Deliverable 4.2: Research needs assessment mapped to CARGO-ACT capabilities, and remediation plan

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1. Introduction

This deliverable focuses on requirements for aerosol and cloud parameters that are relevant for atmospheric chemistry / physics scientific research and applications:

Researchers study their formation, transport, deposition, and transformation, as well as their physical, chemical, optical, and biological properties.

Key research and application areas are:

- Atmospheric and environmental aerosols: Studying air pollution, climate impacts, and indoor air quality. This includes an important area of research concerning the interactions between aerosol and clouds and their radiative impacts.

  Stratospheric aerosol and Polar Stratospheric Clouds (PSC) also play an important role in the ozone depletion issue.

  Stratospheric aerosol injection (SAI) is one of the geoengineering options that are investigated today to mitigate climate change.

- Combustion and industrial aerosols: Understanding emissions from engines, factories, and energy systems, with applications in industrial processes.
- Health and inhalation studies: Investigating lung deposition, filtration, and drug delivery via aerosols – leading to public health and medical applications.
- Nanoparticles and nanotechnology: Aerosol-based synthesis and characterization of nanomaterials with applications in energy and materials production.
- Instrumentation and measurement: Developing tools for studying particle size, concentration, optical properties, and chemical composition with applications for environmental monitoring.
- Modeling and simulation: Numerical models for aerosol transport, nucleation, and deposition processes, also to be used in environmental monitoring and forecasting.

The field of aerosol and clouds research combines theoretical, numerical, and experimental approaches to understand aerosol dynamics and chemistry, aerosol-cloud-radiation impacts, and to develop technological applications and observation and modelling tools.

Experimental approaches include laboratory experiments as well as observations 'in the field'.

Aerosol science continues to evolve with interdisciplinary research, combining physics, chemistry, engineering, and health sciences to address global challenges in air quality, climate, and human health.

In the context of aerosol-cloud interactions, important research questions are:

- *What are the physical properties of different types of aerosols and clouds?*

- *What are the radiative processes and feedbacks of different types of aerosols and clouds?*
- *What are the aerosol-cloud-precipitation relationships and their impacts on the Earth Energy Imbalance (EEI) and the climate system.*
- *How to improve the climate model representations of aerosols and clouds and their related processes and thus to improve predicting the societal impacts of future climate change?*

Takuro Michibata · et al, (2025; https://doi.org/10.1007/s40726-025-00382-6) provide a review with a focus on improving the understanding of the effects of anthropogenic aerosols on cloud processes, precipitation, radiation, climate, associated feedback mechanisms, and Earth's energy imbalance (EEI), with a particular emphasis on literature published after the IPCC AR6.

In this deliverable in the frame of CARGO-ACT, we will focus on the atmospheric observations ('in the field') of aerosol and clouds required for research and applications such as the Global Energy and Water Cycle Experiment (GEWEX) in the World Climate Research Programme (WCRP), and applications for climate and air quality research, as expressed in the Global Climate Observing System (GCOS), etc. Speciifc meteorological apllications won't be considered explicitly here.

Additional variables such as trace gases, solar irradiance variables, aerosol precursors, are also required in these research and application areas, and may also be available in the networks represented by the CARGO-ACT consortium, but are not considered here.

2. Inventory of requirements that are relevant for CARGO-ACT based on existing reviews of requirements.

This inventory of requirements concerns CARGO-ACT - relevant observation and/or measurement requirements based on existing international requirements frameworks, review processes with expert panels and in consultation with the wider research community, and otherwise identified stakeholder needs.

The requirements for the observed aerosol / cloud parameters have been extracted from various sources, in particular WMO OSCAR rolling review of requirements (RRR)| The repository of requirements for observation of physical variables and The 2022 GCOS ECVs Requirements (updated in 2025 as GCOS-245-ECVs-Requ-2022-Upd-2025_en.pdf)- see also Essential Climate Variables (ECV).

An ECV is a physical, chemical or biological variable (or group of linked variables) that critically contributes to the characterization of Earth's climate. An ECV product is a measurable parameter needed to characterize the ECV.

The tables below show the requirements for the aerosol and cloud parameters that potentially can be observed from ground-based networks. Nevertheless, it is important to note that this inventory of requirements represents what is required to be met by the totality of the observing system, not by a single instrument.

Column 1 (ID) indicates the source, either from the OSCAR RRR or from the GCOS updated ECV requirements. Both reviews are partly overlapping – so in the below Tables they are merged as best as possible.

Reading the Tables:

Each requirement for an Application Area is expressed quantitatively as a specific geophysical variable to be observed, in a specific domain (vertical layer/s and horizontal coverage), with a performance level quantified in terms of up to ***eight criteria (attributes):*** uncertainty, horizontal resolution, vertical resolution, observing cycle, timeliness and stability (where appropriate). In addition, each requirement (for a geophysical variable) should be prioritized to indicate its relative importance for an Application Area (Application-dependent Technical Priority – ATP (in magenta)).

The "*uncertainty*" quoted in the OSCAR/Requirement characterizes the estimated range of observation errors (Root-Mean-Square-Error - RMSE) on the given variable, with a 68% confidence interval (*1 σ*). Providers of observations should interpret the RRR uncertainty requirement as bias and random error, combined in the root-mean square sense.

To maintain compatibility between OSCAR RRR and GCOS ECV requirements, the Tables below express the GCOS ECV uncertainty requirements divided by a factor of 2 in order to make them directly comparable to the OSCAR RRR uncertainty requirements (1 σ).

