



CHALMERS
UNIVERSITY OF TECHNOLOGY



Probing Aerosol–Weather–Cloud Interactions with Multi-Instrument Measurements at the Onsala Space Observatory

Cloud-Aerosol Measurements at the Onsala Observatory

Degree project report in Physics

VICTOR WIDÉEN

DEPARTMENT OF PHYSICS AND ASTRONOMY

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

www.chalmers.se

DEGREE PROJECT REPORT 2026

Probing Aerosol–Weather–Cloud Interactions with Multi-Instrument Measurements at the Onsala Space Observatory

Cloud-Aerosol Measurements at the Onsala Observatory

VICTOR WIDÉEN



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Physics and Astronomy
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026

Probing Aerosol–Weather–Cloud Interactions with Multi-Instrument Measurements
at the Onsala Space Observatory
Cloud-Aerosol Measurements at the Onsala Observatory
VICTOR WIDÉEN

© VICTOR WIDÉEN, 2026.

Supervisor: Faustine Mascout, Department of Physics and Astronomy
Examiner: Rüdiger Haas, Department of Physics and Astronomy

Degree project report 2026
Department of Physics and Astronomy
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

Cover: Picture of the Onsala Space Observatory.

Typeset in L^AT_EX
Gothenburg, Sweden 2026

Probing Aerosol–Weather–Cloud Interactions with Multi-Instrument Measurements
at the Onsala Space Observatory
Cloud-Aerosol Measurements at the Onsala Observatory
VICTOR WIDÉEN
Department of Physics and Astronomy
Chalmers University of Technology

Abstract

One of the key uncertainties in our understanding of the climate system is the production of aerosols and their interactions with clouds. The Onsala Space Observatory (OSO) provides an ideal site, at the land-sea interface, to address this knowledge gap, offering a comprehensive set of instruments for integrated *in situ* and remote-sensing observations. This thesis investigates the production mechanisms of aerosols - primarily sea salts - and their influence on clouds from late 2024 to early 2025, while confirming the local climate properties of the OSO site. To supplement existing observatory data, ground measurements at OSO and a drone flight at a nearby site were conducted using a Portable Optical Particle Spectrometer (POPS). Our findings confirm the previously established climatic baselines for the OSO site and highlight several key atmospheric relationships. Specifically, strong winds originating from the ocean correlate with high local aerosol concentrations, particularly sea salts; precipitation events drive aerosol scavenging (washout); and higher aerosol loading is directly associated with increased local cloud cover.

Keywords: aerosols, clouds, wind, rain, Onsala, Sea Salt Aerosols (SSA), atmosphere, climate, coastal, marine.

Acknowledgements

Thanks to Rüdiger Haas for being my examiner and to Faustine Mascout for being my project supervisor offering her experience and guidance every step of the way. Also thanks to Valery Chernoray and his student team for allowing us to fit our instrument to their fixed-wing drone and making the effort to make it attachable, and thanks to Emil Ellenius for being the drone pilot. Also thanks to Patxi Rodriguez Acero for trying to find appropriate circumstances for us to fly our instrument on his rotary wing drone, even though that didn't end up working out.

Victor Widéen, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AERONET	AErosol RObotics NETwork
AOD	Aerosol Optical Depth
ASI	All Sky Imager
CCN	Cloud Condensation Nuclei
CN	Cloud Nuclei
GCCN	Giant Cloud Condensation Nuclei
HATPRO	Humidity And Temperature PROfiler
IN	Ice Nuclei
IWV	Integrated Water Vapor
LWP	Liquid Water Path
MBL	Marine Boundary Layer
OSO	Onsala Space Observatory
PBL	Planetary Boundary Layer
POPS	Portable Optical Particle Spectrometer
PW	Precipitable Water
RH	Relative Humidity
SSA	Sea Salt Aerosols
TCWV	Total Column Water Vapor

Contents

List of Acronyms	ix
List of Figures	xiii
List of Tables	xvii
1 Introduction	1
1.1 Background	1
1.2 Purpose & Goal	2
2 Theory	5
2.1 Earth's Atmosphere	5
2.2 Aerosols	6
2.2.1 Marine & Sea Salt Aerosols	7
2.2.2 Dust Aerosols	8
2.2.3 Miscellaneous Particles	8
2.3 Physical Quantities	9
2.3.1 Particle Size Distribution	9
2.3.2 Aerosol Optical Depth	12
2.3.3 Ångström Exponent	13
2.3.4 Atmospheric Water Contents	14
2.4 Clouds	15
2.4.1 Cloud Classification	15
2.4.2 Cloud Formation	19
2.5 Aerosol Effects	20
2.5.1 Direct Effects	20
2.5.2 Indirect Effects	21
2.5.2.1 Cloud Condensation Nuclei	21
2.5.2.2 Effects on Clouds	23
2.6 Onsala Site	25
3 Methods	29
3.1 Instruments & Models	29
3.1.1 AERONET	29
3.1.2 HATPRO Microwave Radiometer	32
3.1.3 Vaisala Weather Station	33
3.1.4 All Sky Imager	34

3.1.5	Portable Optical Particle Spectrometer (POPS)	35
3.1.6	Global Navigation Satellite System (GNSS)	36
3.1.7	Copernicus Atmosphere Monitoring Service (CAMS)	37
3.2	Data Analysis Methods	40
3.2.1	2024-2025 Period	40
3.2.2	Cloud Cover Categorization	42
3.3	POPS Measurements	44
3.3.0.1	Drone Flight	44
3.3.0.2	Ground Measurements	45
4	Results	47
4.1	Data Sets	47
4.1.1	Availability	47
4.1.2	Comparisons	48
4.1.2.1	Aerosol Optical Depth (AOD)	48
4.1.2.2	CAMS AOD Sources	50
4.1.2.3	Water Vapor	51
4.1.2.4	Microwave radiometer HATPRO & Weather Station	53
4.1.2.5	Microwave radiometer HATPRO & CAMS reanalysis	55
4.1.2.6	CAMS SSA Mixing Ratios	57
4.2	Characteristics of the OSO Site	58
4.3	2024-2025 Period Results	60
4.3.1	Wind-Particle Connection	60
4.3.2	Rain Impact	68
4.3.3	Cloud Cover Connection	70
4.4	POPS Results	74
4.4.1	Drone Flight (2026-05-05)	74
4.4.2	Ground Measurements	77
5	Conclusion	81
5.1	Summary of Results	81
5.2	Commentary & Future Outlook	82
	Bibliography	85
A	Cloud Cover Categories	I
B	Wind-Cloud Cover Correlation Attempt	V
C	AOD-Temperature Connection Attempt	VII
D	Full 2024-2025 Period	IX

List of Figures

1.1	Radiative-Forcing bar chart: ©IPCC 2007: WG1-AR4 [4].	2
1.2	Cloud fields over the Swedish West Coast [5].	2
2.1	Main natural sources of aerosols.	6
2.2	Schematic of production mechanisms of the first two marine aerosol formation mechanisms (film droplets and jet droplets).	7
2.3	Example of classification scheme for the study of aerosol sizes.	9
2.4	Typical number and volume distributions of atmospheric particles according to different modes (adapted from Fig. 8.10 of [14]).	11
2.5	Type examples of some cloud genera, from left to right: Cirrus (© Stephen Burt), Cirrocumulus (© George Anderson), Cirrostratus (© Usynina Luybov) [36].	16
2.6	Type example of Altocumulus clouds (© Kwong Hung Tam) [36].	17
2.7	Type examples of some cloud genera, from left to right: Altostratus (© Frank Le Blancq), Nimbostratus (© Martin Gudd), Stratocumulus (© Michael Bruhn) [36].	17
2.8	Type examples of some cloud genera, from left to right: Stratus (© Michael Bruhn), Cumulus (© Stephen Burt), Cumulonimbus (© Antonio J. Galindo) [36].	18
2.9	Cloud types and associated altitude levels from the Australian Government Bureau of Meteorology [44].	19
2.10	Sizes, concentrations, and fall velocities (within the Earth’s reference frame) of particles in a cloud [47].	23
2.11	Picture of the Onsala Space Observatory site © Roger Hammargren.	26
2.12	Map of Swedish West coast, with Onsala marked in red and Gothenburg marked in purple.	26
3.1	Global coverage of the AERONET network [52].	30
3.2	The AERONET sun-photometer at the OSO.	30
3.3	The HATPRO microwave radiometer on-site at the OSO.	32
3.4	The weather station located at the OSO.	33
3.5	Image of sky camera near the Weather Station, as well as an example image from its archive.	34
3.6	Image of the POPS instrument in one of its protective boxes.	35
3.7	Two GNSS receivers.	36

3.8	Map of arbitrary CAMS data at an arbitrary time step (PM2.5 at 2024-12-02 12:00, given in $\mu\text{g}/\text{m}^3$) showing data grid structure. Coastal OSO location marked in red. Gothenburg location marked above it in purple.	38
3.9	Combined plot of various data points from AERONET, HATPRO, Weather Station, and CAMS. Constructed for manual data analysis. .	41
3.10	The POPS instrument installed in the drone chassis.	44
3.11	Picture of fully-equipped drone prior for flight.	44
3.12	Drone coming in for landing at end of flight.	44
3.13	POPS instrument secured at the OSO site and pointed toward the West coast.	45
4.1	Data availability during the 2024-2025 period from October 1st 2024 to March 31st 2025.	47
4.2	Comparison between AERONET $\text{AOD}_{500\text{nm}}$ data and CAMS $\text{AOD}_{550\text{nm}}$ data. Transparent dots/lines of other colors represent data for AOD of other wavelengths, where redder equals longer wavelengths and bluer equals shorter wavelengths.	49
4.3	Comparisons between different CAMS $\text{AOD}_{500\text{nm}}$ sources, alongside total $\text{AOD}_{500\text{nm}}$	50
4.4	Precipitable Water [mm] (AERONET), Integrated Water Vapor [kg/m^2] (HATPRO) and Total Column Water Vapor [kg/m^2] (CAMS) plotted together over the periods 2024-12-09 to 2024-12-24, 2024-12-24 to 2025-01-15, and 2025-02-28 to 2025-03-23. Vertical lines represent rain flags assigned by the HATPRO instrument.	52
4.5	Weather Station data plotted alongside radiometer HATPRO data. .	53
4.6	Weather Station data subtracted from HATPRO data to obtain differences.	53
4.7	Windrose of HATPRO data from 2025-01-01 to 2025-01-15.	54
4.8	Windrose of Weather Station data from 2025-01-01 to 2025-01-15. . .	54
4.9	Comparisons between CAMS reanalysis and HATPRO profile data of RH and temperature.	56
4.10	CAMS SSA mixing ratios for different diameter ranges at all relevant pressure levels averaged over the entire 2024-10-01 to 2025-03-31 period. .	57
4.11	AERONET data for precipitable water, $\text{AOD}_{500\text{nm}}$, and $\alpha_{500-870\text{nm}}$, categorized into bins to obtain distributions.	58
4.12	CAMS data for $\text{AOD}_{550\text{nm}}$ categorized into bins to obtain distribution. .	59
4.13	Three examples of strong Western winds influencing aerosol concentrations, in particular SSA fractions. Periods are — from left to right — 2024-11-14 to 2024-11-16, 2025-01-05 to 2025-01-08, and 2025-02-27 to 2025-03-02.	61
4.14	Three examples of strong Eastern winds influencing aerosol concentrations. Periods are — from left to right — 2024-10-12 to 2024-10-13, 2025-10-25 to 2025-10-27, and 2025-03-21 to 2025-03-24.	63

4.15	Three potential counter-examples to previously established phenomena. Periods are — from left to right — 2024-10-16, 2024-11-22 to 2024-11-24, and 2025-02-19 to 2025-02-21.	65
4.16	Histograms of AOD and PM fractions over the October 2024 to March 2025 period, filtered based on wind origins.	66
4.17	SSA mixing ratios averaged over West wind conditions during the 2024-2025 period.	67
4.18	SSA mixing ratios averaged over East wind conditions during the 2024-2025 period.	67
4.19	SSA mixing ratios averaged over North wind conditions during the 2024-2025 period.	68
4.20	SSA mixing ratios averaged over South wind conditions during the 2024-2025 period.	68
4.21	Three examples of rain influence on various quantities. Periods are — from left to right — 2024-10-06 to 2024-10-08, 2024-12-24, and 2025-01-27.	69
4.22	Mean CAMS AOD and PM over the October 2024 to March 2025 period categorized by defined cloud cover categories.	70
4.23	Mean CAMS SSA mixing ratios over the October 2024 to March 2025 period categorized by defined cloud cover categories.	71
4.24	Mean weather station temperature and mean CAMS temperature profiles over the October 2024 to March 2025 period categorized by defined cloud cover categories.	71
4.25	Mean CAMS TCWV and relative humidity profiles over the October 2024 to March 2025 period categorized by defined cloud cover categories.	72
4.26	2D and 3D plots of flight path during drone flight. Larger dots represent the start and end points of applicable measurements. On-location ground level starts at 85 m altitude.	74
4.27	Altitude profile of POPS measurements from drone flight data, with calculated median concentrations.	75
4.28	Average concentrations of each aerosol particle size bin.	75
4.29	Median concentrations at altitudes for each of the aerosol particle size bins. Right figure is zoomed in toward the larger size bins.	76
4.30	Meteorological conditions during drone flight, represented in all plots by the green line.	77
4.31	Ground measurements during 2025-05-09 coupled with miscellaneous coinciding meteorological data.	79
4.32	Total aerosol concentrations from ground measurements during 2025-05-09.	79
4.33	Ground measurements during 2025-05-11 coupled with miscellaneous coinciding meteorological data.	80
4.34	Total aerosol concentrations from ground measurements during 2025-05-11.	80
B.1	Average wind speeds from the West for each cloud cover category. . .	V
B.2	Average wind speeds from the East for each cloud cover category. . .	V

B.3	Average wind speeds from the North for each cloud cover category. . .	V
B.4	Average wind speeds from the South for each cloud cover category. . .	V
C.1	Measured ground temperatures divided into CAMS AOD bins. . . .	VII

List of Tables

3.1	Type examples of the seven established cloud cover categories 0-6, from top to bottom.	43
4.1	Average values and values corresponding to count maxima for AERONET PW, AOD _{500nm} , and $\alpha_{500-870nm}$ data.	58

1

Introduction

1.1 Background

In the modern state of human activity, the pertinence of the challenges of the Anthropocene age calls for a deeper understanding of our shared climate systems, and highlights the growing importance of research into every facet of its complex dynamics.

One such influential component are aerosols, which are microscopic particles suspended in the air — released by human activity as well as nature by various production mechanisms — and are prevalent in the lower altitudes of the Earth’s gaseous envelope. These influence many components of the atmosphere, such as the formation of clouds, which form from the condensation of water vapor on these suspended aerosols. Variations in physical parameters such as humidity, temperature, or aerosol quantity can impact the existence, evolution, and dissipation of clouds. The latter — being systems that interact with their environment — have their own diverse environmental effects, including radiative forcing and precipitation. However, uncertainties remain regarding the precise effects of these parameters on clouds (their life cycle and individual properties), their spatial organization, and, *a fortiori*, their impact on the climate [1]. In fact, the unknown and entangled interactions and connections between clouds and aerosols persist as one of the most significant uncertainties in our estimates of climate forcing [2] [3] (see the error bars on aerosol effects in Figure 1.1).

When looking at a cloud field on a sufficiently large scale (a few hundred kilometers), observed by satellite for instance, one quickly notices, under certain conditions, an apparent organization or structuring (example provided in Figure 1.2). The question that arises is whether this organization is governed by fundamental laws, and thus whether it can be understood within a specific theoretical framework. In other words, is this organization random or self-organized with a certain degree of order? Is it possible to predict or reproduce these structured cloud fields from thermodynamic parameters (e.g., temperature, humidity, aerosol type)? And conversely, is it possible to determine these parameters from a cloud structure? Answering these questions is invaluable in climate science, and they guide the research work presented in this study. Broadly speaking, it is in particular the production of aerosols and the interactions between them, clouds, and water vapor that present the core of this study. Additionally, general inquiries into typical aerosol and climatic be-

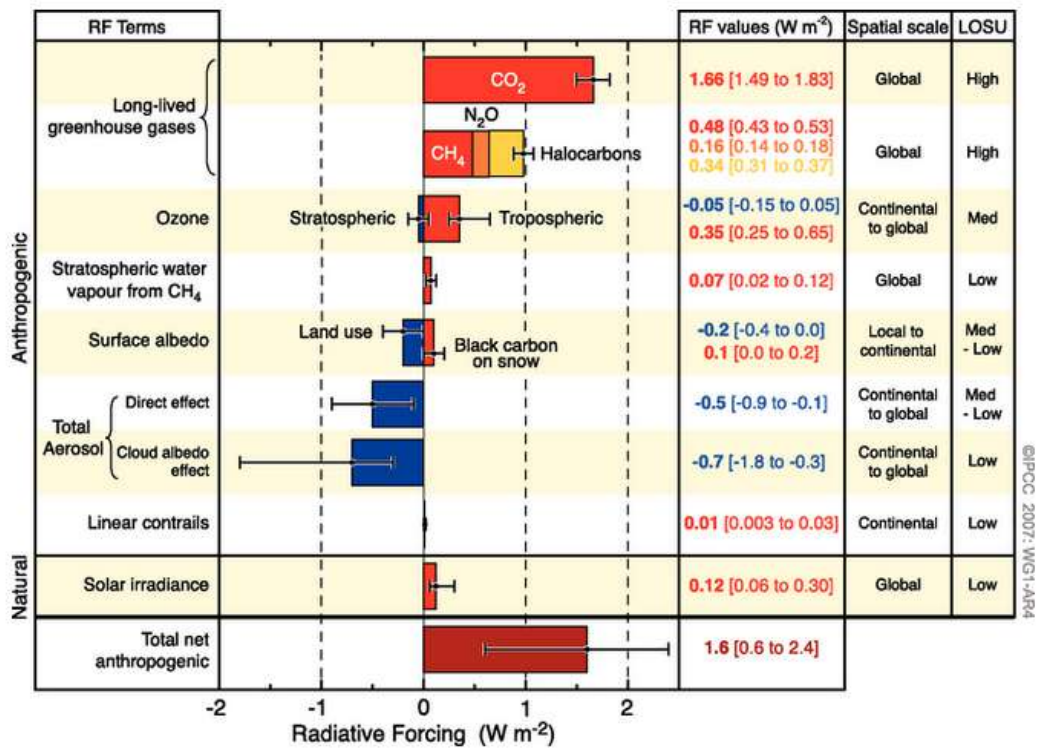


Figure 1.1: Radiative-Forcing bar chart: ©IPCC 2007: WG1-AR4 [4].



Figure 1.2: Cloud fields over the Swedish West Coast [5].

haviors will be examined. In general, this research subject aims to improve our understanding of these interactions through in-situ measurements.

1.2 Purpose & Goal

In an attempt to provide some clarity to the questions mentioned above, we set out to investigate the production mechanisms and climactic influences of aerosols,

particularly their effects on cloud formation at the coastal Onsala Space Observatory site, just south of the city of Gothenburg, Sweden. This site is set mostly in a pristine oceanic region, meaning its conditions can often be considered close to a pre-industrial environment [6]. This choice allows us to analyze the natural component of aerosol-vapor-cloud interactions and to set aside, as a first step, the effects of anthropogenic aerosols.

The guiding thread of this project is punctuated by one primary objective: to collect *in-situ* data to characterize the physical properties of natural aerosols and their vertical distribution in a pristine context at the land/sea interface. For this purpose, numerous instruments and methods of data collection at the site were utilized. This provided us with data on cloud, weather, and atmospheric conditions over several spans of time, especially focusing on the periods October 2024 to March 2025, and the first half of 2026.

In the following sections, we will provide a review of current knowledge on aerosols and clouds, and present the context, motivation, and methodology of this study. Thereafter, we present the results, and any relevant conclusions we can draw from them.

2

Theory

The concept of 'aerosols' refers to fine solid or liquid particles suspended and prevalent in a gaseous medium, in particular Earth's atmosphere. They constitute a dispersed phase, which together with the medium in which they evolve, form a stable colloid [7]. Aerosols are regularly introduced into the atmosphere via various different processes, both natural and anthropogenic. They travel, transform, and interact both with each other and with hydrometeors, eventually impacting our health, air quality, and climate [8].

The means by which aerosols impact the environment and the larger climate system are numerous, but among them are their influence on radiative forcing, cloud formation, precipitation, extreme weather, and large-scale circulations. The exact effects, however, also depend on the specific properties of their surrounding environment [2] [9]. The details of this influence is what will ultimately be discussed below, but we will begin with a general discussion of the Earth's atmosphere.

2.1 Earth's Atmosphere

Earth's atmosphere is typically divided into — in increasing altitude — the troposphere, stratosphere, mesosphere, and thermosphere, with associated -pauses dividing them. This study will mainly focus on the lowermost layer: the troposphere, covering altitudes from 0 to 15 km, as this is the part of the atmosphere primarily responsible for the Earth's weather and the hosting of clouds [10].

Within the troposphere, temperature typically decreases linearly with altitude. It is heated both by radiation from the Sun and by heat from the Earth's surface, but primarily the latter, creating a differential temperature profile that supports convection currents which make the troposphere a relatively turbulent and well-mixed environment. The presence of moist air parcels may additionally cause temperature mismatches between different altitudes, further contributing to convection [10].

The troposphere is bounded from above by the tropopause, which is marked by a region of temperature inversion, disrupting convection. Due to this, it acts as a strong barrier between the troposphere and the stratosphere, resulting in very little mixing between these two layers of the atmosphere [10]. As such, excluding contributions from sunlight, the troposphere can be approximated as an enclosed environment.

The part of the troposphere below 1–2 km in altitude is known as the *planetary boundary layer* (PBL) [11], bounding it from below, and is where roughly 80% of atmospheric aerosol mass concentrates [10]. This is the particular region of the troposphere which we will lay most of our focus on. Another division of the troposphere is via the so-called *marine boundary layer* (MBL), which can exist around coastal and oceanic environment, and has a significant range of possible altitudes. Under certain conditions, its altitude may be no more than a few hundred meters, and sometimes less than even 100 m [11] [12]. Boundary layers such as these are typically characterized by subtle changes in certain meteorological and compositional characteristics between layers [12].

As the Earth and the atmosphere absorb heat, that same amount of heat is eventually expelled by the Earth into space. This balance of ingoing and outgoing energy is referred to as *radiative balance*, under which the temperature of the atmosphere equilibrates around a certain temperature range. Some effects, such as the well-known greenhouse effect, may over time shift this equilibrium toward higher or lower temperatures. This shifting is referred to as *radiative forcing* [10].

2.2 Aerosols

The collection of particles that can be categorized as aerosols is as diverse as the multifaceted effects they might have on the wider climate [13]. Efforts in classifying aerosols can take several different routes, such as classifying them by their size, chemical composition, or place of origin. For example, they may be categorized by origin into the categories of natural (see Figure 2.1) or anthropogenic aerosols, being those emitted by natural sources versus those emitted by human activity. Globally, natural aerosols represent between 80% and 90% of emitted particle mass fluxes, whereas the remainder is anthropogenic [14].



Figure 2.1: Main natural sources of aerosols.

A less human-focused classification of origin is the division into **primary** vs. **secondary** particles. **Primary particles** are those which are released directly into the atmosphere by some manner of ground-based processes [13]. These types of aerosols are typically considered to make up 75% of global aerosol mass [10]. **Secondary particles**, meanwhile, refer to those that form in the atmosphere by some means of chemical action or accumulation, such as the oxidation of gaseous precursors [13]. These make up the remaining 25% of global aerosol mass [10].

With this categorization established, we will move onto descriptions of specific aerosols.

2.2.1 Marine & Sea Salt Aerosols

Because oceans cover $> 70\%$ of Earth's surface, one of the largest contributors to global aerosol loading are sea salt aerosols (SSAs) [1], also known as sea spray aerosols. As their name implies, these are a type of primary marine aerosol consisting mainly of inorganic salts [13]. It is SSAs that are at the heart of this project.

SSAs are produced mainly by wind friction over breaking waves and wave crests in marine and coastal environments. Due to this, the production rate of these aerosols is evidently highly dependent on wind speed. Three main mechanisms for this production exist: film droplets, jet droplets, and spume droplets [15] [16] [17]. The first two of these mechanisms involve rising air bubbles trapped in the ocean following the turbulent motion of the water caused by wind. When these bubbles reach the surface and burst, aerosols from the surface film are ejected into the atmosphere. These are what are referred to as film droplets, and typically have a size range of $0.5\text{--}5\mu\text{m}$. Once the air bubble has burst, a water jet forms and subsequently breaks into several droplets with diameters between $3\text{--}50\mu\text{m}$. It is these droplets that are referred to as jet droplets. These first two formation mechanisms are visualized in Figure 2.2. The third production mechanism arises from winds tearing particles directly from the crest of waves and into the atmosphere. This typically occurs for wind velocities in excess of 30 km/h . The produced droplets are referred to as spume droplets, and typically have diameters exceeding $20\mu\text{m}$. While the full size range of SSAs thus covers the wide span from 500 nm to above $50\mu\text{m}$ in diameter, number concentrations are typically highest among the smaller diameters [1] [13]. The number concentrations of these droplets normally lie around $10/\text{cm}^3$, but

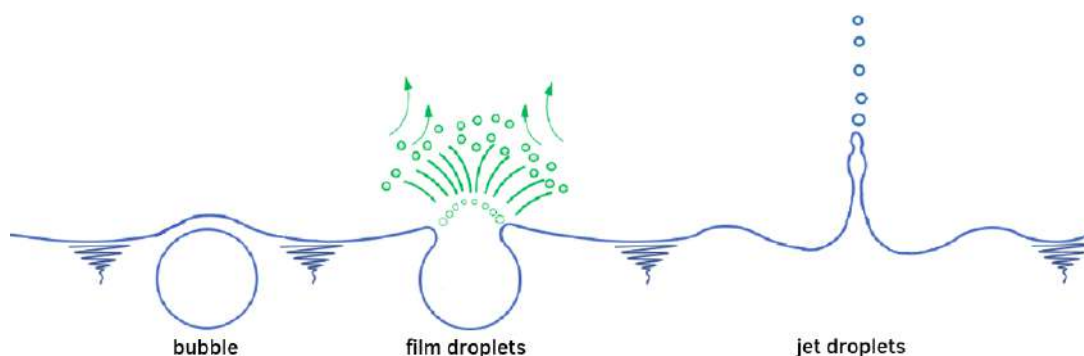


Figure 2.2: Schematic of production mechanisms of the first two marine aerosol formation mechanisms (film droplets and jet droplets).

wind can increase that concentration to as high as $50/\text{cm}^3$ or more in strong wind conditions [13].

As mentioned, SSAs are one type of aerosol in the wider category of marine aerosols.

Marine aerosol masses consist primarily of sodium chloride (NaCl) — i.e. sea salt aerosols — typically making up 85% of number concentrations, but certain ions present in seawater, such as sulfate (SO_4^{2-}), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) can also be observed [18]. These aerosols also sometimes contain an organic fraction, the concentration of which depends on the biological activity of the local ocean [19]. Additionally, sea salts are highly reactive with other species in the atmosphere, and as such their chemical composition can change during transport [20] [21] [22]. Thus, many factors can affect the production, nature, and transport of marine aerosols.

Since oceans cover the majority of the planet (about 70% of its surface), marine aerosols account for the largest contribution to global aerosol load, surpassing both anthropogenic aerosols and those emitted from other natural sources [23], especially elevating overall aerosol number densities around coastal and oceanic regions.

2.2.2 Dust Aerosols

Dust is a primary aerosol consisting mainly of large supermicron particles of suspended soil and mineral dust [13]. They consist mainly of silicate particles mobilized by winds passing over land surfaces such as deserts, semi-arid regions, and agricultural regions [10]. On a global scale, emission of these particles enjoys a significant flux, making them one of the largest contributors to global aerosol loading and the most prominent aerosol type observed in satellite imagery [2] [13]. Due to similarities to sea salt aerosols in their physical characteristics, issues may arise in distinguishing the two, so it may be useful to eliminate one of them as a potential contributor in a given region [1].

2.2.3 Miscellaneous Particles

Additional particles classified as aerosols include for example soot, sulfates, and biogenic particles. **Soot**, also referred to as black carbon, are a dominant primary aerosol component of submicron residual particles, having median diameters of 0.1–0.2 μm with another noticeable concentration peak around 4 μm . They are typically produced by various sources of combustion, including fossil fuel burning, vehicles, industrial applications, as well as volcanic eruptions and grass and forest fires [13].

Sulfates are secondary aerosols which can increase the solubility of other particles in the atmosphere by coating them. Sources of atmospheric sulfate include fossil fuel burning as well as global shipping traffic [13], wherein the burning of fossil fuels accounts for roughly 70% of sulfate emissions into the atmosphere. The remaining non-anthropogenic sulfate emission comes from volcanoes and oceans [10].

Biogenic aerosols are primary particles consisting of bacteria, pollen, spores and miscellaneous biogenic debris [2] [13]. Biogenic aerosols tend to be large and cover a wide size range comparable to that of SSAs, making up a significant fraction of

aerosols above $0.2\mu\text{m}$. Their influence is especially pronounced in pristine atmospheric environments, though their exact mechanisms and influences are still largely unknown. As biogenic aerosols arise from organisms which may have daily or annual cycles, their release may share similar cyclical characteristics [13].

2.3 Physical Quantities

There are various different physical quantities which may be of interest when studying the prevalence and effects of aerosols in the atmosphere. An obvious quantity is number concentration, i.e. the number of particles per unit volume. Another measure of concentration that is sometimes used is the mixing ratio, which is given as kg of aerosols per kg of air. Alongside these quantities there also exist more specialized measurements, which we will lead with presenting here before discussing aerosol effects more thoroughly.

2.3.1 Particle Size Distribution

Particle size distribution refers to the distribution of particle sizes among the aerosols in the atmosphere, and is one of the more important metrics concerning the physical properties of both aerosols and the clouds they influence [2].

Given a particle size distribution, one can approximately deduce the types of aerosols encountered, and thus also the aerosol composition of the atmosphere. The full size distribution of aerosols typically ranges from approximately 1 nm to $10\mu\text{m}$, where particles larger than $10\mu\text{m}$ are rarely found in the atmosphere as they tend to quickly settle to the ground [10].

Aerosols are conventionally divided into *modes* based on average particle diameters (under the assumption of sphericity), however the exact divisions and modes involved varies between authors. In this study, we mainly follow the scheme visualized in Figure 2.3:

- **Nucleation mode:** $10\text{--}20\text{ nm}$
- **Aitken mode:** $20\text{--}100\text{ nm}$
- **Accumulation mode:** $100\text{--}1000\text{ nm}$
- **Coarse mode:** $1\text{--}10\mu\text{m}$

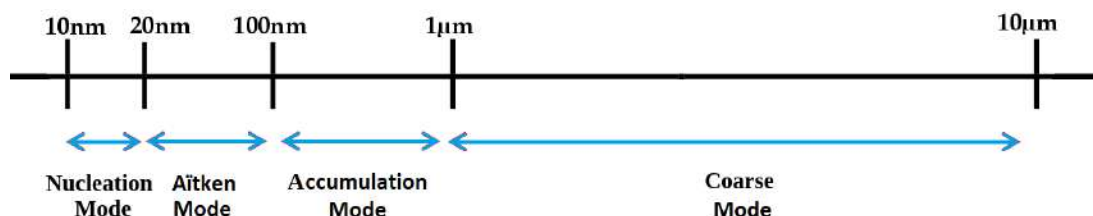


Figure 2.3: Example of classification scheme for the study of aerosol sizes.

Variations of this scheme involve subsuming Aitken mode into nucleation mode, and extending accumulation mode to $2\mu\text{m}$. These will not be relevant for this particular

study, but are noted for comparison with the schemes chosen by other authors. A more relevant variation in classification is the possible categorization of nucleation, Aitken, and accumulation mode into one combined "fine mode" [10], taken as the obverse to the already defined coarse mode.

The differences in categorization mainly arise due to the classifications being defined by formation process rather than explicit size. **Nucleation mode** particles correspond to those formed via the process of nucleation, during which a particle embryo is produced by the collision and subsequent rearrangement of molecules (gas-to-particle conversion processes [10]). Nucleation can occur in the absence or presence of a liquid or solid phase, and thus of pre-existing nuclei. If embryos form within the gas phase alone, it is called homogeneous nucleation. Conversely, when it takes place on pre-existing substrates, the nucleation is termed heterogeneous. Aerosols in the nucleation mode are the most numerous in the atmosphere, even though their mass contribution is low (mass percentage: approximately 5% over the oceans [24]).

