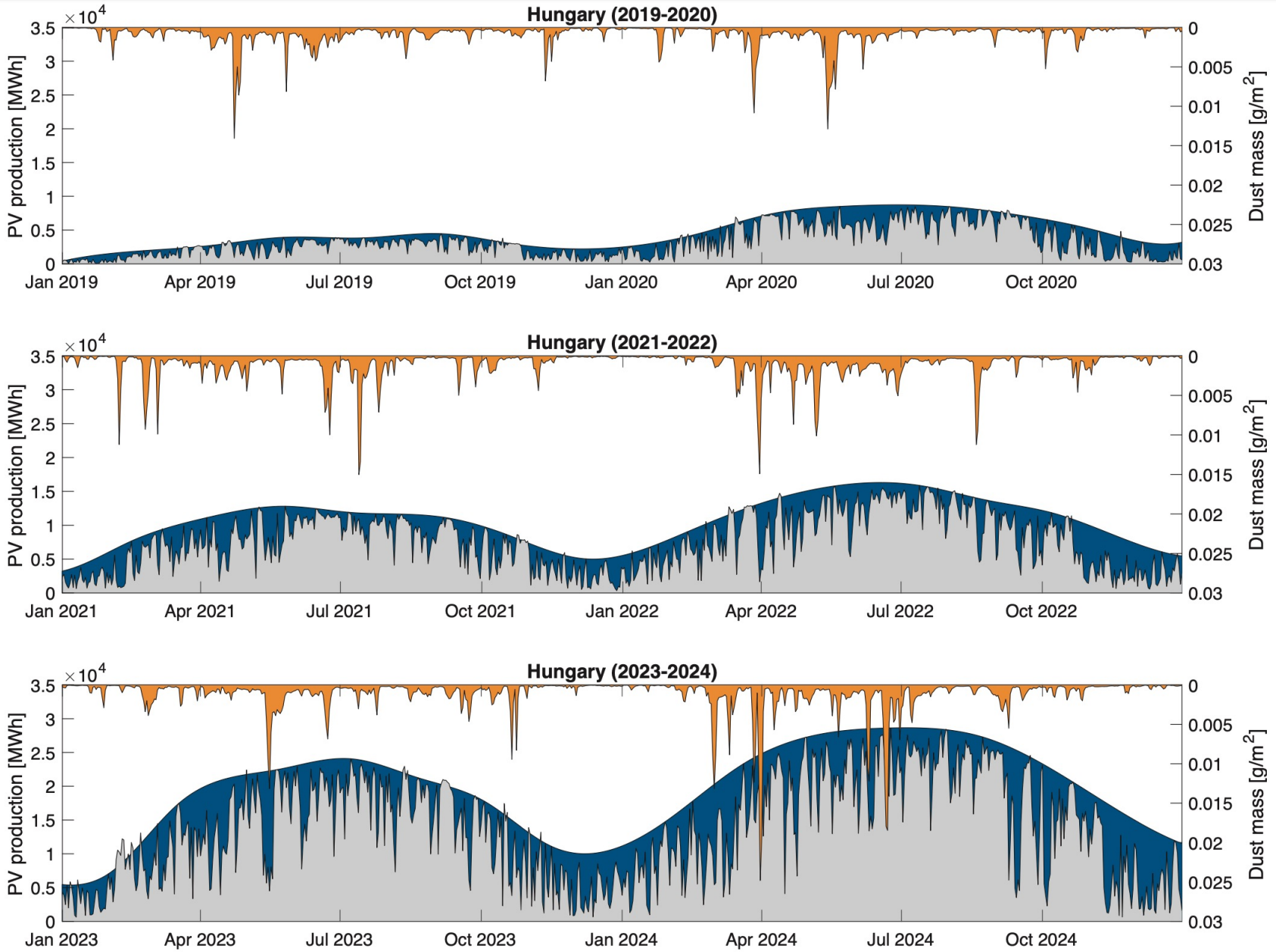
Bootstrap inference

Block resampling (2000 iterations)
Confidence interval estimation

Results and Interpreation

Direct vs. indirect effects
Robustness assessment
Physical insights

Saharan dust and photovoltaic energy production



Data acquisition

PV generation and capacity (ENTSO-E, MEKH)
Dust column mass (MERRA-2)
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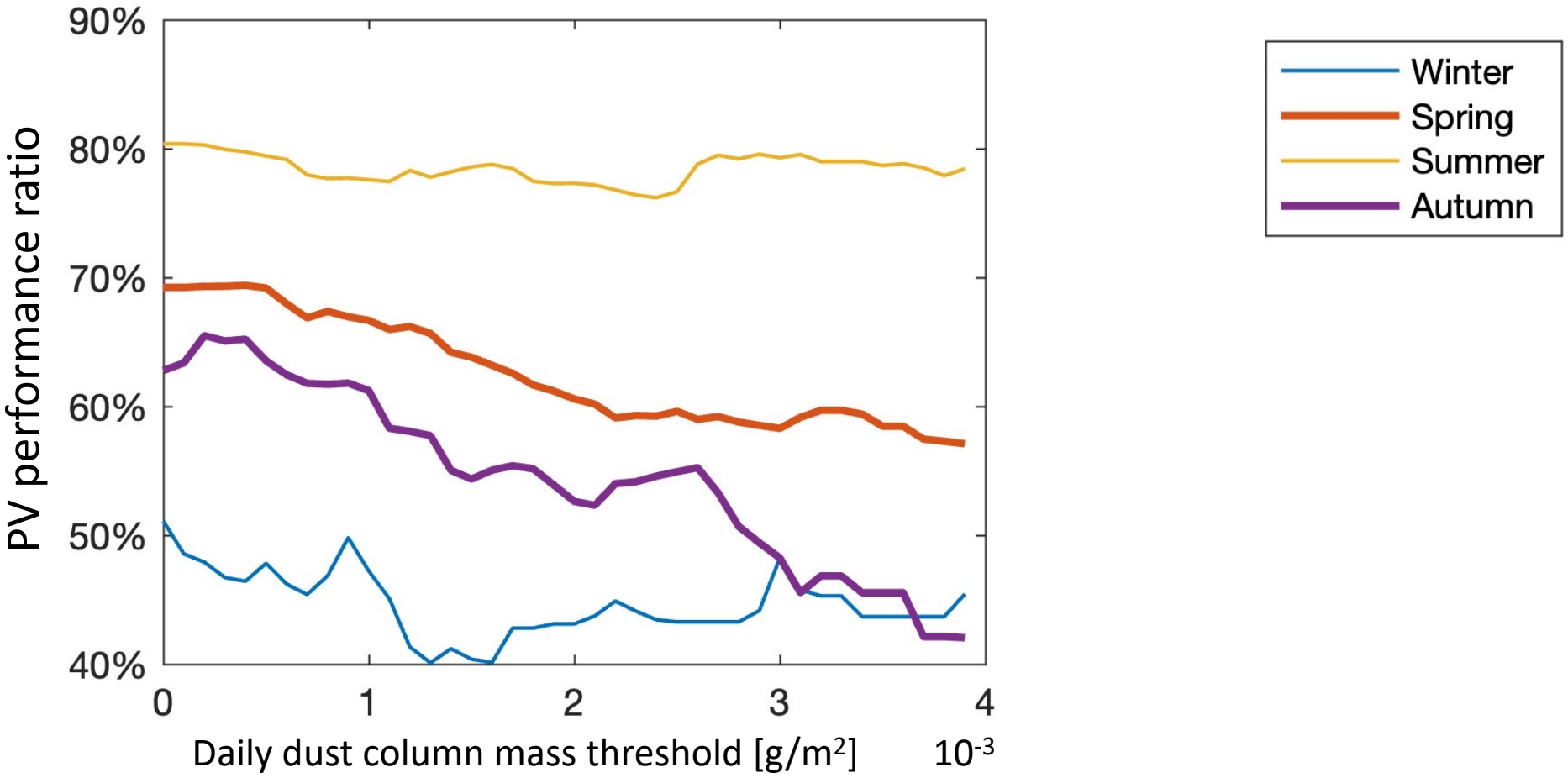
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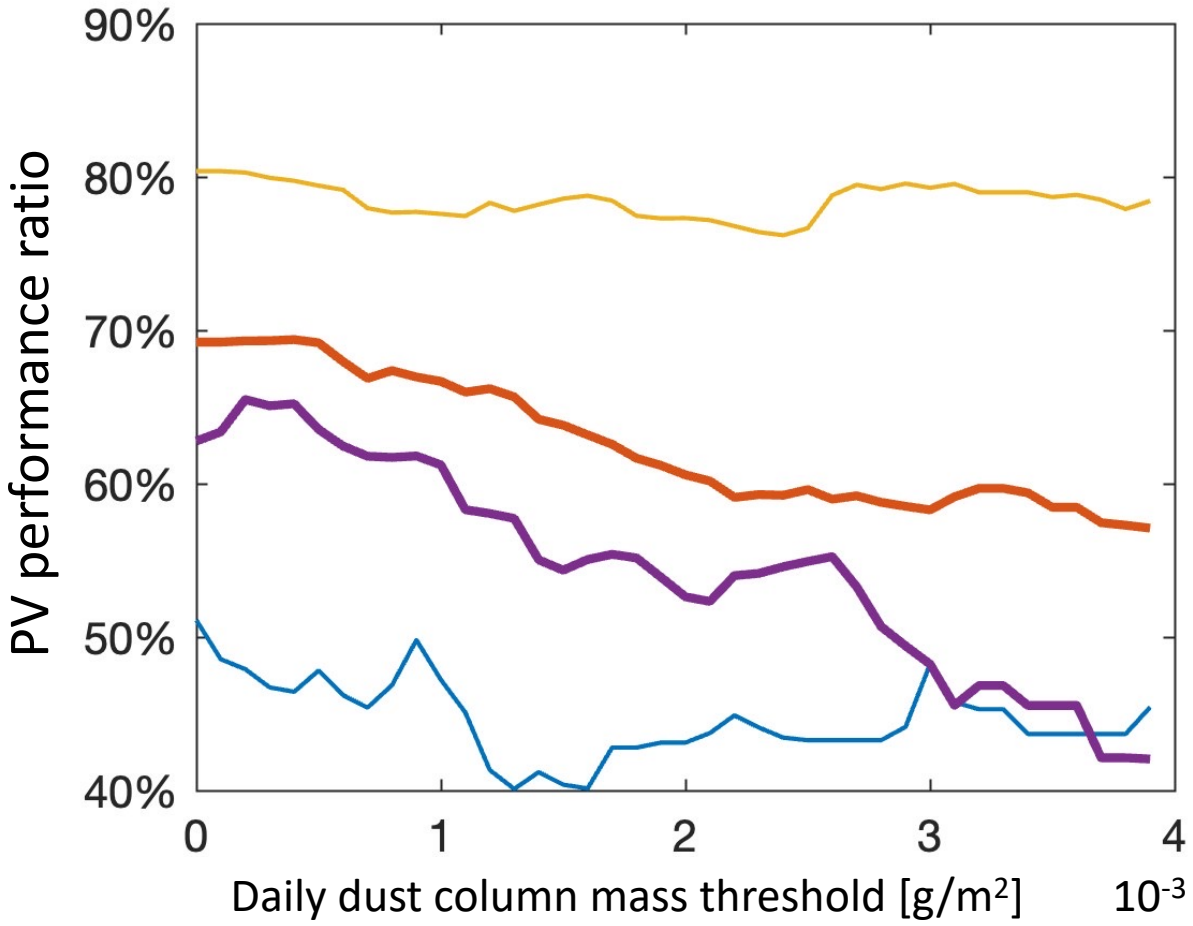
Results and Interpreation

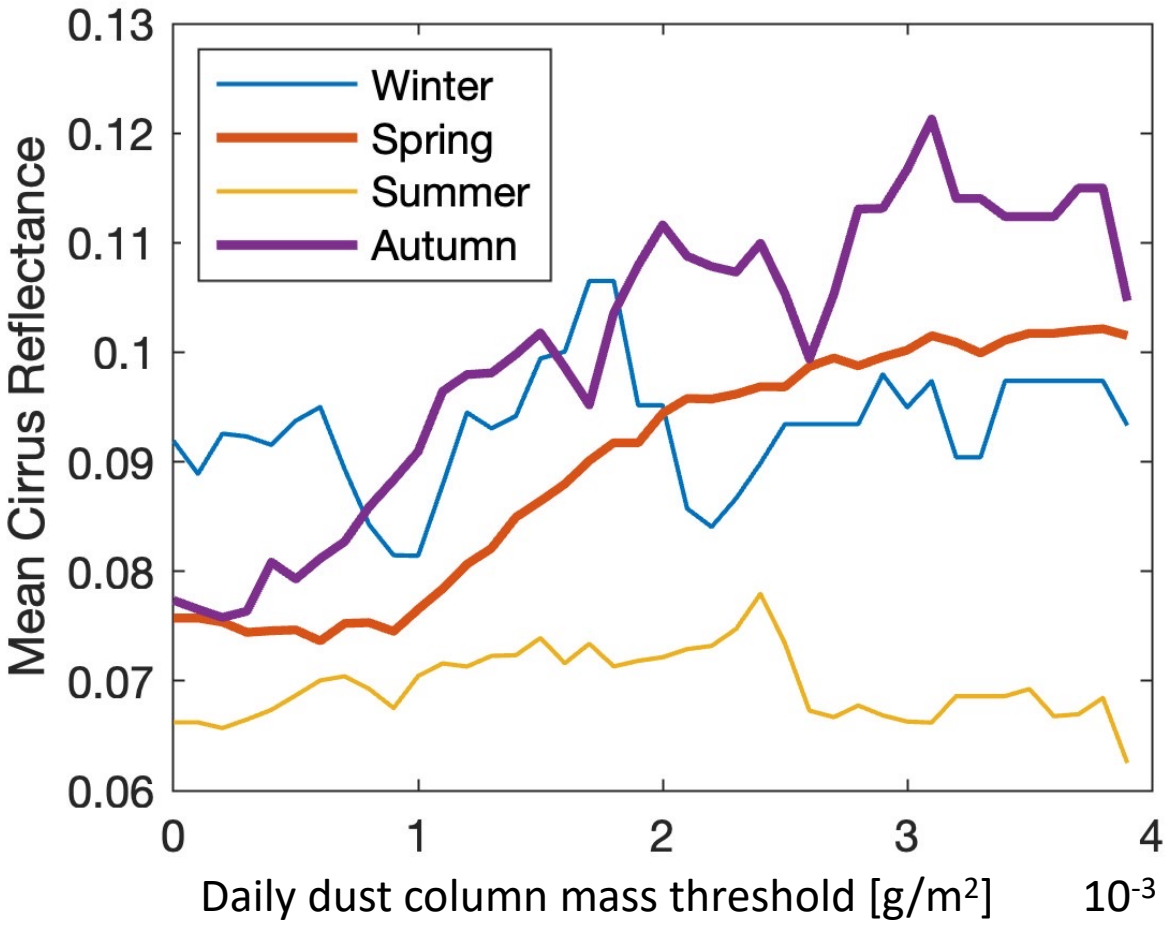
Direct vs. indirect effects
Robustness assessment
Physical insights

Saharan dust and photovoltaic energy production



Saharan dust and photovoltaic energy production







Solar Energy 307 (2026) 114385

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Solar Energy

journal homepage: www.elsevier.com/locate/solener

Saharan dust and cirrus clouds: Dominating indirect impact of dust events on photovoltaic energy generation in Hungar y (2019–2024)

György Varga [a,b,*], Fruzsina Gresina [a], András Gelencsér [b,c], Adrienn Csávics [a], Ágnes Rostási [b,c]

[a] HUN-REN Research Centre for Astronomy and Earth Sciences, Budapest, Hungary
[b] Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary
[c] MTA-PE Air Chemistry Research Group, Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary

ARTICLE INFO

Handling Editor: Dr

Keywords:
Photovoltaic energy
Atmosphere
Mineral dust
Climate change

ABSTRACT

Saharan dust outbreaks increasingly affect Europe, yet their full impact on photovoltaic (PV) performance remains insufficiently represented in models. We investigate Saharan dust events over Hungary, a country with the highest share of PV-based electricity generation (2024: 25%). Using 2019–2024 PV production for Hungary, combined with MERRA-2, MODIS and CAMS datasets, we show that the dominant losses arise not from the direct radiative attenuation of dust, but from dust-induced enhancement of cirrus clouds, which substantially increases atmospheric extinction.

Across the study period, PV performance ratio during high-dust and high-cirrus conditions fell to 46%, compared to > 75% on low-dust days. Cirrus reflectance increased by 55%, and cirrus coverage by 60–85% during high-dust episodes, highlighting a robust aerosol-cloud interaction (ACI) signal.

Seasonal analyses reveal that these indirect impacts peak in the transitional seasons (spring and autumn), when thermodynamic conditions favour heterogeneous ice nucleation. In these seasons, PV performance ratio exhibits a clear sensitivity to dust load (R^2=0.94–0.96), and cirrus optical thickening is most pronounced. Bootstrap-based mediation analysis also demonstrates that the dominant impact of dust on performance operates indirectly through dust-induced cirrus enhancement rather than through direct aerosol attenuation alone.

This study provides the first quantitative separation of direct dust effects and cirrus-mediated indirect pathways in national-scale photovoltaic performance, revealing that ACI dominate PV losses during dust intrusions. By moving beyond correlation-based analyses, it introduces a transferable, statistically robust framework for diagnosing dust impacts on solar energy systems under real-world operating conditions.

1. Introduction

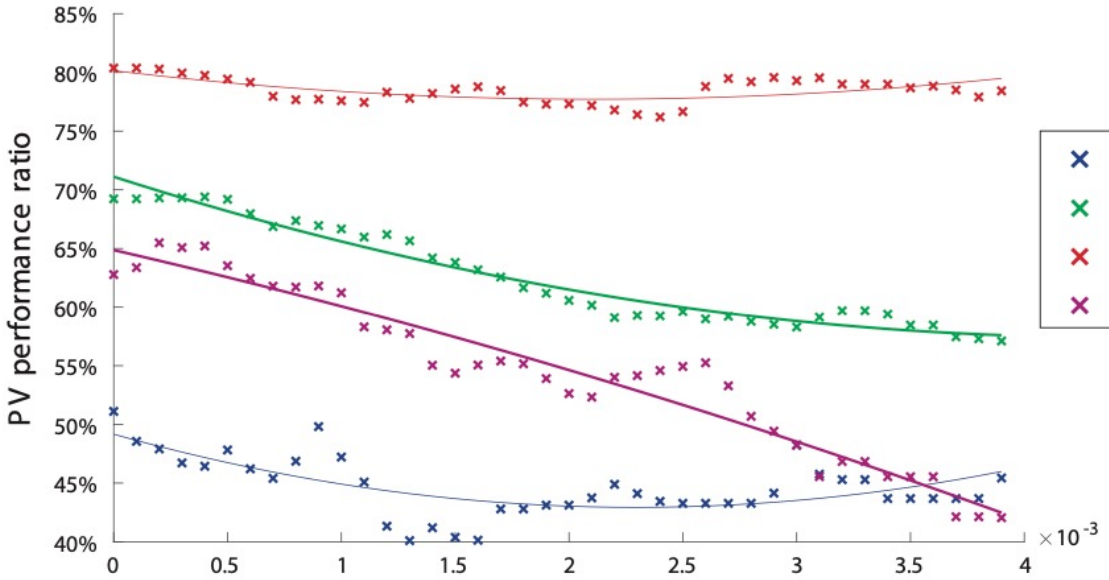
In recent years, renewable electricity generation has gained strategic importance against the backdrop of sustainability imperatives, climate change, and the energy crisis of geopolitical instability [1–3]. Balancing the traditional pillars of the power sector (security of supply, affordability, and sustainability) has become increasingly challenging [4–6]. National energy policies, shaped by both energy sovereignty goals and climate commitments, have accelerated the shift toward renewables, with a strong emphasis on weather-dependent technologies [7].

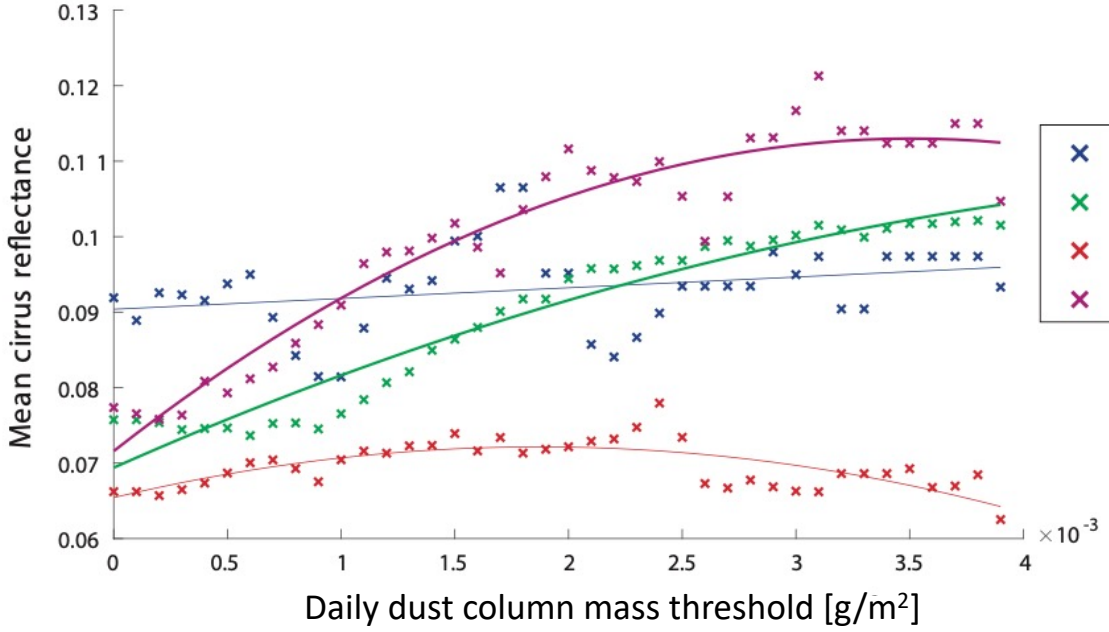
In Hungary, photovoltaic (PV) generation has grown into a leading component of the energy mix. This expansion has heightened the operational importance of accurate production forecasts, which are essential for maintaining the real-time balance between electricity supply and demand [8–10]. Yet, forecasting PV output is inherently complex, as it depends on meteorological conditions that are becoming more variable under climate change [11,12]. The increasing frequency of extreme and anomalous weather events further compounds these challenges, exposing limitations in existing forecasting approaches and underscoring the need to account for less conventional atmospheric influences.

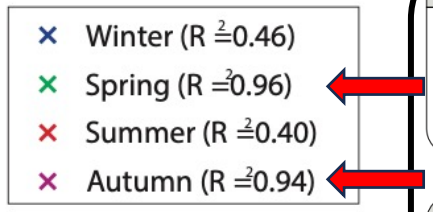
Across Europe, including Hungary, it has been observed in recent years that the frequency and intensity of Saharan dust storm events, which can directly modify radiation transfer and indirectly alter cloud formation, have increased significantly [13–16]. The significance of meridional dust transport in shaping cloud formation processes is of

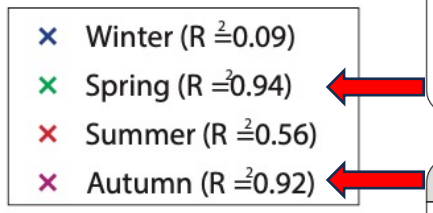
* Corresponding author at: Budaorsi ut 45 H-1112, Hungary.
E-mail address: varga.gyorgy@csfk.org (G. Varga).

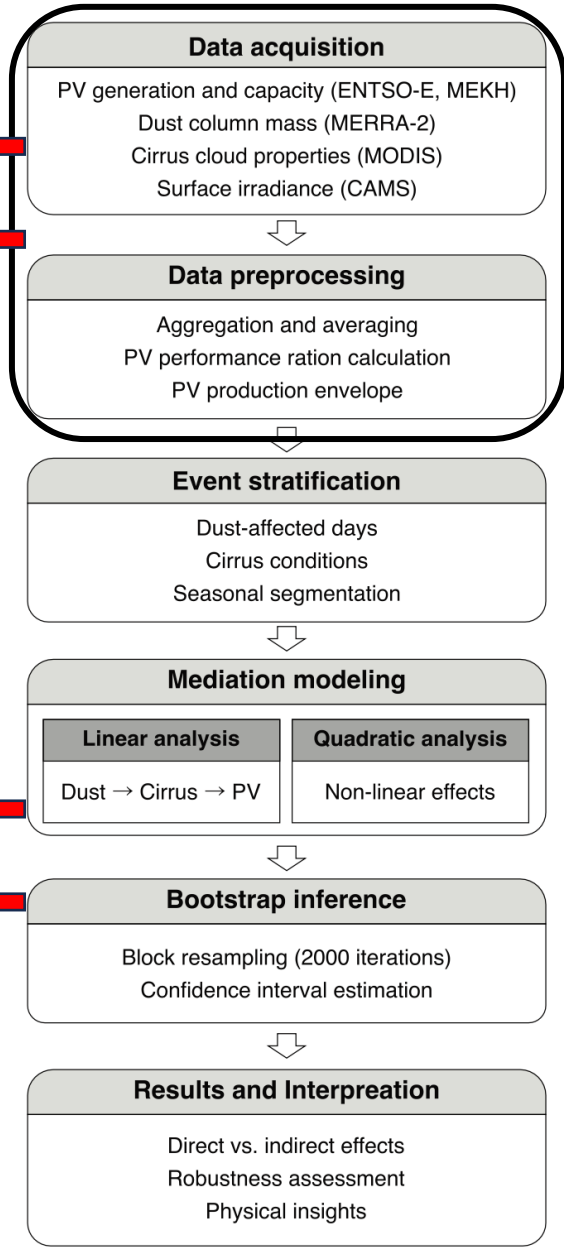
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Received 14 November 2025; Received in revised form 19 January 2026; Accepted 23 January 2026
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0038-092X/© 2026 The Author(s). Published by Elsevier Ltd on behalf of International Solar Energy Society. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).







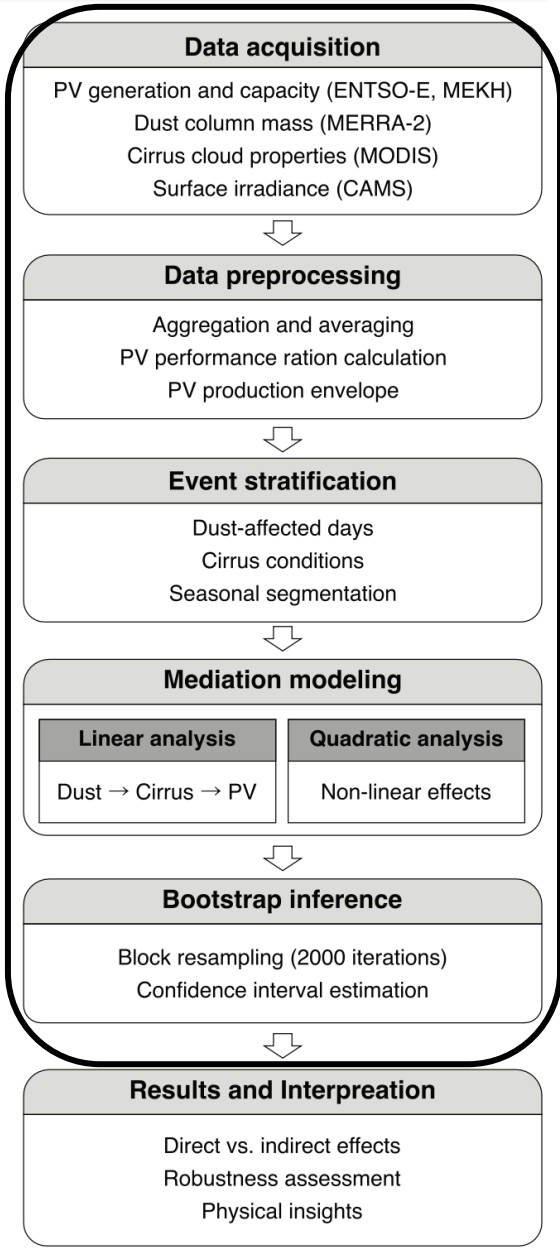


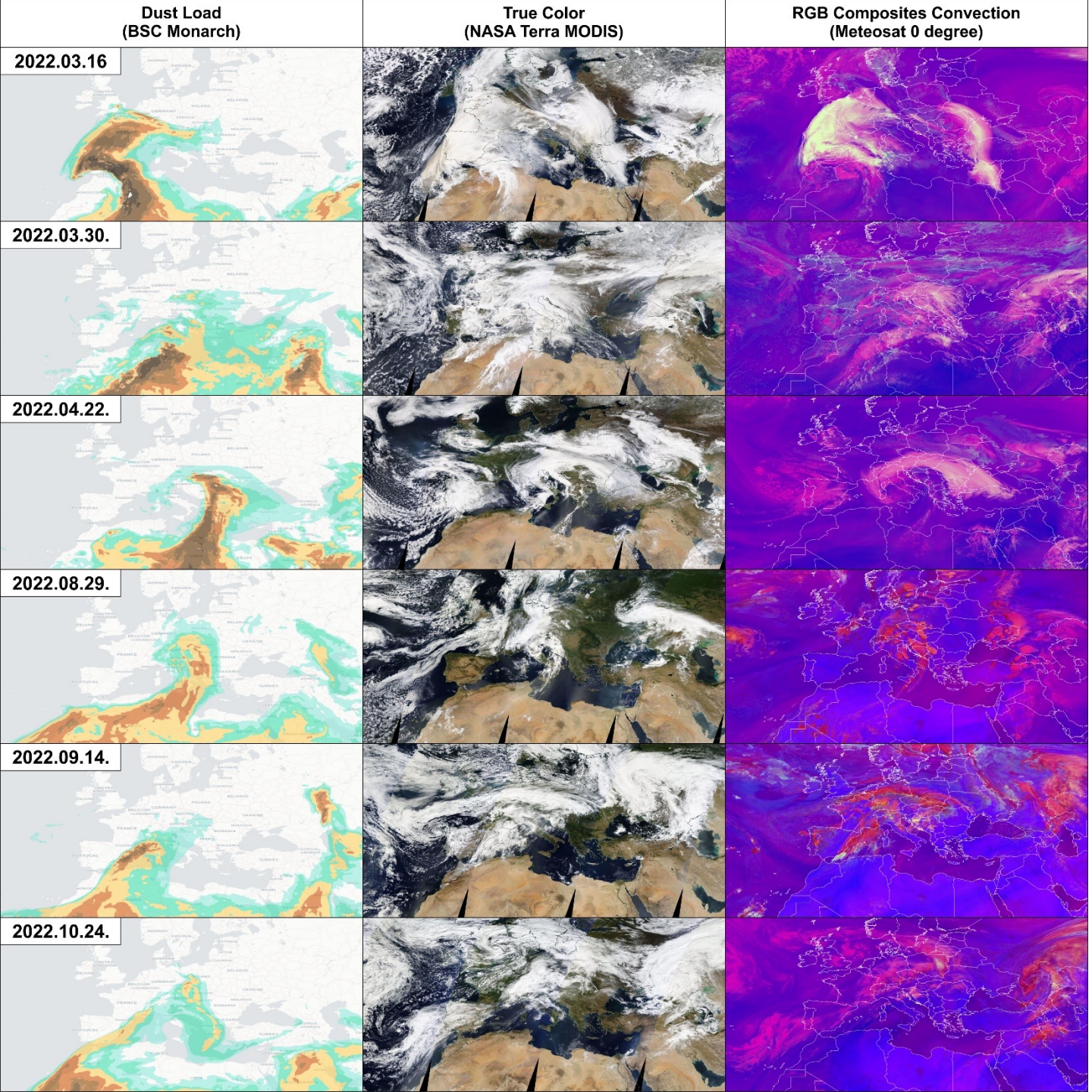


Varga, Gy., Gresina, F., Gelencsér, A., Csávics, A., Rostási, Á. (2026). **Saharan dust and cirrus clouds: Dominating indirect impact of dust events on photovoltaic energy generation in Hungary (2019–2024).** Solar Energy 307. 114385

Saharan dust and photovoltaic energy production

Season	Condition	Mean PV loss percent	95% CI	Days (n)
Spring	Cirrus only (top quartile)	40.9	[36.7, 45.5]	92
	Dust + cirrus	43.2	[35.4, 50.7]	35
	Dust only (top 10%)	38.6	[33, 44.4]	65
	Low dust & low cirrus	24.5	[22.3, 26.8]	360
Summer	Cirrus only (top quartile)	24.3	[20.4, 28.1]	86
	Dust + cirrus	34.4	[27.4, 42.3]	18
	Dust only (top 10%)	19.5	[15.2, 24]	51
	Low dust & low cirrus	17.5	[16.2, 18.9]	397
Autumn	Cirrus only (top quartile)	52.2	[47.4, 57.2]	123
	Dust + cirrus	58.6	[47.7, 67.8]	11
	Dust only (top 10%)	38	[28.2, 48]	20
	Low dust & low cirrus	30.9	[28.1, 33.7]	392
Winter	Cirrus only (top quartile)	58.9	[54.6, 63.1]	177
	Dust + cirrus	78.3	[65.9, 87.2]	6
	Dust only (top 10%)	45.2	[32.8, 58]	14
	Low dust & low cirrus	41.7	[38.7, 44.9]	345





Cloud formation and mineral dust

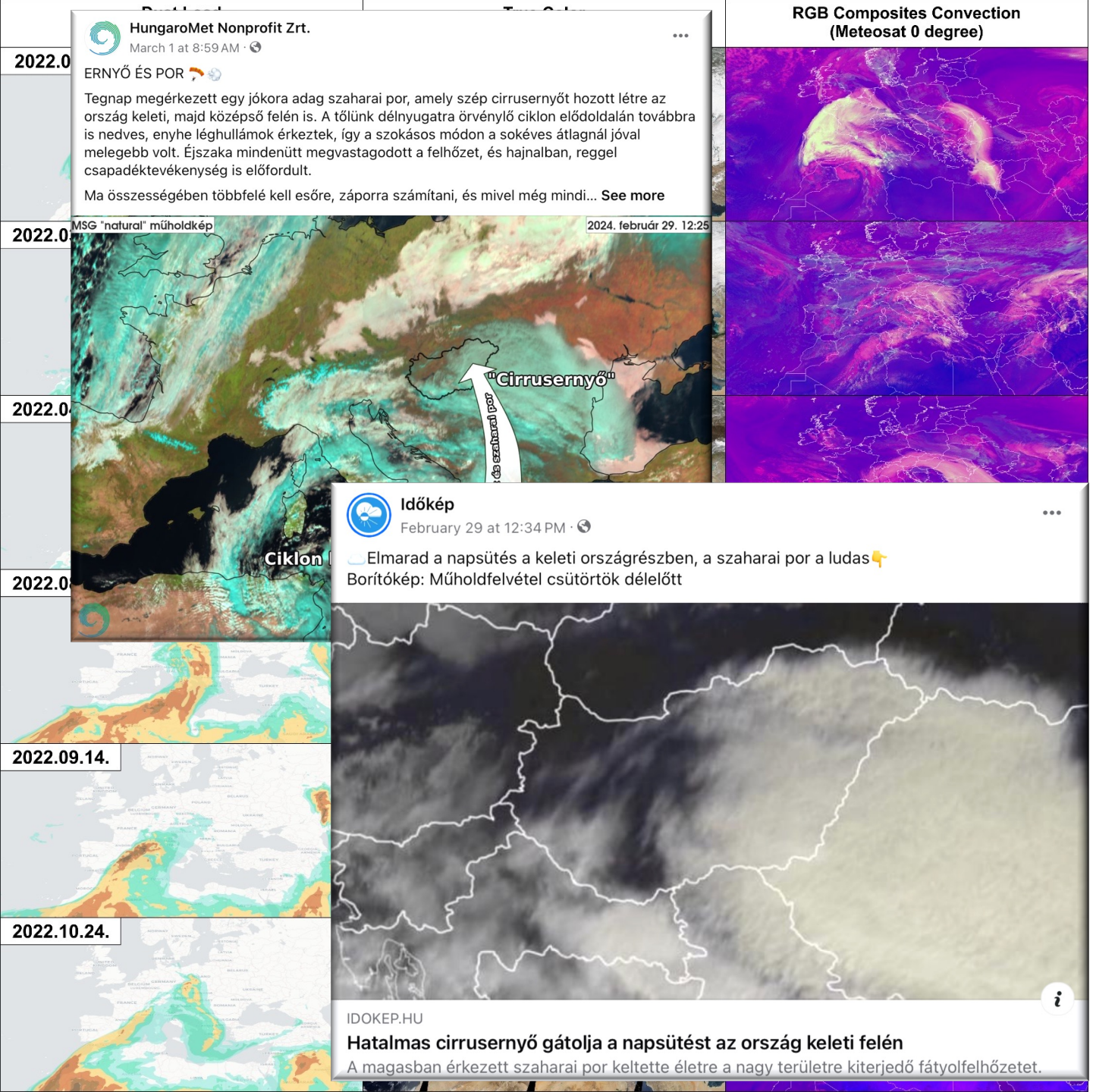
indirect effects* of mineral dust played a major role in the drops of PV power production
(*the dust particles as **ice nucleating particles** (INPs), and cloud condensation nuclei (CCNs))

increased atmospheric mineral particle number concentrations can lead to the formation of **more, but smaller, ice particles and cloud droplets** for a given amount of water vapour

dust is a polymineral agent with a wide range of grain size and shape properties

has a diverse influence on cloud formation

Cloud formation and mineral dust

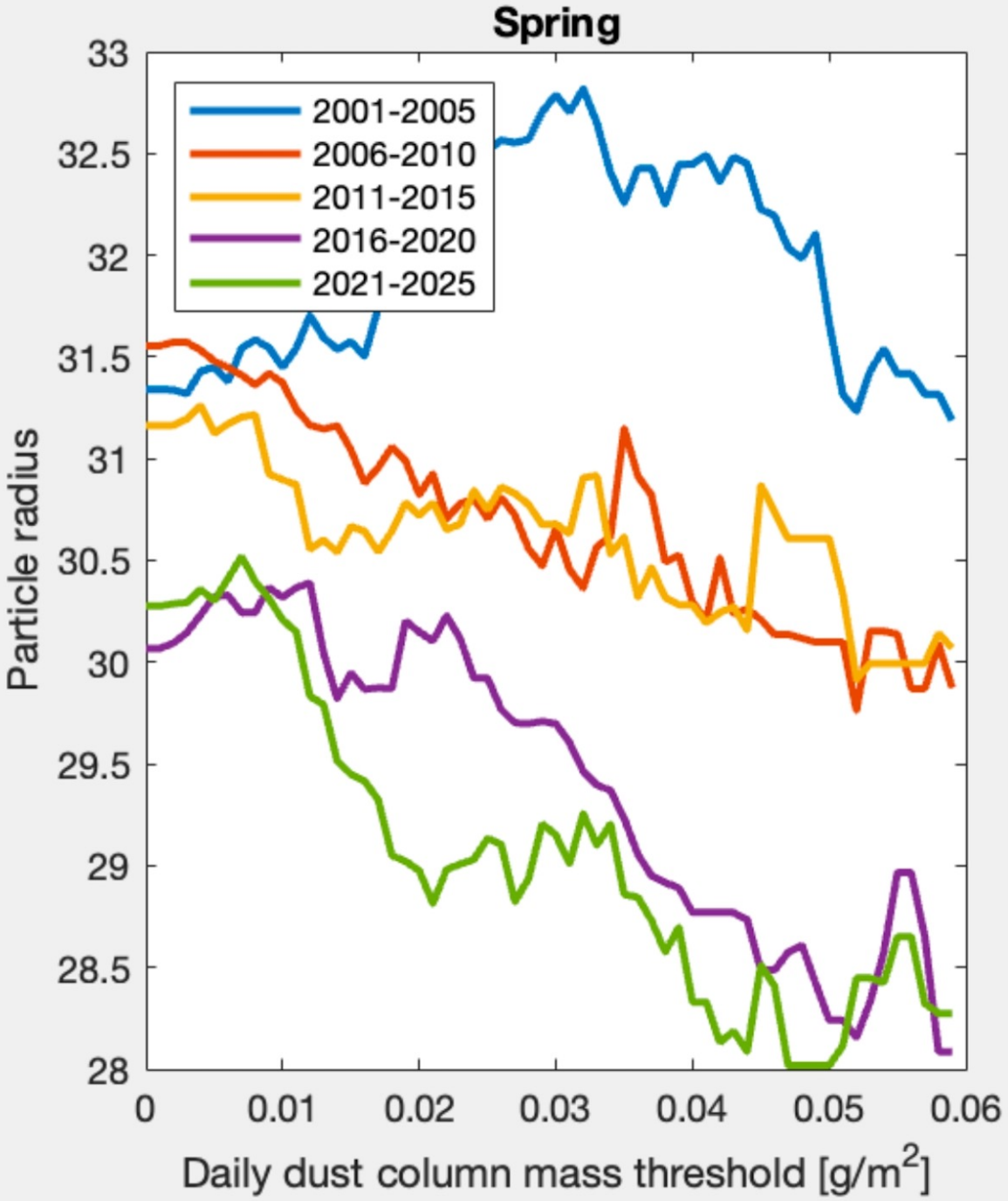


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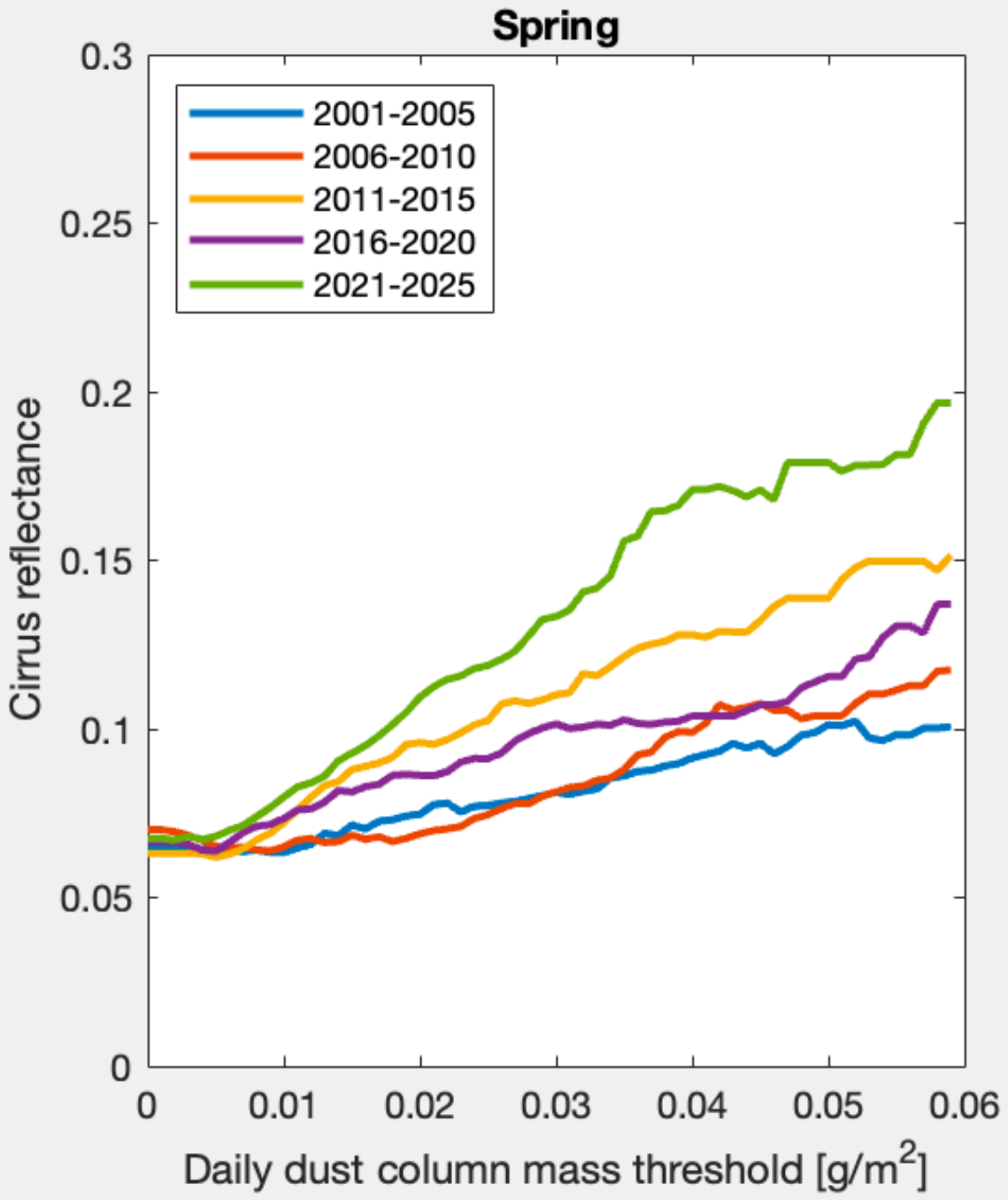
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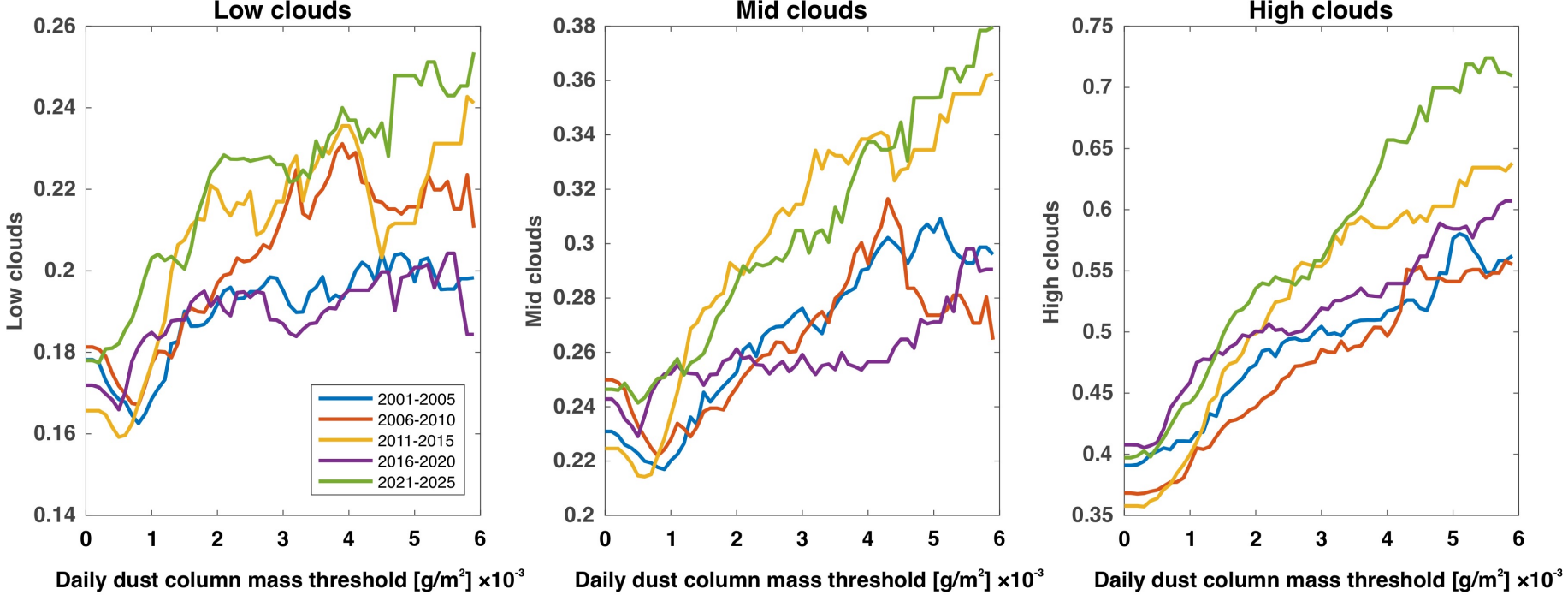


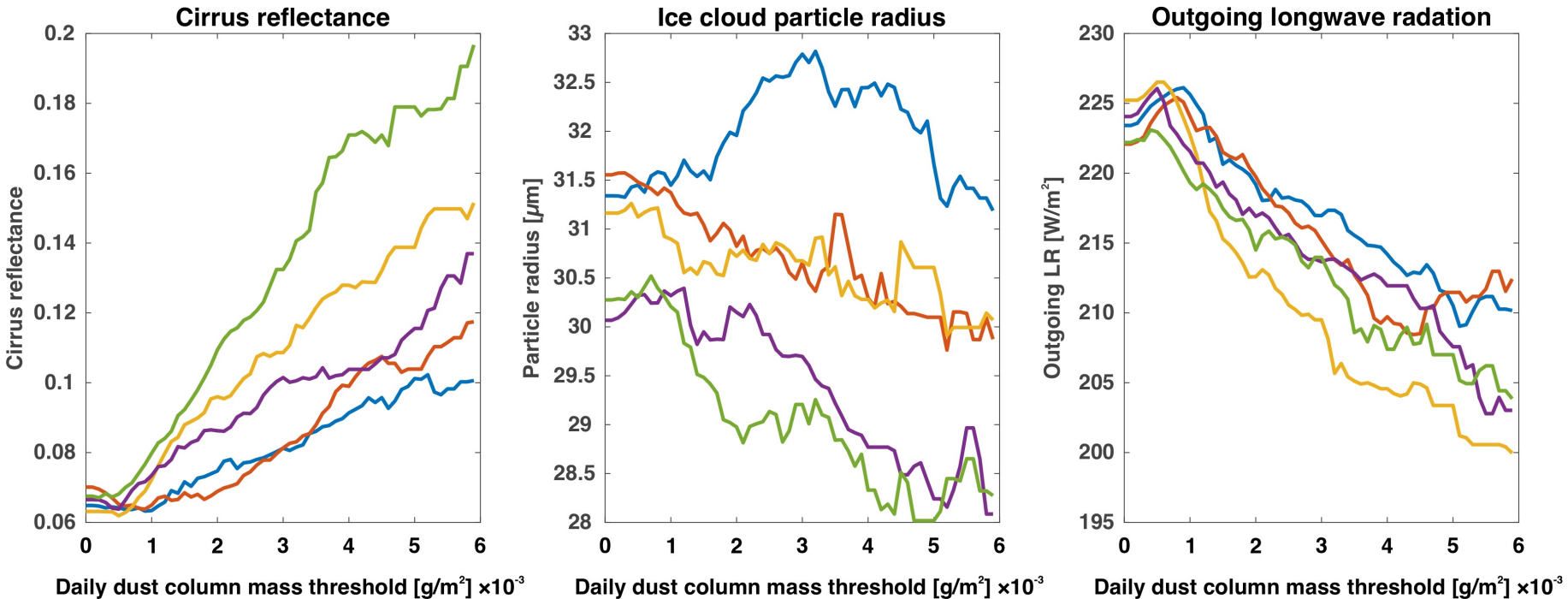
Cirrus formation: 2001-2025

There is more Saharan dust in Europe, but something has also happened in the atmosphere

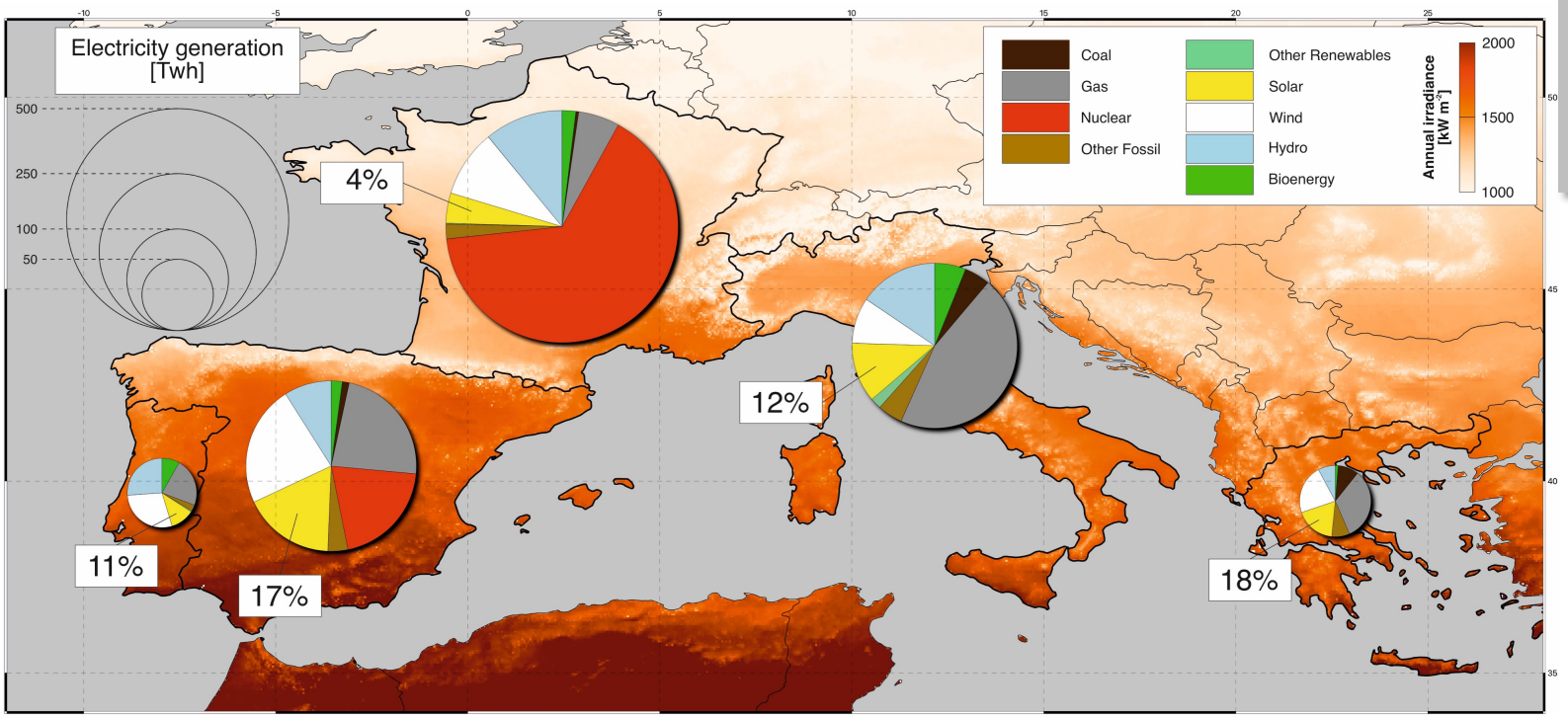
With similar dust levels, there are differing but trend-like (?) changes in cirrus cloud formation