For each of the above criteria the table indicates 3 values determined by experts:

- The **"Threshold"** (“**T**”) is the minimum requirement to be met to ensure that data are useful
- The **"Goal" (**“**G**”**)** is an ideal requirement above which further improvements are not necessary
- The **"Breakthrough"** (“**B**”) is an intermediate level between "threshold" and "goal" which, if achieved, would result in a significant improvement for the targeted application. Note that the concept of a "breakthrough" level is different to the concept of the optimum cost-benefit level, since it refers to a significant increase in the value or benefit of an observation, without reference to the costs involved.

In reading the values, **Goal** is marked *blue*, **Breakthrough** *green*, **Threshold** *orange*.

More details about the interpretation of the Tables, the review process and contributors to it can be found in the references given above.

To maintain compatibility between OSCAR RRR and GCOS ECV requirements, the Tables below express the GCOS ECV uncertainty requirements divided by a factor of 2 in order to make them directly comparable to the OSCAR RRR uncertainty requirements (1 σ).

In all Tables below, vertical range/ layer is indicated as

- PBL: Planetary Boundary Layer
- FT: free troposphere
- UTLS: upper tropo- lower stratosphere
- S: stratosphere
- MUS: mid- to upper stratosphere
- M: mesosphere
- TC: total column
- IS-S: In situ surface

Compliance with requirements is indicated as

- G; if Goal is met;
- T; if Threshold is met;
- B, if Breakthrough is met.

In case of vertical profiling capability, the compliance with the horizontal resolution requirement depends on atmospheric dynamics – e.g., advection, horizontal winds, ….: it is therefore indicated as ‘P’ in the Tables below.

2.1 Clouds

Cloud-parameters are essential for numerical weather applications and are also critical for climate modelling.

In CARGO-ACT, we focus on atmospheric chemistry / physics applications as described in the Global Energy and Water Cycle Experiment (GEWEX) (rather than meteorological applications), and applications for climate and air quality research, e.g., through the aerosol-cloud-radiative forcing interactions.

Parameters relevant in this application area are:

- Cloud base height
- Cloud cover
- Cloud ice
- Cloud ice Total Column
- Cloud liquid water (CLW)
- Cloud liquid water (CLW) total column
- Cloud top temperature
- Cloud top height
- Cloud optical depth
- Number of Cloud Condensation Nuclei
- Cloud type
- Cloud drop effective radius

The first cloud base height and column integrated cloud cover (not the vertical profile of cloud cover) can be provided by ceilometer alone, with thousands of stations providing these two parameters worldwide as part of the ground-based synoptic weather station networks. Ice and liquid water microphysical profiles require cloud radar profiling (usually in tandem with lidar) and the major uncertainty in these measurements result from the uncertainty in the retrieval methodology rather than the instrument, hence the similar performance across heterogeneous networks. For example, ice microphysical retrievals have inherent uncertainties due to the variability in the shape and density of ice particles.

Measurements of cloud condensation nuclei are typically made at the surface at aerosol in situ measurement stations. There is no routine profiling capability, and the surface-based measurements are not necessarily co-located with other cloud profiling instrumentation.

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
205	Cloud base height	n/a (2D)	GEWEX (deprecated)		0.5 km 1 km 2 km		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	tentative	1998-10-29	WCRP
ACTRIS	Y				G (< 50 m)		P	< 50 m	G (< 1 min)	G (< 3 d)		firm		
ARM	Y				G (< 50 m)		P	< 50 m	G (< 1 min)	G (< 3 d)		firm		
MPLNET	Y				G (< 50 m)		P	< 50 m	G (< 1 min)	G (< 3 d)		firm		
81	Cloud cover	TC	Climate-AOPC[1] (deprecated)		10 % 15 % 20 %		99 km 100 km 500 km		3 h 4 h 6 h	3 h 6 h 12 h	Global	firm	2007-07-19	AOPC
206	Cloud cover	TC	GEWEX (deprecated)		5 % 10 % 20 %		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	reasonable	1998-10-29	WCRP
GCOS	Cloud cover		ECV		1,5 % 3 % 6 %	0.3 % 0.6 % 1.2 %	25 km 100 km 500 km		1 h 24 h 720 h	1 h 3 h 12 h			2025	GCOS-245-ECVs-Requ-2022-Upd-2025_en.pdf

[1] Atmospheric Observation Panel for Climate (AOPC)

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
ACTRIS	Y	FT PBL			G (< 1%)		P (advective)	< 100 m	G (< 1 h)	< 3 d		firm		
ARM	Y	FT PBL			G (< 1%)		P (advective)	< 100 m	G (< 1 h)	< 3 d		Firm		
MPLNET														
795/ GCOS	Cloud drop effective radius[2]		2.5 Atmospheric Climate Monitoring	0.5	1/2 µm 2/4 µm 4/8 µm 0.5	0.1 /0.2 µm 0.2 /0.4 µm 0.4/0.8 µm 0.5	25 km 100 km 500 km 0.5		60 min 24 h 30 d 0.5	60 min 3 h 12 h 0.5	Global	firm	2025-04-11	GCOS-245: The 2022 ECVs Requirements (GCOS-245)
977	Cloud drop effective radius		Forecasting Atmospheric Composition		0.5 µm 2 µm				3 h 30 d	3 h 12 h	Global	firm	2022-07-27	GAW Expert Team on Atmospheric Composition Network Design and Evolution
978	Cloud drop effective radius		2.6 Atmospheric Composition Forecasting		0.5 µm 2 µm				3 h 30 d	3 h 12 h	Global	firm	2022-07-27	GAW Expert Team on Atmospheric Composition

[2] Stability values given separately for cloud water and ice effective particle size as water/ice. Ohring et al. 2005 specifies stability and accuracy requirements separately for cloud water particle size as percentage forcing, and ice particle size as percentage feedback.
Breakthrough is estimated with a factor of 2 times the goal value, whereas the threshold is calculated with a factor of 4 times the goal value.

