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Study of aerosol water uptake effect on the particle microphysical properties

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Geophysical Laboratory I

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Abstract

In this Geophysical Laboratory we aim towards understanding the physical properties of aerosols when under the influence of varying levels of humidity. This is performed in a laboratory setup at the Radiation Transfer Laboratory of the Faculty of Geophysics, University of Warsaw. Thereby, most of the conditions being ideal. The measurements of the experiment are taken using the ACS1000, which has the ability to collect air using its inlet alongwith applying varying levels of relative humidity upon it. The device, internally also consists of a Particle Counter (OPC-N3), which aids in taking measurements of the particulate matter in the air depending upon the humidity range adjusted. The data furthermore, is utilized to understand the physical properties of the aerosols with an emphasis towards understanding the nature of its hygroscopicity.

Contents

1 Introduction

While walking on a street or strolling across the road, we often come across small and light flying objects. Pollen, pollution and dust are some of the most commonly experienced objects. Some of these can be seen within naked eyes, while others can only be visualized with the help of a microscope. Our atmosphere consists of so many of these type of particles. These are called aerosols[1][2] and play a significant role in many different types of phenomena on earth. With growing effects of climate change and corresponding factors it has therefore become important to assess and understand the impact of these aerosol particles on our health and daily activities [1][3].

1.1 ACS 1000

There are different kinds of instruments used to analyse and understand the properties of aerosols in the atmosphere. For the experiment, we have used two devices. One of the instruments used is ACS1000[4], which has the ability to collect samples of aerosols using its inlet and then applying varying levels of relative humidity upon it. The ACS1000 collects the aerosol sample in two ways. The 1st way consists of the original sample being collected at a humidity of less than 30%, and the 2nd way involves collecting the original sample with a relative humidity range from 40% to 90%. This is done with the help of a humidifier. The analysis of these collected samples helps us to understand the hygroscopic[5] nature of the sample/aerosols. One might ask themself, what does hygroscopic means? Particle have the tendency to attract water from its surroundings. This can happen either through absorption or adsorption. This tendency or ability of particles is called hygroscopicity[6] and such particles/objects are called hygroscopic substances.

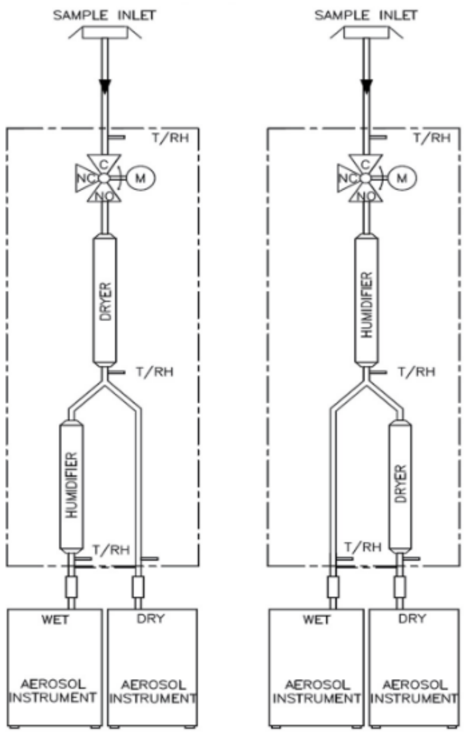


Figure 1: ACS 1000 [4]

1.2 Optical Particle Counter - N3

The second device used for this experiment are the Optical Particle Counters (OPCs)[7]. Each of the particles in the atmosphere has the ability to scatter light as they move through the beam of light. An optical particle counter detects these particles and sizes by measuring the intensity of light scattered by these particles[8]. The data for these counts is collected in units of $\mu g/m^3$. The OPCs collects the size of particles in the range from PM1, PM2.5 upto PM10. PM[8] is the short form for Particulate Matter. Particulate Matter is a combination of all particles suspended in the air. This could either be in liquid or solid state. Interestingly, some of these contribute to pollution and are a major cause of breathing problems when inhaled by human beings[2].