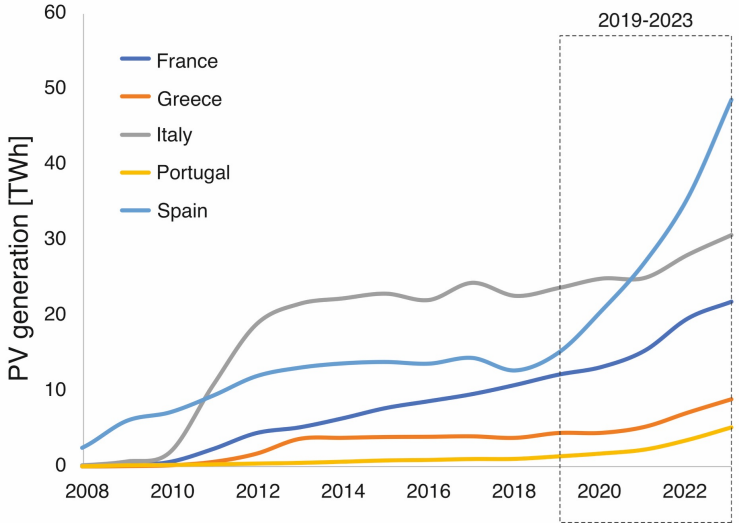
More frequent cirrus shields (in spring)

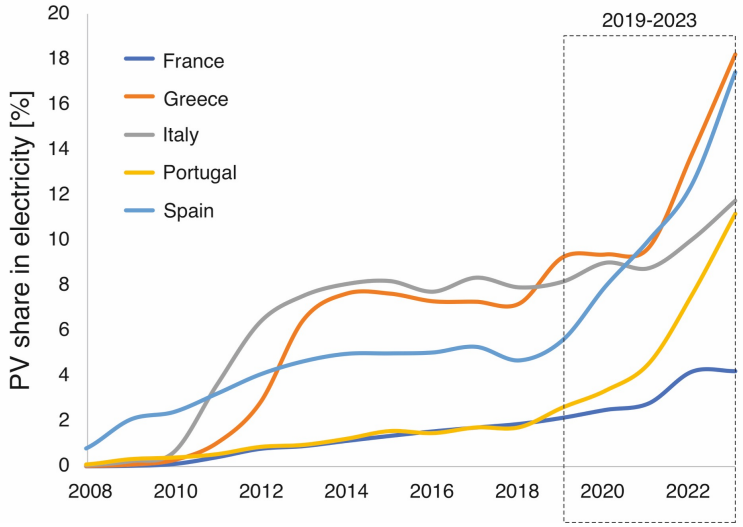

Low clouds
Low clouds
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0 1 2 3 4 5 6
Daily dust column mass threshold [g/m²] ×10⁻³
2001-2005
2006-2010
2011-2015
2016-2020
2021-2025
Mid clouds
Mid clouds
0.38
0.36
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0 1 2 3 4 5 6
Daily dust column mass threshold [g/m²] ×10⁻³
High clouds
High clouds
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0 1 2 3 4 5 6
Daily dust column mass threshold [g/m²] ×10⁻³


Cirrus reflectance
Cirrus reflectance
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0 1 2 3 4 5 6
Daily dust column mass threshold [g/m²] ×10⁻³
Ice cloud particle radius
Particle radius [μm]
33
32.5
32
31.5
31
30.5
30
29.5
29
28.5
28
0 1 2 3 4 5 6
Daily dust column mass threshold [g/m²] ×10⁻³
Outgoing longwave radation
Outgoing LR [W/m²]
230
225
220
215
210
205
200
195
0 1 2 3 4 5 6
Daily dust column mass threshold [g/m²] ×10⁻³

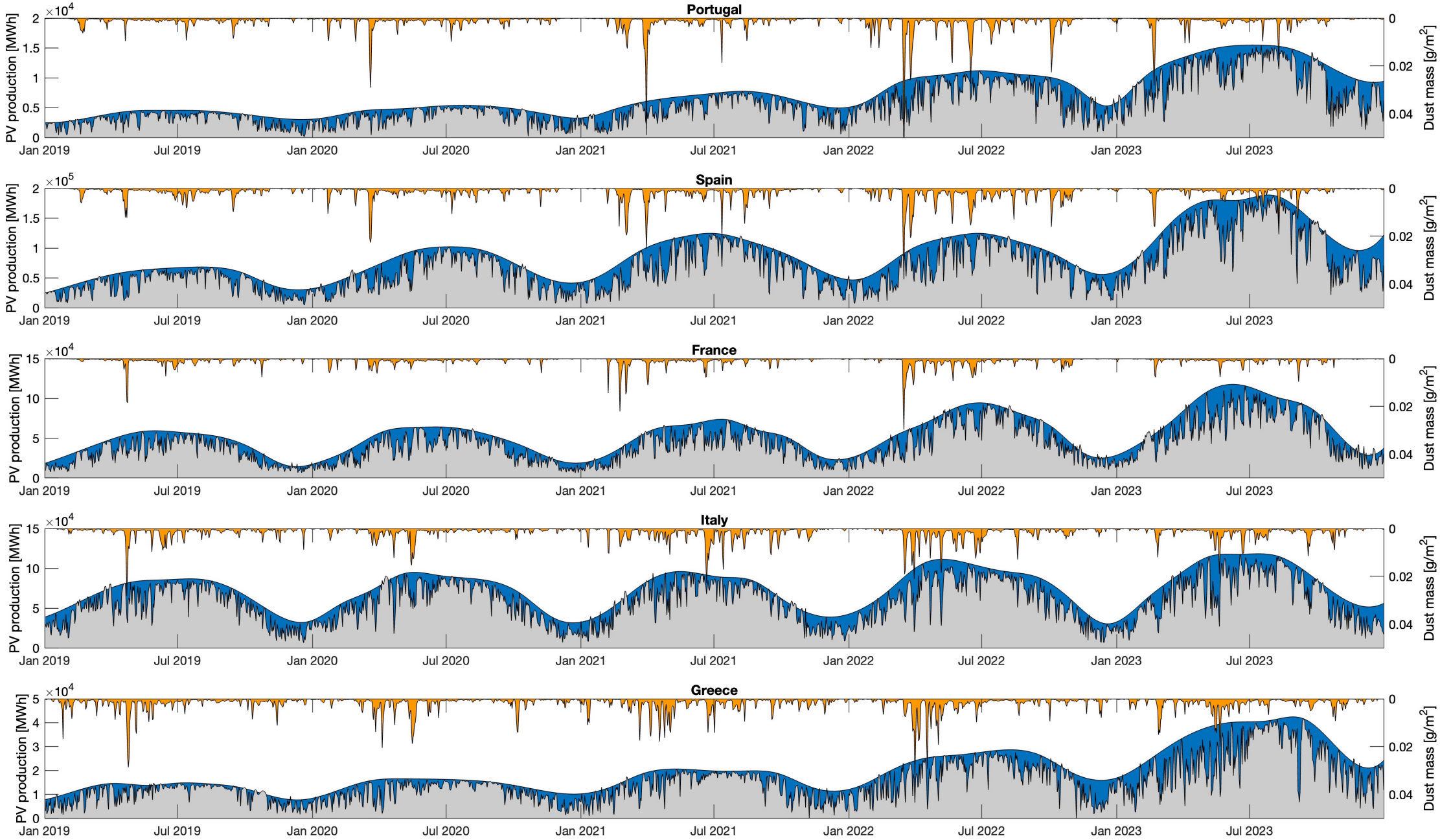
Photovoltaic energy in Southern Europe

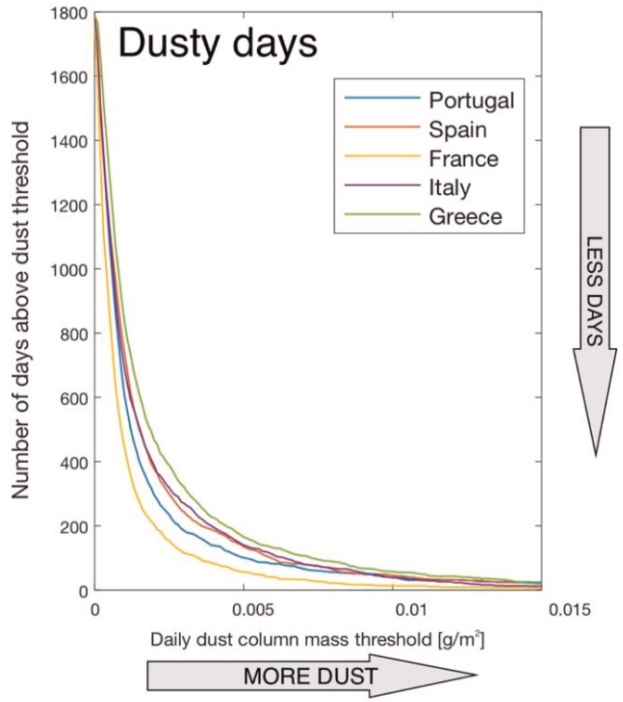


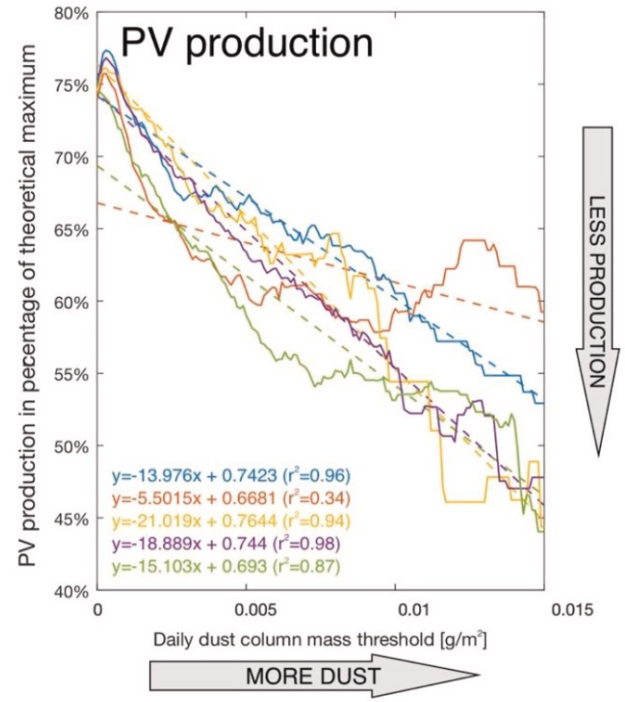


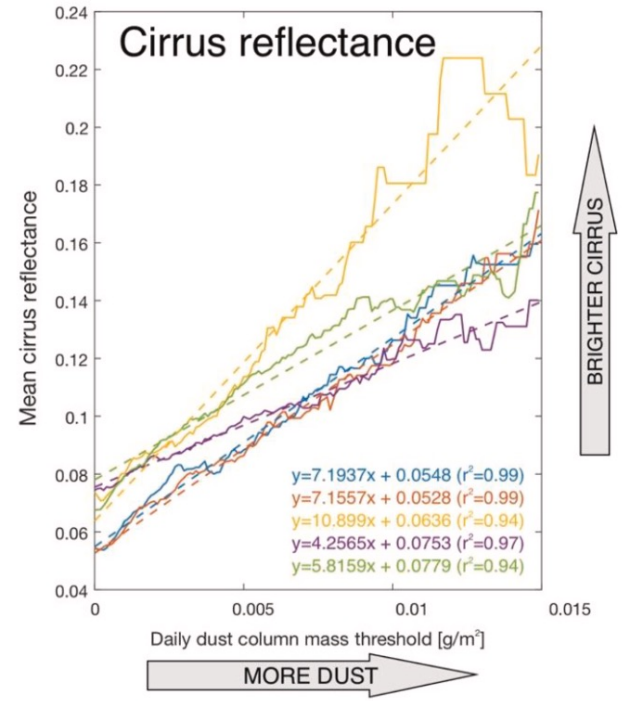


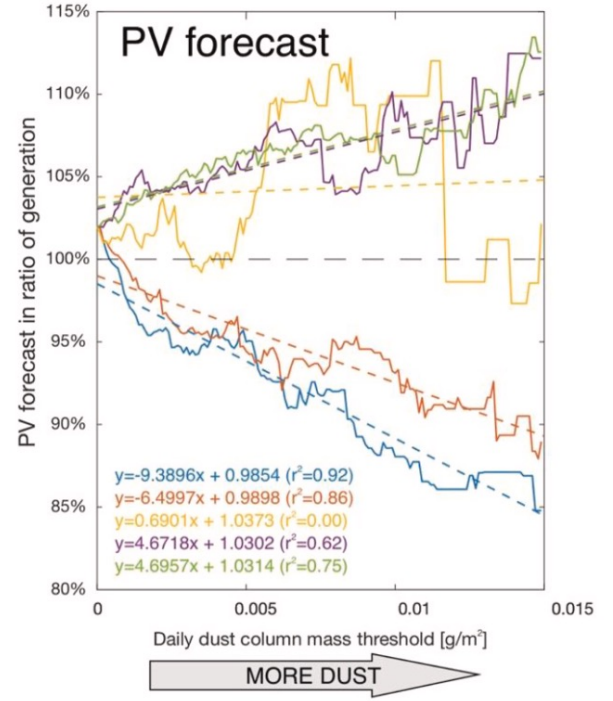
Saharan dust and photovoltaic energy in Southern Europe



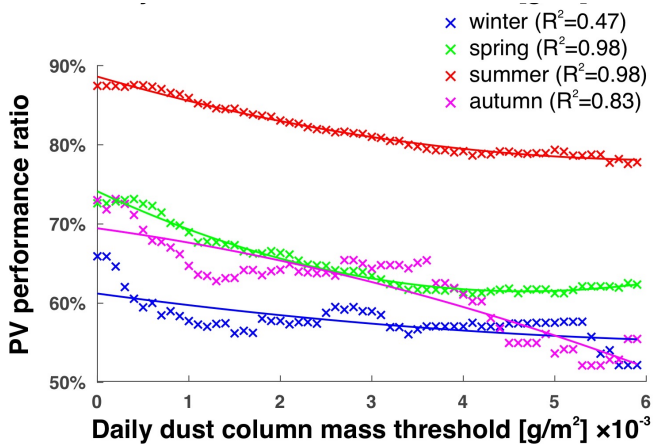

Dusty days
Portugal
Spain
France
Italy
Greece
Number of days above dust threshold
Daily dust column mass threshold [g/m²]
LESS DAYS
MORE DUST

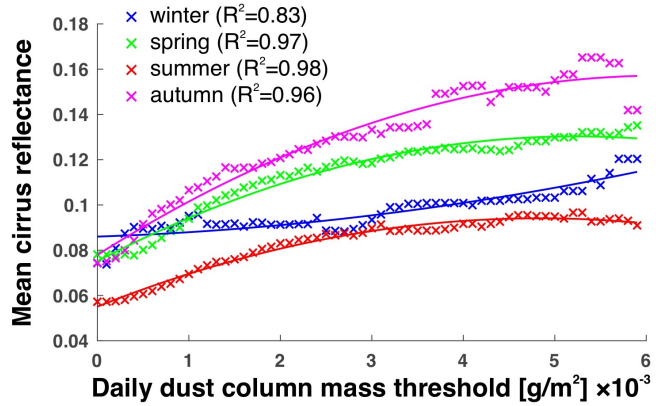

PV production
PV production in pecentage of theoretical maximum
y=-13.976x + 0.7423 (r²=0.96)
y=-5.5015x + 0.6681 (r²=0.34)
y=-21.019x + 0.7644 (r²=0.94)
y=-18.889x + 0.744 (r²=0.98)
y=-15.103x + 0.693 (r²=0.87)
Daily dust column mass threshold [g/m²]
LESS PRODUCTION
MORE DUST

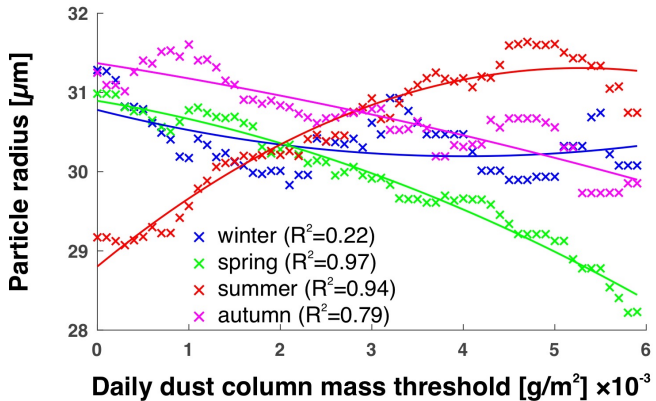

Cirrus reflectance
Mean cirrus reflectance
y=7.1937x + 0.0548 (r²=0.99)
y=7.1557x + 0.0528 (r²=0.99)
y=10.899x + 0.0636 (r²=0.94)
y=4.2565x + 0.0753 (r²=0.97)
y=5.8159x + 0.0779 (r²=0.94)
Daily dust column mass threshold [g/m²]
BRIGHTER CIRRUS
MORE DUST


PV forecast
PV forecast in ratio of generation
y=-9.3896x + 0.9854 (r²=0.92)
y=-6.4997x + 0.9898 (r²=0.86)
y=0.6901x + 1.0373 (r²=0.00)
y=4.6718x + 1.0302 (r²=0.62)
y=4.6957x + 1.0314 (r²=0.75)
Daily dust column mass threshold [g/m²]
MORE DUST

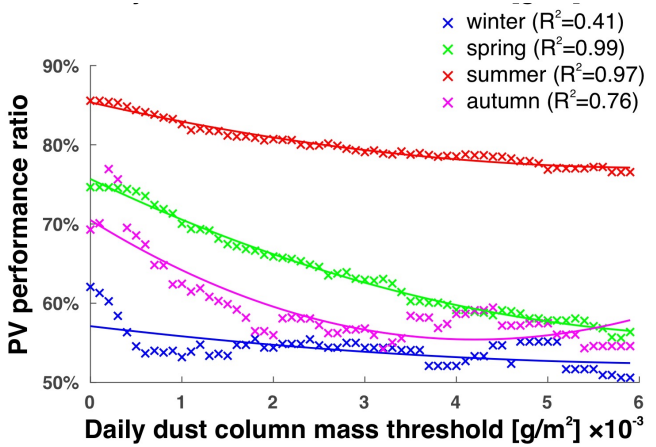
Spain

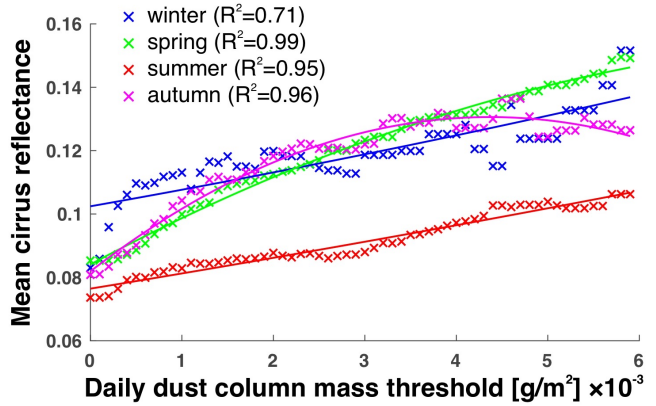


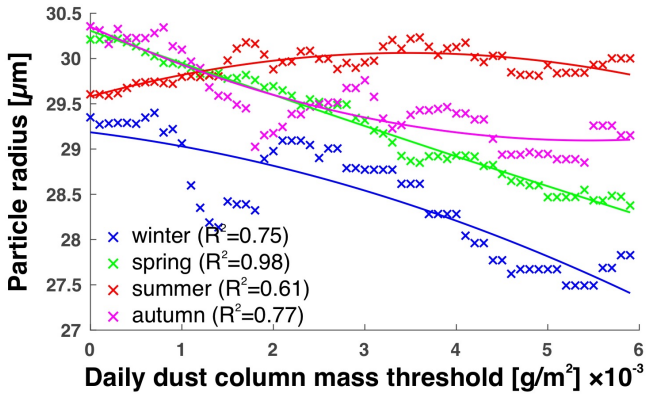




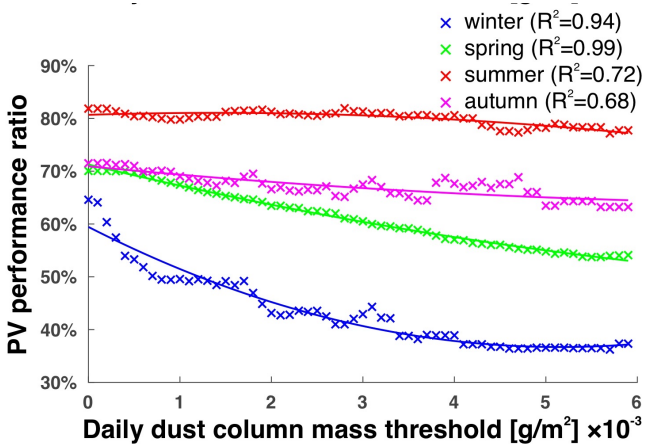
Italy

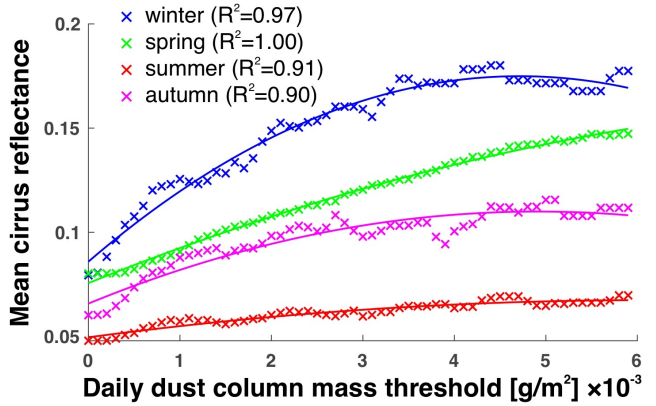


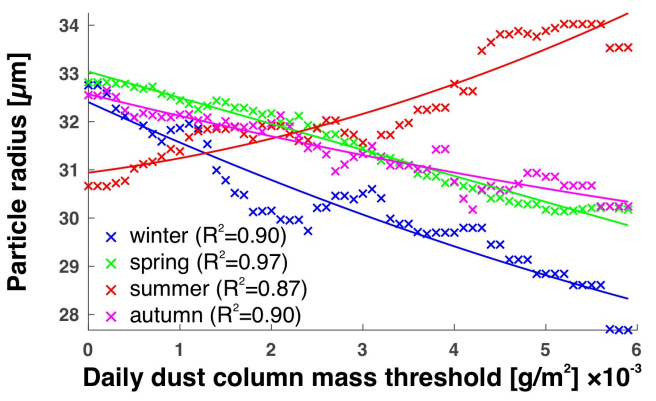




Greece

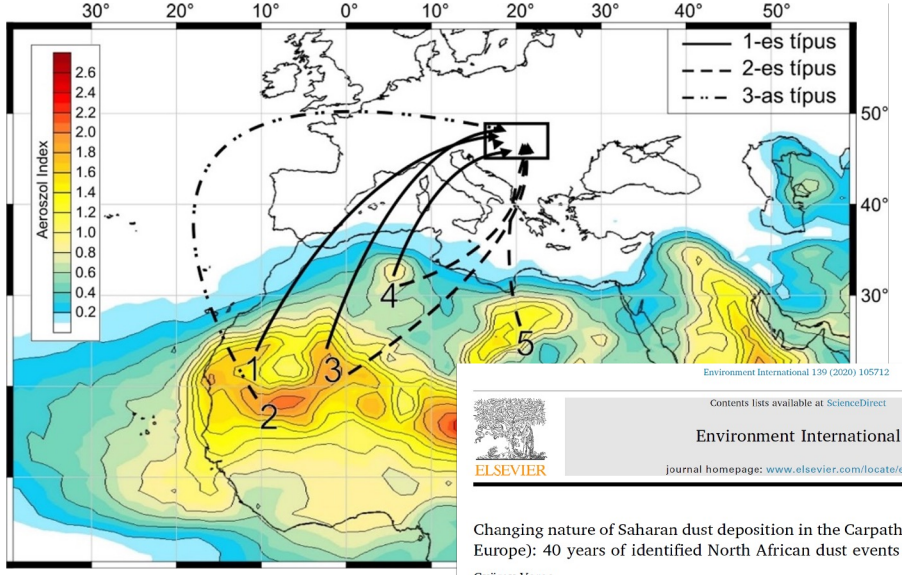






Importance of atmospheric dust in photovoltaic power generation

- Saharan dust storm events affecting Hungary are relatively frequent (**n>300 under 45+ years**)
  - their **frequency and intensity are increasing;**
  - the amount of dust deposited in the country is estimated to be in the **hundreds of thousands of tons** per year;
  - the amount is expected to increase as a result of climate change.



Environment International 139 (2020) 105712

Contents lists available at ScienceDirect

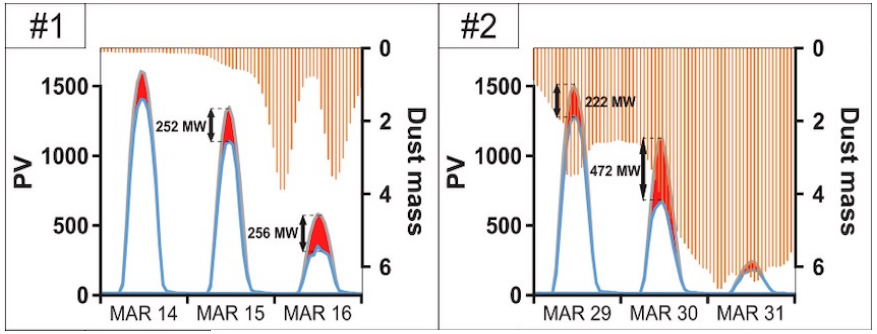
Environment International

journal homepage: www.elsevier.com/locate/envint

ELSEVIER

Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018)

György Varga




Renewable and Sustainable Energy Reviews 193 (2024) 114289

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

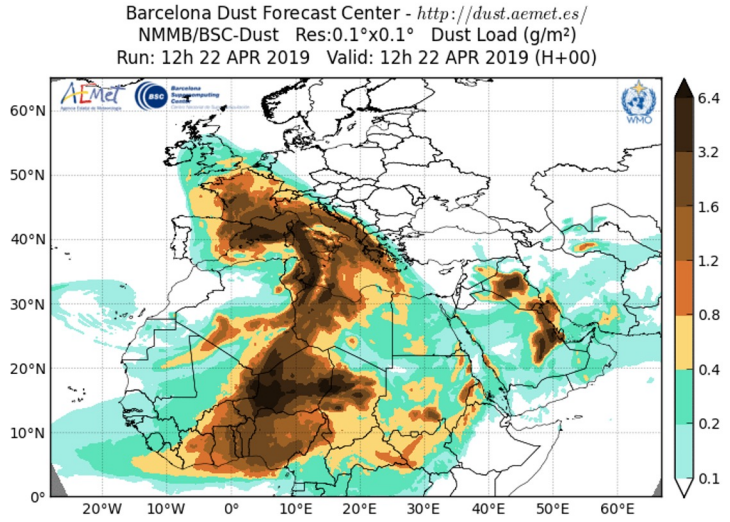
ELSEVIER

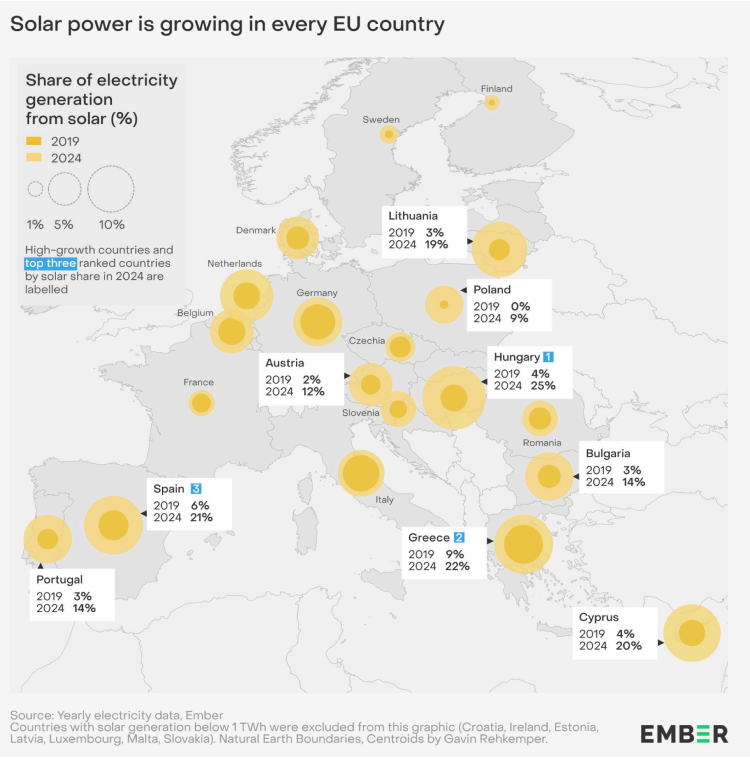
Effect of Saharan dust episodes on the accuracy of photovoltaic energy production forecast in Hungary (Central Europe)

György Varga [a,b,c,d,*], Fruzsina Gresina [a,c,d], József Szeberényi [a,d], András Gelencsér [c,e], Ágnes Rostási [c,e]

- **reduces irradiance** through direct and indirect (e.g. cloud formation) effects;
  - dust deposited on the surface of the panels reduces their efficiency;

- an atmospheric component **relevant for forecasting, but**:
  - **parameterisation** of atmospheric dust is not appropriate in numerical simulations;
  - calculations rely on **aerosol climatology** (i.e. multi-year average) data
  - **its role in cloud formation** is not taken into account





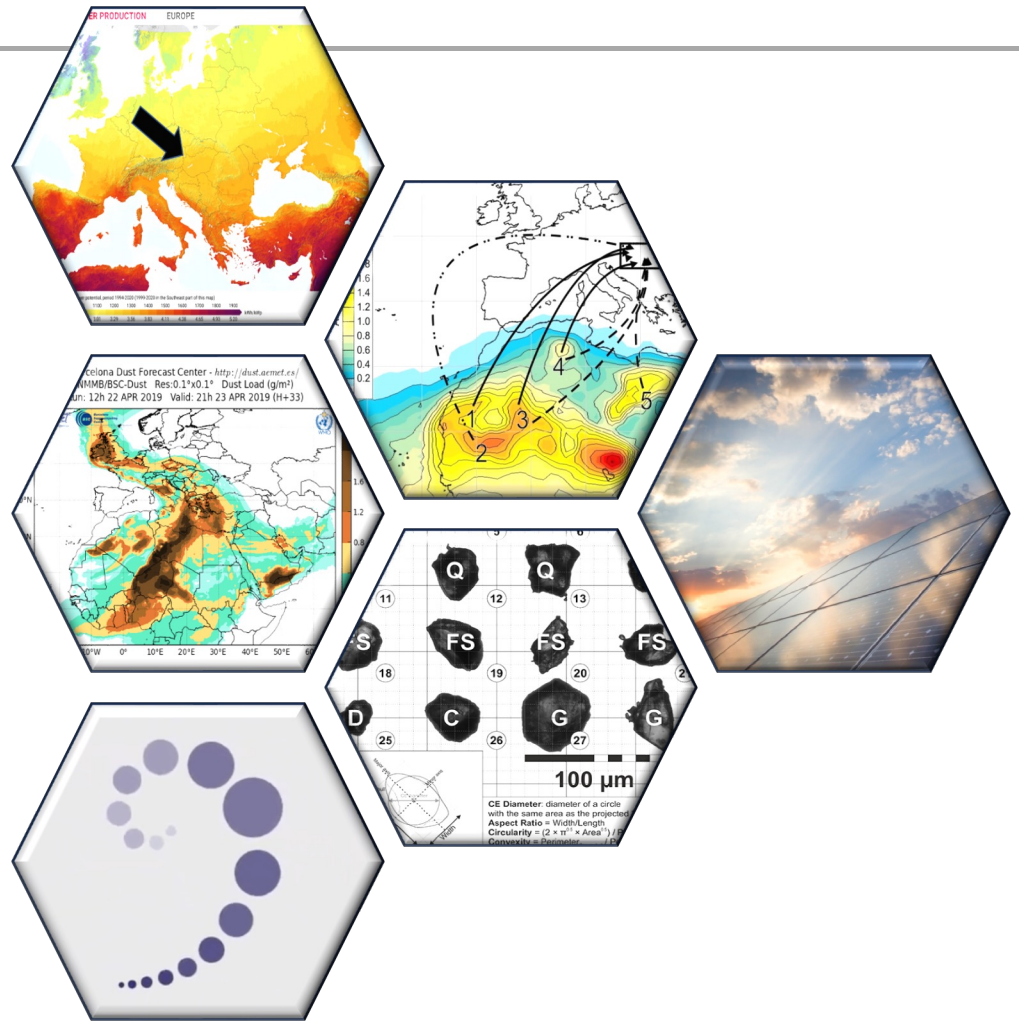
The main lessons we have highlighted:

Atmospheric dust has a **significant impact** on PV production and forecasting, especially during south-to-north dust transport, which can intensify cloud formation processes.

Accurate PV production forecasts require **up-to-date dust loading data** and proper **cloud-physics relationships**, as coarse-resolution aerosol climatology data alone are insufficient.

The **amount, transport dynamics, and properties** (grain size, shape) of atmospheric dust are not fully understood, but they have **diverse effects on cloud formation** processes, requiring further study.

Climate change and the natural variability of the climate system introduce **uncertainties in forecasts, which will grow** alongside increasing PV capacity, necessitating growing storage capacity and improved forecasting accuracy: **vulnerability of electricity generation**



Thank you for your kind attention!

HARMONIA

Building Sustainable Air Quality Monitoring Networks Using Low-Cost Sensors in Sub-Saharan Africa

Maurizio Bacci

National Research Council of Italy - Institute of BioEconomy (IBE-CNR)

University of Valladolid, Spain

30 June 2026

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Consiglio Nazionale delle Ricerche
Istituto per la BioEconomia

Context

Particulate matter (PM) air pollution is a major global challenge, particularly across many African countries.

Saharan dust plays a significant role as a source of atmospheric dust transport.

Knowledge of PM pollution levels and their impacts remains limited across much of Africa. This is largely due to the scarcity of reliable and routinely operating air quality monitoring stations.

The recent advent of low-cost (LC) air quality monitoring sensors has increasingly enabled the acquisition of PM2.5 and PM10 measurements in Africa bridging the knowledge gap.

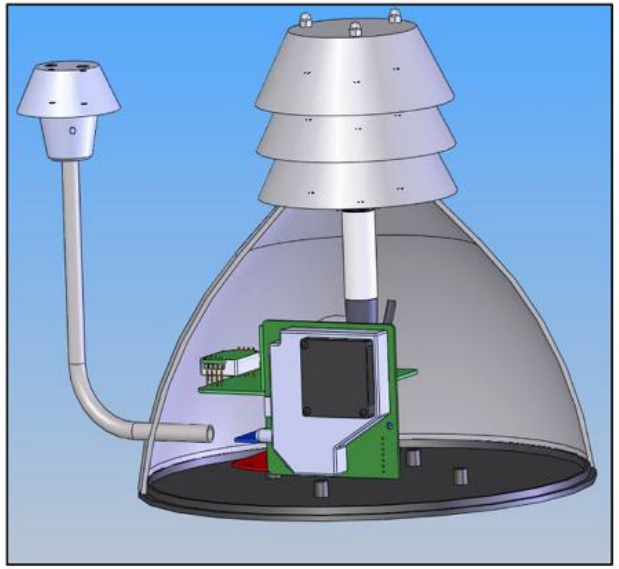
AirQino Low-Cost Air Quality Stations

AirQino (AQ) stations are low-cost (LC) air quality monitoring units developed by the Institute of BioEconomy of the National Research Council (IBE-CNR), Florence, Italy, in collaboration with TEA Group S.p.A. The stations are equipped with sensors for the measurement of gaseous pollutants and particulate matter (PM).

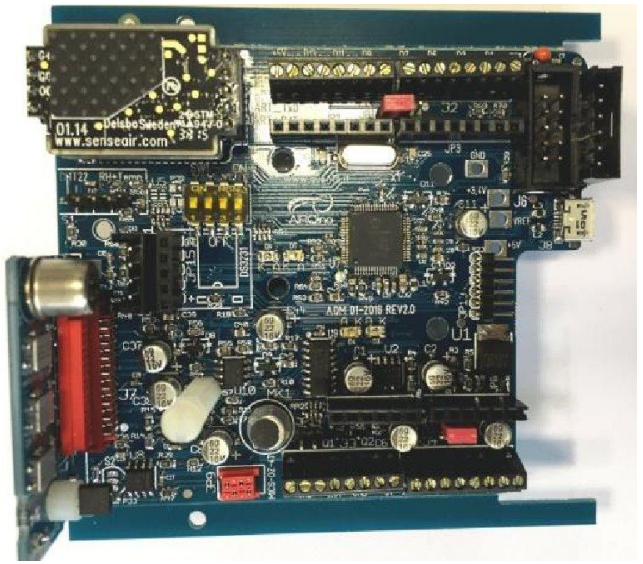
PMs measurements are obtained using the SDS011 optical particle sensors (Nova Fitness, Jinan, China), which operate according to the laser light-scattering principle. The operating range of the SDS011 sensor for PM2.5 and PM10 is 0–1000 µg/m3, the resolution 1.0 µg/m3, and the accuracy 10%.

AQ stations have been deployed for PM monitoring in local scale networks over several European cities, and in challenging environments such as the Arctic region and Sub-Saharan Africa.



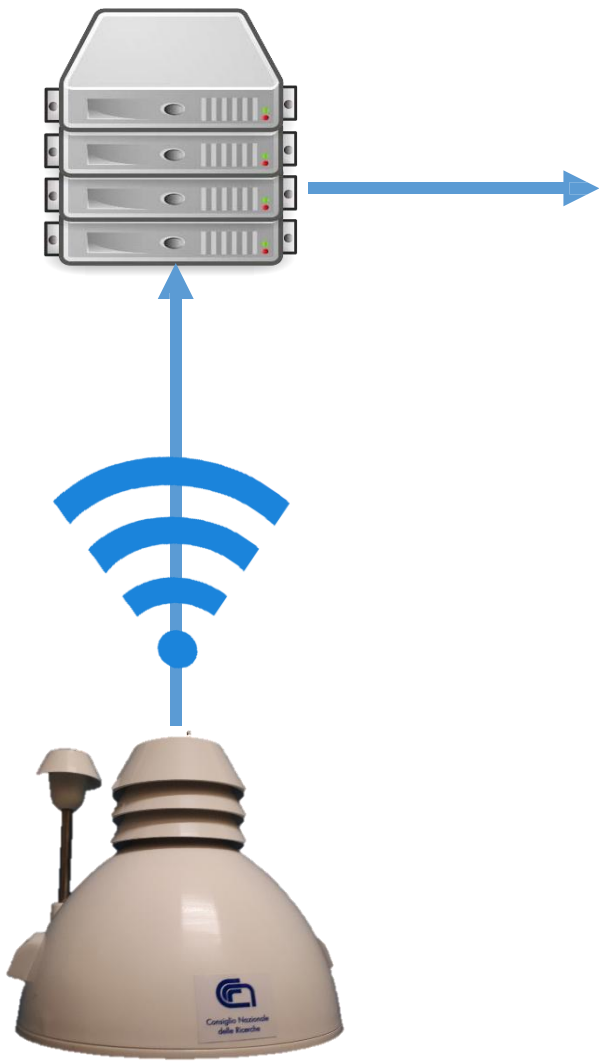




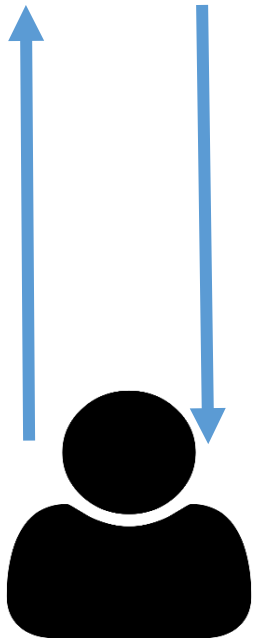


Data Acquisition, Processing and User Query

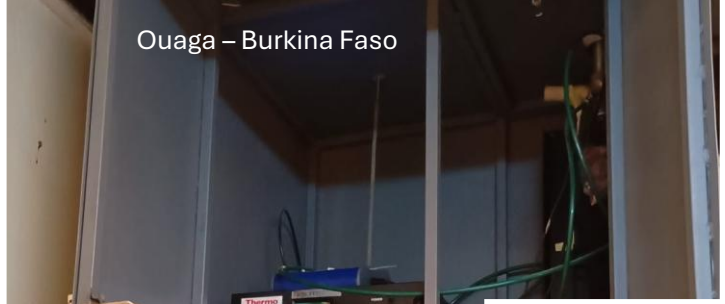
- Sensor geolocation
- GPRS data transmission
- Data packets transmitted to the central server
- Online data processing and visualization
- Database queries available through GUI and API

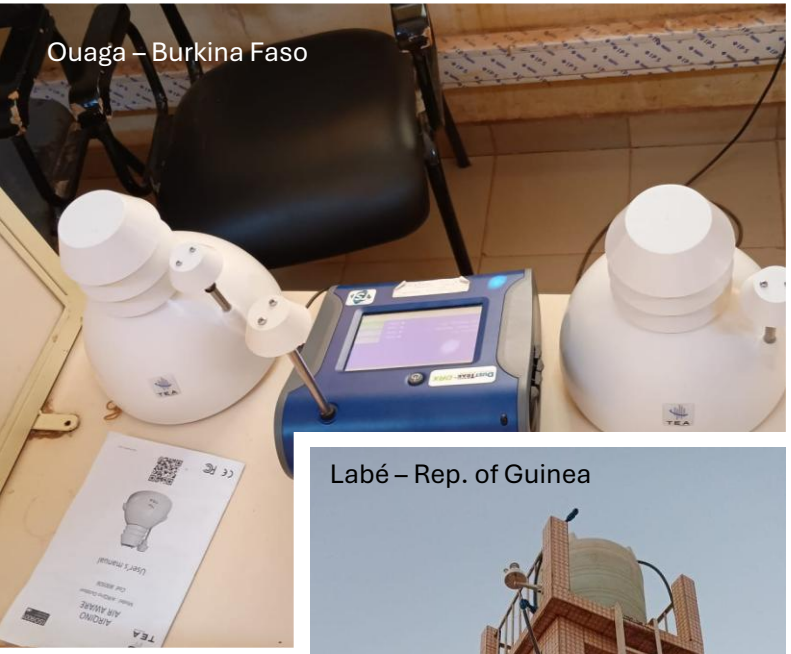




















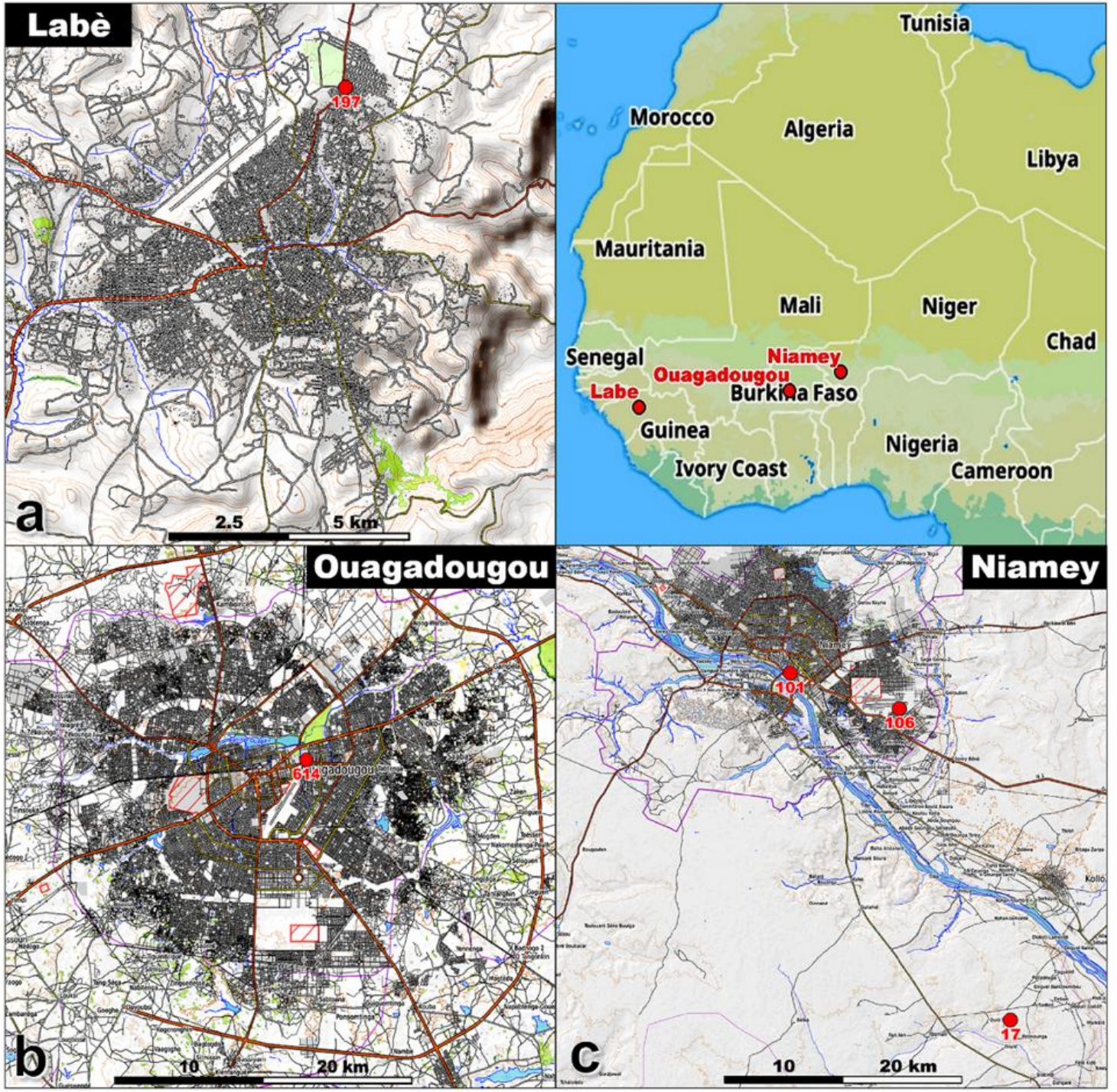
Examples of Our Installations in West Africa

Monitoring campaigns conducted over the three areas during the following periods:

I. Niamey, 07/01/2022–31/08/2022 (236 days);
II. Labé, 16/03/2024–16/09/2024 (184 days).
III. Ouagadougou, 01/03/2025–31/08/2025 (183 days);

Country	Niger			Burkina Faso	Rep. Guinea
City	Niamey			Ouagadougou	Labé
Population (inhab.)	1,492,414 [1]			2,415,266 [1]	110,795 [1]
Census Year	2024			2019	2020
Station ID	101	106	17	614	197
Location	Downtown Niamey	Niamey airport	Sadore (~37 km from city centre)	Université Joseph KI-ZERBO	Projet WAWATER
Site type	Urban	Suburban	Rural	Urban	Suburban
Sensor's height (m a.g.l.)	4.0	1.3	1.3	4.0	8.0
Operator	DMN [2]	Int. Airport of Niamey	ICRISAT [3]	ANAM [4]	IRD [5]
Latitude (deg N)	13.5065	13.4789	13.2355	12.3778	11.3510
Longitude (deg E)	2.1128	2.1977	2.2841	−1.4975	−12.2687
Elevation (m a.s.l.)	209	216	235	294	1026

Bacci, M.; Gualtieri, G.; Katiellou, G.L.; Nana, B.; Descroix, L.; Zaldei, A. Building and Maintaining Low-Cost Particulate Matter Monitoring Networks in Sub-Saharan Africa: Lessons from Burkina Faso, Niger, and Republic of Guinea. Environments 2026, 13, 351. https://doi.org/10.3390/environments13060351



Operational status, power supply configurations, data transmission methods, and main challenges encountered during the AQ monitoring campaigns addressed in Western SSA

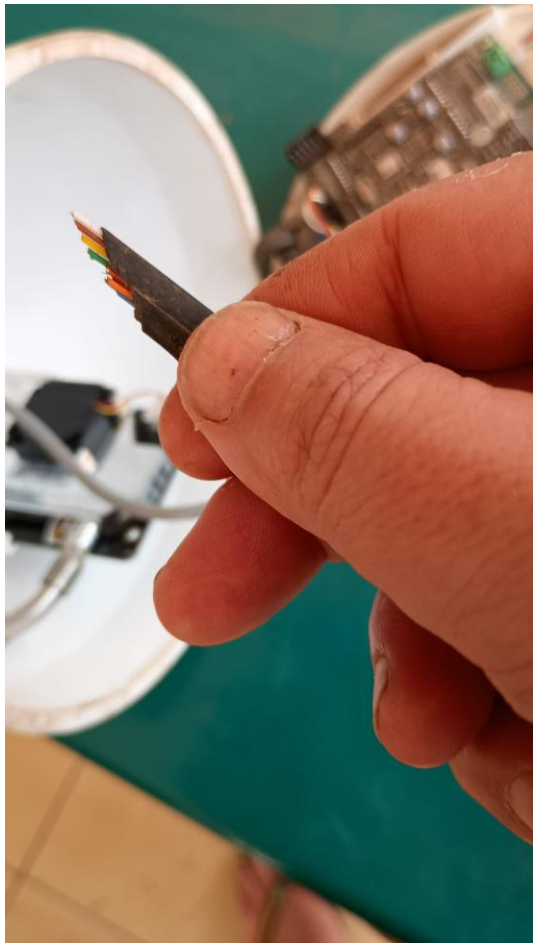
Country	Niger			Burkina Faso	Guinea
City	Niamey			Ouagadougou	Labé
Station ID	101	106	17	614	197
Status [1]	inactive			active	inactive
Power supply	• battery backup • tested with solar panels			• grid power • no battery/solar panels	• battery + solar panels
Transmission	• local and international SIM			• local SIM	• international SIM
Key issues	• intermittent transmission (mobile network) • insufficient battery during outages • cable damage (ID 17) • difficulties in sourcing spare parts • difficulties in using solar panels • personal security			• voltage drops causing data gaps	• poor transmission • no maintenance • cable damage (caused by animals/humans) • difficulties in using solar panels
Downtime (%)	4.2	0.5	3.0	16.8	4.2
Tests	• power supply (battery, solar panels) • connectivity (local/international SIM)			• co-location with TSI DustTrak	• installed with battery and solar panels

[1] As of 10 June 2026.

When monitoring systems meet the real world…



Termites inside battery enclosure



Damaged cables due to improper handling



Missing basic hardware (e.g. screws) on local markets

And…

- Low-quality replacement batteries
- Poor-performing solar panels
- Plastic cable ties breaking during installation
- Buried cables cut during agricultural activities
- Beehives built inside radiation shields
- Spider nests blocking ventilation ducts (during power outages)
- ….

Advantages of Low-Cost Sensors (1/2)

Robustness

The AQ sensors demonstrated robustness when deployed in extreme African environments, as they did not show any drifts due to malfunctioning. They operate unattended over campaigns lasting 6-8 months with high data recovery rates, ranging from 76% (Ouagadougou), 85% (Niamey) and 95% (Labé).

Redundancy and Risk Mitigation

In environments exposed to theft, vandalism and electrical failures, LC units enable a redundancy-based monitoring approach. The replaceability of these instruments means that the loss of a sensor (theft or voltage fluctuations) has a negligible economic impact compared with the loss of a high-end PM analyser.

Energy Autonomy and "Invisibility"

Power outages and solar panel theft can be considered issues closely associated with hardware size and energy demand. A key advantage of LC sensors is their low power consumption. PM-monitoring LC sensors, which are generally based on the optical light-scattering principle, typically consume only a few watts or even milliwatts.

Simplified Maintenance and "Plug-and-Play" Operation

Simplified instrument maintenance represents a major advantage in contexts characterised by limited local technical training and difficulties in sourcing small components and hardware. Moreover, LC solutions are often designed as integrated systems with "plug-and-play" functionality.

Advantages of Low-Cost Sensors (2/2)

Management of High Aerosol Loads (Saturation and Cleaning)

PM size distribution and chemical composition can strongly influence the accuracy of LC sensors. The SSA environment is characterised by PM concentrations that may rapidly saturate monitoring instruments. In reference-grade systems, the accumulation of Saharan dust requires specialised and costly cleaning procedures to avoid compromising instrument certification. (This issue was directly encountered during the use of a reference-grade DustTrak instrument for LC sensor calibration in Ouagadougou)

Adaptability to Local Pollution Peaks

Pollution from biomass combustion and road traffic is highly localised. Networks of LC monitoring systems make it possible to identify specific “hotspots” (e.g., markets, road intersections and residential areas) that would not be detected by a single central monitoring station

Local Capacity Building for Sustainable Low-Cost Observation Networks

The use of LC instruments with the active involvement of local teams in the installation, calibration, and configuration phases, enables an effective transfer of technical knowledge and operational skills to local experts. This capacity-building process not only increases local autonomy in managing the instruments, but also improves the long term sustainability, maintenance, and scalability of LC observation networks by reducing dependence on external support.

Calibration of Low-Cost Sensors

Sensor calibration is one of the most recurrent challenges associated with the use of LC monitoring networks.

In situ calibration is particularly important in African environments, where the optical properties of Saharan dust differ substantially from those of urban combustion related PM.



Operational considerations for designing effective field calibration strategies

- Build a monitoring network by combining a **reference-grade station with a dense cloud of LC sensors**.
- **Bias correction algorithms** incorporating meteorological variables such as air temperature, and relative humidity, returned the highest **calibration accuracy** (in SSA priority**: RH and Seasonality**)
- Considering the logistical difficulties in Sahelian environments, a valuable approach is the **“travelling sensor”** strategy. In this framework, a mid-range portable instrument (more accurate than LC sensors, yet easier to transport than reference-grade instrumentation) is first carefully calibrated at the reference station. A technician then carries this “portable master” instrument to the various LC nodes distributed across the study area.
- Remote data transmission via mobile telephony represent a practical solution. However, mobile communication networks frequently experience connectivity instability. Solutions based on local **Wi-Fi connectivity or a Local data-logging systems** represent a viable alternative.