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
			and Monitoring											Network Design and Evolution
ACTRIS		FT PBL			50 %		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
ARM		FT PBL			50 %		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
MPLNET														
207 208 209 210	Cloud ice	M MUS FT UTLS PBL	GEWEX (deprecated)		5 % 10 % 20 %		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	tentative	1998-10-29	WCRP
ACTRIS		FT PBL			50% (100 % for T < -40 C)		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
ARM		FT PBL			50% (100 % for T < -40 C)		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
MPLNET														

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
82	Cloud ice Total Column	TC	Climate-AOPC (deprecated)		10 $g.m^{-2}$ 15 $g.m^{-2}$ 20 $g.m^{-2}$		100 km 200 km 500 km		3 h 4 h 6 h	3 h 6 h 12 h	Global	firm	2007-07-19	AOPC
211	Cloud ice Total Column	TC	GEWEX (deprecated)		10 $g.m^{-2}$ 15 $g.m^{-2}$ 20 $g.m^{-2}$		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	tentative	1998-10-29	WCRP
GCOS	Cloud ice water path[3]				0.025 kg m^{-2} 0.05 kg m^{-2} 0.1 kg m^{-2}	0.005 kg m^{-2} 0.01 kg m^{-2} 0.02 kg m^{-2}	25 km 100 km 500 km		1 h 24 h 720 h	1 h 3h 12 h				GCOS-245-ECVs-Requ-2022-Upd-2025_en.pdf
ACTRIS		TC			50 %		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
ARM		TC			50 %		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
MPLNET														
212 213	Cloud liquid water (CLW)	FT PBL	GEWEX (deprecated)		5 % 10 % 20 %		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	tentative	1998-10-29	WCRP

[3] This variable is identical to the also used "Cloud ice water total column" which is given in g/m² and often used in NWP and climate models. The uncertainty values are below would then by re-scaled from kg/m² to g/m². These requirements include: Global, continental, and regional Climate monitoring, feedback and improved knowledge about the interaction between clouds, aerosols and atmospheric gases.

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
794	Cloud liquid water (CLW)	FT PBL	2.5 Atmospheric Climate Monitoring		25 %	5 %	50 km		3 h		Global	reasonable	2019-09-25	GCOS-200: The Global Observing System for Climate: Implementation Needs (Published 2016)
ACTRIS		FT PBL			25 %		P	< 100 m	G (< 1 min)	< 3 d		firm		
ARM		FT PBL			25 %		P	< 100 m	G (< 1 min)	< 3 d		firm		
MPLNET														
84	Cloud liquid water (CLW) total column	TC	Climate-AOPC (deprecated)		5 $g.m^{-2}$ 10 $g.m^{-2}$ 20 $g.m^{-2}$		100 km 200 km 500 km		3 h 4 h 6 h	3 h 6 h 12 h	Global	firm	2007-07-19	AOPC
214	Cloud liquid water (CLW) total column	TC	GEWEX (deprecated)		10 $g.m^{-2}$ 20 $g.m^{-2}$ 50 $g.m^{-2}$		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	tentative	1998-10-29	WCRP

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
GCOS	Cloud liquid water path[4]				0.025 kg m^{-2} 0.05 kg m^{-2} 0.1 kg m^{-2}	0.005 kg m^{-2} 0.01 kg m^{-2} 0.02 kg m^{-2}	25 km 100 km 500 km		1 h 24 h 720 h	1 h 3 h 12 h				GCOS-245-ECVs-Requ-2022-Upd-2025_en.pdf
ACTRIS		TC			25 %		P	< 100 m	G (< 1 min)	< 3 d		firm		
ARM		TC			25 %		P	< 100 m	G (< 1 min)	< 3 d		firm		
MPLNET														
3	Cloud optical depth	TC	CLIC (deprecated)[5]		15 % 20 % 30 %		100 km 200 km 500 km		12 h 16 h 24 h	24 h 30 h 2 d	Global	reasonable	1998-10-29	WCRP
793/ GCOS	Cloud optical depth	TC	2.5 Atmospheric Climate Monitoring	0.5	10 % 20 % 40 % 0.5	2 % 4 % 8 % 0.5	25 km 100 km 500 km 0.5		60 min 24 h 30 d 0.5	60 min 3 h 12 h 0.5	Global	firm	2023-04-27	GCOS-245: The 2022 ECVs requirements (GCOS-245)

[4] This variable is identical to the also used "Cloud liquid water total column" which is given in g m^{-2} and often used in NWP and climate models. The uncertainty values would then by re-scaled from kg m^{-2} to g m^{-2}. These requirements include: Global, continental, and regional Climate monitoring, feedback and improved knowledge about the interaction between clouds, aerosols and atmospheric gases.

[5] Climate and Cryosphere (CliC) is the Climate and Cryosphere project of the World Climate Research Programme (WCRP). **WARNING: the requirements recorded under CLIC are those communicated by the WCRP for the Arctic Climate System Study (ACSYS) project . The last update dates back to 1998.