Aitken mode particles meanwhile (named after the Scottish scientist John Aitken, who developed the first instrument to measure the size distribution of dust and droplets in fog) are intricately connected to condensation and coagulation mechanisms of water vapor. This coagulation occurs on pre-formed aerosol or the existing particle embryos from the nucleation mode, increasing the mass and size of the particles. Coagulation occurs during the collision of two aerosols. Under the influence of gravity, turbulent flows, or Brownian motion, colliding particles have a certain coagulation efficiency, describing the probability of merging to form a single, larger particle [14]. As these and the previous particle modes grow over time, their size can be used as an indication of their lifetimes [10]. As with the nucleation mode, Aitken mode aerosols contribute significantly to the total number of aerosols, but show a low mass and volume contribution (see Figure 2.4).

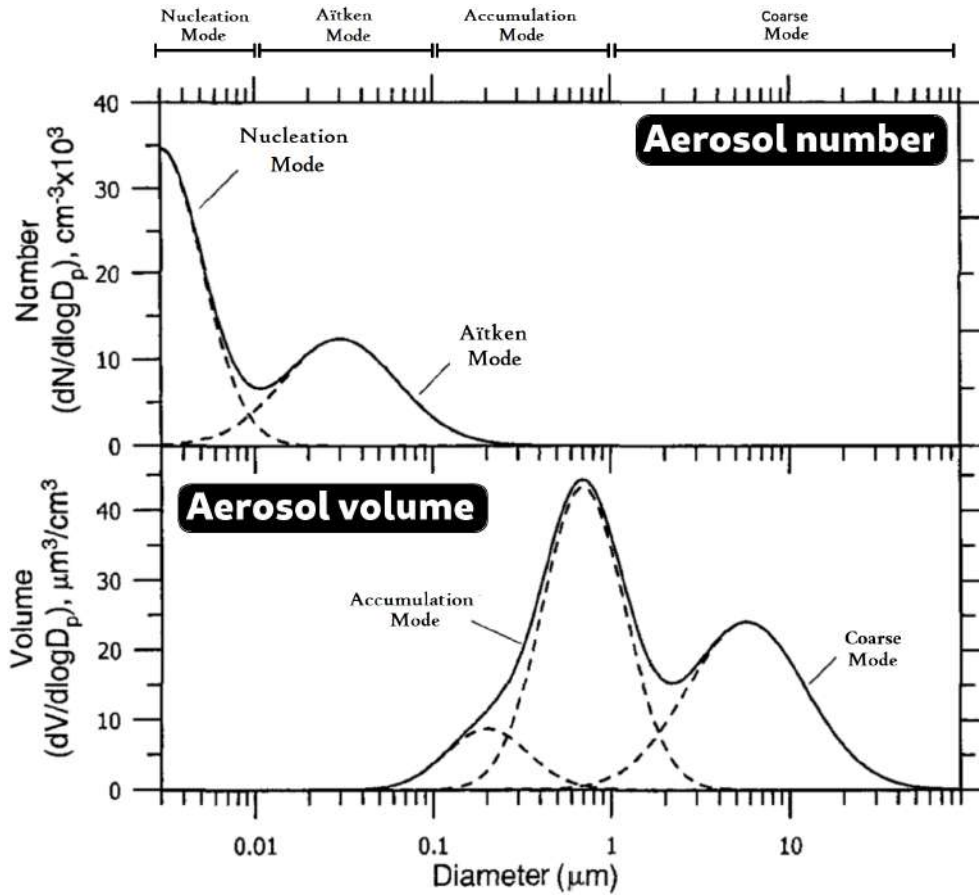


Figure 2.4: Typical number and volume distributions of atmospheric particles according to different modes (adapted from Fig. 8.10 of [14]).

Accumulation mode particles are characterized by further growth via condensation and coagulation. These particles can grow until they become large enough to deposit themselves on the ground [10]. This phenomenon of deposition is known as wet deposition or scavenging. Aerosols located below a layer of precipitating clouds can also be entrained by falling drops. These processes decrease the concentration, number, and mass of particles in the accumulation mode. However, unlike the nucleation and Aitken modes, accumulation mode particles contribute significantly to the total mass of atmospheric particles, particularly near the surface (see Figure 2.4). The mass median diameter of aerosols in this mode in the troposphere typically lie between 100 and 250 nm [25].

Coarse mode particles are the rarest of the modes (see Figure 2.4), due to their weight giving them short atmospheric lifetimes. These are typically ground particles sent airborne from the Earth's surface by passing winds [10]. They tend to quickly settle to the ground in the absence of sufficiently strong convective or turbulent motions. This settling known as dry deposition. Under normal conditions, roughly one third of aerosol mass corresponds to coarse mode particles, while the remaining two thirds correspond to fine mode particles. Due to their larger size, coarse mode particles are typically concentrated especially close to the surface [10].

Applying this scheme to previously described aerosols, marine and sea salt aerosols can be said to predominantly belong to the accumulation and coarse modes.

2.3.2 Aerosol Optical Depth

Aerosol optical depth — henceforth referred to as AOD — is, as its name implies, the optical depth attributable to the presence of aerosols in the atmosphere. Specifically, it is a measure of how much aerosols contribute to the extinction of incoming light in a direct line of sight from the sun to the ground, on account of its absorption and scattering of photons [26] [27]. Mathematically, optical depth (τ) can be expressed as:

$$\tau = -\ln(T)$$

where T is the transmittance [28], which thus itself can be expressed as:

$$T = e^{-\tau}$$

For the sake of reference, an optical depth of $\tau = 1$ implies a transmittance of $e^{-1} \approx 0.368$, meaning roughly 36.8% of incoming light reaches the surface.

AOD changes with wavelength, and so is typically labelled as such [27]. For example, $\text{AOD}_{550\text{nm}}$ refers to AOD measured for light with a wavelength of 550 nm. This division of AOD can also be used as a rough indicator of the size of involved aerosol particles, as particles typically scatter and absorb photons with wavelengths comparable to their size [10] [11]. In this way it can help to derive the particle size distribution. For example, $\text{AOD}_{532\text{nm}}$ is typically associated with the presence of SSAs [13].

In the context of AOD, a value of 0.01 would indicate an extremely clean atmosphere, whereas a value above 0.4 would correspond to an atmosphere with considerable haze [26]. In the utilization of AOD as a climate indicator, values below 0.1 ($>\sim 90\%$ of incoming light reaches the ground) are typically associated with that of a **pristine atmosphere**. This term is used to describe atmospheric conditions which are approximately comparable to what conditions were like prior to the advent of industrialization [1].

However, given that aerosols can travel hundreds of kilometers during their lifetimes, and that few places have greater than such distances from major pollution sources, this implies that truly pristine conditions cannot be found anywhere, at least in the northern hemisphere. In the northern hemisphere, the contribution to total AOD from natural aerosols was determined in 2005 to be around 52%, while in the southern hemisphere, it was determined to be around 71% [29]. In true pre-industrial conditions, both of these would be 100%. In the present case, the difference implies that the southern hemisphere is cleaner in regards to anthropogenic aerosols than the northern hemisphere. The closest approximations of a true pristine atmosphere are reached in the specific scenario where clean marine air masses reach practically uninhabited continental boreal regions [13]. Luckily, the site investigated in this

study approximately exhibits some of those qualities, as we shall see later in the site description given in Section 2.6.

2.3.3 Ångström Exponent

The Ångström exponent meanwhile, typically denoted α [27], is a measure of how strong the AOD depends on light wavelength (otherwise known as its 'spectral dependence' [27]). The dependence itself typically follows the principle that AOD takes higher values for shorter wavelengths (i.e. blue light) and smaller values for longer ones (i.e. red light) [27]. The parameter is derived from the established power law relationship:

$$\frac{\tau_\lambda}{\tau_{\lambda_0}} = \left(\frac{\lambda}{\lambda_0} \right)^{-\alpha} \quad (2.1)$$

where τ_λ refers to the optical depth — as discussed in section 2.3.2 — for a specific wavelength λ , and λ_0 is a chosen reference wavelength [10] [30].

Correspondingly, α can be estimated from measurements of AOD by taking measurements at different wavelengths and comparing them as follows [30]:

$$\alpha = -\frac{\log \frac{\tau_{\lambda_1}}{\tau_{\lambda_2}}}{\log \frac{\lambda_1}{\lambda_2}}$$

where measurements have been made for the two different wavelengths λ_1 and λ_2 , and where the resulting Ångström exponent can be denoted $\alpha_{\lambda_1-\lambda_2}$. For typical atmospheric aerosols, the Ångström exponent is expected to take values between $\alpha \approx 0.2 - 2$. In marine air masses — specifically around the tropical island of La Réunion, east of Madagascar — multiyear daily averages have been measured to be approximately $\alpha = 0.7 \pm 0.36$ [1].

The interpretations of the Ångström exponent are twofold. Due to the underlying phenomena between the interactions of particles and light, the Ångström exponent is inversely related to the average size of interacted aerosols. That is, the smaller the particles are, the larger the exponent is [30]. Specifically, using $\alpha_{500-870\text{nm}}$ as an example, values around $\alpha_{500-870\text{nm}} = 1$ indicate that measurements taken of AOD in the range 500 – 870nm also correspond to particle diameters in the range 500 – 870nm, whereas $\alpha_{500-870\text{nm}} < 1$ indicates that the diameters of measured particles may have a tendency to exceed 870nm, and equivalently $\alpha_{500-870\text{nm}} > 1$ indicates diameters tend to be short of 500nm [11]. This makes the Ångström exponent a good indicator of the mean size of sampled aerosols [1], useable to help derive the particle size distribution. For example, marine aerosols, due to their relatively large sizes, can typically be associated with measurements of small Ångström exponent values [10]. SSAs specifically are associated with Ångström exponents below 1.2. As a rule of thumb, values of $\alpha < 1$ suggest dominance of coarse particles, whereas values of $\alpha > 1$ suggests dominance of fine particles [27].

Additionally, as can be interpreted from the power law relationship in Eq. 2.1, the

smaller α is — i.e. the larger the particles are — the less the observed AOD depends on wavelength. This is why clouds primarily appear white or gray when observed. The large size of the accumulated cloud droplets absorbs and scatters all light in the visible spectrum almost equally, resulting in an appearance of homogeneous opaque achroma [30].

2.3.4 Atmospheric Water Contents

There are various possible measures that can be used to determine the water contents of the atmosphere, each framed within a different context and with different interpretations. Mentioned in this study are **humidity**, **precipitable water**, **liquid water path** and **integrated water vapor**.

Humidity refers specifically to the concentration of water vapor present in the air. It is typically expressed mainly in three ways: as absolute humidity, specific humidity, or as relative humidity. **Absolute humidity** is given directly as the mass of water vapor per volume of air, typically as g/m^3 . **Specific humidity** is given more in the context of mass, given as the mass of water vapor per mass of air — akin to mixing ratio — and typically has units of g/kg . **Relative humidity** (RH) meanwhile expresses the current absolute humidity relative to the maximum achievable humidity in the medium (at the same temperature and pressure) given its physical constraints, and is typically given as a percentage from 0-100%. Typically, as temperature increases, the RH tends to decrease, and vice versa [10] [31].

At an RH of 100%, known as the *dew point*, the air is said to be **saturated** with water vapor. Under these conditions, the water vapor will become primed for either condensing (liquid) or depositing (ice) onto any available surface or particle. Further detail on this phenomenon will be given in section 2.5.2.1. In the absence of sufficient surfaces or particles for the water vapor to condense or deposit onto, RH may reach values exceeding of 100%, at which point the air is said to be **supersaturated** [31].

As a metric of environmental conditions, RH can be used as an indicator for the likelihood of precipitation, as well as dew or fog [10] [31]. RH values may approximately be interpreted as follows:

- **<30%:** dry air, fire risk, high evaporation.
- **60–80%:** comfortable, typical for mid-latitudes.
- **>90%:** fog or rain likely, feels moist.

where the percentages are taken to be at the surface.

Precipitable water (PW) — also sometimes simply referred to as ‘water vapor’ — is the depth of rain that would fall if all water in a column of atmosphere were to precipitate, given in millimeters [32]. As should be obvious, it is intrinsically connected to humidity.

Integrated water vapor (IWV), also known as total column water vapor (TCWV),

is defined as the total amount of water vapor present in a vertical column of the atmosphere from the Earth's surface to the top of the atmosphere in units of mass per area, typically kg/m^2 [33] [34].

IWV (kg/m^2) is technically equivalent to precipitable water (mm) through the following relations: IWV of 1 kg/m^2 means 1 kg of water vapor in a column over an area 1 m^2 of the sky. If all vapor condenses, mass is conserved:

$$m_{\text{liquid}} = m_{\text{vapor}} = 1 \text{ kg}$$

Given that the density of liquid water is roughly $\rho_{\text{water}} \approx 1000 \text{ kg/m}^3$, the volume of that liquid water is:

$$V = \frac{m_{\text{liquid}}}{\rho_{\text{water}}} = \frac{1 \text{ kg}}{1000 \text{ kg/m}^3} = 0.001 \text{ m}^3$$

This volume spreads over 1 m^2 of area. The depth h is thus:

$$h = \frac{V}{A} = \frac{0.001 \text{ m}^3}{1 \text{ m}^2} = 0.001 \text{ m} = 1 \text{ mm}$$

In other words, 1 kg/m^2 of IWV $\approx 1 \text{ mm}$ of PW.

Liquid water path (LWP) is the vertical integral of liquid water contents through the depth of clouds, where liquid water contents refers to the integration over the mass of the drop size distribution, where the drop size distribution in turn is the number density of water droplets as a function of drop radius [35]. In other words, LWP is the total mass of all the cloud water droplets stacked in a vertical column of the atmosphere per unit area of cloud.

2.4 Clouds

One half of the cloud-aerosol connection is of course the clouds. Clouds can be categorized into belonging to various different groups based on a multitude of different factors, such as shape, composition, occurrence, etc. As such, we include this general description of clouds and cloud types. The following descriptions are based on those given by the World Meteorological Organization (WMO) International Cloud Atlas for the observation and identification of clouds [36].

2.4.1 Cloud Classification

One important category of clouds not covered by the to-be-described standardized classification scheme are so called 'warm clouds'. These are defined as clouds which consist of only liquid water droplets, i.e. no ice particles are present [37] [38]. The importance of this category arises from the fact that certain studies and phenomena can only be ascribed specifically to warm clouds.

That said, standardized cloud classification is based on a scheme of genera, species, and varieties, similar to the Linnean classification of plants and animals, where genera is the topmost grouping. Exactly ten genera of clouds have been defined, their names being composed from a handful of Latin terms, which may be useful to know the meaning of in order to establish a meaningful shorthand:

- *Cirrus*: Curl, fiber, or mane [39]. "Hair-like".
- *Cumulus*: Heap or pile [40]. "Puffy mass".
- *Stratus*: Spread out or covering [41].
- *Alto*:- High or raised [42].
- *Nimbus*: Rainy or stormy [43].

With this in mind, the ten defined cloud genera are [36]:



Figure 2.5: Type examples of some cloud genera, from left to right: Cirrus (© Stephen Burt), Cirrocumulus (© George Anderson), Cirrostratus (© Usynina Luybov) [36].

- **(H) Cirrus:** (Latin: "fiber") White filaments or narrow bands of fibrous clouds.
- **(H) Cirrocumulus:** (Latin: "fibrous heaps") Thin, white patches or sheets of clouds, commonly with grainy or rippled features.
- **(H) Cirrostratus:** (Latin: "fibrous covering") Whitish transparent cloud veil of fibrous or smooth appearance, totally or partly covering the sky, capable of showing halo phenomena but not of completely obscuring the sun.



Figure 2.6: Type example of Altocumulus clouds (© Kwong Hung Tam) [36].



Figure 2.7: Type examples of some cloud genera, from left to right: Altostratus (© Frank Le Blancq), Nimbostratus (© Martin Gudd), Stratocumulus (© Michael Bruhn) [36].

- **(M) Altocumulus:** (Latin: "raised heaps") Rounded, puffy patches of clouds typically arising in larger groups.
- **(M) Altostratus:** (Latin: "raised covering") Grayish or blueish cloud veil of fibrous or uniform appearance, totally or partly covering the sky, not capable of showing halo phenomena or completely obscuring the sun.
- **(M) Nimbostratus:** (Latin: "stormy covering") Gray, dark cloud layer typically associated with precipitation. Thick enough to completely obscure the sun. Usually accompanied by low, ragged clouds below.
- **(L) Stratocumulus:** (Latin: "covering heaps") Gray or whitish sheet or layer of cloud composed of dark rounded masses or rolls. Non-fibrous.



Figure 2.8: Type examples of some cloud genera, from left to right: Stratus (© Michael Bruhn), Cumulus (© Stephen Burt), Cumulonimbus (© Antonio J. Galindo [36]).

- **(L) Stratus:** (Latin: "covering") Gray cloud layer with a fairly uniform base, associated with drizzle or snow. Outline of sun is clearly visible through layer when not obscured. Does usually not produce halo phenomena.
- **(L) Cumulus:** (Latin: "heaps") Detached, puffy clouds, developed vertically.
- **(L) Cumulonimbus:** (Latin: "stormy heaps") Heavy and dense cloud, with a considerable vertical development. Flattened tops, spread out in the shape of an anvil or vast plume.

Most cloud genera are subsequently divided into various species and varieties with additional defined features etc. [36], though these will not be described here.

The labels (H), (M), (L) beside the genera refer to their altitude levels classified into High, Medium, and Low. In temperate regions, these are defined as follows [36]:

- **High:** 5-13 km
- **Medium:** 2-7 km
- **Low:** Surface-2 km

Most cloud types are confined to their altitude levels, though ex. altostratus, nimbostratus, cumulus and cumulonimbus may extend into the other levels due to upward and downward vertical extent from the core cloud [36]. This, alongside the cloud types themselves, are visualized in Figure 2.9. In our case, our focus on the PBL concentrates us toward clouds at the low level, i.e. stratus, cumulus, cumulonimbus, and potentially nimbostratus.

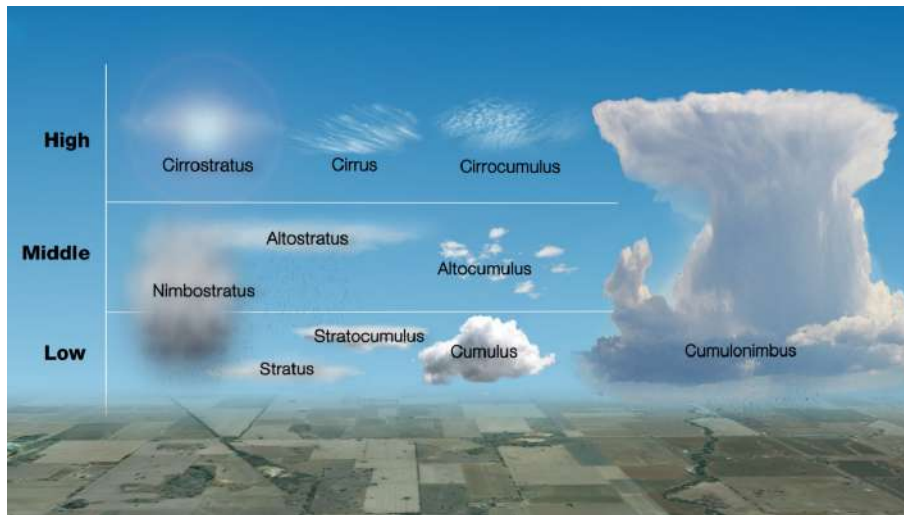


Figure 2.9: Cloud types and associated altitude levels from the Australian Government Bureau of Meteorology [44].

2.4.2 Cloud Formation

Cloud formation occurs through different processes. Here, we briefly review the main ones:

- Formation by *isobaric cooling*, when a mass of warm air comes into contact with colder ground. The air is then cooled by contact. This can occur at night, but also on coasts due to the land/sea contrast. This results in fog, stratocumulus, or stratus.
- Cooling by *adiabatic expansion*, which can occur:
 - by lifting of an air mass, either by terrain such as a mountain (orographic lifting), or via a front (frontal lifting) when a warm air mass meeting a cold air mass is carried to the condensation level. This typically creates cirrus and nimbostratus.
 - by convection resulting from thermal instability, such as a warm air mass in a much cooler environment. This is common in summer, and cumulus or cumulonimbus — which sometimes lead to thunderstorms — form in this way. With high summer temperatures, the air warms upon contact with the ground, and the configuration of warm air near the ground and colder air above is thermodynamically unstable. The warm air mass can then, through a perturbation, rise in altitude. When it contains enough moisture, the water vapor condenses at the saturation vapor pressure altitude. Thus, depending on the vertical temperature profile, the following may form: (i) cirrocumulus, altostratus, or stratocumulus for an unstable air layer with little vertical development; (ii) cumulus or cumulonimbus for a well-developed convective instability. Cumulus can also develop into cumulonimbus when their vertical extension becomes significant.
- *Moisture supply* into air near saturation. This additional vapor can come from aquatic surfaces (seas, oceans), water-saturated soils, or the advection of moist

air. Such a process generally produces fog.

In oceanic conditions, all types of clouds can form: from cirrus to cumulonimbus [45] [46].

2.5 Aerosol Effects

The effects which aerosols have on the wider climactic system of the Earth are multifaceted and diverse [10]. Their influence arises primarily from the direct and indirect effects they have on the Earth's radiative balance — that is, the balance between how much energy the Earth receives from the Sun versus how much energy it radiates into space. **Direct effects** are those that arise immediately from the interaction between aerosols with the incoming radiation. **Indirect effects** on the other hand refers to those which arise from the aerosols' influence on the formation and propagation of clouds and precipitation, and the involved climactic effects that these in turn cause [13] [25]. It is purported that indirect effects dominate over direct ones, and are estimated to account for roughly 70% of total aerosol forcing [2].

Aerosols only affect the properties and dynamics of the atmosphere while they inhabit it, the duration of which is referred to as their *lifetimes*. In mathematical terms, this can be given as their e-folding lifetimes, which is the time required to reach $\frac{1}{e}$, or 37%, of initial concentrations. Typically, aerosols have atmospheric e-folding lifetimes of 3-10 days depending on their specific characteristics. As such, their effects can be interpreted to last for roughly that long after emission [13].

2.5.1 Direct Effects

As stated, direct effects involve those that arise from the immediate interaction between aerosols and the incoming radiation from the Sun. This typically involves particles in the atmosphere absorbing or scattering the incoming light, in turn causing light extinction from the point of view of the surface [13]. The scattering efficiency of aerosols is largest against light with wavelengths comparable to the diameter of the particles [11]. As such, of particular interest are the particles in the accumulation mode with diameters comparable to the visible light range, i.e. the peak of the solar emission spectrum [10].

As aerosols absorb photons, their energy is deposited as heat in the atmosphere. At the same time, these photons are prevented from reaching the surface, cooling it. The end result is thus a simultaneous cooling effect on the surface and heating effect on the atmosphere [10] [13].

Due to this shift in energy distribution, the process of thermal convection — which relies on the presence of sinking cold air above and rising hot air below, i.e. a pronounced vertical temperature gradient — is partially suppressed. Convection currents are a key component for the activation of rainfall, thus suppressing them can also be taken to result in a suppression of rainfall. Drawing the connection, the presence of aerosols should contribute to an overall reduction in the amount of

observed precipitation, which is indeed an observed phenomenon [2] [13].

However, it is worth noting that on larger scales, the influences of indirect effects might under certain circumstances counteract this effect, making these kinds of simplistic conclusions less definitive [2] [13]. Additionally, the effect may also be partially negated by elevated atmospheric moisture levels, due to the ability of moisture to stimulate convection [10].

2.5.2 Indirect Effects

Indirect aerosol effects primarily arise from their influence on the formation of clouds and their subsequent precipitation. The connection between aerosols and clouds will be discussed below.

2.5.2.1 Cloud Condensation Nuclei

Cloud formation typically occurs when rising air cools and becomes supersaturated by humidity, resulting in the formation of either water droplets or ice crystals depending on surrounding conditions. However, due to physical constraints, this process cannot under normal circumstances occur through the presence of water vapor alone. Instead, a core supporting particle is necessary, which the vapor may then condense around. This process of accumulation onto a core particle is referred to as 'nucleation', and the aerosols which have the physical characteristics required to act as such a particle are referred to as 'nuclei' [2] [10].

Nuclei can be categorized into two main categories: cloud condensation nuclei (CCN) and ice nuclei (IN). As their names imply, CCN are the subset of aerosol particles capable of allowing for the condensation of water vapor into droplets, while IN are the subset of nuclei capable of supporting the formation of airborne ice crystals [13]. In the context of this paper, our interest lies mainly in those particles classified as CCN.

Nuclei may variously be either homogeneous particles or conglomerations of various materials, in which case their ability to act as CCN depends on their composition [37]. Outer coatings forming on the outside of certain particles by the deposition of various gases (i.e. secondary aerosols) can also contribute to changing the activation potential of the nuclei [13]. This is the means by which secondary aerosols can change CCN concentrations, notably without changing the particle number and without apparent connection to any particular source [13]. However, the most dominant factor in determining whether a particle may act as CCN or not is the particle size, which additionally has both an upper and a lower limit for activation [13]. Due to these constraints, it is primarily accumulation mode particles that act as CCN in the atmosphere [10] [13]. In particular, marine and sea salt aerosols possess the highest activation potential for CCN.

Metrics relating to CCN include 'CCN efficiency', which is a value representing the fraction of cloud nuclei (CN) that can properly stimulate droplet formation as CCN. It is given as the ratio between the number of activation-capable nuclei and

total number of nuclei: CCN/CN . Conventionally, this fraction is denoted simply as 'CCN'. The ratio CCN/CN is influenced directly by the nuclei particle diameter, as well as the surrounding supersaturation, increasing with both. The exact rate of increase depends on the type of particle [13]. Typically, the ratio of activated CCN is small, being circa $200/\text{cm}^3$ out of the total number of nuclei, which may be larger by an order of magnitude [10].

For the fraction of CCN at or above a given supersaturation S (given as a percentage above 100%), a notation of CCN_S is typically used. This is the subset of the total aerosol population which is capable of activating droplet formation at a given supersaturation of S or higher [13]. For example, a fraction of particular interest is $\text{CCN}_{1\%}$, representing the CCN fraction at 101% saturation. The interest arises from the fact that this metric indirectly represents the maximum number of particles that can be activated at the base of clouds, given that the supersaturation at cloud bases rarely ever exceeds 1% [13].

The growth rate of droplets around CCN particles is related positively to the temperature and RH of the surrounding environment [10]. As droplets continue to accumulate water, they eventually surpass the limits in mass and volume that the atmosphere can support, causing them to fall. Typically, droplets must attain a radius of approximately 1 mm for this to occur. This threshold is visualized in Figure 2.10 by the size of typical raindrops, additionally visualizing the size difference between these and the original CCN as well as typical cloud drops [47]. As these droplets fall, they may subsequently interact with other suspended droplets in the air, subsuming them into themselves and growing even further. These are the processes underlying precipitation [38]. At a given supersaturation where multiple CCN are present and able to activate, the primary selector determining which particles activate first is the solubility of the particles, though other chemical effects also play a role [13].

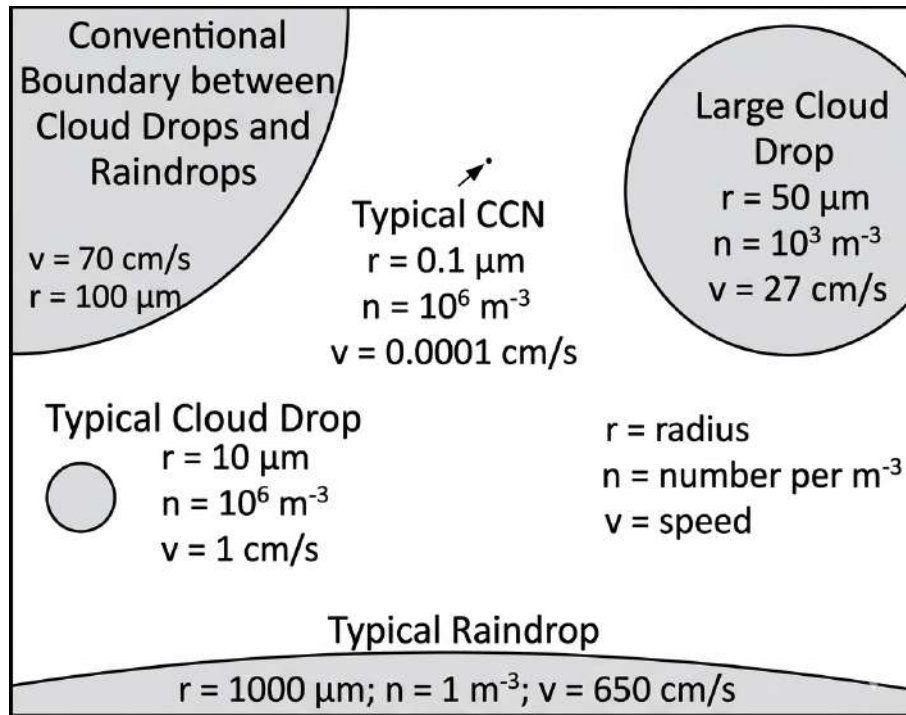


Figure 2.10: Sizes, concentrations, and fall velocities (within the Earth's reference frame) of particles in a cloud [47].

One particular subset of condensation nuclei are Giant CCN (GCCN), defined as CCN with dry diameters greater than $5 \text{ }\mu\text{m}$. These mainly arise in the form of biogenic particles or SSAs. During condensation, they may reach wet diameters in excess of $10 \text{ }\mu\text{m}$, and during their descent they act as significant accumulators of smaller droplets. GCCN are of particular interest in the study of precipitation due to their ability to activate at particularly low supersaturations ($< 0.02\%$), typically making them the first nuclei to activate [10] [13]. Due to these characteristics, higher GCCN concentrations tend to have the opposite effect compared to higher CCN concentrations, as they are associated with a strong ability to induce rainfall rather than suppress it [2].

2.5.2.2 Effects on Clouds

The effects which aerosols have on clouds and their evolution is dependent on the type of cloud(s) interacted with, as well as the current stage of their development. As an example, the effects that aerosols have on warm clouds has been well-studied. Within these clouds, it has been established that an increase in CCN number, i.e. aerosol number, will lead to an increase in cloud droplet number. If the liquid water content remains the same, this coincides with a decrease in droplet size. This in turn results in an increase in cloud surface area, increasing albedo, inducing a cooling effect on the Earth's surface [48]. However, this albedo effect goes both ways, and as such it will similarly apply to radiation trying to leave the Earth-atmosphere system, resulting in a contribution to the greenhouse effect. Which of these effects is most dominant remains uncertain and variable [2] [10]. While aerosols might influence cloud albedo, clouds apply these kinds of albedo effects to some degree

irrespective of cloud aerosol contents, so in every case where cloud cover is present some combination of these effects can be assumed to shift the local radiative balance [10].

In addition to albedo, the smaller droplet sizes suppress collision and coalescence processes. This effect and the phenomenon of increased albedo are summarized under the so-called "Twomey effect", from the 1977 study which proposed it [48]. Due to this suppression of droplet growth, droplets remain small and face greater difficulty in reaching sufficient volume and mass to eventually fall. The end result of this is a reduction in cloud water content and cloud thickness alongside slowed precipitation rates and reductions in observed rainfall [2] [10] [49], referred to as the Albrecht effect [50]. These are the same end results of surface cooling and rain suppression as described from the consequences of direct effects in subsection 2.5.2.1, and as such both of these processes compound each other.

A further feedback loop arising from the reduction in precipitation is that ongoing rainfall collects and scavenges aerosols from the atmosphere, essentially cleaning it by reducing aerosol number concentrations. This effect is sometimes referred to as "washout". Thus the reduction in rainfall induced by aerosols allows for those same aerosols to further accumulate in the atmosphere. The end result is that areas with a clean atmosphere tend to remain clean, whereas areas with a polluted atmosphere tend to remain polluted [10].