Conclusions

Low-cost (LC) sensors represent an effective solution for addressing PM2.5 and PM10 monitoring gaps across Africa. While they **cannot replace high-quality reference instruments**, they can serve as valuable **complementary tools** within integrated air quality monitoring systems.

The deployment of **integrated networks combining official monitoring stations with LC sensors can substantially improve the spatial and temporal resolution of PM observations**, providing measurement accuracy sufficient for both scientific research and air quality monitoring applications.

However, achieving this objective requires careful attention to the operational methodologies adopted.

- **Protocols related to co-location and calibration** procedures for LC stations
- **AI** may play a role in **enhancing sensor performance** (advanced calibration techniques and algorithms for the detection and correction of systematic measurement errors)
- Environmental, logistical and technical **constraints specific to these contexts must be carefully considered during network design** to avoid the risk of achieving results not commensurate with the investment made (preliminary assessment prior to network deployment and lessons learnt)



Thank you

Maurizio Bacci
maurizio.bacci@cnr.it

Bacci, M.; Gualtieri, G.; Katiellou, G.L.; Nana, B.; Descroix, L.; Zaldei, A. Building and Maintaining Low-Cost Particulate Matter Monitoring Networks in Sub-Saharan Africa: Lessons from Burkina Faso, Niger, and Republic of Guinea. Environments 2026, 13, 351. https://doi.org/10.3390/environments13060351

Low-Cost Complementary Aerosol Observations in North Africa: From Capacity Building to Dust Early Warning Applications

África Barreto (abarretov@aemet.es)
Izaña Atmospheric Research Center, Meteorological State Agency of Spain (AEMET)
WMO Regional Training Center & WMO ET Atmospheric Composition Capacity Building and Education

II HARMONIA WG4 meeting, Valladolid, 30 June 2026

@ ICOS-ERIC

Outline

I. Motivation: Health Effects + Status of Dust Observations in North Africa – Middle East

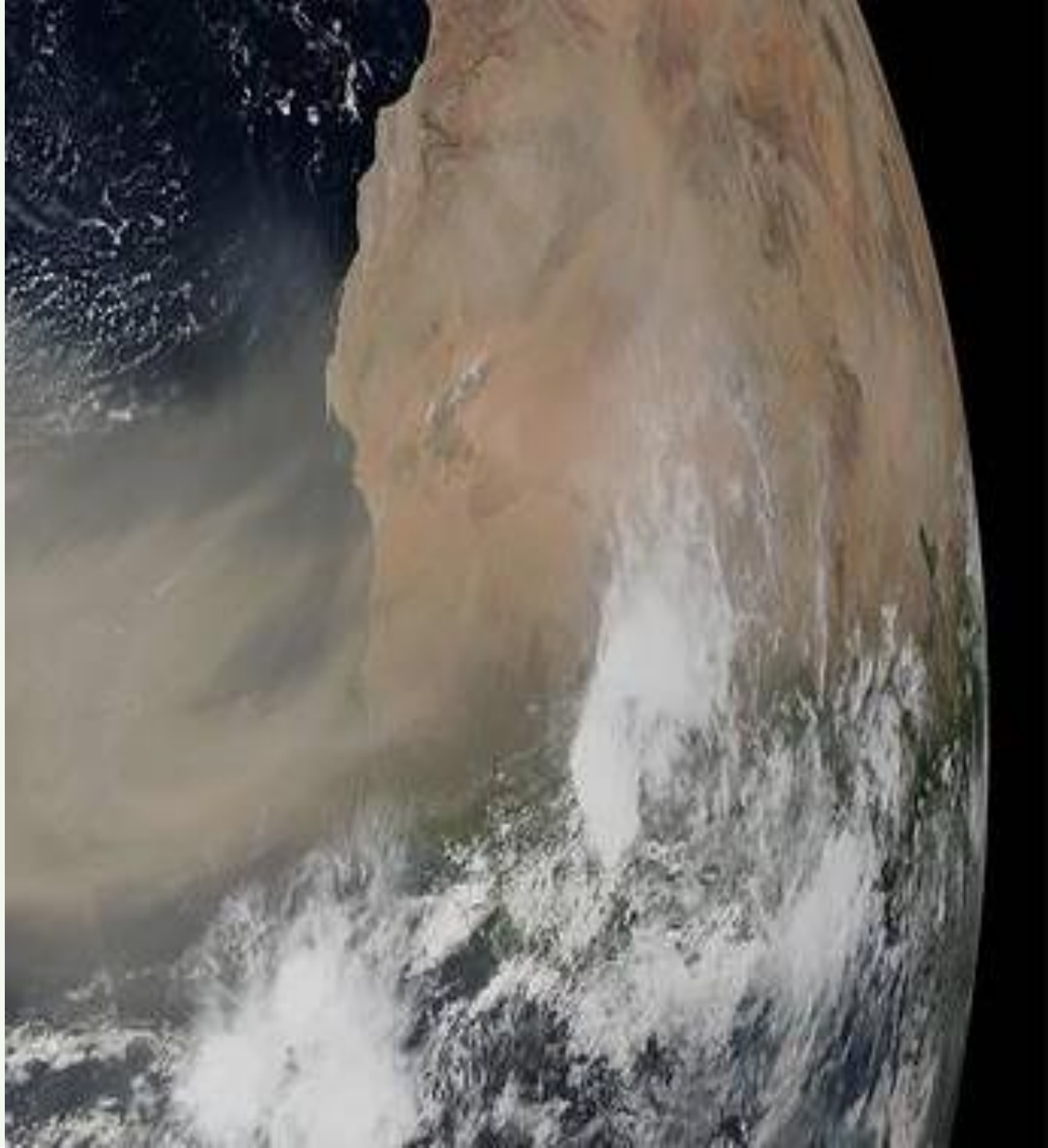
II. International Efforts to Strengthen Dust Observation and Early Warning Systems

III. Capacity Building in Action: Current Aerosol Observations

1.

MOTIVATION:

Health Effects + Status of dust observations in North Africa – Middle East



1. MOTIVATION

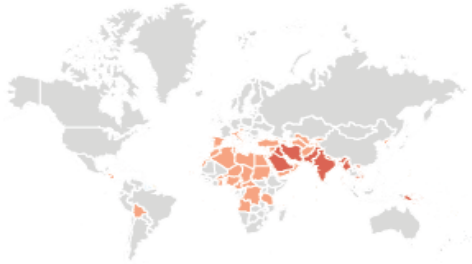
I. Health Effects

STATE OF GLOBAL AIR /2025

36%
of the world's population is exposed to levels of $PM_{2.5}$ above the least stringent interim target of 35 µg/m³ (IT-1).

11%
of the global population lives in areas where there are no national air quality standards.

Low- and middle-income countries face the largest burden. 90% of all air pollution deaths were in these countries:



India and China each had more than **2 million deaths** attributable to air pollution in 2023.

Bangladesh, Pakistan, and Nigeria each saw more than **200,000 deaths.**

Indonesia, Myanmar, and Egypt each saw more than **100,000 deaths.**

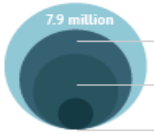
Noncommunicable diseases accounted for 6.8 million deaths.

86%
of global deaths were attributable to air pollution in 2023.

Air pollution continues to be the second leading risk factor for early death, surpassed only by high blood pressure.

7.9 million
deaths attributed to air pollution in 2023,

about **1 in 8** deaths worldwide.



Of this total, **4.9 million deaths** were attributable to ambient $PM_{2.5}$ exposure,

2.8 million were from household air pollution, and

470,000 were from ozone.

In 2023, dementia attributable to air pollution resulted in 626,000 deaths and 11.6 million healthy years of life lost.

95%
of deaths in adults over the age of 60 are due to noncommunicable diseases.

1 in 2 chronic obstructive pulmonary disease (COPD) deaths

1 in 4 heart disease deaths

More than **1 in 4** dementia deaths

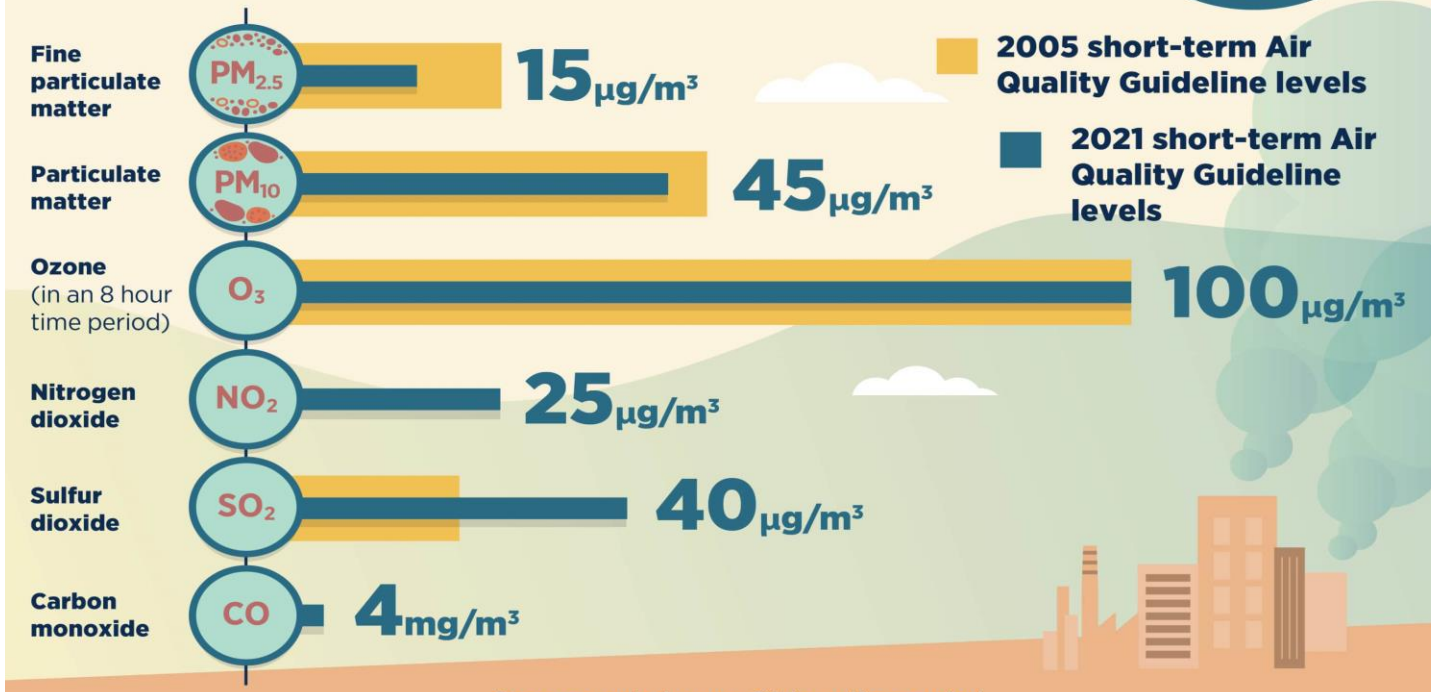
Nearly **1 in 6** diabetes deaths

October 2025
www.stateofglobalair.org

© 2025 Health Effects Institute. State of Global Air. Boston, MA.

NEW WHO AIR QUALITY GUIDELINES SET CLEAR GOALS TO HELP IMPROVE AIR QUALITY FOR ALL





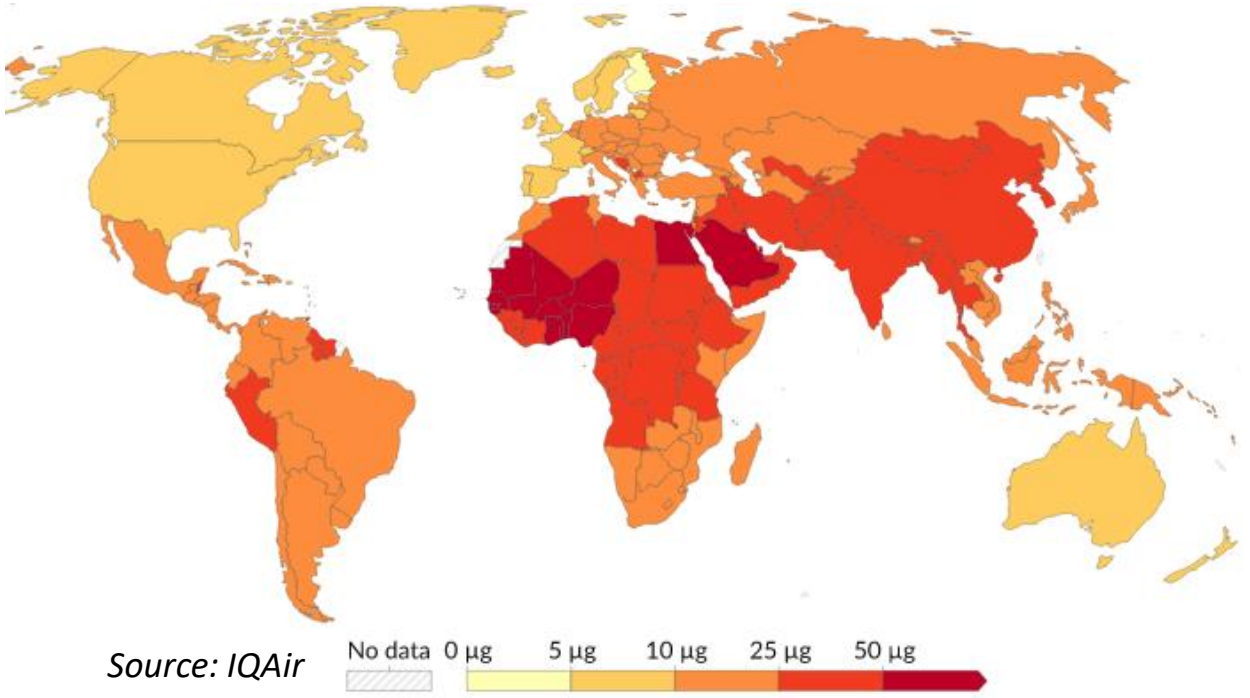
WHO Air Quality Guidelines set goals to protect millions of lives from air pollution.

CLEAN AIR FOR HEALTH #AirPollution World Health Organization

Countries without any legal regulation for AQ Standards



Source: Clarity



Source: IQAir

Air quality by country
Annual concentration of PM2.5 (µg/m^3)

1. MOTIVATION

II. Status of Dust Observations in NA and ME

WMO GAW

GAW World Data Centres

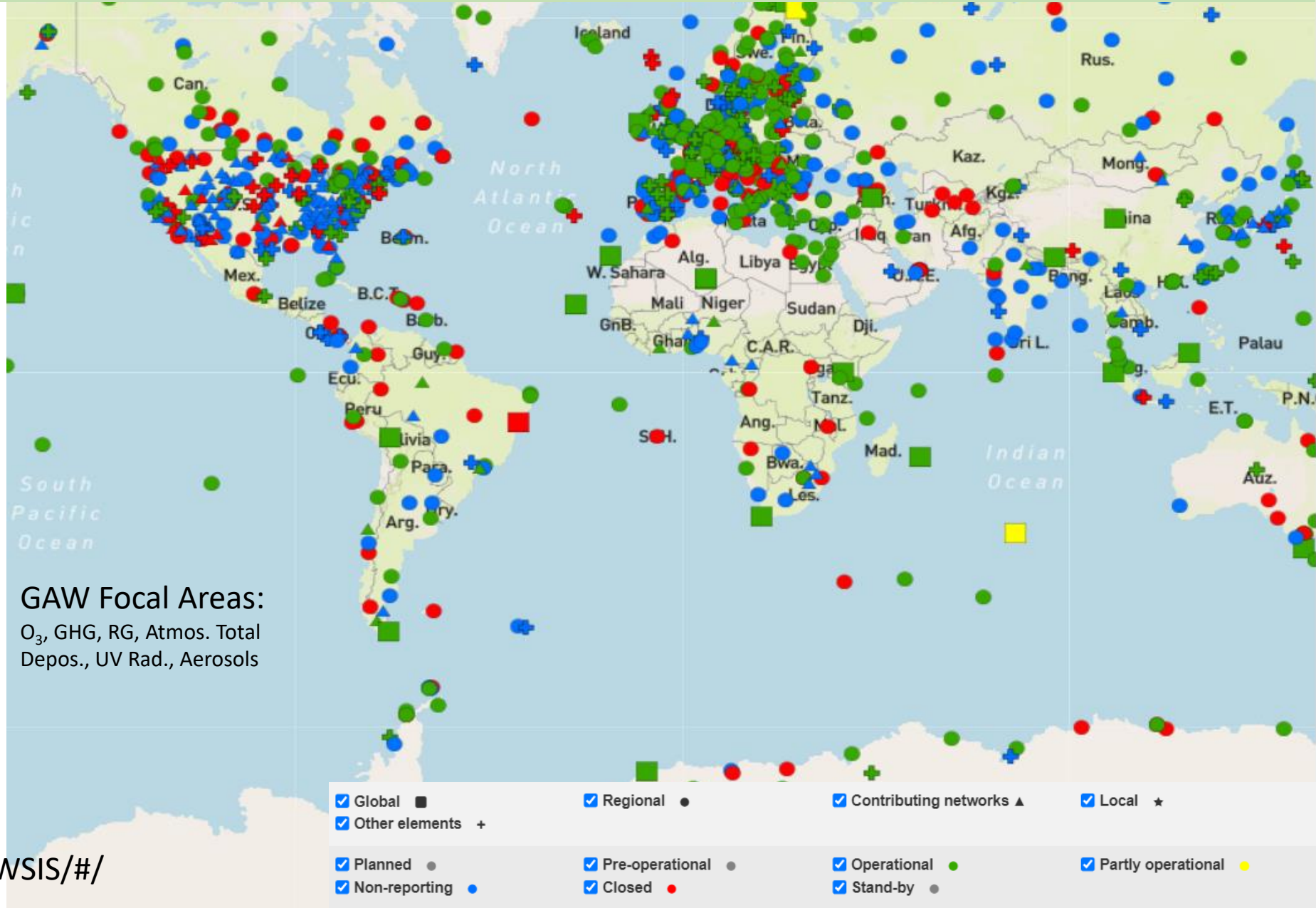
- WDC-RSAT (World Data Center for Remote Sensing of the Atmosphere)
- WDCA (World Data Centre for Aerosols)
- WDCGG (World Data Centre for Greenhouse Gases)
- WDCRG (World Data Centre for Reactive Gases)
- WOUDC (World Ozone and UV Data Centre)
- WRDC (World Radiation Data Centre)

Contributing networks data archives

- CASTNET (Clean Air Status and Trends Network)
- IMPROVE (IMPROVE Optical Aerosol)
- INDAAF (International Network to study Deposition and Atmospheric chemistry in AFrica)
- NADP (National Atmospheric Deposition Program)
- TCCON (Total Carbon Column Observing Network)

Other relevant data archives

- EMEP (EMEP)
- NDACC (NDACC Data Center)

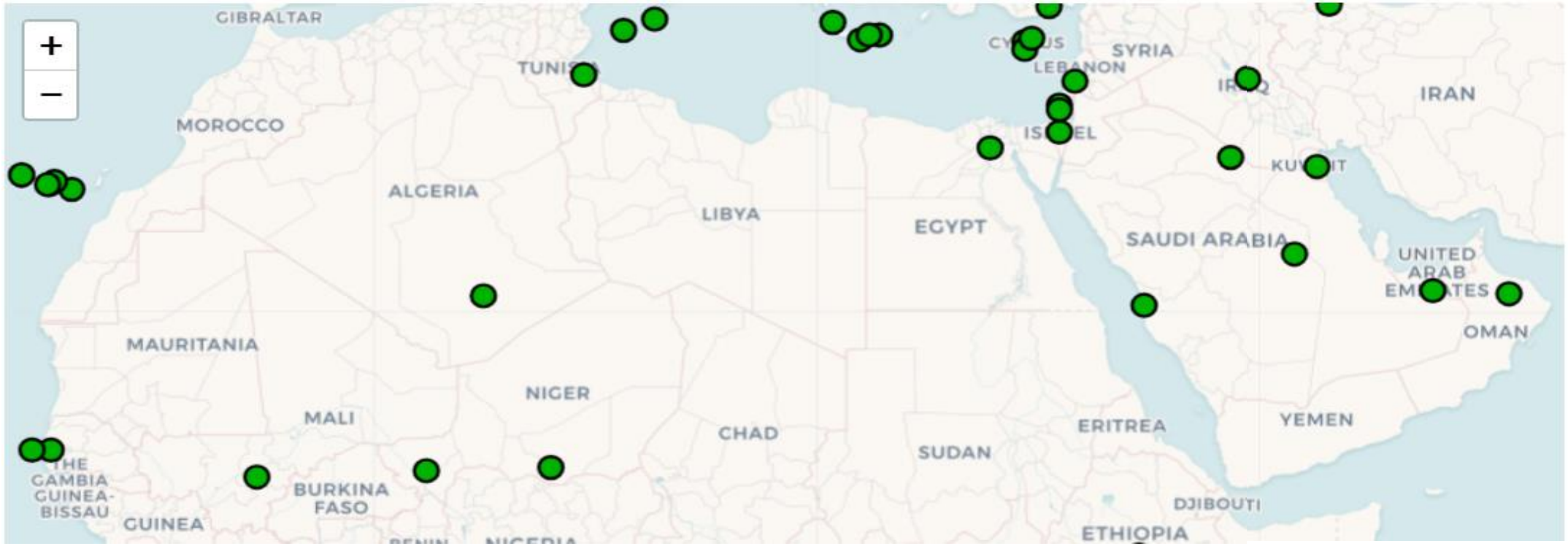


GAW Focal Areas:

O_3, GHG, RG, Atmos. Total Depos., UV Rad., Aerosols

https://gawsis.meteoswiss.ch/GAWSIS/#/

AERONET over N. Africa – Middle East



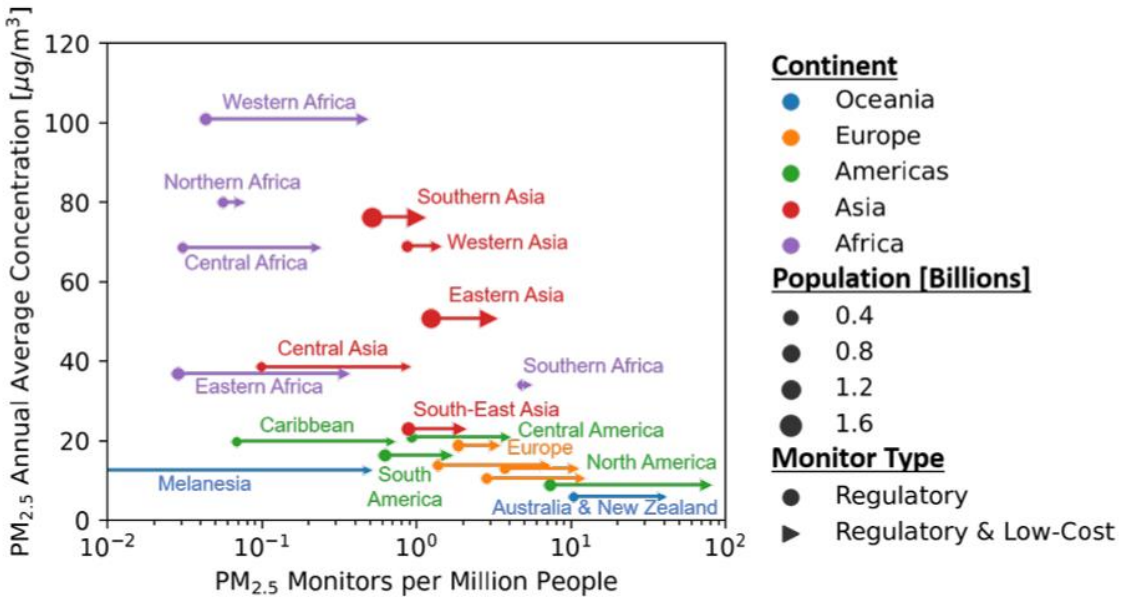
- 21 active stations (11 in N.Africa, 12 in Middle East) + Qatar (2, not in AERONET)
- Active NA: Algeria, Mali, Niger (x2), Tunisia, Senegal (x2), Cameroon, Cape Verde (x2), Egypt, Nigeria.
- Active ME: Israel (x3), Lebanon, Kuwait, Saudi Arabia (x3), U.A. Emirates, Oman, Irak, Iran.
- **Significant gaps regarding the most important dust source.**

1. MOTIVATION

II. Status of Dust Observations in NA and ME



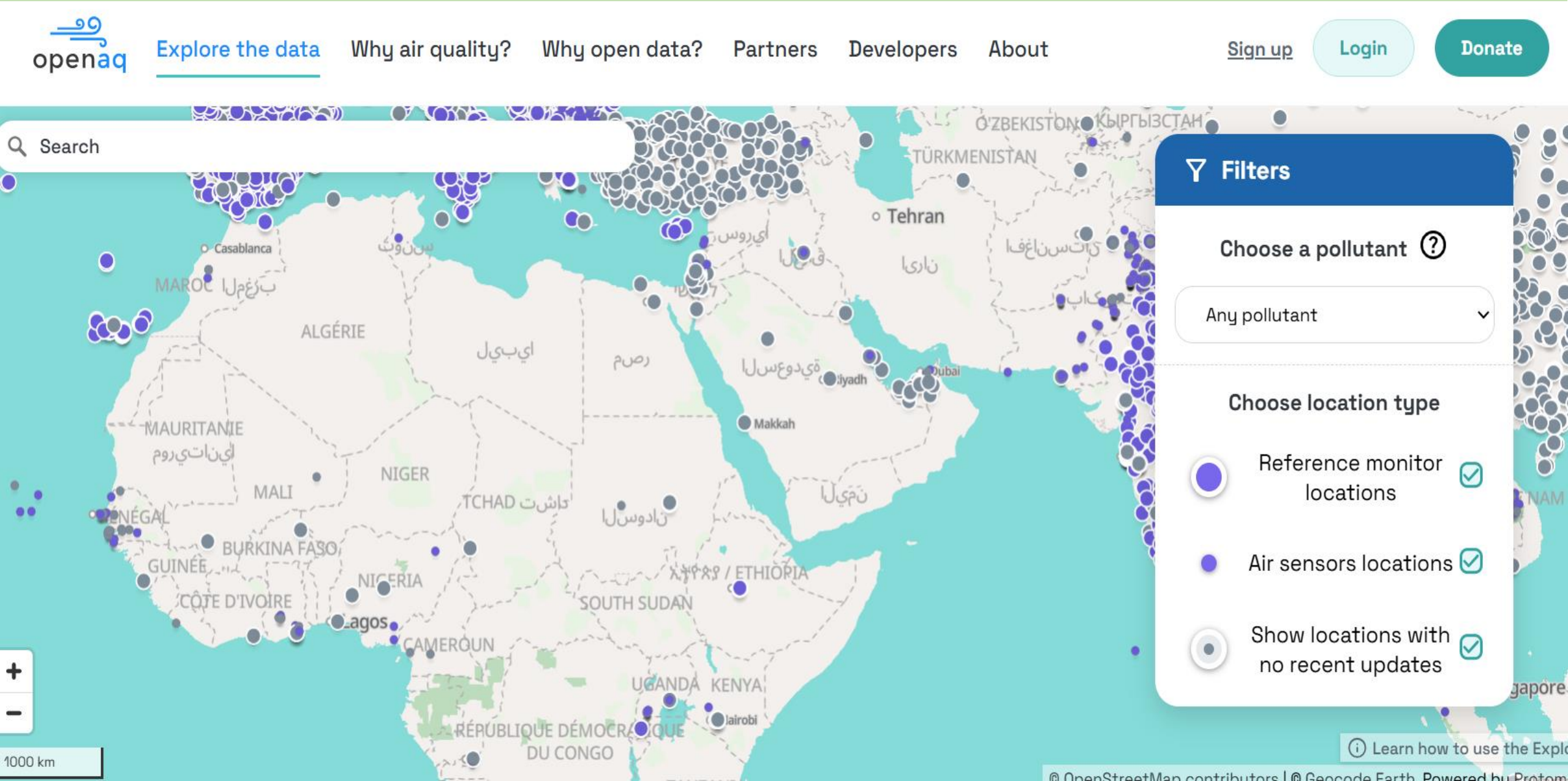
clarity NASA airqo PurpleAir IQAir



Mailings et al., 2024 (GAW Report No. 293)

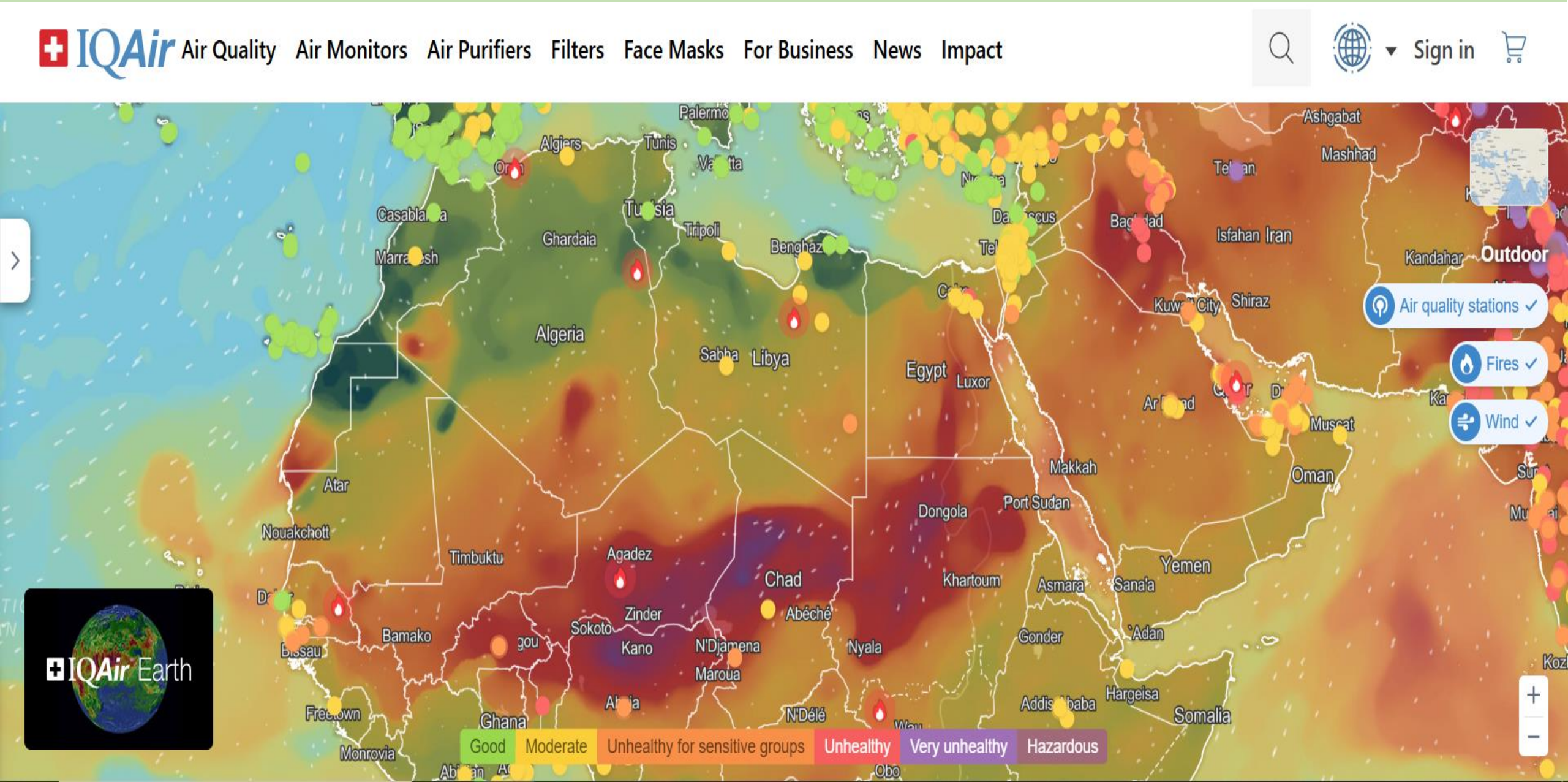
1. MOTIVATION

II. Status of Dust Observations in NA and ME



1. MOTIVATION

II. Status of Dust Observations in NA and ME



1. MOTIVATION

II. Status of Dust Observations in NA and ME

clarity

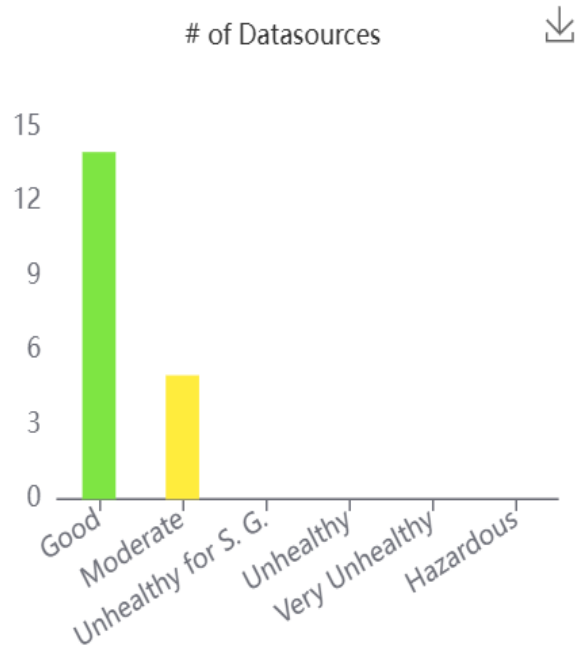
- Overview
- Datasources
- Analytics
- Devices
- Organization
- AQ Alarms
- Reports

NASA

Current Air Quality Conditions

Latest Measurement

Latest Measurement by Category

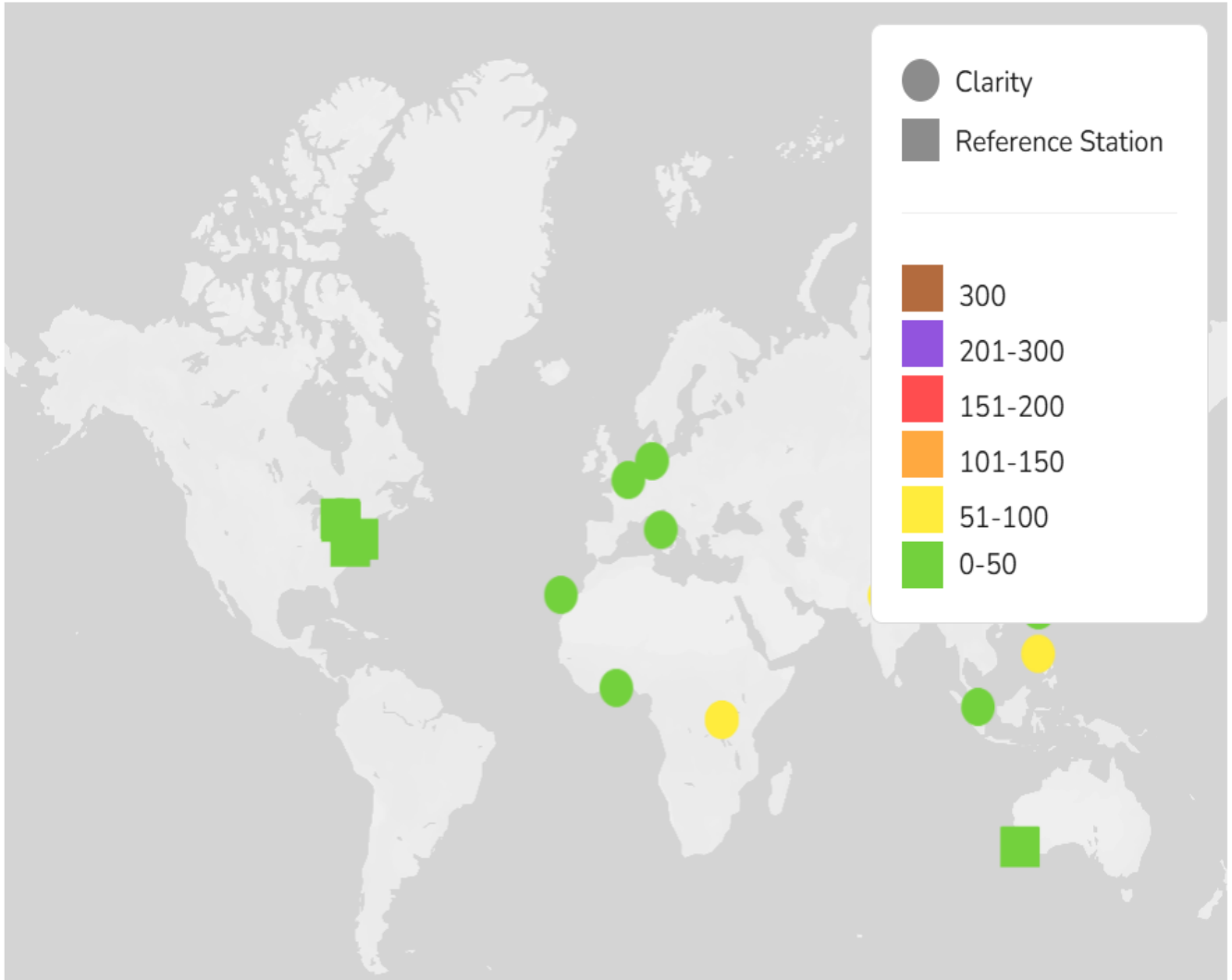


Latest Measurement by Datasource

Go to Ranking

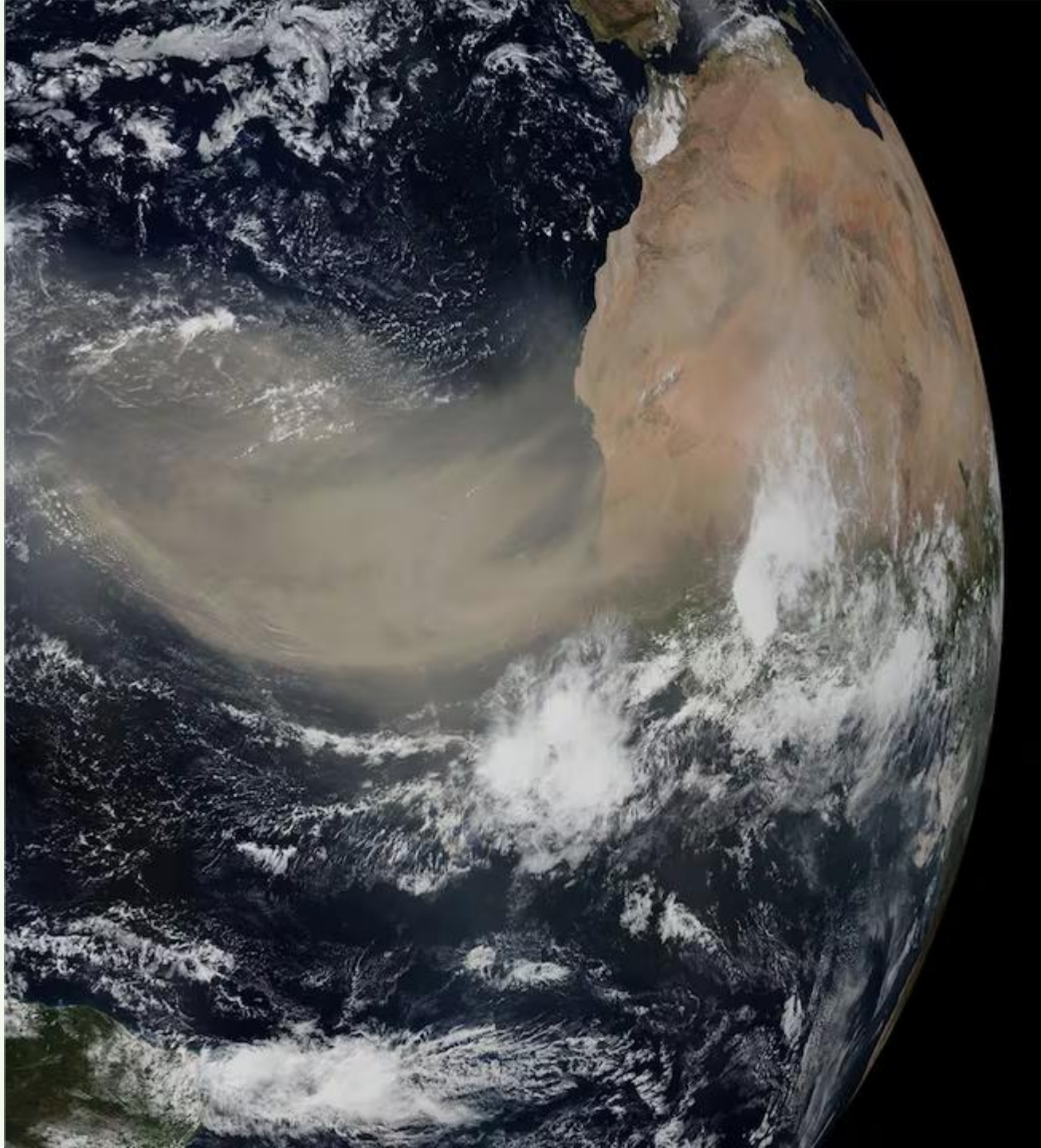
Datasource	PM2.5 NowCast AQI (
Name	Value

Latest Measurement by Location

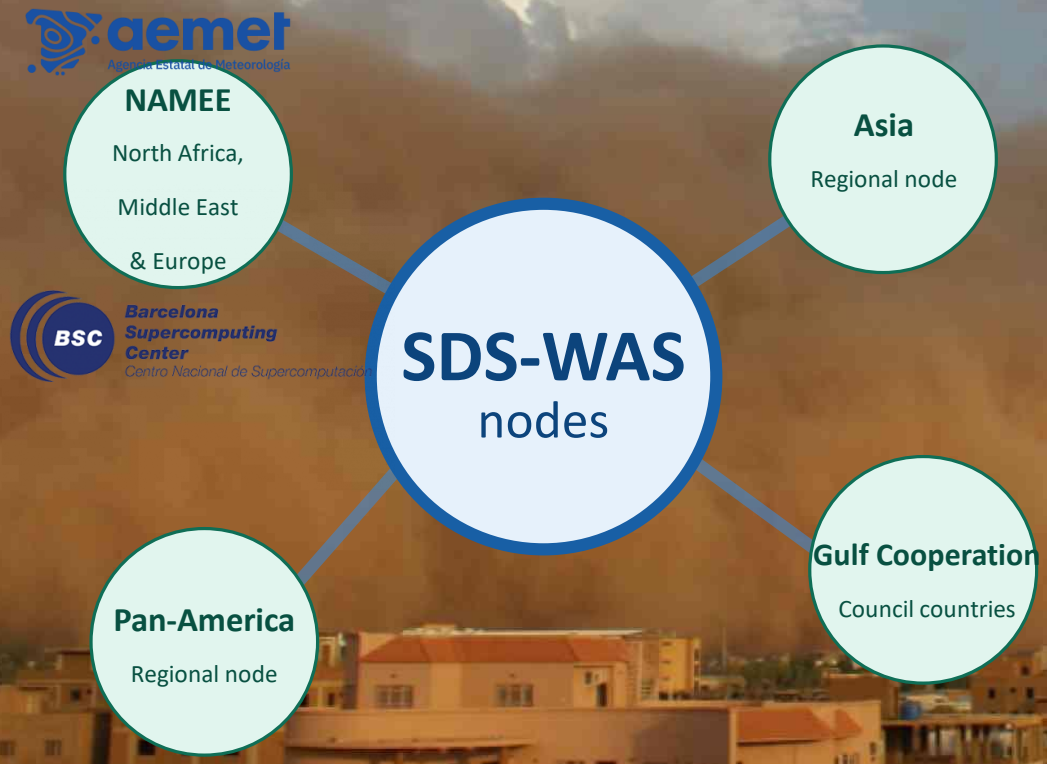


2.

International Efforts



THE SAND AND DUST STORM WARNING ADVISORY AND ASSESSMENT SYSTEM (SDS-WAS)



WORLD METEOROLOGICAL ORGANIZATION

A regional/global research programme established by the WMO in 2007 with the mission of improving WMO Members' capability to provide timely and high-quality observations and forecasts, thereby helping to mitigate the adverse impacts of these phenomena on society.

2. INTERNATIONAL EFFORTS

II. Barcelona Dust Regional Center

Barcelona Dust Regional Center

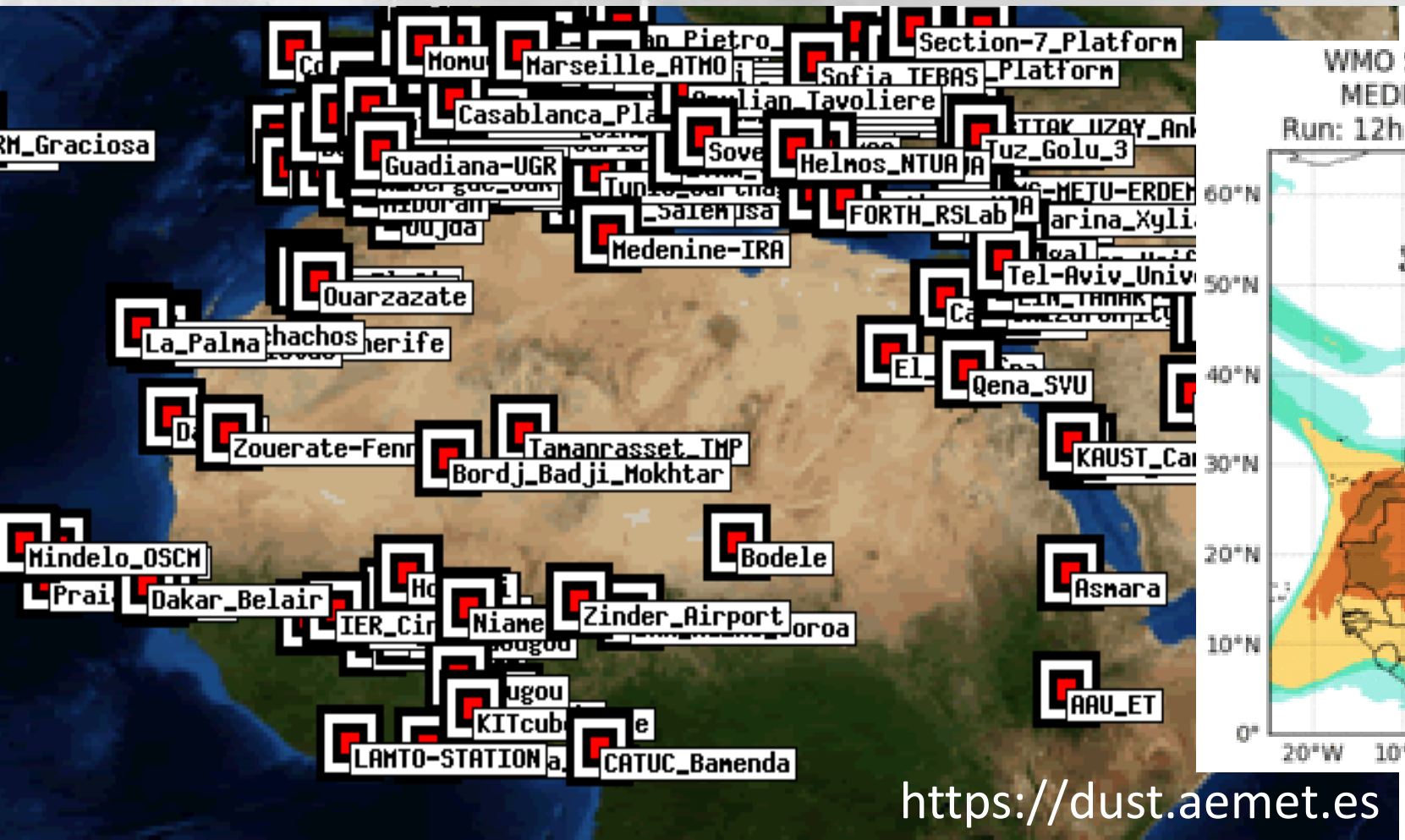
FAQ Contact Us Log in Search...