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
ACTRIS		FT PBL			50% (160 % for T < -40 C)		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
ARM		FT PBL			50% (160 % for T < -40 C)		P	< 100 m	G (< 1 min)	< 3 d		reasonable		
MPLNET														
4	Cloud top height	n/a (2D)	CLIC (deprecated)		0.5 km 0.7 km 1 km		100 km 200 km 500 km		12 h 15 h 24 h	24 h 30 h 2 d	Global	reasonable	1998-10-29	WCRP
85	Cloud top height	n/a (2D)	Climate-AOPC (deprecated)		0.5 km 1 km 2 km		100 km 200 km 500 km		3 h 4 h 6 h	3 h 6 h 12 h	Global	firm	2007-07-19	AOPC
GCOS	Cloud top height				0.15 km 0.3 km 0.6 km	0.03 km 0.06 km 0.12 km	25 km 100 km 500 km		1 h 14 h 720 h	1 h 3 h 12 h				GCOS-245: The 2022 ECVs requirements (GCOS-245)
ACTRIS		FT PBL			G (< 100 m)		P	< 100 m	G (< 1 min)	< 3 d		firm		
ARM		FT PBL			G (< 100 m)		P	< 100 m	G (< 1 min)	< 3 d		firm		

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
MPLNET		FT PBL			G (< 100 m for non-attenuating clouds)		P	< 100 m	G (< 1 min)	< 3 d		firm		
86	Cloud top temperature	Cloud-top	Climate-AOPC (deprecated)		0.3 K 0.4 K 0.6 K		100 km 200 km 500 km		3 h 4 h 6 h	3 h 6 h 12 h	Global	firm	2007-07-19	AOPC
218	Cloud top temperature	Cloud-top	GEWEX (deprecated)		0.5 K 1 K 2 K		50 km 100 km 250 km		3 h 6 h 12 h	30 d 45 d 60 d	Global	reasonable	1998-10-29	WCRP
792/ GCOS	Cloud top temperature	Cloud-top	2.5 Atmospheric Climate Monitoring	0.5	1 K 2 K 4 K 0.5	0.2 K 0.4 K 0.8 K 0.5	25 km 100 km 500 km 0.5		60 min 24 h 30 d 0.5	60 min 3 h 12 h 0.5	Global	firm	2023-04-27	GCOS-245: The 2022 ECVs Requirements
ACTRIS														
ARM														
MPLNET														
152	Cloud type	n/a (2D)	Atmospheric Chemistry (deprecated)				100 km 126 km 200 km		3 h 5 h 12 h	3 d 4 d 7 d	Global	firm	2002-05-24	GAW Report No. 159

Id	Variable	Layer	App Area	ATP	Uncertainty (1 σ)	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
ACTRIS														
ARM														
MPLNET														
1142/ GCOS	Number of Cloud Condensation Nuclei		2.5 Atmospheric Climate Monitoring / ECV linked to aerosol	0.5	20/10 % 40/20 % 60/30 % 0.5		50 km 100 km 500 km 0.5	1 km 5 km	12 h 24 h 30 d 0.5	58 min 24 h 1 y 0.5	Global	firm	2025-04-15	GCOS-245: The 2022 ECVs Requirements (GCOS-245)
ACTRIS														
ARM														
MPLNET														

2.2 Aerosol

The WMO Global Atmosphere Watch (GAW) Programme coordinates global collaboration on the understanding of atmospheric composition, its change, and its interaction with the atmosphere, oceans and biosphere. Members of the GAW observational network provide high-quality atmospheric composition observations including measurements of aerosol properties. In the following discussion the focus is limited to the aerosol properties themselves, not including the aerosol precursors as e.g., carbon, sulfur and nitrogen-bearing trace gases.

The GAW report 197 (2011) Table 2 reproduced here below provides a list of aerosol variables recommended for long-term measurements.

Table 2 - Comprehensive aerosol variables recommended for long-term measurement in the global network

Variable	Frequency of observation
Multiwavelength aerosol optical depth	Continuous
Mass concentration in two size fractions (fine, coarse)	
Mass concentration of major chemical components in two size fractions	
Light absorption coefficient at various wavelengths	
Light scattering and hemispheric backscattering coefficient at various wavelengths	
Aerosol number concentration	
Aerosol number size distribution	
Cloud condensation nuclei number concentration at various super-saturations	
Vertical distribution of aerosol backscattering and extinction	
Detailed size fractionated chemical composition	Intermittent
Dependence of aerosol variables on relative humidity, especially aerosol number size distribution and light scattering coefficient.	

The GAW report 227 (2nd edition, 2016) provides aerosol measurement procedures, guidelines and recommendations.

In “A global analysis of climate-relevant aerosol properties retrieved from the network of Global Atmosphere Watch (GAW) near-surface observatories” (2020) (https://doi.org/10.5194/amt-13-4353-2020), Laj et al. analyse data from almost 90 stations worldwide for a reference year, 2017, to provide a unique and very robust view of the variability of these variables worldwide. Current gaps in the GAW network are analysed and requirements for the Global Climate Monitoring System are proposed.

Similarly to the tables regarding cloud variables, we merged the requirements for the observing system of aerosol properties extracted from the OSCAR RRR and the GCOS ECV

requirements, and analyse the current and potential contributions of the CARGO-ACT consortium to the required observations.

It is important to note that some requirements (e.g., uncertainty, stability, vertical resolution) depend on the aerosol load. The values reported here mostly refer to an aerosol load corresponding to an extinction larger than 2.5 10^{-2} km^{-1} at a wavelength of 532nm wavelength.

Aerosol particle size number distribution, single scattering albedo and chemical composition are measured at the surface using in-situ instrumentation. Variables where networks use the same instrumentation and similar measuring protocols have been combined in the table. As for CCN measurements there is no routine profiling capability.