On top of this, the suppression of precipitation compels a further response from the clouds, manifesting as changes in organization, liquid water path, radiative effects, etc. Generally, precipitation suppression leads to an overall increase in cloud lifetimes, which in turn results in more overall cloud cover due to cloud build-up [2]. This is corroborated by satellite observations made over the oceans, which appear to show that greater aerosol concentrations coincide with an increased coverage of stratocumulus clouds [2]. Additionally, as this is another means by which sunlight can be blocked from reaching the surface and be absorbed in the atmosphere, it is another means by which the effect of surface cooling and atmospheric heating is compounded.

The cumulative effects of all these heating and cooling influences have been studied previously in climate models. From these, the ultimate effective radiative forcing of all industrial-era aerosol-induced cloud adjustments has been estimated to lie somewhere between -1.33 and -0.6 W/m². This is a wide estimate, and is given with a low level of confidence, but it does imply an overall cooling effect, partially counteracting the heating effects of global warming. Still, on a regional scale, the presence of aerosols may result in either a cooling or a heating effect depending on the conditions [2] [10].

An additional consequence caused by the process of cloud build-up is that greater masses of water will simultaneously accumulate in the atmosphere as part of these clouds. When precipitation then eventually does occur, it manifests as heavier ex-

perienced rainfall. This has been shown in studies of open cell clouds, wherein a modest increase in aerosol concentrations has been observed to lead to an increase in cloud water, cloud depth, and rain [2]. Thus while higher aerosol concentrations may result in a reduction in precipitation in the short term, it may also result in greater rain volumes at a later time. Global increases in the occurrence of extreme precipitation events may in part be attributable to this effect [2].

However, the exact effects of aerosols depends on the specific characteristics of individual clouds. For short-lived clouds, the effect may even result in a suppression of cloud cover and precipitation altogether [13], as the droplets become small enough to evaporate completely when mixed with ambient dry air [2]. Additionally, in the case of clouds with low number concentrations of aerosols to begin with, an increase in aerosol number may instead spur the onset of rainfall rather than suppress it [2].

Another process which is spurred by the presence of aerosols is the transformation of early morning shallow cumulus or stratus clouds into late morning convective clouds (vertically developed). Previous studies suggest that the presence of CCN during this transition might enhance the process, which is a conclusion arising from the apparent observed result of fewer shallow cumulus clouds and more deep convective clouds when CCN concentrations are heightened [2].

2.6 Onsala Site

The Onsala Space Observatory (OSO) — the site of interest in this study and partly pictured in Figure 2.11 — is an observatory site located in the coastal regions of Sweden’s west coast, 45 km south of the city of Gothenburg. The location — and its relation to Gothenburg — are marked in relation to the coastline in Figure 2.12. Note that the site is flanked from the West and the South by ocean. The inland geography of the area is characterized by grass, forests, and sea. At the site, the climate is influenced and modulated strongly by the interaction between oceanic and continental air masses [6]. Specifically, according to a study by Wängberg et al. (2016) [51], the OSO site is situated far enough away from major sources of air pollutants (including Gothenburg) that measurements performed at the site can be assumed to be performed in background air most of the time (approx 60 % of the time) [6].



Figure 2.11: Picture of the Onsala Space Observatory site © Roger Hammargren.

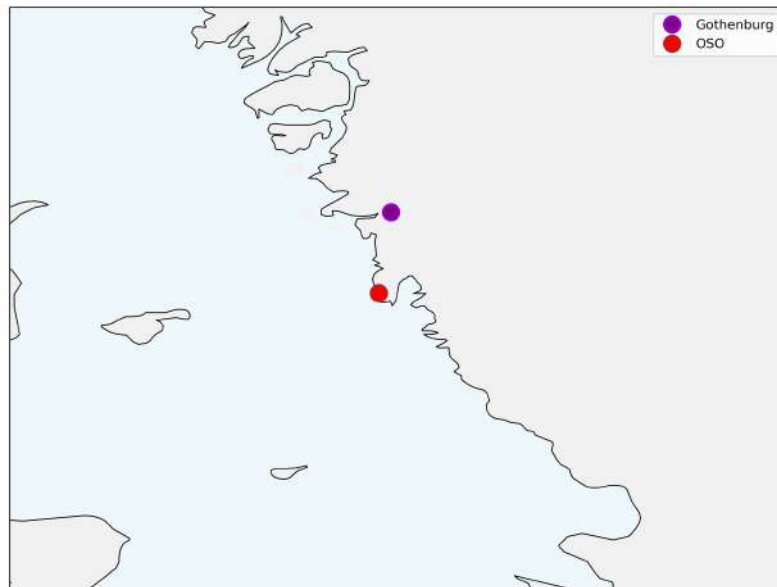


Figure 2.12: Map of Swedish West coast, with Onsala marked in red and Gothenburg marked in purple.

In a previous study by Mascout et al. (2026) [6], various characteristics of the site were established over a 15 year period (2009 - 2025). They defined the seasonal temperature cycle as characterized by cold winters, with minimum temperatures reaching -5°C to -10°C , and mild summers, with maximum temperatures reaching 20°C to 25°C . The annual average temperature was found to be roughly 9°C , which is typical for such a temperate maritime climate [6].

The daily activity at the site was found to be characterized by a seasonally-dependent

semidiurnal cycle of temperature and pressure with two maxima and minima per day. Pressure was found to reach lower values during the night than during the day as part of this oscillation [6].

Precipitation at the site was found to demonstrate a regime of frequently-observed light to moderate rain and/or snow, with intense events being more rare. The annual variability of this rainfall was taken to indicate exposure from North Atlantic storm tracks [6].

Winds were found to arrive predominantly from the West-Southwest, i.e. from the Kattegat sea, carrying moisture and marine aerosols over land and contributing to cloud formation and precipitation. The strongest winds were found to exceed 10 m/s (36 km/h). This regime was found to occasionally shift to predominantly dry and cool East-Northeastern winds, which lead to clearer skies and warmer daytime temperatures. These winds were often more moderate in velocity, typically staying below 6 m/s (21.6 km/h) [6].

3

Methods

Various instruments were used to collect data for this study. The details of these instruments and what data they were used to collect will be described below. Additionally, various analysis schemes were devised for data examination and evaluation. These will also be described below.

3.1 Instruments & Models

Below is information regarding the instruments and models used during this study. In addition to the data types listed, all instruments also provide information on the time and date they were recorded.

These instruments are located on the grounds of the Onsala Space Observatory site. An exception is the AERONET instrument, which is no longer present, but was active during part of the 2024-2025 period as a guest instrument, and the CAMS data, which comes from a global reanalysis model and data set.

3.1.1 AERONET

The AErosol RObotics NETwork (AERONET) collaboration is a program established by NASA and collaborators to create a global network of ground-based remote aerosol-sensing instruments, in order to provide a comprehensive database of aerosol data from all around the world, the extent of which is visualized in Figure 3.1. The project is based on the standardization of instruments, calibration, processing and distribution for ease of comparative analysis [52].



Figure 3.1: Global coverage of the AERONET network [52].

The standardizations include a sun-photometer used to determine spectral AOD, Ångström exponents, and precipitable water at various sites. For the data at this particular location, a CE318-T Sun Sky Multispectral Photometer by Cimel Electronique S.A.S was used [53]. This sun-photometer as it was installed at the OSO is pictured in Figure 3.2.



Figure 3.2: The AERONET sun-photometer at the OSO.

The general operation mechanisms of a sun-photometer is to measure incoming ra-

diation directly from the Sun as it passes through the layers of the atmosphere [54]. This is then used to determine various quantities for the characterization of the atmosphere. Measurements were taken using photons from the ultraviolet to short-wave infrared wavelengths from the solar spectrum [1] [52].

As the photometer measurements rely on receiving radiation directly from the Sun, the photometer is always angled to point toward it, and not necessarily directly upwards. This is worth remembering, as the photometer will take measurements from a deeper slice of the atmosphere when pointed at a shallow angle from the Earth than when it is pointed upwards. Additionally, as the photometer also needs to receive this radiation, it is not capable of taking measurements when the Sun is obscured, for example by clouds. As such, measurement periods are irregularly scattered over the 2024-2025 period, and then only on days and time periods when there were clear skies [11]. Specifically, AERONET data is available for the OSO site from October 3rd, 2024 to March 24th, 2025.

The data is assigned to one of three different quality levels [52]:

- **Level 1.0:** Raw measurement data.
- **Level 1.5:** Cloud-screened data.
- **Level 2.0:** Cloud-screened and quality-assured data.

Cloud-screening excludes data which may have been collected under measurement-interfering cloud conditions. Quality-assurance in turn excludes data which cannot be positively assured to reach quality standards. Examples of data which can be excluded via quality-assurance include data collected while the instrument might have been misaligned or occluded [1].

Relevant data available from the AERONET sun-photometer instrument includes the following:

- **AOD:** Available for various specific wavelengths between 380 nm and 1640 nm.
- **Ångström Exponent:** Calculated from various differences in AOD across wavelengths.
- **Precipitable Water:** The total water vapor in a vertical column given as cm of rain if all water vapor were to condense.

The AERONET network data is open access. As such, it is available on the AERONET website for anyone to use [52].

3.1.2 HATPRO Microwave Radiometer



Figure 3.3: The HATPRO microwave radiometer on-site at the OSO.

HATPRO is a microwave radiometric profiler located on the OSO site — pictured in Figure 3.3 — which measures microwave radiation emitted by the troposphere. This is then processed to create vertical tropospheric profiles of absolute humidity and temperature directly above the site up to 10 km in altitude [1]. Due to the fact that the HATPRO radiometric profiler measures *microwaves*, it is capable of measuring both under cloudy conditions and in severe weather, unlike the AERONET instrument [11]. In addition to these profile measurements, the instrument also measures various quantities on ground level, much like a weather station.

Included alongside the data is information on the direction and angle of the instrument at the time of measurement. The instrument cycles between different angles to create distinct profiles for each direction over time. Our interest lies primarily in data collected from vertical measurements.

The specific relevant data available from the HATPRO instrument, as well as the data that can be derived from it, includes the following long list of items:

- Upward into atmosphere:
 - **Absolute Humidity:** Given at various altitudes (vertical profile).
 - **Temperature:** Given at various altitudes (vertical profile).
 - **Integrated Water Vapor (IWV):** The total mass of water vapor per m^2 of observed sky, given in kg/m^2 .
 - **Liquid Water Path (LWP):** The total mass of liquid water in a vertical column, given in g/m^2 . Does not include vapor.
- At the instrument location (on the ground):
 - **Temperature** in $^{\circ}\text{C}$

- **Pressure** in hPa
- **Relative Humidity (RH)** in %
- **Wind Speed** in m/s
- **Wind Direction** in °
- **Rain Flag**, a boolean representing when the instrument detects rainfall
- **Rain Rate** in mm/h

3.1.3 Vaisala Weather Station



Figure 3.4: The weather station located at the OSO.

The OSO site is equipped with an instrumented mast weather station mounted with various sensors at 16 m above the surface of the site. This is pictured in Figure 3.4.

Instruments on the mast include a Vaisala weather transmitter WXT520, which continuously collects data and records minute-averages. Also included on the mast is a wind sensor providing data on wind speed, wind gust, and wind direction. Finally, a rain sensor is attached, measuring rain rates [6].

The specific relevant data available from the weather station's instruments includes the following:

- **Air Temperature** in $^{\circ}\text{C}$
- **Pressure** in hPa
- **Relative Humidity (RH)** in %
- **Wind Speed**, averaged over each minute, given in m/s
- **Wind Direction** in $^{\circ}$
- **Wind Gust**, or the maximum wind speed recorded every 3 second interval, given in m/s
- **Instantaneous Rain** in mm
- **Rain Rate** in mm/h
- **1h Rain** in mm/h
- **24h Rain** in mm/day

3.1.4 All Sky Imager

The OSO site is additionally equipped with two sky cameras (All Sky Imagers or ASIs), one located near the HATPRO microwave radiometer and the other located near the Weather Station. These regularly capture high-resolution images of the sky with 180° field of view every 15 minutes for most of the 2024-2025 period, and every 2 minutes toward the end of the period and forward, allowing atmospheric conditions to be viewed from horizon to horizon [6].

During this study, we used the sky camera installed near the Weather Station. This camera, alongside an example image taken by it, are pictured in Figure 3.5.



Figure 3.5: Image of sky camera near the Weather Station, as well as an example image from its archive.

3.1.5 Portable Optical Particle Spectrometer (POPS)



Figure 3.6: Image of the POPS instrument in one of its protective boxes.

The Portable/Printed Optical Particle Spectrometer (POPS), seen in Figure 3.6, is an instrument designed by US laboratories NOAA and CIRES, and is used to count aerosol particles based on size, taking measurements primarily on accumulation and coarse mode particles. Specifically, it provides aerosol number size distributions in the size range 132 nm to 3 μm , categorized into various bins of different size ranges. Its method for counting particles by size is based on single-particle light scattering, wherein the amount of scattered light is proportional to the particle's optical size [1] [25].

Measurements are taken via individual aerosol particles being ingested by a protruding inlet nozzle, subsequently passing through a laser beam where they scatter the light, which is measured by a photomultiplier tube. This is then used to determine the scattering amplitude, and thereafter the scattering cross section, i.e. the optical size. The instrument is able to effectively analyze particle rates up to 10 000/s, which should be well above any fluxes encountered during this study. Meanwhile, the base standard deviation in measured diameters corresponds roughly to 3%, though additional factors may introduce further uncertainties, especially for coarse mode particles [25].

The instrument used is a prototype 3D-printed for lightness. Alongside its airtight humidity-resistant instrument box, this resulted in a weight of roughly 900 g [1] [25]. This specific prototype was also used in a previous aerosol study by Mascout et al. (2022) off the coast of Réunion Island, demonstrating its effective instrument useable for the given purpose [1].

The specific relevant data available from the POPS instrument is the size distribution of detected aerosols, sorted into 15 irregularly-sized bins, dividing into size ranges as follows (in μm):

- **b0:** <0.13

- **b1:** 0.13 – 0.15
- **b2:** 0.15 – 0.167
- **b3:** 0.167 – 0.19
- **b4:** 0.19 – 0.21
- **b5:** 0.21 – 0.23
- **b6:** 0.23 – 0.27
- **b7:** 0.27 – 0.32
- **b8:** 0.32 – 0.47
- **b9:** 0.47 – 0.59
- **b10:** 0.59 – 0.98
- **b11:** 0.98 – 1.3
- **b12:** 1.3 – 1.6
- **b13:** 1.6 – 2.2
- **b14:** 2.2 – 2.9

Summing the measurements for all bins at a particular time also derives the total aerosol number concentrations detected by the instrument.

During the study, the POPS instrument was used to collect data during one drone flight and two ground measurement periods during the first half of 2026.

3.1.6 Global Navigation Satellite System (GNSS)



Figure 3.7: Two GNSS receivers.

GNSS stands for Global Navigation Satellite System, and its purpose is to gather accurate positional data, which it does by utilizing a global satellite network [55]. The specific relevant data available from the GNSS instrument includes the latitude, longitude, and altitude. A GNSS instrument was used during this study primarily to determine the 3-dimensional position over time of the drone during POPS drone

measurements. GNSS instruments as were used during this project are pictured in Figure 3.7.

GNSS positioning can be divided into two different methods: Precise Point Positioning (PPP) and Real-Time Kinematic (RTK). In the PPP method, the position of the GNSS receiver is determined using GNSS satellite triangulation against global reference stations available all across the world. In the RTK method, the same applies except that the global reference stations are replaced with a regional reference station with a well-established position, against which all subsequent position measurements will be referenced [55]. If a regional reference station is available within the region of use, the results of the RTK method tend to be more accurate [11]. For the measurements performed during this project, the positions were referenced against the GNSS reference station situated at the OSO.

3.1.7 Copernicus Atmosphere Monitoring Service (CAMS)

The Copernicus Atmosphere Monitoring Service (CAMS), specifically the CAMS global reanalysis (EAC4), is a global reanalysis data set covering the period 2003 to August 2025 focused on atmospheric composition. It consists of both ground-level data as well as 3-dimensional profiles of climate variables, such as aerosols [56]. Total aerosol AOD is available, but also AOD specifically attributable to sea salt, dust, organic matter, black carbon, and sulfate [9] [57]. Additional information regarding how the model determines its data values can be found in articles by Morcrette et al. (2009) [58] and Benedetti et al. (2009) [59].

Reanalysis is a method for generating data sets with global coverage across time by combining available atmospheric measurement data from past to present with modern climate models and data assimilation to fill in the gaps in observations [57] [60] [61]. As such, CAMS is most accurate when looking at atmospheric developments on larger scales and larger trends. When using data for a specific location, such as in this study, it is thus important to remember that not every single individual data point is necessarily accurate, though larger trends in the data can be taken to be more reliable.

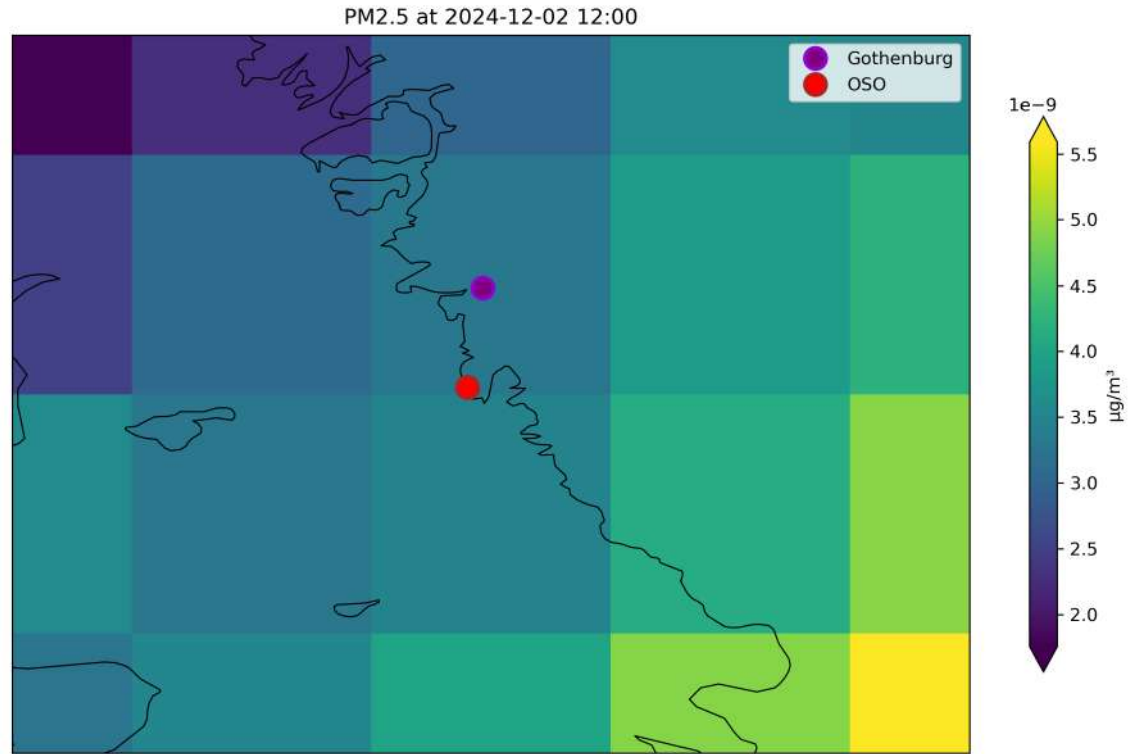


Figure 3.8: Map of arbitrary CAMS data at an arbitrary time step (PM2.5 at 2024-12-02 12:00, given in $\mu\text{g}/\text{m}^3$) showing data grid structure. Coastal OSO location marked in red. Gothenburg location marked above it in purple.

CAMS divides its data into a grid of $0.75^\circ \times 0.75^\circ$ latitude/longitude squares across the surface of the Earth, where each square has values assigned to it for each of CAMS' tracked data points every 3 hours. This roughly results in a resolution of 80 km for each square, i.e. the squares have an approximate area of 80×80 km [56] [57]. This resolution is visualized in Figure 3.8, wherein OSO is additionally seen to be located on the very edge between two grid squares, and suboptimally shares its grid square with the city of Gothenburg. As such, we choose to use data from the lower of the two grid squares instead, taking this to be more representative of the OSO's coastal environment.

CAMS includes both ground data and 3-D profile data at assigned pressure levels. Profile data was downloaded for the six levels in the pressure range 1000-800 hPa. The specific relevant data obtained and used from the CAMS data set included the following:

- Ground:
 - **Total AOD** at the following wavelengths: 469 nm, 550 nm, 670 nm, 865 nm, and 1240 nm
 - **SSA AOD** available at 550 nm
 - **Organic Matter (OM) AOD** available at 550 nm
 - **Particulate Matter** For particle diameters $d < 1 \mu\text{m}$, $< 2.5 \mu\text{m}$, and $< 10 \mu\text{m}$ (PM1, PM2.5, and PM10 respectively), given in $\mu\text{g}/\text{m}^3$
 - **Total Column Water Vapor (TCWV)** in kg/m^2

- 3-D Profiles:
 - **SSA Mixing Ratio** for the ranges 0.03–0.5 μm , 0.5–5 μm , and 5–20 μm , given in kg/kg
 - **Specific Humidity** in kg/kg
 - **Temperature** in $^{\circ}\text{C}$

From the specific humidity (q), relative humidity (RH) at the different pressure levels was calculated via the following steps. First, the saturation vapor pressure e_s (in Pa) over liquid water was computed using the Tetens equation [62]:

$$e_s = 610.78 \times \exp\left(\frac{17.27 \times T_C}{T_C + 237.3}\right) \quad (3.1)$$

where $T_C = T_K - 273.15$ is the CAMS temperature at the specific pressure level converted to Celsius. The saturation mixing ratio w_s (kg/kg) was then derived from e_s as follows [63]:

$$w_s = \frac{0.622 \times e_s}{P_{Pa} - e_s} \quad (3.2)$$

where P_{Pa} is the pressure level in Pa and 0.622 is the ratio of molecular weights of water vapor to dry air.

The actual mixing ratio w (in kg/kg) was obtained from specific humidity q itself as [64]:

$$w = \frac{q}{1 - q} \quad (3.3)$$

This conversion accounts for different reference masses (total air mass vs. dry air mass). Finally, relative humidity RH (%), being the ratio between the actual vs saturation mixing ratios, was computed as [63]:

$$\text{RH} = 100 \times \frac{w}{w_s} \quad (3.4)$$

which is the RH used when it is labeled to come from the CAMS data set.

For comparison with cloud cover and HATPRO altitudes, the pressure levels were converted to approximate altitudes using the following simplified Barometric formula for the troposphere, assuming constant temperature lapse rate [65] [66]:

$$\text{altitude} = \frac{T_0}{L} \left(1 - \frac{P}{P_0}\right)^{\frac{RL}{g}}$$

where P is the pressure in hPa, P_0 is the sea level atmospheric pressure in hPa (set as the average measured ground pressure over our specified time periods), T_0 is the sea level temperature in Kelvin (set as the average measured ground temperature over our specified time periods), $L = 0.0065\text{K/m}$ is the temperature lapse rate, $R \approx 287$ is the specific gas constant for dry air, and $g = 9.81\text{m/s}^2$ is the gravitational acceleration.

More exact altitudes could presumably be determined by utilizing measured ground

temperatures and pressures for each individual point in time, but this was forgone in favor of ease of data processing, with the reasoning that the resolution of pressure levels (50 hPa between each level) still leaves the values approximately representative of the implicit altitude ranges.

3.2 Data Analysis Methods

Below we will discuss the methods used to ultimately analyze and draw conclusions from the above mentioned instrument and model data.

3.2.1 2024-2025 Period

For the purpose of analysis, the data plotting setup as presented in Figure 3.9 was used to determine correlations between data over various periods in the 2024-2025 data interval. This particular figure shows data from the interval 2025-03-18 to 2025-03-24. The possibility to add colored vertical lines to all shown plots was also implemented to be able to better analyze developments around specific points in time across graphs. In the areas of wind data and rain data, the Weather Station was given primacy, while the HATPRO data was given primacy in the remainder of its measured areas. During periods for which HATPRO data was unavailable, CAMS and Weather Station data were used as backups where applicable. The reasoning for these choices will be given in Section 4.1.2 on data comparisons.

Analysis of these plots under various conditions can be cited as the inspiration for looking into the various different apparent correlations between different data points going forward.

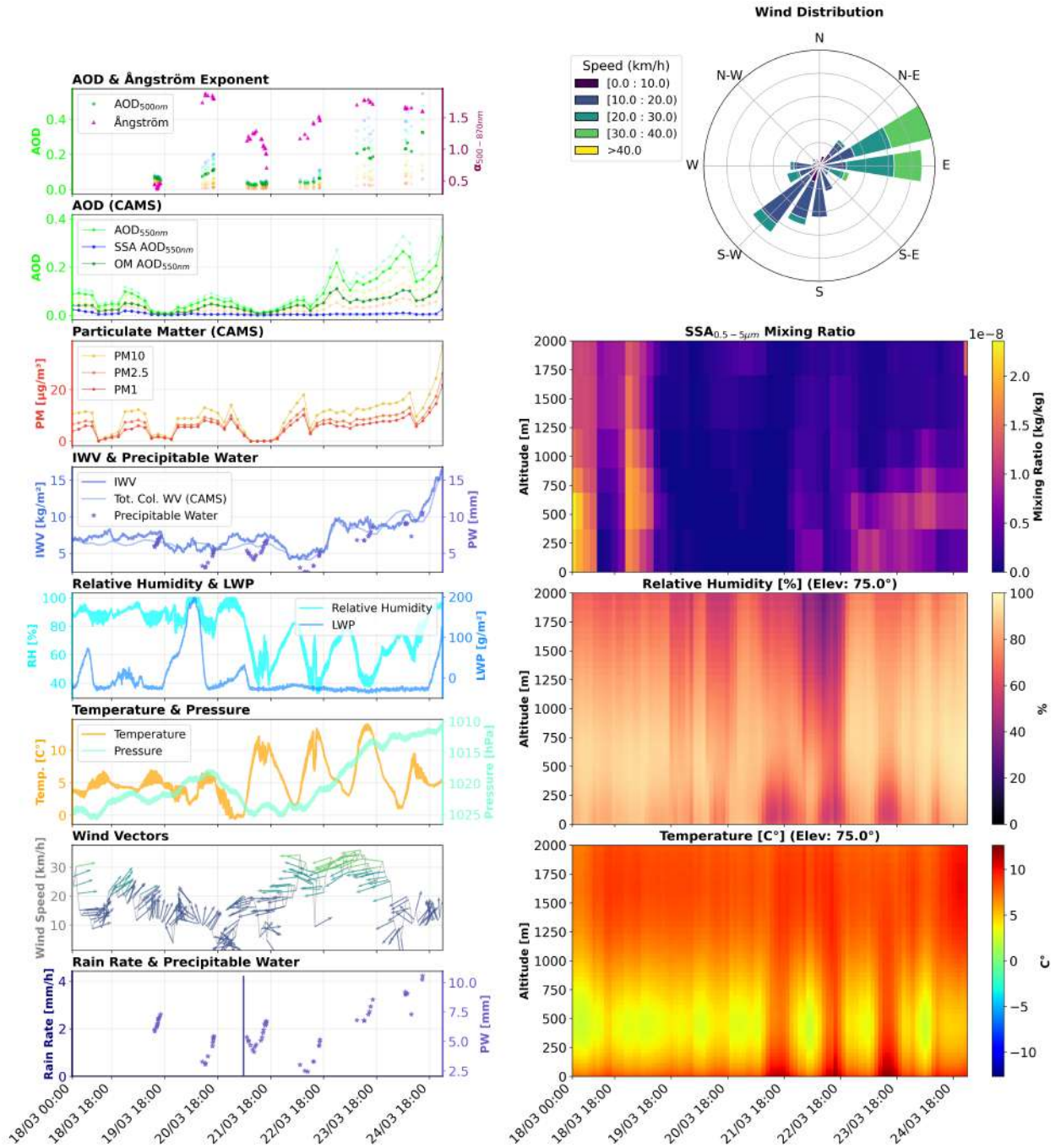


Figure 3.9: Combined plot of various data points from AERONET, HATPRO, Weather Station, and CAMS. Constructed for manual data analysis.

3.2.2 Cloud Cover Categorization

For our analysis of the connections between cloud cover and other variables, a rough cloud cover categorization scheme was devised based on the criteria given in Table 3.1, where cloud cover was divided into seven categories (labeled from 0-6) as the table describes. Then, using a randomized selection method, sky camera images were manually labeled one by one with the values 0-6 associated with each category.

As such, this categorization of cloud cover is entirely subjective. However, the hope was that even this rough manual categorization would still be able to indicate some kinds of possible trends when compared to other data given enough sky camera images being labeled to reach statistical significance.

During categorization, cirrus and cirrus-like clouds were mainly ignored in category determination, as the altitude of these clouds excludes them from our atmospheric volume of interest. Certain images with significant cirrus and cirrus-like cover were excluded from the data set for being deemed too ambiguous to categorize. Mainly, we aimed to categorize only images with cumulus or cumulus-like cloud cover.

See Appendix A to view all relevant labeled cloud images used during the study.

Table 3.1: Type examples of the seven established cloud cover categories 0-6, from top to bottom.



0: Perfectly clear.

1: Mostly clear.

2: Scattered cloud cover.

3: Roughly 50% cloud cover.

4: Roughly 75% cloud cover.

5: Full cover (visible Sun and/or spots of sky)

6: Full cover (opaque)

3.3 POPS Measurements

In addition to retroactively analyzing data from the 2024-2025 period, measurements were also performed using the POPS instrument during the course of the study in the first half of 2026. This took the form of flying the POPS instrument on a fixed-wing drone during one instance and taking ground measurements at the OSO site during two instances.

3.3.0.1 Drone Flight

The drone flight was performed on the Vingtippen airfield roughly 10 km inland, ran by the Mölndal model flight club, and was a collaboration with Valery Chernoray, a research professor of fluid dynamics and mechanical engineering, and his team of students working on their own project involving the manufacture a fixed wing drone. The pilot of the drone was Emil Ellenius. This drone is pictured in Figure 3.11. The drone flight was performed on the 5th of May, 2026.

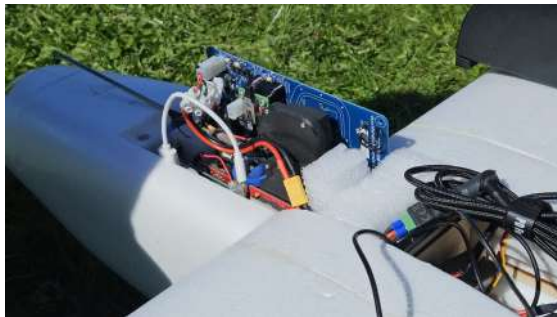


Figure 3.10: The POPS instrument installed in the drone chassis.



Figure 3.11: Picture of fully-equipped drone prior for flight.



Figure 3.12: Drone coming in for landing at end of flight.

For more information on the drone, we refer to the student team's associated article "Utveckling av UAS för atmosfäriska partikelmätningar" (Eng.: "Development of UAS for Atmospheric Particle Measurements") [67].

The POPS instrument was attached by installing it in the chassis and securing it with tape, with the inlet nozzle poking out and pointed forward in the direction

of travel. This can be seen in Figures 3.10 and 3.11. The drone took off from the airfield at 15:00 and ascended to altitudes between 100 and 200 m above ground level, where the drone was flown in approximate spirals for the duration of the flight. The flight lasted roughly 5 minutes, after which the drone landed. The final moments of the flight are captured in Figure 3.12. The collected data was extracted at a later time for analysis.

3.3.0.2 Ground Measurements



Figure 3.13: POPS instrument secured at the OSO site and pointed toward the West coast.

Ground measurements were performed by securing the POPS instrument within its protective box on the coast of the OSO site during 2026-05-09 and 2026-05-11, taking measurements during daytime and evening work hours (during good weather). The inlet was pointed toward the coast. The setup can be seen in Figure 3.13. These ground measurements were performed in order to have a longer time series of applicable measurements and for the comparison with drone flight measurements.

4

Results

4.1 Data Sets

Before presenting our results of the climate and aerosol measurements at and near the OSO, we will provide a brief overview of data availability and data set differences in order to have them be established.