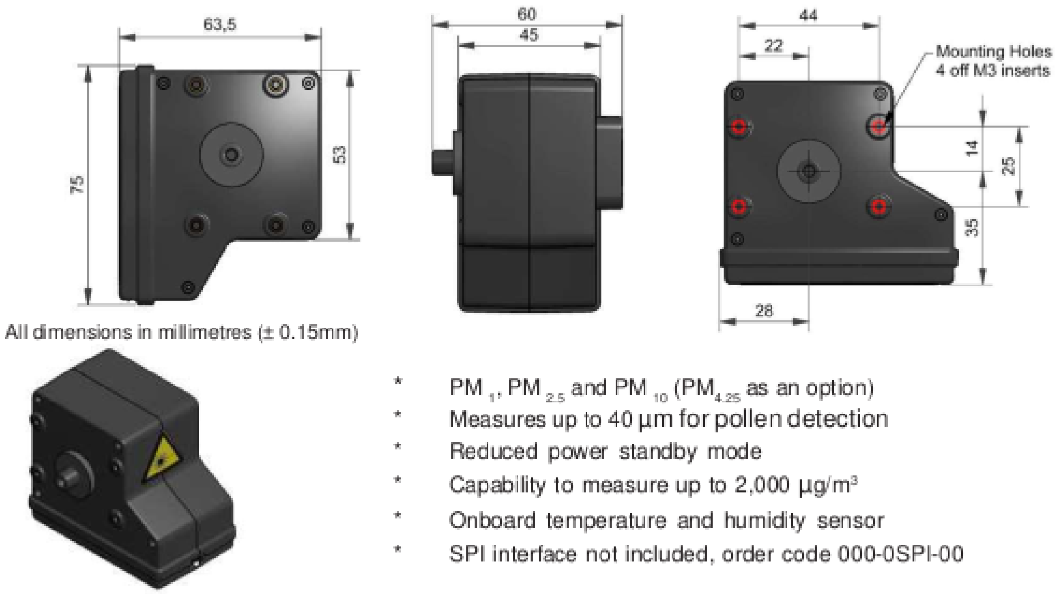


Figure 2: OPC-N3 Schematic Diagram [7]

1.3 Importance of the Study of Atmospheric Aerosols

If we have a look at the aerosols, we would realize that there are different categories of aerosols in the atmosphere. These can be natural in origin such as desert dust or volcanic[2] dust or could be pollutants as a result of human activities. As a matter of fact, most of them are man made in origin. Industrial activities, releases from vehicles and burning coal and other non renewable objects, are some of the commonly most sources of man made aerosols. They also can be intrinsic to the locations where they are detected or even could be from the surrounding regions. With increasing instances of climate change[2], thereby the effects of aerosols have a lot to be researched upon. The human health seems to be major consequence of this. Certain types of breathing problems are one of the major causes of this effect. Therefore, more we research aerosols and its properties, more we can identify how they affect the environment, if they play a role in climate change and based on that we could figure out techniques/solutions to the present and future world problems.[1][9].

1.4 κ - Kohler theory

The atmosphere consists of a wide range of suspended particles. As a matter of fact, some of these particles are influenced by the condensation of water and as a result get larger in size untill they reach a particular limit. Interestingly, at this limit/threshold the particles takes the form of cloud droplets. We call these kind of particles as Cloud Condensation Nuclei (CCN)[10][11][12].

The Kohler[13] theory describes the process how a particle becomes a CCN.

In this experiment the hygroscopicity of a particle is an important criterion for us, therefore we make use of the κ-Kohler theory[10], that describes this relationship between the hygroscopicity of a particle and it's CCN ability. The hygroscopicity parameter κ, equates this relation in the form of the following equation[14][15]

$$\frac{1}{a_w} = 1 + \kappa \frac{V_p}{V_w} \tag{1}$$

$$a_w = \frac{V_w}{V_w + \kappa V_p} \tag{2}$$

V_p denotes the volume of the dry PM, a_w is the activity of water and V_w is the volume of the water. Furthermore, we can rearrange equation 2 to obtain the Growth Factor G with respect to the activity of water, a_w[15][11].

$$a_w = \frac{\frac{m-m_o}{\rho_w}}{\frac{m-m_o}{\rho_w} + \frac{\kappa m_o}{\rho_p}} = \frac{\frac{m/m_o-1}{\rho_w}}{\frac{m/m_o-1}{\rho_w} + \frac{\kappa}{\rho_p}} = \frac{m/m_o - 1}{m/m_o - 1 + \kappa\rho_w/\rho_p} = \frac{G-1}{G - 1 + \kappa\rho_w/\rho_p} \tag{3}$$

m denotes the wet aerosol mass and m_0 being the dry aerosol mass. And therefore, $V_w = \frac{m-m_0}{\rho_w}$. Interestingly, we can also derive Growth Factor as a function of Relative Humidity. Using equation 3 and RH $= a_w \times 100\%$ from [15] we can therefore write,

$$\frac{RH}{100\%} = \frac{G-1}{G-1+\kappa/1.65} \tag{4}$$

where $\rho_w = 1$ and $\rho_\rho = 1.65$

$$\frac{RH}{100\%} = \frac{1}{1+\kappa/1.65(G-1)} \tag{5}$$

$$1 + \frac{\kappa}{1.65(G-1)} = \frac{100\%}{RH} \tag{6}$$

$$\frac{1}{G-1} = \frac{1.65}{\kappa}\left(\frac{100\%}{RH} - 1\right) \tag{7}$$

$$\frac{\kappa}{1.65}\left(\frac{RH}{100\% - RH}\right) = G - 1 \tag{8}$$

$$\frac{\kappa}{1.65}\left(\frac{RH}{100\% - RH}\right) + 1 = G \tag{9}$$

The equation clearly displays that G is a function of the Relative Humidity, RH.