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
55		Aerosol Extinction Coefficient	MUS UTLS FT PBL M	Climate-AOPC (deprecated)		1.0E-5 m^{-1} 1.5E-5 m^{-1} 2.0E-5 m^{-1}		10 km 20 km 100 km	0.5 km 0.65 km 1 km	24 h 2 d 7 d	7 d 14 d 60 d	Global	reasonable	2007-07-19	AOPC
810		Aerosol Extinction Coefficient	FT PBL	Atmospheric Climate Monitoring		0.1 m^{-1}	0.2 m^{-1}	200 km 500 km	1 km 2 km	7 d		Global	reasonable	2019-09-26	GCOS-200: The Global Observing System for Climate: Implementation Needs (Published 2016)
ACTRIS		Aerosol extinction coefficient profile	PBL FT UTLS			Median value: 1.3E-5 m^{-1} @532nm 1.0E-5 m^{-1} @355nm *(calculated on ext value higher than 2.5e-5 m-1)*		P	Typically 60 m	Measurements performed 5 times per week with run of at least 3 hours (https://	Typically < 3d	Europe	firm		

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
										zenodo.org/records/18016402)					
ARM															
MPLNET															
1139		Aerosol Light Extinction Vertical Profile		2.5 Atmospheric Climate Monitoring	0.5	20 % 40 % 60 % 0.5	10 % 20 % 30 % 0.5	50 km 100 km 500 km 0.5	0.2 km 1 km 2 km 0.5	24 h 30 d 90 d 0.5	26 h 29 d 1 y 0.5	Global	firm	2025-04-15	GCOS-245: The 2022 ECVs Requirements (GCOS-245)
GCOS		Aerosol light extinction vertical profile	FT	ECV		10 % 20 % 30 %	10 % 20 % 30 %	50 km 100 km 500 km	0.2 km 1 km 2 km	1 d 30 d 90 d	0.003 y 0.08 y 1 y				GCOS-245: The 2022 ECVs Requirements
GCOS		Aerosol light extinction vertical profile	S	ECV		10 % 20 %	20 % 40 %	200 km 500 km (lat) x 6000 km (lon)	1 km 1 km UTLS 2 km MUS 2 km	5 d 5 d 30 d	5 d 5 d 1 y				GCOS-245: The 2022 ECVs Requirements

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
ACTRIS		Aerosol extinction coefficient profile	PBL FT UTLS			Median value: 25%@532nm 17% @355nm *(calculated on ext value higher than 2.5e-5 m-1)*		P	G (Typically 60 m)	Measurements performed 5 times per week with run of at least 3 hours (https://zenodo.org/records/18016402)	Typically < 3d	Europe	Firm		
ARM		@355 nm	FT UTLS					P	G	G 10 min	G		firm		
MPLNET		@532 nm with AERONET AOD	PBL FT					P	G	G	G		firm		
63		Aerosol Optical Depth	MUS UTLS FT	Climate-AOPC		0.01 Dimensionless 0.015 Dimensionl		1 km 2 km 10 km		24 h 2 d 7 d	7 d 14 d 60 d	Global	reasonable	2007-07-19	AOPC

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
			PBLM	(deprecated)		ess 0.02 Dimensionless									
66		Aerosol Optical Depth	PBL	Climate-AOPC (deprecated)		0.01 Dimensionless 0.015 Dimensionless 0.02 Dimensionless		1 km 2 km 10 km		24 h 2 d 7 d	7 d 14 d 60 d	Global	reasonable	2007-07-19	AOPC
807		Aerosol Optical Depth	FT PBL	2.5 Atmospheric Climate Monitoring		0.03 Dimensionless	0.02 Dimensionless	5 km 10 km		4 h		Global	reasonable	2019-09-26	GCOS-200: The Global Observing System for Climate: Implementation Needs (Published 2016)
1140/ GCOS		Multi-wavelength Aerosol Optical Depth		2.5 Atmospheric Climate Monitoring/ ECV	0.5	2 % or 0.01AOD 5 % or 0.015 AOD 10 % or 0.03 AOD 0.5	2 % or 0.01 AOD 4 % or 0.02 AOD 10 % or 0.04 AOD 0.5	20 km 100 km 500 km 0.5		14 min 24 h 30 d 0.5	24 h 7 d 30 d 0.5	Global	firm	2025-04-15	GCOS-245: The 2022 ECVs Requirements (GCOS-245)

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
684		Aerosol Absorption Optical Depth	MUSFT PBLM	Climate-AOPC (deprecated)		0.004 Dimensionless 0.01 Dimensionless 0.02 Dimensionless		1 km 2 km 10 km		24 h 2 d 7 d	7 d 14 d 60 d	Global	reasonable	2007-07-19	AOPC
955		Aerosol Optical Depth [550nm]	TC	2.6 Atmospheric Composition Forecasting and Monitoring						60 min 28 d	60 min 12 h	Global	firm	2022-07-01	GAW Expert Team on Atmospheric Composition Network Design and Evolution
964		Aerosol Optical Depth [FM, anthr.]	TC	Forecasting Atmospheric Composition		1 % 5 %				3 h 30 d	12 h 30 d	Global	firm	2022-07-06	GAW Expert Team on Atmospheric Composition Network Design and Evolution
965		Aerosol Optical Depth	TC	2.6 Atmospheric Compositio		1 % 5 %				3 h 30 d	12 h 30 d	Global	firm	2022-07-06	GAW Expert Team on Atmospheric Composition

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
		[FM, anthr.]		n Forecasting and Monitoring											Network Design and Evolution
966		Aerosol Optical Depth [CM, anthr.]	TC	Forecasting Atmospheric Composition		1 % 5 %				3 h 30 d	12 h 30 d	Global	firm	2022-07-06	GAW Expert Team on Atmospheric Composition Network Design and Evolution
967		Aerosol Optical Depth [CM, anthr.]	TC	2.6 Atmospheric Composition Forecasting and Monitoring		1 % 5 %				3 h 30 d	12 h 30 d	Global	firm	2022-07-06	GAW Expert Team on Atmospheric Composition Network Design and Evolution
ACTRIS		AOD - AERONET	TC			0.01 (λ < 400 nm) 0.02 (λ > 400 nm)		P		1 d	< 1d	Europe	firm		