4.1.1 Availability

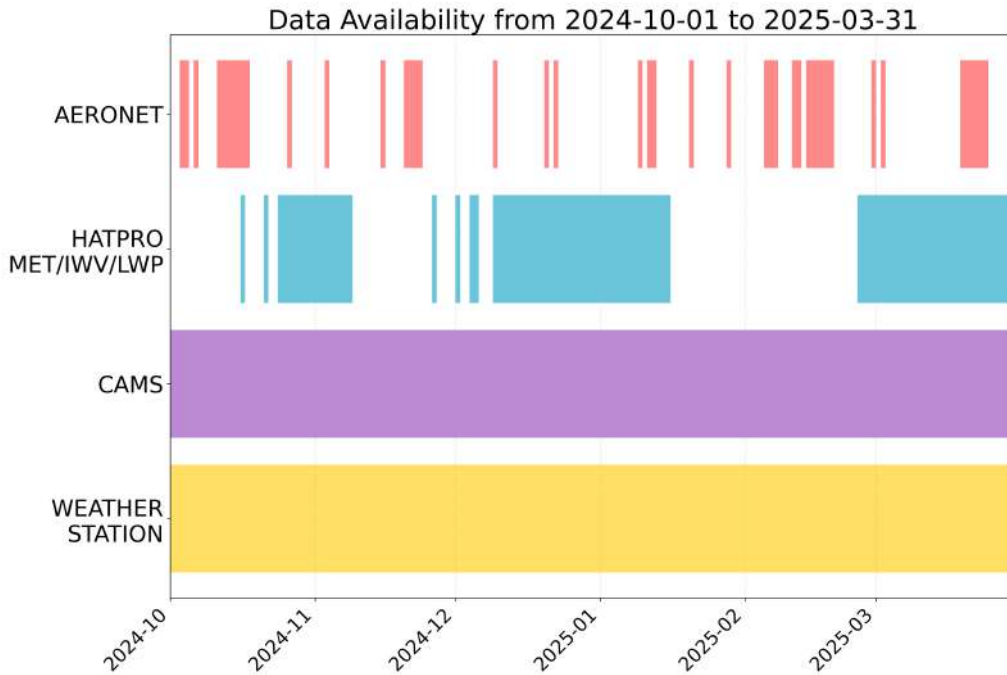


Figure 4.1: Data availability during the 2024-2025 period from October 1st 2024 to March 31st 2025.

Figure 4.1 demonstrates the availability of data from the AERONET, HATPRO, CAMS, and Weather Station data sets at the OSO site.

As the dates primarily selected for analysis were those including AERONET data, the gaps in HATPRO data present an unavoidable inconvenience. To rectify this issue, as stated previously, applicable CAMS and Weather Station data are used as

backups.

Under this use case, it becomes even more important to compare the CAMS and Weather Station data with the HATPRO data. This comparison will be performed in section 4.1.2.

For the period during which the drone flight and POPS ground measurement were performed, AERONET data was not available. CAMS data was also not available, as by the time of this study it does not yet cover 2026.

4.1.2 Comparisons

In this section we compare the data from the various data sets to establish general relationships and differences.

4.1.2.1 Aerosol Optical Depth (AOD)

Figure 4.2 demonstrates the differences between CAMS and AERONET AOD data, primarily between AERONET AOD_{500nm} and CAMS AOD_{550nm}, but secondary AODs at other wavelengths are also included for spread comparisons. The difference in main wavelength is taken to be small enough such that both of the data types can be reasonably compared. This is further exemplified by the proximity of secondary wavelength AODs to the main AODs within each data set. From this comparison we can see that CAMS AOD only very roughly aligns with our measured AERONET AOD, with the typical pattern being that AERONET AOD tends to exceed CAMS AOD, sometimes by twice the CAMS value or more. This makes sense however, given that CAMS data only exhibits averaged, partially-simulated values every 3 hours over a larger area, whereas the AERONET data corresponds to direct measurements taken explicitly from the OSO site. As such, AERONET data can be taken to be more reliable for representing the specific characteristics of the OSO site, but CAMS data can still be trusted to approximately maintain general trends.

On a side note, this figure also demonstrates the general trend of longer wavelength AODs being lower than shorter wavelength AODs, which in turn implies — due to the association between AOD wavelengths and particle size — that smaller particles tend to have greater number concentrations than larger ones, as was visualized in Figure 2.4.

From Figure 4.2 we can also infer that AOD values remain below 0.1 for the majority of days. As a reminder, these days with $\text{AOD} < 0.1$ indicate pristine conditions. This aligns with the findings of Wängberg et al. (2016) [51], who state that the OSO site is situated far away from major sources of air pollution, and that measurements there are performed in pristine air most of the time (approximately 60% of the time).

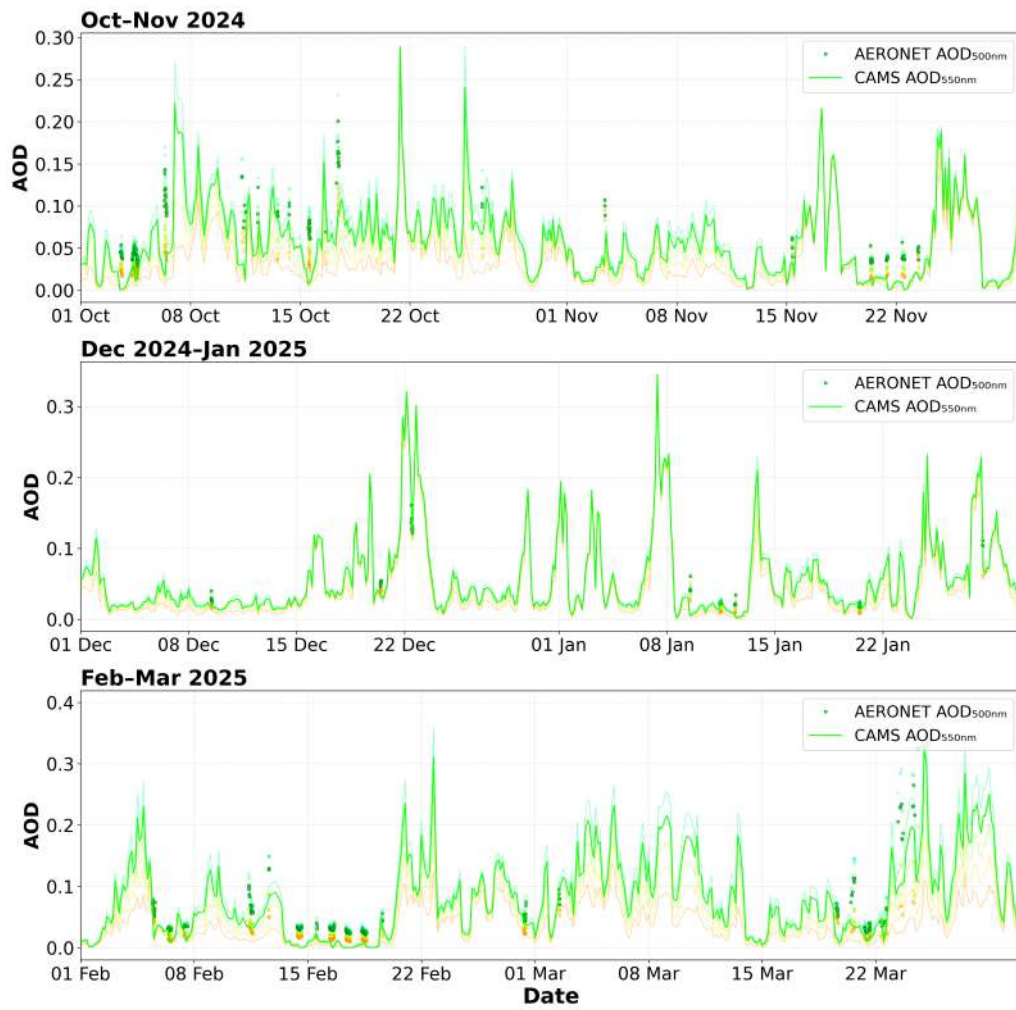


Figure 4.2: Comparison between AERONET AOD_{500nm} data and CAMS AOD_{500nm} data. Transparent dots/lines of other colors represent data for AOD of other wavelengths, where redder equals longer wavelengths and bluer equals shorter wavelengths.

4.1.2.2 CAMS AOD Sources

Figure 4.3 shows total CAMS AOD plotted over the October 2024 to March 2025 period alongside four of the specific AOD contributors tracked by the CAMS reanalysis: dust, sulfate, SSA, and organic matter.

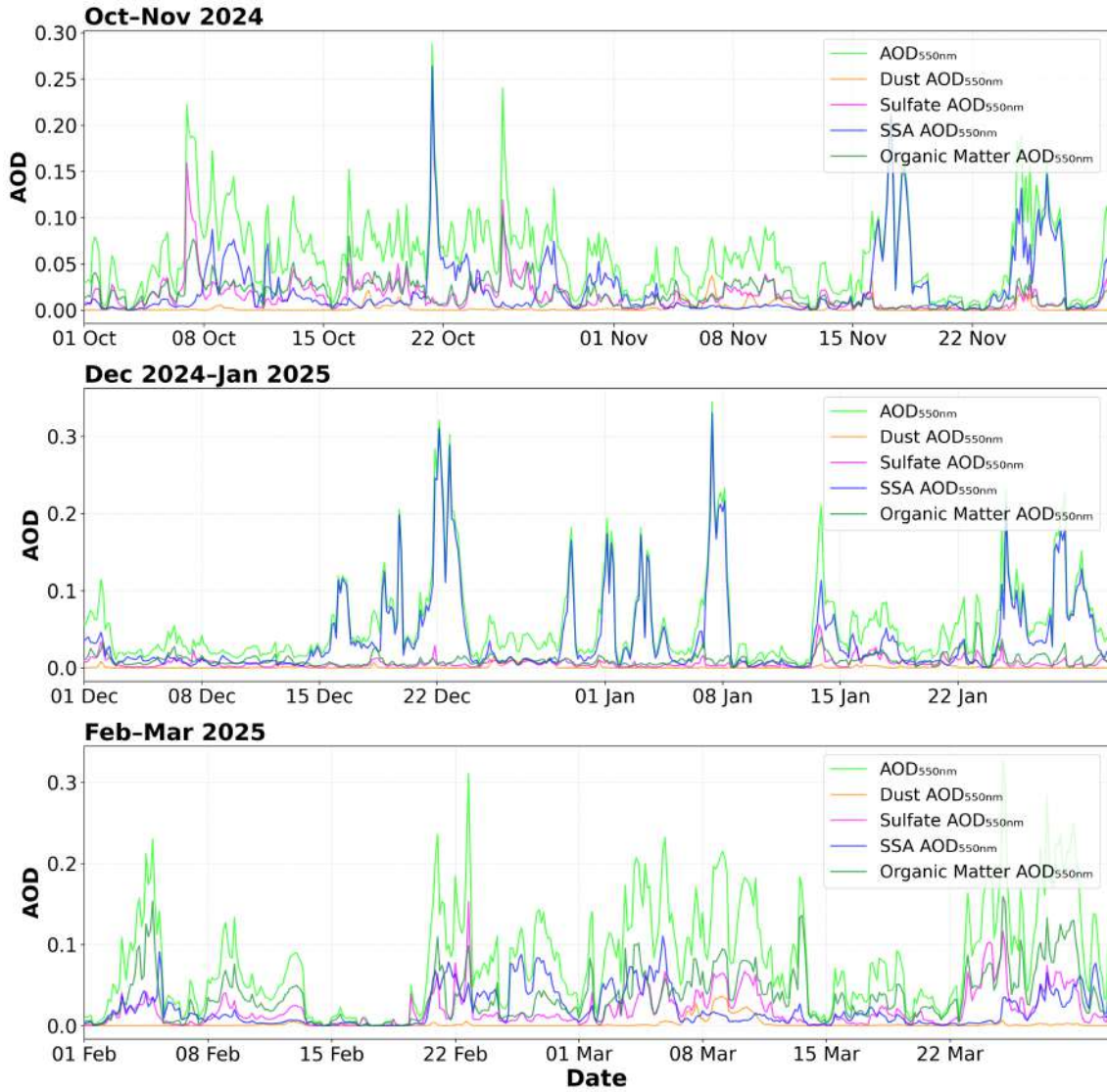


Figure 4.3: Comparisons between different CAMS AOD_{500nm} sources, alongside total AOD_{500nm}.

From this figure we can confirm that dust aerosols rarely contribute to AOD in this region, and when it does it is usually not a significant fraction of the total AOD. As such, we can reasonably neglect this source.

Sulfate aerosols are also shown to occasionally account for a major contribution, which is worth keeping in mind. However, as sulfates are not a particularly applicable target for this study, they will not be further discussed in this paper (could be a possible target of future work).

We can see that SSA and organic matter aerosols are those most prone to contributing major fractions of the total AOD, and as such are the contributors which will be most studied during the coming analysis. These results were expected given the location of our study area, being a coastal environment with inland forests.

4.1.2.3 Water Vapor

As the Precipitable Water (PW) from AERONET, the Integrated Water Vapor (IWV) from HATPRO, and the Total Column Water Vapor (TCWV) from CAMS are all practically equivalent — and should give approximately equivalent values — it is worthwhile to compare these three quantities specifically.

Figure 4.4 shows comparisons of these three data types during the period 2024-12-09 to 2024-12-24, the period 2024-12-24 to 2025-01-15, and the period 2025-02-28 to 2025-03-23. In these figures, translucent vertical lines represent positive rain flags as assigned by the HATPRO instrument, indicating time steps with detected precipitation. From this figure it is evident that the three quantities do approximately align with each other. Specifically PW appears to closely follow IWV, but with a recurring offset trend of generally being lower. TCWV too seems to relatively closely follow IWV with a recurring offset trend of being lower, but with the particular exception that it does not follow suit when IWV rises significantly due to local precipitation. This is especially clear from the rain events around 2025-03-13 in the lowermost plot of the figure, where the TCWV seems completely unresponsive to the recurring rain events picked up by the HATPRO.

However, as TCWV is an average over a significantly larger area, it makes sense that it does not closely follow the development of IWV specifically at the OSO site. As such, this exception is important to keep in mind for our later analysis.

Additionally, as previously stated, this data confirms the trend in the significant rise of IWV in the presence of local precipitation, which is expected as precipitation both contributes to vapor levels and arises from clouds with significant water vapor contents. This is further exemplified by once again drawing the connection that IWV and PW are practically equivalent, as greater amounts of precipitable water are of course expected from precipitating clouds.

Furthermore, as PW measurements can only be found in the valleys of IWV between precipitation events, this exemplifies one of the shortcomings of the sun-based AERONET data, in that it is not available during times of notable cloud cover.

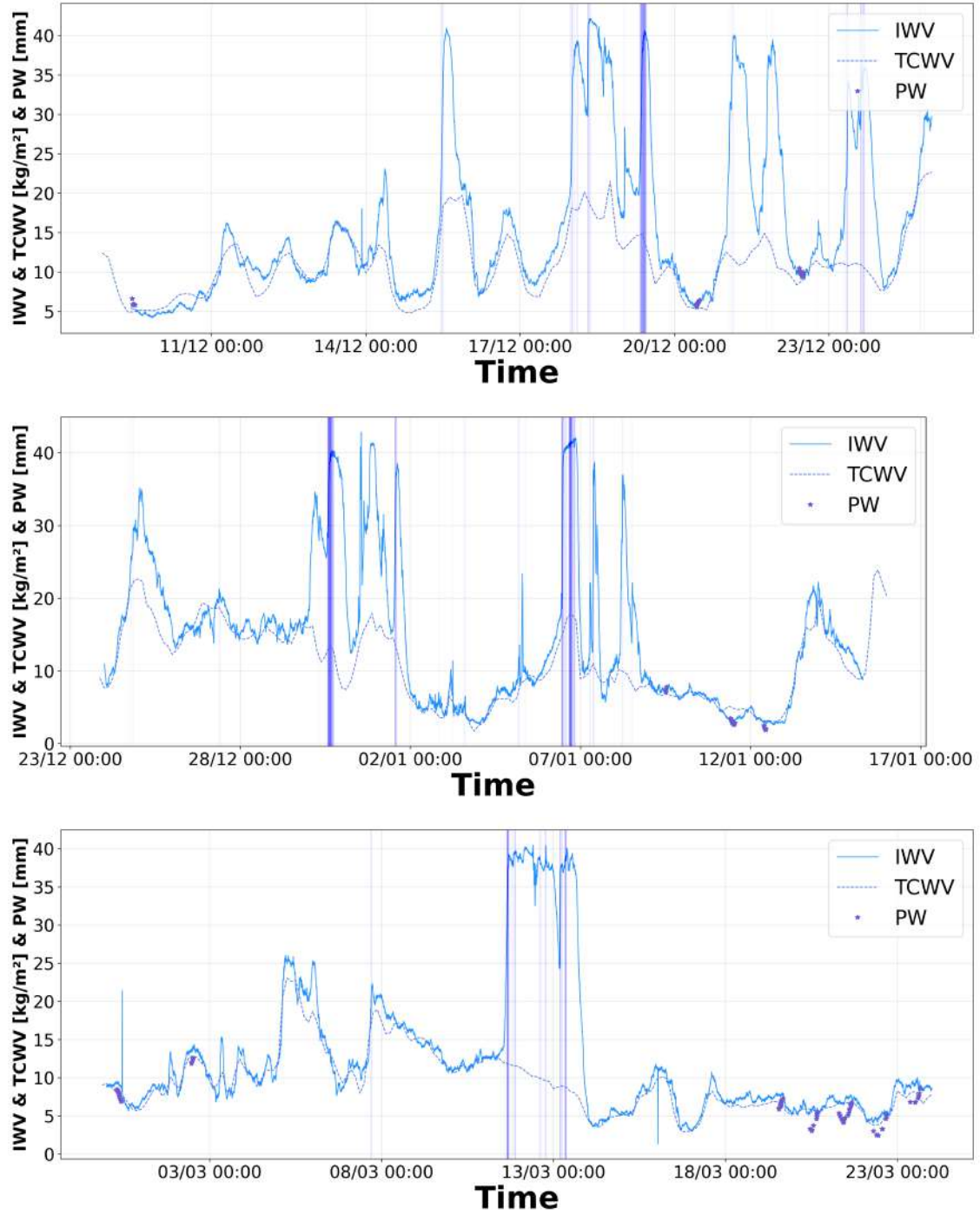


Figure 4.4: Precipitable Water [mm] (AERONET), Integrated Water Vapor [kg/m²] (HATPRO) and Total Column Water Vapor [kg/m²] (CAMS) plotted together over the periods 2024-12-09 to 2024-12-24, 2024-12-24 to 2025-01-15, and 2025-02-28 to 2025-03-23. Vertical lines represent rain flags assigned by the HATPRO instrument.

4.1.2.4 Microwave radiometer HATPRO & Weather Station

Figures 4.5 and 4.6 show comparisons between the OSO Weather Station data and the OSO HATPRO data over the example period 2025-01-01 to 2025-01-15.

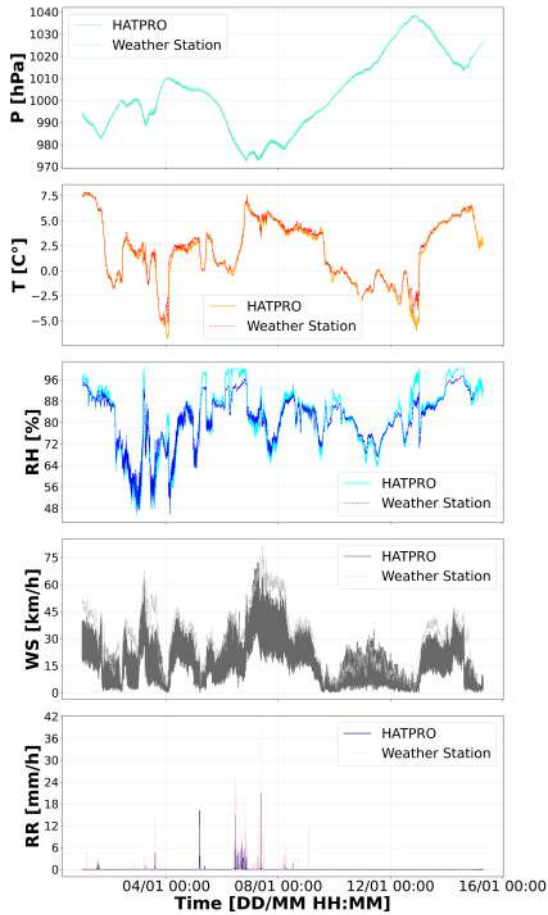


Figure 4.5: Weather Station data plotted alongside radiometer HATPRO data.

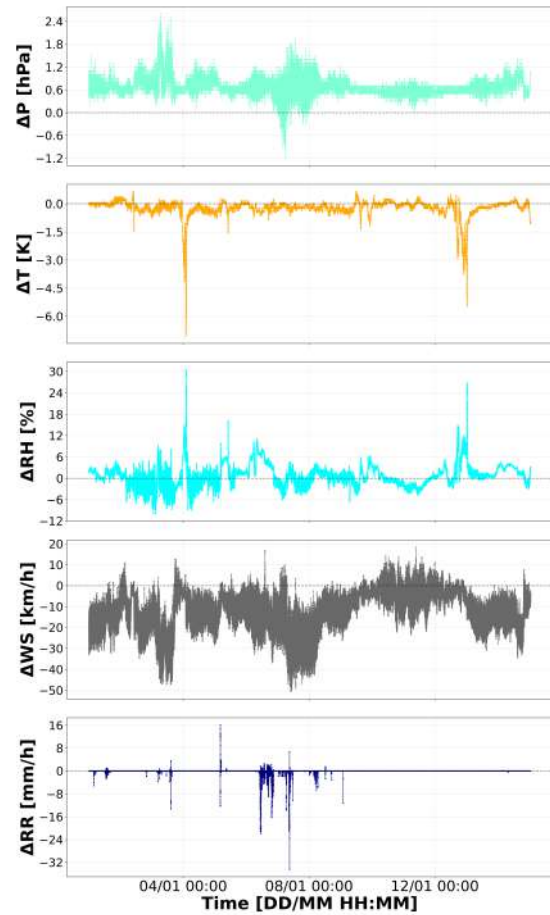


Figure 4.6: Weather Station data subtracted from HATPRO data to obtain differences.

From Figure 4.5 it is evident that there is an offset in measured values between the two instruments, but that they for the most part display satisfactory alignment. However, notable differences include HATPRO measurements of RH significantly exceeding those of the Weather Station during certain peak measurements, while Rain Rate (RR) measurements from the Weather Station tend to exceed those of the HATPRO measurements, on occasion even detecting precipitation when the HATPRO instrument detects none. This is expected, given that rain measurements are not the main objective of the HATPRO. Particularly for this reason, Weather Station rain rate measurements were favored over HATPRO rain rate measurements during analysis steps.

Also notable is the considerable difference in Wind Speed (WS) measurements, where the HATPRO instruments exhibits a significantly larger variance in mea-

4. Results

surements, which additionally tend to be slower than those wind speeds measured by the Weather Station.

Figure 4.6 further exemplifies specific differences between the measurements of the two instruments. With the exception of a few aberrations, this figure displays the typically good alignment between the two instruments in most cases and for more variables.

Notable is the apparent baseline shift for pressure, where the HATPRO instrument is shown to typically measure slightly greater pressures than the Weather Station. This difference is explained by the difference in altitude between the two instruments, with the Weather Station being located 16 m above ground level. This difference in altitude may additionally explain the Weather Station's tendency to measure slightly greater wind speeds, as it is slightly more elevated in relation to surrounding obstacles which may reduce local apparent wind speeds.

Figures 4.7 and 4.8 compare the wind speed and wind direction measurements between the HATPRO and Weather Station instruments over the period 2025-01-01 to 2025-01-15, presented in windrose plots. Here, the bars represent the directions that winds are detected to be coming from.

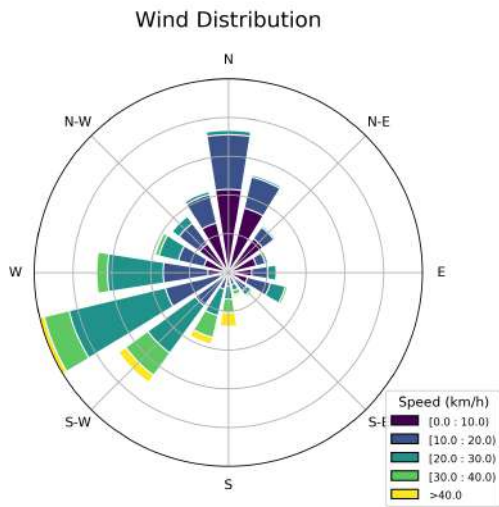


Figure 4.7: Windrose of HATPRO data from 2025-01-01 to 2025-01-15.

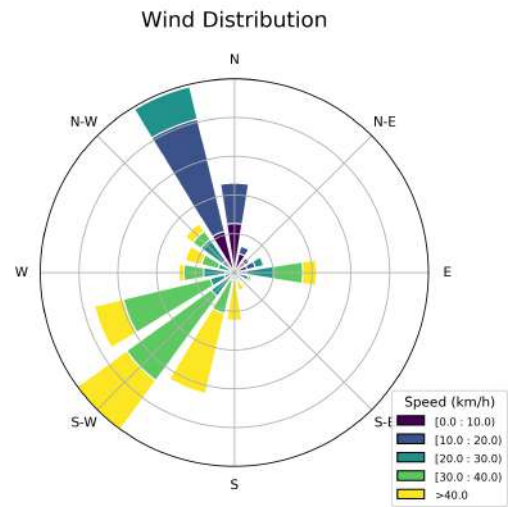


Figure 4.8: Windrose of Weather Station data from 2025-01-01 to 2025-01-15.

Examining the figures appears to show a roughly 30° offset between the two instruments, based on the offset between the identified primary wind directions. Based on the positions of the instruments, the Weather Station measurements of wind direction are taken to be more reliable for the same reason that it registers a lower pressure and appears to measure higher wind speeds: its elevation above ground means it is not surrounding by potential obstacles which may produce a redirecting trend of incoming winds. Additionally, like with rain measurements, wind measurements are not the main objective of the HATPRO, giving further credence to the

Weather Station wind measurements.

For these reasons, Weather Station data took precedence over HATPRO data specifically in regards to rain and wind measurements.

4.1.2.5 Microwave radiometer HATPRO & CAMS reanalysis

Figure 4.9 shows comparisons between HATPRO profile measurements and CAMS profile data in RH and temperature during the 2025-03-14 to 2025-03-31 period. The verdict appears to be that CAMS data is not a perfect approximation of local OSO conditions, which is expected as it consists of average values over a much larger area. The general trend appears to be an underestimation of RH and temperature at altitude. This could also be taken as a result in and of itself as a deficiency of reanalysis models in general. The underestimation of RH could be explained by the fact that OSO is an exclusively coastal site, whereas the CAMS data set is based on an area also including swaths of inland environments. Here it is additionally worth recalling that the altitudes of CAMS measurements are estimates derived from pressures and averaged temperatures, further explaining potential misalignment.

However, the CAMS data does appear to still register the occurrence of larger events, especially concerning RH, where high and low RH peaks and troughs appear to roughly align between the two data sets. As for temperature, the exclusion of obvious high-temperature events visible in the HATPRO data from the CAMS data manifests as a noteworthy misalignment in data, however here too general trends and daily cycles visible in the HATPRO data appear to be captured in the CAMS data to some degree, though perhaps not aligning with exact temperature values. In general, however, order of magnitude and general distribution are not that bad.

Maintaining knowledge of the CAMS data set's deficiencies is thus an important factor to consider in later analysis. However, it is still deemed sufficiently accurate to demonstrate general trends and events.

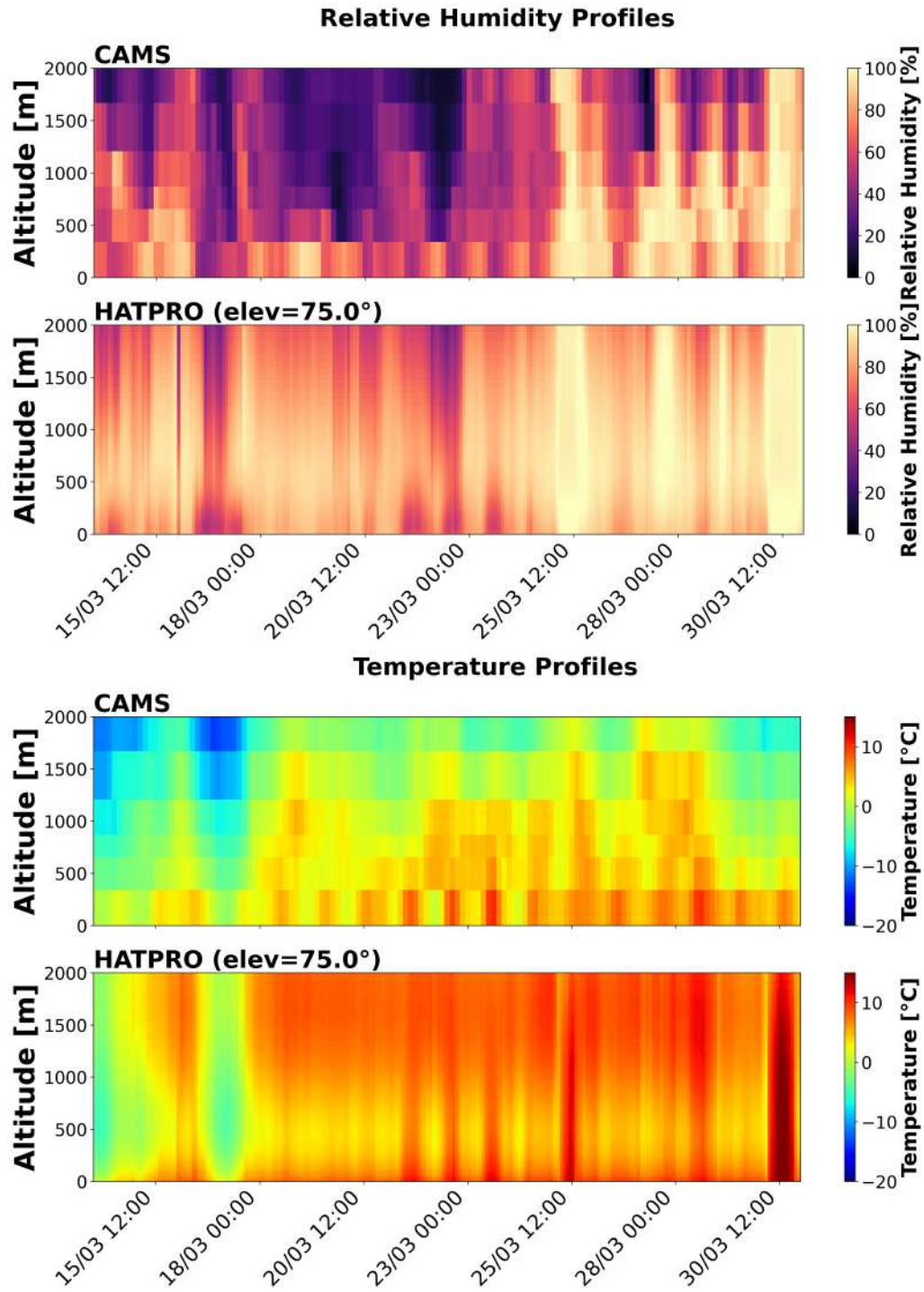


Figure 4.9: Comparisons between CAMS reanalysis and HATPRO profile data of RH and temperature.

4.1.2.6 CAMS SSA Mixing Ratios

Figure 4.10 shows SSA mixing ratios for the three dedicated size ranges offered by CAMS: $0.03\text{--}0.5\text{ }\mu\text{m}$, $0.5\text{--}5\text{ }\mu\text{m}$, and $5\text{--}20\text{ }\mu\text{m}$. Calling back to our theory, we can identify that $0.5\text{--}5\text{ }\mu\text{m}$ corresponds to the size range of film droplets, while $5\text{--}20\text{ }\mu\text{m}$ includes part of the size range of jet droplets.