1.5 Hygroscopicity of atmospheric aerosols

The necessity of understanding atmospheric aerosols have increased in the last couple of years. Climate change owes the major reason for this, but there are other reasons as well, some of which includes understanding the dynamics[2] of the earth's atmosphere and the extent of human activities. As we discussed in section 1.1, we know that particles have the tendency to attract water from its surroundings. This tendency or ability of particles is called hygroscopicity. For the case of atmospheric aerosols, hygroscopicity is a very interesting property to understand as then we can understand the quality of air in a particular region and whether if weather conditions are influenced by a particular type of atmospheric aerosol. For example, with the help of hygroscopicity we can understand the type of aerosols in the city of Warsaw[16] at different

	time_ACS	RHdry	RHwet
0	0.000000	12.68	62.21
1	0.002778	12.68	62.07
2	0.004444	12.68	62.10
3	0.006389	12.70	62.07
4	0.008056	12.68	61.83
...	...	...	...
12696	23.991667	14.83	73.16
12697	23.993333	14.83	73.28
12698	23.995278	14.83	73.25
12699	23.996944	14.83	73.52
12700	23.998889	14.83	73.58

(a) ACS 1000

	time_dry	PM1_dry	PM10_dry	PM25_dry
0	0.000074	6.11	8.46	7.84
1	0.002852	6.54	12.92	8.90
2	0.005629	6.88	9.54	9.20
3	0.008408	6.33	8.72	8.01
4	0.011184	6.20	10.35	9.02
...	...	...	...	...
8635	23.986193	9.44	14.49	13.05
8636	23.988972	10.02	14.46	13.66
8637	23.991750	9.14	15.37	12.84
8638	23.994527	10.19	14.30	13.40
8639	23.997305	9.05	11.41	11.09

(b) OPC N3 Dry

	time_wet	PM1_wet	PM10_wet	PM25_wet
0	0.000469	4.24	6.35	5.86
1	0.003250	4.61	7.13	6.78
2	0.006025	4.52	7.82	6.87
3	0.008802	4.76	9.88	6.92
4	0.011580	4.26	6.98	6.53
...	...	...	...	...
8635	23.986589	7.31	19.20	10.52
8636	23.989366	6.82	12.04	10.37
8637	23.992144	7.25	12.99	11.22
8638	23.994923	7.18	13.14	10.95
8639	23.997699	7.03	17.74	12.94

(c) OPC N3 Wet

Figure 3: Data from the Measurement Channels

time and seasons, and how much do the aerosols influences the local climate and whether they have any bearing on a larger magnitude scale.[14][17].

2 Experiment

The experiment involves taking automatic measurements, obtained by using the environmental chamber - ACS1000, located at the Radiation Transfer Laboratory[18] of the Geophysics Faculty, University of Warsaw. The ACS1000 collects the samples of aerosols/particulate matter by applying relative changes in humidity. As a result, there are two paths/channels for sample collection. Through the dry channel, the sample is collected with a humidity level of less than 30% and through the wet channel, the same original sample is collected in a desired humidity range of 40% to 90%. This is possible by the usage of a humidifier present inside the ACS1000.The measurements for the dry channel and the wet channel takes places simultaneously with the usage of the Optical Particle Counter OPC-N3. The OPC-N3s have recorded a maximum and minimum relative humidity in the wet channel of 61.6 and 35.1 respectively. Furthermore, the average relative humidity in wet channel is 48.775 and for the dry channel being 8.905. The experimental data obtained being in a raw format can be visualized as shown in figure 8. In the section 3.1 we will see on how to obtain a common data points in terms of time domain, since each of the devices used has a different sampling rate[15].

2.1 Motivaton of the Experiment

In this experiment we aim towards understanding the physical properties of aerosols when under the influence of varying levels of humidity[15]. Why does one need to understand how the properties of aerosols/particulate matter changes under varying levels of humidity? With more changes in climate[19] and rise in atmospheric pollution, it becomes necessary to investigate how the aerosols influence daily human activities[2]. Most importantly, whether if the human health[19] is affected by their presence. We know, certain types of particulate matter on being inhaled affects human health, but the extent is not known much. It's also important to understand how much the traffic pollution and weather conditions have bearing on the hygroscopicity levels of the particulate matter. In a broader perspective the result of influence of geographical conditions in Warsaw on the aerosols is a fundamental study towards understanding how weather and geographical conditions influence properties of aerosols and vice versa[1][17].

3 Data

The output of the two measurement devices, APC 1000 and OPC N3, provides us with a set of values. For the data analysis and to achieve the object of this experiment we only need the values as shown in figure 3.

3.1 Data Analysis

The data collected in the format as shown in figure 3 is not standard enough to be used for calculation. As a result we filter our data before we begin our data analysis. Figure 8 shows the comparison of data in the raw format.

3.1.1 Filtering the Data

There are many tools and languages to work with the data. One can use MATLAB, python, java or any programming languages/softwares. In my work I am using python.