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
ACTRIS		AOD	TC (integrated from aerosol lidar extinction)			0.01-0.02		P	Original lidar profile typically 60m, AOD is column	Measurements performed 5 times per week with run of at least 3 hours (https://zenodo.org/records/18016402)	Typically < 3d	Europe	reasonable		For now, available on request
ARM		AOD - AERONET	TC			0.01 (λ < 400 nm) 0.02 (λ > 400 nm)		P		1d	< 1d		firm		
ARM		AOD @355 nm	TC			0.02		P		G	G		reasonable		
MPLNET		AOD - AERONET	TC			0.01 (λ < 400 nm) 0.02 (λ > 400 nm)		P		1d	< 1d		firm		

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
MPLNET		@532 nm with AERONET AOD	TC PBL			0.02		P		G	G		reasonable		
809		Aerosol Layer Height	n/a (2D)	2.5 Atmospheric Climate Monitoring		1 km	0.5	5 km 10 km		4 h		Global	reasonable	2019-09-26	GCOS-200: The Global Observing System for Climate: Implementation Needs (Published 2016)
ACTRIS		Aerosol Layer Height	PBL FT UTLS			30 m		P	G Original lidar profile typically 60 m	Measurements performed 5 times per week with run of at least 3 hours (https://zenodo.o	Typically < 3d	Europe	reasonable		

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
										rg/records/18016402)					
ARM			PBL FT UTLS			30 m		P	G 30 m	G			reasonable		
MPLNET			PBL FT UTLS			75 m		P	G 75 m	G			reasonable		
968		Aerosol particle light extinction coefficient [532nm]		2.6 Atmospheric Composition Forecasting and Monitoring		0.01 km^{-1} 0.1 km^{-1}				60 min 2 d	60 min 1 y	Global	firm	2022-07-07	GAW Expert Team on Atmospheric Composition Network Design and Evolution
969		Aerosol particle light extinction coefficient [532nm]		Forecasting Atmospheric Composition		0.001 km^{-1} 0.01 km^{-1}				60 min 2 d	3 h 1 y	Global	firm	2022-07-07	GAW Expert Team on Atmospheric Composition Network Design an

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
970		Aerosol particle light extinction coefficient [355nm]		2.6 Atmospheric Composition Forecasting and Monitoring		0.015 km^{-1} 0.15 km^{-1}				60 min 2 d	60 min 1 y	Global	firm	2022-07-07	GAW Expert Team on Atmospheric Composition Network Design and Evolution
971		Aerosol particle light extinction coefficient [355nm]		Forecasting Atmospheric Composition		0.0015 km^{-1} 0.015 km^{-1}				60 min 2 d	3 h 1 y	Global	firm	2022-07-07	GAW Expert Team on Atmospheric Composition Network Design and Evolution
ACTRIS		Aerosol extinction coefficient profile	PBL FT UTLS			Median value: 1.3E-5 m^{-1} @532 nm 1.0E-5 m^{-1} @355 nm *(calculated on ext value higher than 2.5e-5 m-1)*		P	G 60 m	Measurements performed 5 times per week with run of at least 3 hours	Typically < 3d	Europe	firm		

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
										(https://zenodo.org/records/18016402)					
ARM		@355 nm	FT UTLS			0.025 km^{-1} @355 nm		P	G 60 m	G	G		firm		
MPLNET		@532 nm with AERONET AOD	PBL FT UTLS					P	G 75 m	G	G		firm		
1141		Chemical Composition of Aerosol Particles		2.5 Atmospheric Climate Monitoring	0.5	20 µg m^{-3} 40 µg m^{-3} 60 µg m^{-3} 0.5	2 % 2 % 4 % 0.5	50 km 100 km 500 km 0.5	1 km 5 km	24 h 30 d 90 d 0.5	2 h 24 h 1 y 0.5	Global	firm	2025-04-15	GCOS-245: The 2022 ECVs Requirements (GCOS-245)
GCOS		Chemical Composition of Aerosol Particles		ECV		10 % 20 % 30 %	2 % 2 % 4 %	50 km 100 km 500 km	1 km 5 km	24 h 30 d 90 d	2 h 24 h 1 y				GCOS-245: The 2022 ECVs Requirements (GCOS-245)
ACTRIS			IS-S			13-27 % of mass contribution		P	G 5 m	G < 1d					

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
						depending on source factor									
ARM			IS-S			0.1-0.28 µg m^{-3}		P	G 30 m	G < 1d					
NFAN			IS-S			0.02-0.17 µg m^{-3}		P	G 10 m	G < 1d					
GCOS		Aerosol number size distribution		ECV		20 % nr/ 10% size 30 % nr/ 20% size 20% nr fine/ 50 % nr coarse	2 % 4 % 4 %	50 km 100 km 500 km	1 km 5 km	0.04 d 1 d 30 d	0.25 d 30 d 1 y				GCOS-245: The 2022 ECVs Requirements (GCOS-245)
ACTRIS/ ARM/NFAN			IS-S			10% for particles 20-200 nm in diameter 20% for particles 200-800 nm in diameter		P	G <5 m	G < 1d					
GCOS		Aerosol single scattering albedo		ECV		0.05 dimensionless 0.1 dimensionless	0.1 % 0.4 % 1 %	50 km 200 km 500 km	1 km 5 km	0.01 d 1 d 30 d	1 d 7 d 30 d				GCOS-245: The 2022 ECVs Requirements (GCOS-245)

Id		Variable	Layer	App Area	ATP	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
						0.2 dimensionless									
ACTRIS /ARM/NFAN			IS-S			0.09 @ 0.7 0.08 @ 0.8 0.05 @ 0.9 0.03 @ 0.95 0.02 @ 1.0		P		G < 1h	G < 1d				

3. Gaps and remediation

WMO updated its Statement of Guidance for Earth System Application Category Atmospheric Applications (WMO-No. 1392) on 26 May 2026 and the Annexes contain observation network Gap Analyses for a range of atmospheric applications. Here we discuss the observation parameters relevant for CARGO-ACT networks.