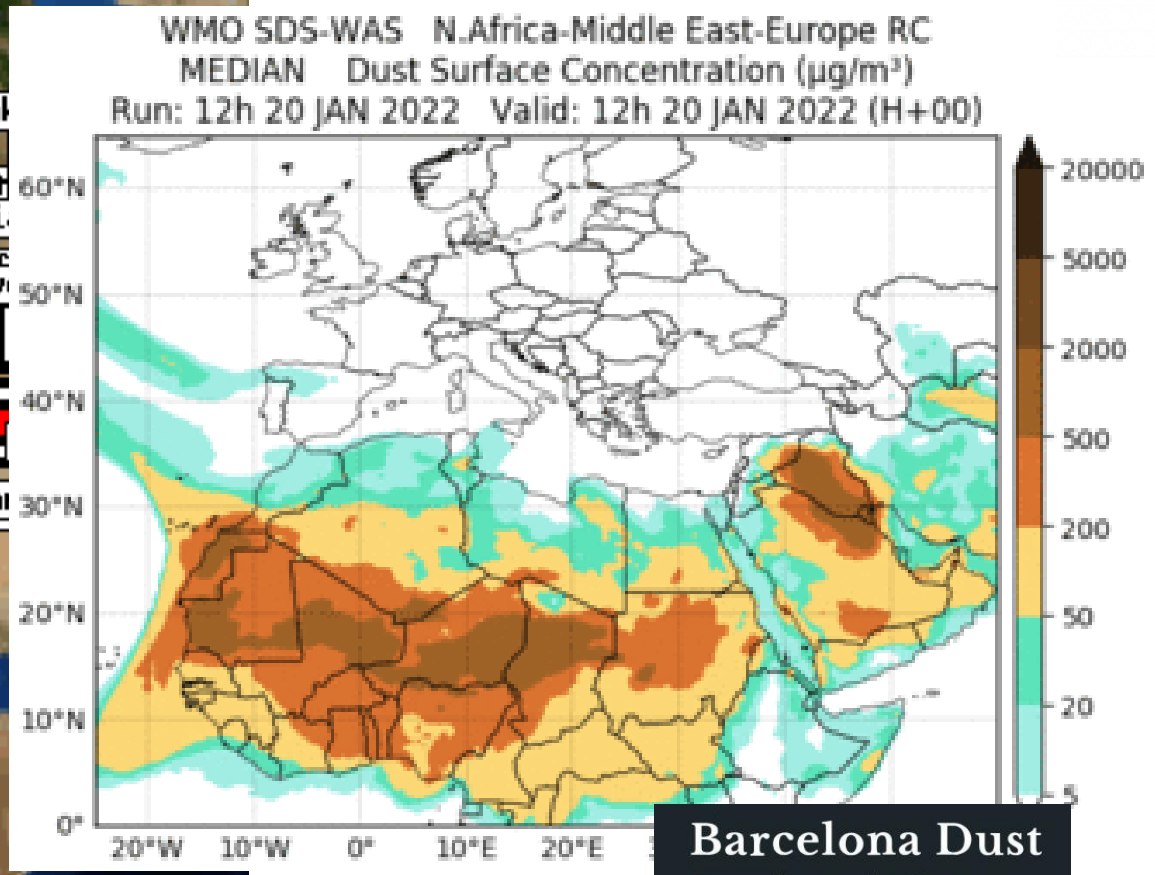
Products Research Resources News & Events About Us

aemet Agencia Estatal de Meteorología

WMO SDS-WAS Regional Center for Northern Africa, Middle East and Europe, conducting research and providing operational products

BSC Barcelona Supercomputing Center Centro Nacional de Supercomputación





https://dust.aemet.es

Barcelona Dust Regional Center

MONARCH: Operational model

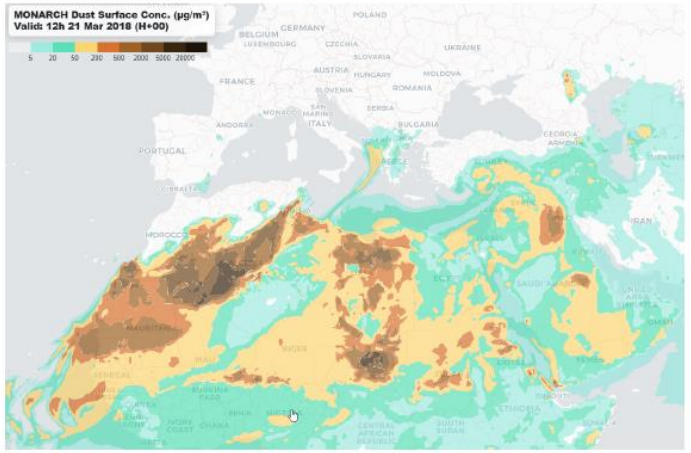
Multiscale Online Nonhydrostatic AtmospheRe CHemistry

- Exécution: Tous les jours à 12 UTC, 84 h prévision, 3 h intervalle
- Résolution: 0.1° x 0.1°
- Domaine: Afrique du Nord, Moyen-Orient et Europe (NAMEE)

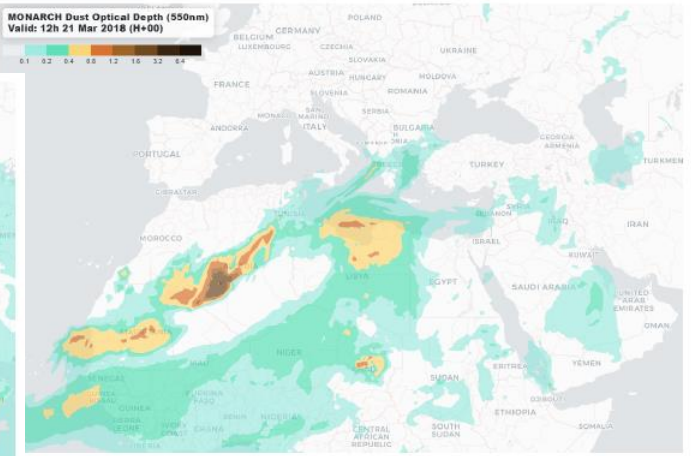
Variables

- **Concentration de poussière en surface [μg/m3]**
- Extinction [M/m]
- Charge de poussière [g/m2]
- **Épaisseur optique des poussières (Dust AOD) [–]**
- Dépôt sec [mg/m2]
- Dépôt humide [mg/m2]

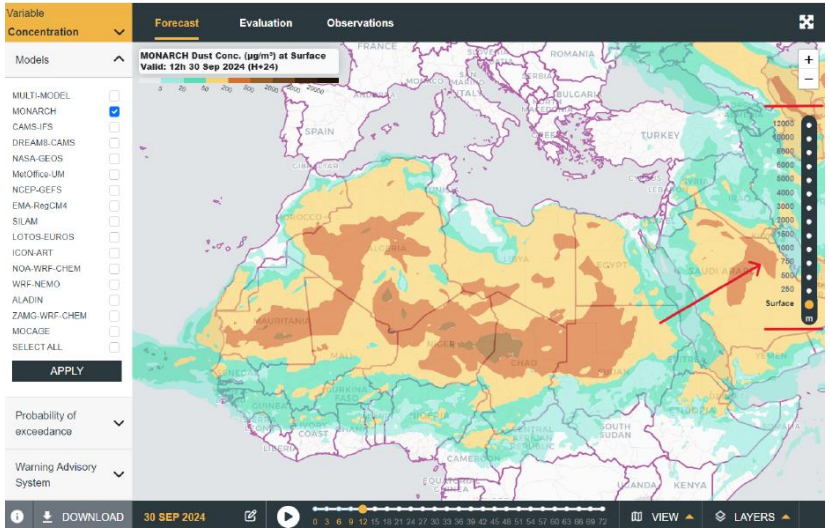
Dust Surface Concentration (µg/m³)



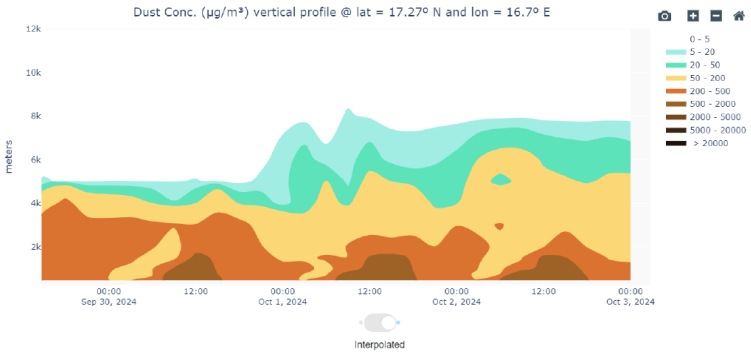
AOD



Dust Surface Concentration (µg/m³) at different levels

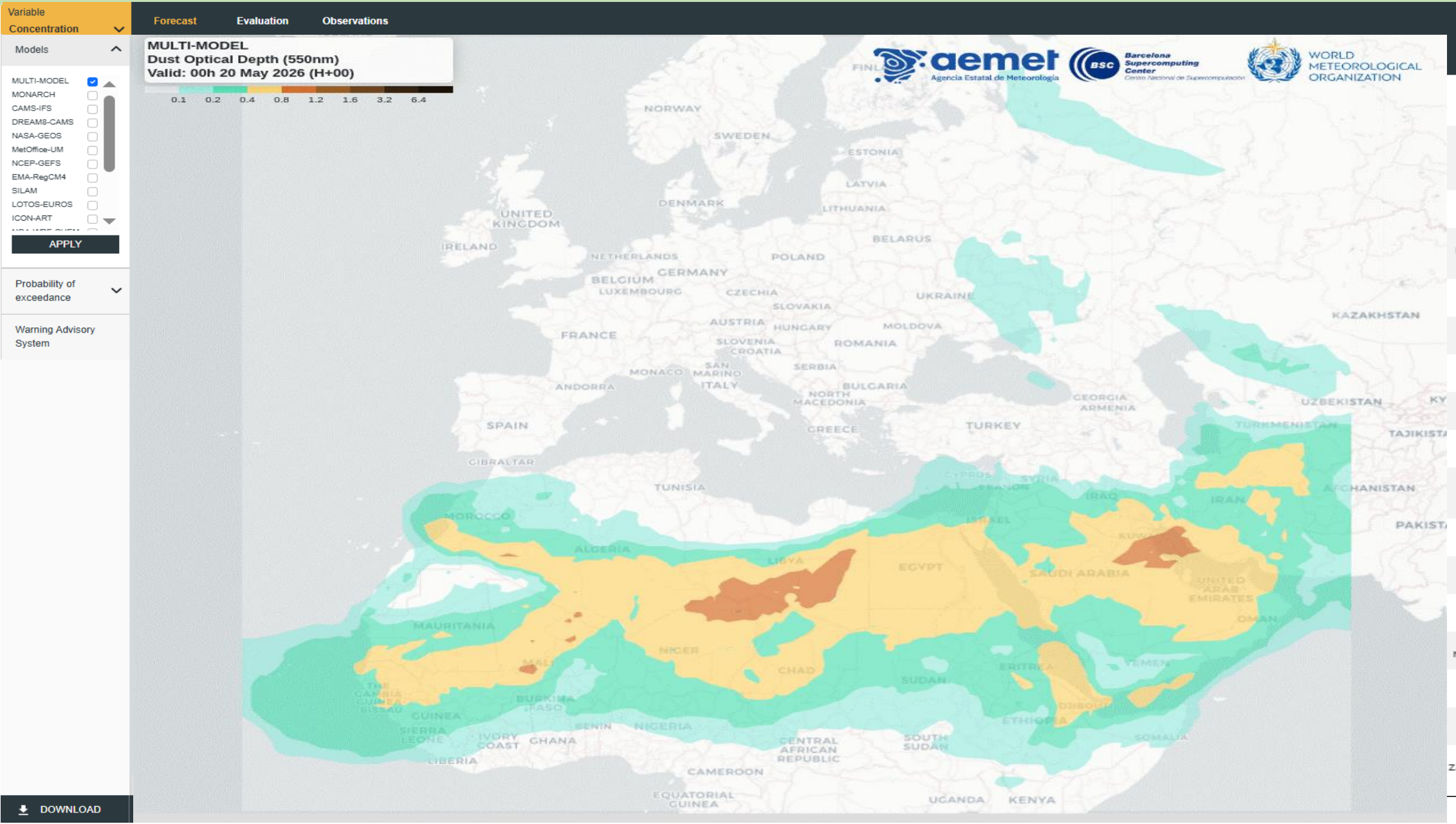


Dust Surface Concentration (µg/m³) vertical profile



2. INTERNATIONAL EFFORTS

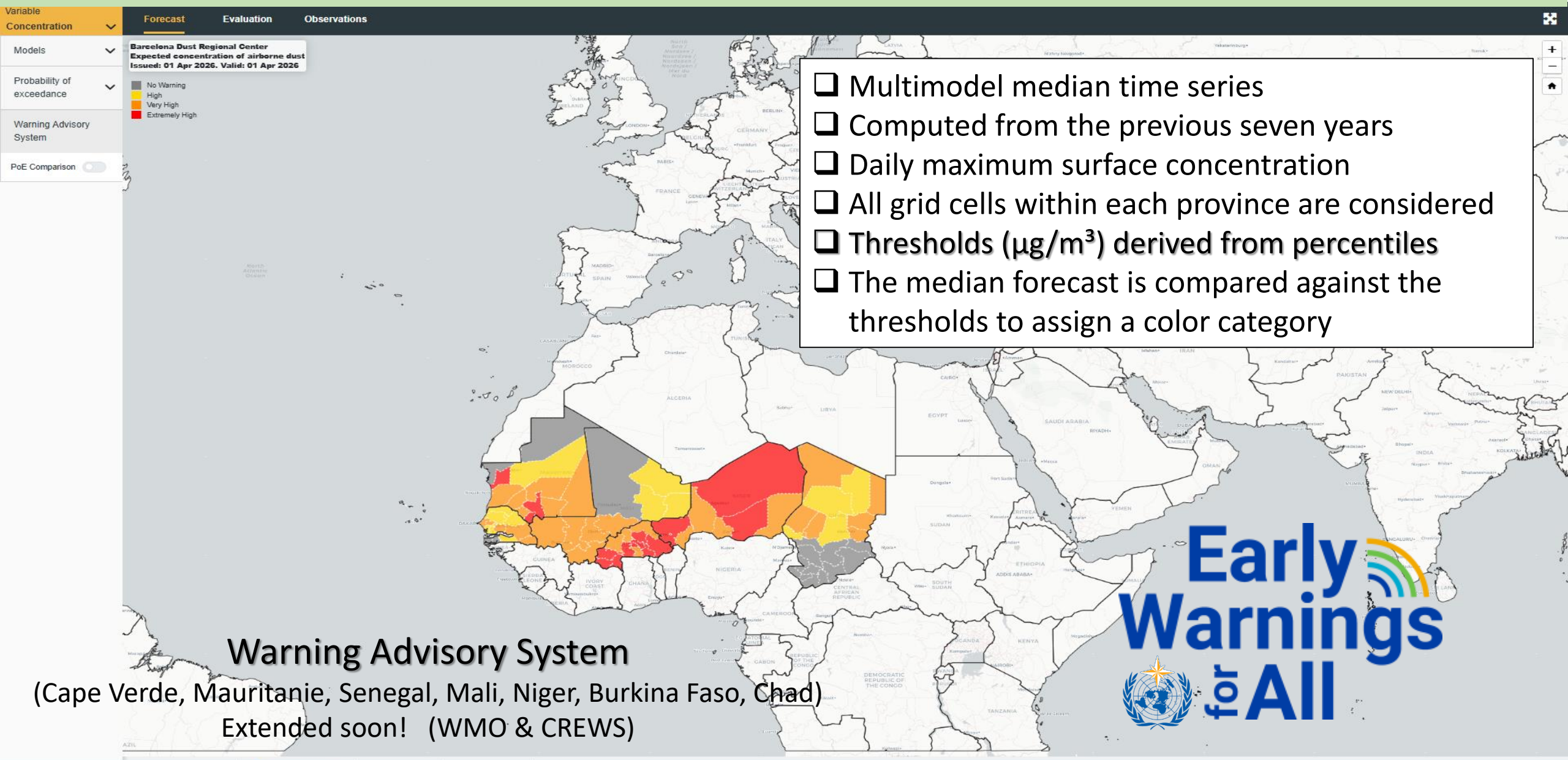
II. Barcelona Dust Regional Center



Model	Institution
ALADIN	Météo Algérie
BSC-DREAM8b	BSC
CAMS-IFS	ECMWF
DREAM8-CAMS	SEEVCCC
EMA RegCM4	EMA
ICON-ART	DWD
LOTOS-EUROS	TNO
MetOffice-UM	UK MetOffice
MOCAGE	MétéoFrance
MONARCH	BSC
MULTI-MODEL	AEMET
NASA-GEOS	NASA
NCEP-GEFS	NCEP
NOA-WRF-CHEM	NOA
SILAM	FMI
WRF-NEMO	AUTH
ZAMG-WRF-CHEM	ZAMG

2. INTERNATIONAL EFFORTS

II. Barcelona Dust Regional Center



- ❑ Multimodel median time series
- ❑ Computed from the previous seven years
- ❑ Daily maximum surface concentration
- ❑ All grid cells within each province are considered
- ❑ Thresholds (μg/m³) derived from percentiles
- ❑ The median forecast is compared against the thresholds to assign a color category

Early Warnings for All

Warning Advisory System

(Cape Verde, Mauritanie, Senegal, Mali, Niger, Burkina Faso, Chad)

Extended soon! (WMO & CREWS)

2. INTERNATIONAL EFFORTS

III. Other Projects

MACCLIMA Interreg
Fondo Europeo de Desarrollo Regional
EUROPEAN UNION

KADI

CREWS CLIMATE RISK & EARLY WARNING SYSTEMS

WORLD METEOROLOGICAL ORGANIZATION

CREWS CLIMATE RISK & EARLY WARNING SYSTEMS

MACCLIMA

Aerosol Measurements

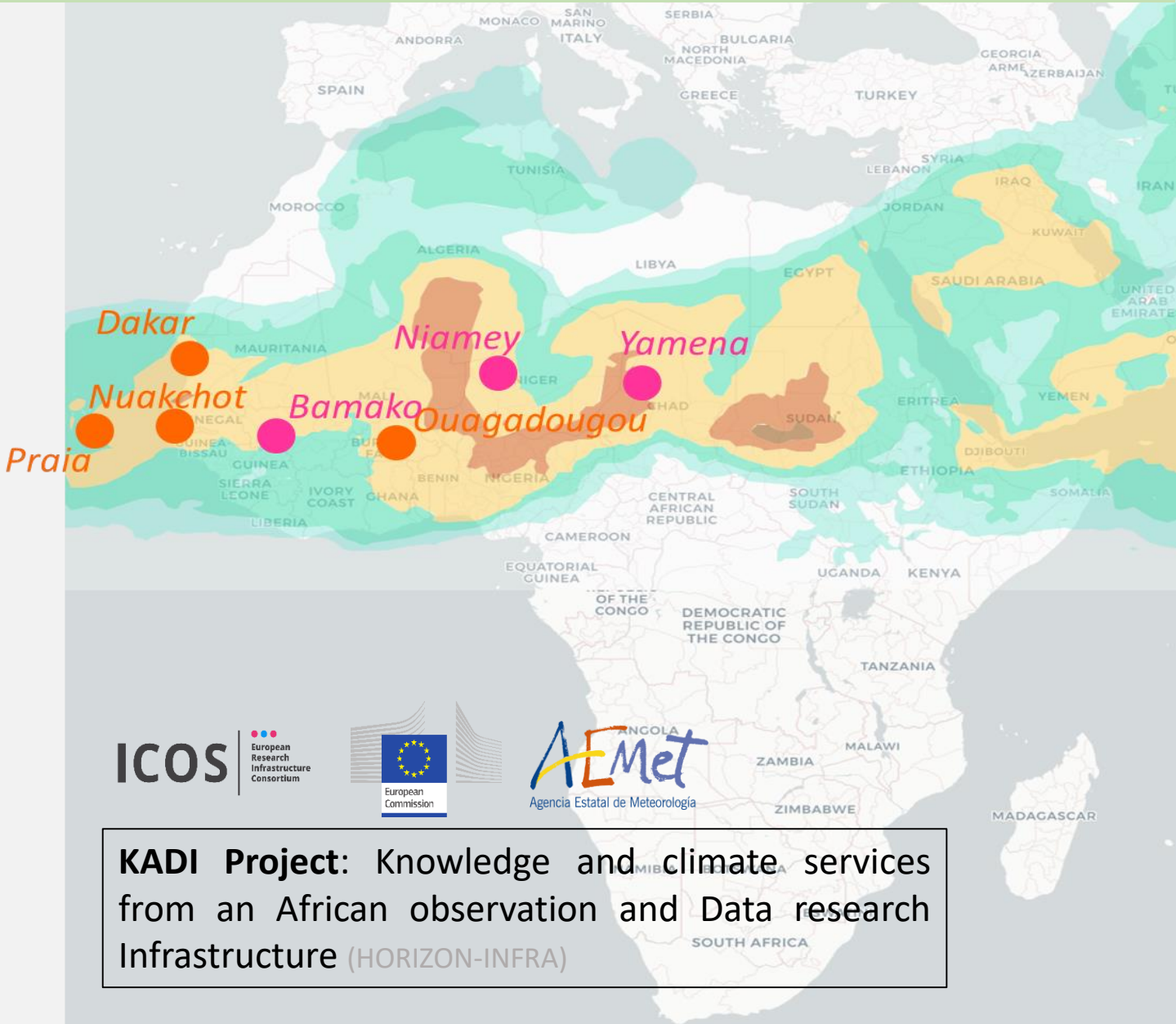


Hand-Held Photometer Calitoo

+



PM LCS



ICOS European Research Infrastructure Consortium

European Commission

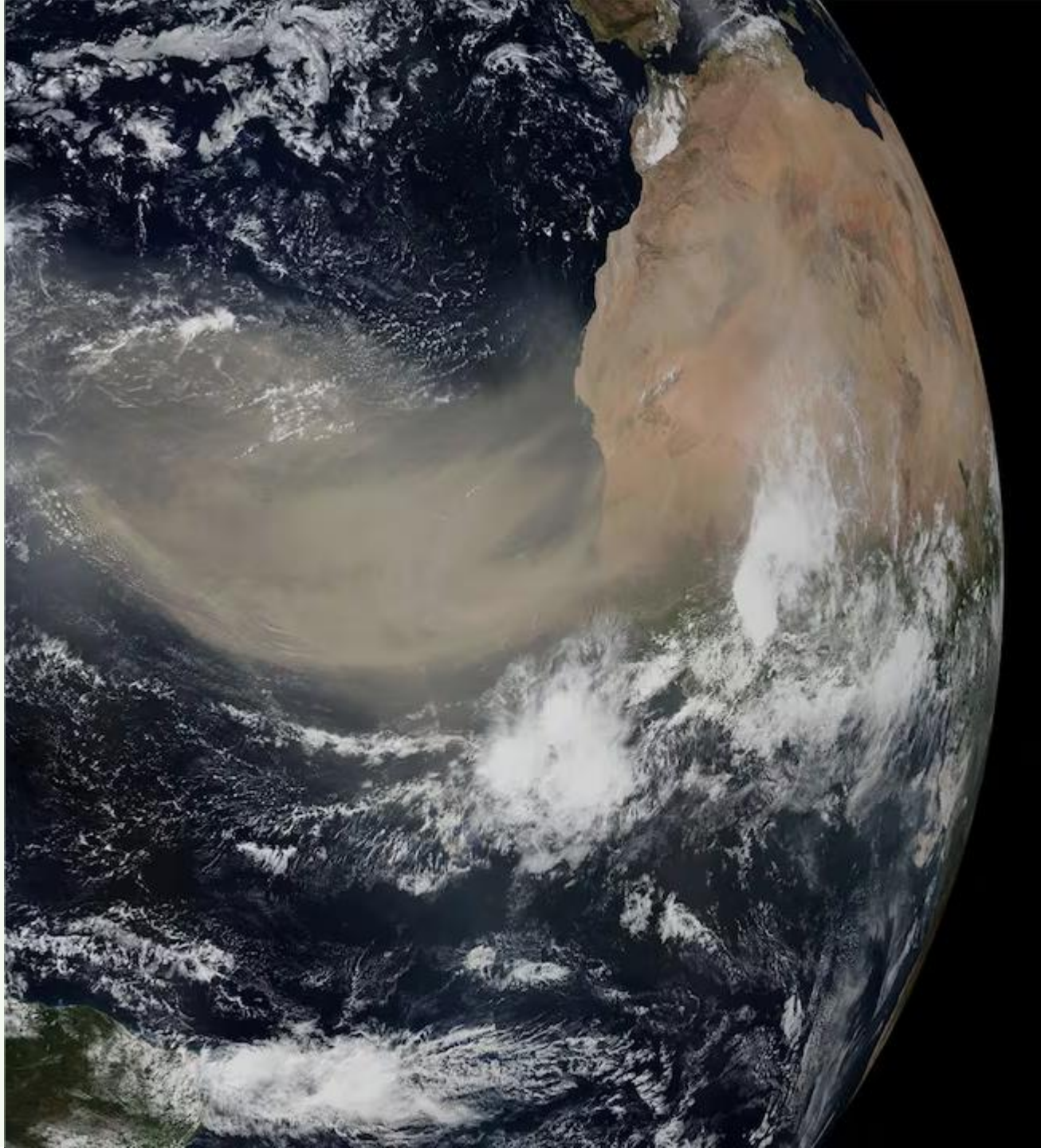
AEMet Agencia Estatal de Meteorología

CREWS & MAC-CLIMA Projects: Training of personnel, development of new instrumentation and installation of climate monitoring systems in North Africa.

KADI Project: Knowledge and climate services from an African observation and Data research Infrastructure (HORIZON-INFRA)

3.

Capacity Building in Action: Current Aerosol Observations



3. CURRENT AEROSOL OBSERVATIONS

I. Historical Observations





PILOT PROJECT
2020-2023

CREWS CLIMATE RISK & EARLY WARNING SYSTEMS

MACCLIMA

Main problems: Technical

Station	Calitoo	IMDS
Burkina Faso	some	Oct21-Aug22
Senegal	some	Feb21-Apr22
Mauritania	>1.5yr	Nov21-Nov22
Cape Verde	no data	no data





CREWS CLIMATE RISK & EARLY WARNING SYSTEMS

Main problems: Political instabilities & Comunication

Country	Shipment	First data	Last data
Mali	June 2025	February 2026	March 2026
Chad	June 2025	September 2025	February 2026
Cape Verde	June 2025	no data	no data
Niger	June 2025	no data	no data

*NO Calitoo data on the server

Chad





GODDARD SPACE FLIGHT CENTER + Visit NASA.gov

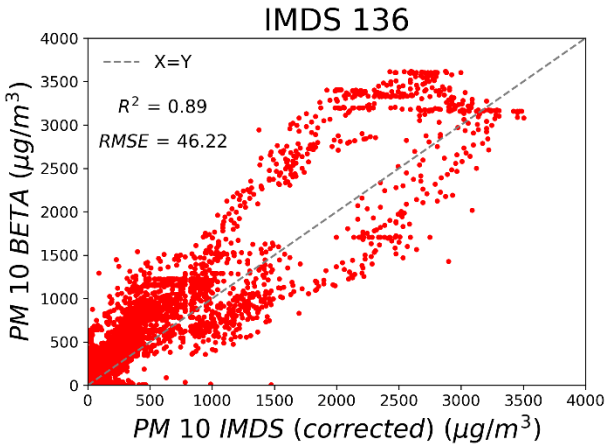
AERONET
AEROSOL ROBOTIC NETWORK

NASA-AERONET co-PI sites: Tunis (Carthage), Egypt (Cairo), Morocco (Ouazarzate), Libya (Sabha), Argelia (Tamanrasset – GAW Twining)

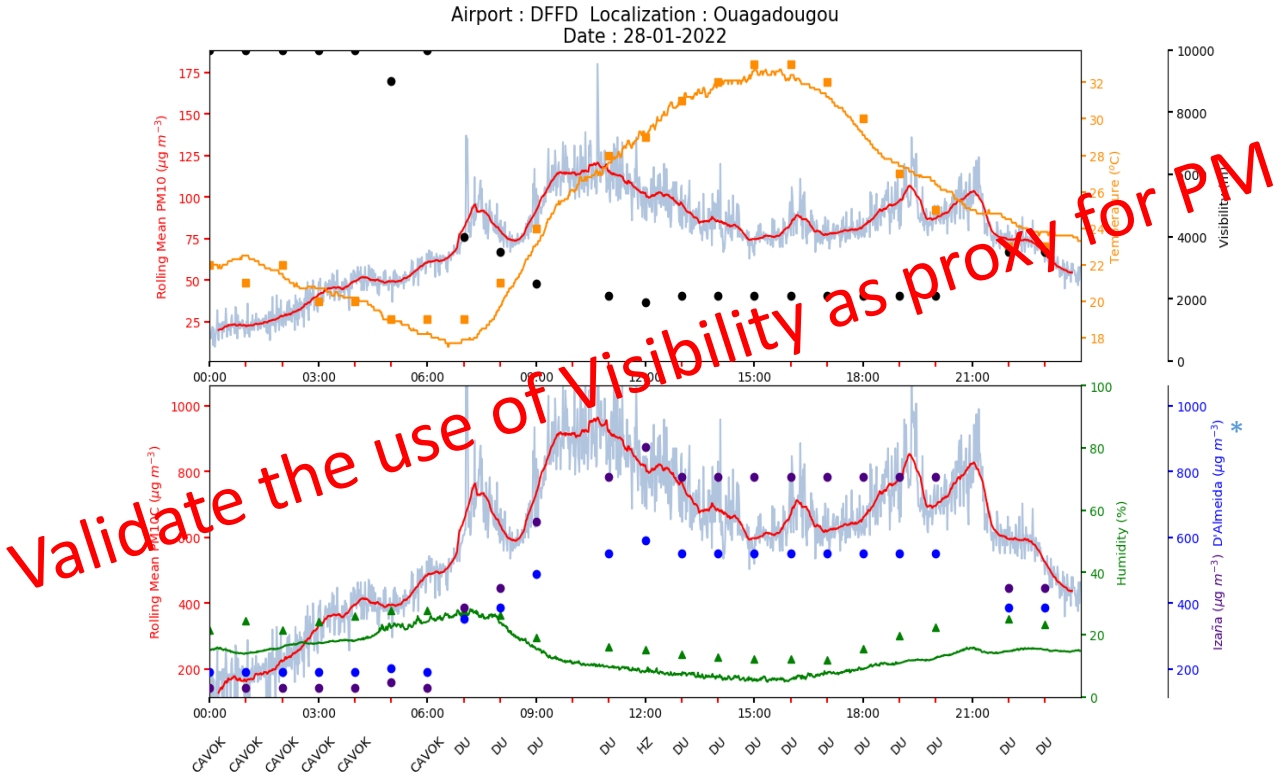
20 years!

4 LCS sensors checked and validated at Santa Cruz de Tenerife (vs BETA Monitor)





Burkina Faso, Senegal, Mauritania and Cape Verde



Validate the use of Visibility as proxy for PM_{10}!!

- ✓ Clear underestimation of IMDS
- ✓ Proposed a correction based on different steps, with a linear variation with PM considered in order to avoid artifacts

*Empirical equations to estimate dust concentration (PM_{10} or TSP in µg/m³) using visibility (V, in km)

Camino et al. (2015) $PM_{10} = 1772.24\,V^{-1.1}$

D'Almeida et al. (1986) $PM_{10} = 914.0\,V^{-0.73} + 19.03$

3. CURRENT AEROSOL OBSERVATIONS

III. LCS PM_x (2nd Experience)



LCS sensors checked and validated at Santa Cruz de Tenerife (vs BETA Monitor)



Sensirion SPS30 – DUST010

Nova SDS011 – DUST011

Plantower PMS5003 – DUST012

Table 1: Different low-cost sensors used in the intercomparison analysis.

Reference

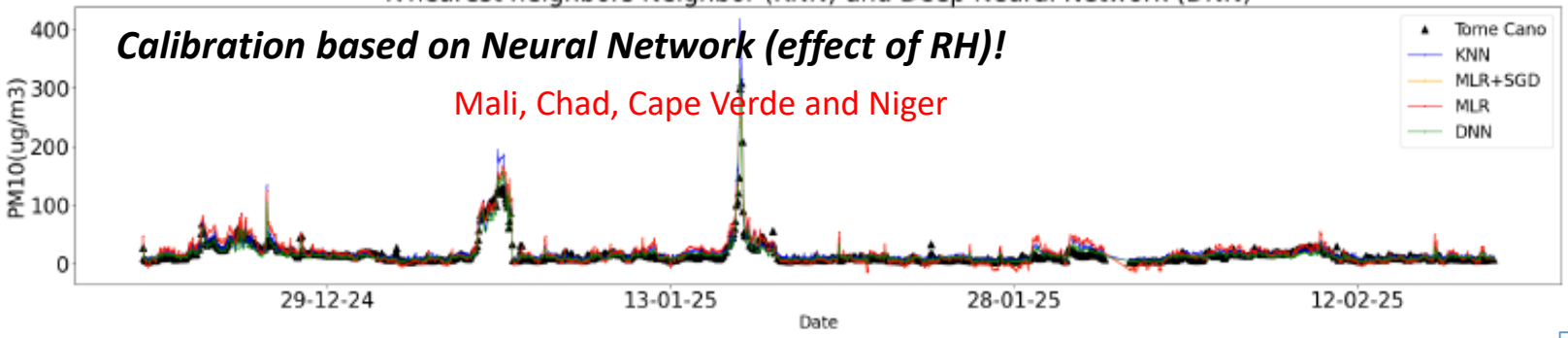


Data Filters : Y Parameters : PM10, Humidity

Multiple Linear Regression(MLR) ,Multiple Linear Regression with Stochastic Gradient Descent (MLR+SGD), K-nearest neighbors Neighbor (KNN) and Deep Neural Network (DNN)

Calibration based on Neural Network (effect of RH)!

Mali, Chad, Cape Verde and Niger



ID	KNN	ID	MLR+SGD	ID	MLR	ID	DNN
Counts	1362	Counts	1362	Counts	1362	Counts	1362
Pearson	0.94	Pearson	0.93	Pearson	0.93	Pearson	0.95
R2 score	0.77	R2 score	0.74	R2 score	0.73	R2 score	0.88
BIAS	3.67	BIAS	3.04	BIAS	2.84	BIAS	-0.29
MSE	108.24	MSE	120.83	MSE	127.46	MSE	54.58
RMSE	10.4	RMSE	10.99	RMSE	11.29	RMSE	7.39
MAE	5.87	MAE	7.45	MAE	7.67	MAE	4.45
MAPE	45.85 %	MAPE	61.5 %	MAPE	64.3 %	MAPE	30.47 %
Pm10 = 0.76KNN+1.41		Pm10 = 0.75MLR+SGD+2.16		Pm10 = -0.49HR+3.64MLR+20.24		Pm10 = 0.9DNN+1.94	

Best skill scores for Deep Neural Network (DNN) algorithm, with high Pearson coeff (0.95) and low RMSE (7.39 µg/m^3)

CREWS CLIMATE RISK & EARLY WARNING SYSTEMS

WORLD METEOROLOGICAL ORGANIZATION

aemet Agencia Estatal de Meteorología

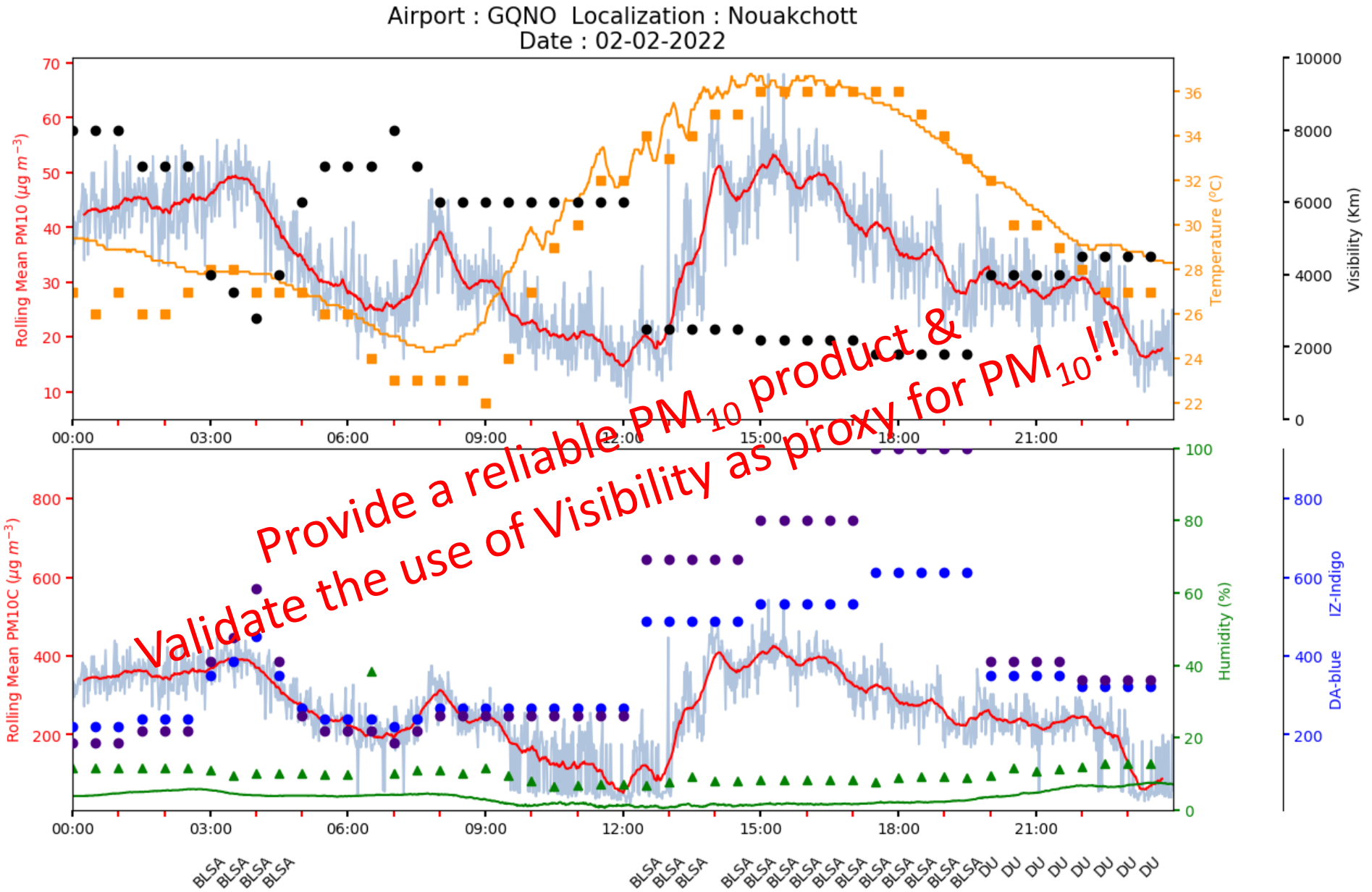
3. CURRENT AEROSOL OBSERVATIONS

III. LCS PM_x (2nd Experience)

DUST SENSORS

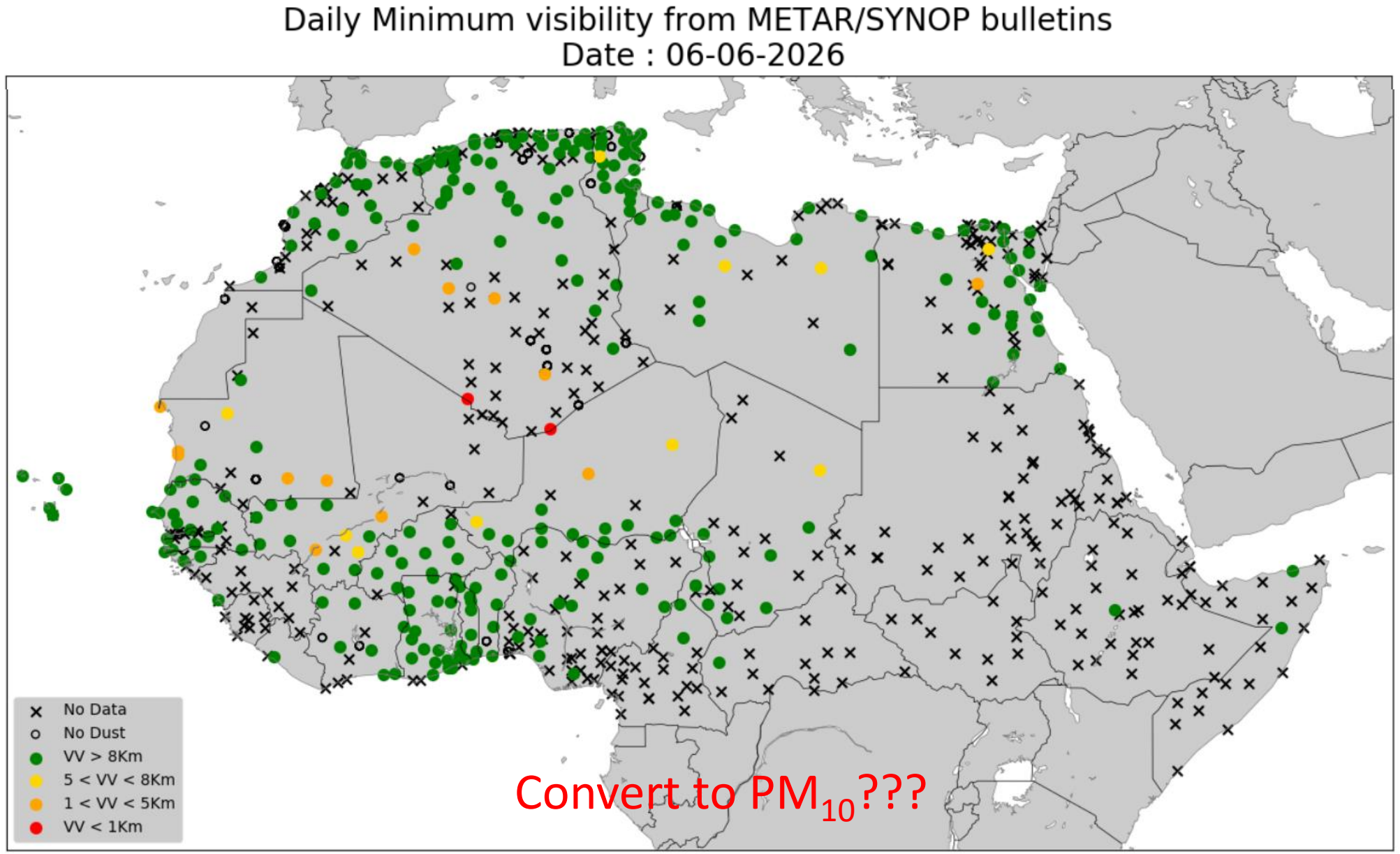
MAURITANIA





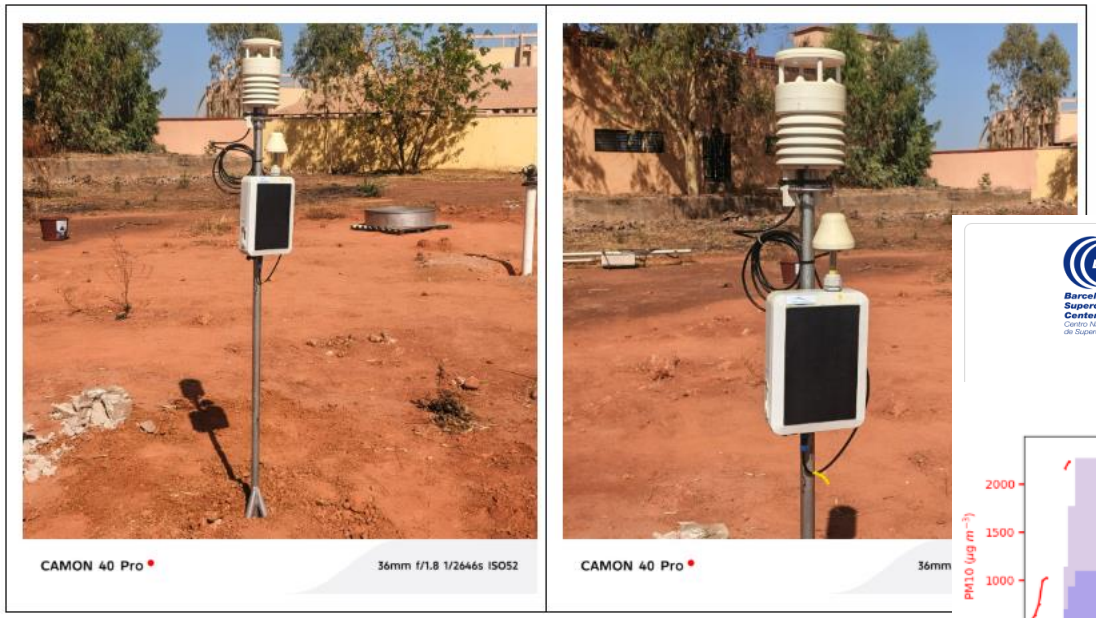
3. CURRENT AEROSOL OBSERVATIONS

III. LCS PM_x (2nd Experience)



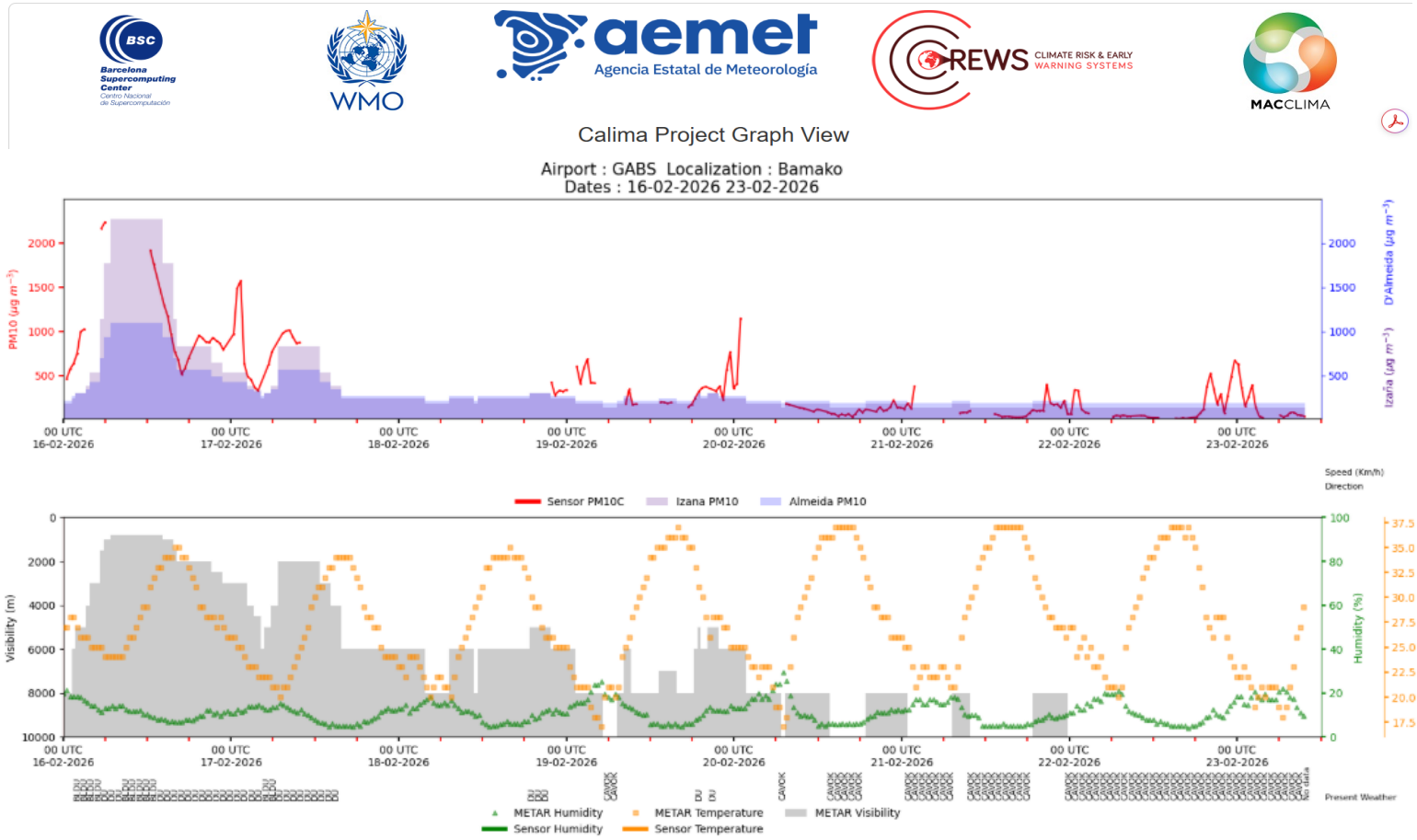
3. CURRENT AEROSOL OBSERVATIONS

III. LCS PM_x (2nd Experience)



DUST SENSORS

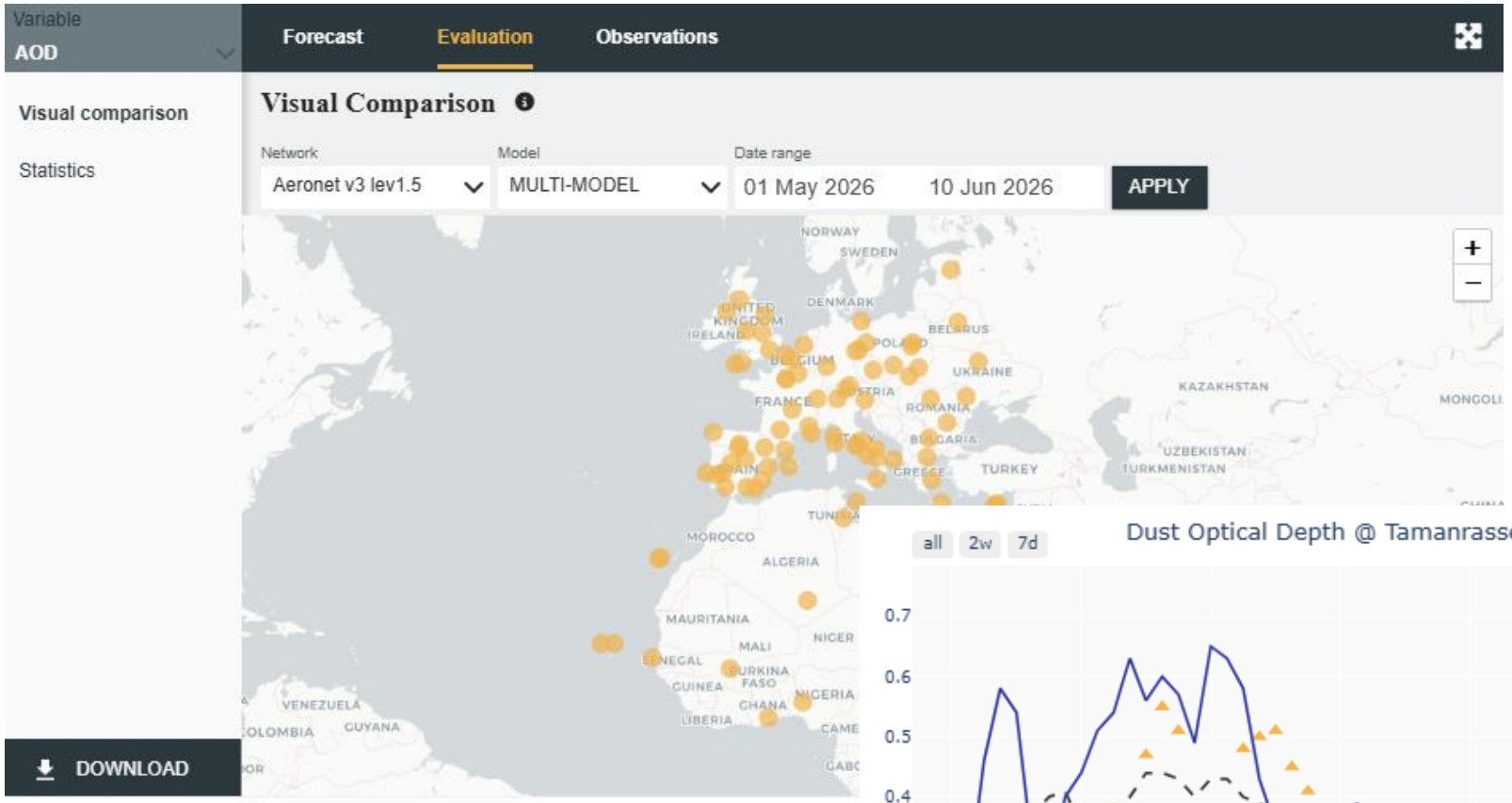
MALI



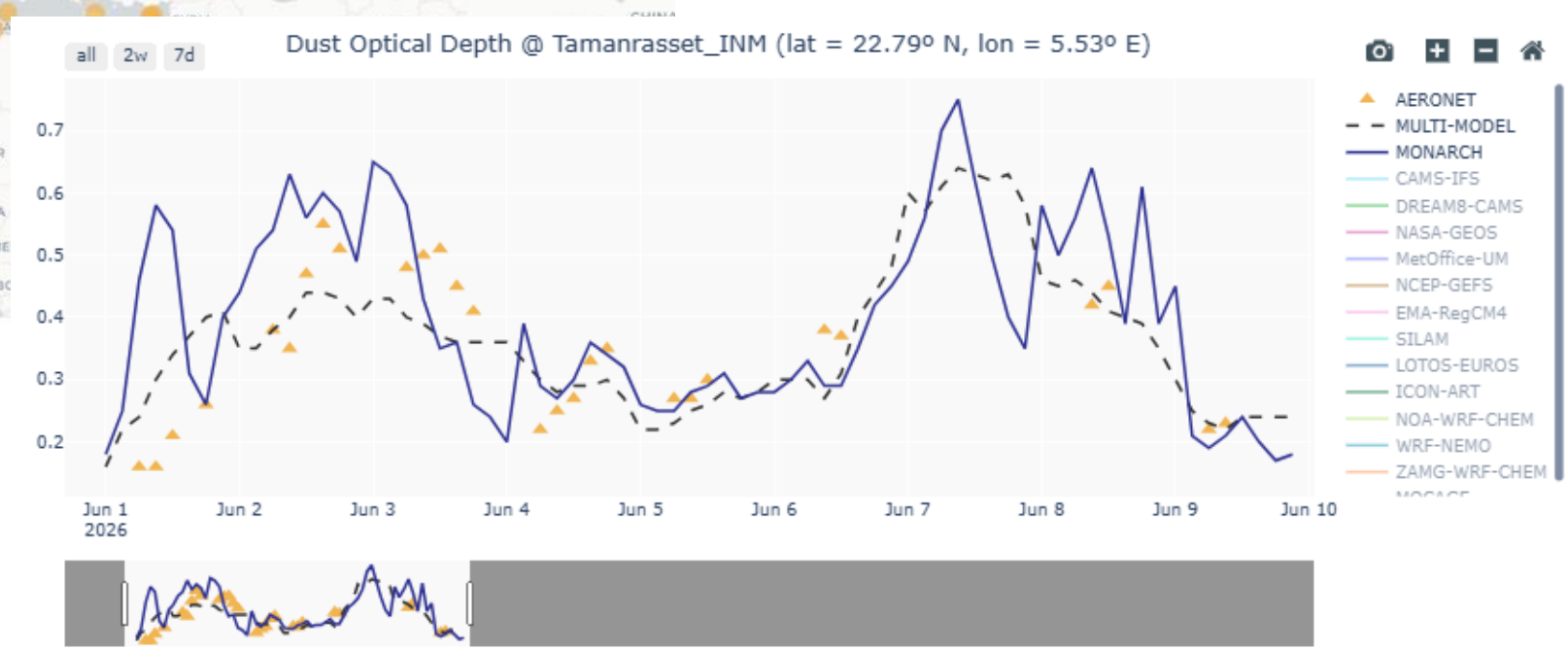


3. CURRENT AEROSOL OBSERVATIONS

IV. AERONET Sites



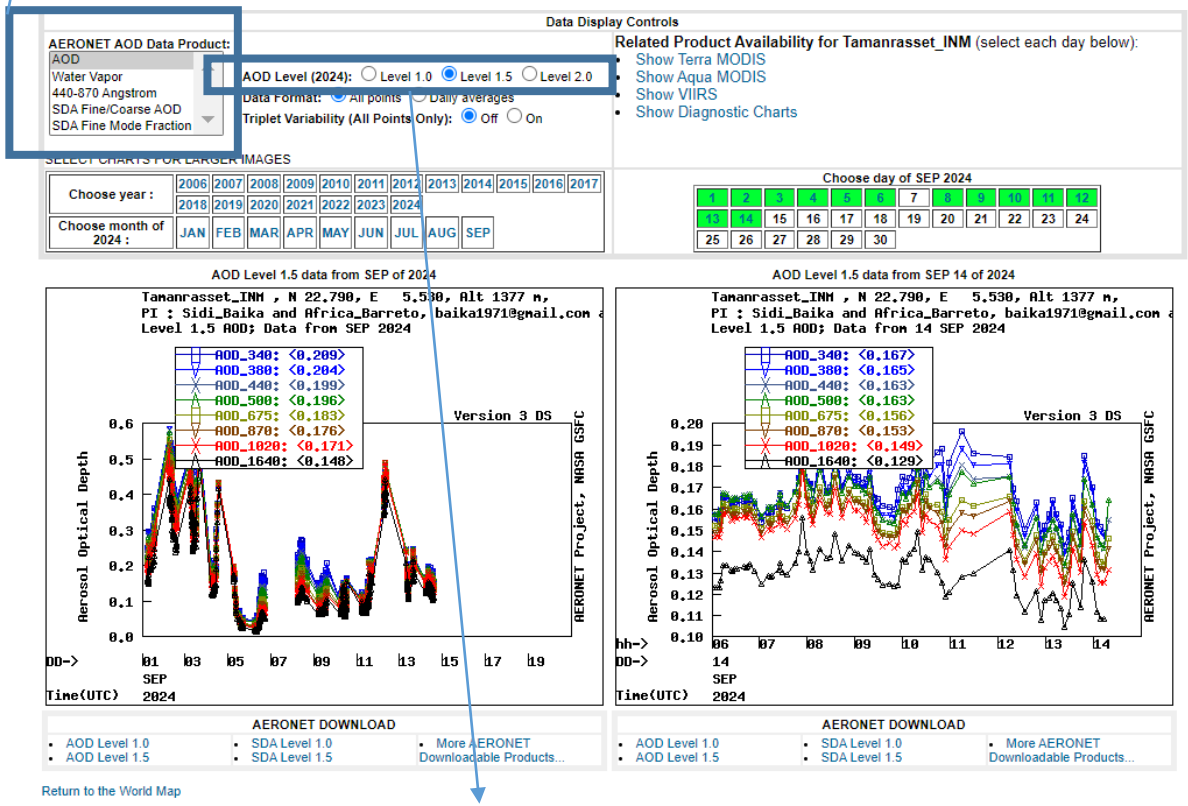
AOD FORECAST EVALUATION



AERONET Products

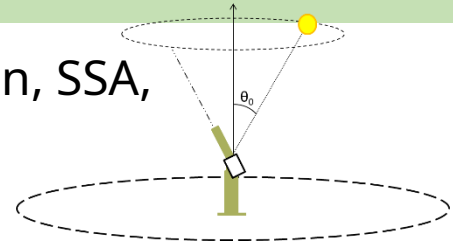


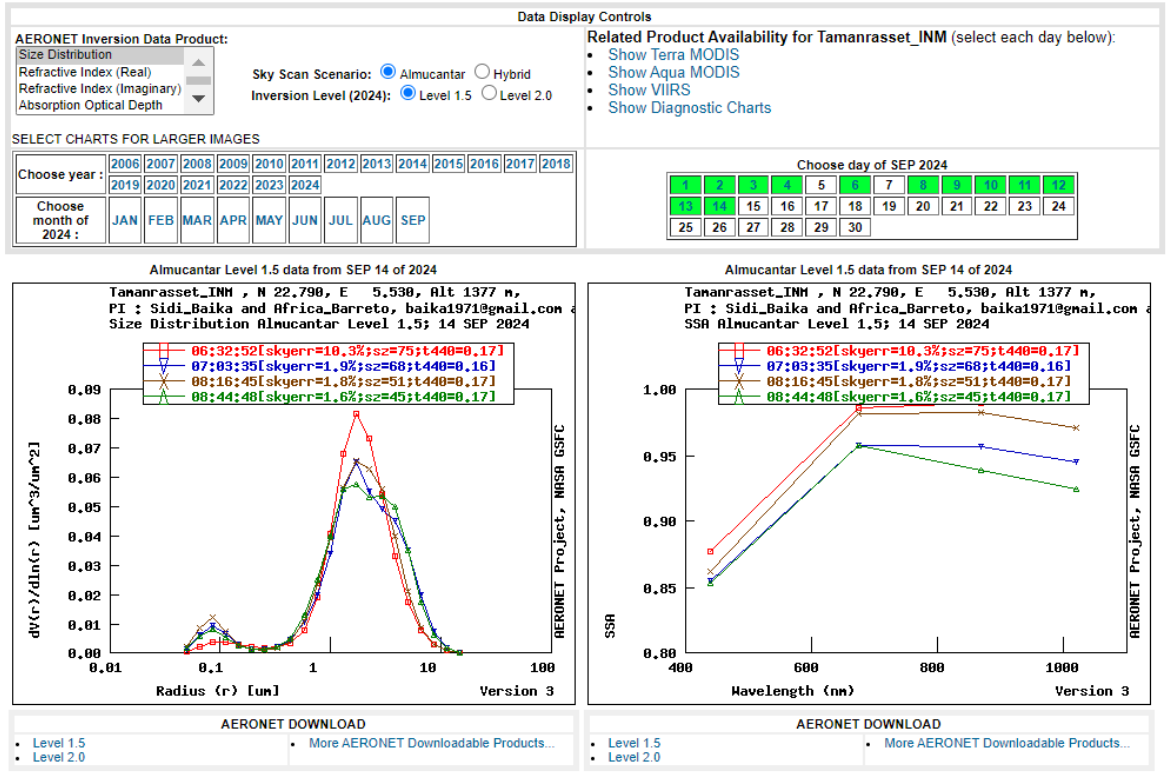
Direct SUN-MOON: Aerosols Optical Depth –**AOD**-, Angstrom Exponent –**AE**-, Single Deconvolution algorithm –**SDA**- to provide fine/coarse fraction