- The data collected from the instruments, ACS1000 and OPCN3s have a different time domain. Before we begin our data analysis, it becomes necessary to obtain or retrieve values for the instruments in one single time domain. In other words, the analysis can be done only when the values of mass concentrations (PM10, PM2.5, PM1) and values of relative humidity (RHwet, RHdry) are in the common time domain. The best way to do this is by interpolating[15][20] data points between the values of mass concentrations and relative humidity from ACS1000 and OPC-N3s. In interpolation by using linear curve fit method we can obtain new data points within the required set of known data points..

	time_ACS	RHdry	RHwet	PM1_dry_IP	PM10_dry_IP	PM25_dry_IP	PM1_wet_IP	PM10_wet_IP	PM25_wet_IP
0	0.000000	12.68	62.21	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
1	0.002778	12.68	62.07	6.528478	12.800496	8.871598	4.547206	6.997624	6.623864
2	0.004444	12.68	62.10	6.734946	10.982003	9.072012	4.571252	7.427066	6.818748
3	0.006389	12.70	62.07	6.729635	9.315820	8.874665	4.551464	8.090066	6.876555
4	0.008056	12.68	61.83	6.399767	8.824016	8.160951	4.695464	9.326066	6.906555
...	...	...	...	...	...	...	...	...	...
12696	23.991667	14.83	73.16	9.166483	15.342614	12.864677	7.176133	12.826806	11.073985
12697	23.993333	14.83	73.28	9.738694	14.759902	13.159304	7.220041	13.054198	11.104444
12698	23.995278	14.83	73.25	9.881775	13.518622	12.775438	7.160832	13.727831	11.204301
12699	23.996944	14.83	73.52	9.197843	11.784796	11.389577	7.070769	16.489765	12.399137
12700	23.998889	14.83	73.58	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Figure 4: Interpolated Data with the common time domain

- One of the OPC N3s is not calibrated[21] properly and as a result the nature of output produced by it is different from the other OPC N3. Therefore, we adjust the values of mass concentration of one of the OPC N3s by applying a proper calibration correction. The general form of the calibration curve is linear and described by the following equation[15]

$$OPC_{ID:3} = 0.67 \times OPC_{ID:1} - 0.18 \tag{10}$$

In the ideal scenario both the outputs would be the same. Therefore, using the above consideration and equation 10, we obtain the corrected values as given by figure 5 below, which shows the corrected values after applying the calibration correction.

PM1_dry_c	PM10_dry_c	PM25_dry_c
-0.180000	-0.180000	-0.180000
4.194080	8.396332	5.763970
4.332414	7.177942	5.898248
4.328856	6.061599	5.766026
4.107844	5.732091	5.287837
...	...	...
5.961543	10.099552	8.439334
6.344925	9.709134	8.636733
6.440789	8.877477	8.379544
5.982555	7.715813	7.451017
-0.180000	-0.180000	-0.180000

Figure 5: Corrected Values from OPC Dry Channel

- We calculate values of Growth Factor, [15]G.

$$
\begin{aligned}
G_{PM10} &= \frac{PM10_{Wet}}{PM10_{Dry}} \\
G_{PM1} &= \frac{PM1_{Wet}}{PM1_{Dry}} \\
G_{PM2.5} &= \frac{PM2.5_{Wet}}{PM2.5_{Dry}}
\end{aligned}
\tag{11}
$$

PM1_wet_IP	PM10_wet_IP	PM25_wet_IP	PM1_dry_c	PM10_dry_c	PM25_dry_c	G1	G10	G25
0.000000	0.000000	0.000000	-0.180000	-0.180000	-0.180000	-0.000000	-0.000000	-0.000000
4.547206	6.997624	6.623864	4.194080	8.396332	5.763970	1.084196	0.833414	1.149184
4.571252	7.427066	6.818748	4.332414	7.177942	5.898248	1.055128	1.034707	1.156063
4.551464	8.090066	6.876555	4.328856	6.061599	5.766026	1.051424	1.334642	1.192599
4.695464	9.326066	6.906555	4.107844	5.732091	5.287837	1.143048	1.626992	1.306121
...	...	...	...	...	...	...	...	...
7.176133	12.826806	11.073985	5.961543	10.099552	8.439334	1.203738	1.270037	1.312187
7.220041	13.054198	11.104444	6.344925	9.709134	8.636733	1.137924	1.344527	1.285723
7.160832	13.727831	11.204301	6.440789	8.877477	8.379544	1.111794	1.546366	1.337102
7.070769	16.489765	12.399137	5.982555	7.715813	7.451017	1.181898	2.137139	1.664087
0.000000	0.000000	0.000000	-0.180000	-0.180000	-0.180000	-0.000000	-0.000000	-0.000000

Figure 6: Values for Growth Factor

- Further we obtain a Humidogram[15] by plotting Growth Factors vs RH_{Wet}, which is illustrated by figure 9.
- For better visualization[15], we simplify the plots by calculating average values of Growth Factor for particular changes in the intervals of Relative Humidity. Further we include the uncertainity/error to obtained values. This is displayed in Figure 10.
- Finally, to obtain the value of κ we fit equation 10 to the plots obtained above. In our case we obtain the values of coefficients in equation 10 by a linear curve fitting as in figure 11.