Ground-based measurements of almost all cloud variables in the table are made. Both profiling and integrated column measurements are provided and meet the Goal requirements for measurement uncertainty and vertical resolution. These measurements are point (vertical or slant profile) measurements or potentially scanning measurements with limited spatial coverage but provide excellent reference observations for verifying satellite measurement accuracy. The goal requirement for timeliness is met for non-forecasting applications; it has been demonstrated that the much stricter timeliness goal for forecasting applications can be met in principle but that this is not yet met in standard operation mode.

The exception is for measurements of cloud condensation nuclei. These are typically made at the surface at aerosol in situ measurement stations rather than at cloud profiling stations (although both measurement types may be co-located). There is no current operational profiling capability; vertical profiling of cloud condensation nuclei has been demonstrated using in situ instrumentation on UAVs but this is not yet possible at many locations due to airspace restrictions. This also true for the aerosol measurements made at the surface; vertical profiling has been demonstrated using in situ instrumentation on UAVs but airspace restrictions apply in many locations.

Cloud top temperature is also not measured directly by ground-based cloud profiling but is inferred from measured cloud-top height and co-located thermodynamic profiles from radiosonde or numerical weather prediction model.

The tables also show that aerosol variables measured in ACTRIS, MPLNET and ARM generally meet the Goal for climate monitoring applications but should be performed more frequently and delivered more rapidly for meeting the “Goal” requirements for atmospheric composition forecasting and monitoring. The measurements are useful and meet the Threshold requirements for atmospheric composition forecasting and monitoring; more automation and accelerating the data processing and delivery procedures is required in order to meet the Goal requirements.

The currently operational (active) ACTRIS-Cloudnet profiling sites and ARM sites (cloud and aerosol profiling, and aerosol in-situ observations) are provided in the Annex, together with the currently operational (active) ACTRIS-EARLINET and MPLNET aerosol profiling sites, ACTRIS in-situ aerosol composition (aerosol mass spectrometry) and ACTRIS in-situ cloud condensation nuclei sites.

For both aerosol and clouds, the spatial coverage of CARGO-ACT networks is essentially limited to Europe (for ACTRIS) and the US for MPLNET and ARM – see tables below and CARGO-ACT deliverable 4.3 for more details.

4. Remediation

No remedial actions are required for **measurement uncertainty** and **vertical resolution**; the current ground-based observations of clouds and aerosol are capable of meeting the Goal requirements and can make vertically resolved profiles with high resolution even where only integrated quantities are currently requested.

No remedial actions are required for the **observation cycle** for cloud measurements and the majority of aerosol measurements. The cloud profiling instruments operate continuously at temporal resolutions of less than 30 s and aerosol profiling instruments can also operate with similar nominal raw resolution. Subsequent temporal averaging of certain aerosol parameters to achieve sufficient sensitivity still results in an observation cycle that meets requirements. Note that while autonomous versions of Raman lidars are capable of continuous operation and providing aerosol parameters with sufficient accuracy, not all large laboratory-based aerosol profiling instruments have continuous operation capability.

For **timeliness**, remedial actions are only required for forecasting applications, as the Goal requirement is met for non-forecasting applications by ground-based observations of clouds and aerosol. Automated calibration and processing chains are already implemented, and the remedial action required is to enable more rapid data delivery from the instruments to the processing centre.

The major issue for ground-based cloud and aerosol observational networks is the **horizontal resolution**; the measurement stations require significant infrastructure and are sparsely distributed. Remediation actions to improve the spatial distribution are to be discussed in Deliverable 4.3 “CARGO-ACT site distribution strategy”.

The above statements are not true for measurements of cloud condensation nuclei. Remedial actions for surface measurements must start with wider deployment of instrumentation across current in situ aerosol measurement stations. Vertical profiles are much more challenging and may not be possible to achieve at most locations with current technological options.

ANNEX

ACTRIS-Cloudnet Active cloud profiling sites

Site name	Latitude	Longitude	Elevation (m)
Bucharest, Romania	44.344	26.012	77
Cabauw, Netherlands	51.968	4.927	-1
ATTO-Campina, Brazil	-2.181583	-59.021861	30
Cluj-Napoca, Romania	46.7678	23.54006	459
Galați, Romania	45.435	28.037	40
Granada, Spain	37.164	-3.605	680
Hyytiälä, Finland	61.844	24.287	150
Invercargill, New Zealand	-46.4173	168.3307	5
Jülich, Germany	50.908	6.413	111
Kappelrodeck , Germany	48.59729	8.10794	199
Kenttärova, Finland	67.987	24.243	345
Lampedusa, Italy	35.5183	12.6303	45
L'Aquila, Italy	42.383	13.315	683
Leipzig , Germany	51.353	12.435	126
Limassol, Cyprus	34.677	33.038	10
Lindenberg, Germany	52.208	14.118	104
Maïdo, La Réunion, France	21.079	55.383	2200
Melpitz, Germany	51.53	12.93	86
Mindelo, Cabo Verde	16.8778	-24.995	13
Munich, Germany	48.148	11.573	538
Neumayer, Antarctica	-70.66	-8.284	43
Norunda, Sweden	60.086	17.479	46
Ny-Ålesund, Norway	78.923	11.922	19
Palaiseau, France	48.717	2.209	156
Payerne, Switzerland	46.813	6.944	491
Potenza, Italy	40.601	15.724	760
Troll Station, Antarctica	-72.01	2.545	1320
Vehmasmäki, Finland	62.738	27.543	190