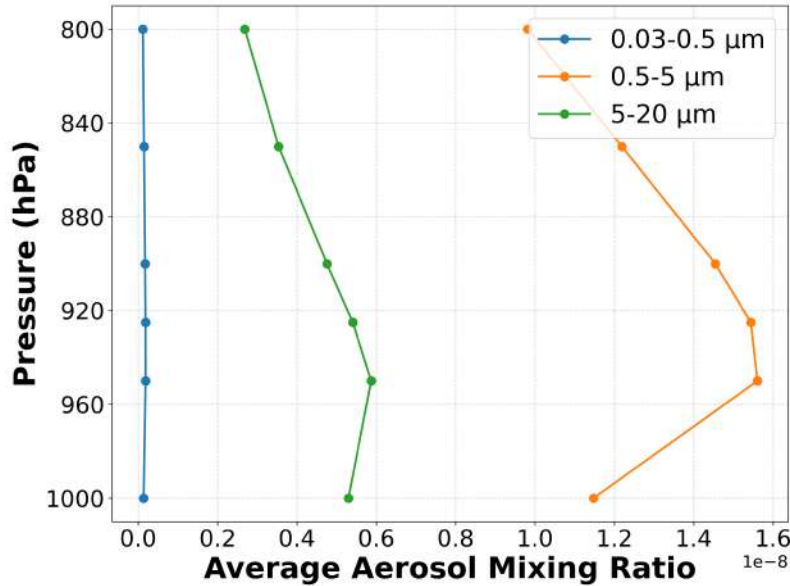


Figure 4.10: CAMS SSA mixing ratios for different diameter ranges at all relevant pressure levels averaged over the entire 2024-10-01 to 2025-03-31 period.

From this plot we can see that the size range $0.5\text{--}5\text{ }\mu\text{m}$ dominates, with some significant contribution from the larger size range of $5\text{--}20\text{ }\mu\text{m}$, whereas the smallest size range, $0.03\text{--}0.5\text{ }\mu\text{m}$, barely shows any contribution at all. This aligns with our understanding that SSAs typically consist of larger particles in the accumulation and coarse modes.

Given its lack of prevalence, the SSA mixing ratio for the size range $0.03\text{--}0.5\text{ }\mu\text{m}$ was largely ignored in later analysis.

4.2 Characteristics of the OSO Site

In this section we will give a brief overview of some of the characteristics of the Onsala Space Observatory site, based primarily on the 2024-2025 AERONET data.

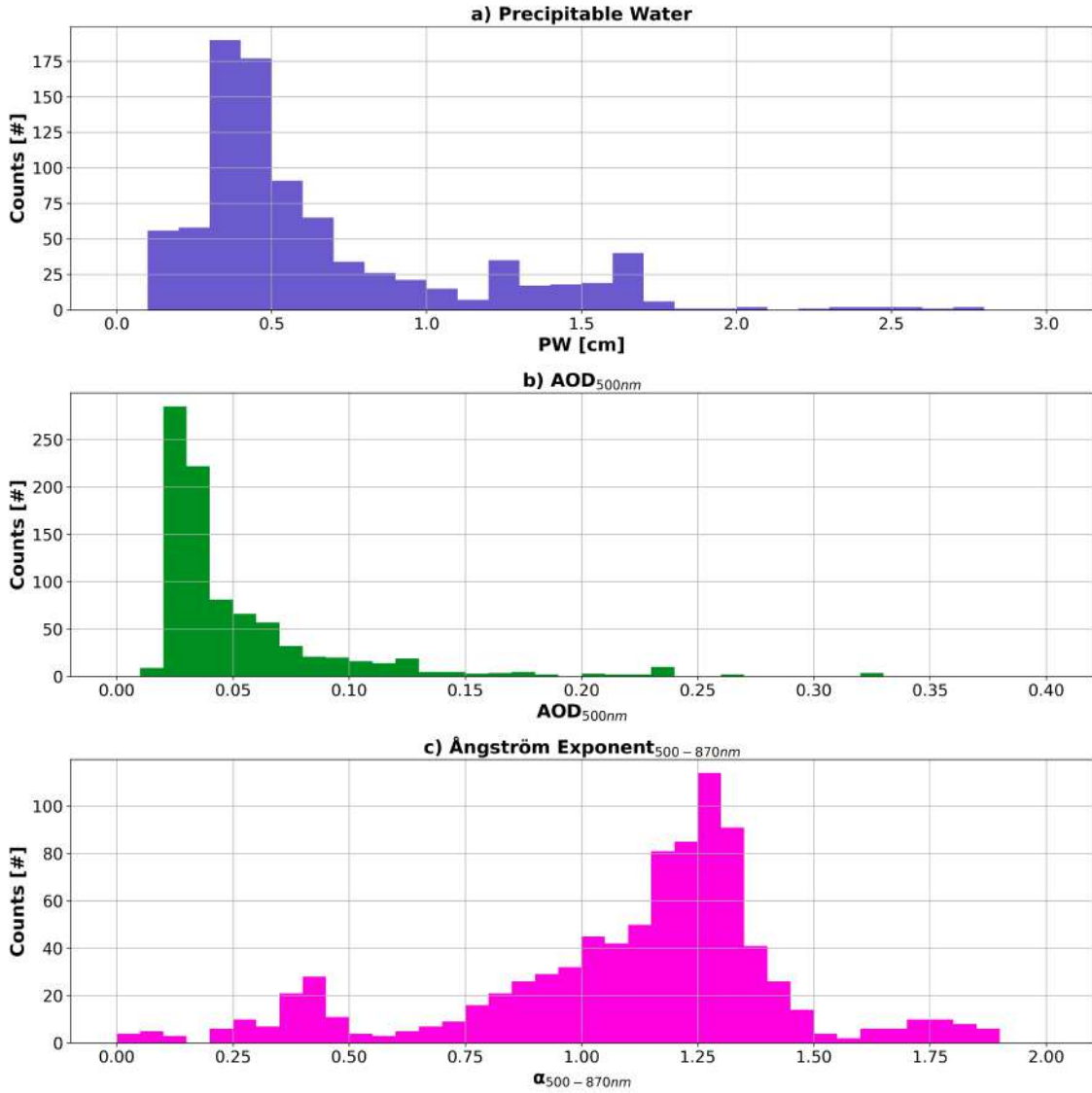


Figure 4.11: AERONET data for precipitable water, $\text{AOD}_{500\text{nm}}$, and $\alpha_{500-870\text{nm}}$, categorized into bins to obtain distributions.

Table 4.1: Average values and values corresponding to count maxima for AERONET PW, $\text{AOD}_{500\text{nm}}$, and $\alpha_{500-870\text{nm}}$ data.

QUANTITY	MAXIMUM AT	AVERAGE
PW	0.35 cm	0.657 cm
AOD	0.025	0.053
α	1.27	1.101

Figure 4.11 shows histograms of all the AERONET data collected at OSO during the October 2024 to March 2025 period. Averages and maxima were also determined and are displayed in Table 4.1.

This data once again seems to indicate that OSO exists within a primarily pristine environment, as AOD values are concentrated below 0.1, applying to both the maximum and the average.

However, it is once again worth noting that the sun-photometer used to gather data for AERONET was only capable of doing so during clear skies. Thus we miss out on the AOD measurements on cloudy days. For comparison, Figure 4.12 includes the same histogram for AOD over the same period, but with CAMS data, in which data from cloudy days is included.

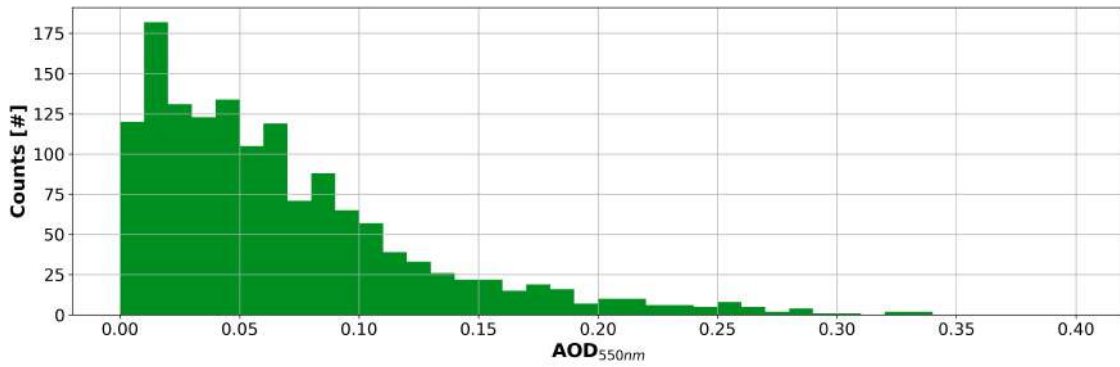


Figure 4.12: CAMS data for AOD_{550nm} categorized into bins to obtain distribution.

Figure 4.12 shows a broader distribution of AOD values, implying that the sun-photometer's inability to take measurements during cloudy conditions makes it underestimate the occurrence of higher-AOD conditions, likewise overestimating the occurrence of pristine conditions. Additionally, this seems to imply a connection between greater aerosol number and cloudy conditions, a correlation which will be further discussed in section 4.3.3.

However, the peak of the histogram, while broader, is still centered below 0.1. Additionally, the average AOD as calculated for the CAMS data histogram was 0.068, marginally higher than the AERONET average of 0.053 and still below 0.1. So while the AERONET data might overestimate just how pristine the atmosphere around the OSO site is, the OSO site can still be said to be approximately pristine on average.

Regarding the Ångström exponent, the average of $\alpha = 1.101$ appears to be slightly higher than the range $\alpha = 0.7 \pm 0.36$ expected for marine air masses, however it is worth remembering that this estimate was derived from a study in tropical conditions (Réunion Island) [1]. Still, this implies that the Ångström exponent in coastal Sweden tends to be larger than that of tropical islands, which trend is additionally exemplified by the maximum at the OSO being reached at around $\alpha = 1.27$.

This being greater than 1 also seems to indicate the prevalence of aerosols smaller than 500 nm in diameter most of the time. However, this could possibly be another consequence of the restriction of AERONET data to clear weather. From Figure 4.11 we can also recognize a secondary peak around $\alpha \approx 0.4$, indicating regular occurrences of aerosol sizes exceeding 870 nm. One hypothesis — which may be further strengthened by the coming results in section 4.3 — is that these are remnant measurements from the leading and tailing ends of periods of significant cloud cover, which may carry greater quantities of larger aerosols, particularly SSAs.

For further characterization of the OSO site, we recall the contents of Figure 4.3, showing that the site is primarily under the influence of SSA and organic matter aerosols, occasionally under notable influence of sulfates, and very rarely if ever significantly affected by dust aerosols. Given that OSO is a coastal, near-boreal region, with the Gothenburg Harbor and shipping lane of the Kattegatt sea nearby (potentially accounting for sulfate emissions), this matches our expectations.

4.3 2024-2025 Period Results

Below we will discuss results from our multi-instrument and model analysis during the period from October 2024 to March 2025.

4.3.1 Wind-Particle Connection

One relationship noted during analysis of the 2024-2025 period data was the apparent influence of wind direction and wind speed on aerosol concentrations. In particular, the apparent correlation between strong winds arriving from the South-West and an increase in AOD and Particulate Matter concentrations, specifically in regard to their SSA fractions and the SSA Mixing Ratio. To confirm this relationships, periods of particularly strong winds were identified, and are displayed in Figure 4.13, displaying data for the periods — from left to right — 2024-11-14 to 2024-11-16 (3 days), 2025-01-05 to 2025-01-08 (4 days), and 2025-02-27 to 2025-03-02 (4 days). For clarity, there was no precipitation detected during any of the periods mentioned in this entire section.

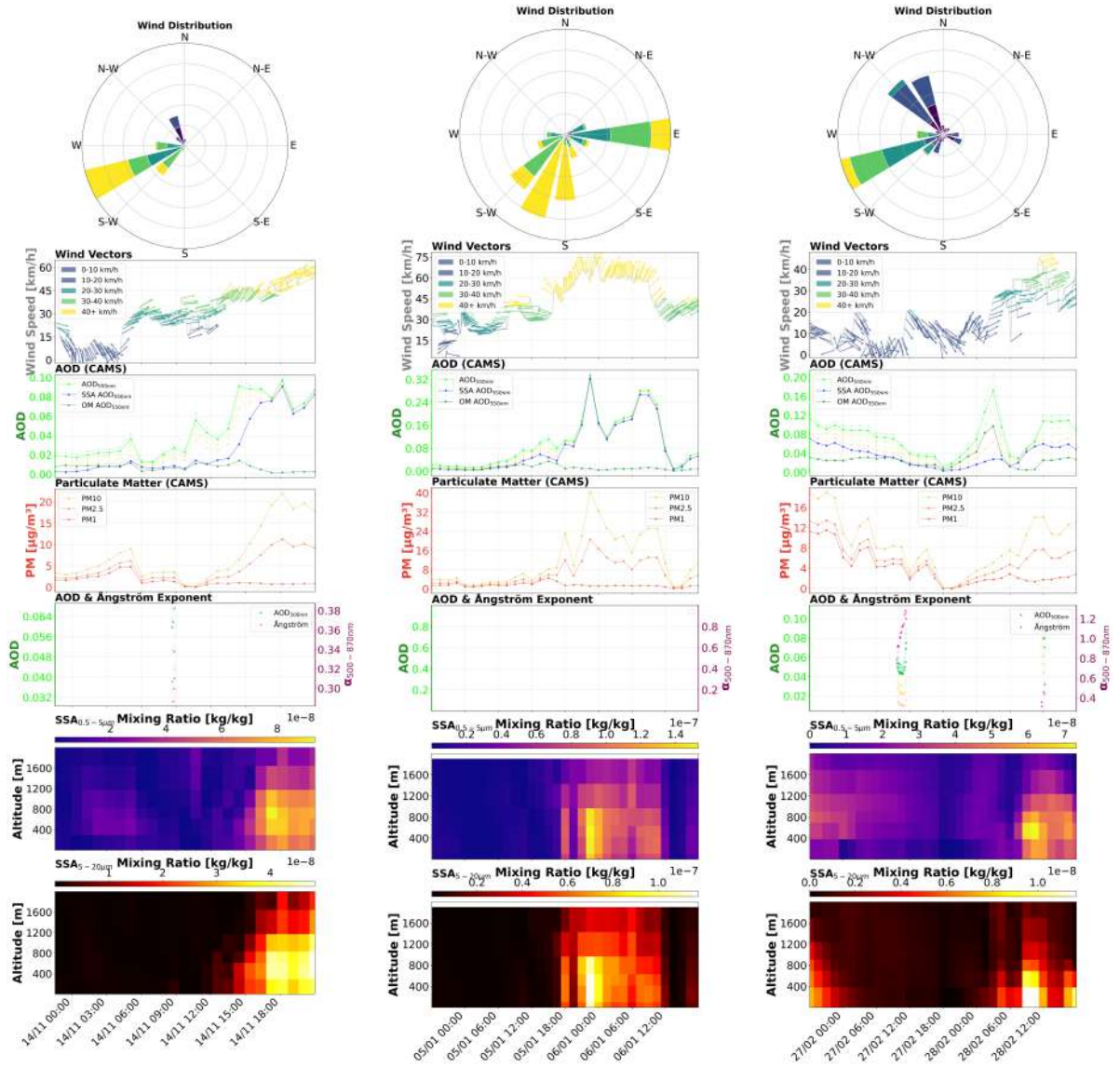


Figure 4.13: Three examples of strong Western winds influencing aerosol concentrations, in particular SSA fractions. Periods are — from left to right — 2024-11-14 to 2024-11-16, 2025-01-05 to 2025-01-08, and 2025-02-27 to 2025-03-02.

2024-11-14 to 2024-11-16: In the left-most figure, winds can be seen to shift from weak, Northern winds during the 14th, to strong, Western winds culminating on the 16th. This coincides with a drop in organic matter AOD fractions and an increase in the SSA fraction of AOD_{550nm} rising to almost 100%, as can be seen in the AOD (CAMS) plot. This is additionally synchronized with significant rises in PM_{2.5} and PM₁₀, as well as very notable low-altitude peaks in the SSA_{0.5–5µm} and SSA_{5–20µm} mixing ratios. This is particularly noticeable for SSA_{5–20µm}, as prior to this event this mixing ratio appears to be almost 0 for all altitudes.

The increases in PM_{2.5} and PM₁₀ but not PM₁ indicates that these extracted particles tend to have diameters in excess of 1 µm, coinciding nicely with the size

range of film and jet droplets, and specifically implying that they belong to the coarse mode. This is further implied by the increased mixing ratios of SSAs in both size ranges, and the fact that in the AOD (CAMS) data, the AOD for shorter wavelengths appear to go down as those for higher wavelengths appear to go up, implying the presence of larger particles in general.

This indicates that the strong Western winds — the threshold for which appear to be roughly 30–40 km/h — are extracting SSAs from the oceans and suspending them in the air, supplanting previous concentration of organic matter and other aerosols. This threshold appears to roughly coincide with the theoretical threshold of 30 km/h.

2025-01-05 to 2025-01-08: The middle figure points to similar conclusions. Here, strong winds start as originating from the East, gradually shifting to origin from a Southward and South-Westward direction. Alongside this shift in direction, the SSA fraction of AOD rises to once again dominate, again alongside increases in PM2.5, PM10, and the SSA mixing ratios.

2025-02-27 to 2025-03-02: The right-most figure tells a similar story. As AOD and PM are seen to settle down under weak winds from previous peaks, subsequent strong Western winds raise them up again. In the case of AOD, the stronger winds appear to supplant a previous organic matter AOD peak with one of SSAs, again raising PM2.5, PM10 and the SSA mixing ratios. During the organic matter AOD peak around 18:00 on 2025-03-01, no particular offset between PM1 and larger PMs appears, indicating that the phenomenon of increasing PM2.5 and PM10 but not PM1 is specifically indicative of increasing SSA fractions, and not so much organic matter fractions.

Additionally, in this third figure, the Ångström exponent makes a strong case for the large size of SSAs, as before the winds it was $\alpha \approx 1$, while during the winds it can be seen to be $\alpha \approx 0.4 < 1$, indicating the presence of larger aerosols.

On another note, comparing the two profiles for the SSA mixing ratios, we can see that larger SSAs are concentrated toward lower altitudes, indicating that these largest of aerosols tend to stay lower to the ground, or in this case the ocean.

To ensure that this phenomenon of raised SSA concentrations is primarily a consequence of strong Southern/Western winds specifically, we also looked at some examples of the influences of strong Eastern winds. Examples of this can be seen in Figure 4.14.

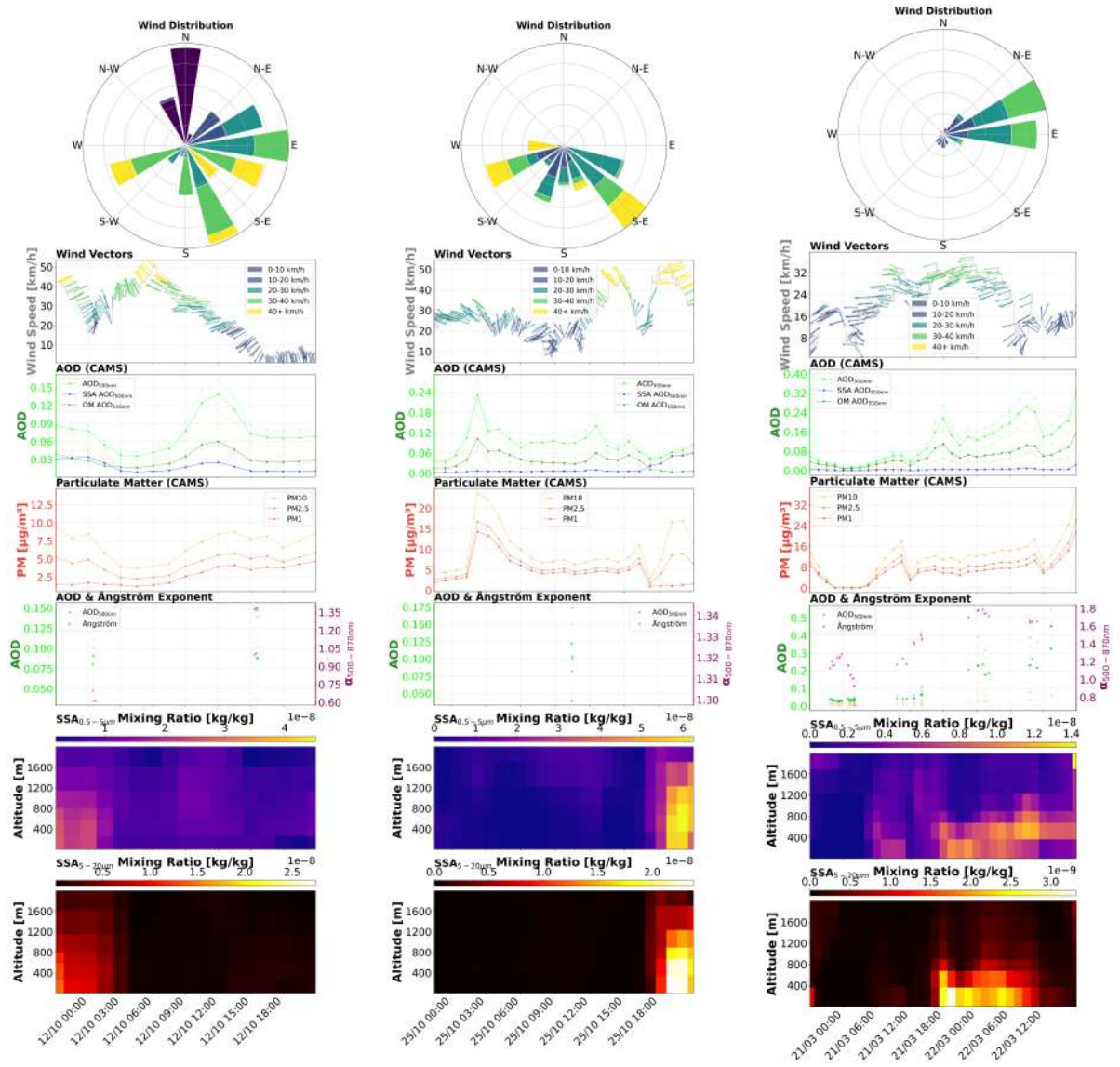


Figure 4.14: Three examples of strong Eastern winds influencing aerosol concentrations. Periods are — from left to right — 2024-10-12 to 2024-10-13, 2025-10-25 to 2025-10-27, and 2025-03-21 to 2025-03-24.

2024-10-12 to 2024-10-13: In the left-most figure we can see strong South-Western winds being supplanted by strong South-Eastern winds before fading into weaker Eastern winds and ending finally in very weak Northern winds.

These strong South-Eastern winds give no indication of raising SSA AOD levels or SSA mixing ratio levels, which remain consistently low after the shift away from South-Westerly winds, being supplanted by rising organic matter AOD. Alongside this lack in SSA AOD we also discern a lack of any significant offset between PM concentration data, confirming that the phenomenon of raised PM2.5 and PM10 and unaffected PM1 is to be taken as an indication of SSAs being present.

Additionally, we note that the Ångström exponent, which was previously low at around $\alpha \approx 0.6$ during the initial wind reorientation, rises to $\alpha \approx 1.4$ around the onset of the weak, Northerly winds, indicating the dominant presence of smaller aerosols over larger ones, where of course the opposite would be true in the case of the larger SSAs.

2025-10-25 to 2025-10-27: In the middle figure we can more clearly observe the contrast between the influences of weak and/or Easterly winds vs. strong Westerly winds, as the former turn into the latter toward the end of the period.

Before the shift, we observe raised organic matter AOD fractions associated with Easterly winds with the SSA AOD consistently near 0, as well as a lack of PM offset and notable SSA mixing ratios. With the onset of strong Westerly winds, we see this paradigm change as the SSA AOD fraction becomes dominant and the organic matter AOD falls toward 0, alongside PM_{2.5} and PM₁₀ rising above PM₁ and the SSA mixing ratios reaching significant peaks.

2025-03-21 to 2025-03-24: The right-most figure shows the influence of consistently present, relatively strong Eastern winds. Here we see stronger winds raising AOD in general, and specifically the organic matter AOD fraction, as the SSA AOD once again remains near 0. This period also benefits from a relative abundance of AERONET data, showing rising AOD with stronger winds and consistently large values of the Ångström exponent, implying the presence of more but smaller aerosols, consistent with our previously established correlation that organic matter aerosols tend to be small.

However, the 2024-2025 period also contains potential counter-examples to the previously established relationships, some of which are exemplified in Figure 4.15.

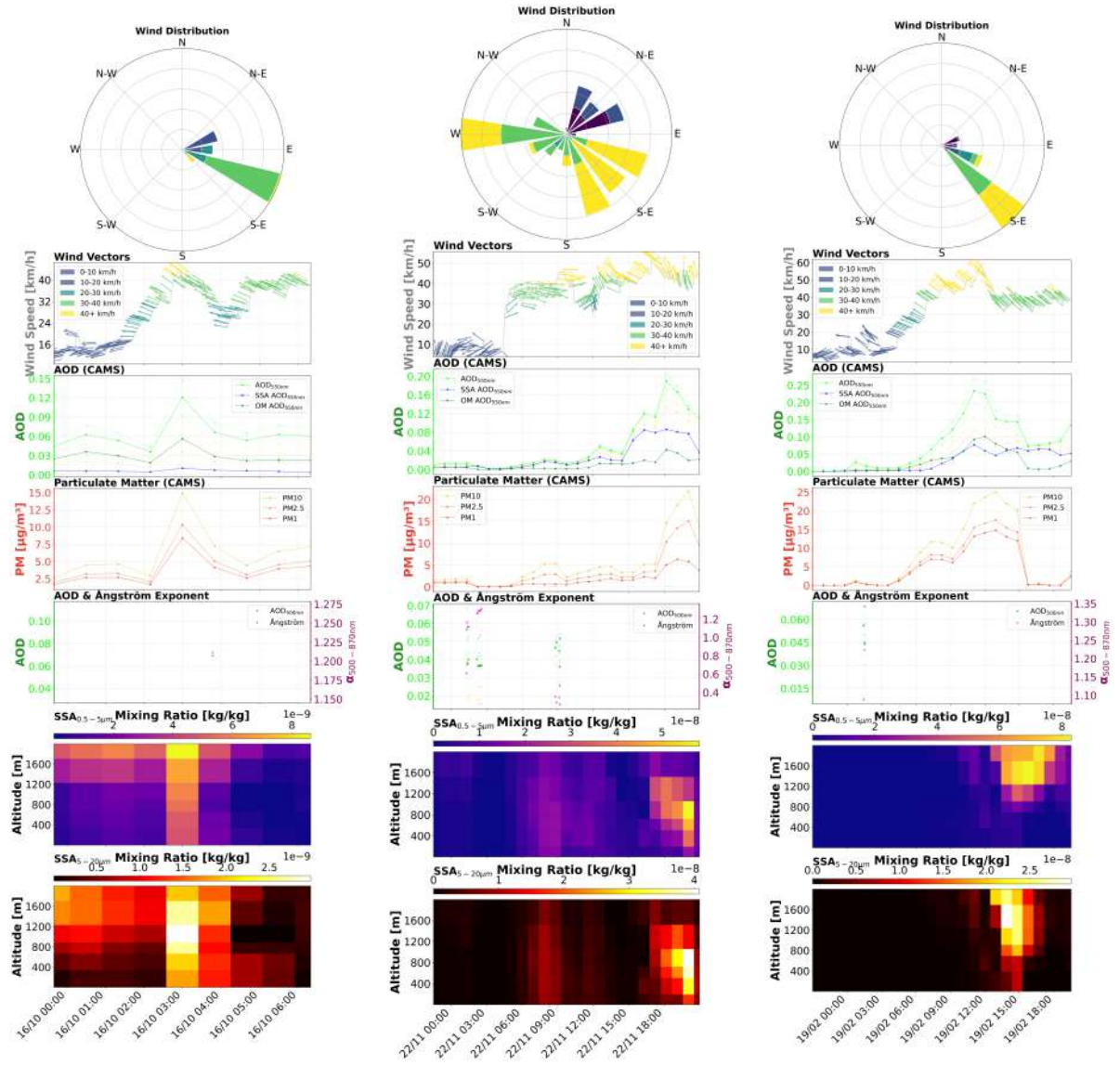


Figure 4.15: Three potential counter-examples to previously established phenomena. Periods are — from left to right — 2024-10-16, 2024-11-22 to 2024-11-24, and 2025-02-19 to 2025-02-21.

In Figure 4.15, we can see the following occurrences: in the left-most figure, we can see apparent SSA mixing ratio peaks during Eastern winds, with no apparent correlation to heightened SSA concentrations in the other variables. In the middle figure, we can see apparent SSA AOD and SSA mixing ratio peaks associated with primarily strong Eastern winds. In the right-most figure, we can see apparent SSA mixing ratio peaks under low AOD, low PM conditions, with strong South-Eastern winds.

Looking at the SSA mixing ratio peaks, their apparent concentrations at higher altitudes rather than at ground level could indicate that these SSA concentrations were carried over the CAMS grid square at high altitudes from other regions, per-

4. Results

haps as part of passing cloud covers which developed elsewhere.

However, to confirm for ourselves that the relationships seen in Figures 4.13 and 4.14 are indeed genuine and significant, we plot AOD and PM fractions over wind speed for each of the four cardinal directions over the entirety of the relevant 2024-2025 period, as can be seen in Figure 4.16.

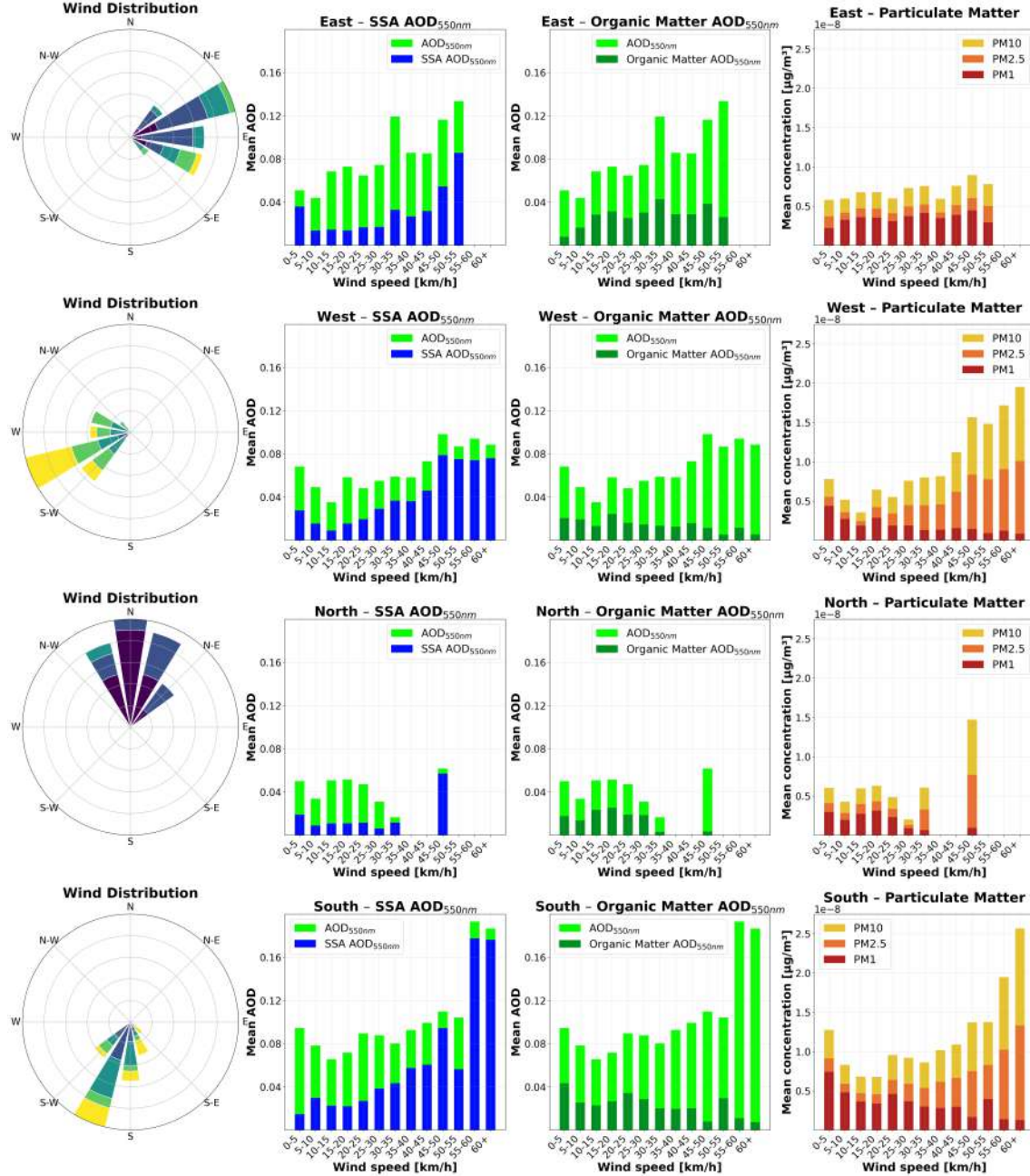


Figure 4.16: Histograms of AOD and PM fractions over the October 2024 to March 2025 period, filtered based on wind origins.