3.2 Calculations

In order to obtain the values of κ to determine hygroscopicity, we obtain a curve fit of the plot displayed in figure 8 by utilising equation 10. The coefficients/parameters obtained are then equated on both sides of the equation 9. For each of the 3 Particle Concentrations, we have the following coeffcients and values of κ.

Parameters of the Curve Fit				
Particulate Matter	Coefficient a	Error - Δ a	Coefficient b	Error - Δ b
PM1	0.0597653755425589295	0.00244363	0.9334269741826507	0.01117383
PM10	0.08012324116566054	0.00452127	1.010092010582826	0.02067416
PM25	0.07738343894372761	0.00375904	1.0389195022996531	0.01718876

Table 1: Curve Fit for each PM

We know from equation 9, that

$$G = \frac{\kappa}{1.65}\left(\frac{RH}{100\% - RH}\right) + 1 \tag{12}$$

is of the form $y = ax + b$. Therefore, using the values obtained from curve fit (Table 1), we can estimate,

$$\begin{aligned} y &= G \\ a &= \kappa/1.65 \\ x &= \frac{RH}{100\% - RH} \end{aligned} \tag{13}$$

Therefore, for each of the 3 Particulate Matter (PM1, PM10 & PM2.5) we would have 3 different values of κ. In general, from equation 13 and using table 1 for error and values of coefficient.

$$\kappa_{PM} = 1.65 \times (a_{PM} \pm \Delta a_{PM}) \tag{14}$$

The values of κ for each PM are as follows.

$$\begin{aligned} \kappa_{PM1} &= 1.65 \times (0.0597653 \pm 0.00244363) \\ \kappa_{PM1} &= 0.098612 \pm 0.004036 \\ \kappa_{PM10} &= 1.65 \times (0.0801232 \pm 0.00452127) \\ \kappa_{PM10} &= 0.13220 \pm 0.0074600955 \\ \kappa_{PM2.5} &= 1.65 \times (0.0773834 \pm 0.00375904) \\ \kappa_{PM2.5} &= 0.12768 \pm 0.006202416 \end{aligned} \tag{15}$$

4 Results and Discussion

In order to understand, what type of aerosol particles we have in the experiment above, we compare the values of κ obtained from equation 15 with that of the hygroscopicity level chart in figure 7, that showcases the types of aerosol particles for each kappa. In short we estimate the hygroscopicity of each of the Particulate Matter(PM).

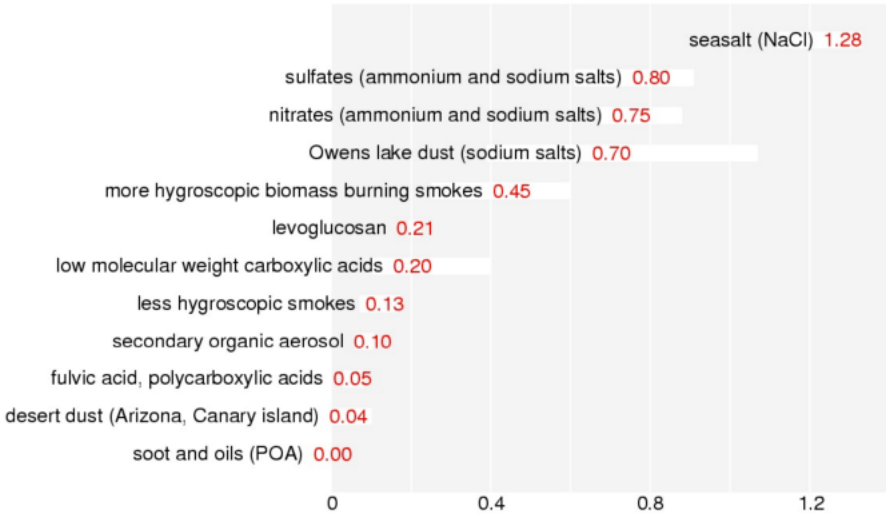


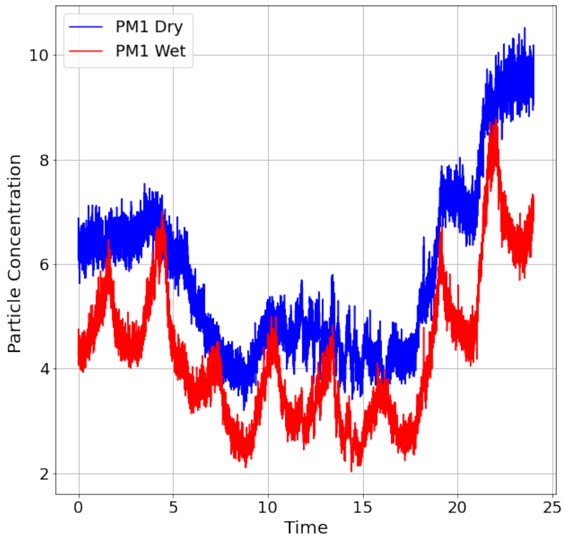
Figure 7: Hygroscopicity level based on CCN measurements for atmospheric aerosols [15]

For PM1, the value of obtained hygroscopicity level indicates it to have property/type inbetween that of polycarboxylic acids and secondary organic aerosols. PM10 and PM2.5 particles with κ of 0.132 and 0.127 respectively indicates particles of the type of hygroscopic smokes and low weight carboxylic acids in the atmosphere.

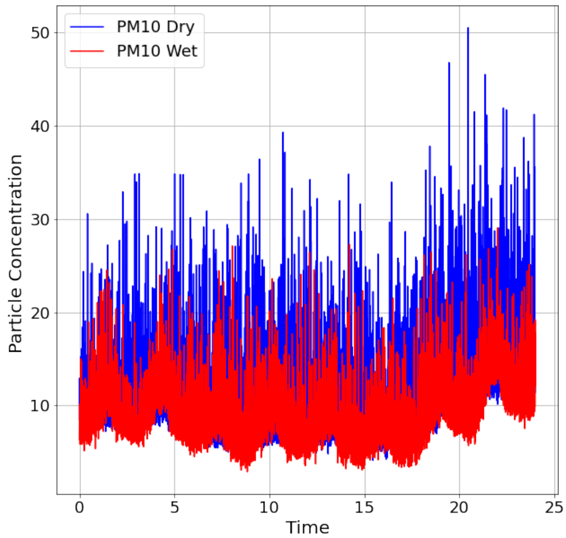
4.1 Graphs and Figures

Based on our calculations, we will now see on the next page the nature of the plots obtained from the values in the datasets. These will be crucial in helping us understand the significance of our objective.

- Figure 8 shows visual comparison of the unprocessed/raw data obtained from the wet and dry channels of the OPC-N3s. We showcase how each of the 3 Particulate Matter change with respect to time, in their respective time domain.
- Figure 9 is a scattered plot comparison that shows the variation of Growth Factor with the values of Relative Humidity obtained from the APC1000. We can see that the Humidogram for PM10 shows a quite different variation compared to that of PM1 and PM2.5.
- Figure 10 shows the extent of error/uncertainity in our calculations of values from the datasets for each of the 3 Particulate Matter. Prior to that we have obtained average values of Growth Factor for each interval change in Relative Humidity
- Figure 11 shows the nature of curve fit for each of the Particulate Matter.



(a)



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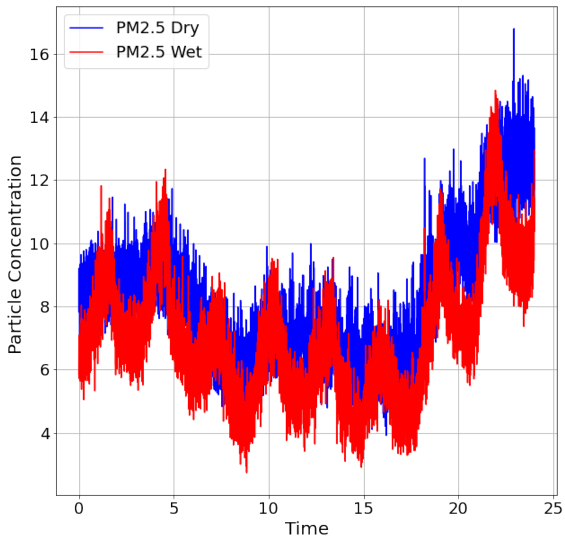


(c)