AOD levels: level 1.0 raw data
level 1.5 Preliminary QC
level 2.0 Datos validados (final QC/QA)

Inversion SUN-SKY: Size distribution, SSA, refraction Index, ….





https://aeronet.gsfc.nasa.gov/cgi-bin/data_display_inv_v3?site=Banizoumbou&nachal=0&year=2025&aero_water=0&level=2&if_day=0&if_err=0&place_code=10&DATA_TYPE=76&year_or_month=1

3. CURRENT AEROSOL OBSERVATIONS

V. Calitoo Sites

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

WMO

aemet
Agencia Estatal de Meteorología

CREWS CLIMATE RISK & EARLY WARNING SYSTEMS

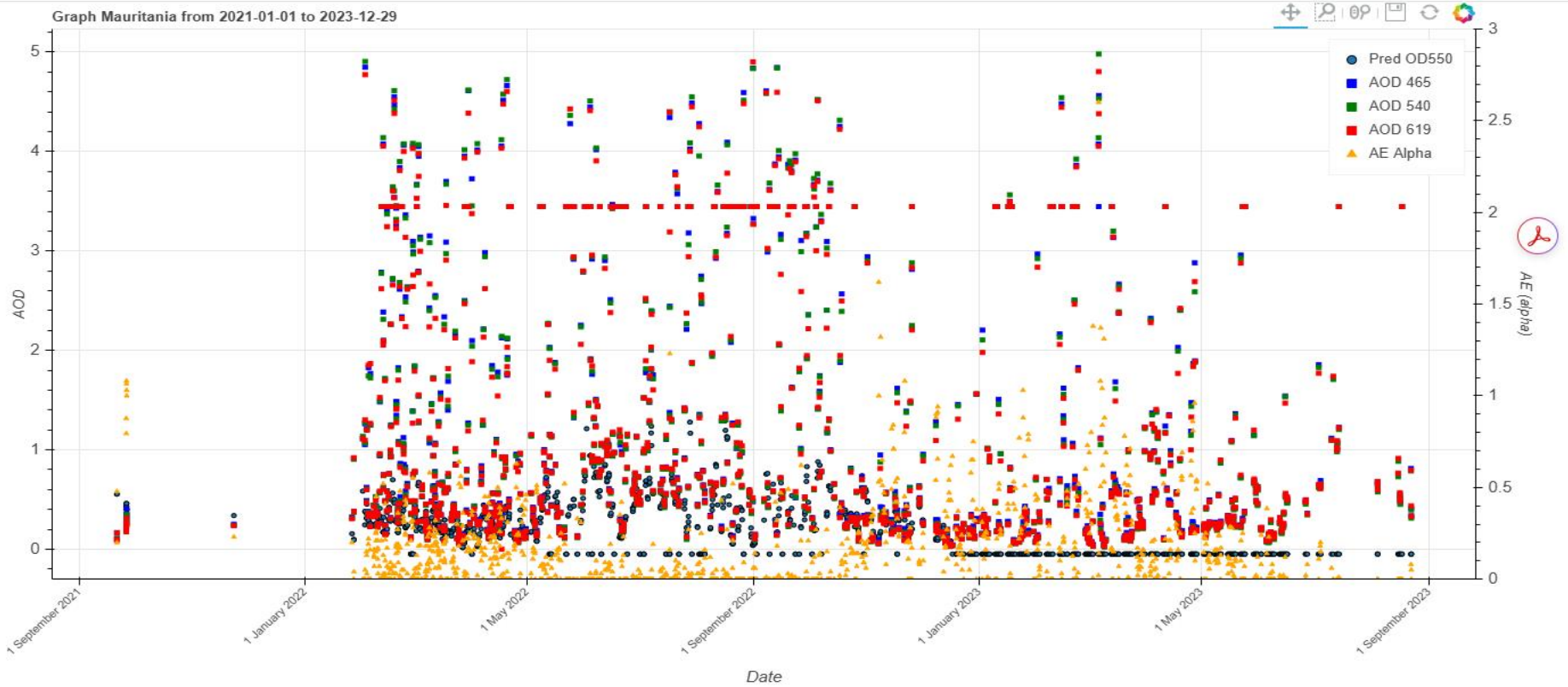
MACCLIMA



Calima Project Graph View

Station:
Choose station
From:
01/01/2021
To:
12/29/2023

Plot Graph



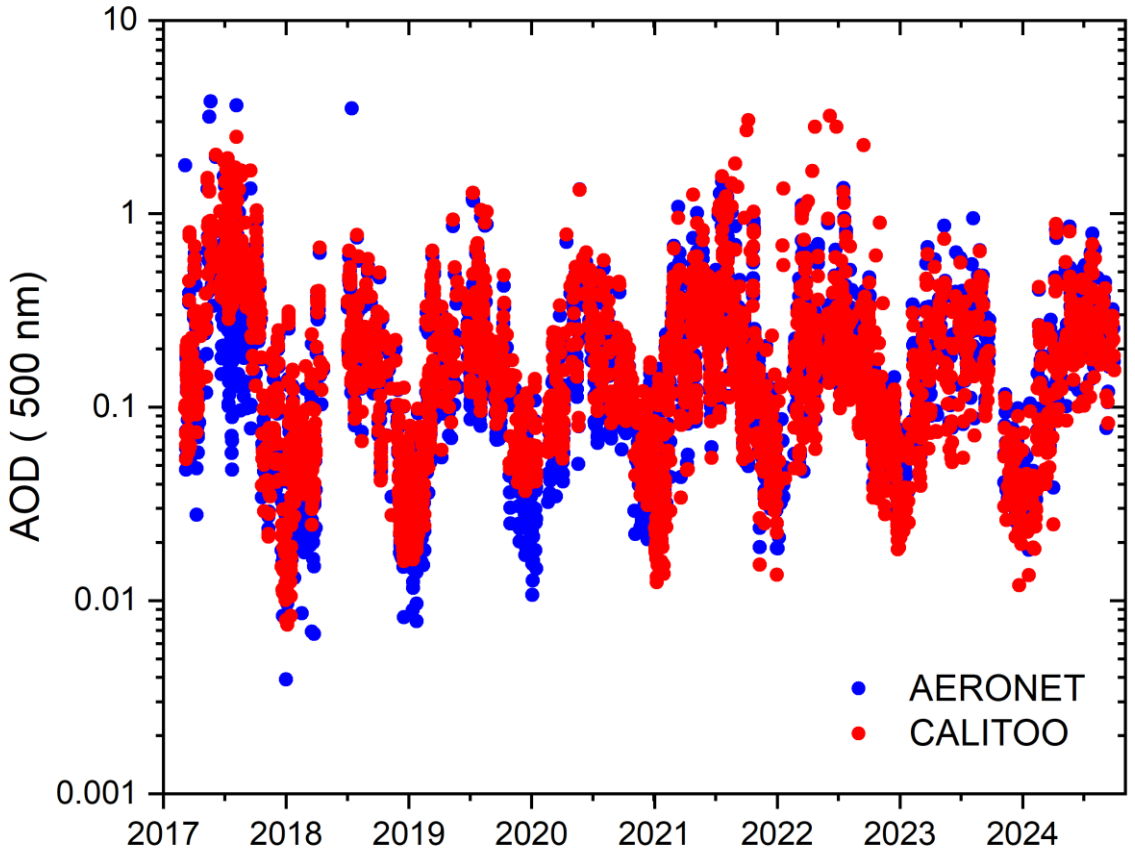
Download CSV file

View data table

Tamanrasset (Algeria) GAW Global Station



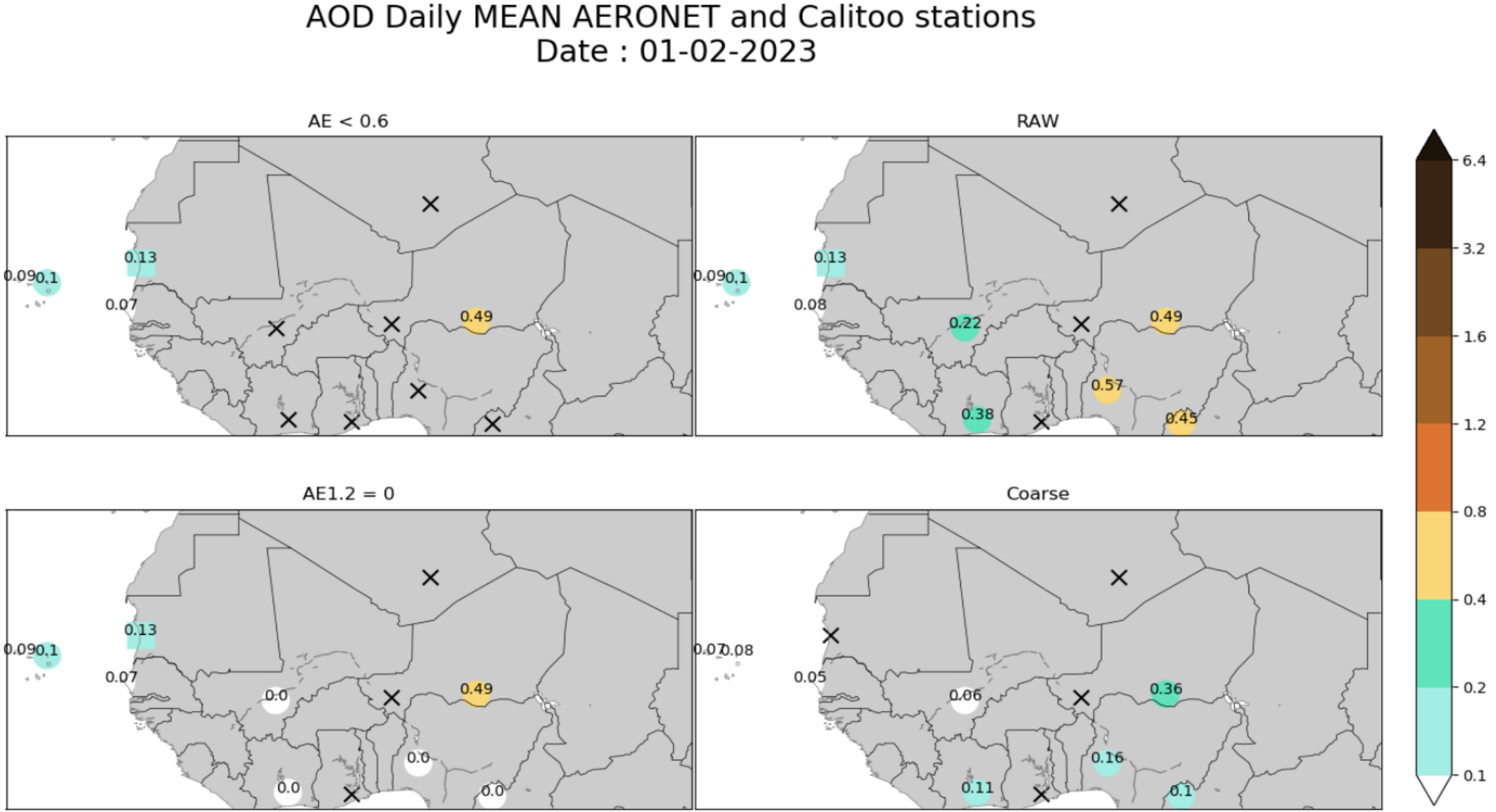




RGM versus LCS!!

3. CURRENT AEROSOL OBSERVATIONS

V. Calitoo Sites



abarretov@aemet.es

aemet
Agencia Estatal de Meteorología



Thanks for your attention!!!

HARMONIA
International network for harmonization of atmospheric aerosol retrievals from ground based photometers

A zenith looking radiometer (ZEN-R52) for the retrieval of aerosol properties

II HARMONIA WG4 Workshop
30 June 2026 - Valladolid, Spain

Sara Herrero-Anta (sara.herrero.anta@uva.es)
University of Valladolid (Spain)

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
Funded by the European Union

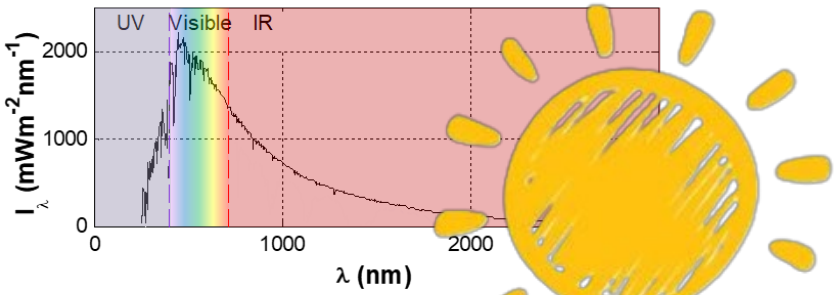


ZEN-R52 in the rooftop of the Faculty of Sciences from University of Valladolid

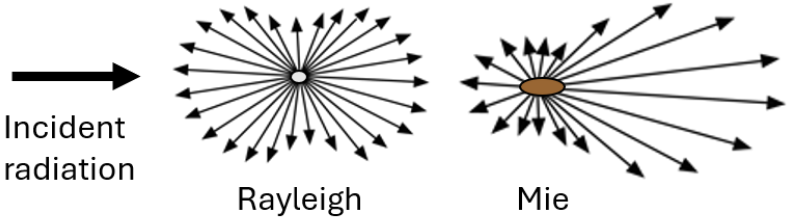
ZEN-R52 radiometer (*Sieltec Canarias S.L.*)

- **5 detectors** under **5 filters**: 440, 500, 675, 870 and 940 nm
- Leveled and looking in the zenithal direction
- **Zenith sky radiance (ZSR) at 440, 500, 675, 870** y 940 nm (WV) in analogit-to-digital units (ADU)
- **ZSR every minute** (mean of 30 measurements taken within the minute)
- **ZEN Variability** (standard deviation of the 30 measurements)
- **Advantages: Low-cost** and **robust** instrument **without moving parts**

Use of sky radiances for the retrieval of aerosol properties



SCATTERING $\left(\frac{r}{\lambda}, n\right)$



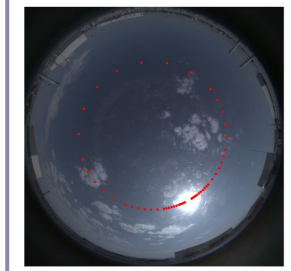
DIRECT SUN IRRADIANCE (I)

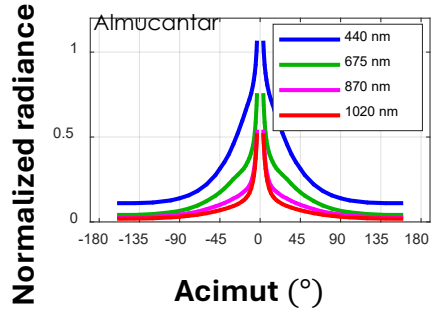
$I_0(\lambda)$

Holben et al., (1998)

AERONET AEROSOL ROBOTIC NETWORK

CE318-T





+ Aerosol Optical Depth (AOD)

SKY RADIANCE (L)

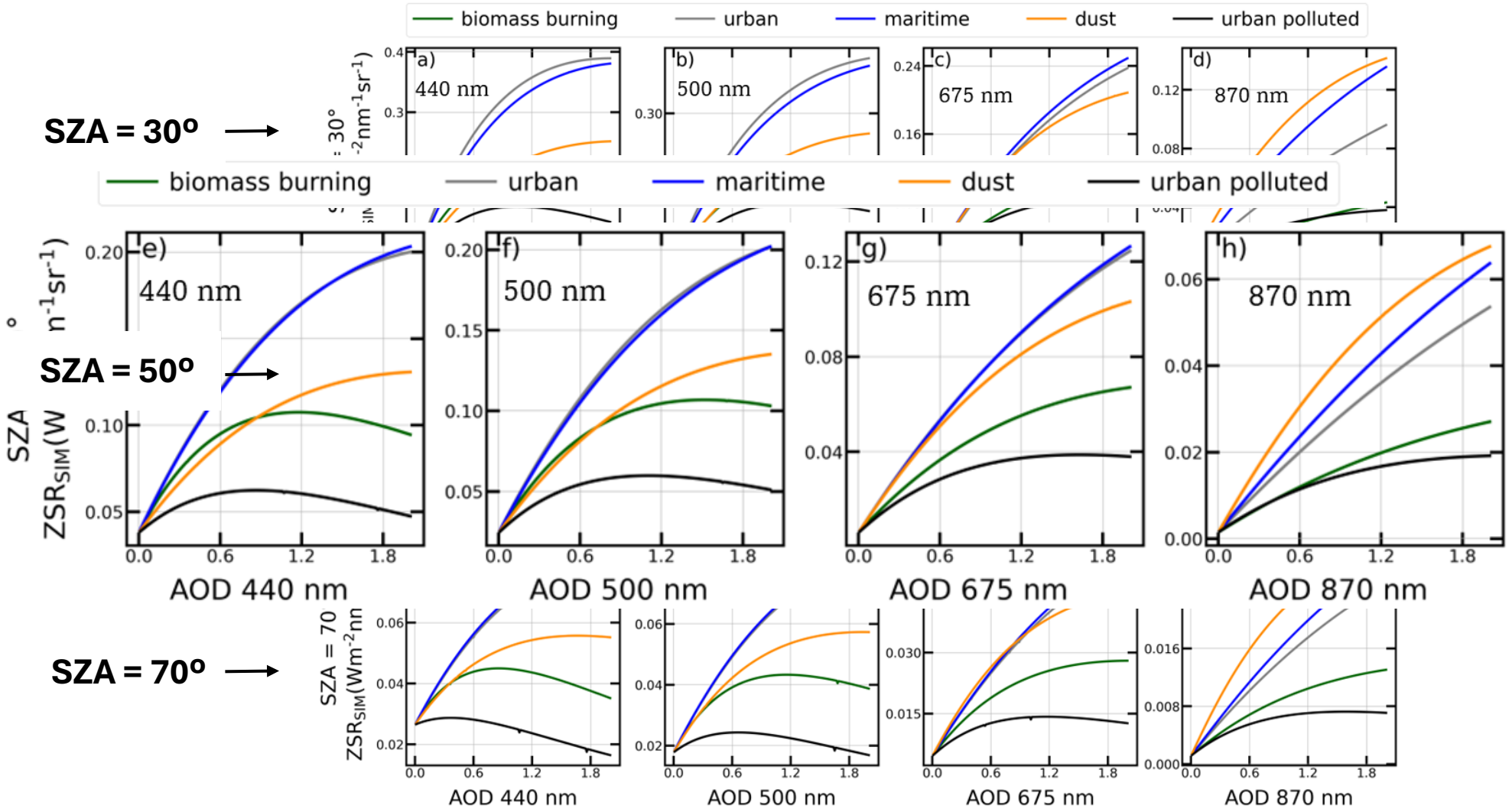
$I(\lambda)$

Optical and microphysical aerosol properties

Use of ZSR to retrieve aerosol properties

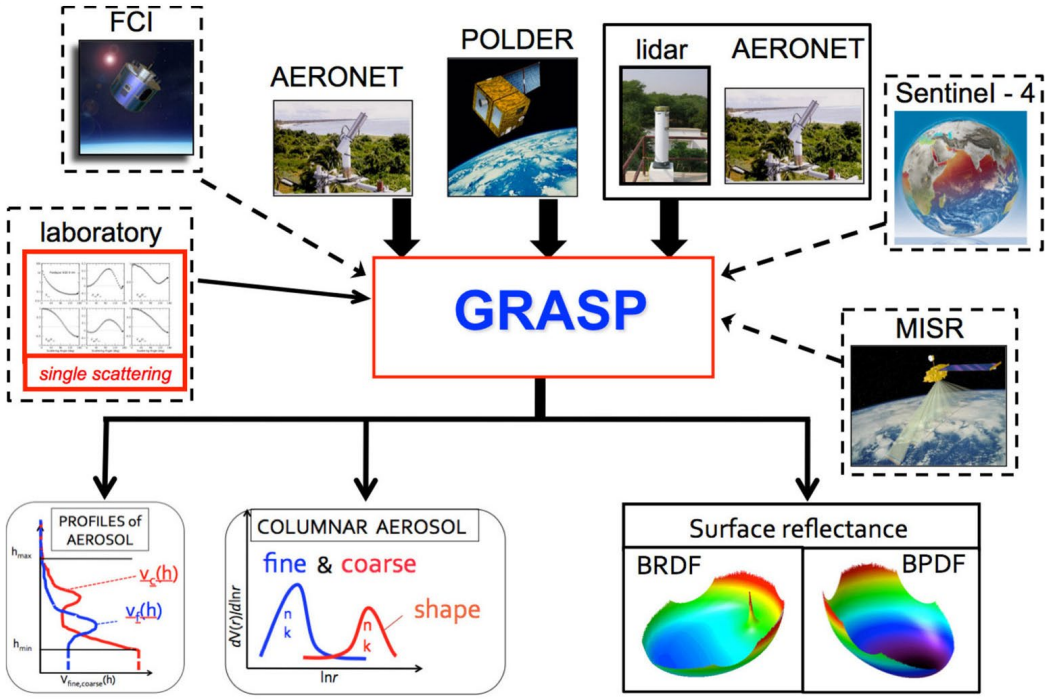


ZSR at 440, 500, 675 and 870 nm → **Useful to retrieve aerosol information**



GRASP (Generalized retrieval of aerosol and surface properties)

Dubovik et al., (2021)
Inversion algorithm designed for **the retrieval of aerosol** and surface **properties**
It is a free and open code, **flexible and versatile**
It admits diverse types of observations as input



Mode: forward/inversion

SETTINGS

Inversion strategy
(Type of observations, constrains,…)

SDATA

Observations
(AOD, sky radiances, RCS…)

GRASP
Iterative method

OUTPUT

Aerosol properties
(RRI, IRI, size distribution,…)
Residual of the inversion (quality of the fitting)

GRASP-ZEN inversion strategy

GRASP-ZEN

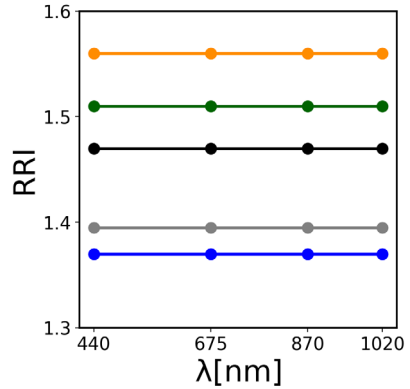
INPUT: ZSR at 440, 500, 675 and 870 nm

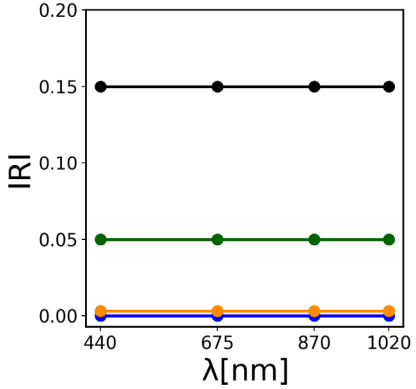
***models* method:** the aerosol can be represented as a external mixture of the 5 types of aerosol most common in the world

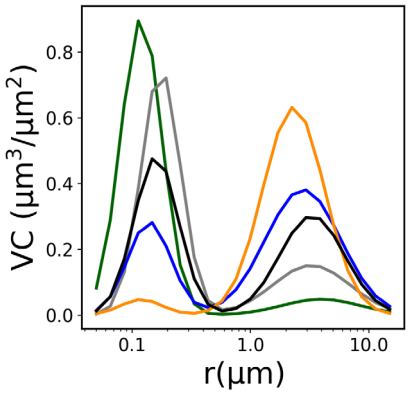
OUTPUT: total volume concentration and fraction of each of type of aerosol in the mixture

***models* GRASP:** pre-defined aerosol properties

- Biomass burning
- Urban
- Oceanic
- Desert dust
- Urban polluted







Sphericity parameter:

Biomass burning: 100 %

Urban: 100 %

Oceanic: 100 %

Desert dust: 0%

Urban polluted: 100 %

Calibration of the ZEN-R52



$\mathbf{ZSR_{Tc}}$ at **440, 500, 675** and **870** nm in **ADU**

"in-situ" calibration

Available dataset: April 2019 - September 2021

Simulation of ZSR ($\mathbf{ZSR_{SIM}}$) simultaneous to the $\mathbf{ZSR_{Tc}}$ measured by the ZEN-R52

Aerosol and gases properties (AERONET)
Surface reflectance (BRDF)
Elevation, location, SZA, date, time…

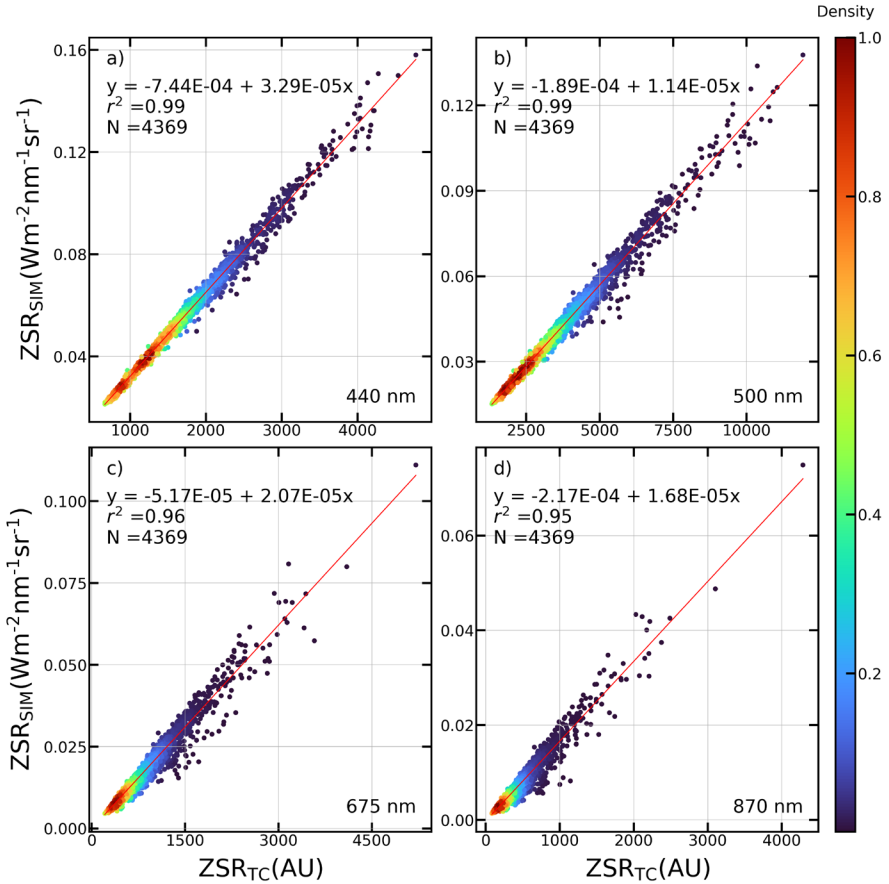
forward mode

GRASP

$\mathbf{ZSR_{SIM}}$ at **440, 500, 675** and **870** nm in $\mathbf{Wm^{-2}m^{-1}sr^{-1}}$

1 Dark signal correction
2 Quality control filters:
- 30° < SZA < 80°
- ZEN variability < 4 % (cloud indicator)

3 Temperature correction
4 Obtention of the calibration coefficients



Calibration of the ZEN-R52

ZEN-R52



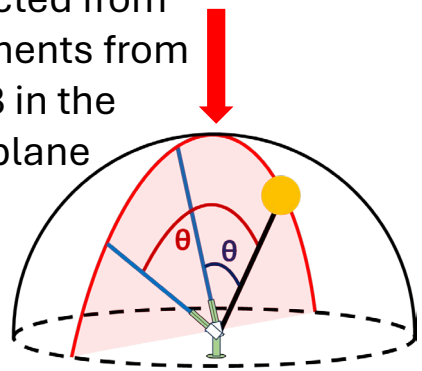
$\pm$ 1 min

ZSR_{ZEN}

Vs.

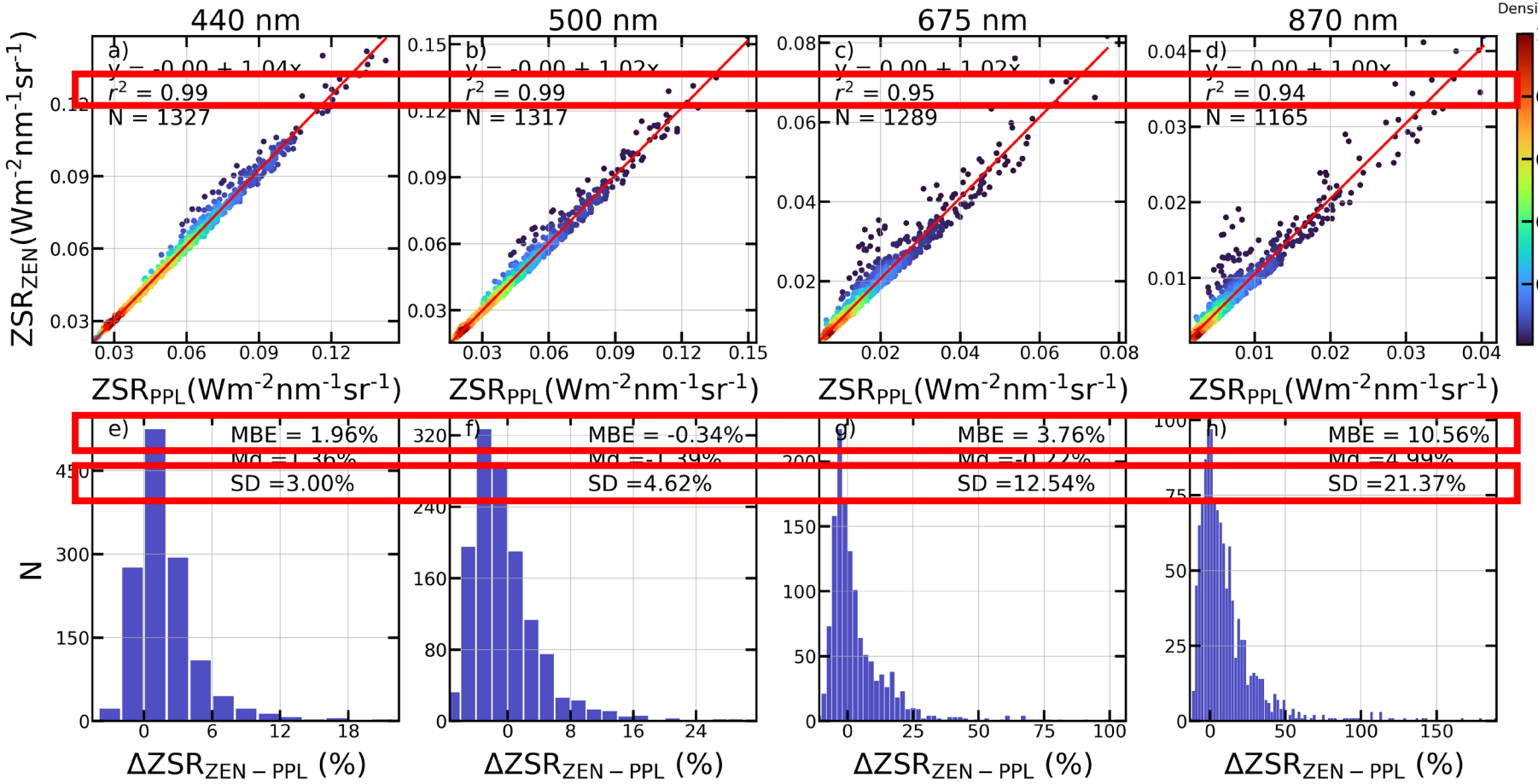
ZSR_{PPL}

ZSR extracted from measurements from the CE318 in the principal plane (PPL)



AERONET
AEROSOL ROBOTIC NETWORK

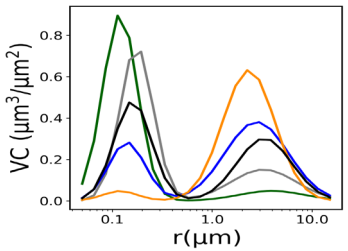
CE318



SD ⟶ theorical uncertainty of the calibrated ZSR values

GRASP-ZEN synthetic study

Fraction of each of the 5 types of aerosols from *models*



&

CVT = 0.01 - 0.15 $\mu m^3 \mu m^{-2}$

Aerosol created as a mixture of the 5 types of aerosols used by the *models* method

1000 random synthetic scenarios
SZA = 30°, 50° y 70°

Synthetic aerosol scenarios
AOD, RRI, IRI, size distribution, sphericity parameter

GRASP ***forward mode***

Simulation of the ZEN-R52 observations

ZSR a 440, 500, 675, 870 nm

GRASP ***inversion mode***

Aerosol properties retrieved in the inversion
AOD, RRI, IRI, size distribution, sphericity parameter

SYN ⟷ **INV**



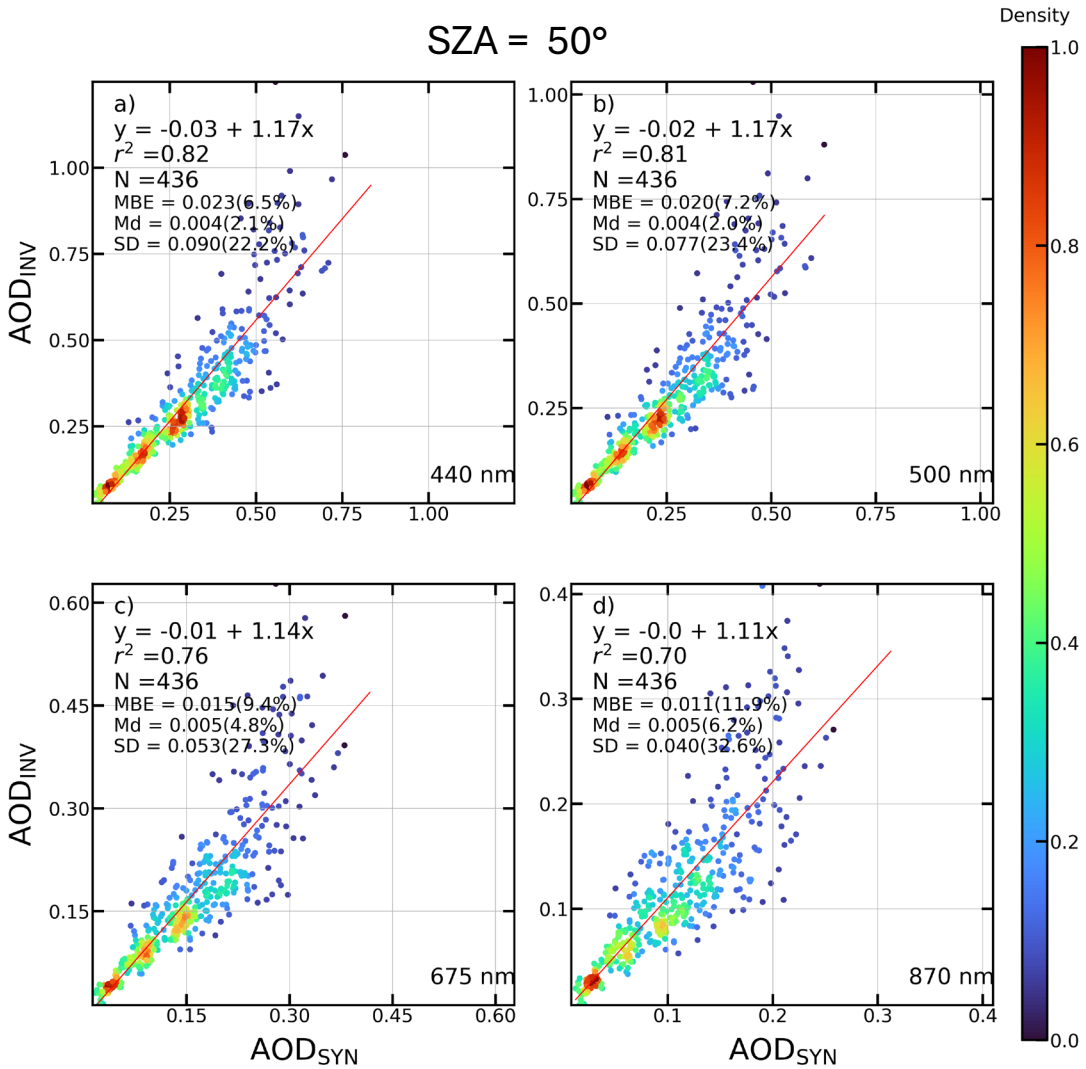
Aerosol properties retrieved from AERONET level 1.5 during 2019-2021

Real aerosol scenarios; it does not have to be a mixture of the 5 types of aerosols used by the models method

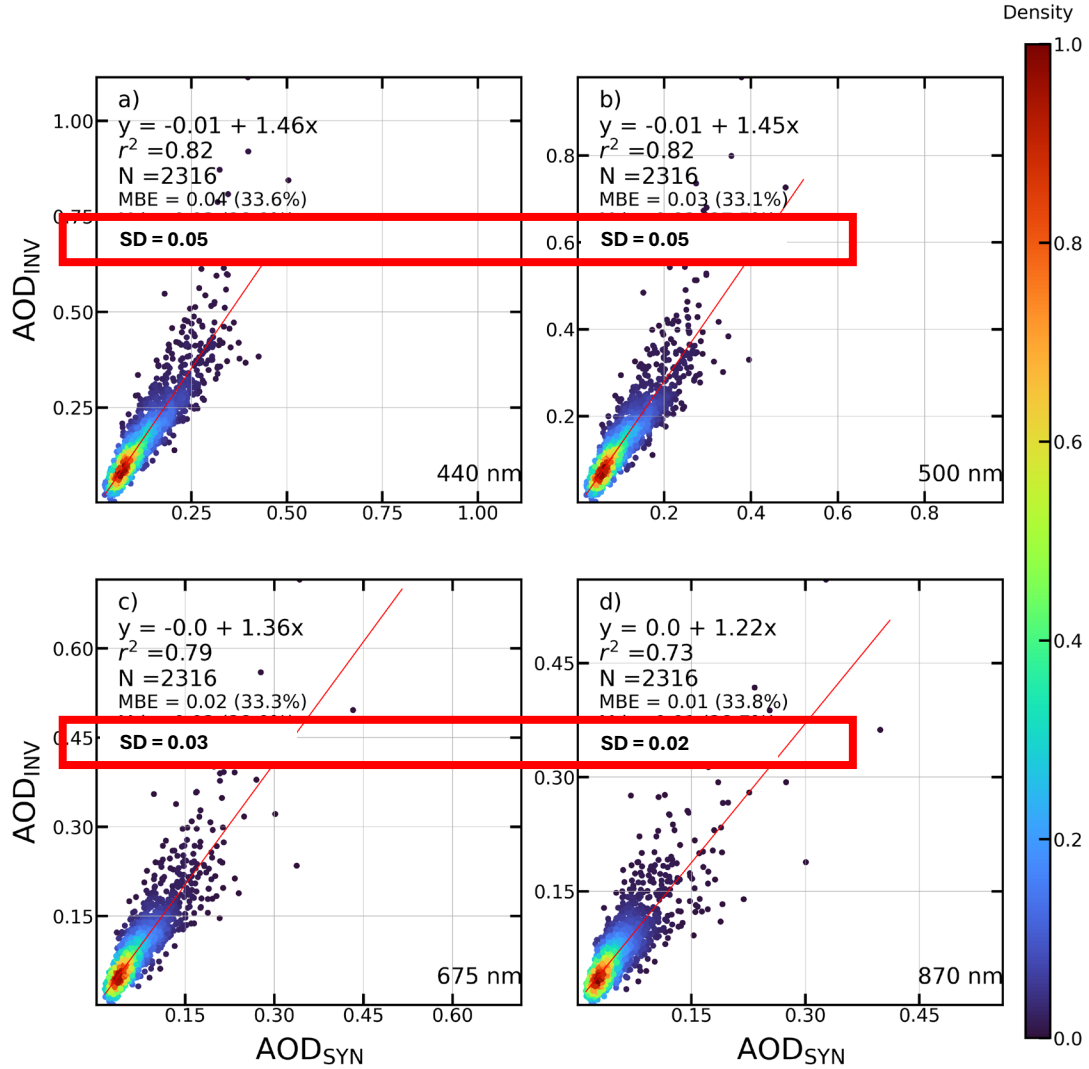
5321 synthetic scenarios
2019–2021 with sky error < 5 %

GRASP-ZEN synthetic study

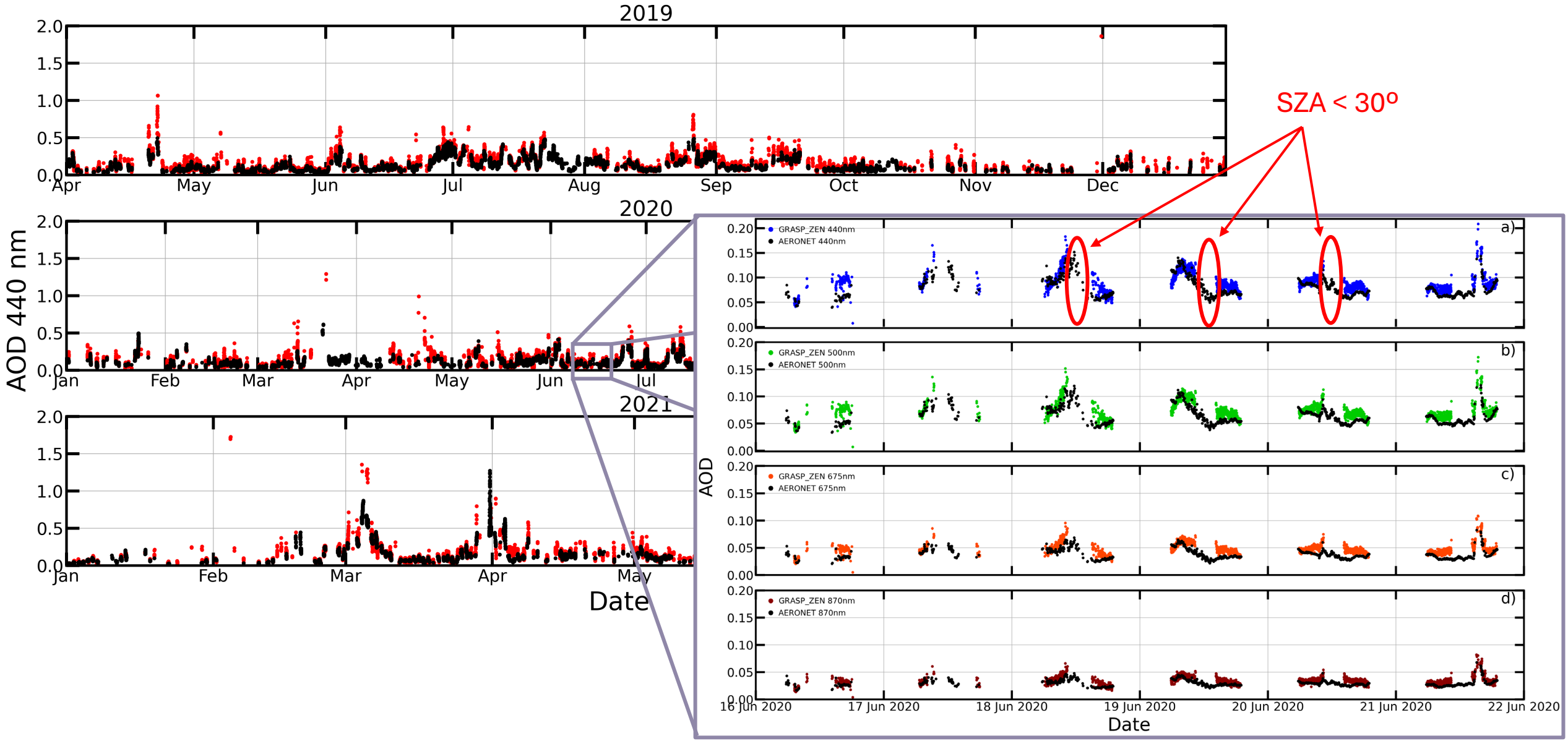
Scenarios as a random mixture of the 5 types of *models*



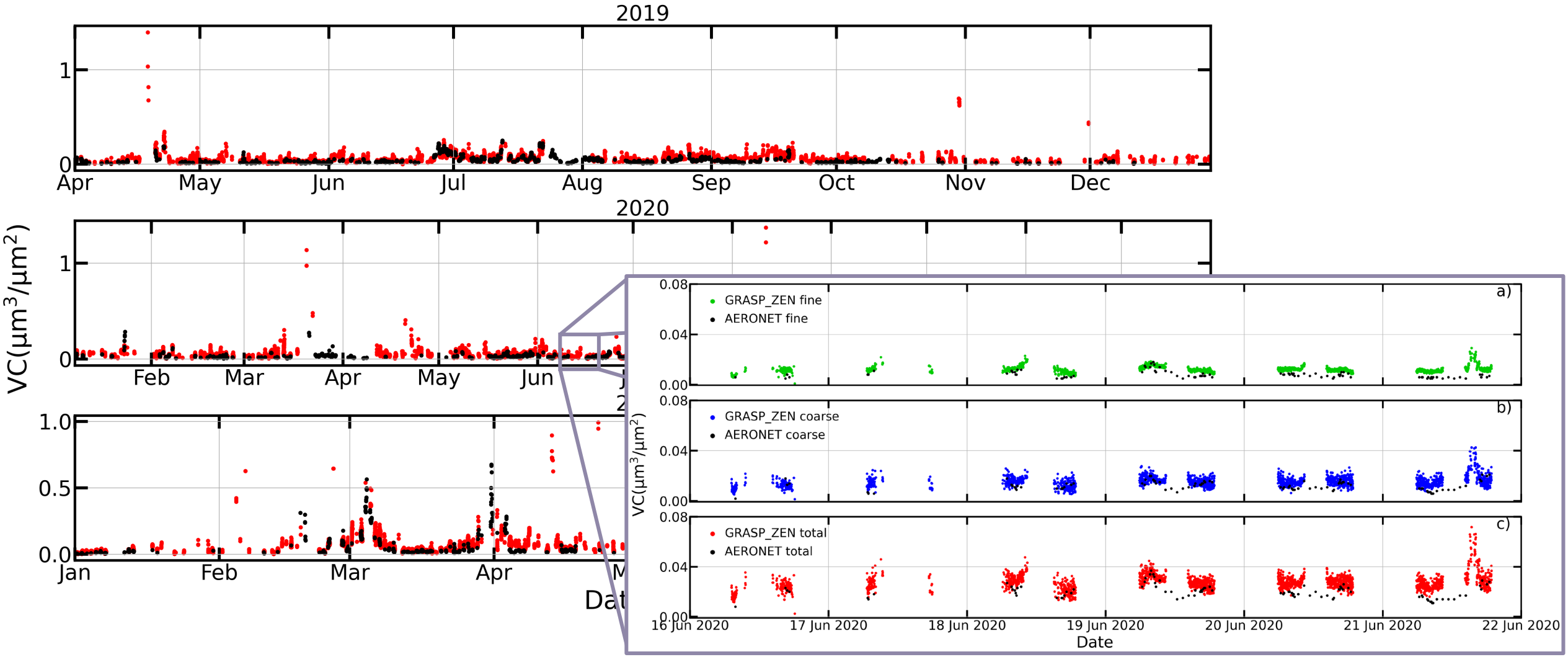
Real scenarios from AERONET



Retrieval of AOD with GRASP-ZEN



Retrieval of VC with GRASP-ZEN



Conclusions & Outlooks

- **ZSR** measurements from the ZEN-R52 **are sensitive to load and type of aerosol** and therefore are **useful** to **retrieve** information about **aerosols**.
- The **calibration coefficients** obtained with the proposed in-situ calibration are similar to those obtained through laboratory calibration. It is observed that the **accuracy and uncertainty** is **worse** for **longer wavelengths**.
- The **synthetic study** shows that the inversion strategy **GRASP-ZEN** is **limited to** the obtention of **extensive aerosol properties**, like AOD and volumen concentration (fine and coarse modes and total).
- **GRASP-ZEN** tends to **overestimate AOD** at all wavelengths, particularly under realistic aerosol conditions, but shows strong agreement with AERONET (r^2 = 0.72–0.86), especially at shorter wavelengths.
- The **Md** and **standard deviation** of the differences between the **total volume concentration** obtained with GRASP-ZEN and AERONET are **0.01 and 0.02 $\mu m^3 \mu m^{-2}$**, respectively, with even smaller values for the fine and coarse modes. These results indicate that GRASP-ZEN is able to retrieve volume concentration with good precision and accuracy.
- The **ZEN-R52 radiometer** is presented as a potential, more affordable **alternative** for **obtaining aerosol properties** in **remote areas**, or even at locations where a co-located CE318 photometer is available, in order to increase the temporal resolution of certain aerosol properties.

HARMONIA
International network for harmonization of atmospheric aerosol retrievals from ground based photometers

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

Thank you for your attention!

¡Muchas gracias por vuestra atención !

Grupo de Óptica Atmosférica - GOA-UVA - Universidad de Valladolid

LaDIS
Laboratory for Disruptive Interdisciplinary Science

CALITOO

Aerosol photometer



- Origin of the Calitoo
- How does it work ?
- Advantages and limitations
- Calibration methods

Tenum

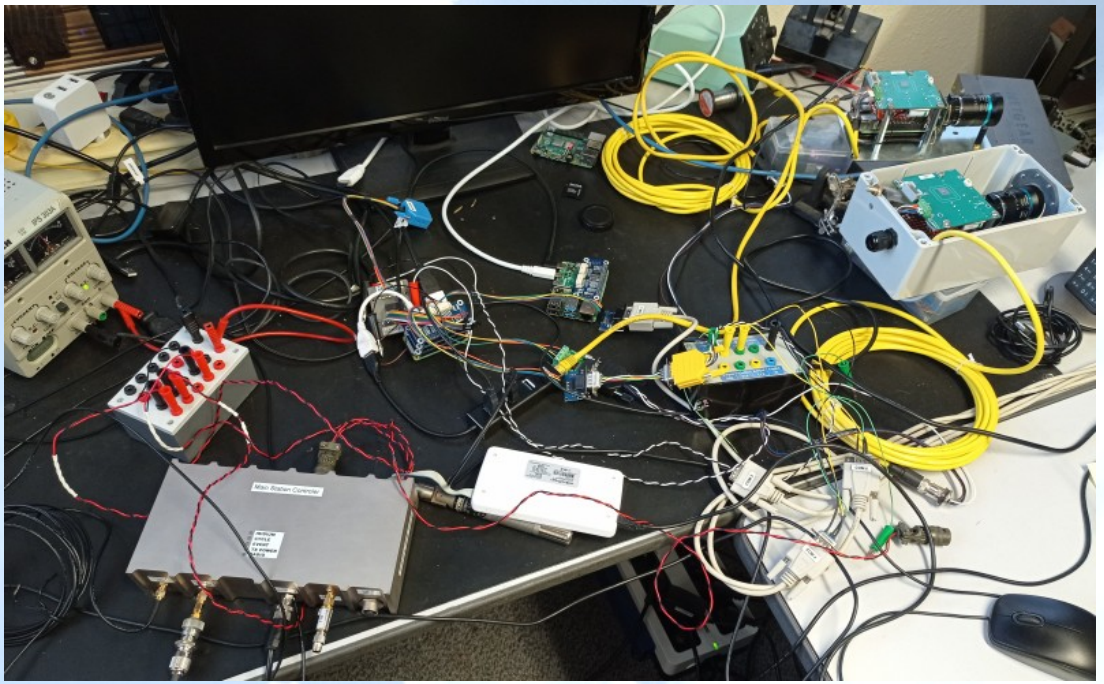
cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

The GLOBE Program

TENUM

Design office





ORIGIN OF THE CALITOO

CALITOO

The origin

Educational activity between Tenum and the CNES



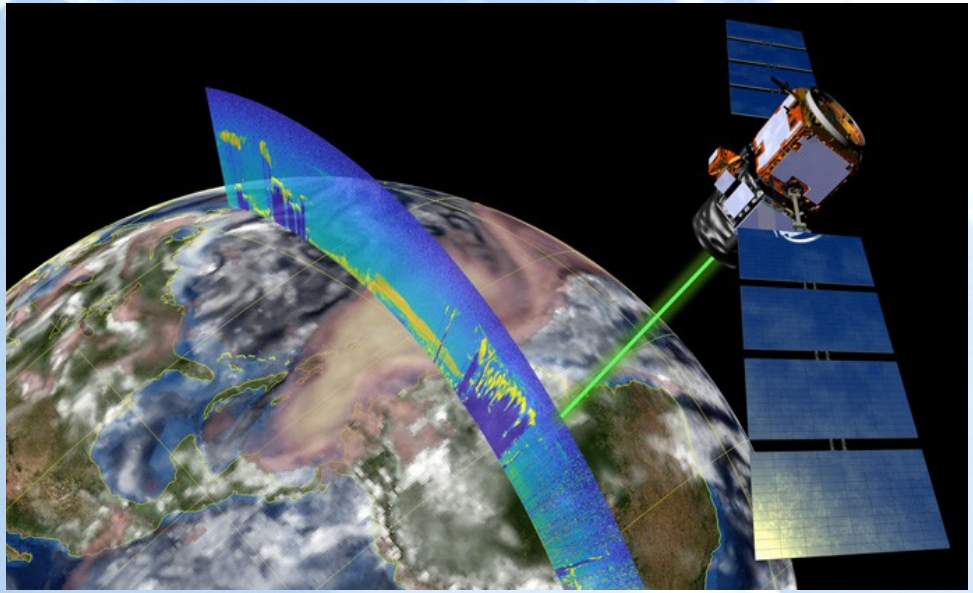




Radio emitter for student projects : Rocket, Balloon, Buoy

CALITOO

The origin





2006

CNES : Calipso and Globe => Educational program to initiate student to measure aerosols

CALITOO

Prototypes





HOW DOES IT WORK ?