From Figure 4.16 we can establish that Western and Southern winds, especially strong ones, can clearly be correlated to high SSA, low organic matter conditions,

where PM2.5 and PM10 fractions dominate over PM1 fractions. Additionally, their wind speeds are shown to be capable of exceeding 60 km/h, which is apparently not a characteristic shared with the other two wind directions. Additionally, we are able to reconfirm the previously established characteristics of the OSO site that Western and Southern winds are capable of reaching greater wind speeds than Eastern and Northern winds.

Strong Eastern winds are shown to still be capable of producing heightened AODs and even heightened SSA concentrations at the highest of wind speeds, though this is not shown to be correlated with specific increases in PM2.5 and PM10, perhaps indicating that these are not the same type of SSAs encountered in the other scenarios.

Lastly, Northern winds are shown to by far to be the weakest of the four directions, rarely exceeding 35 km/h, and keeping to very low AODs. The one aberration of the isolated bar of data in the 45–50 km/h wind speed bin, seeing as there is no data available for intermediate wind speeds, may indicate that this is the product of a few or perhaps only one event of these wind speeds being achieved by other directions and then simply shifting to Northern winds for one brief period. If this is the case, this particular 45–50 km/h wind speed is not representative of general Northern characteristics.

These same relationships can additionally be seen in the averaged SSA mixing ratios shown in Figures 4.17 through 4.20.

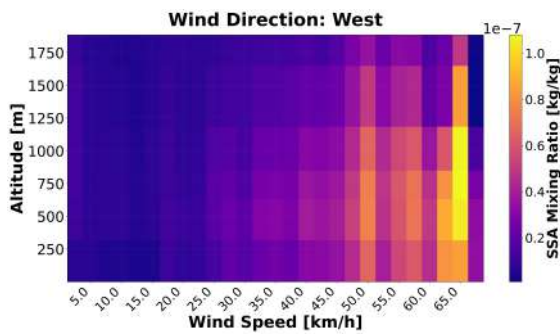


Figure 4.17: SSA mixing ratios averaged over West wind conditions during the 2024-2025 period.

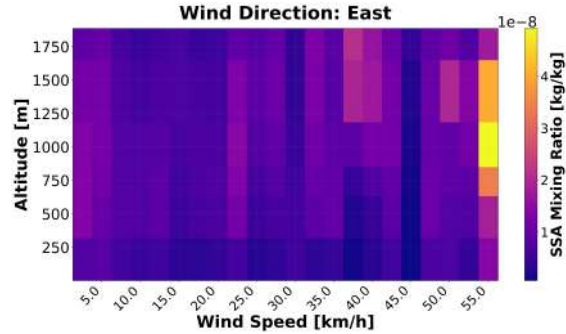


Figure 4.18: SSA mixing ratios averaged over East wind conditions during the 2024-2025 period.

In these Figures, we can see the vertical distribution of SSA according to the wind speed and direction. Again we can identify strong Southern and Western winds as being the main contributors in raising SSA mixing ratios, while Eastern winds struggle to do so, and Northern winds appear to be incapable of reaching sufficient wind speeds. The isolated bars in the Northern wind SSA plot (Figure 4.19) may further indicate that these Northern winds are rare enough such that single deviating events may corrupt the averages.

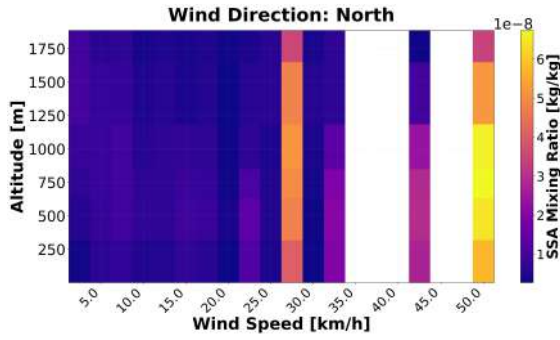


Figure 4.19: SSA mixing ratios averaged over North wind conditions during the 2024-2025 period.

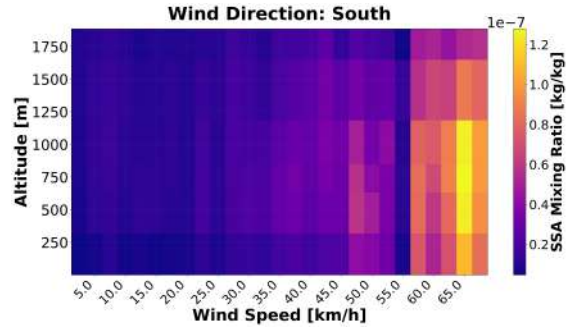


Figure 4.20: SSA mixing ratios averaged over South wind conditions during the 2024-2025 period.

4.3.2 Rain Impact

In the previous section, we exclusively looked at periods lacking any precipitation events. To establish the impact of these events, this section is included. Examples of rain impact are shown in Figure 4.21. From these plots we can see that rain raises the local IWV and RH at all displayed altitudes, while also reducing local AOD, PM and SSA mixing ratio, illustrating a clear example of "washout", where rainfall scavenges particles from the atmosphere during their descent. These interactions are present to some degree over all three example periods.

However, we also note that these concentrations appear to quickly replenish after the rainfall is over, which is most obvious in the middle and right-most periods. We also note that for the left-most and middle periods, rainfall appears to be preceded by an increase in AOD and PM, which may indicate instances of aerosol-spurred rainfall.

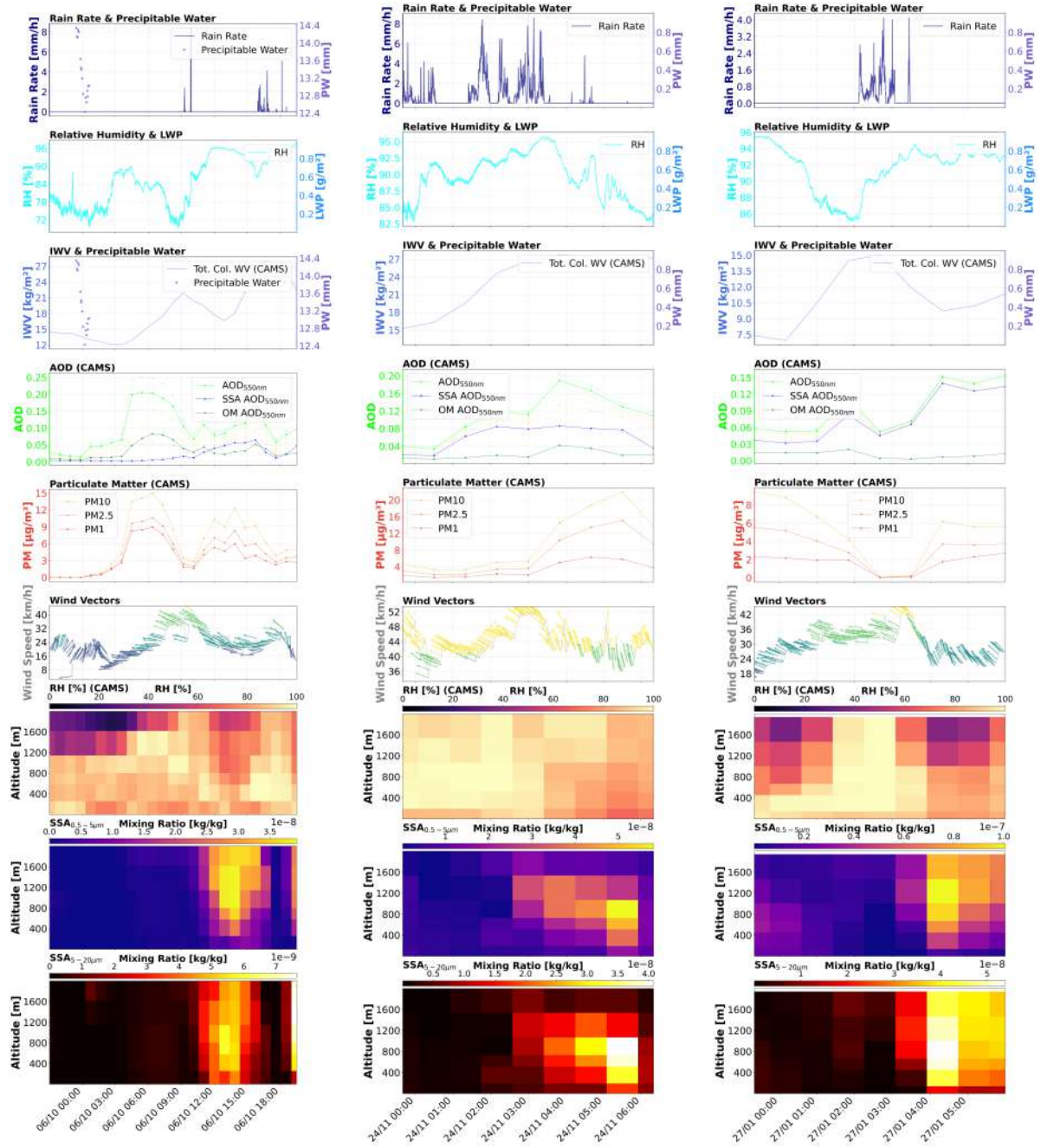


Figure 4.21: Three examples of rain influence on various quantities. Periods are — from left to right — 2024-10-06 to 2024-10-08, 2024-12-24, and 2025-01-27.

4.3.3 Cloud Cover Connection

In this section we set out to find potential correlations between average AOD, PM, and low-altitude cloud cover.

Figure 4.22 shows mean CAMS AOD and CAMS PM over the October 2024 to March 2025 period, categorized by concurrent cloud cover based on the manually-assigned cloud cover categories defined in section 3.2.2. This figure includes averaged data from exactly 136 matched CAMS-Cloud points, from the periods 2024-10-01 to 2024-10-31, 2024-11-19 to 2024-11-24, 2025-01-08 to 2025-01-13. These specific periods were chosen as they contained mainly non-ambiguous cloud cover. The exact images assigned to each category can be found in Appendix A.

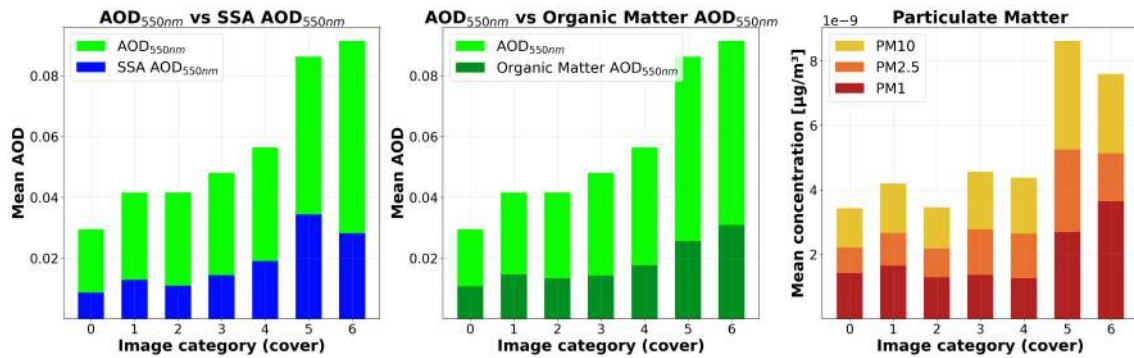


Figure 4.22: Mean CAMS AOD and PM over the October 2024 to March 2025 period categorized by defined cloud cover categories.

From this figure we can see that there appears to be a clear correlation between more cloud cover and higher AOD, especially for times of almost total cover (categories 5 and 6). This shows a clear relationship between aerosols and cloud cover, likely demonstrating the CCN composition of clouds and possibly indicating the spurring of cloud formation by aerosols. All PMs meanwhile appear roughly constant for categories 0 – 4, but increasing for categories 5 and 6.

During the categorization of the sky camera images, it was further established that categories 5 and especially 6 can be associated with dark, stormy cloud cover. In particular, rainfall was determined to primarily fall under category 6 cloud cover conditions. As such, we can associate category 6 with precipitation events, influencing its averages. One could take the fact that AOD and PM are highest for these categories to be an argument *against* washout. However, here it is also worth remembering that these CAMS data points are taken for the total column of the atmosphere, and as such washout at the lower altitudes may be overridden in the data by the conditions in the rest of the column. In this case, the generally raised aerosol composition of clouds, exacerbated by the fact that "100% cloud cover" implies ubiquitous cloud presence over a large area — which especially affects CAMS data over its large grid squares — presumably has significantly more influence over the resulting AOD and PM data than the washout does.

A similar relationship can be discerned from Figure 4.23, showing SSA mixing ratios averaged over the 2024-2025 period for each cloud category and altitude.

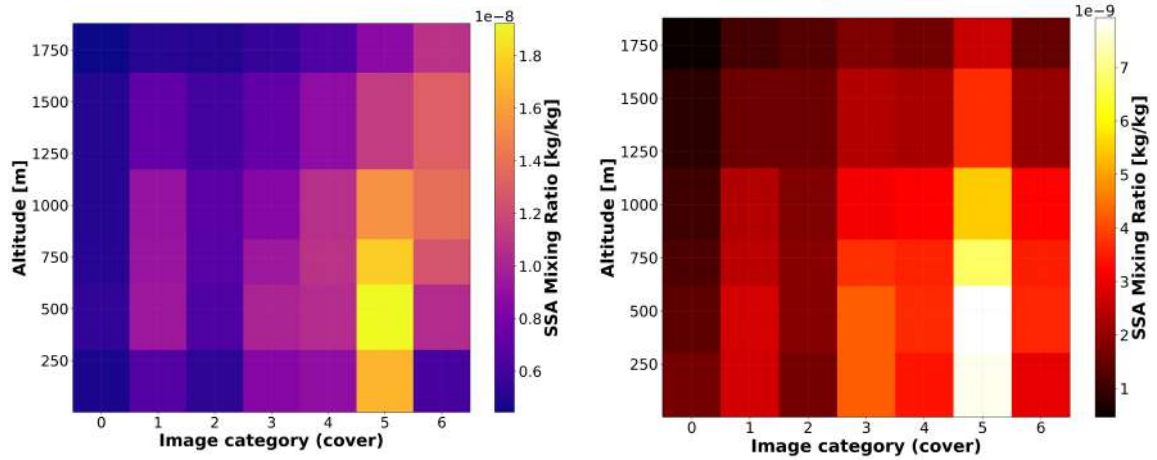


Figure 4.23: Mean CAMS SSA mixing ratios over the October 2024 to March 2025 period categorized by defined cloud cover categories.

From this figure we can see that SSA mixing ratios typically rise with increased cloud cover, just like AOD. However, we can also discern that concentrations are on average greater for category 5 than for category 6. This might be a consequence of the aforementioned washout, not particularly seen in Figure 4.22, but possibly seen here in what could be an implication that washout is more visible with the added dimension of altitudes.

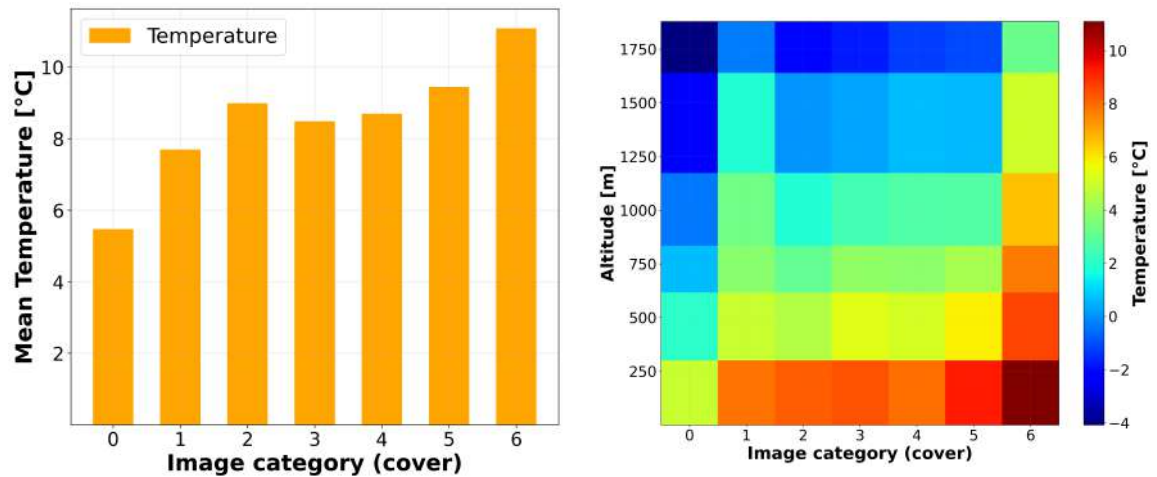


Figure 4.24: Mean weather station temperature and mean CAMS temperature profiles over the October 2024 to March 2025 period categorized by defined cloud cover categories.

To draw further connections between cloud cover and other contemporary data, we also plot the averages of weather station and CAMS temperature over the period and for each cloud cover category in Figure 4.24.

For temperature, we can see that category 0 (perfectly clear) in particular is associated with low overall temperatures at all altitudes. This is not unexpected, as during the analysis of cloud camera images, category 0 images were recurrently associated with mornings and evenings, during which the temperatures tend to be lower.

Categories 1 – 5 appear to be roughly uniform in temperature in the CAMS profile, though a slightly more clear trend of rising temperatures appears to be present in the averages weather station data. The next large aberration occurs for category 6, where temperatures appear to be particularly high at all altitudes, possibly indicating that warmer temperatures spur rainfall, or at least the formation of clouds with the potential for rainfall. Another interpretation is that this rise in temperature accounts for greenhouse warming effects, with the cloud cover trapping heat beneath the cloud cover and keeping it at the surface. The slight trend of rising temperatures among the 1 – 5 categories may also corroborate this relationship between temperature and all cloud cover in general. If this is the case, then the radiative effects of clouds in this particular region during this particular time of year can be associated with a warming effect.

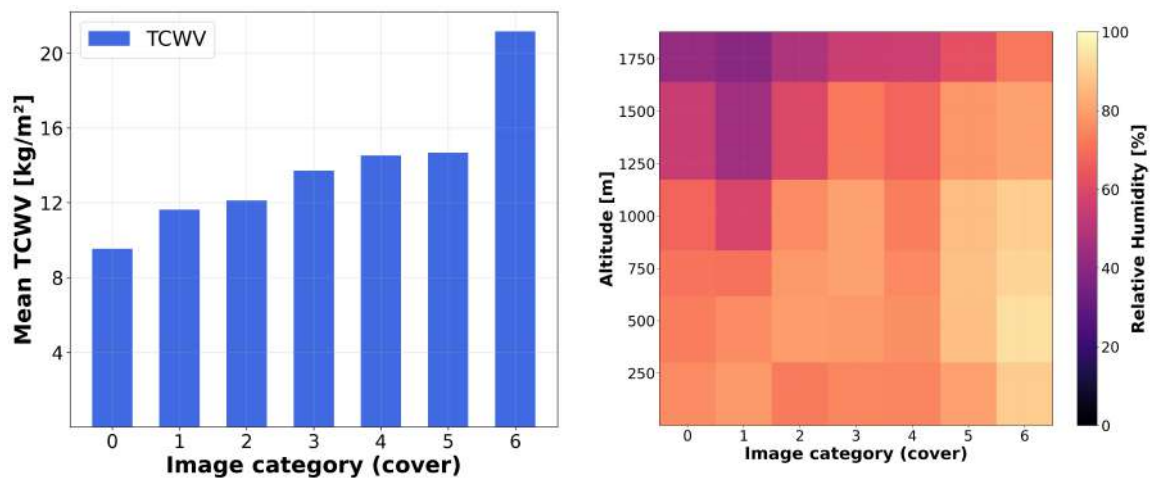


Figure 4.25: Mean CAMS TCWV and relative humidity profiles over the October 2024 to March 2025 period categorized by defined cloud cover categories.

Another attempt at drawing connections can be found in Figure 4.25, containing mean CAMS TCWV and mean relative humidity profiles over the 2024-2025 period.

For RH, we can see a roughly linear increase in RH with cloud cover, also rising in altitude, which is expected given the fact that clouds are composed of water, and given the association between category 6 and precipitation.

In the same vein, TCWV shows the same general characteristics as the RH profile, which makes sense given their inherent connection. Again, water vapor appears to increase with cloud cover. Additionally, the particularly large average for category 6 could be another consequence of its connection to precipitation, which we have already established in section 4.1.2.3 to be a contributor toward increased

IWV/TCWV.

An attempt was also made to find correlations between cloud cover and wind direction as well as wind speed. However, this yielded no clear results, presumably because the 136 matched CAMS-Cloud points may have become too diluted with the additional level of division between wind directions. The associated plots can be found in Appendix B.

Furthermore, an attempt was also made to draw a direct connection between AOD values and local mean temperatures. However, the results of this analysis were vague and not definitive. These results and their brief discussion can be found in Appendix C.

4.4 POPS Results

4.4.1 Drone Flight (2026-05-05)

The drone flight was performed on the 5th of May from the Vingtippen airfield, starting at 15:00 local time and lasting roughly 5 minutes. Its flight path is visualized in both 2- and 3-dimensions in Figure 4.26, also showing total measured concentrations at each point.

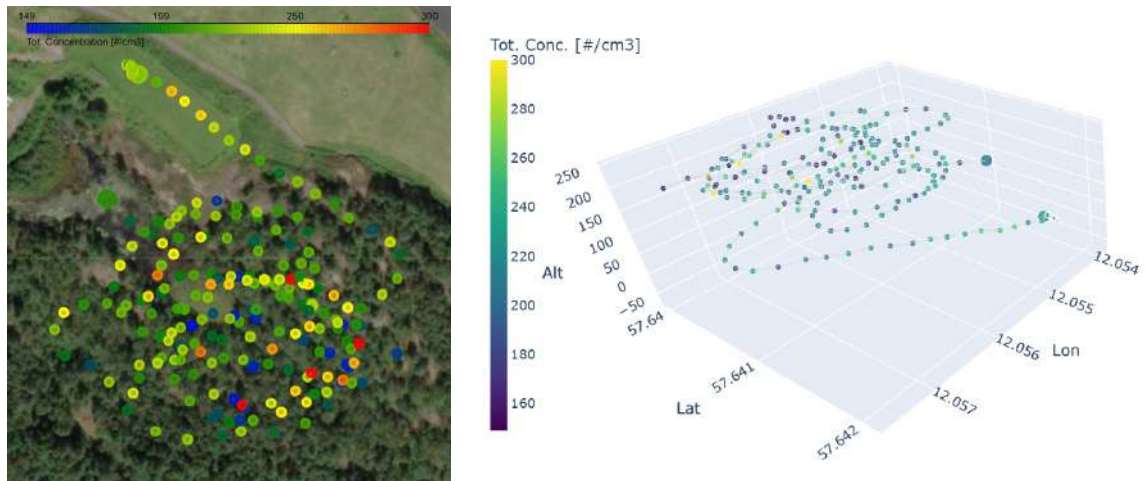


Figure 4.26: 2D and 3D plots of flight path during drone flight. Larger dots represent the start and end points of applicable measurements. On-location ground level starts at 85 m altitude.

To utilize the best accuracy of GNSS measurements, the latter were referenced against a regional reference station at the OSO. As such, the altitude levels shown are not relative to the Vingtippen site, but relative to the OSOs coastal location. The Vingtippen airfield itself was located at roughly 85 m above sea level, which can be taken as the local ground level.

Figure 4.27 shows the aerosol profile over altitude from the drone flight, alongside calculated median concentrations. From this we can see that aerosol number appears approximately constant around $220/\text{cm}^3$ up to an altitude of roughly 200 m above sea level, where aerosol concentrations decrease markedly. This could be a sign of atmospheric boundary layer at this altitude, keeping aerosols out from reaching higher layers.

From Figure 4.28, we can see that the smaller particle sizes dominate, with bin b0 ($<0.13\mu\text{m}$ in diameter) having the highest concentrations. Concentrations then drop off with particle size thereafter. This indicates that the majority of particles are in the nucleation and Aitken modes.

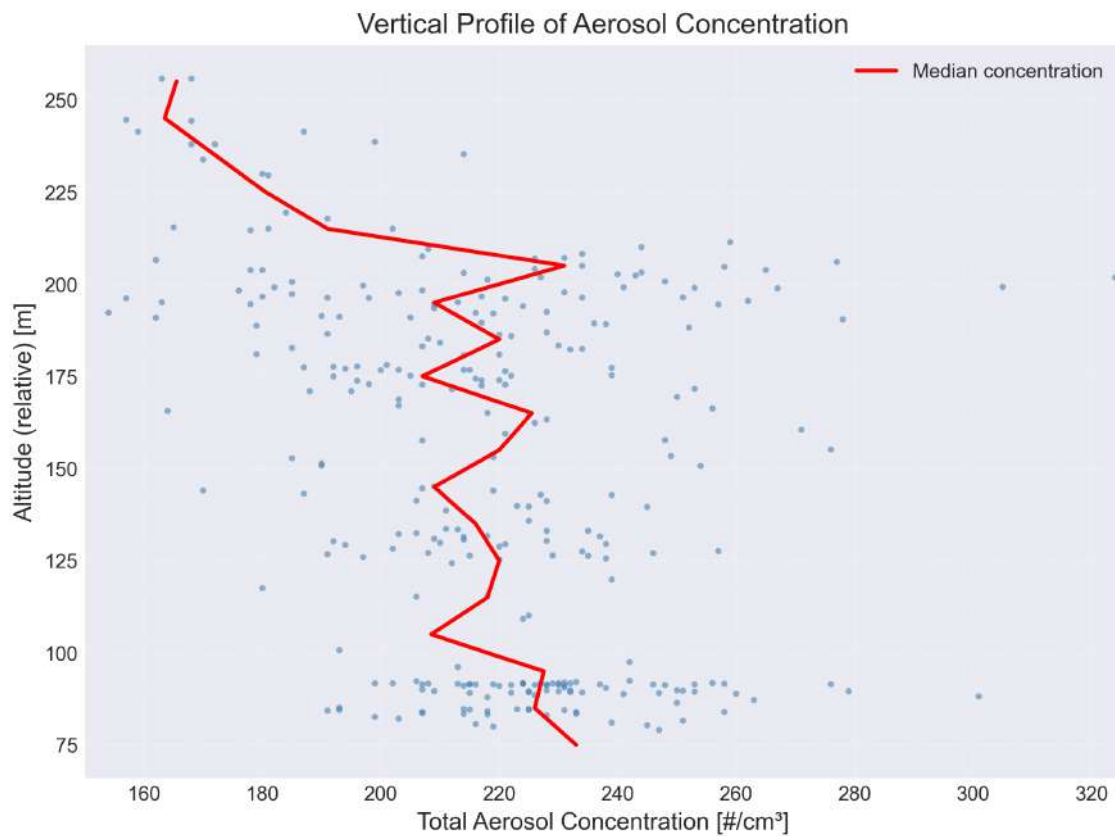


Figure 4.27: Altitude profile of POPS measurements from drone flight data, with calculated median concentrations.

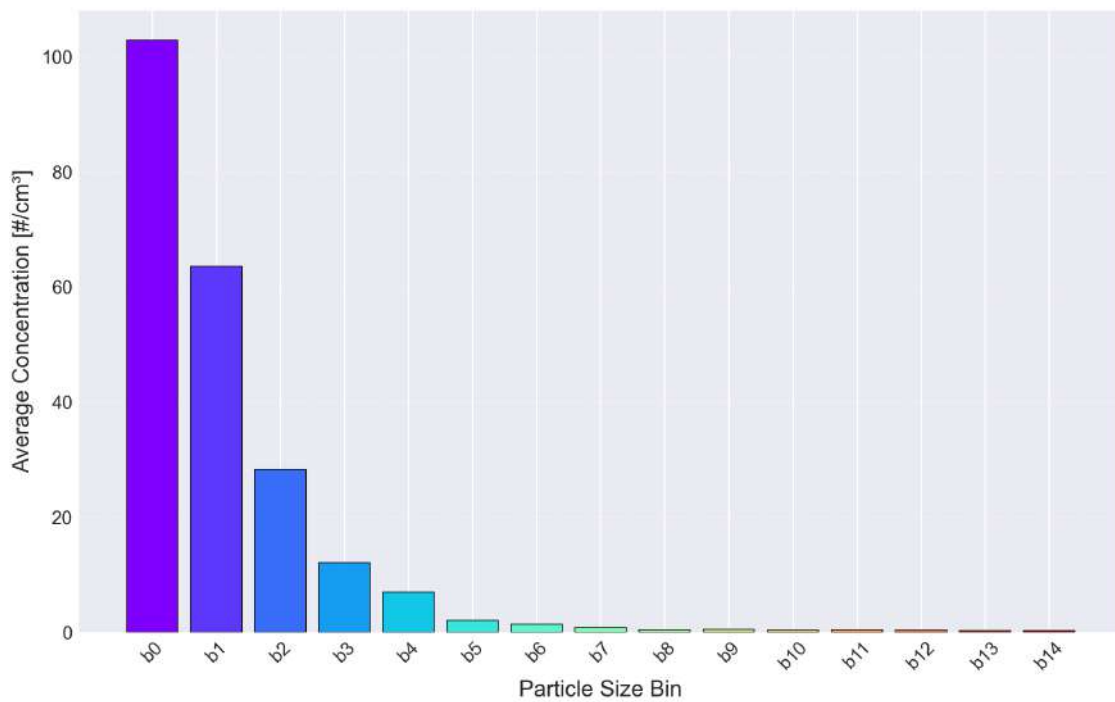


Figure 4.28: Average concentrations of each aerosol particle size bin.

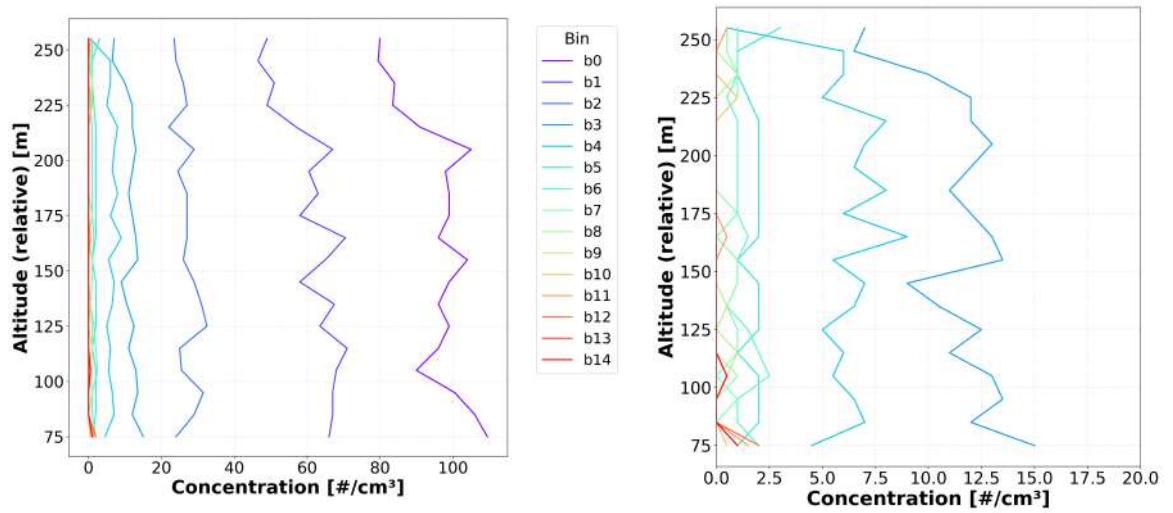


Figure 4.29: Median concentrations at altitudes for each of the aerosol particle size bins. Right figure is zoomed in toward the larger size bins.

Figure 4.29 additionally shows the median concentrations for each size bin. This shows the same dominant aerosol diameters as Figure 4.28 shows, but also shows that the drop in concentrations seen in Figure 4.27 is experienced primarily by these smaller aerosols, with little apparent effect on larger ones.