Figure 8: Raw data comparison of the OPC N3 channels

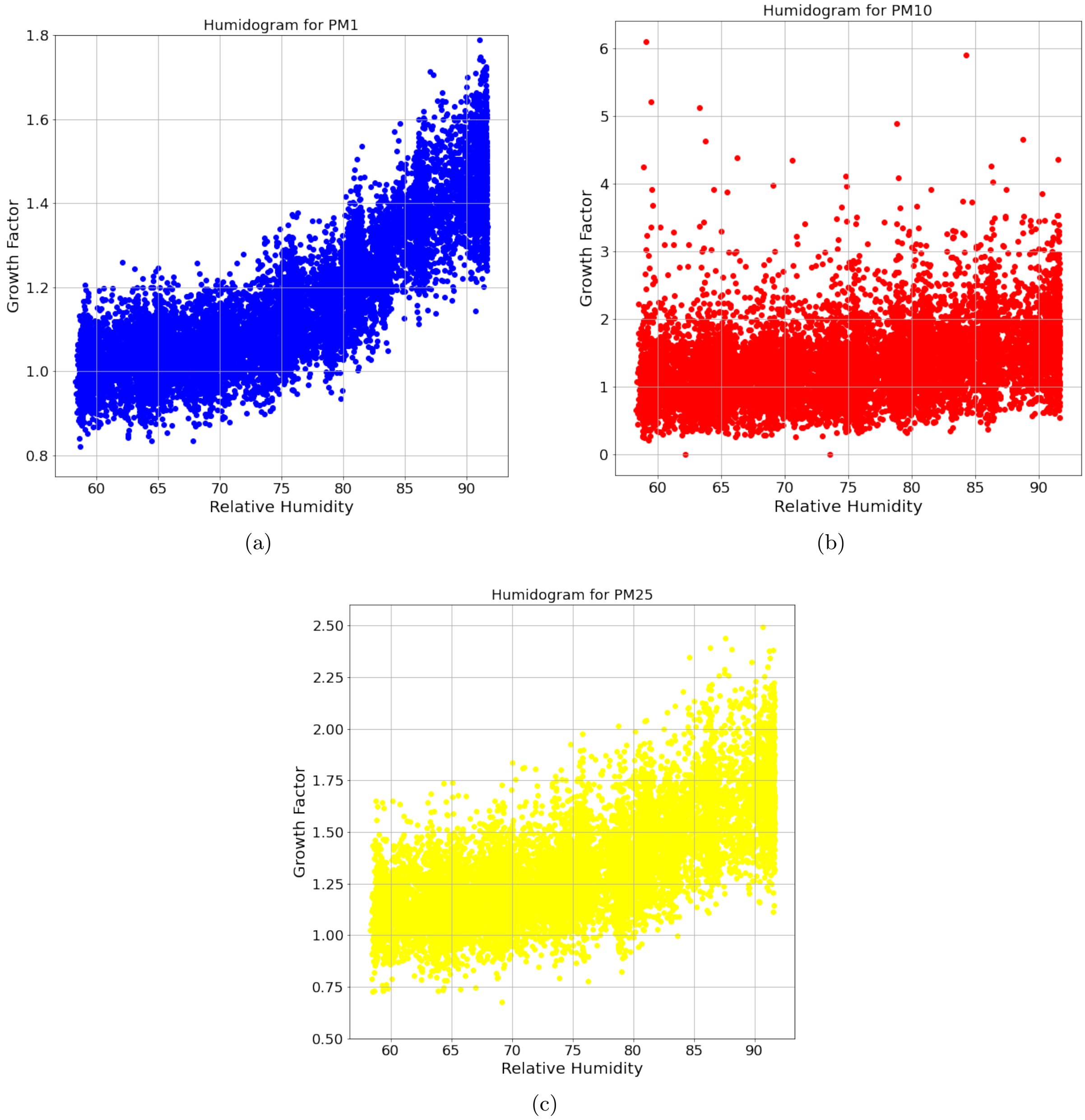
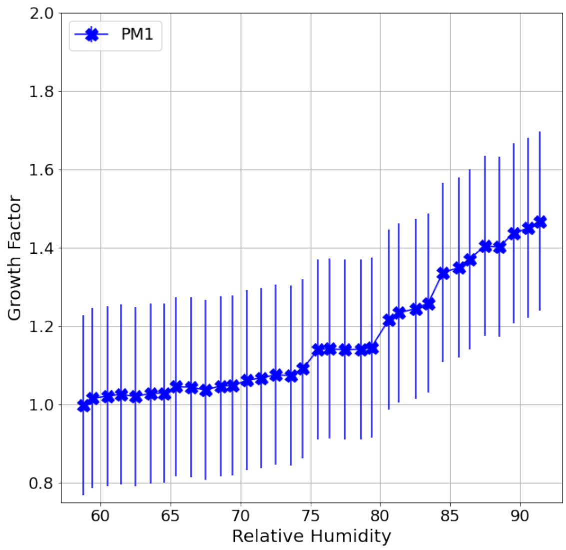
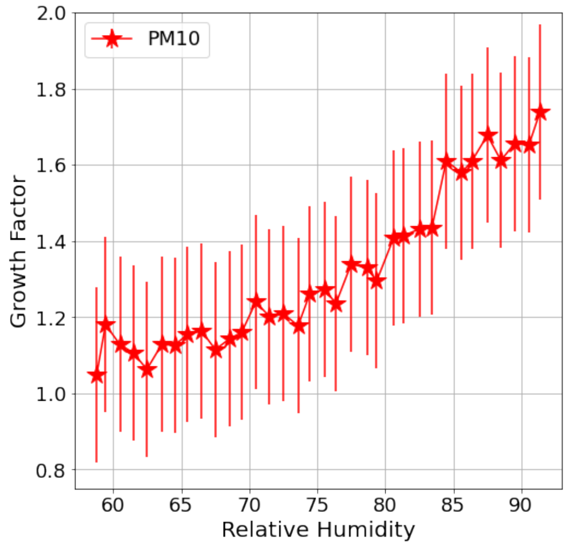


Figure 9: Humidograms



(a)



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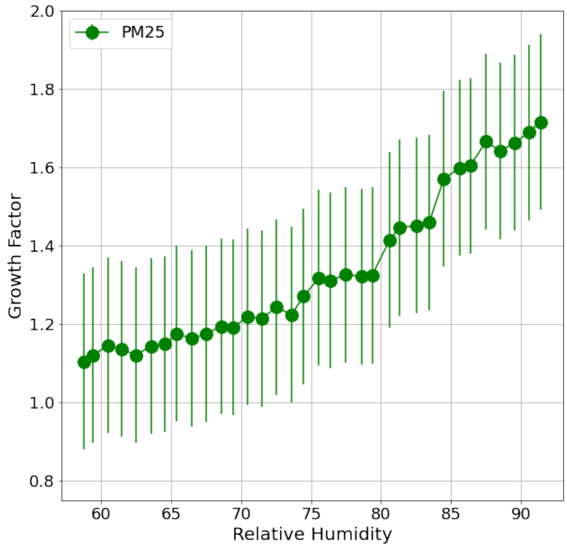

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Figure 10: Error Bars for Humidograms

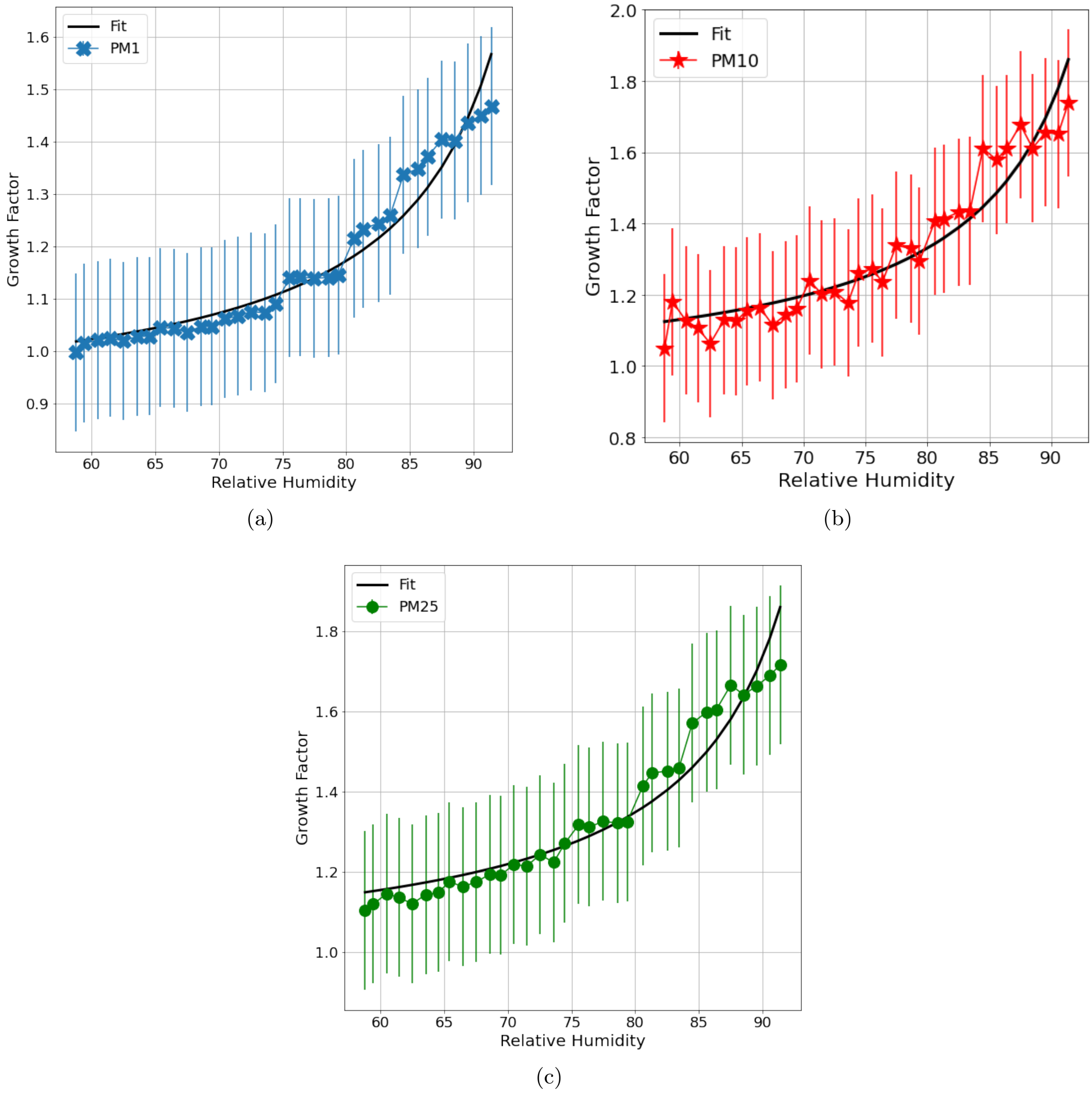

Figure 11: Curve Fitting to the Humidograms

4.2 Conclusion

If we have a look at figure 7, we would find that the general values of κ present within our atmosphere fall in the range of $0.1 < \kappa < 0.9$. Sea salt with high hygroscopicity has a κ of 1.4. Therefore, we can say that as κ approaches zero, the particle becomes non-hygroscopic. Henceforth, PM10 and PM2.5, are highly hygroscopic in nature, whereas PM1 because of its affinity towards zero is non-hygroscopic in comparison to PM10 and PM2.5 particle sizes.

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