CALITOO

Aerosol photometer

Calibration parameter

Measure

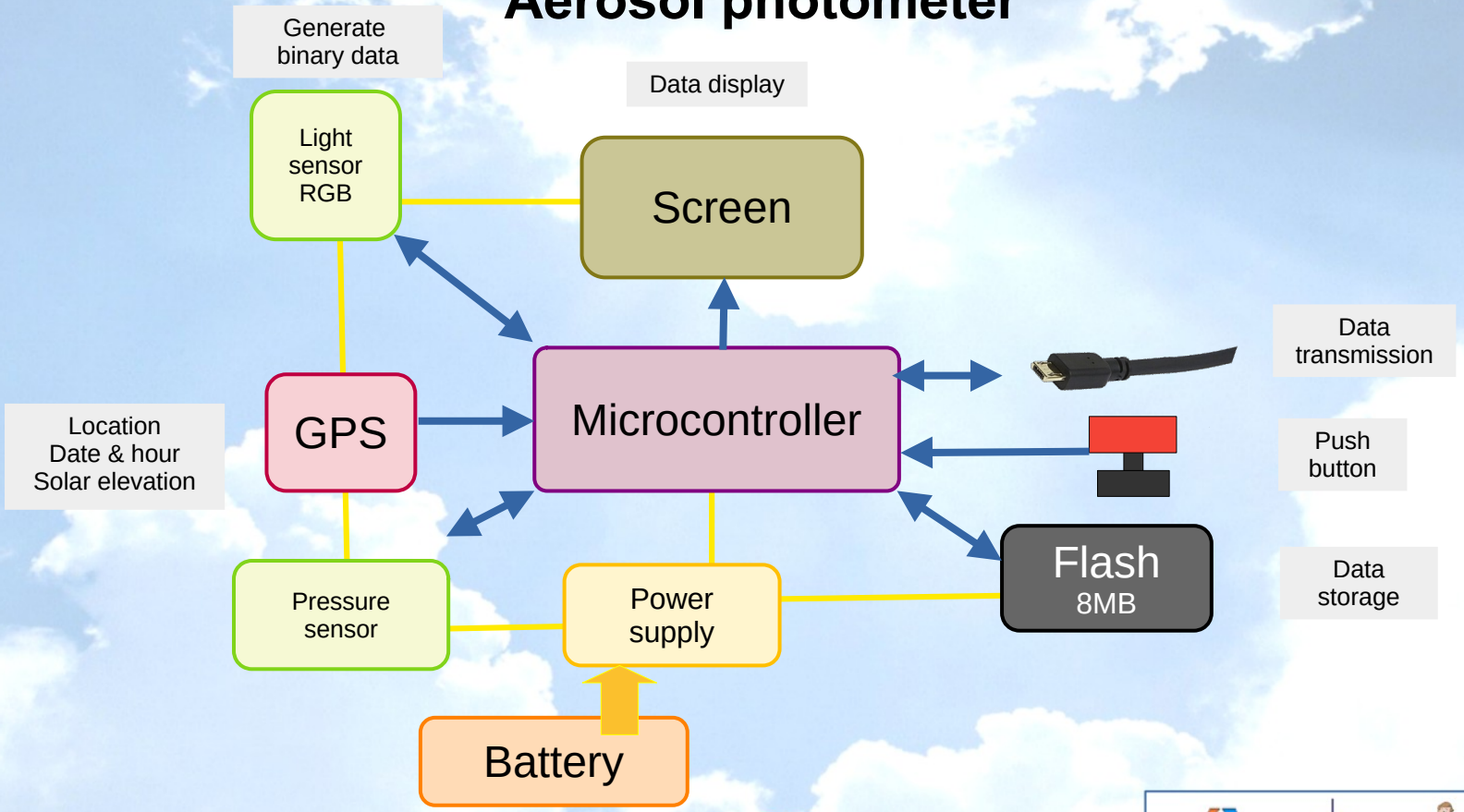
Pressure sensor

$$\tau_a = \frac{\left[\ln\left(N_0 \cdot \left[\frac{r_0}{r}\right]^2\right) - \ln\left(N\right)\right]}{m} - a_R \cdot \frac{p}{p_0} - \tau_{o3}$$

GPS

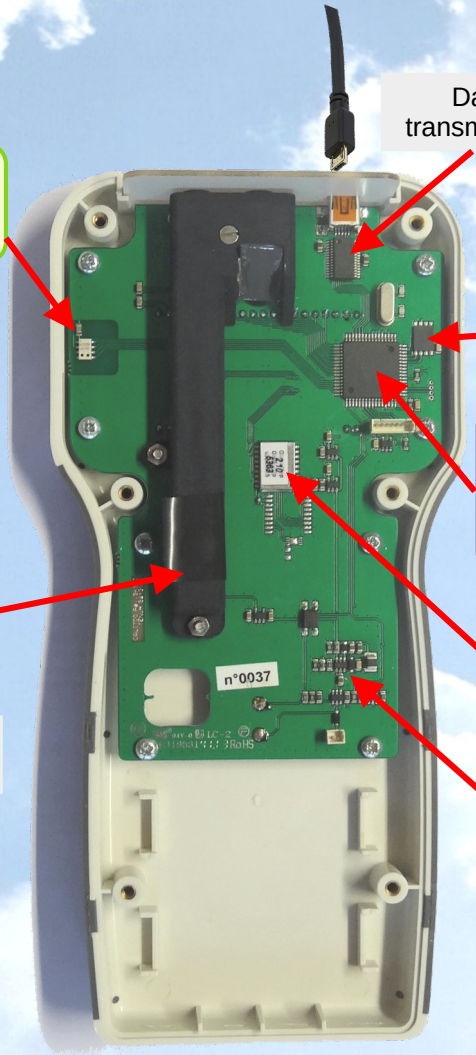
CALITOO

Aerosol photometer



CALITOO

Aerosol photometer



Pressure sensor

Data transmission

Flash 8MB

Data storage

Microcontroller

Light sensor RGB

GPS

Location
Date & hour
Solar elevation

Generate binary data

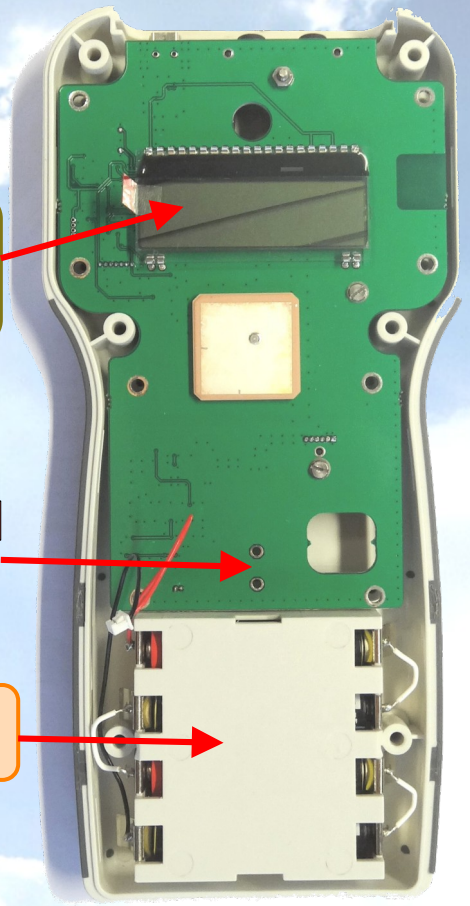
Power supply

Data display

Screen

Push button

Battery



Tenum

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

The GLOBE Program

ADVANTAGES
LIMITATIONS

CALITOO

Aerosol photometer

- Low cost, made with durable components.
- Easy to use with only one button





CALITOO

Aerosol photometer

+ Each device is calibrated at the Aeronet photometer reference site : Izana, in Tenerife

- Calibration campaign need an extensive preparation.



AEMet
Agencia Estatal de Meteorología

ACTRiS
Aerosols, Clouds, and Trace gases
Research InfraStructure Network

Tenum

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

The GLOBE Program

CALITOO

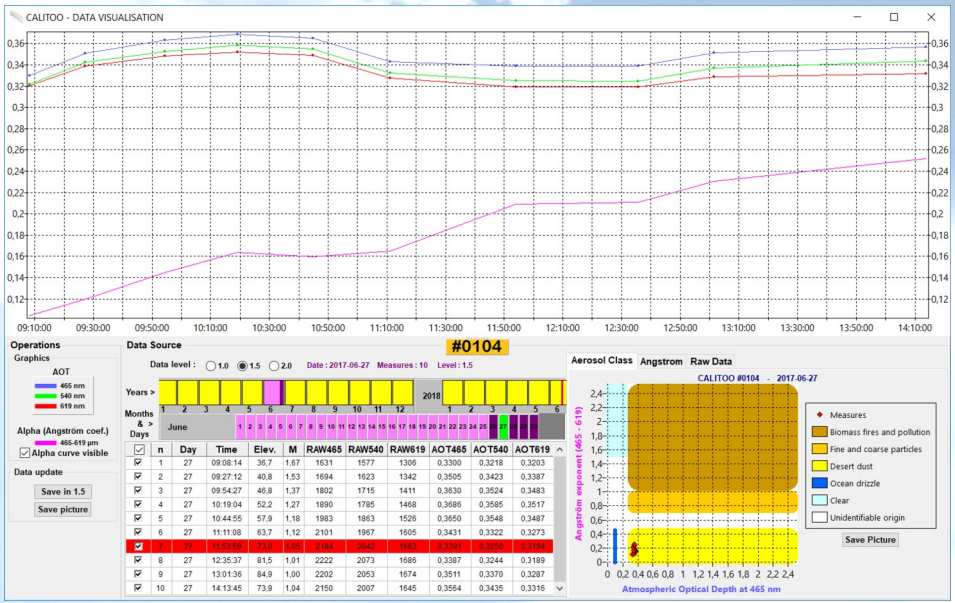
Aerosol photometer

+

Calitoo software for reading, processing, displaying and transmitting AOD data to Calinet data center.

calitoo.fr





+

And finally, the Calitoo is easy to put in your pocket and travel the world :




TRUE HEADING




00:42

CALITOO

Aerosol photometer

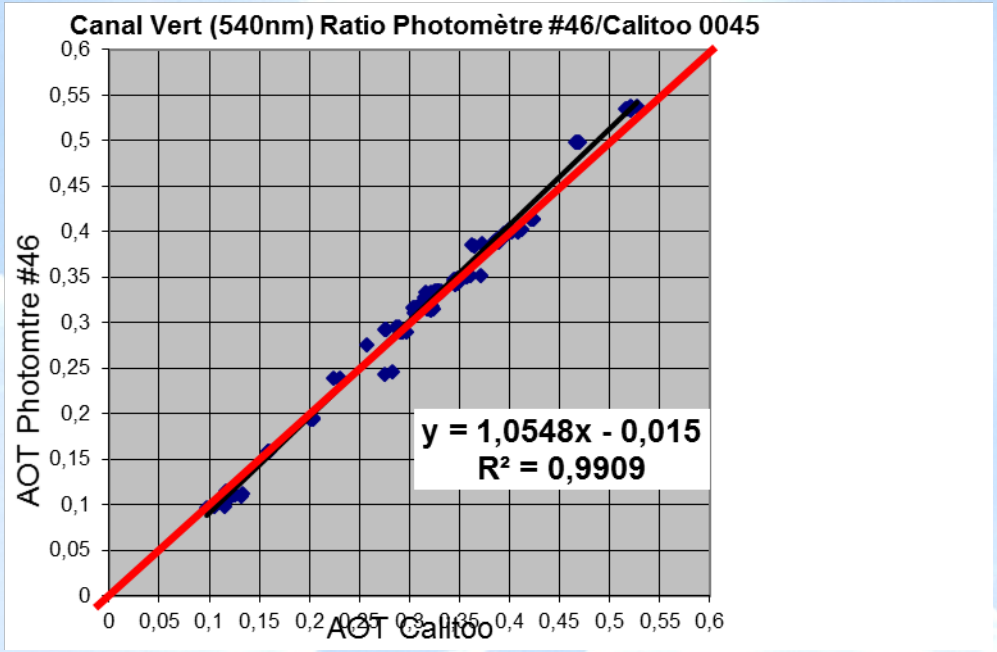
- The device is not automatic which explains why the volume of data generated is very low.



CALITOO

Aerosol photometer

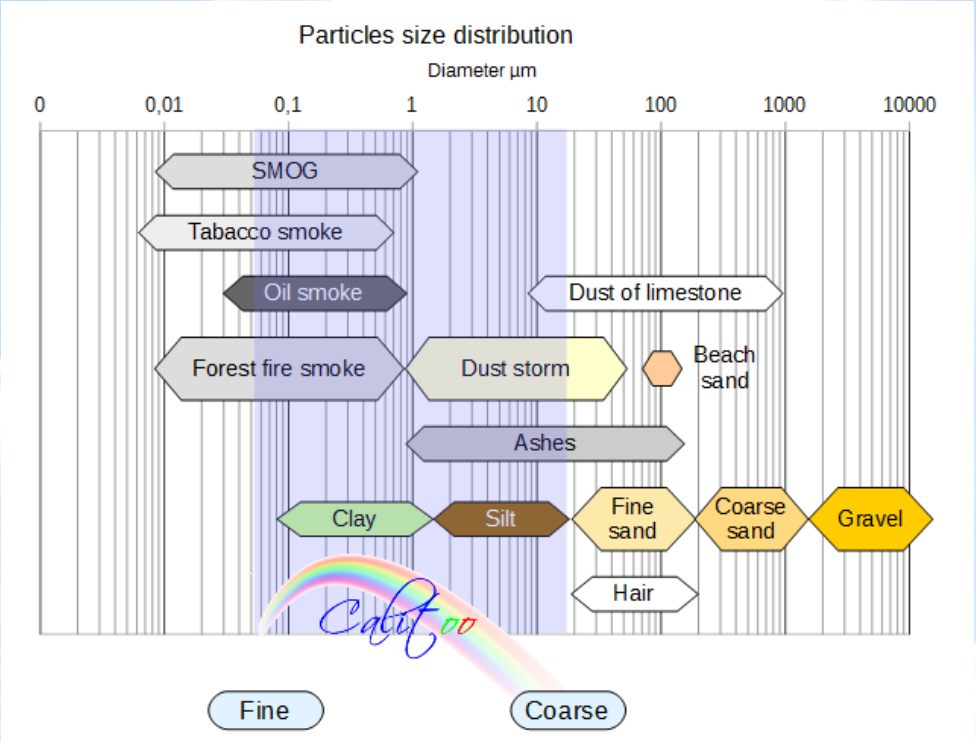
- Lack of precision in light AOD (<0,1) and high AOD (>0,5)



CALITOO

Aerosol photometer

- Only 3 wavelengths : Lack of precision in particle detection field



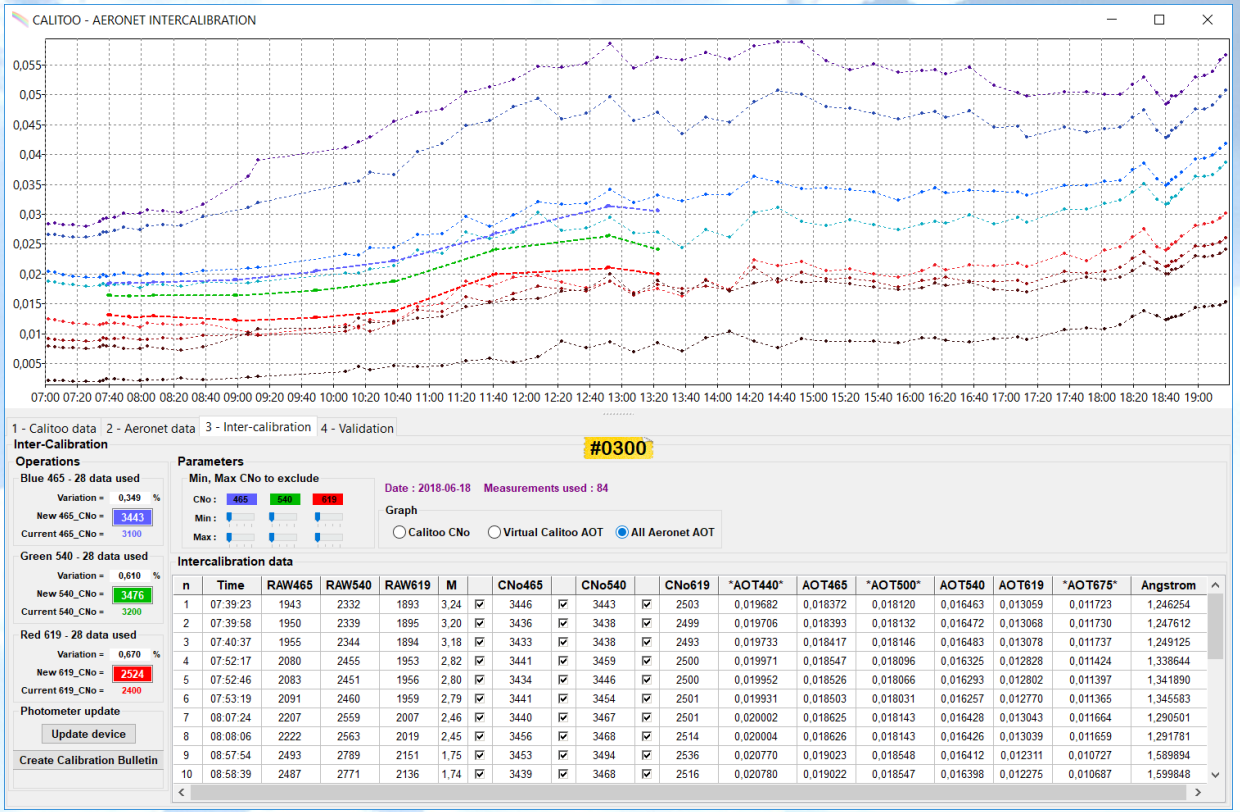
CALIBRATION METHODS

CALITOO

Aerosol photometer

Intercalibration with aeronet (Cimel) data.

We use Aeronet data to create three virtual curves with the same wavelength as calitoo.

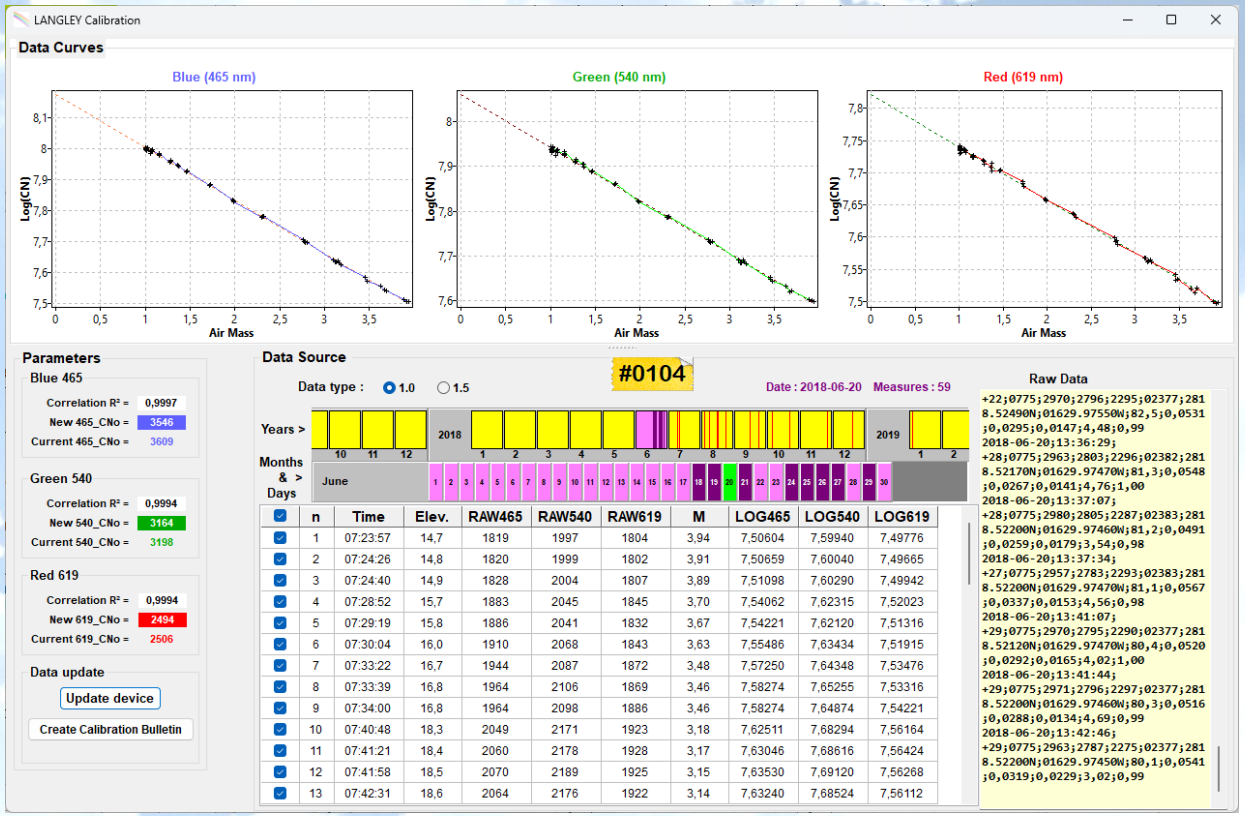


n	Time	RAW465	RAW540	RAW619	M		CNo465		CNo540		CNo619	"AOT440"	AOT465	"AOT500"	AOT540	AOT619	"AOT675"	Angstrom
1	07:39:23	1943	2332	1893	3,24	☑	3446	☑	3443	☑	2503	0,019682	0,018372	0,018120	0,016463	0,013059	0,011723	1,246254
2	07:39:58	1950	2339	1895	3,20	☑	3436	☑	3438	☑	2499	0,019706	0,018393	0,018132	0,016472	0,013068	0,011730	1,247612
3	07:40:37	1955	2344	1894	3,18	☑	3433	☑	3438	☑	2493	0,019733	0,018417	0,018146	0,016483	0,013078	0,011737	1,249125
4	07:52:17	2080	2455	1953	2,82	☑	3441	☑	3459	☑	2500	0,019971	0,018547	0,018096	0,016325	0,012828	0,011424	1,338644
5	07:52:46	2083	2451	1956	2,80	☑	3434	☑	3446	☑	2500	0,019952	0,018526	0,018066	0,016293	0,012802	0,011397	1,341890
6	07:53:19	2091	2460	1959	2,79	☑	3441	☑	3454	☑	2501	0,019931	0,018503	0,018031	0,016257	0,012770	0,011365	1,345583
7	08:07:24	2207	2559	2007	2,46	☑	3440	☑	3467	☑	2501	0,020002	0,018625	0,018143	0,016428	0,013043	0,011664	1,290501
8	08:08:06	2222	2563	2019	2,45	☑	3456	☑	3468	☑	2514	0,020004	0,018626	0,018143	0,016426	0,013039	0,011659	1,291781
9	08:57:54	2493	2789	2151	1,75	☑	3453	☑	3494	☑	2536	0,020770	0,019023	0,018548	0,016412	0,012311	0,010727	1,589894
10	08:58:39	2487	2771	2136	1,74	☑	3439	☑	3468	☑	2516	0,020780	0,019022	0,018547	0,016398	0,012275	0,010687	1,599848

CALITOO

Aerosol photometer

Langley : a method without reference device



n	Time	Elev.	RAW465	RAW540	RAW619	M	LOG465	LOG540	LOG619
1	07:23:57	14,7	1819	1997	1804	3,94	7,50604	7,59940	7,49776
2	07:24:26	14,8	1820	1999	1802	3,91	7,50659	7,60040	7,49665
3	07:24:40	14,9	1828	2004	1807	3,89	7,51098	7,60290	7,49942
4	07:28:52	15,7	1883	2045	1845	3,70	7,54062	7,62315	7,52023
5	07:29:19	15,8	1886	2041	1832	3,67	7,54221	7,62120	7,51316
6	07:30:04	16,0	1910	2068	1843	3,63	7,55486	7,63434	7,51915
7	07:33:22	16,7	1944	2087	1872	3,48	7,57250	7,64348	7,53476
8	07:33:39	16,8	1964	2106	1869	3,46	7,58274	7,65255	7,53316
9	07:34:00	16,8	1964	2098	1886	3,46	7,58274	7,64874	7,54221
10	07:40:48	18,3	2049	2171	1923	3,18	7,62511	7,68294	7,56164
11	07:41:21	18,4	2060	2178	1928	3,17	7,63046	7,68616	7,56424
12	07:41:58	18,5	2070	2189	1925	3,15	7,63530	7,69120	7,56268
13	07:42:31	18,6	2064	2176	1922	3,14	7,63240	7,68524	7,56112


THANK YOU !

CALITOO

Aerosol photometer



- CIMEL & Calitoo
- Calitoo at school
- Exploration of possible uses
- Calinet

Tenum

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

The GLOBE Program

CIMEL
&
CALITOO

CALITOO

Aerosol photometer

The CIMEL photometer is the big brother of the Calitoo.

CIMEL photometers has been used by LOA to evaluate our photometer in 2013.



CALITOO

Aerosol photometer

Since 2014, CIMEL photometers and Aeronet network are used to calibrate Calitoo devices.



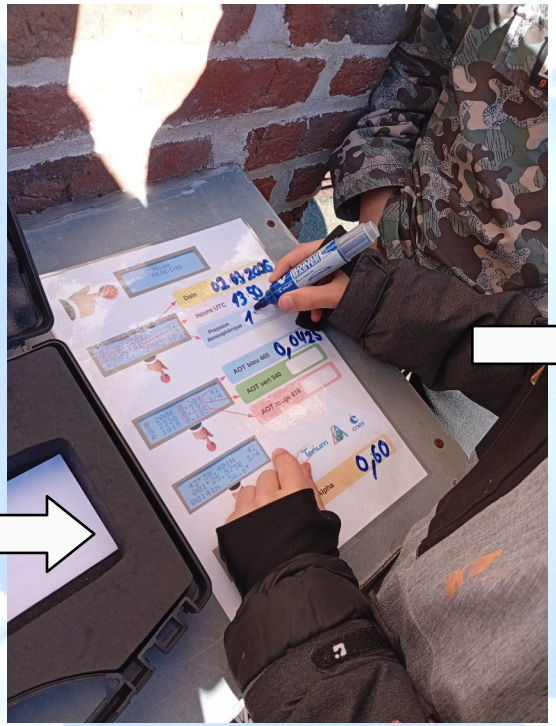
CALITOO AT SCHOOL

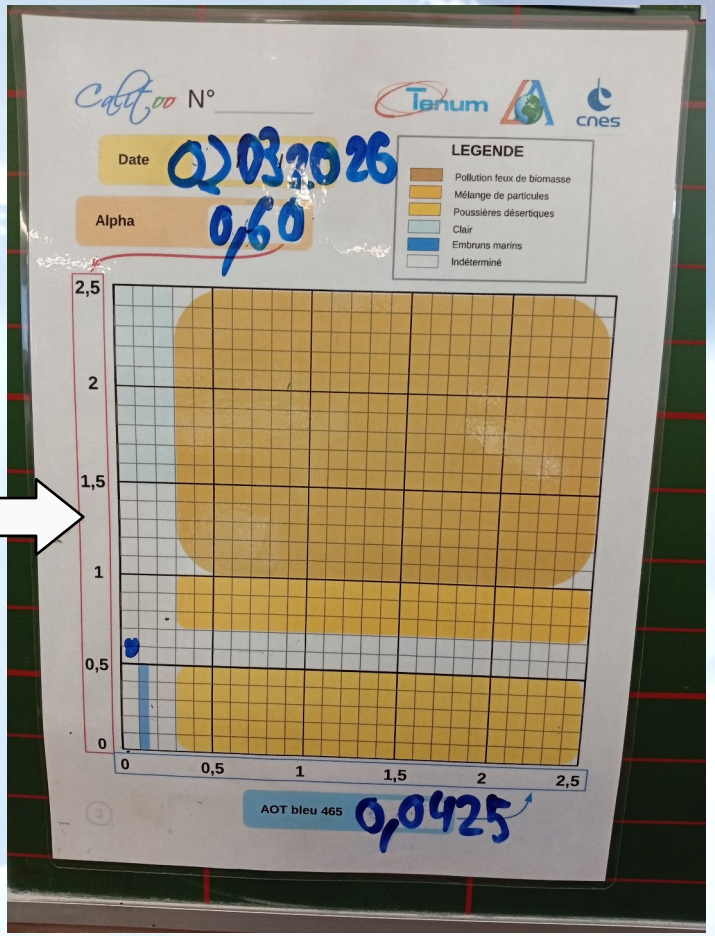
CALITOO

Aerosol photometer

Sainte-Marie-Cappel school.
10-11 years old students.
The teacher's objectives are :
- read decimal numbers
- read invisible sky parameters
- complete, read and explain a graph
- talk about environment problems







CALITOO

Aerosol photometer

Older students (15 18 ya) use the Calitoo and the PC software to study aerosols.



CALITOO

Aerosol photometer

IESO(*) 2017
Valbonne University
(near Cannes)

(*) International Earth Science Olympiad

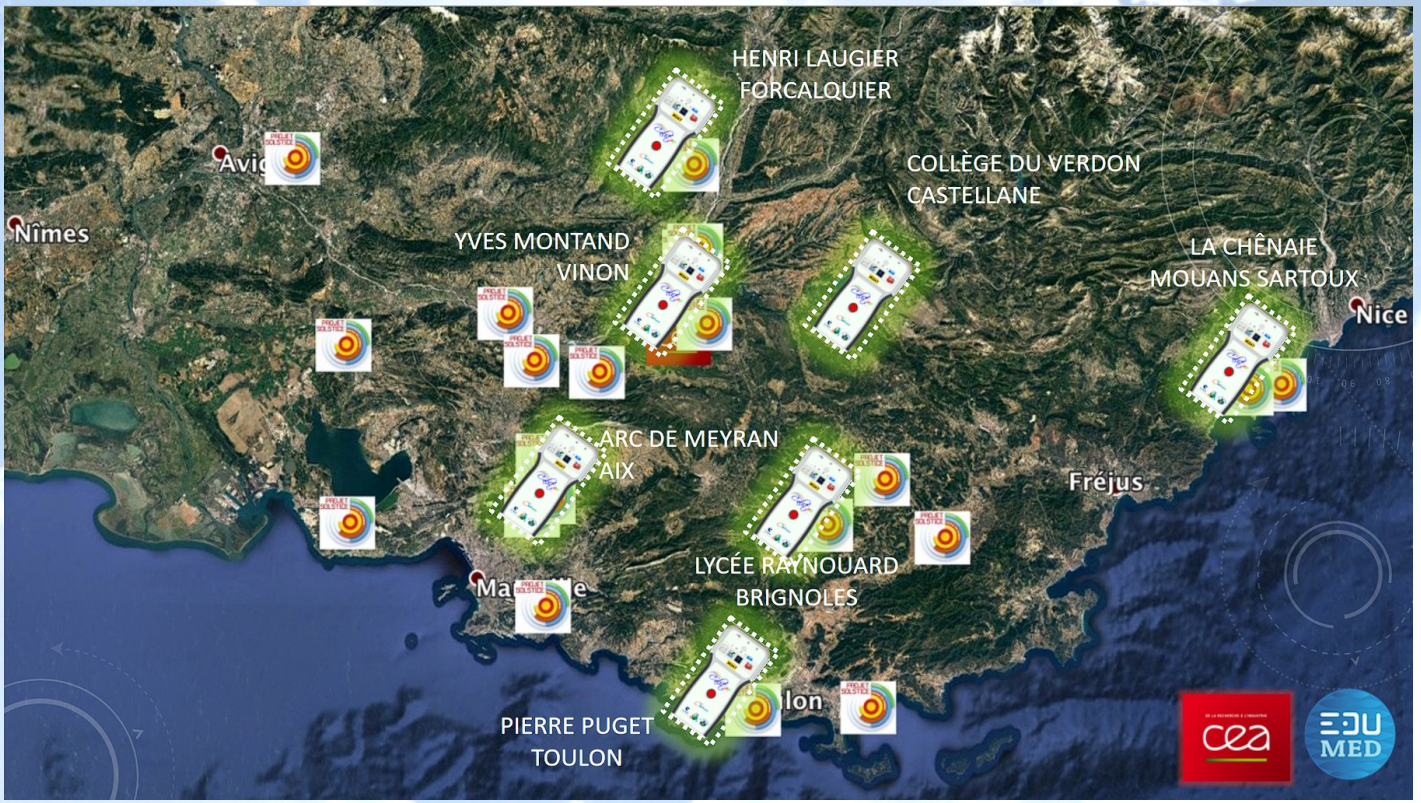


CALITOO

Aerosol photometer

EDUMED 2021

A group of schools, use several Calitoo and share data together.

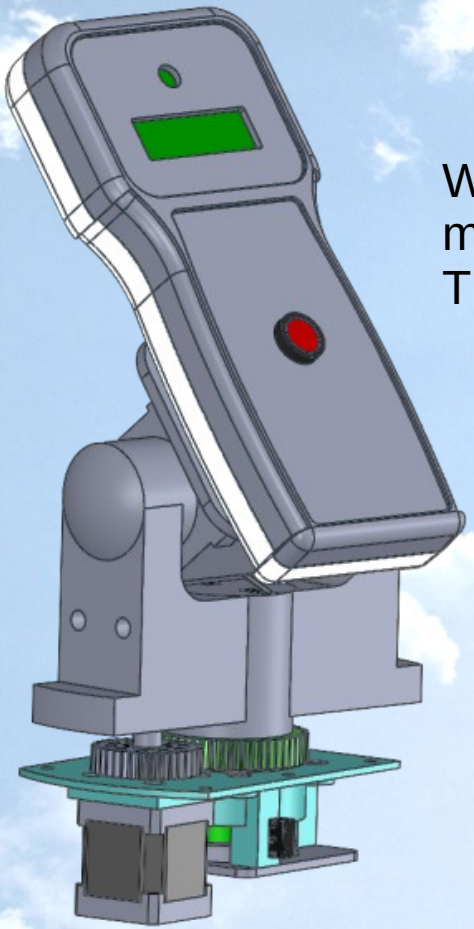


EXPLORATION OF POSSIBLE USES

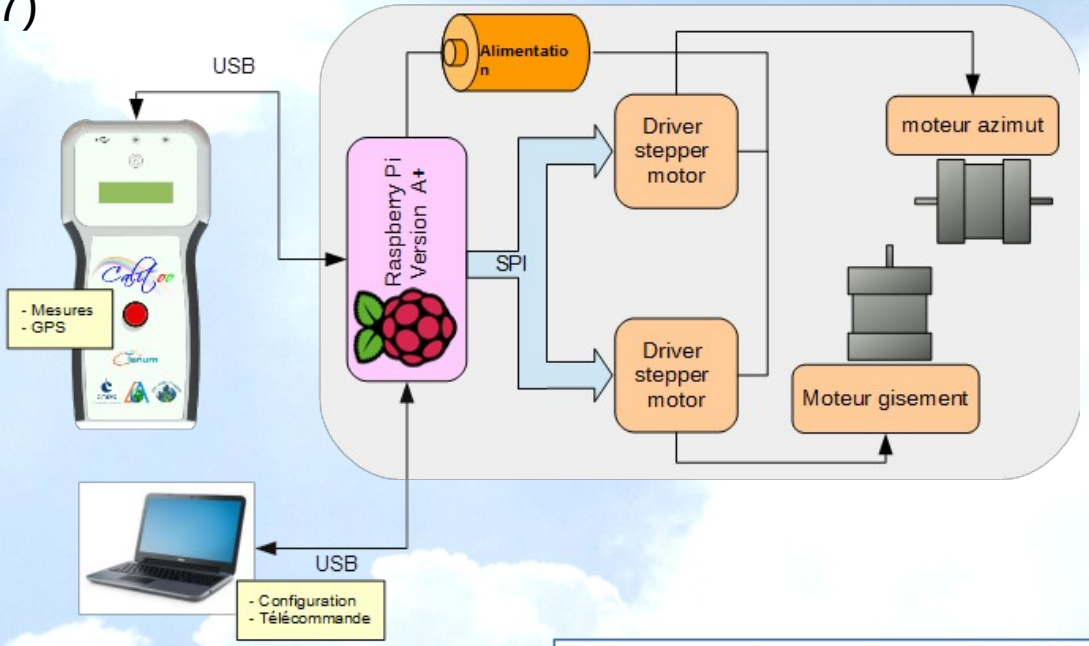
CALITOOBOT

Aerosol photometer





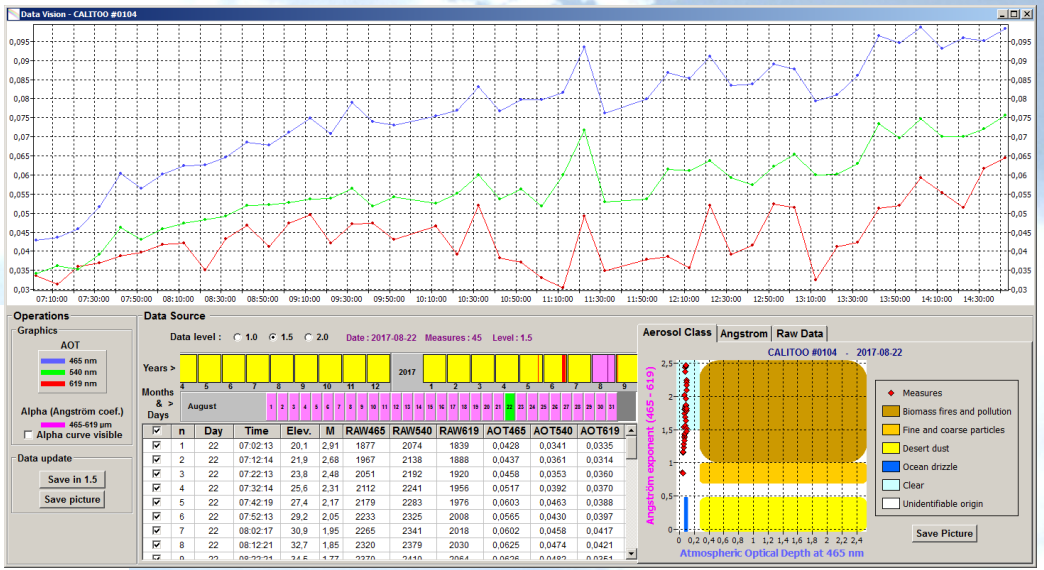
We have worked with a trainee to test an automatic methode of measurement :
The CALIBOT (2017)

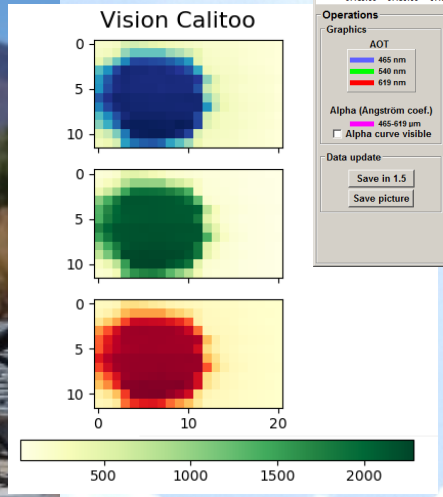


CALITOOBOT

Aerosol photometer







CALITOOMIR

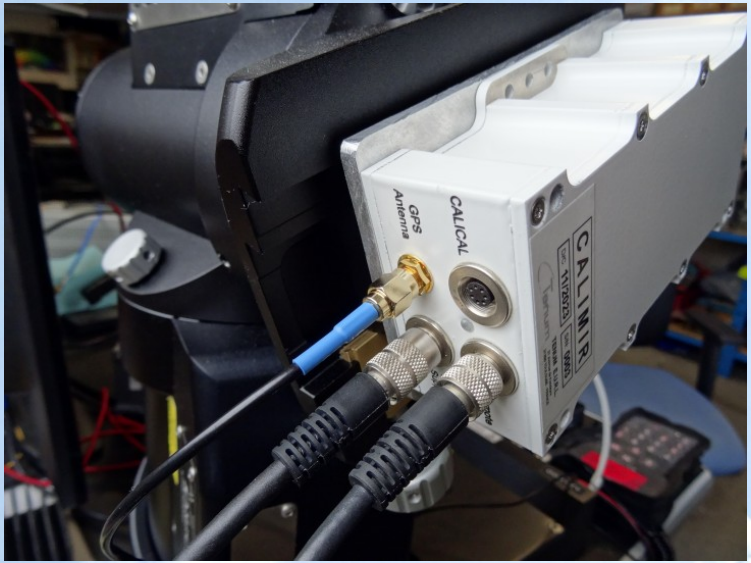
Aerosol photometer

In 2022, a startup named MIRATLAS has contacted us to design a waterproof Calitoo to measure automaticaly Aerosols every sunny days all the year.



CALITOOMIR

Aerosol photometer







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The GLOBE Program

CALINET



CALINET

Calitoo network



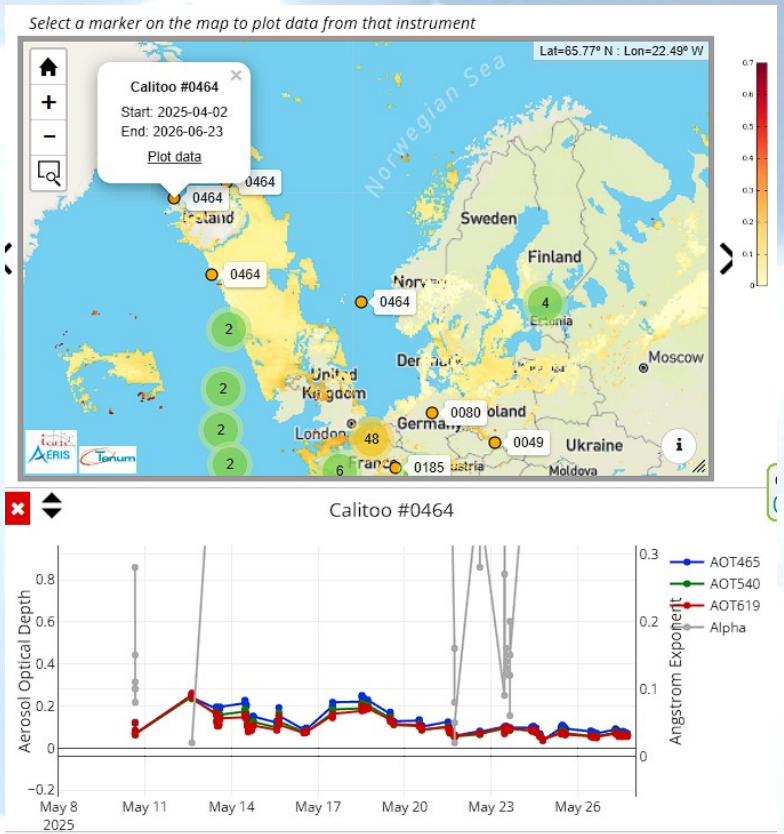
After AOD measurements taken by the Calitoo, you have to download data in you PC with the Calitoo PC software.

Then, you can send data to the Icare Aeris data center by an Internet link.

CALINET

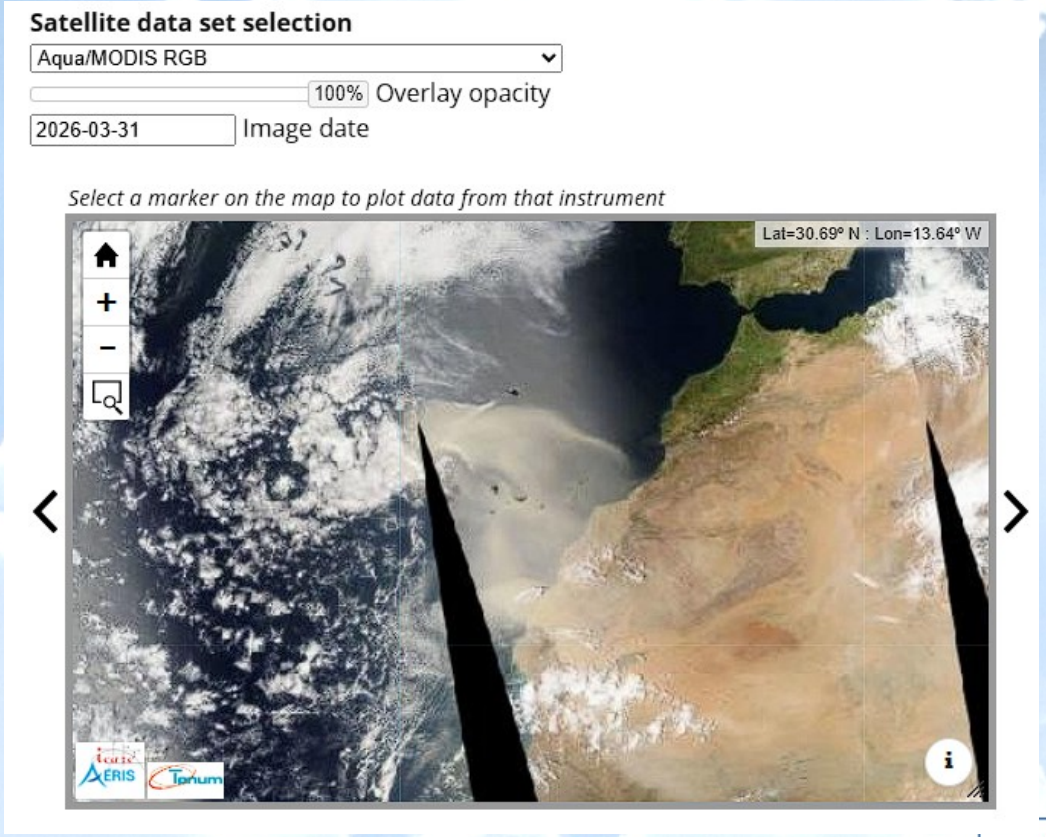
Calitoo network





CALINET

Calitoo network



THANK YOU !



HARMONIA

International network for harmonization of atmospheric aerosol retrievals from ground based photometers

Real-Time Aerosol Detection by Interferometric System: Development of a Prototype Device

Gülhan USTABAŞ KAYA

Zonguldak Bülent Ecevit University, Türkiye

Industry engagement towards innovative hardware & software products

2nd WG4 Meeting

30 June 2026

RESEARCH MOTIVATION

- To develop **a portable optical sensing system** capable of **real-time detection** and concentration measurement of atmospheric aerosols under outdoor conditions.
- To investigate the effects of environmental factors on system performance and **AOD analysis**.
- To establish a cost-effective and versatile **alternative to conventional photometric aerosol monitoring systems** through real-time ground-level aerosol detection and measurement.

MULTIDISCIPLINARY COLLABORATION



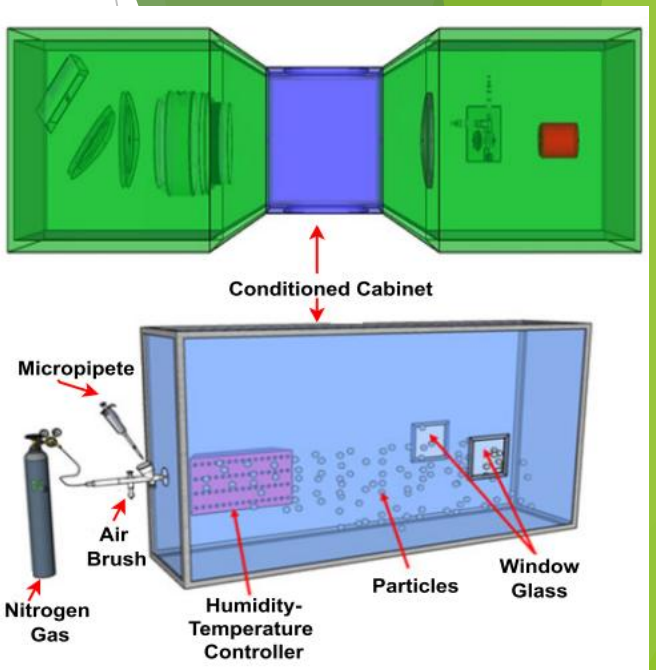
Prof. Dr. Şenol Hakan KUTOĞLU, Map (Geomatics) Engineering
Prof. Dr. Seda TIĞLI AYDIN, Biomedical Engineering
Prof. Dr. Hakan KAYA, Electrical and Electronics Engineering
Assoc. Prof. Dr. İshak Özel TEKİN, School of Medicine, Immunology
Assoc. Prof. Dr. Gülhan USTABAŞ KAYA, Electrical and Electronics Engineering
Asst. Prof. Dr. Sefa KOCABAŞ, Environmental Engineerimg

Res. Asst. Duygu DEMİRCAN , Electrical and Electronics Engineering
Fatemeh GHASEMPOUR , Map (Geomatics) Engineering

PROPOSED METHODOLOGY (LATERAL SHEARING DIGITAL HOLOGRAPHIC MICROSCOPY (LS-DHM) SYSTEM

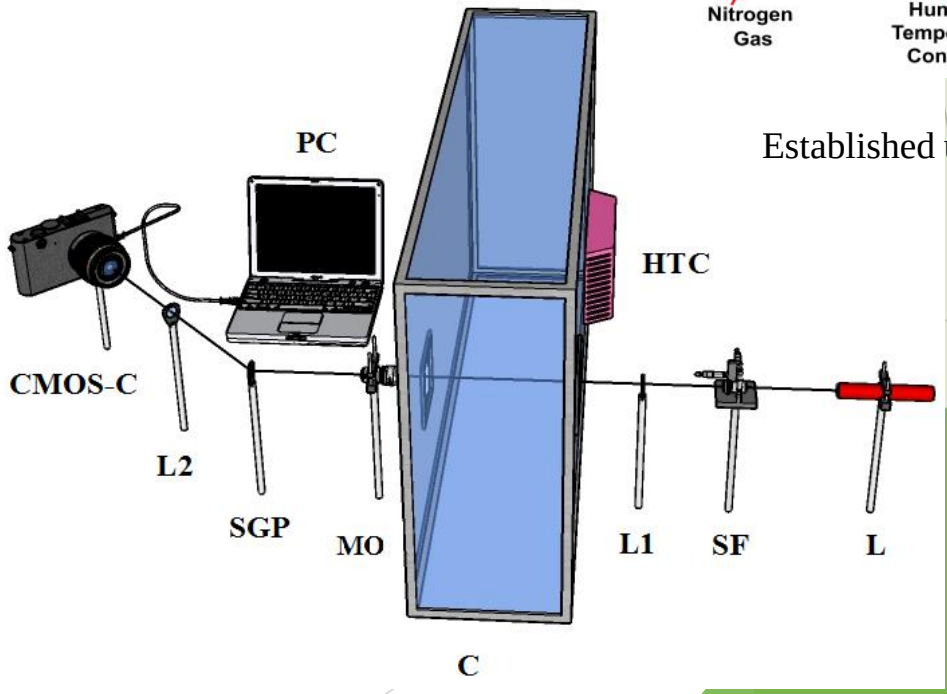






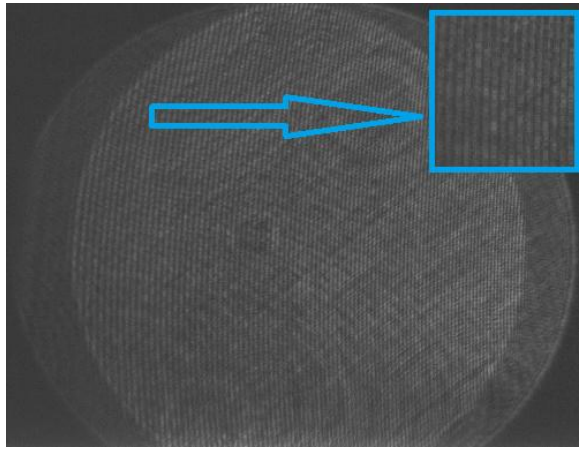
Established under controlled laboratory conditions

Ustabas Kaya, G , Kocabas S , Kartal S, Kaya H , Tekin IÖ, Aydın RST , Kutoglu SH. 2022. Detection of airborne nanoparticles with lateral shearing digital holographic microscopy. *Optics and Lasers In Engineering.* Volume 151,106934

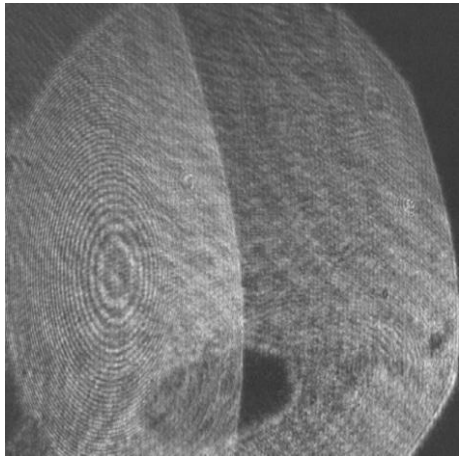


Kocabas S, Ustabas Kaya G, Tekin IÖ, Kaya H, Kutoglu SH, Aydın RST. 2025. A novel intelligent optical system for detection of nano particles: Imaging virüs mimicking samples in the air. *IEEE ACCESS.* Volume 13.

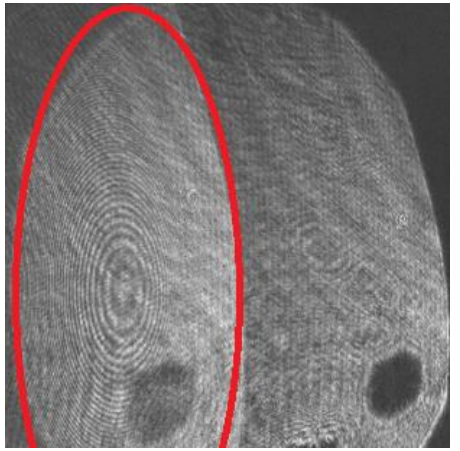
ELIMINATION OF THE DUPLICATE (TWIN IMAGE) IMAGE PROBLEM



The captured hologram obtained with LS-DHM system



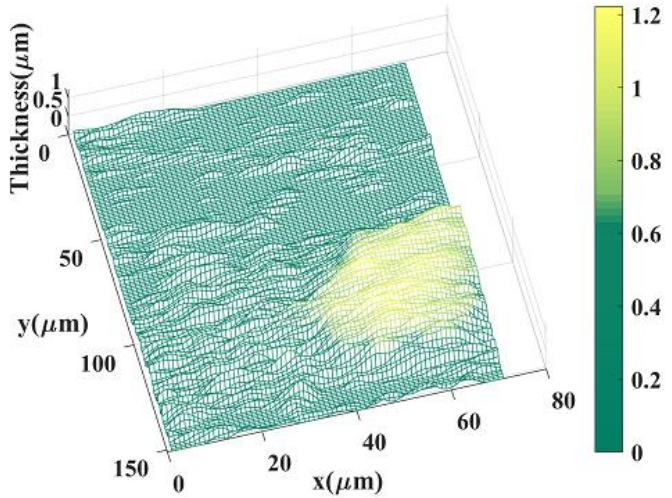
Hologram affected by the overlapping (twin-image) problem



Hologram after elimination of the overlapping (twin-image) problem

By adjusting the angle of L2 and SGP, the target object is shifted away from the optical axis, enabling formation of effecrive interference area

Improve modulation depth and supress high-frequency speckle noise.

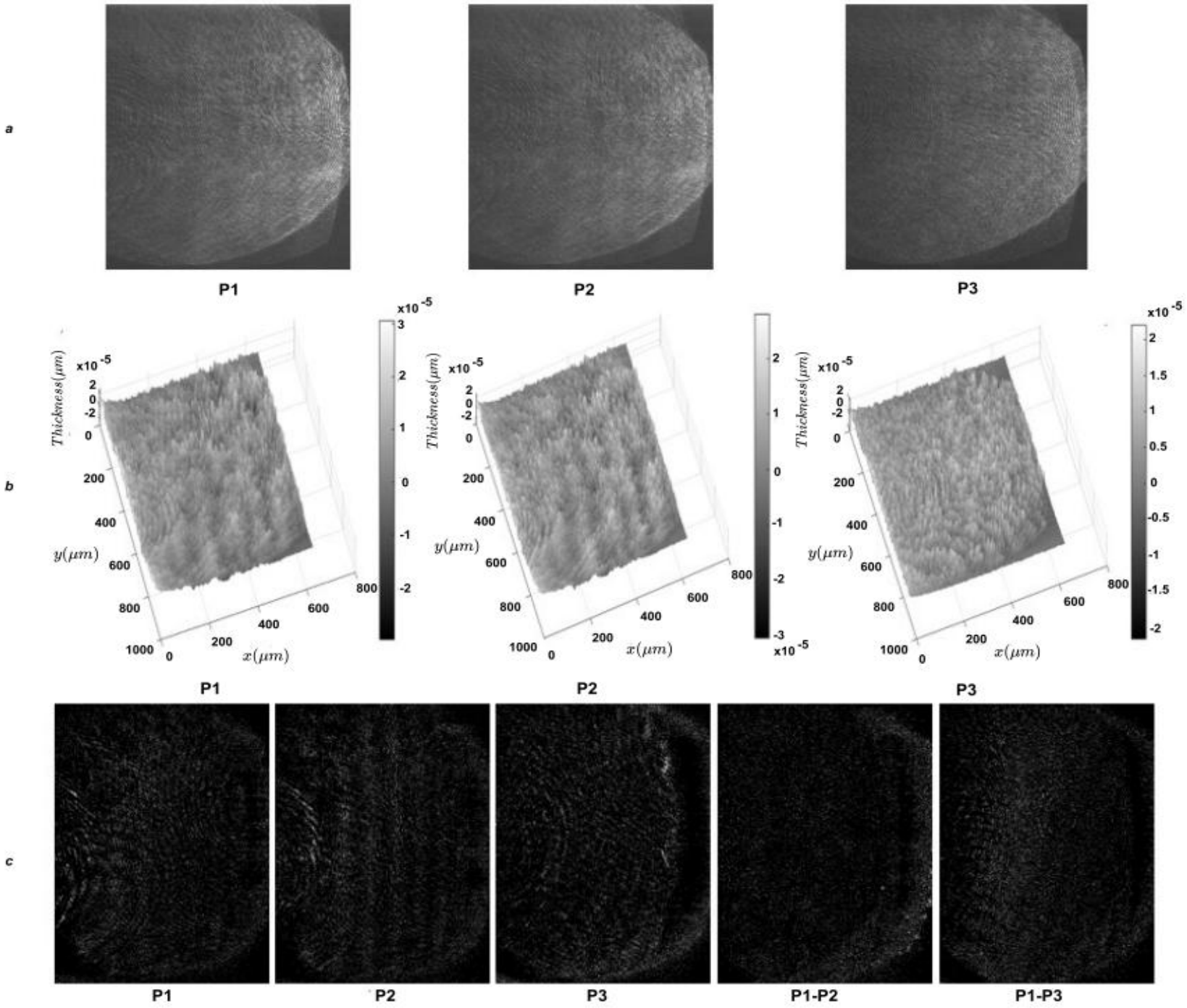


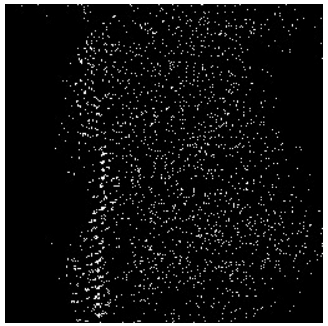
Reconstructed 3D phase image obtained from the hologram

Captured holograms for different sample
3D phase image
Binarized phase image

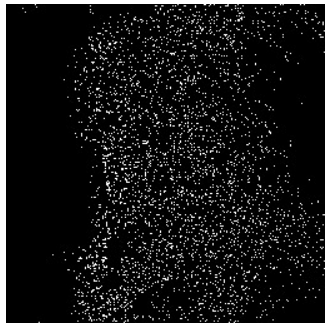
After optical alignment optimization, particle holograms are recorded and numerically reconstructed to obtain unwrapped phase maps.

The 2D phase images are then converted into grayscale and transformed into binary images for particle detection and analysis.

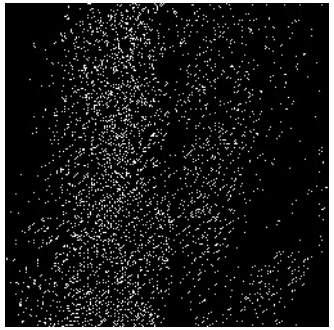




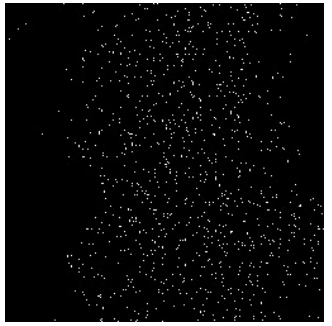
(a)



(b)

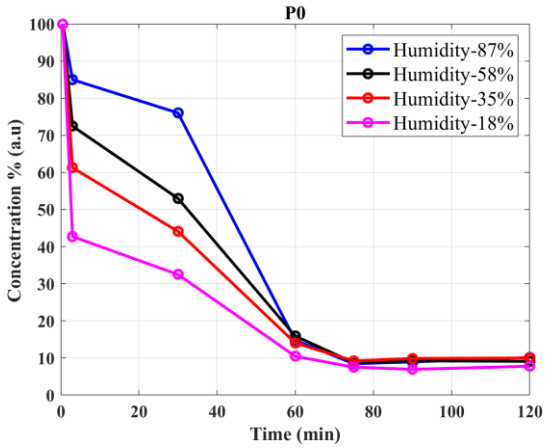


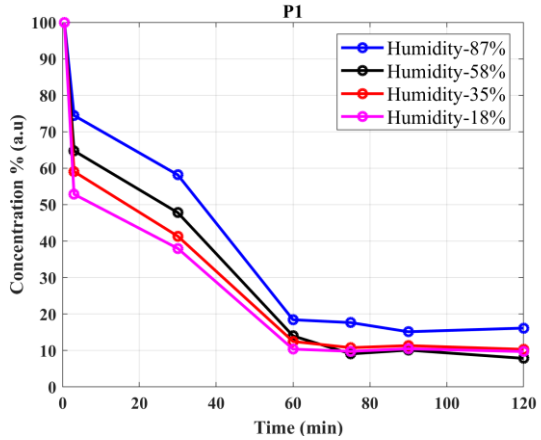
(c)

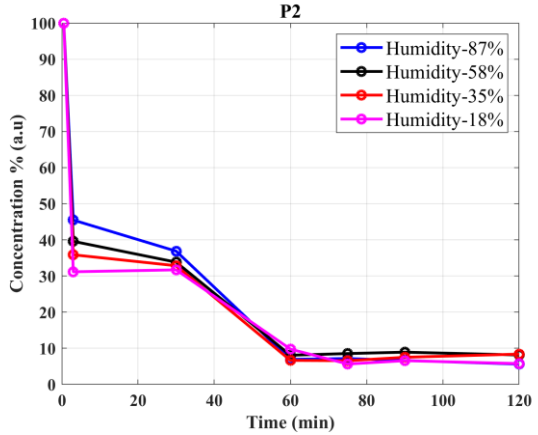


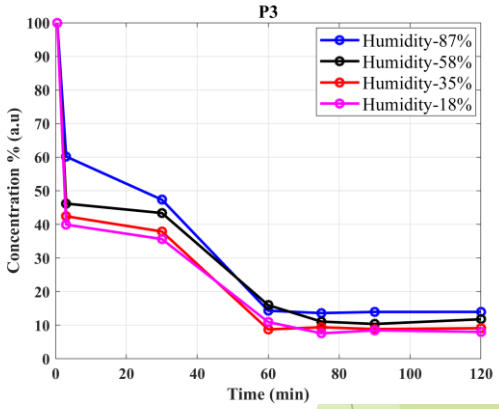
(d)

The white spots in the binarized images correspond to aerosol particles, and their quantity is used as an indicator of aerosol concentration.

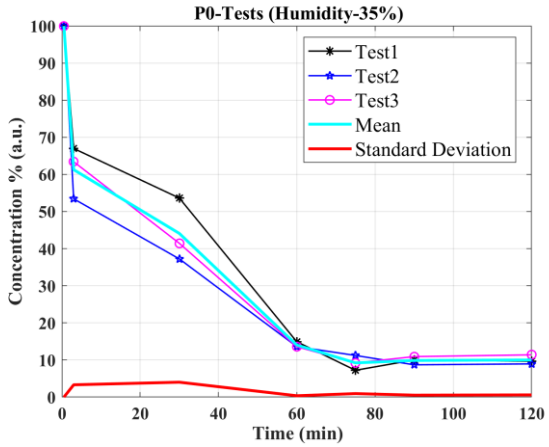


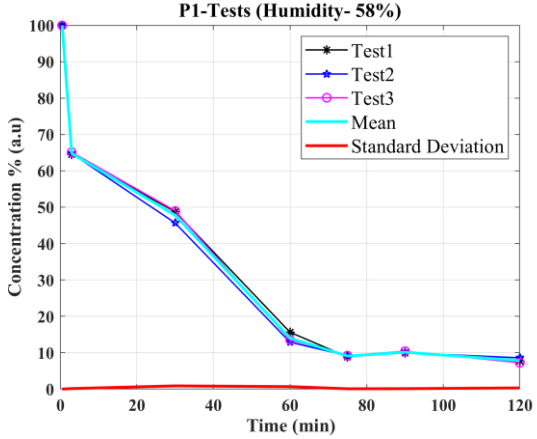


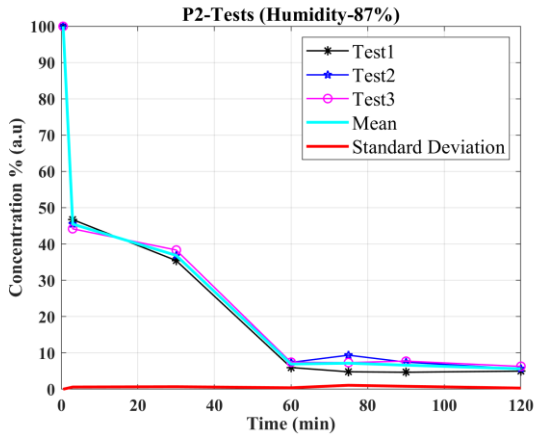


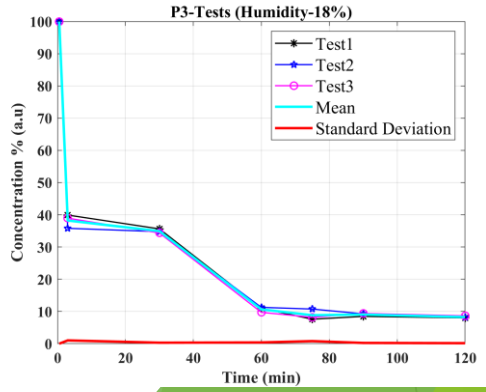


Concentration graphs against time, monitored continuously over time



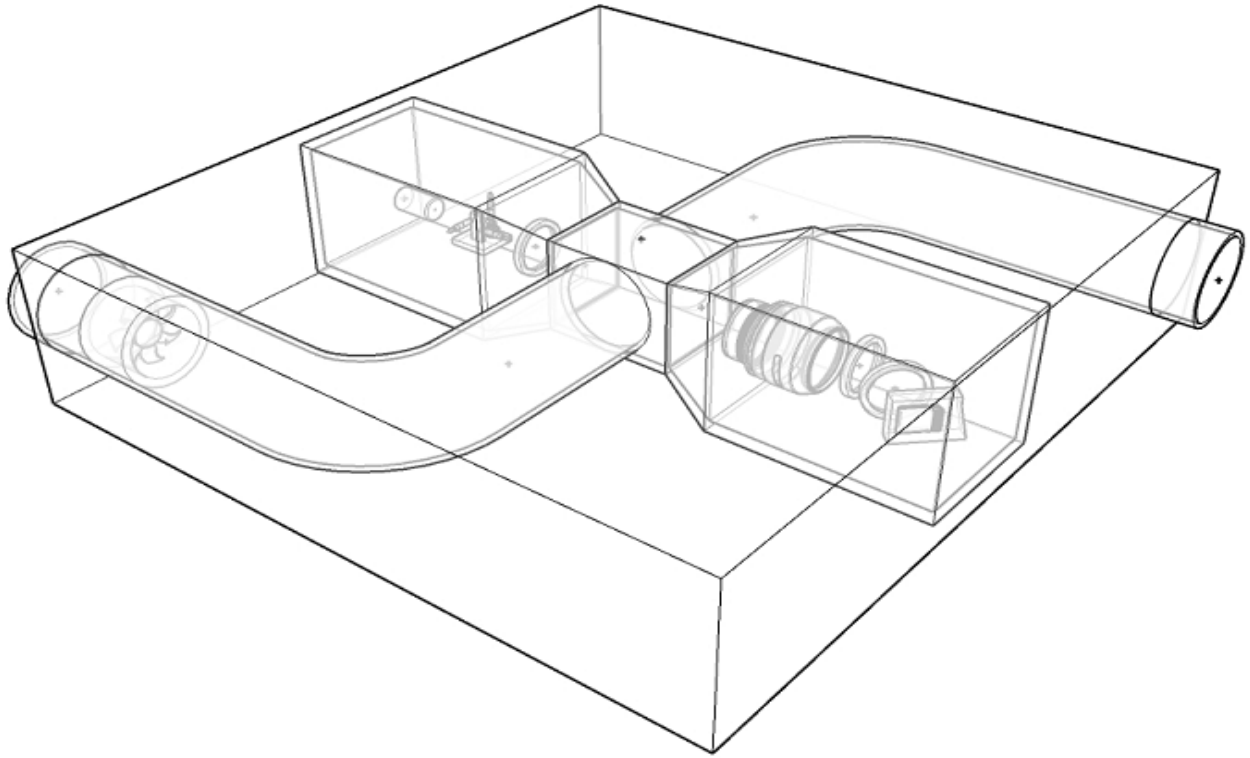


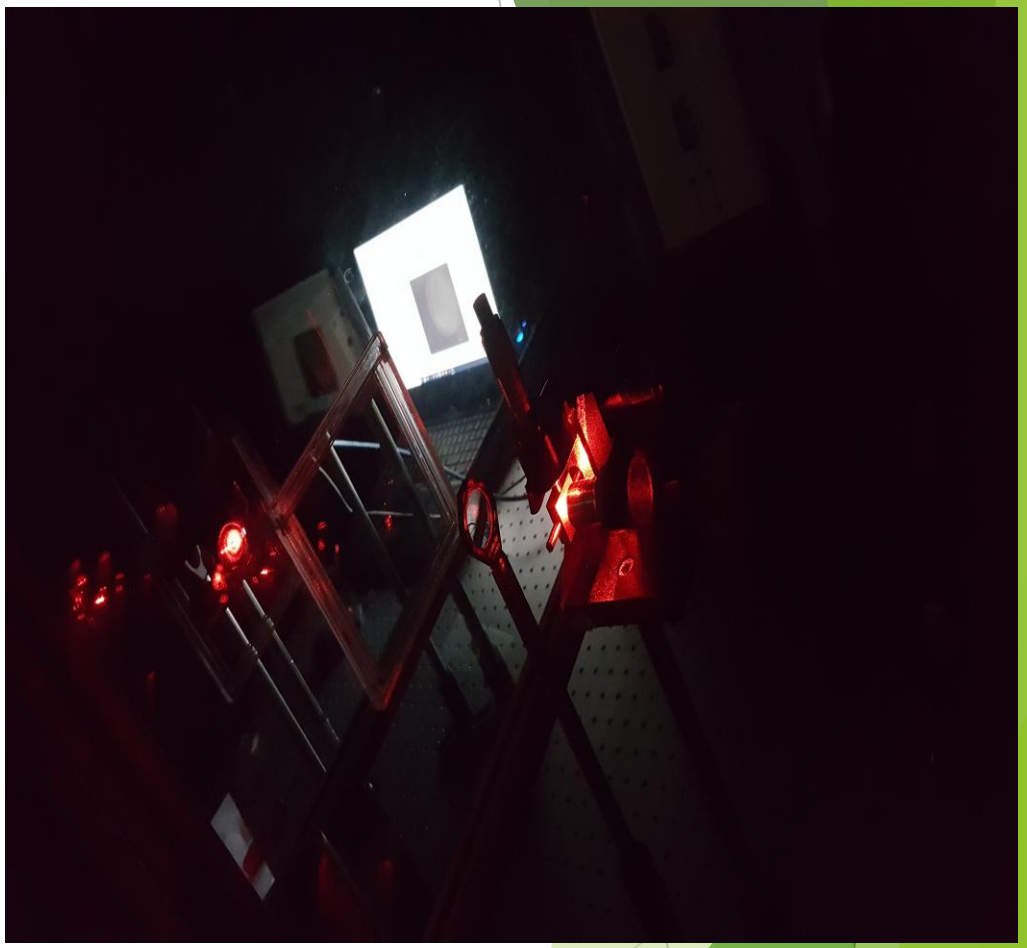




Measured during the first 20s was defined as 100%, then normailzed relative to this reference.

REDESIGNED PROTOTYPE FOR IN-SITU ATMOSPHERIC AEROSOL MEASUREMENT



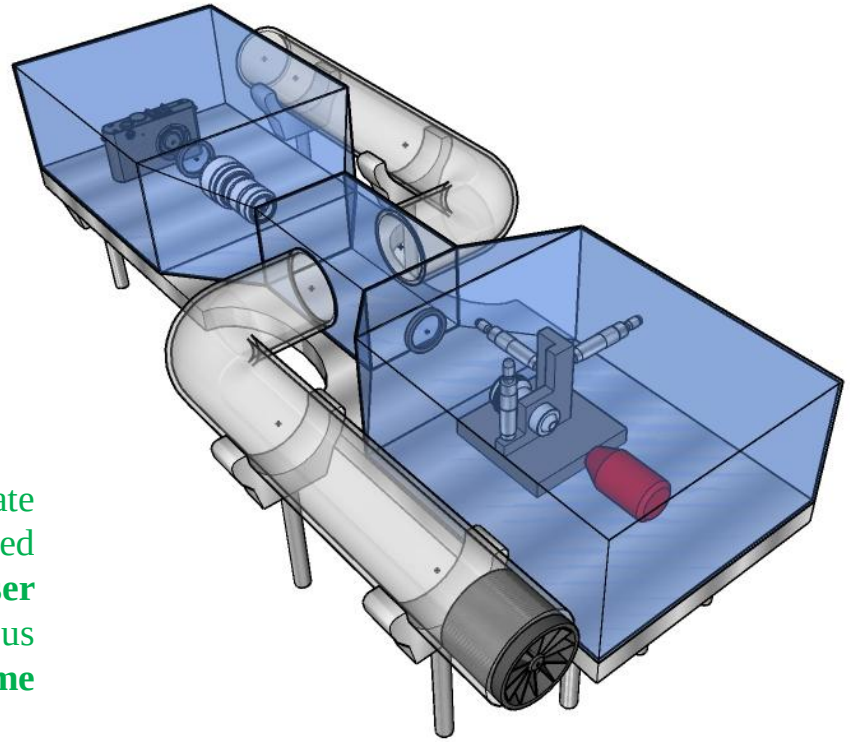


- Patent No: TR 2022 009873 B, YANAL KESME SAYISAL HOLOGRAFİK MİKROSKOPİ TABANLI NANO PARTİKÜL ALGILAMA SİSTEMİ, Türk Patent ve Marka Kurumu

- 2515-COST Program (European Cooperation in Science and Technology), 125E938, Ortam Havasındaki Aerosollerin Interferometrik Yöntemle Gerçek Zamanlı Saptanması için Prototip Cihaz Gelistirilmesi, The Scientific and Technological Research Council of Türkiye (TÜBİTAK)- FINANCIAL SUPPORT

Aerosol samples will be transported to the central sensing volume through an **S-shaped** air-sampling channel designed to prevent interference from external light sources.

The central measurement chamber and airflow system will be mechanically isolated from the optical components to minimize vibration-induced measurement errors.



The sensing chamber will operate as a **dark enclosure** with dedicated optical windows for **laser transmission**, enabling continuous measurements under both **daytime and nighttime** conditions.

For outdoor aerosol monitoring, a **fan-assisted sampling** system will be used to draw ambient aerosols into the central channel at controlled and adjustable flow rates.

A pen-type flow meter will be used to perform measurements at different suction rates and determine the optimal airflow that provides the highest correlation with satellite-derived data.

AEROSOL GENERATION / OUTDOOR SAMPLING PROCEDURE

Aerosol measurements acquired at different sampling flow rates will be compared with satellite-derived aerosol data to determine the optimum operating conditions.

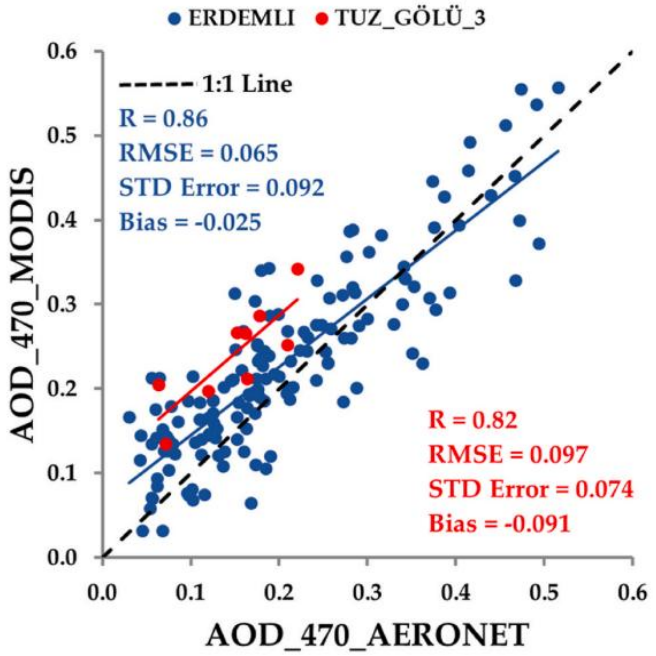
The effects of environmental parameters, including wind speed, ambient temperature, relative humidity, and atmospheric pressure, will be investigated through correlation analyses using meteorological data.

The obtained correlation results will be used for prototype calibration, ensuring accurate and reliable outdoor aerosol measurements.

The calibration process will be completed during the prototype installation phase, eliminating the need for additional calibration during field measurements.

The effects of ambient environmental conditions on AOD measurements will be investigated and quantified.

AEROSOL GENERATION / OUTDOOR SAMPLING PROCEDURE



Ghasempour, F., Sekertekin, A., Kutoglu, S. H. 2021. "Google Earth Engine based spatio-temporal analysis of air pollutants before and during the first wave COVID-19 outbreak over Turkey via remote sensing", Journal of Cleaner Production, 319, 1-20.

Ground-based aerosol measurements obtained from our system and MCD19A2 AOD data derived from the Terra and Aqua MODIS sensors will be compared evaluated using statistical methods.

The relationship between the two datasets will be analyzed using the correlation coefficient (R), Root Mean Square Error (RMSE), standard error, and bias metrics, while the temporal consistency of AOD variations will be examined through correlation plots.

Daily and monthly AOD maps will be generated and compared with the AOD measurements obtained from our proposed optical prototype system.

This assessment will help determine how effectively satellite-based AOD products represent ground-based observations.

EXPECTED OUTCOMES

The sensing system will operate as a dark enclosure with dedicated optical windows for laser transmission, enabling continuous measurements under both daytime and nighttime conditions.

- **Development of a low-cost, novel, portable, real-time interferometric aerosol monitoring system**
- **Real-time aerosol monitoring and measurement**
- **Validation using the MODIS sensors onboard the Aqua and Terra satellite-derived aerosol data**
- **Contribution to the European research network and standardization calibration procedures for AOD measurements within the Harmonia activities**


Thank you for your attention…



HARMONIA

Aerosol Profiling through bottom-to-top Atmosphere from the Synergetic Observations of Sun-Sky Photometer, Spectrometer and Lidar/Ceilometer

Masahiro Momoi, Anton Lopatin, Marie Charlotte Stockhardt, Elena Lind, Manuel Veloso, Lucja Janicka, Dominika Szczepanik, Oleg Dubovik, Marcos Herreras-Giralda, Benjamin Torres, Tatyana Lapyonok, Axel Kreuter, Alexander Cede, and Iwona Stachlewska

GRASP

LOA LABORATOIRE D'OPTIQUE ATMOSPHÉRIQUE

NASA

MEDIZINISCHE UNIVERSITÄT INNSBRUCK

LUFTBLICK EARTH OBSERVATION TECHNOLOGIES

UNIVERSITY OF WARSAW

Atmospheric aerosol is complex

- Chemical component
- 4-dimensional dynamics
  - Spatial
  - Vetical
  - Temporal

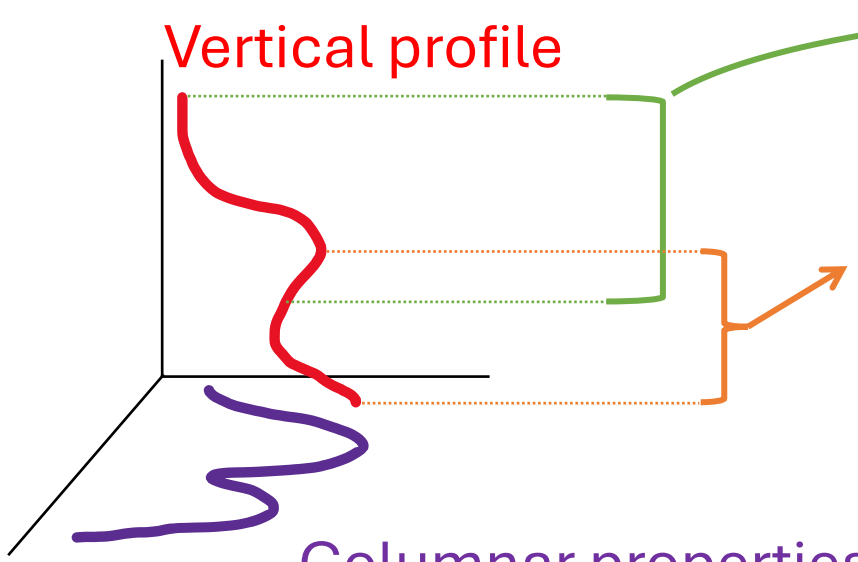


Many (kind of) observations are desired!

- Lidar (optional: tilt observation)
- AERONET photometer
- PGN spectrometer

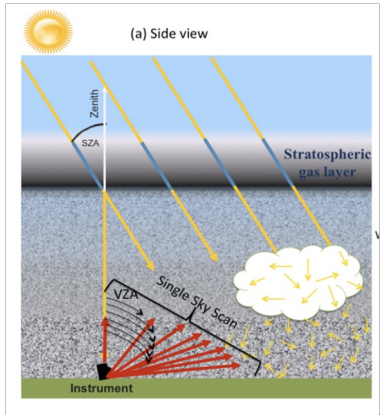
...

Profiling from ground-based passive and active measurement synergy: photometer + spectrometer + lidar

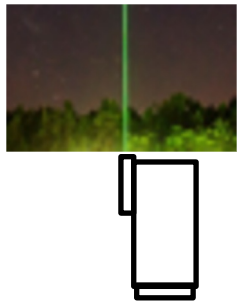


Spectrometer

PANDONIA GLOBAL NETWORK
Reference Measurements of Atmospheric Composition



Lidar/Ceilometer



Columnar properties

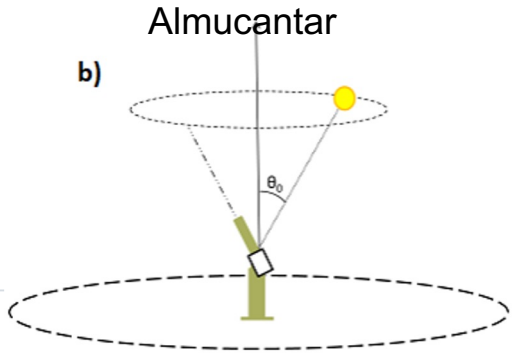
AERONET calibrated absolute radiances:
- Standard AERONET observation protocol;

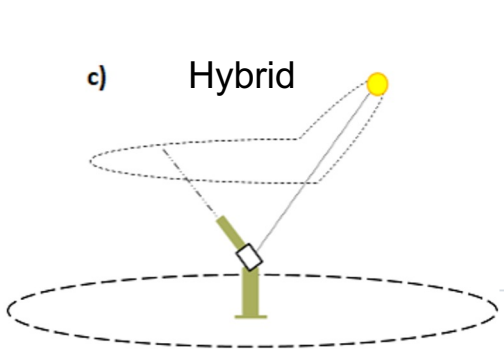
PGN spectral measurements:
- Differential slant column densities of O_2O_2;
  - Sensitive near surface

Lidar vertical profiles:
- Back-scattering, depolarization, extinction;
  - Limited in lower atmosphere

Photometer

AERONET
AEROSOL ROBOTIC NETWORK





Profiling from ground-based passive and active measurement synergy: photometer + spectrometer + lidar

AERONET calibrated absolute radiances:
- Standard AERONET observation protocol;
- At different elevation angles (similar to multi-axis DOAS but at AERONET channels)

PGN spectral measurements:
- Differential slant column densities of O_2O_2;
  - Sensitive near surface

Lidar vertical profiles:
- Back-scattering, depolarization, extinction;
  - Limited in lower atmosphere

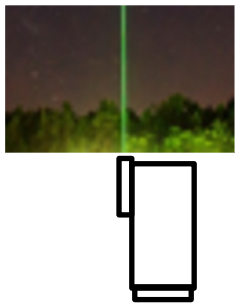
Retrieved properties

- **Total aerosol columnar**: size distributions, complex index of refraction, SSA, non-sphericity fractions, etc.;
- **Aerosol vertical profile**: concentration and extinction
- **Gas vertical profiles**: NO_2, HCHO, H_2O, etc.

Photometer + **Spectrometer** + **Lidar**



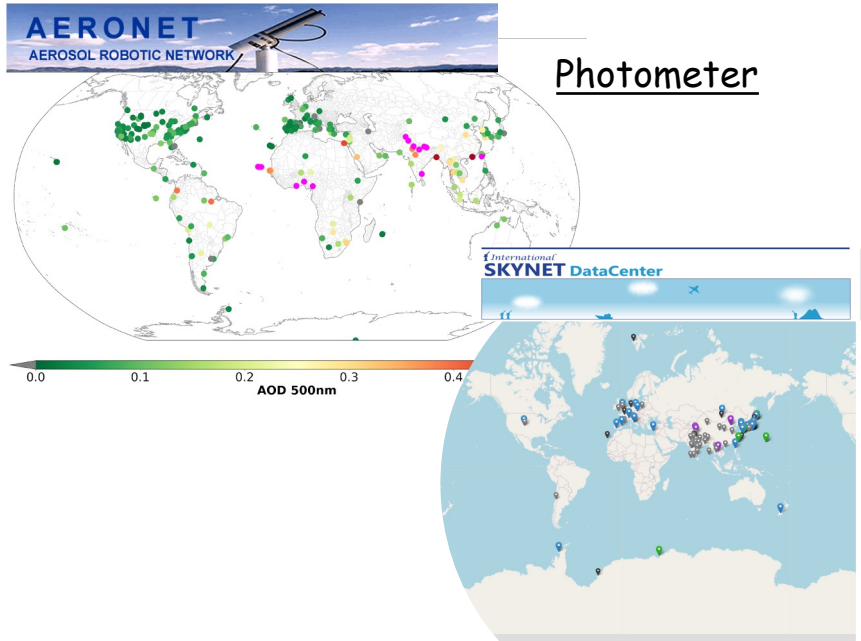




Profiling from ground-based passive and active measurement synergy: photometer + spectrometer + lidar

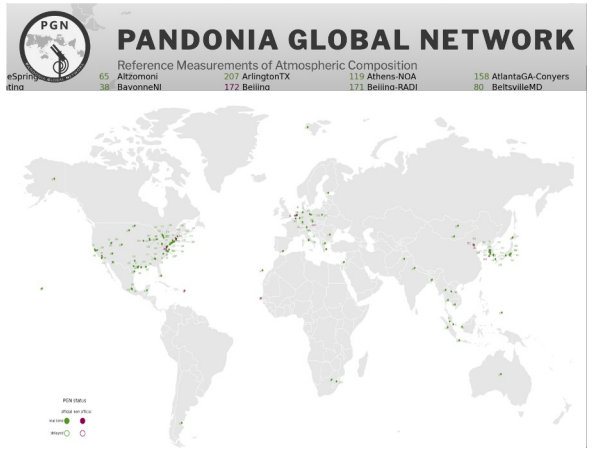
Synergetic combined retrieval of photometer + spectrometer (DOAS) + lidar measurements produces advanced aerosol vertical profile from BOA until TOA. ***DOAS (spectrometer) fills the information near surface where lidar can not see due to overlapping***.

The approaches can be applied at collocated sites of each network (AERONET/SKYNET, PGN, EARLINET/AD-net) for the generation of advanced Cal/Val ground truth data, such as for EarthCARE/ATLID aerosol profile.

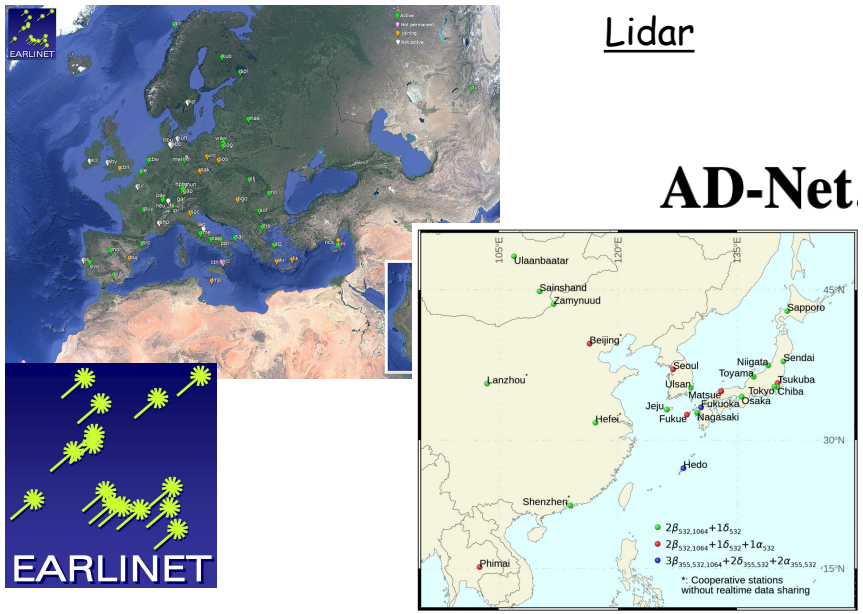


Photometer

Spectrometer



Lidar

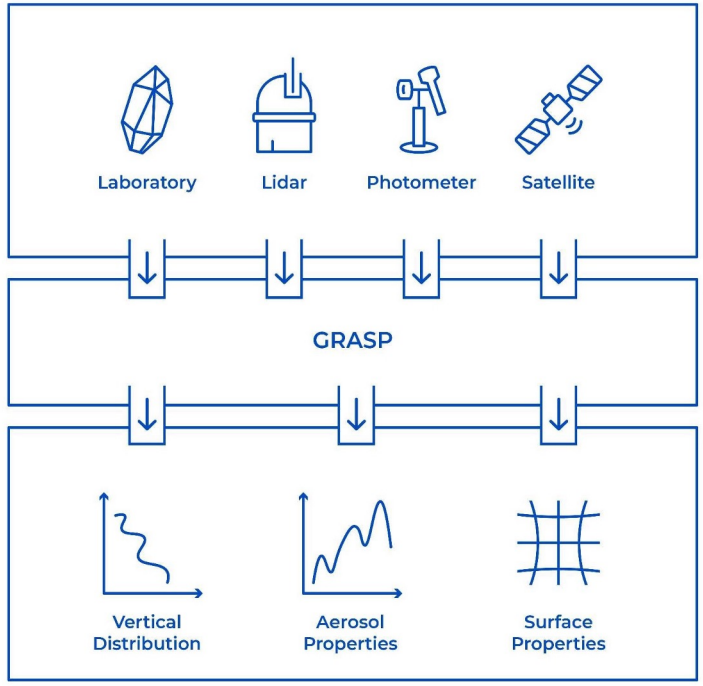


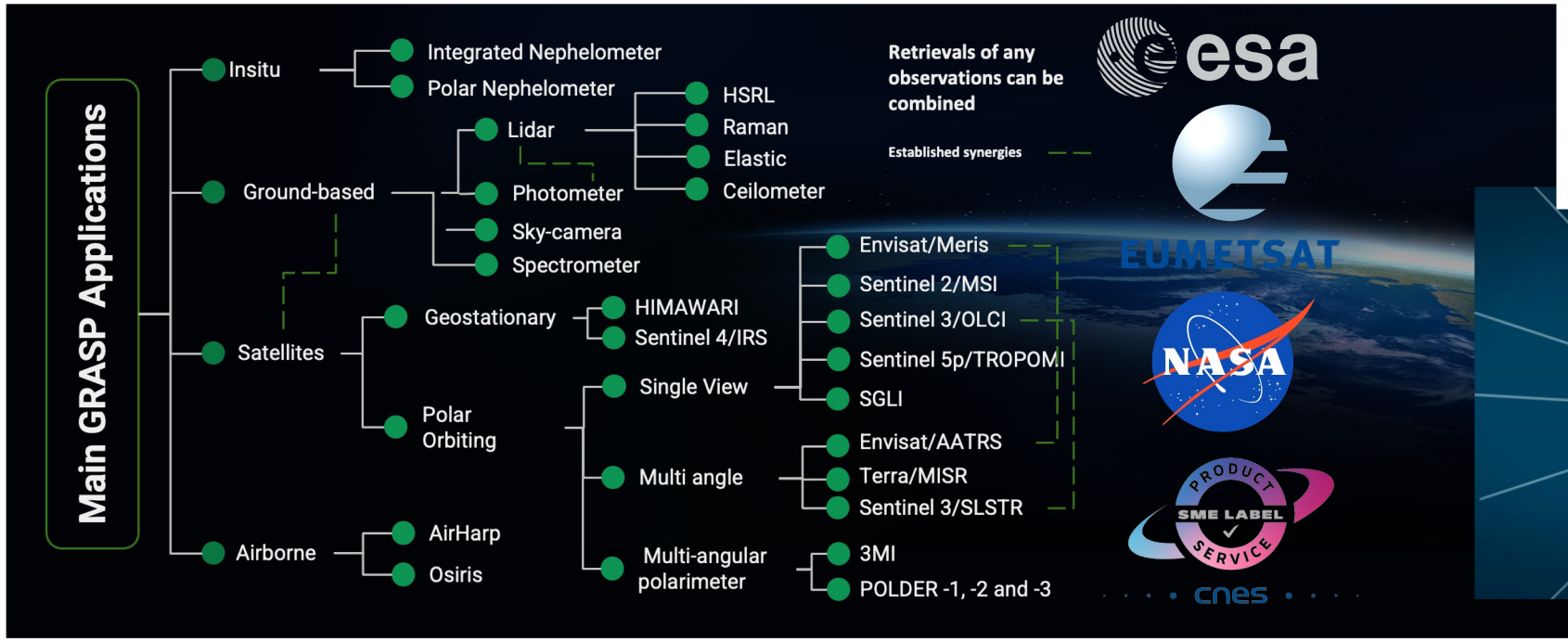
Surface database generated by GRASP

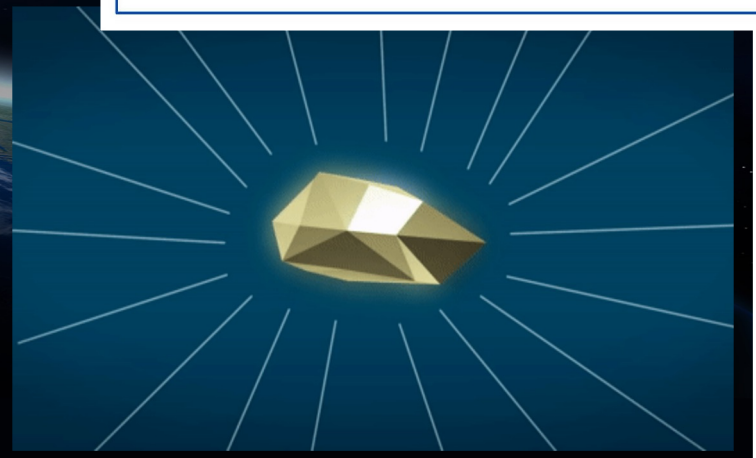
Generalized Retrieval of Atmosphere and Surface Properties

GRASP
In principle, yes!

... is ant advanced algorithm for deriving aerosol, gas and surface properties. This inversion algorithm is currently used by space agencies worldwide for operational products. It was originally developed for use in AERONET sun-sky radiometers.







SKY measurement differences between AERONET and PGN

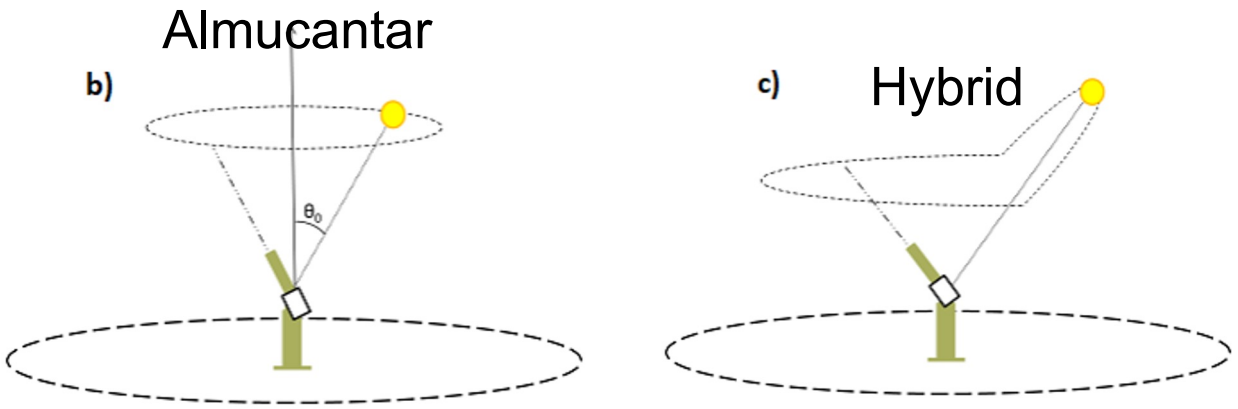
AERONET standard SKY retrievals: 440, 675, 870, 1020 nm filter bands

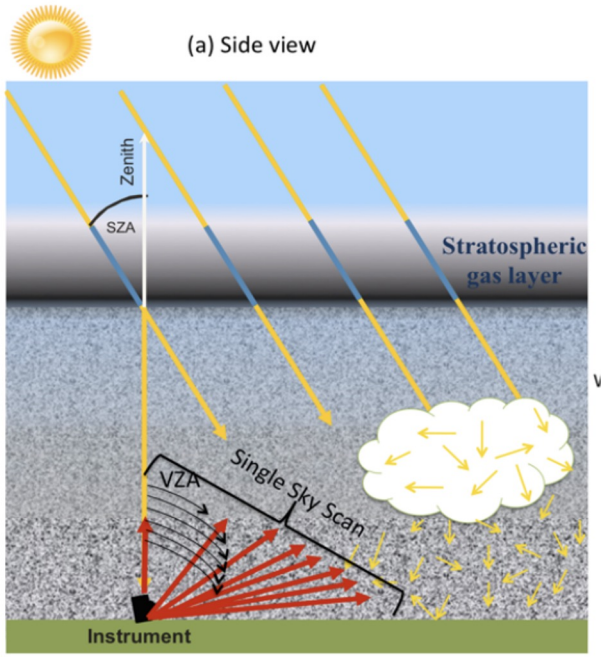
AERONET standard SKY measurements: 340, 380, 440, 500, 675, 870, 1020, 1640 nm filter bands

Absolute radiance calibration of all channels

PGN standard SKY measurements: 300 – 530 nm at spectral resolution of 0.6 nm per FWHM, 0.1 nm sampling

No absolute radiance calibration





Horizontal sky scan from the sun at **a fixed zenith angle: minimal sensitivity to profiles**

Vertical sky scan from the horizon at **a fixed azimuth angle: maximum sensitivity to near surface profiles**

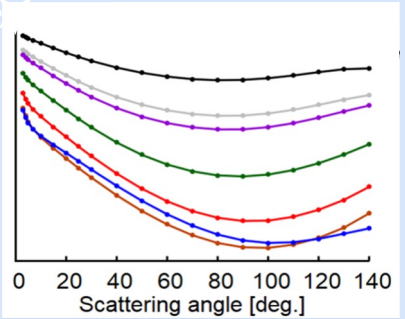
Products and processing of AERONET and PGN

AERONET
AEROSOL ROBOTIC NETWORK

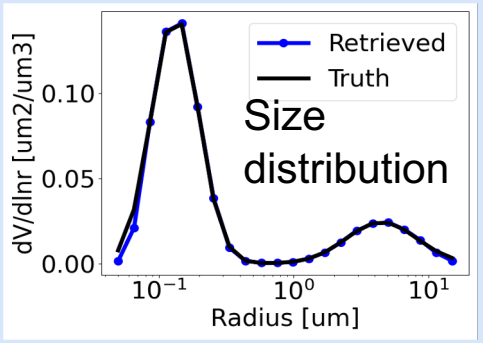
AERONET sun-sky photometer

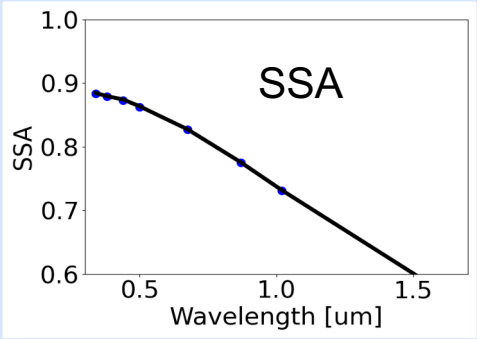


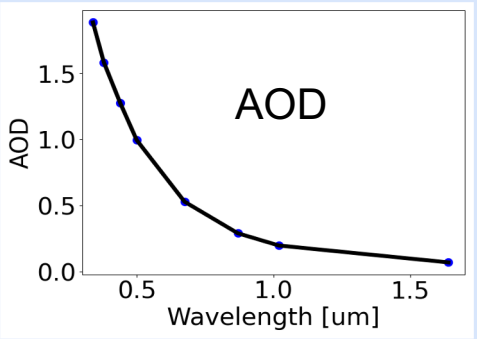
Radiance measurement



Aerosol **columnar** properties







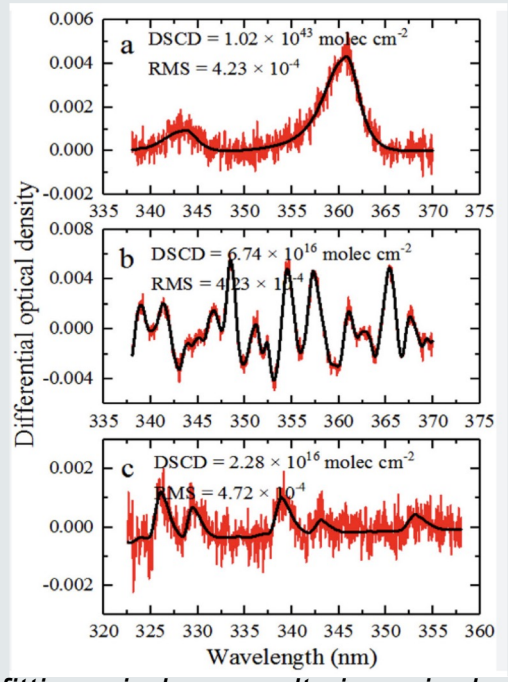
Aerosol optical properties
(e.g., AERONET: SSA, ASY)

spectrometer

PGN
PANDONIA GLOBAL NETWORK



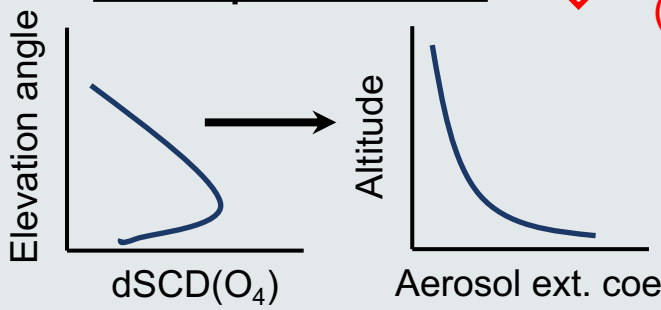
Spectral measurement



One fitting window results in a single dSCD(gas) at an effective window wavelength

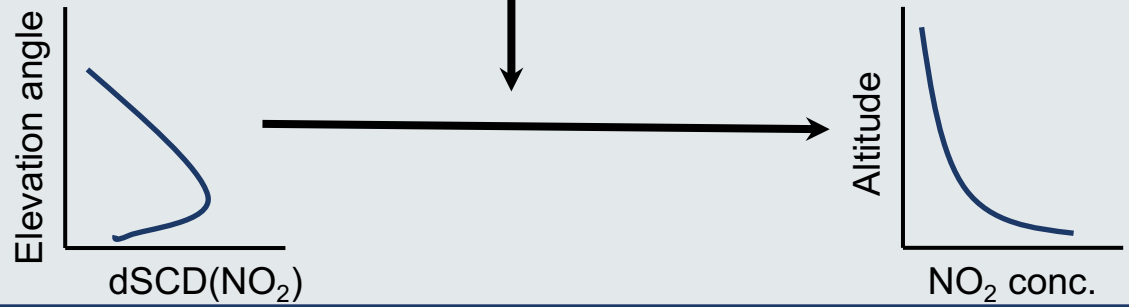
dSCD(O_4)

Aerosol **profile** retrieval



dSCD(NO_2)
dSCD(HCHO)

Trace-gases profile retrieval

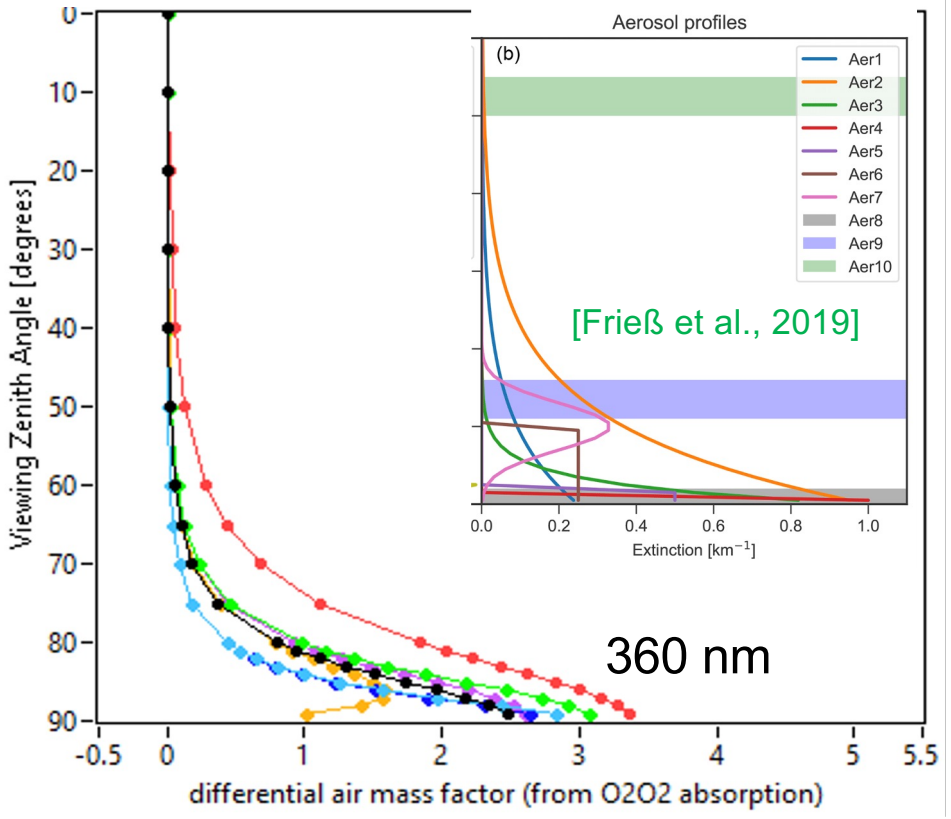


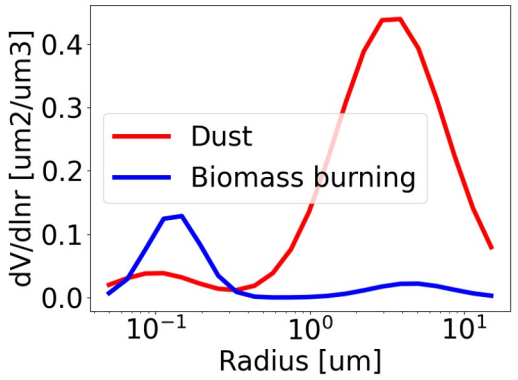
Multi-axis dSCD (gas) sensitivity to aerosol information at low elevation angles

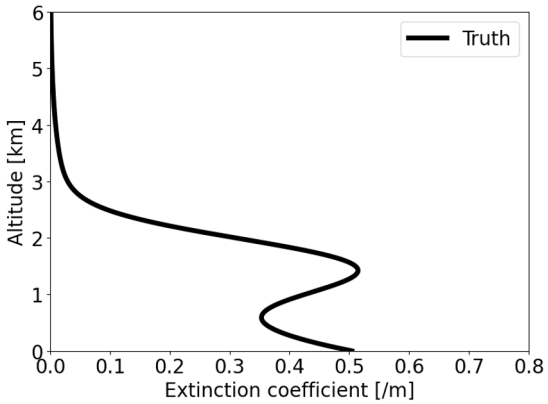
Aerosol vertical profiles effect on dSCD(O_4) measured at low elevations angles

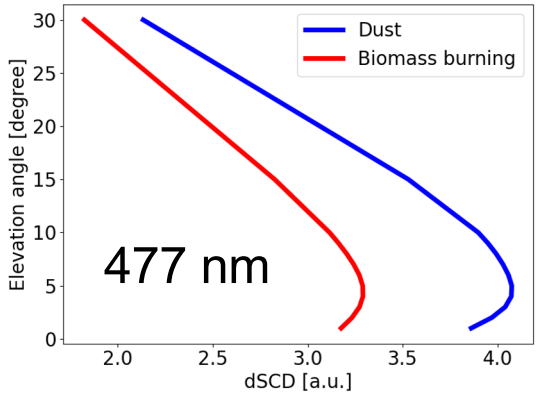
Aerosol microphysical properties effect on dSCD (O_4) at low elevations angles

O_4 differential air mass factor (simulations)







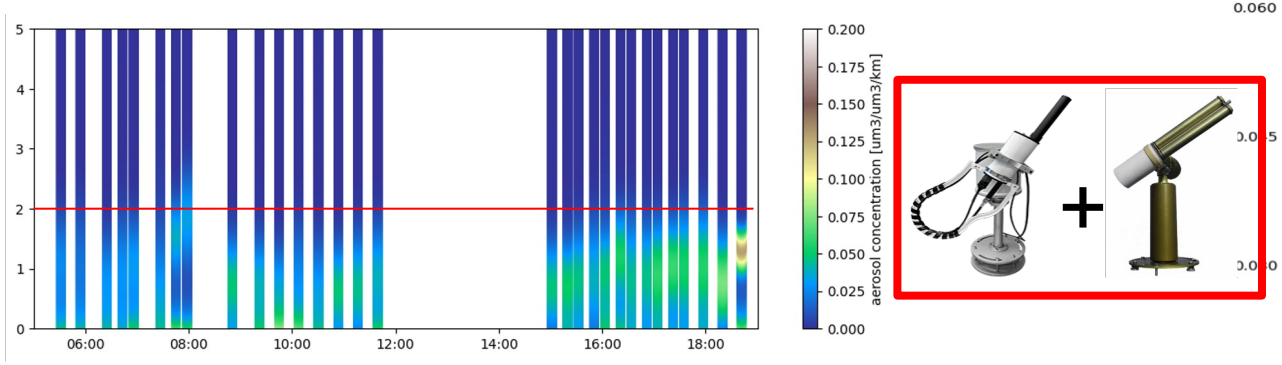


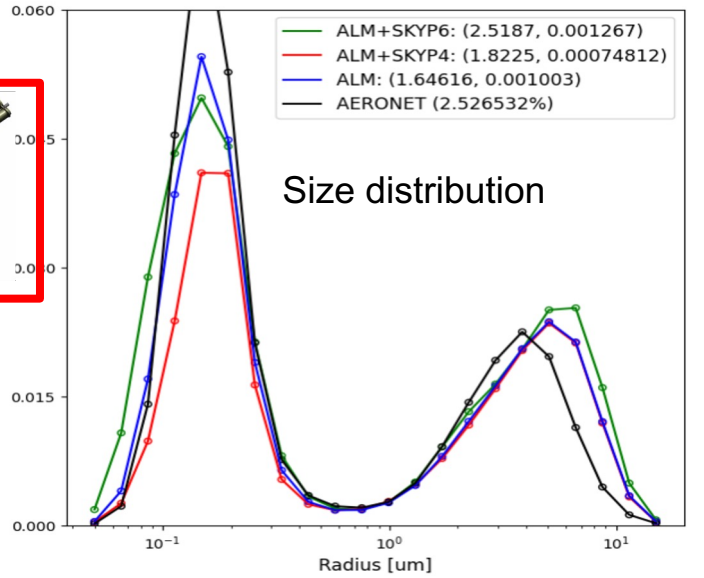
AOD at 477nm = 1.0

Aerosol profiles from radiometer + spectrometer

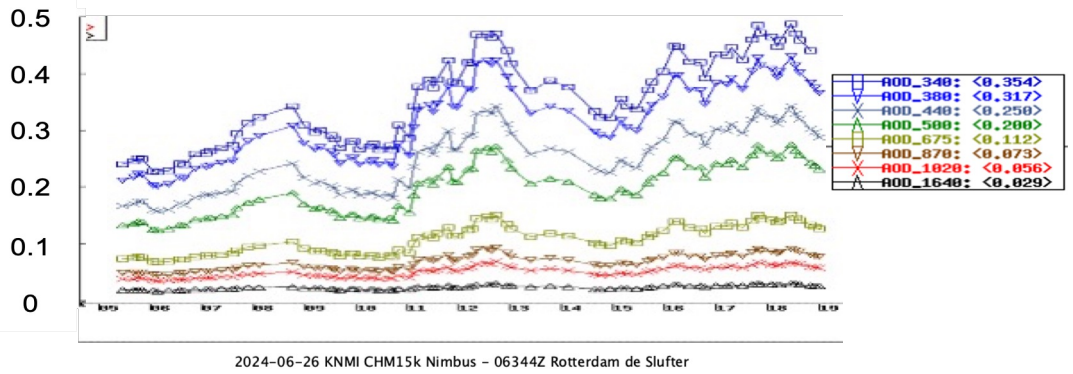
CINDI-3 (26 June 2024, Rotterdam de Slufter)

aerosol profiles
retrieved from
the radiometer (ALM/HYB)
+
spectrometer (O4-UV)





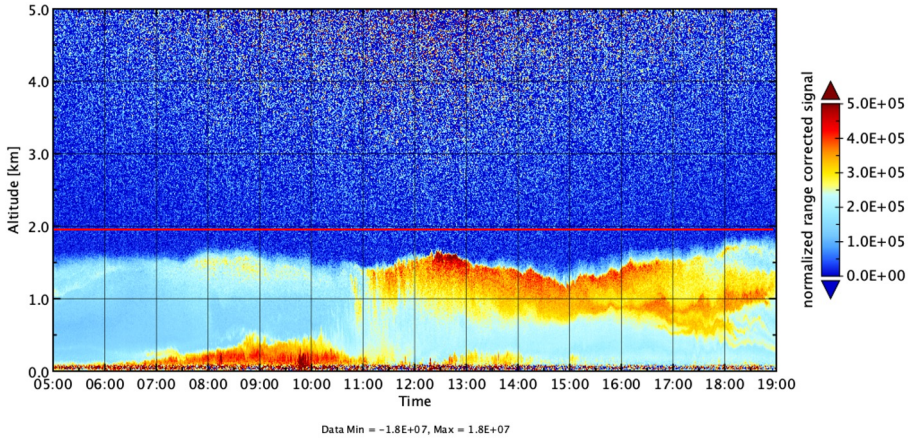
aerosol optical depth
from
the radiometer (sun)

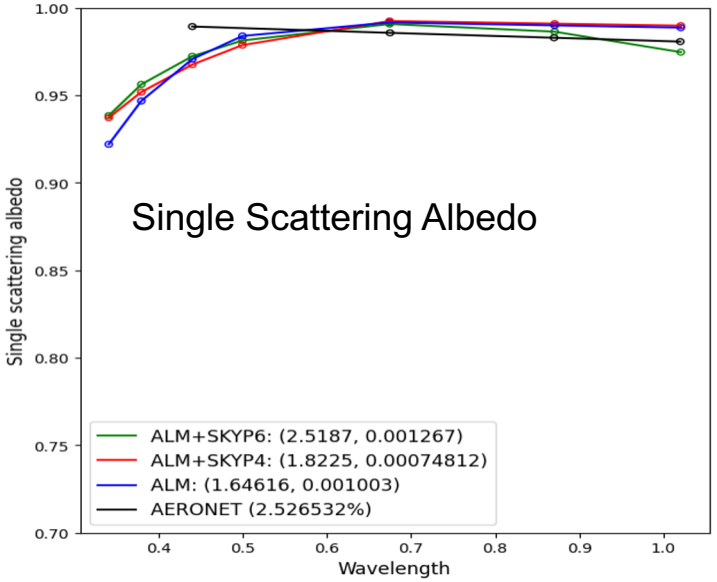


2024-06-26 KNMI CHM15k Nimbus - 06344Z Rotterdam de Slufter

Ceilometer
Normalized
RCS

Courtesy of Diego Alves Gouveia (KNMI)

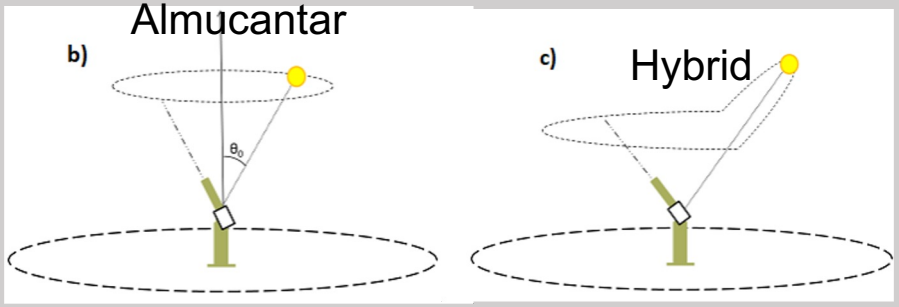




How about to combine with lidar
in addition to the synergy of AERONET and PGN?

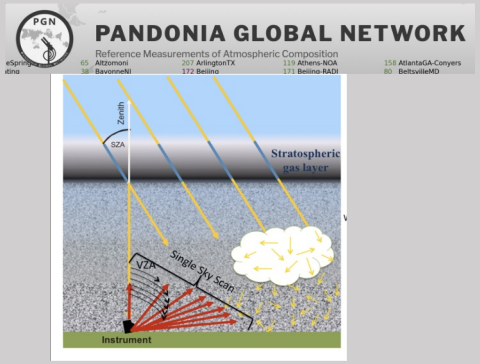
Photometer





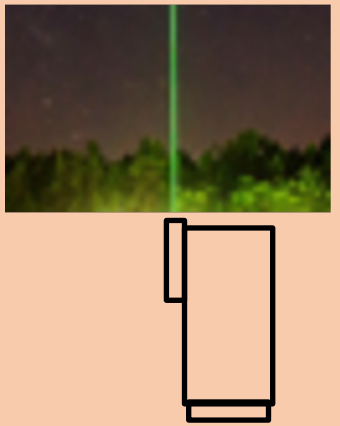
+

Spectrometer



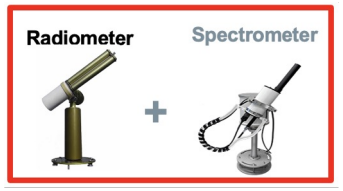
+

Lidar/Ceilometer

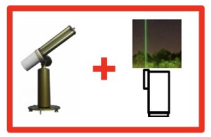


Aerosol profiles from radiometer + spectrometer + lidar/ceilometer

CINDI-3 (26 June 2024, Rotterdam de Slufter)

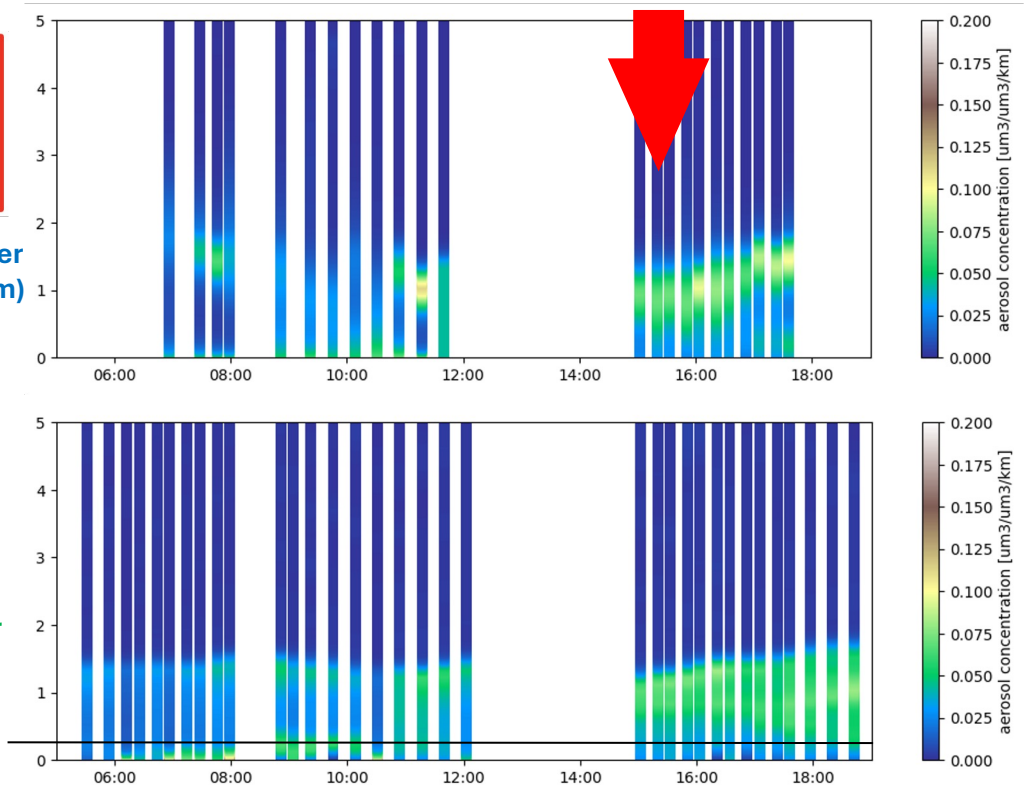


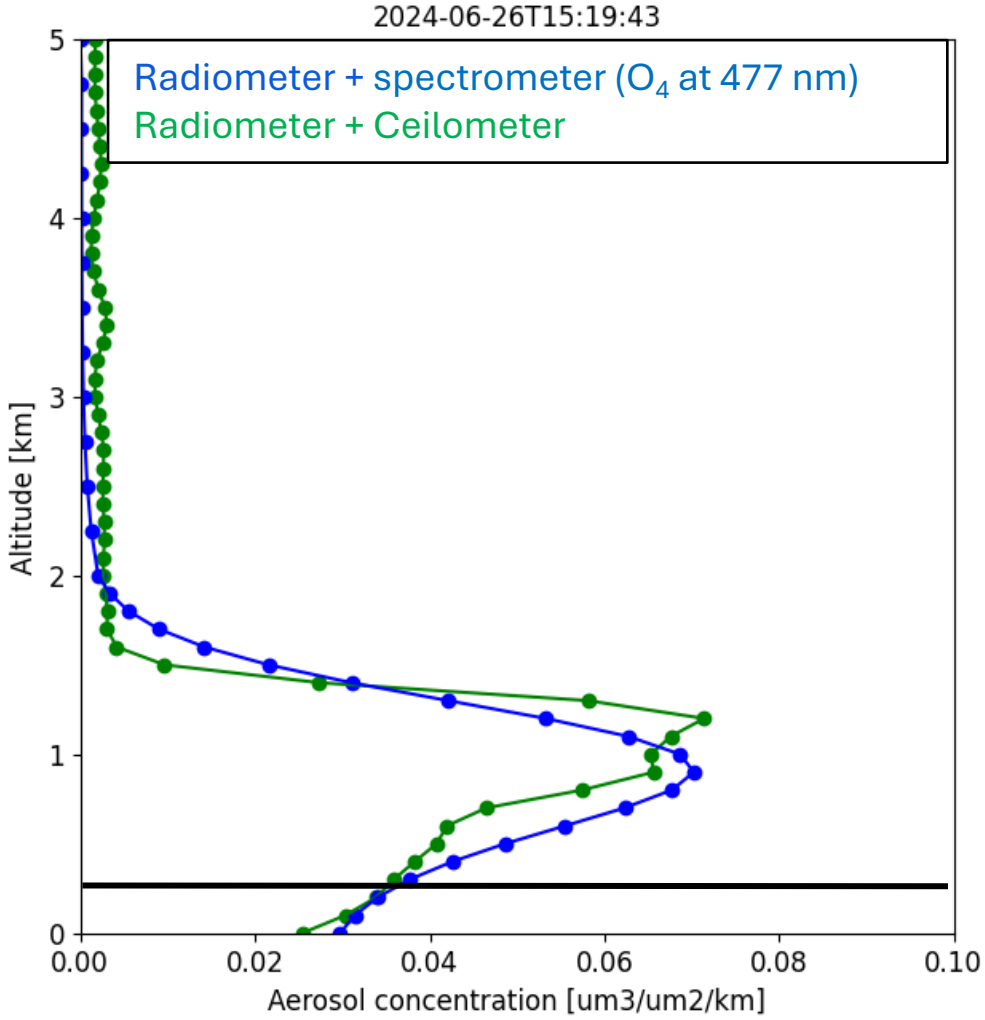
radiometer (ALM/HYB) + spectrometer (O_4 at 477 nm)



radiometer (ALM/HYB) + Ceilometer

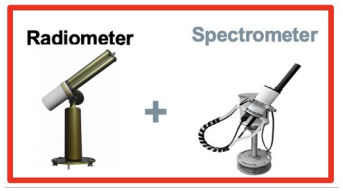
Cut-off: 0.25km



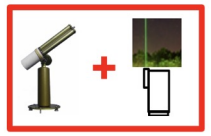


Aerosol profiles from radiometer + spectrometer + lidar/ceilometer

CINDI-3 (26 June 2024, Rotterdam de Slufter)

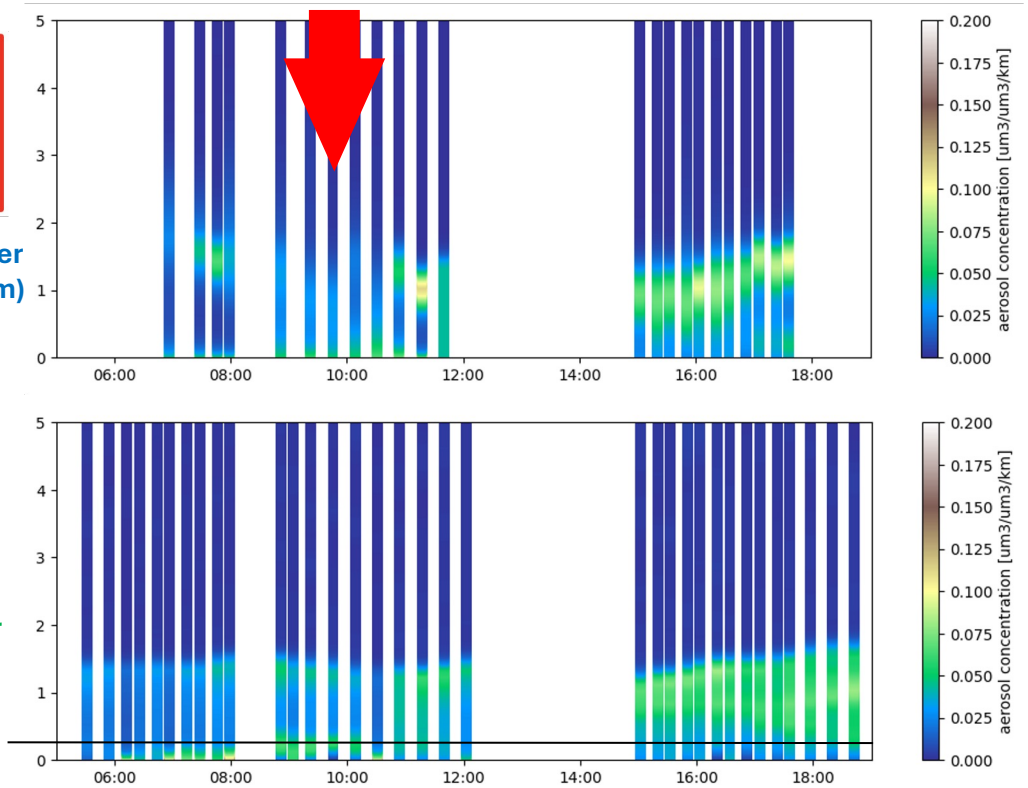


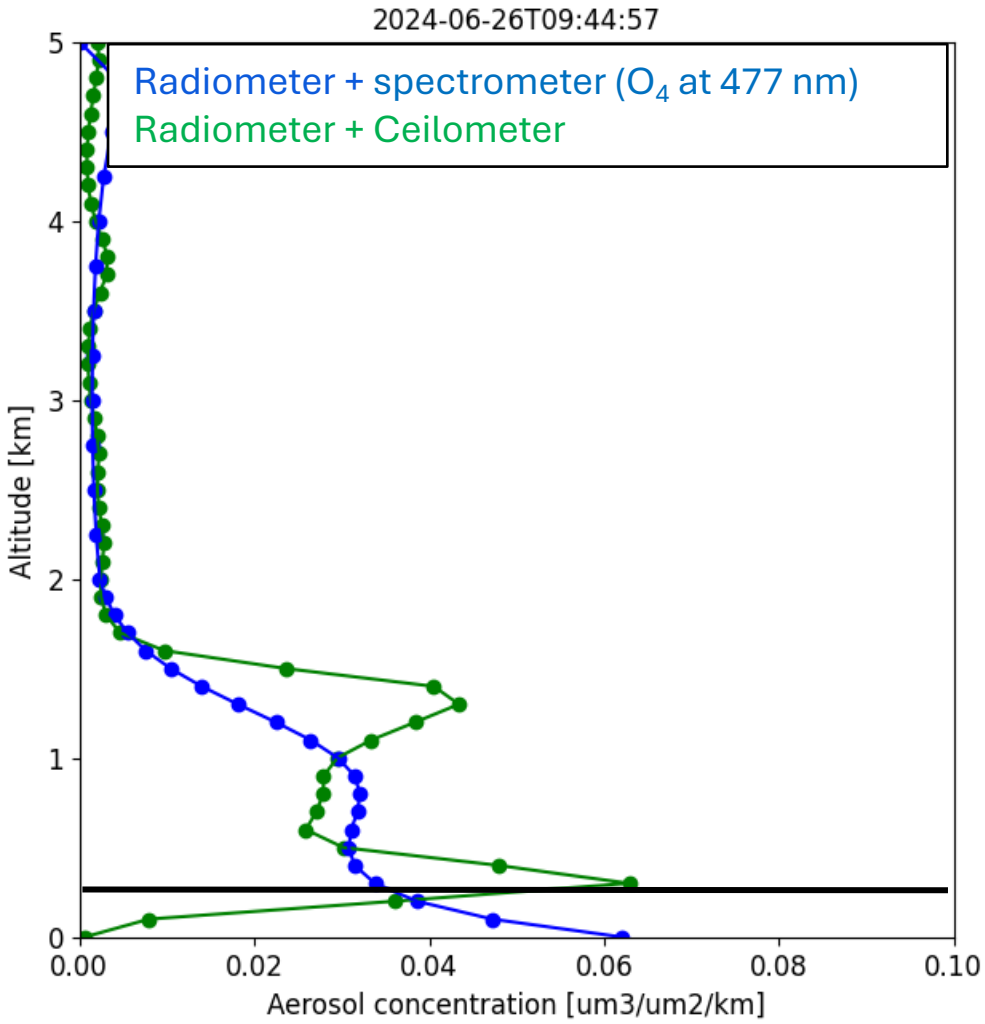
radiometer (ALM/HYB) + spectrometer (O_4 at 477 nm)



radiometer (ALM/HYB) + Ceilometer

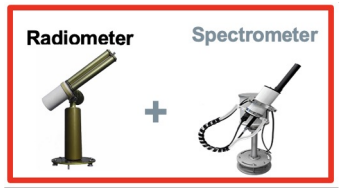
Cut-off: 0.25km



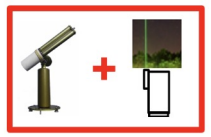


Aerosol profiles from radiometer + spectrometer + lidar/ceilometer

CINDI-3 (26 June 2024, Rotterdam de Slufter)



radiometer (ALM/HYB) + **spectrometer (O_4 at 477 nm)**

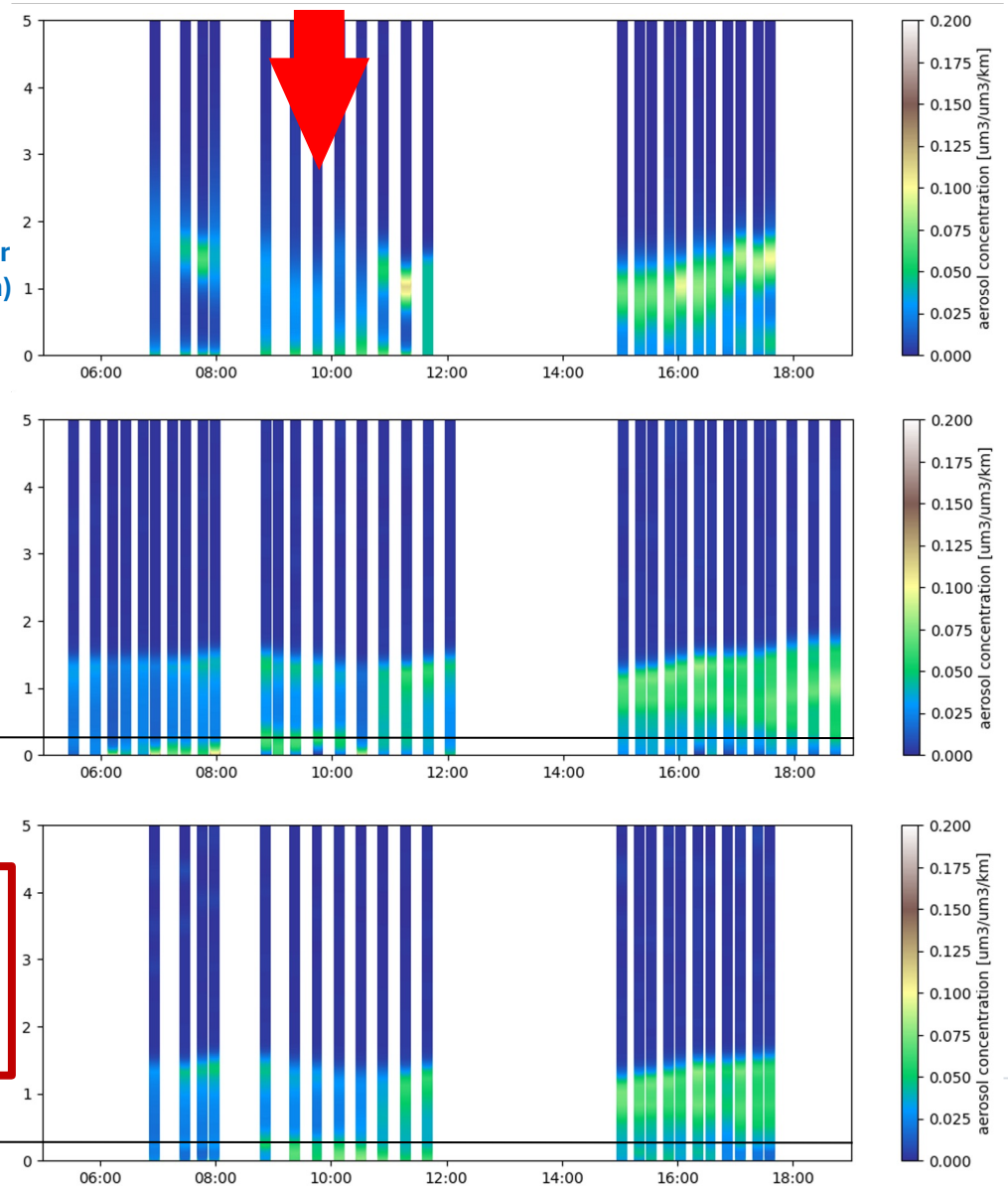


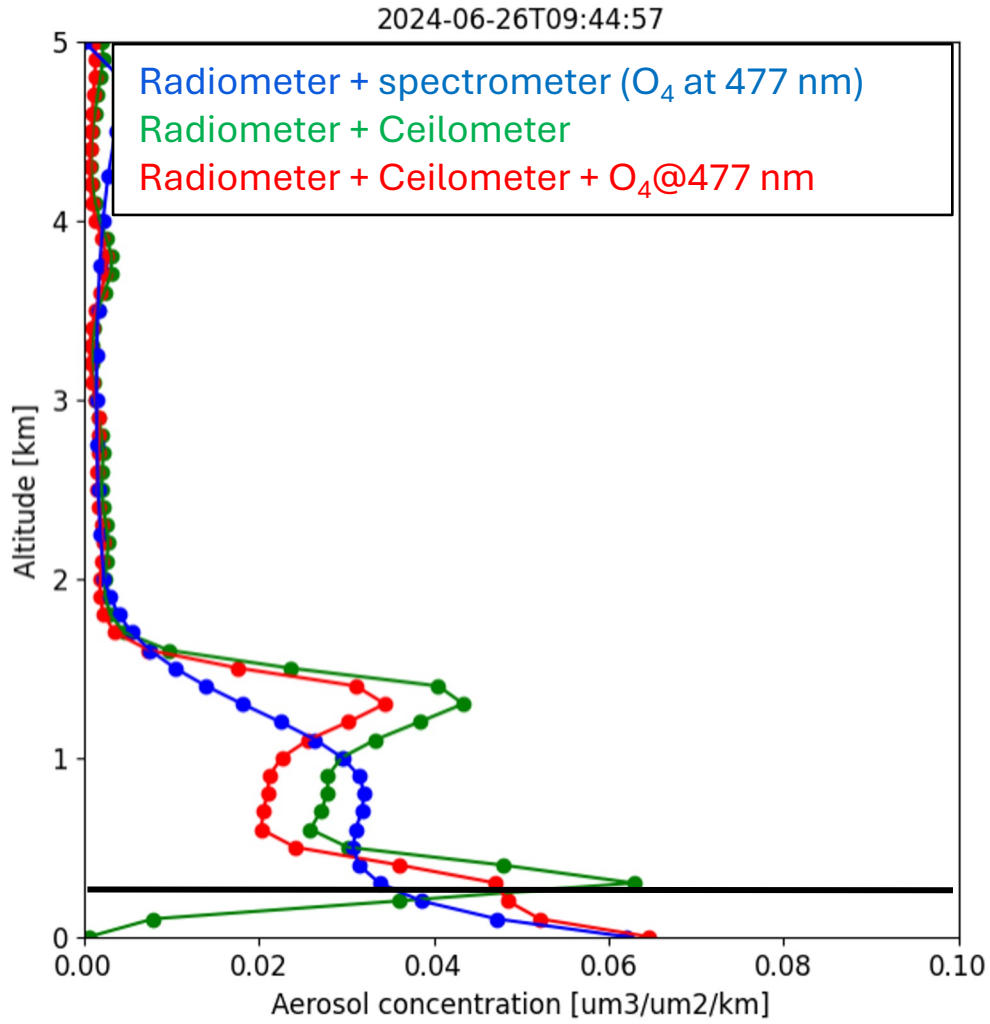
radiometer (ALM/HYB) + **Ceilometer**

Cut-off: 0.25km



Cut-off: 0.25km





Aerosol profiles from radiometer + spectrometer + lidar/ceilometer

CINDI-3 (26 June 2024, Rotterdam de Slufter)

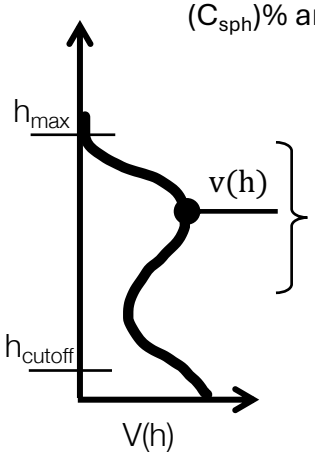
Pilot demonstration over Warsaw site with PollyXT lidar

	University of Warsaw
Photometer (AERONET)	380, 440, 500, 675, 870, 1020 nm
Spectrometer (PGN)	360 nm (long scan) 477 nm (short scan)
Lidar - PollyXT (ACTRIS/EARLINET)	Backscattering: 355, 532, 1064 nm Depolarization: 355, 532 nm Cut-off: 0.6 km

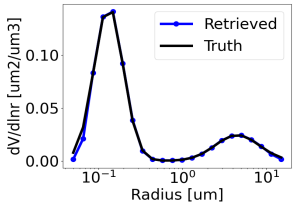
22bins+CR: AERONET like approach

Mixture of spherical (C_{sph})% and spheroidal (1-C_{sph})% particles

- $dV(r)/dlnr$,
- $n(\lambda)$, $k(\lambda)$
- $\omega_o(\lambda)$, $P_{ij}(\lambda,\Theta)$



Smooth



$$\sigma_a(h,\lambda) = v(h)\tau^{ext}$$

$$\beta_a(h,\lambda) = v(h)\tau^{ext}/S$$

Retrieval combinations

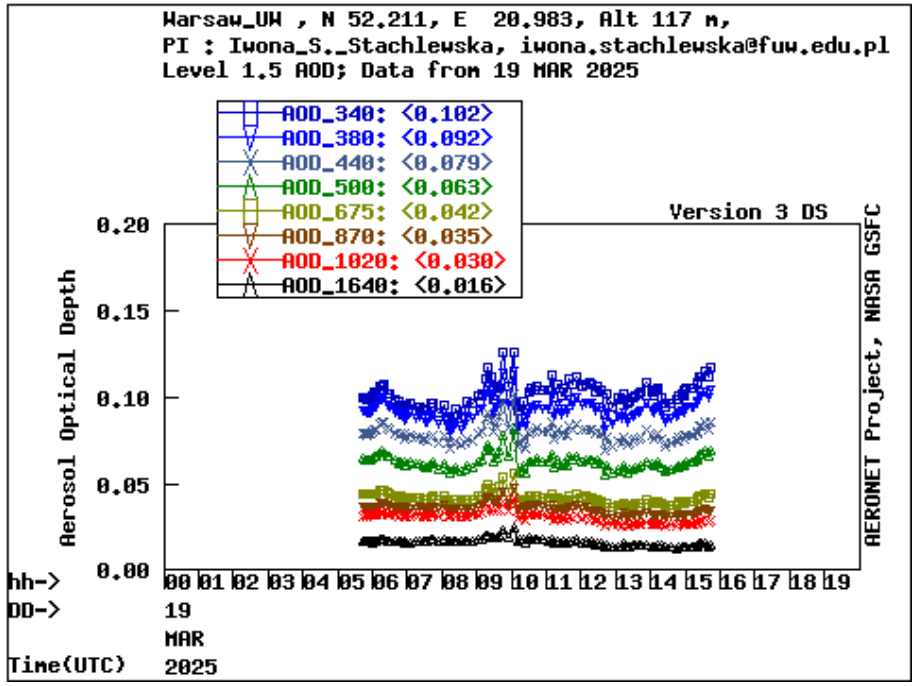
	AERONET + Lidar (AL)	**AERONET + PGN**	**AERONET + PGN + Lidar (APL)**
Photometer	✓	✓	✓
Spectrometer		✓	✓
Lidar / Ceilometer	✓		✓
References	Lopatin et al. (2021)	This work (last year)	This work

Profiling from ground-based passive and active measurement synergy: photometer + spectrometer + lidar

Test case of clear sky day

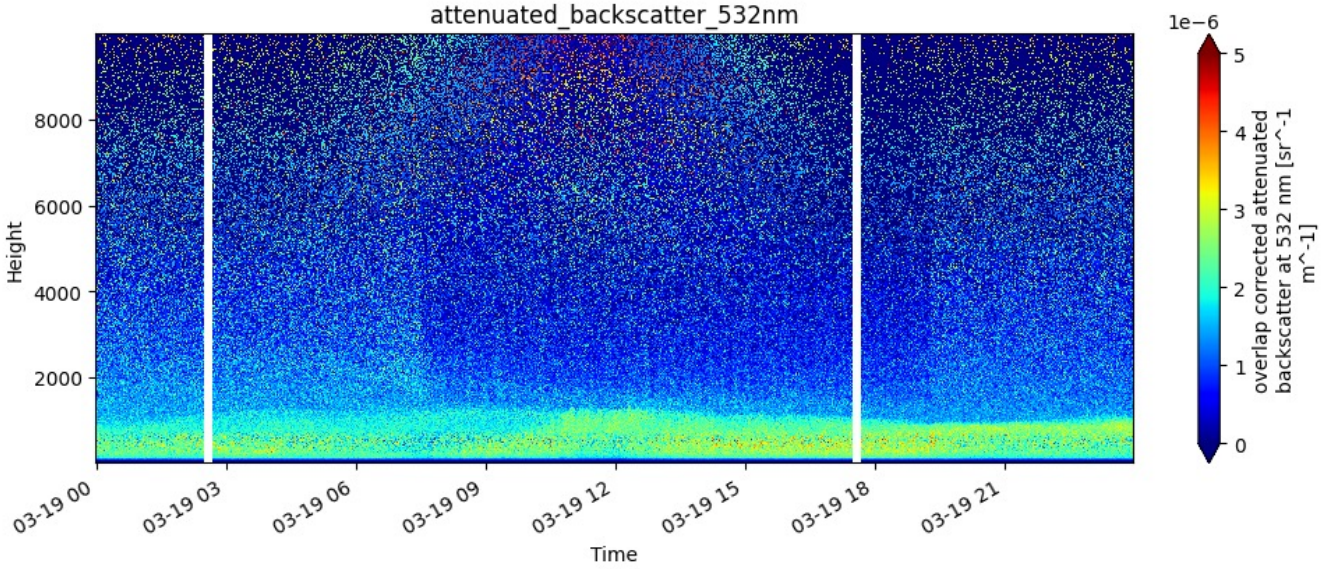
AERONET direct sun measurement

AOD @ 500 nm ~ 0.06



PollyXT Lidar measurement

Attenuated backscatter at 532nm

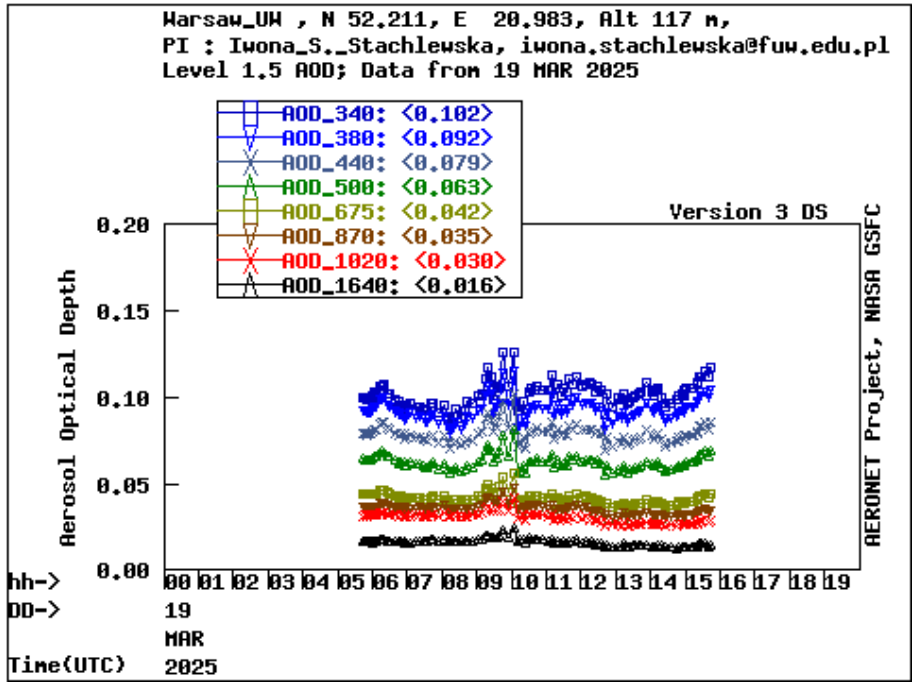


Profiling from ground-based passive and active measurement synergy: photometer + spectrometer + lidar

Test case of clear sky day

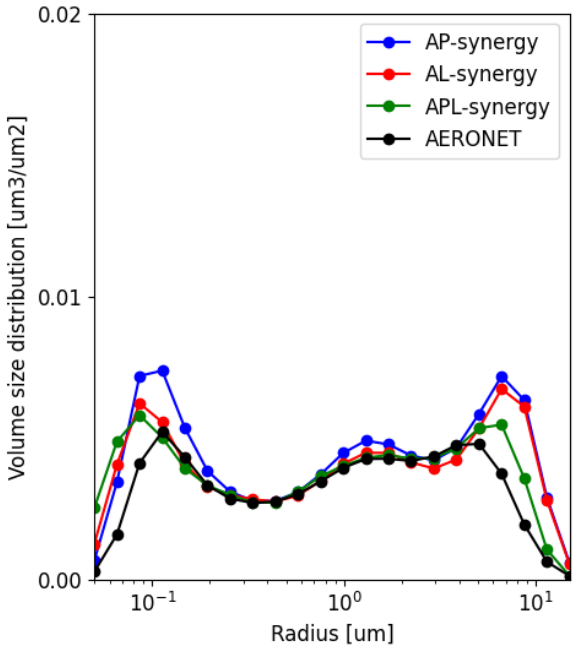
AERONET direct sun measurement

AOD @ 500 nm ~ 0.06

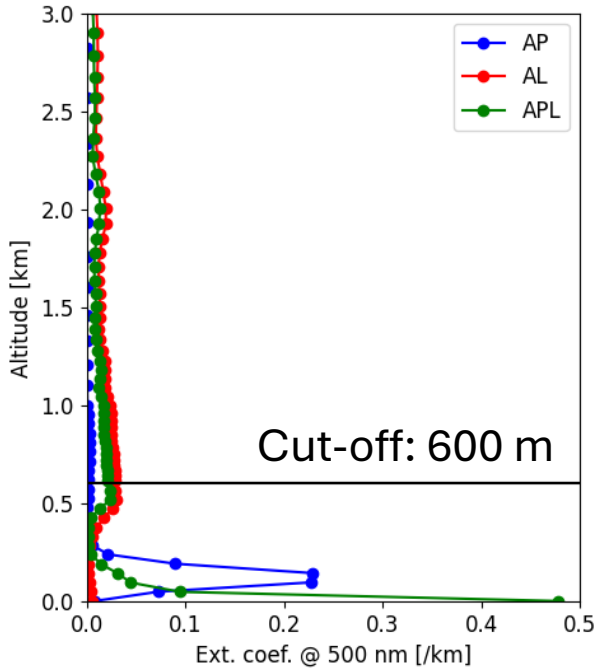


Retrieved aerosol mycrophysics

Volume size distribution



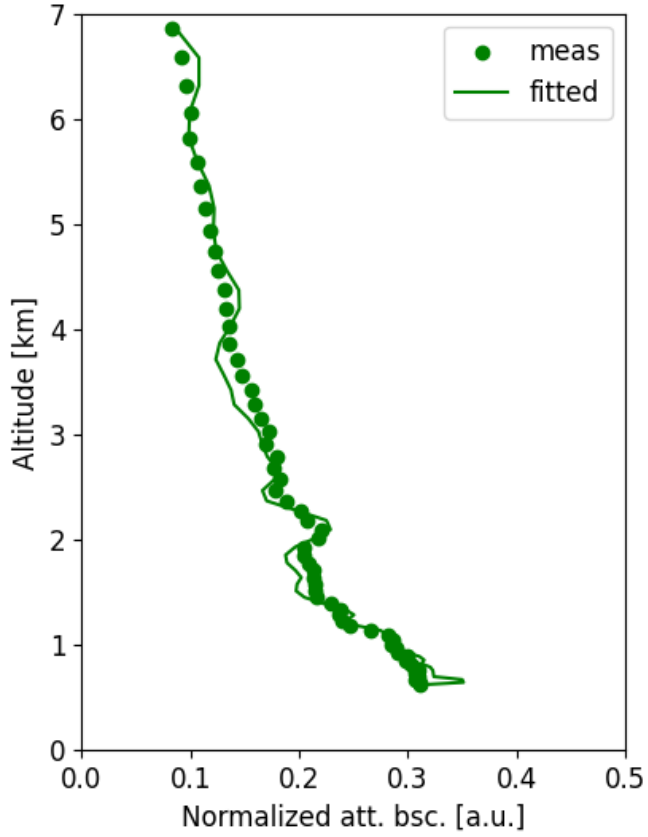
Aerosol vertical profile



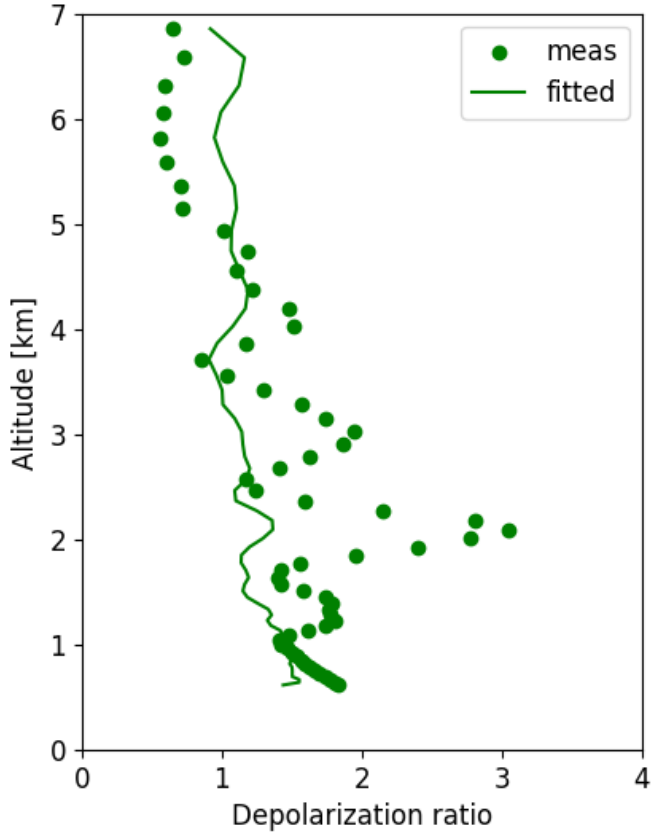
Profiling from ground-based passive and active measurement synergy: photometer + spectrometer + lidar

PollyXT Lidar measurements (at 532 nm)

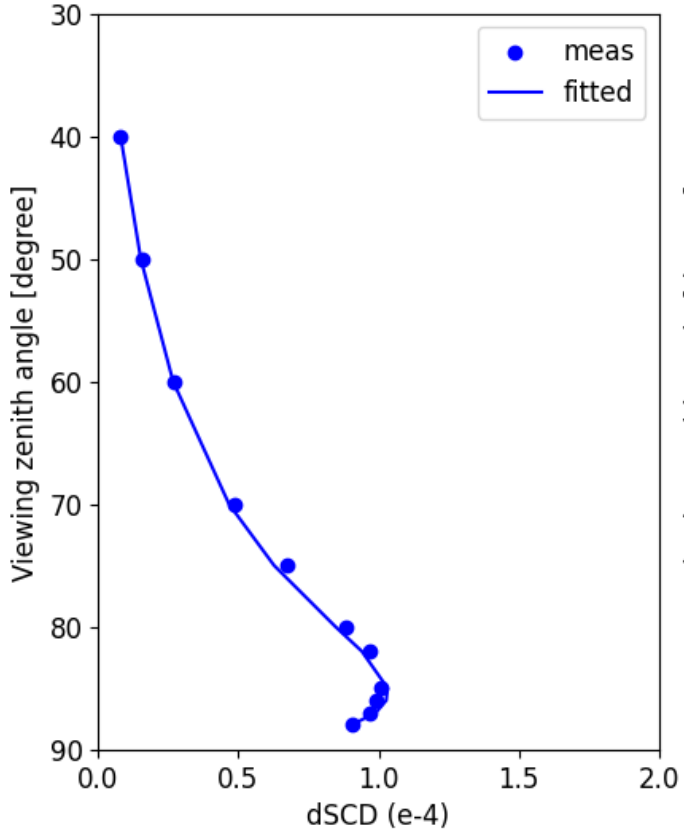
Normalized attenuated backscattering



Depolarization ratio



Pandora dSCD measurements (at 360 nm)



Sensitivity to NO_2 profiles in simulated synergetic radiances + $dSCD(O_4)$ + $dSCD(NO_2)$

Radiometer (AERONET): AOD (sun) + ALM/HYB + Vertical scan (SKYP)

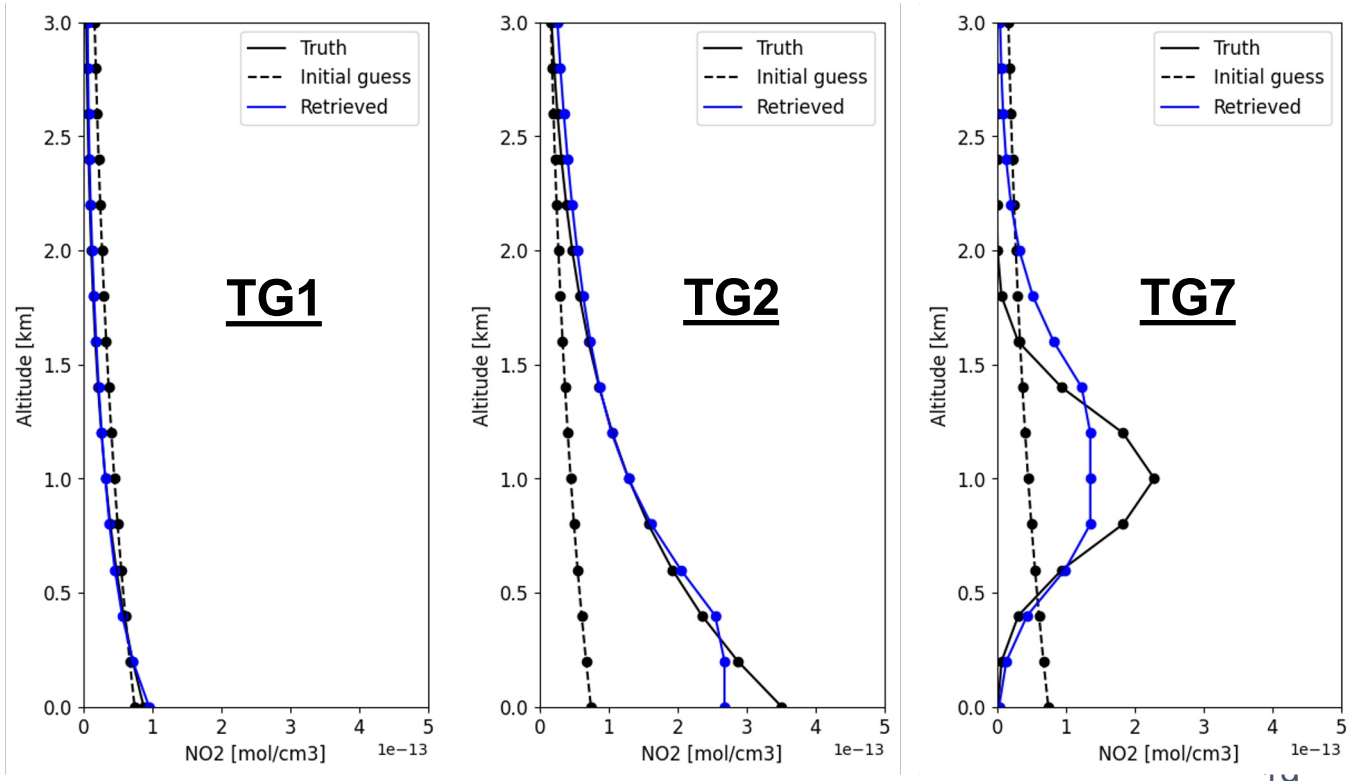
Spectrometer (PGN): dSCD of NO2 at 477 nm
dSCD of O4 at 360, 477, 577, 630 nm

NO_2 profiles used in the synthetic tests

[Frieß et al., 2019]

Table 2. Description of the trace gas profiles shown in Fig. 2. The VCD and the maximum number concentration ρ_{max} are given in units of 10^{15} molec cm^{-2} and 10^{11} molec cm^{-3}, respectively.

	Description	VCD	ρ_{max}
TG0	No trace gas	0.00	0.00
TG1	Exponential, 1 km scale height	5.00	0.48
TG2	Exponential, 1 km scale height	19.99	1.90
TG3	Exponential, 250 m scale height	9.93	3.27
TG4	Box profile, 100 m height	5.00	5.00
TG5	Box profile, 200 m height	5.00	2.50
TG6	Box profile, 1 km height	10.00	1.00
TG7	Gaussian at 1 km, 300 m FWHM	10.00	1.31
TG8	NO_2 balloon sonde (CINDI-2, 20160914)	17.73	3.30
TG9	NO_2 balloon sonde (CINDI-2, 20160921)	40.88	5.82



Retrieved NO_2 profiles

Summary

- GRASP has been updated to incorporate DOAS measurements
  - Expand the functionality of gas calculation to allow gas vertical profile retrieval

- Synergetic aerosol profile retrieval scheme was developed from photometer, spectrometer, and lidar measurements.
  - The synergetic retrieval was demonstrated from the AERONET Warsaw site
  - Validation is needed => Planed at ACTRIS Lille site with tilted lidar observation.