ARM Active Sites (cloud and aerosol profiling, and aerosol in-situ observations)

Site name	Latitude	Longitude	Elevation (m)
Southern Great Plains (SGP), US	36.608	-97.488	316
Utqiaġvik (NSA), US	71.323	-156.615	8
Graciosa (ENA), Portugal	39.092	-28.031	30
Bankhead National Forest (BNF), US	34.342	-87.338	293
Phoenix (DST), US	33.606726	-112.166912	379

ACTRIS-EARLINET Active aerosol profiling (multi-wavelength lidar) sites

Site name	Latitude	Longitude	Elevation (m)
Antikythera, Greece	35.8600	23.3100	193
Andøya, Norway	69.2780	16.0080	380
Athens, Greece	37.9600	23.7800	212
Barcelona, Spain	41.3930	2.1200	115
Belsk, Poland	51.8300	20.7800	180
Belgrade, Serbia	44.8557	20.3913	89
Bucharest, Romania	44.3480	26.0290	93
Cabauw, Netherlands	51.9700	4.9300	0
Cluj-Napoca, Romania	46.7682	23.5509	405
Clermont-Ferrand, France	45.7610	3.1110	420
Dushanbe, Tajikistan	38.5594	68.8561	864
Evora, Portugal	38.5678	-7.9115	293
Garmisch-Partenkirchen, Germany	47.4770	11.0640	730
Granada, Spain	37.1640	-3.6050	680
Ispra, Italy	45.8167	8.6167	209
Kuopio, Finland	62.7333	27.5500	190
L'Aquila, Italy	42.3440	13.3270	683
Lecce, Italy	40.3330	18.1000	30
Leipzig, Germany	51.3500	12.4330	125
Lille, France	50.6117	3.1417	60
Limassol, Cyprus	34.6771	33.0376	11
Madrid, Spain	40.4565	-3.7257	669
Mindelo, Capo Verde	16.8778	-24.9954	30
Naples, Italy	40.8380	14.1830	118
Hohenpeissenberg, Germany	47.8019	11.0119	974
Palaiseau, France	48.7130	2.2080	156
Potenza, Italy	40.6000	15.7200	760
Payerne, Switzerland	46.8167	6.9333	491
Roma-Tor Vergata, Italy	41.8330	12.6500	110
Saint-Denis, La Reunion, France	-20.9020	55.4850	84
Sofia, Bulgaria	42.6537	23.3874	610
Thessaloniki, Greece	40.6300	22.9500	50

MPLNET Active Sites (aerosol profiling)

Site name	Latitude	Longitude	Elevation (km)
Appalachian_State	36.215	-81.694	1.080
Barcelona	41.386	2.117	0.125
CARTEL	45.379	-71.931	0.251

Cambridge_Bay	69.121	-105.040	0.002
Douliu	23.712	120.545	0.060
EPA-NCU	24.967	121.181	0.135
El_Arenosillo	37.105	-6.734	0.059
GSFC	38.993	-76.840	0.050
Izana	28.309	-16.499	2.401
Kaohsiung	22.676	120.292	0.015
London-CDN	43.008	-81.270	0.258
OPAL	79.990	-85.939	0.005
SEDE_BOKER	30.855	34.782	0.480
Sandy_Cove	44.469	-63.553	0.019
Santa_Cruz_Tenerife	28.472	-16.247	0.052
Silpakorn_Univ	13.819	100.041	0.072
Singapore	1.298	103.780	0.030
South_Pole	-89.980	-24.800	2.835
Stony_Plain	53.547	-114.109	0.766
Toronto_Downtown	43.660	-79.399	0.152
UMBC	39.255	-76.710	0.062
Univ_of_Nevada-Reno	39.541	-119.814	1.410
Univ_of_Saskatchewan	52.132	-106.633	0.504
Xitun	24.162	120.617	0.091

ACTRIS Active in-situ aerosol composition (aerosol mass spectrometry) sites

Site name	Latitude	Longitude	Elevation (m)
Barcelona, Spain	41.3875	2.1153	80
Birkenes, Norway	58.3885	8.2520	219
Bucharest (RADO), Romania	44.3439	26.0119	77
Dublin, Ireland	53.3125	6.2600	19
Hohenpeissenberg, Germany	47.8015	11.0096	975
Hyytiälä, Finland	61.8500	24.2833	181
Jungfraujoch, Switzerland	46.5475	7.9850	3578
Melpitz, Germany	51.5250	12.9277	86
Monte Cimone, Italy	44.1932	10.7014	2165
Ny Ålesund (Zeppelin), Norway	78.9072	11.8867	474
Palaiseau (SIRTA), France	48.7160	2.2120	156
Payerne, Switzerland	46.8131	6.9447	489
Puy de Dôme, France	45.7722	2.9649	1465
Villeneuve d'Ascq, France	50.6110	3.1404	70

ACTRIS Active in-situ cloud condensation nuclei sites

Site name	Latitude	Longitude	Elevation (m)
Hyytiälä, Finland	61.8500	24.2833	181
Ny Ålesund (Zeppelin), Norway	78.9072	11.8867	474