Figure 4.30 displays an overview of climate conditions during the time of the drone flight, showing weak winds and stability. Most notable in this case are the RH and temperature profiles measured by the HATPRO instrument. In these, we can recognize a layer of slightly cooler, slightly more humid air starting around 200 m above sea level, which coincides with our apparent boundary layer recognized in Figures 4.26 and 4.29.

This 200 m boundary layer is notably not the top boundary of the PBL, as this starts at roughly 1 km above sea level, but we do recognize that this layer does end at roughly 1 km in the temperature and RH profiles, which may indicate the end of the PBL. The 200 m boundary layer may instead be the marine boundary layer, which has been recognized to be capable of reaching lower much lower altitudes than the PBL.

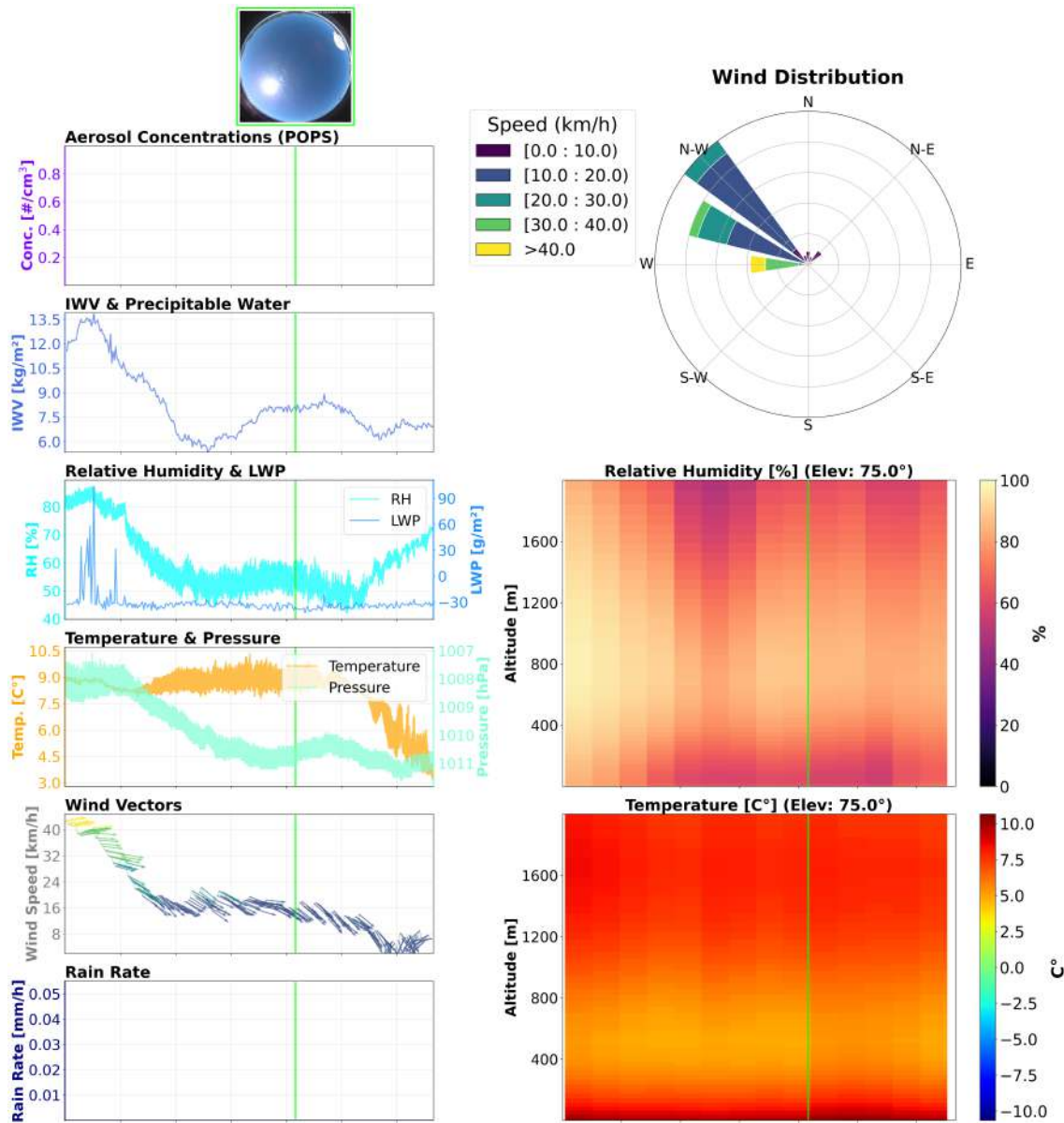


Figure 4.30: Meteorological conditions during drone flight, represented in all plots by the green line.

4.4.2 Ground Measurements

Figures 4.31 and 4.33 show the data from the POPS ground measurements (upper left plots) performed during 2025-05-09 and 2025-05-11, with coinciding meteorological data from the HATPRO and Weather Station instruments.

Additionally, the total aerosol concentrations across all bins for both measurement days are shown in Figures 4.32 and 4.34. Peaks are visible in the POPS data in Figures 4.31 and 4.32, but no particular disturbance in the other data seems to coincide with these.

The main piece of information that can be gleaned from these plots is that greater aerosol concentration were on average measured during 2025-05-09 compared to 2025-05-11. A likely explanation could be the slightly stronger, more Western winds observed during 2025-05-09 compared to 2025-05-11, sending more particles directly into the instrument inlet.

Comparing these measurements with those from the drone flight, however, we note that concentrations measured appear to be larger near the coast. In Figure 4.27 for the drone flight, we note the total measured aerosol number concentrations of around $220/\text{cm}^3$ at ground level. In Figure 4.32, we see it plateau around $500/\text{cm}^3$, while in Figure 4.34 it hangs around $450/\text{cm}^3$.

Given that the drone flights were performed in a more inland area, this could explain why its measured aerosol number concentrations are the lowest, and might be an indication of the influences of the sea in raising aerosol levels, as well as the range of this influence (recalling that the Vingtippen airfield is located roughly 10 km inland).

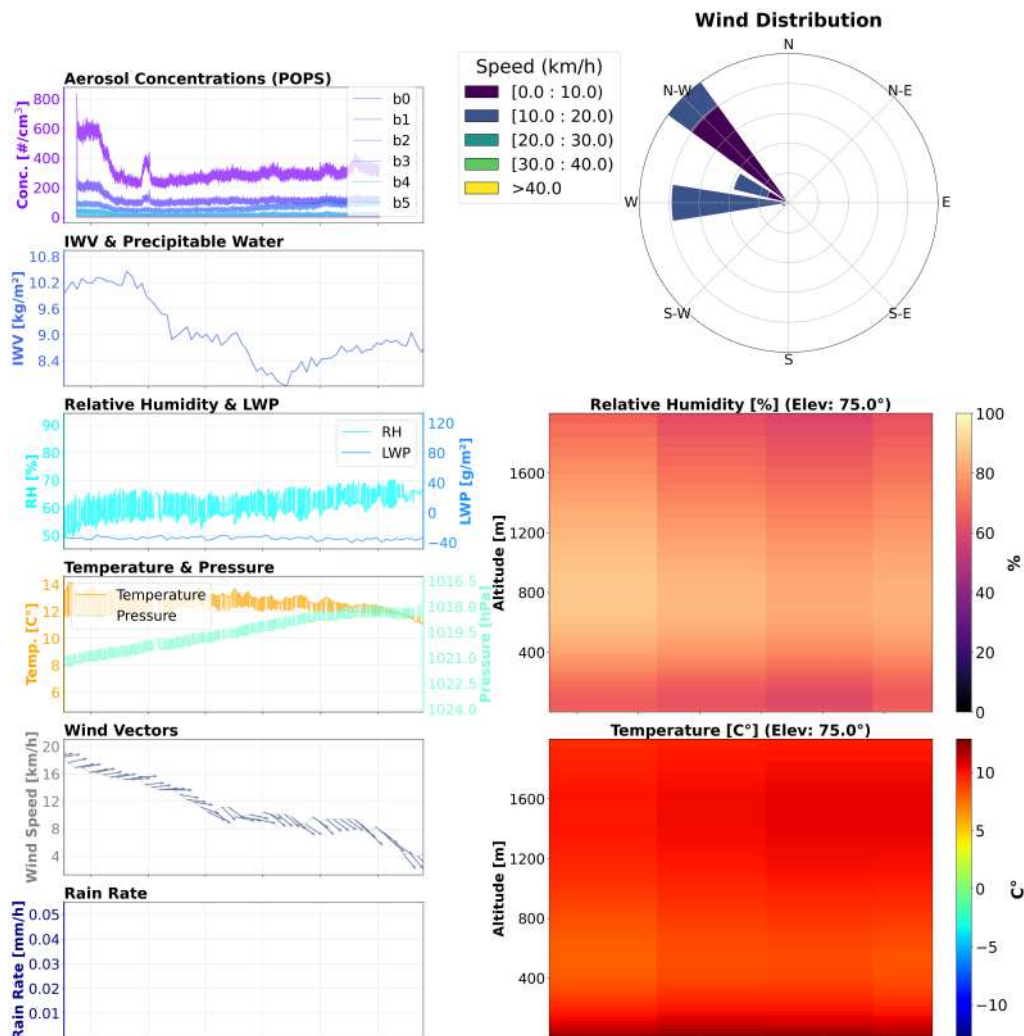


Figure 4.31: Ground measurements during 2025-05-09 coupled with miscellaneous coinciding meteorological data.

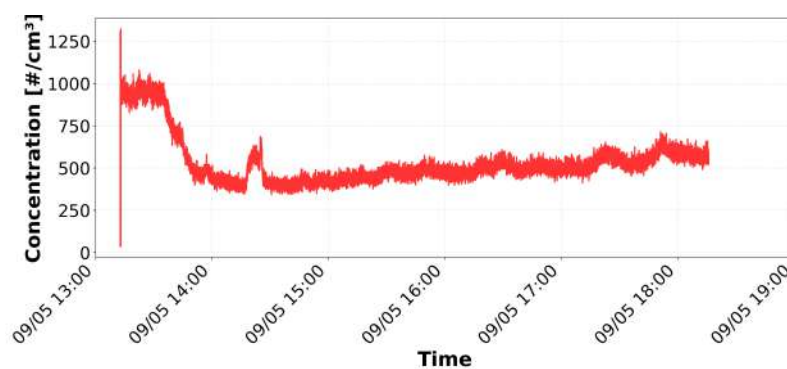


Figure 4.32: Total aerosol concentrations from ground measurements during 2025-05-09.

4. Results

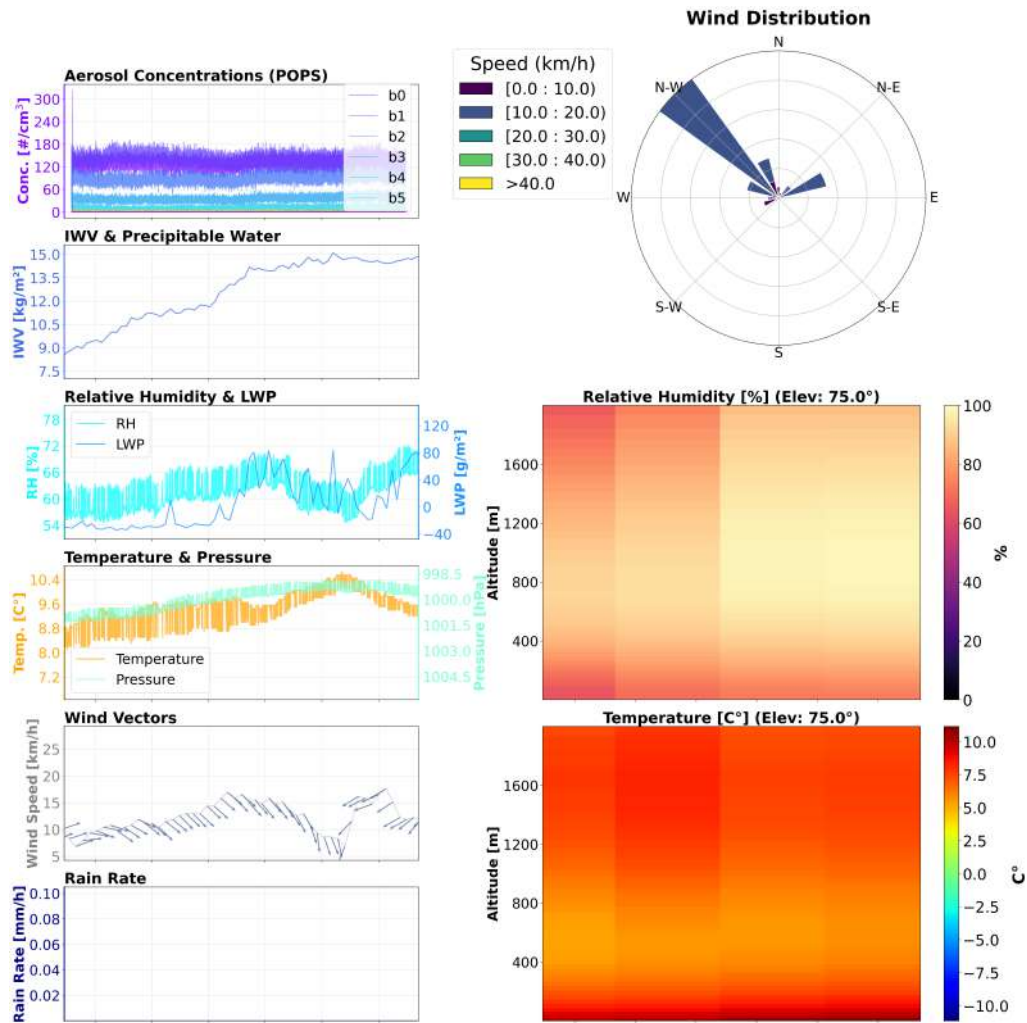


Figure 4.33: Ground measurements during 2025-05-11 coupled with miscellaneous coinciding meteorological data.

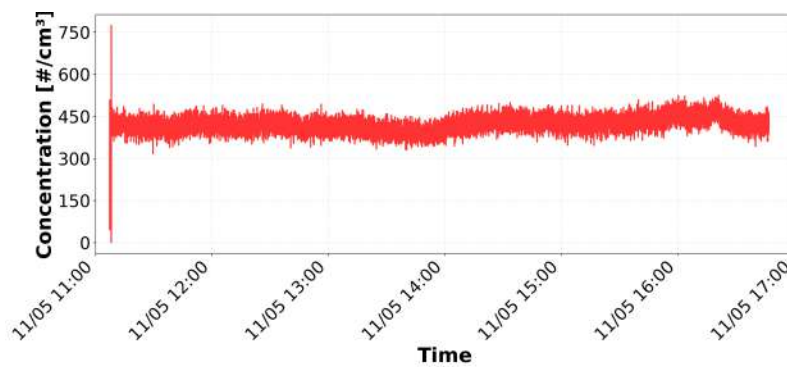


Figure 4.34: Total aerosol concentrations from ground measurements during 2025-05-11.

5

Conclusion

5.1 Summary of Results

Various conclusions can be drawn from the results of this multi-faceted data analysis, some more definitive than others, though we do we confident that most of them point toward important relationships in local as well as global climate phenomena.

Our results, for clarity, can be summarized as follows, starting first with comparisons between data sets:

- Local AOD measurements (via the AERONET sun-photometer) are shown to have a tendency to be higher than CAMS reanalysis AOD (when used to represent local conditions).
- CAMS reanalysis TCWV (when used to represent local conditions) tends to underestimate rises in local atmospheric water vapor caused by precipitation.
- CAMS reanalysis profiles (when used to represent local conditions) tend to underestimate RH and temperature at altitude. However, significant events in these parameters still tend to be registered.

Regarding the characteristics of the OSO site, we can state:

- It can generally be assumed to exist within pristine ($\text{AOD} < 0.1$) atmospheric conditions most of the time.
- **Aerosol Composition:** Dust aerosols rarely contribute to local AOD; sulfate aerosols are present in notable amounts; SSAs and organic matter aerosols are the dominant contributors to AOD.
- **SSAs:** The dominant SSA diameters at the OSO are within the size range $0.5\text{--}5\text{ }\mu\text{m}$, corresponding to film droplets. The $5\text{--}20\text{ }\mu\text{m}$ size range comes in second, corresponding to jet droplets. The $0.03\text{--}0.5\text{ }\mu\text{m}$ range barely contributes to mixing ratios. Additionally, overall SSA concentrations tend to be highest slightly above ground level.
- **Wind Speeds:** Reconfirmed paradigm where Western and Southern winds are capable of reaching speeds in excess of 60 km/h , whereas the maximum wind speeds recorded for Eastern winds tend to be lower, and Northern winds are by far the slowest of the four. Alongside this, Northern winds are also the rarest encountered at the site.

Finally, as the main results of this study, we have been able to establish:

- Precipitation coincides with heightened concentrations of water vapor and humidity in the atmosphere, and contributes to the (temporary) washout of local aerosol particle concentrations.

- Western and Southern winds (winds from the sea) can be clearly associated with raised SSA levels, in certain cases raising the SSA AOD contribution to nearly 100%. SSA mixing ratios indicate these particles to be jet droplets. The threshold for SSA extraction by winds appears to be roughly 30–40 km/h. Meanwhile, Eastern winds (from inland) tend to raise organic matter aerosol AOD concentrations.
- High-SSA concentrations are associated with raised PM_{2.5} and PM₁₀ levels, with PM₁ levels unaffected or reduced, further implying the large size of SSAs.
- Perfectly clear skies are associated with mornings and evenings (and thus presumably nights) and also reduced aerosol concentrations and lowered temperatures at altitudes up to 2000 m.
- Fully-covering, opaque clouds are associated with precipitation events, alongside raised aerosol concentrations and raised temperatures at altitudes up to 2000 m.
- AOD and SSA mixing ratios tend to increase as cloud cover increases, as does ground temperature, water vapor, and humidity up to 2000 m.
- Total aerosol concentrations in the near-Onsala region (further from the coast) were measured to be roughly 220/cm³ in May. Immediately coastal total aerosol concentrations, while variable, tended to be higher.
- Aerosol concentrations at ground level in the near-Onsala region tend to be dominated by those <200 nm in diameter, corresponding to nucleation and Aitken mode particles and small accumulation mode particles.
- A boundary layer was detected in the near-Onsala region at roughly 200 m above sea level, mainly blocking the ascension of smaller particles in the nucleation and Aitken modes. Presumed to be the marine boundary layer.

Of course, given the inherent chaotic and unpredictable complexity of atmospheric physics and the climate in general, it is very difficult to be 100% certain about any apparent results derived hereof. Nonetheless, it is our hope that these results will add to the corroborations of a larger collective of past and future studies which together can establish proper relationships between the intertwined phenomena and parameters of Earth’s atmospheric system.

5.2 Commentary & Future Outlook

Conclusions can also be drawn from the way the project unfolded, as well as what ended up being most important, and what the goals of the project were versus what results were actually obtained.

In this project, we set out to better understand aerosol-cloud interactions, land-sea interface exchanges, and the climate system in play at the OSO site in general using mainly AERONET and HATPRO data, with ambitions to make multiple drone flights over the OSO site during the course of the project to create reliable vertical profiles. In the end, we focused primarily on aerosol production via wind action and the relationship between cloud cover and other statistics using mainly CAMS and weather station data, packaged alongside several other miscellaneous results and one low-altitude drone flight.

This was based partly on what data ended up dominating the analyses, and what relationships could be discerned specifically from these. For example, while the availability of AERONET data defined the bounds of the 2024-2025 period over which analysis was mainly conducted, the scattered nature of this data through time lead it to mostly not contribute significantly to most of the end results, being replaced in prominence by the CAMS data set. Similarly, the lack of availability of HATPRO instrument data during this period lead to the Vaisala weather station and once again the CAMS data set to take most of the spotlight in climate data representations. In the end, the reliability of data availability ended up mattering more than the local representativeness of the data.

Another source of data that ended up having a great influence was the sky camera, from which the cloud categorization scheme was devised, which in turn was used to filter AOD, mixing ratios, temperatures, RH, TCWV, and wind speed and direction against apparent cloud cover. While the cloud categorization scheme is still known to be subjective, the apparent number of relationships shown to apply across various different kinds of data makes us believe in the scheme's ability to at least discern general trends.

Sources of data which ended up being less important were those from the combination of POPS and GNSS data, with data available for one 5 minute drone flight and two (largely uneventful) days of ground measurements. This can largely be attributed to the difficulties associated with having all circumstances align for the application of drone flights. Obstacles encountered during the course of the project included finding interested collaborators among persons capable of organizing and making drone flights; finding agreement between all involved schedules, the flight-readiness and instrument-compatibilities of the drone(s), and the weather; and conforming to regulations involving drone flights, particularly in our attempts to have the drone flights be performed directly at the OSO and attempting to confirm permissions for higher altitudes. As such, the ambitions for drone flights consumed considerable time and effort during the course of the project, resulting in only one drone short, low-altitude drone flight at a nearby location alongside two ground measurements to compensate.

However, all problems considered, the variety of data studied and familiarized with during its course is not to be understated, as this project has still been a considerable learning experience in data analysis data set merging, particularly as we ended up working with more data sets and data techniques than were initially planned. Another important factor which cannot be understated is the applicability and qualified nature of the OSO site. The coastal locale, as well as the multitude of available instruments — and the variety of weather and seasonal conditions encountered there — make the Onsala Space Observatory a very appropriate location for exactly this kind of data analysis. As such it is also very fit for continued studies of exactly this nature heading into the coming future, which is especially pertinent given the continually growing importance of the climate and climate analysis in this industri-

alized age of global warming.

On the topic of future work, multiple facets of this project have the potential to be continued into the future. For example, looking at data relationships with sulfate AOD concentrations, which was neglected in this study. Another example could be that considerably more data can be added to the cloud cover categorization scheme. In this study, hundreds of (applicable) cloud cover images were categorized only over three isolated periods within our time span of interest, in total accounting for little over one month of data. However, image archives are available for the sky cameras on the OSO site going back to 2017, with image capture still being ongoing as of the present, right now in June of 2026. As such, the data set is still largely untapped regarding the full potential of the cloud categorizations scheme.

However, a more objective facet with great potential that could be pursued by future projects is the continued effort to perform additional drone flights with the POPS instrument and GNSS receiver near or more preferably at the OSO site. The drone flight results from this project, while having fallen short of initial expectations, still illustrate the applicability of the POPS instrument for collecting aerosol concentration data and the potential that future drone flights could bring in creating vertical profiles of the aerosol conditions at the OSO, contributing considerable insight in the characterization of the climate at the site and climatically similar regions in general. For example, more drone flights would allow aerosol conditions to be studied more locally, instead of depending on large area data sets such as CAMS reanalysis, and would open the door for more closely studying the seasonal variability and land-sea transport of the site.

Bibliography

- [1] F. M. et al., “Aerosol characterization in an oceanic context around Reunion Island (AEROMARINE field campaign),” *Atmospheric Environment*, vol. 268, 2022.
- [2] J. F. et al., “Review of Aerosol–Cloud Interactions: Mechanisms, Significance, and Challenges,” *Journal of Atmospheric Sciences*, vol. 73, 2016.
- [3] O. e. a. Dubovik, “Variability of absorption and optical properties of key aerosol types observed in worldwide locations,” *Journal of the Atmospheric Sciences*, vol. 59, 2001.
- [4] G. Schmidt. “The evolution of radiative forcing bar-charts,” RealClimate, Accessed: Jun. 9, 2026. [Online]. Available: <https://www.realclimate.org/index.php/archives/2013/10/the-evolution-of-radiative-forcing-bar-charts/>.
- [5] NASA. “Nasa worldview,” NASA, Accessed: Jun. 9, 2026. [Online]. Available: <https://worldview.earthdata.nasa.gov/>.
- [6] F. M. et al., “Ground-Based Atmospheric Measurements at the Onsala Space Observatory (Sweden): Data & Trends (2009–2025),” *Earth System Science Data*, 2025.
- [7] A. M. Society. “Glossary of Meteorology,” American Meteorological Society. [Online]. Available: <https://glossary.ametsoc.org/wiki/Welcome>.
- [8] W. Foundation. “Aerosol.” [Online]. Available: <https://en.wikipedia.org/wiki/Aerosol>.
- [9] e. a. A. Bozzo, “Implementation of a cams-based aerosol climatology in the ifs,” 2017. DOI: 10.21957/84ya94mls. [Online]. Available: <https://www.ecmwf.int/en/elibrary/80028-implementation-cams-based-aerosol-climatology-ifs>.
- [10] G. Ritchie, *Atmospheric Chemistry: From the Surface to the Stratosphere*, M. Kumar Suraj. Simpson, Ed. 57 Shelton Street, Covent Garden, London WC2H 9HE: World Scientific Publishing Europe Ltd., 2017.
- [11] F. Mascout, *Personal communication*, 2026.
- [12] J. Garratt, “Review: The atmospheric boundary layer,” *Earth-Science Reviews*, vol. 37, no. 1, pp. 89–134, 1994, ISSN: 0012-8252. DOI: [https://doi.org/10.1016/0012-8252\(94\)90026-4](https://doi.org/10.1016/0012-8252(94)90026-4). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/0012825294900264>.
- [13] D. R. M.O. Andreae, “Aerosol–cloud–precipitation interactions. Part 1. The nature and sources of cloud-active aerosols,” *Earth-Science Reviews*, vol. 89, 2008.

- [14] Seinfeld and Pandis, *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. 1998, p. 1326.
- [15] D. C. Blanchard, "The production, distribution, and bacterial enrichment of the sea-salt aerosol," in *Air-Sea Exchange of Gases and Particles*, P. S. Liss and W. G. N. Slinn, Eds. Dordrecht: Springer Netherlands, 1983, pp. 407–454, ISBN: 978-94-009-7169-1. DOI: 10.1007/978-94-009-7169-1_7. [Online]. Available: https://doi.org/10.1007/978-94-009-7169-1_7.
- [16] E. C. Monahan, D. E. Spiel, and K. L. Davidson, "A model of marine aerosol generation via whitecaps and wave disruption," in *Oceanic Whitecaps: And Their Role in Air-Sea Exchange Processes*, E. C. Monahan and G. M. Niocaill, Eds. Dordrecht: Springer Netherlands, 1986, pp. 167–174, ISBN: 978-94-009-4668-2. DOI: 10.1007/978-94-009-4668-2_16. [Online]. Available: https://doi.org/10.1007/978-94-009-4668-2_16.
- [17] A. S. Zakey, F. Giorgi, and X. Bi, "Modeling of sea salt in a regional climate model: Fluxes and radiative forcing," *Journal of Geophysical Research: Atmospheres*, vol. 113, no. D14, 2008. DOI: <https://doi.org/10.1029/2007JD009209>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JD009209>.
- [18] J. Piazzola, K. Sellegri, L. Bourcier, M. Mallet, G. Tedeschi, and T. Missamou, "Physicochemical characteristics of aerosols measured in the spring time in the mediterranean coastal zone," *Atmospheric Environment*, vol. 54, pp. 545–556, 2012, ISSN: 1352-2310. DOI: <https://doi.org/10.1016/j.atmosenv.2012.02.057>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1352231012001720>.
- [19] F. Cavalli et al., "Advances in characterization of size-resolved organic matter in marine aerosol over the north atlantic," *Journal of Geophysical Research: Atmospheres*, vol. 109, no. D24, 2004. DOI: <https://doi.org/10.1029/2004JD005137>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004JD005137>.
- [20] W. T. Sturges and G. E. Shaw, "Halogens in aerosols in central alaska," *Atmospheric Environment. Part A. General Topics*, vol. 27, no. 17, pp. 2969–2977, 1993, Arctic air, snow and ice chemistry, ISSN: 0960-1686. DOI: [https://doi.org/10.1016/0960-1686\(93\)90329-W](https://doi.org/10.1016/0960-1686(93)90329-W). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/096016869390329W>.
- [21] A. M. Johansen, R. L. Siefert, and M. R. Hoffmann, "Chemical characterization of ambient aerosol collected during the southwest monsoon and intermonsoon seasons over the arabian sea: Anions and cations," *Journal of Geophysical Research: Atmospheres*, vol. 104, no. D21, pp. 26 325–26 347, 1999. DOI: <https://doi.org/10.1029/1999JD900405>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/1999JD900405>.
- [22] A. Kumar, A. K. Sudheer, and M. M. Sarin, "Chemical characteristics of aerosols in mabl of bay of bengal and arabian sea during spring inter-monsoon: A comparative study," *Journal of Earth System Science*, vol. 117, pp. 325–332, 2008. DOI: 10.1007/s12040-008-0035-9. [Online]. Available: <https://doi.org/10.1007/s12040-008-0035-9>.

-
- [23] O. Boucher et al., “Clouds and aerosols,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. Stocker et al., Eds. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013, ISBN: ISBN 978-1-107-66182-0. DOI: 10.1017/CB09781107415324.018. [Online]. Available: www.climatechange2013.org.
 - [24] J. W. Fitzgerald, “Marine aerosols: A review,” *Atmospheric Environment. Part A. General Topics*, vol. 25, no. 3, pp. 533–545, 1991, ISSN: 0960-1686. DOI: [https://doi.org/10.1016/0960-1686\(91\)90050-H](https://doi.org/10.1016/0960-1686(91)90050-H). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/096016869190050H>.
 - [25] R. S. G. et al., “A light-weight, high-sensitivity particle spectrometer for pm2.5 aerosol measurements,” *Aerosol Science and Technology*, vol. 50, no. 1, pp. 88–99, 2016. DOI: 10.1080/02786826.2015.1131809. eprint: <https://doi.org/10.1080/02786826.2015.1131809>. [Online]. Available: <https://doi.org/10.1080/02786826.2015.1131809>.
 - [26] G. M. Laboratory. “SURFRAD Aerosol Optical Depth.” [Online]. Available: <https://gml.noaa.gov/grad/surfrad/aod/>.
 - [27] A. S. A. Chen B. Howl. “How Aerosols Are Measured: The Science of Deep Blue,” NASA. [Online]. Available: <https://earth.gsfc.nasa.gov/climate/data/deep-blue/science>.
 - [28] W. Foundation. “Optical depth.” [Online]. Available: https://en.wikipedia.org/wiki/Optical_depth.
 - [29] M. Reddy, O. Boucher, Y. Balkanski, and M. Schulz, “Aerosol optical depths and direct radiative perturbations by species and source type,” *Geophysical Research Letters*, vol. 32, no. 12, 2005. DOI: <https://doi.org/10.1029/2004GL021743>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004GL021743>.
 - [30] W. Foundation. “Angstrom exponent.” [Online]. Available: https://en.wikipedia.org/wiki/Angstrom_exponent.
 - [31] W. Foundation. “Humidity.” [Online]. Available: <https://en.wikipedia.org/wiki/Humidity>.
 - [32] W. Foundation. “Precipitable water.” [Online]. Available: https://en.wikipedia.org/wiki/Precipitable_water.
 - [33] P. Yuan et al., “Characterisations of europe’s integrated water vapour and assessments of atmospheric reanalyses using more than 2 decades of ground-based gps,” *Atmospheric Chemistry and Physics*, vol. 23, no. 6, pp. 3517–3541, 2023. DOI: 10.5194/acp-23-3517-2023. [Online]. Available: <https://acp.copernicus.org/articles/23/3517/2023/>.
 - [34] N. N. staff. “Total Column Water Vapor: Integrated Water Vapor from GNSS stations,” National Science Foundation National Center for Atmospheric Research. [Online]. Available: <https://climatedataguide.ucar.edu/climate-data/total-column-water-vapor-integrated-water-vapor-gnss-stations>.
 - [35] D. D. Turner et al., “Thin liquid water clouds: Their importance and our challenge,” *Bulletin of the American Meteorological Society*, vol. 88, no. 2,

- pp. 177–190, 2007. DOI: 10.1175/BAMS-88-2-177. [Online]. Available: <https://journals.ametsoc.org/view/journals/bams/88/2/bams-88-2-177.xml>.
- [36] W. M. Organization. “International Cloud Atlas,” World Meteorological Organization. [Online]. Available: <https://cloudatlas.wmo.int/en/home.html>.
- [37] C. Staff. “Warm Clouds,” Centre for Atmospheric Science, University of Manchester. [Online]. Available: <https://www.cas.manchester.ac.uk/resactivities/cloudphysics/background/warm/>.
- [38] R. A. Pielke. “Precipitation,” Britannica. [Online]. Available: <https://www.britannica.com/science/atmosphere/Precipitation>.
- [39] W. Foundation. “cirrus. ”[Online]. Available: <https://en.wiktionary.org/wiki/cirrus>.
- [40] W. Foundation. “cumulus. ”[Online]. Available: <https://en.wiktionary.org/wiki/cumulus>.
- [41] W. Foundation. “stratus. ”[Online]. Available: <https://en.wiktionary.org/wiki/stratus>.
- [42] W. Foundation. “alto. ”[Online]. Available: <https://en.wiktionary.org/wiki/alto>.
- [43] W. Foundation. “nimbus. ”[Online]. Available: <https://en.wiktionary.org/wiki/nimbus>.
- [44] C. of Australia Bureau of Meteorology staff. “What’s that cloud?” Commonwealth of Australia Bureau of Meteorology. [Online]. Available: <https://media.bom.gov.au/social/blog/895/whats-that-cloud/>.
- [45] S. T. Massie et al., “Hirdls and calipso observations of tropical cirrus,” *Journal of Geophysical Research: Atmospheres*, vol. 115, no. D4, 2010. DOI: <https://doi.org/10.1029/2009JD012100>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JD012100>.
- [46] I. Reinares Martínez et al., “Unprecedented observations of a nascent in situ cirrus in the tropical tropopause layer,” *Geophysical Research Letters*, vol. 48, no. 4, e2020GL090936, 2021, e2020GL090936 2020GL090936. DOI: <https://doi.org/10.1029/2020GL090936>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL090936>.
- [47] M. K. Yau and R. R. Rogers, *A short course in cloud physics*. Elsevier, 1996.
- [48] S. Twomey, “The influence of pollution on the shortwave albedo of clouds,” *Journal of Atmospheric Sciences*, vol. 34, no. 7, pp. 1149–1152, 1977. DOI: 10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2. [Online]. Available: https://journals.ametsoc.org/view/journals/atsc/34/7/1520-0469_1977_034_1149_tiopot_2_0_co_2.xml.
- [49] D. Rosenfeld, R. Lahav, A. Khain, and M. Pinsky, “The role of sea spray in cleansing air pollution over ocean via cloud processes,” *science*, vol. 297, no. 5587, pp. 1667–1670, 2002.
- [50] B. Albrecht, “Aerosols, cloud microphysics, and fractional cloudiness,” *Science*, vol. 245, no. 4923, pp. 1227–1230, 1989.
- [51] I. Wängberg, M. G. Nerentorp Mastromonaco, J. Munthe, and K. Gårdfeldt, “Airborne mercury species at the råö background monitoring site in sweden: Distribution of mercury as an effect of long-range transport,” *Atmospheric*

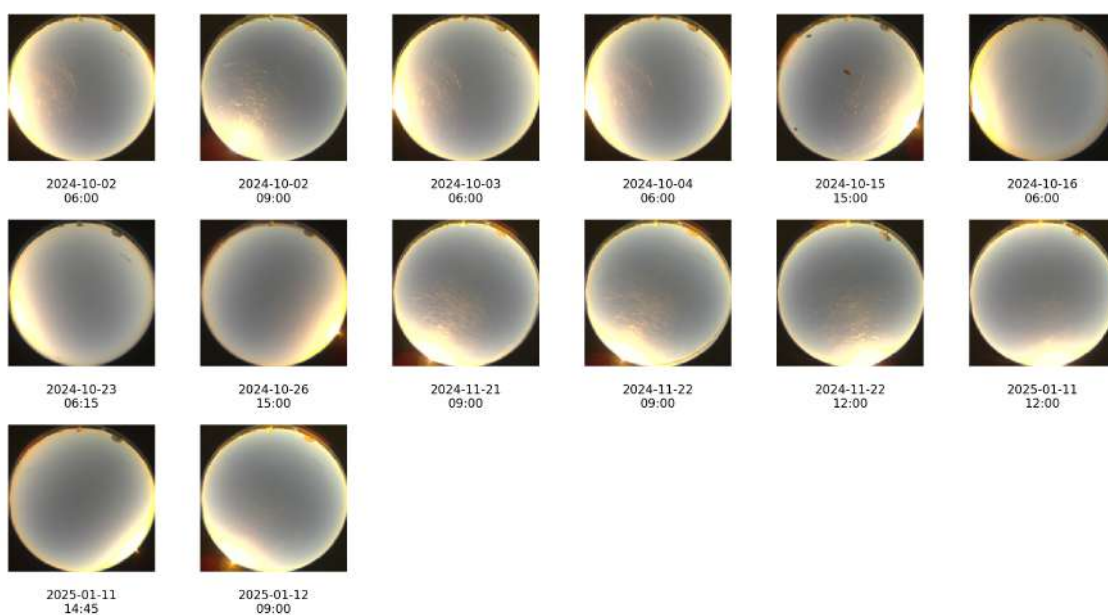
- Chemistry and Physics*, vol. 16, pp. 13 379–13 387, 2016. DOI: 10.5194/acp-16-13379-2016. [Online]. Available: <https://doi.org/10.5194/acp-16-13379-2016>.
- [52] A. Staff. “About AERONET.” [Online]. Available: https://aeronet.gsfc.nasa.gov/new_web/index.html.
- [53] Cimel, *Ce318-t sun sky lunar multispectral photometer*, Cimel Electronique S.A.S, Cimel Electronique S.A.S 172 rue de Charonne, 75011 PARIS.
- [54] W. Foundation. “Sun photometer.” [Online]. Available: https://en.wikipedia.org/wiki/Sun_photometer.
- [55] C. Zang. “Differences between rtk and ppp,” Tersus GNSS, Accessed: Jun. 4, 2026. [Online]. Available: https://tersus-gnss.com/tech_blog/-Differences-between-RTK-and-PPP.
- [56] E. staff. “CAMS: Reanalysis data documentation,” European Centre for Medium-Range Weather Forecasts. [Online]. Available: <https://confluence.ecmwf.int/display/CKB/CAMS%3A+Reanalysis+data+documentation>.
- [57] A. Inness et al., “The cams reanalysis of atmospheric composition,” *Atmospheric Chemistry and Physics*, vol. 19, no. 6, pp. 3515–3556, 2019. DOI: 10.5194/acp-19-3515-2019. [Online]. Available: <https://acp.copernicus.org/articles/19/3515/2019/>.
- [58] J.-J. Morcrette et al., “Aerosol analysis and forecast in the european centre for medium-range weather forecasts integrated forecast system: Forward modeling,” *Journal of Geophysical Research: Atmospheres*, vol. 114, no. D6, 2009. DOI: <https://doi.org/10.1029/2008JD011235>. eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2008JD011235>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JD011235>.
- [59] A. Benedetti et al., “Aerosol analysis and forecast in the european centre for medium-range weather forecasts integrated forecast system: 2. data assimilation,” *Journal of Geophysical Research: Atmospheres*, vol. 114, no. D13, 2009. DOI: <https://doi.org/10.1029/2008JD011115>. eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2008JD011115>. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JD011115>.
- [60] C. staff. “Climate reanalysis,” Copernicus. [Online]. Available: <https://climate.copernicus.eu/climate-reanalysis>.
- [61] E. staff. “Climate reanalysis,” European Centre for Medium-Range Weather Forecasts. [Online]. Available: <https://www.ecmwf.int/en/research/climate-reanalysis>.
- [62] W. Foundation. “Tetens equation.” [Online]. Available: https://en.wikipedia.org/wiki/Tetens_equation.
- [63] J. M. Wallace and P. V. Hobbs, *Atmospheric Science: An Introductory Survey*, 2nd ed. Burlington, MA: Academic Press, 2006, ISBN: 9780127329512.
- [64] M. L. Salby, *Fundamentals of Atmospheric Physics*. San Diego: Academic Press, 1996, ISBN: 9780126151602.
- [65] R. B. Stull, *Practical Meteorology: An Algebra-based Survey of Atmospheric Science*. Vancouver, Canada: University of British Columbia, 2017.

- [66] MIDE. “Air pressure at altitude calculator,” Accessed: Jun. 2, 2026. [Online]. Available: <https://www.mide.com/air-pressure-at-altitude-calculator>.
- [67] O. A. et al., “Utveckling av uas för atmosfäriska partikelmätningar,” Unpublished master’s thesis, 2026.

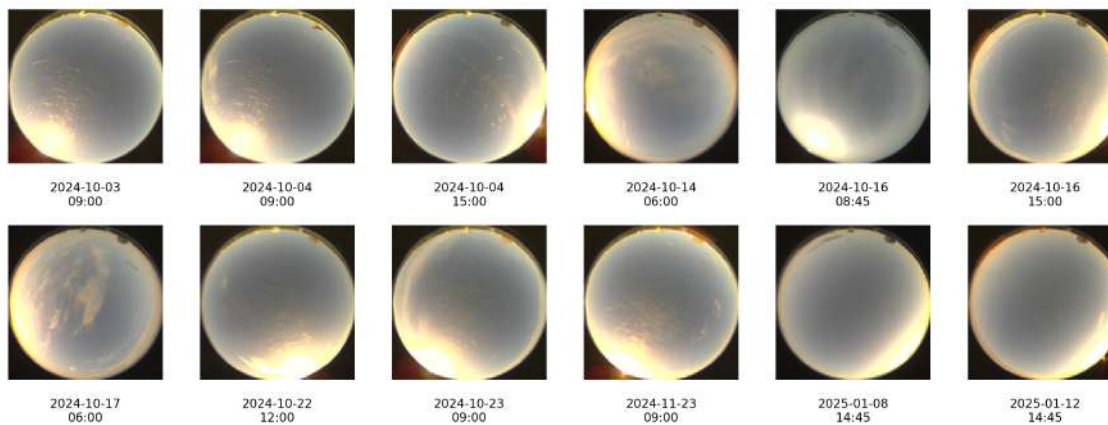
A

Cloud Cover Categories

Images where the closest CAMS point is paired with category 0

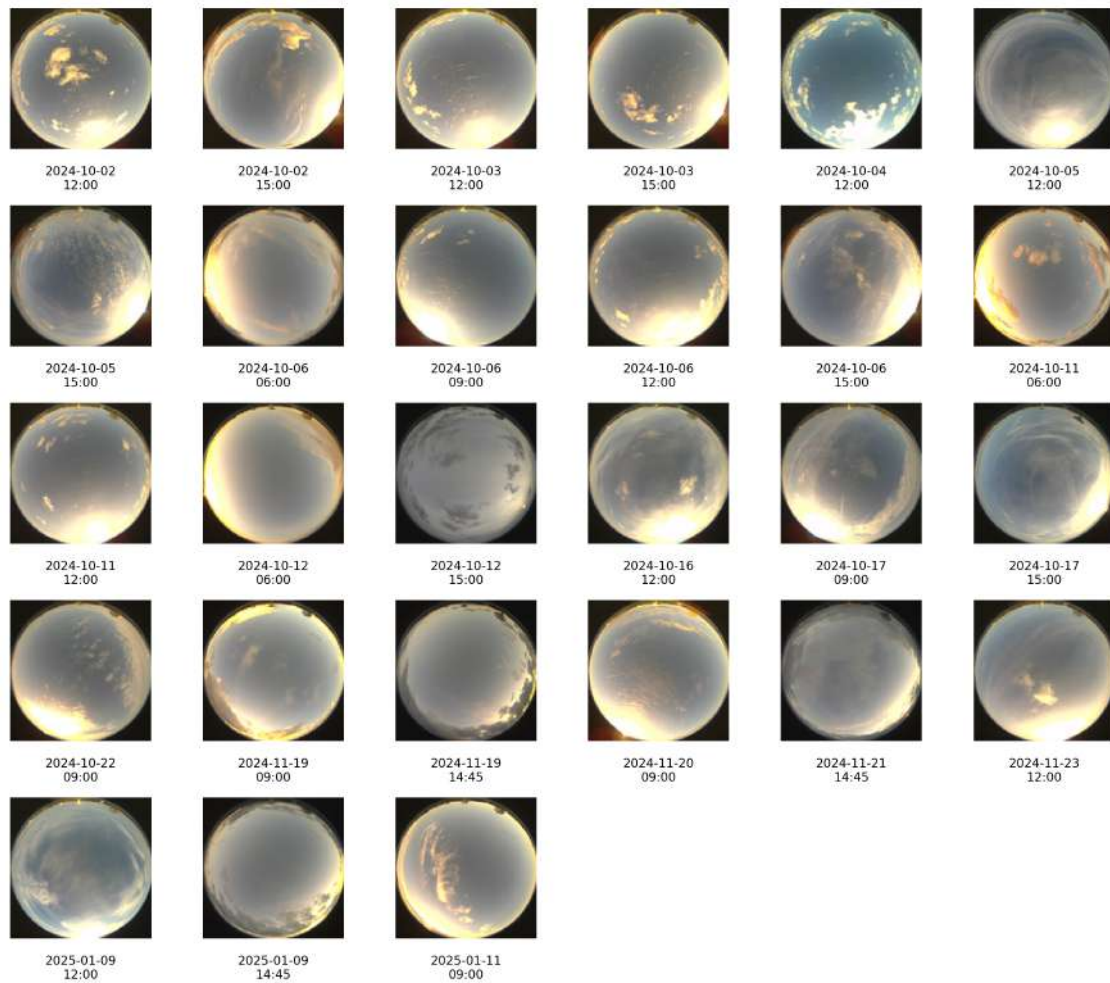


Images where the closest CAMS point is paired with category 1

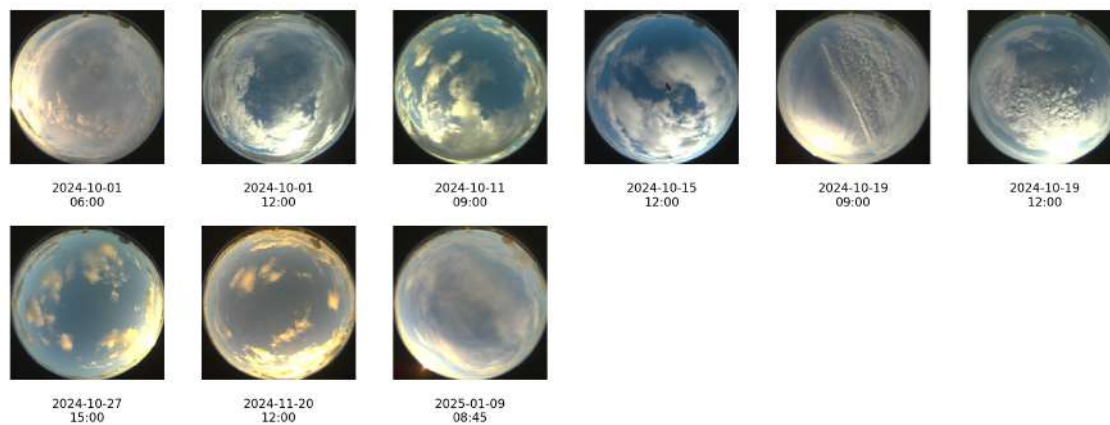


A. Cloud Cover Categories

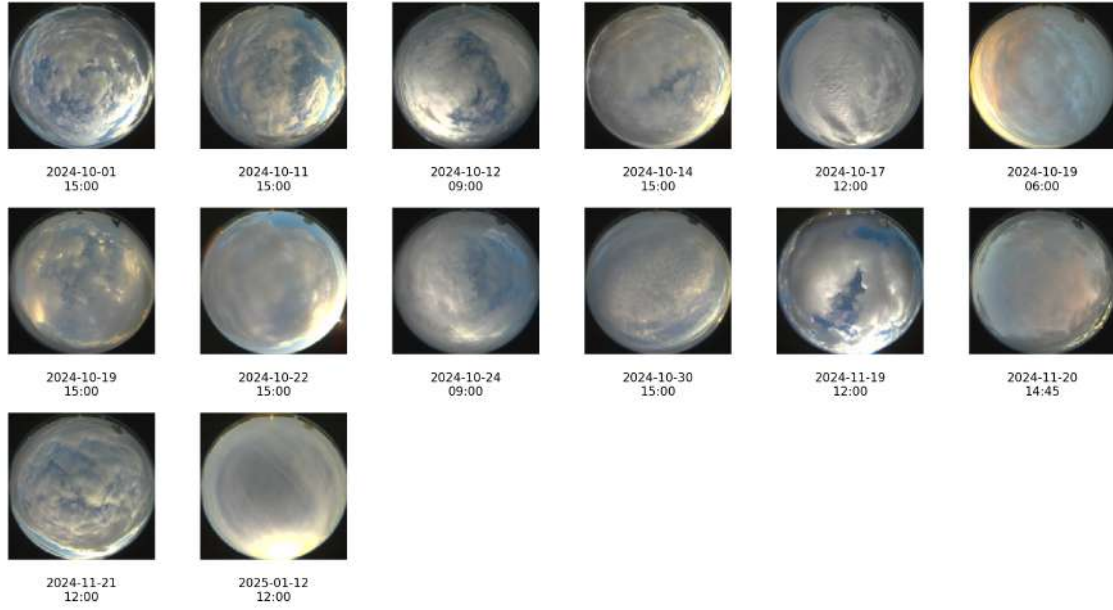
Images where the closest CAMS point is paired with category 2



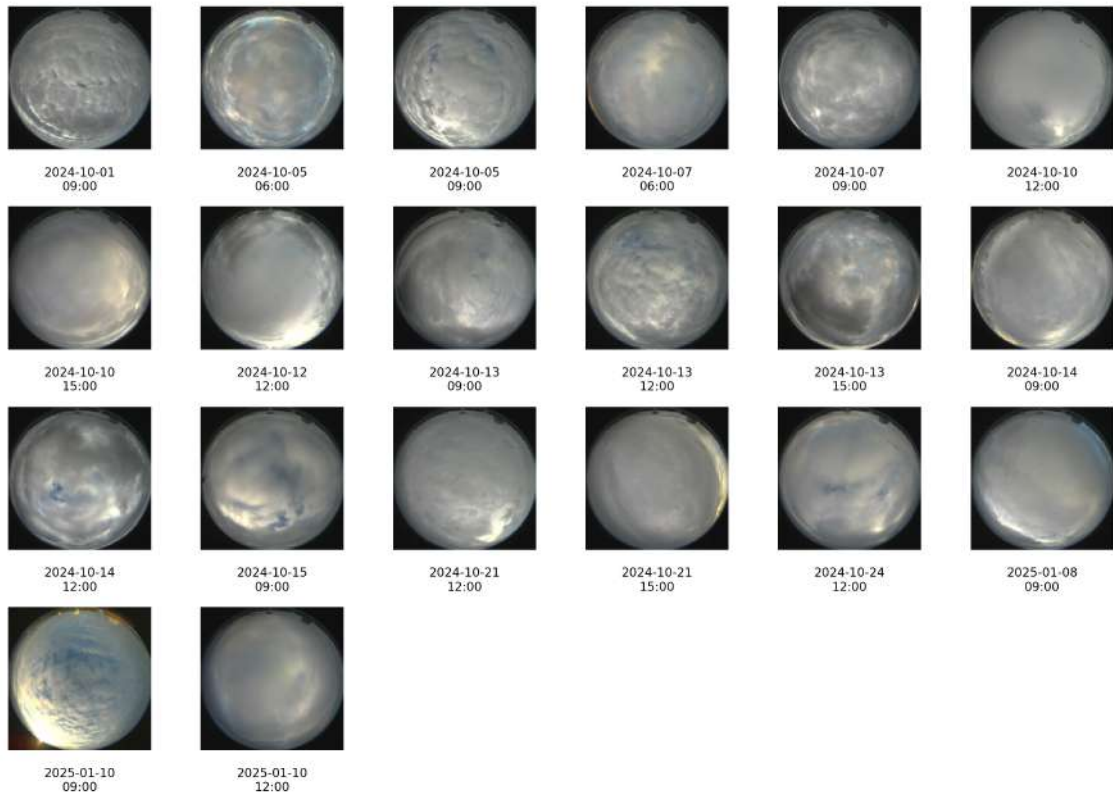
Images where the closest CAMS point is paired with category 3



Images where the closest CAMS point is paired with category 4

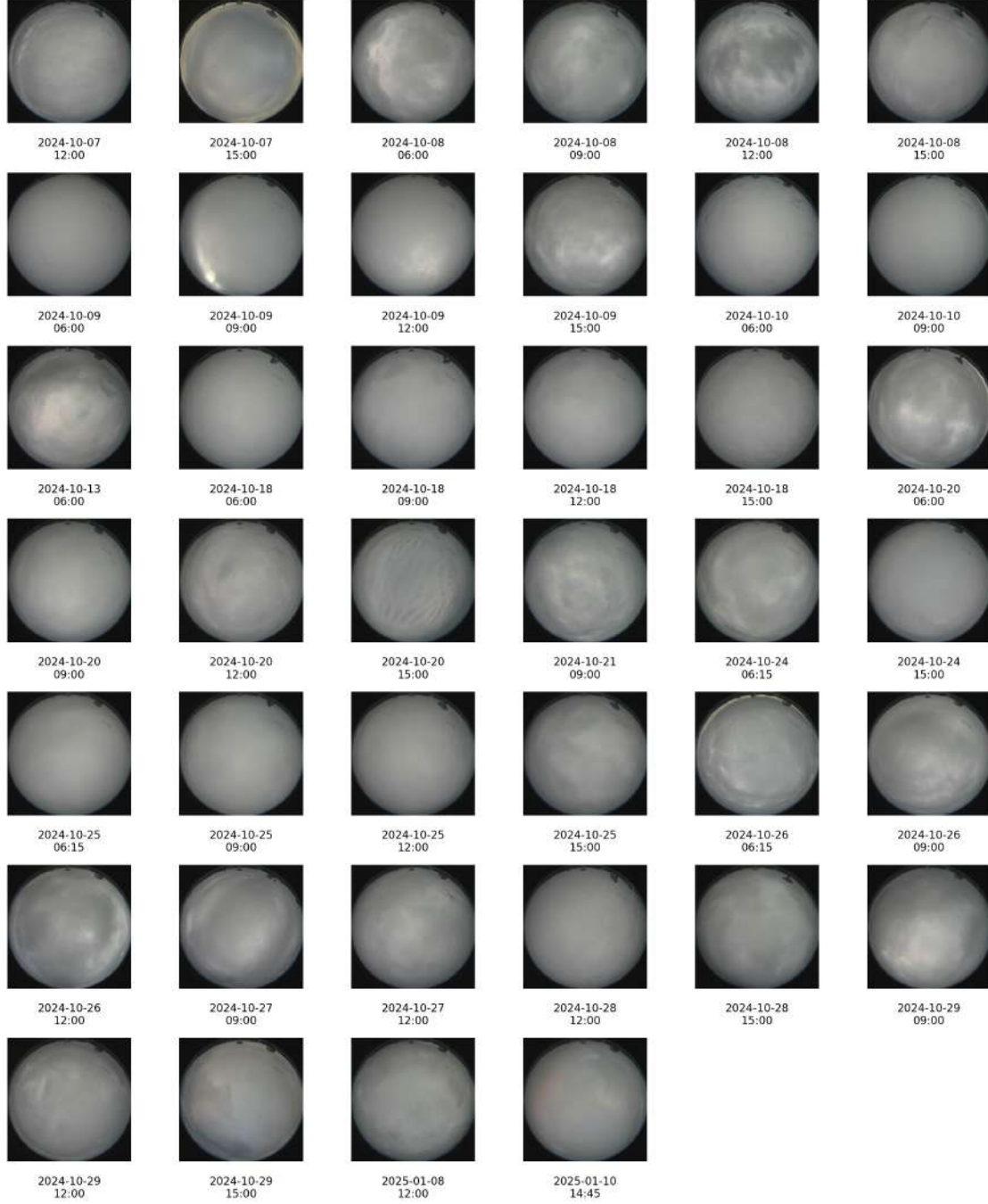


Images where the closest CAMS point is paired with category 5



A. Cloud Cover Categories

Images where the closest CAMS point is paired with category 6



B

Wind-Cloud Cover Correlation Attempt

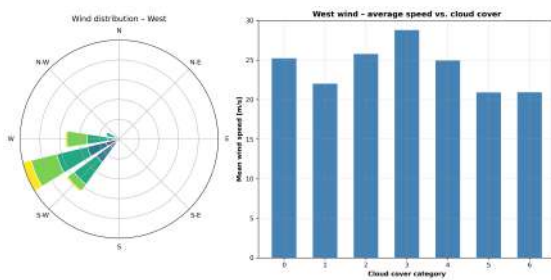


Figure B.1: Average wind speeds from the West for each cloud cover category.

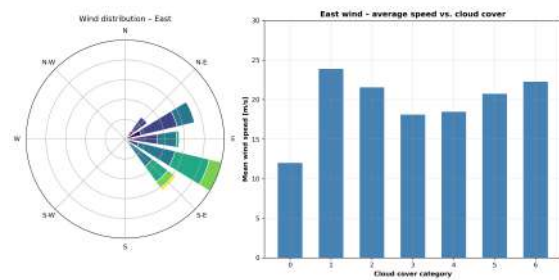


Figure B.2: Average wind speeds from the East for each cloud cover category.

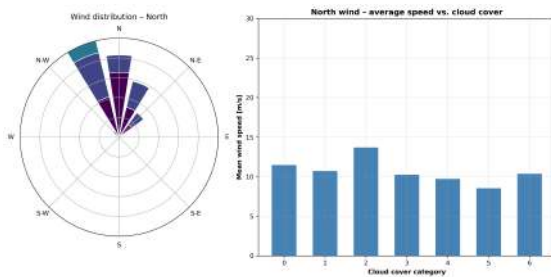


Figure B.3: Average wind speeds from the North for each cloud cover category.

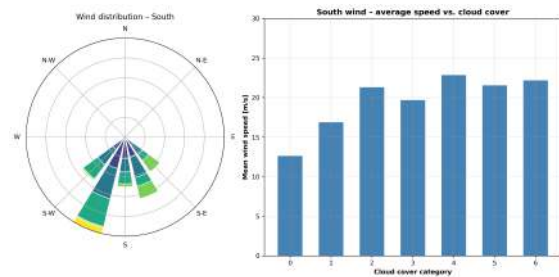


Figure B.4: Average wind speeds from the South for each cloud cover category.

C

AOD-Temperature Connection Attempt

We checked to see whether the concentration of aerosols (measured as AOD) has an influence on the region’s temperature. This can be seen in Figure C.1.

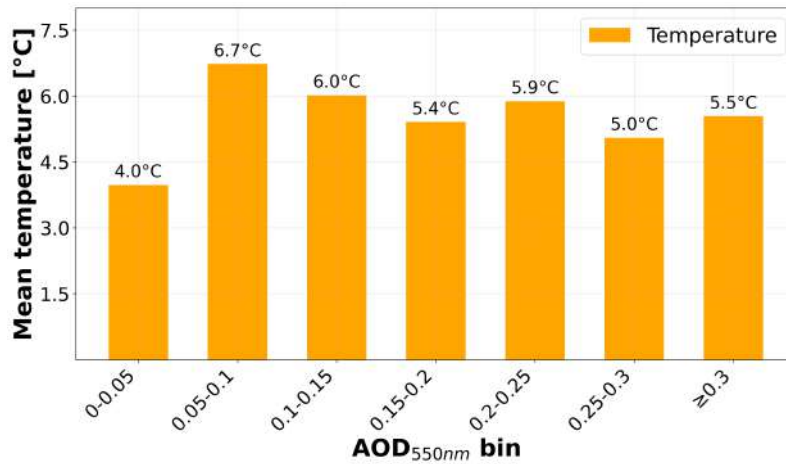


Figure C.1: Measured ground temperatures divided into CAMS AOD bins.

Excluding the first bin, the trend appears to be that an increase in AOD does coincide with very slight decreases in temperature, which is particularly visible when comparing the 0.05 – 0.1 AOD bin with the ≥ 0.3 bin, showing an drop in the average temperatures of roughly 1 °C.

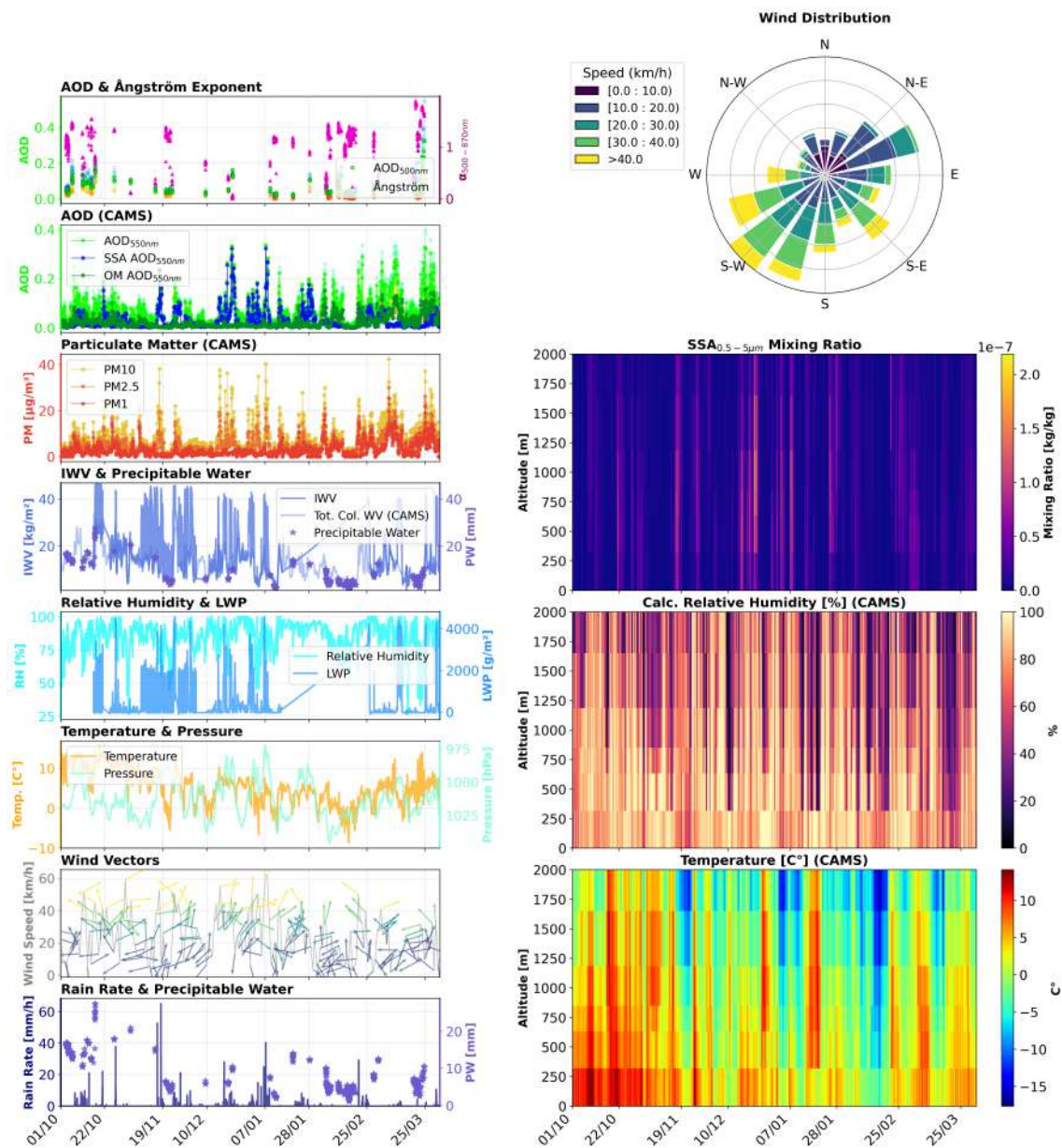
The aberration in the first, lowest AOD bin could be explained via the following framework: as was discussed in section 4.3.3, periods of clear skies were especially associated with mornings and evenings (and presumably also nights), during which the temperatures are lower. Additionally, we found that clear skies are associated with a reduced AOD. Therefore, the low temperatures could be the product of low AOD being associated with the colder mornings and evenings.

There is also an apparent contradiction between this observation and the previous observation in section 4.3.3 that more cloud cover — which has been associated with higher AOD — is associated with an increase in temperature. However, this could be explained by the fact that the previously established Cloud-AOD connection arises from averages over many data points: not every point in time with

higher AOD necessarily has to be associated with more cloud cover, or vice versa. Thus there is nothing to say that both of these two phenomena cannot be in effect simultaneously and be independently detectable from the data.

D

Full 2024-2025 Period



DEPARTMENT OF PHYSICS AND ASTRONOMY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY