New Insights in Aerosol Science using Optical and Digital Holographic Microscopy: From Nano-aerosols to Cloud Droplets

Devendra Pal

देवेंद्र पाल



Department of Atmospheric and Oceanic Sciences

McGill University

Montreal, Canada

April 2023

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Doctorate of Philosophy in Atmospheric Sciences.

© 2023 Devendra Pal. All right reserved.

Dedication

To my Dad Mishri Lal Gangwar and my mom Late Urmila Gangwar

Acknowledgment

First, I want to thank my supervisor, Professor Parisa A. Ariya, for the continuous support over the years, for mentorship, and for allowing me to build my skills as a researcher and educator. Thanks to my thesis committee members, Professor Leonard Barrie and Professor Thomas Preston, for their valuable advice as I progressed through my degree. Thanks to Prof. Andreas Zuend, Prof. Yi Huang, and Prof. Peter Yau for their advice at different stages of the Ph.D. degree.

Thanks to my Atmospheric and Oceanic Sciences officemates, Yanxu Chen, Antoine Savard, and Charles Brunette, for creating a fantastic workspace. I want to express my gratitude towards my chosen brother/friend Charles Brunette for his invaluable contributions; I am confident our brother bonds are for a lifetime. I am also thankful to Lubica Sestak, Victor Brunette and Anna Brunette (Charles's family) for considering me as a family member and supporting me in every situation. I can't forget when I had an issue with my Knee, and Charles's mom (Lubia Sestak) fed me and brought food to my apartment for days even though a challenging period like COVID couldn't stop her. I have been lucky to have amazing friends; Amprita (always be in debt for her care, love and fantastic food), Ryan Hall (a very close friend), Ting Chen, Arvin Sokkappadu, Zi Wang and her Mom, Mattie Hibbs, Houjie Li, Benni, Zaki, Yevgen Nazarenko, Zak, Mussy, Bruce Hicks and special mention to Sushy for being a very amazing friend and her exceptional care, and support.

I want to acknowledge all of my group members, past and present, including Rodrigo Rangel-Alvarado, Uday Kurien, Jim Ghostadidar, Mainak Gaungaly, Sandeep Bose, Bryan Lee, Nagein, Benni, Hem Ghimire, Elliot, and the many undergraduate students we have had the privilege to work with including Mayeesha Rahim, Lewis Mackay, Simon Dib, and Hannah Szeptycki. Their friendship and support have been of immense value to me over these years. Thanks to friends from the Atmospheric and Oceanic Sciences department for making life in Burnside Hall brighter: Jagdeep Sodi, Aditya Bakshi, Kevin Bloxam, Sonja Druke, Andrés Pérez, Camilo Serrano Daha, Marie-Pier Labonté, Yan-Ting Chen, Qiurun Yu, and Valentina Glazatova.

Thanks to the brilliant academic staff whom I had the chance to work alongside: Rick Rossi, Weihua Wang, Jean-Philippe Guay, Jean Marc, Robert Workman, and Hatem Titi from the Chemistry Department. Many thanks to all the students whom I taught ATOC 357 as an instructor. Thanks to the administrative and support staff from AOS Department, Lucy Nunez, Calin Giurgiu, Nevein Gamal Gamaleldin, Olivia Marino, and Ambrish M. Raghoonundun. Special thanks to our graduate coordinator Manuela Franzo for her help and dedication.

I am also thankful to my friends from India, who always treated me as a younger brother: Arvind Rastogi, Gaurav Sharma, Shiv Kumar, Susheel Kumar, Anurag Singh, Amit Kumar Pandit, Sanjeev Dwivedi, Buddhi Prakash, Naveen Chandra Negi and Avdhesh Kumar. Arvind Bhaia became my partner in crime, and we had countless discussions on zoom during the covid time. Thanks to my forever friends; Himanshu, Umesh, Akhil, Hemant, Dushyant, Kapil, Chote Lal, Sonu Kumar, Sashi Kant, Khusboo Jaiswal, Seema Kushwaha, Gaurav Gupta, Mithilesh Kumar, Rakesh Yadav, and Roshan Pathak.

Finally, I want to thank my family. My Mom Late Urmila Gangwar; my dad Mishri Lal Gangawar; my sister (Jayanti); her husband (Guddu); my niece (Ishi) and nephew (Abhi); and my brother Herkesh Gangwar, without whom none of this would be possible. I am ever in your debt.

Contributions of authors

This article-based thesis contains six chapters: an introduction (**Chapter 1**), three articles published in peer-reviewed journals, **Chapter 2** in Urban Climate, **Chapter 3** in Communication Chemistry: Nature, **Chapter 4** manuscript accepted and in press Communication Engineering: Nature, and one manuscript is in preparation and to be submitted to Journal of Geophysical Research: Atmosphere (**Chapter 5**), and a conclusion and future direction (**Chapter 6**).

I performed all the research works presented in this dissertation required for my doctoral studies. I wrote all the chapters, co-designed the studies, conducted the experiments, analyzed the data, developed the code, interpreted the results, and prepared the figures. I am the first author of the original articles.

Professor Parisa A. Ariya (adviser, McGill) co-authored and is the corresponding author of all four articles. She provided continuous guidance and support, co-designed the studies, participated in interpreting results and discussions, provided insights into experiments, and edited all the articles used in this thesis.

Dr. Ashu Dastoor (Scientist, Air Quality Research Division, Environment and Climate Change Canada) is a co-author of Chapter 2, which is included in the thesis. Ashu Dastoor provided scientific insights and reviewed the manuscript.

Professor Thomas C Preston (AOS and Chemistry department at McGill University) and Dr. Yevgen Nazareko (Postdoctoral fellow AOS department at McGill University) are co-authors of Chapter 3, which is included in the thesis. They both provided valuable scientific discussion during this project and reviewed the article.

Professor Marc Amyot (Department of Biological Sciences, Univerité de Montréal) and Professor Chen Liang (Department of Medicine, Division of Experimental Medicine, McGill University and Jewish General Hospital) are co-authors of Chapter 4, which is included in this thesis. Both provided critical constructive suggestions during the project and reviewed the manuscript.

Mr. Ryan Hall (Ph.D. student, Ariya Lab, McGill) is a co-author in Chapter 5. Ryan contributed to the calibration of the MRINC and performed scientific experiments with me. Dr.

Nazarenko has also co-authored Chapter 5 and provided constructive feedback throughout the manuscript.

Finally, the articles used in this thesis reflect the suggestions and constructive comments from all co-authors and several disclosed and anonymous reviewers during the peer-reviewing process.

Statement of originality

This thesis contains original research and represents distinct contributions to knowledge in the field of aerosol science and technology development and ice clouds formation as follows:

Aerosols in a cold urban climate (Chapter 2).

Our first objective was to investigate atmospheric aerosol chemical and physical properties in a cold urban environment and quantify the relationship between emissions of nano to micronsize particles and air quality. To achieve this objective, we first developed the proof of concept and prepared multiple instruments for investigating the physicochemical properties of aerosols.

- A comprehensive 2-year continuous observational dataset was obtained for studying the physicochemical properties of aerosols in the cold climate metropolitan city of Montreal, Canada. Distinct seasonal variations were found with significantly higher nano-aerosol number concentrations observed in winter compared to other seasons. We found that higher concentration of aerosols in winter is affected by (a) the meteorological impact of the lower boundary layer height, suppression of vertical mixing, and cold temperature in Montreal, and (b) a potential increase in anthropogenic emission along with slow traffic due to more extended snowfall events and snow removal process. An ensemble of metals, ions and carbon-containing aerosols were observed in both nano and micron-sized particles, while airborne nanoparticles were also considered emerging chemical contaminants.
- This research project provided the basis for subsequent co-authored studies that inspect hotspots (airport and highways) of aerosols, particularly airborne nanoparticles emissions in Montreal; the relationship between nanoparticles with co-emitted pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), ozone (O₃) and particulate matter (PM_{2.5}). These studies revealed that most airborne nanoparticles are emitted from vehicular traffic exhaust, and airports are one of the major hotspots in cities. Winter meteorology certainly plays a role in the enhancement of airborne nanoparticles number concentration in cold climate cities along with slow traffic due to snowfall events.

Development and application of Nano-DIHM (Chapter 3 and Chapter 4).

- We developed a new prototype technology to determine in situ real-time aerosol physical properties in 3D space based on holographic microscopy, which we named Nano-Digital In line Holographic Microscopy (Nano-DIHM is patent pending; Parisa A. Ariya and Devendra Pal, United States Provisional Patent Application No. 63/161,215). This includes determining 3D size, 3D orientation, phase, shape, surface area and roughness. A long-standing challenge for aerosol researchers was obtaining the aerosol 3D size distribution, orientation, phase, and shape measurements in situ and in real-time. The new dataset obtained from Nano-DIHM will support multiple applications. This data can be used in retrieval algorithms to extract aerosol size and shape data more accurately from satellite observation. The real-time phase, shape and surface information is a critical physical property determining the aerosol's impact on human health.
- We automated the Nano-DIHM to detect and classify bioaerosols in situ in real time. As a proof of concept, SARS-CoV-2 and Bacteriophage MS2 viruses were observed in real-time and automatically classified from mixed samples in air and water. The development of automated classifiers is in progress to identify or target unknown species that can be used as a physicochemical sensor for bioaerosol measurement in situ in real time.

Ice nucleation by nanosized particles using MRINC (Chapter 5).

• We developed the McGill Real-time Ice Nucleation Chamber (MRINC) using a cylindrical continuous flow diffusion chamber. The coupling of MRINC with Nano-DIHM enabled us to (1) distinguish the supercooled droplets and ice crystals from mixed-phase cloud regimes in situ in real-time. (2) The MRINC results would be utilized to improve existing parameterization schemes in mixed-phase cloud conditions where the role of nano-sized ice nuclei is not considered yet.

Abstract

Most atmospheric aerosol particles are too small to be seen with the naked eye, but their health and climate impacts are immense. Detailed investigations of atmospheric aerosols are a top research priority recommended by the World Health Organization and the International Panel on Climate Change. To understand how aerosols impact the global climate, health, and the chemistry of the Earth's atmosphere, we need to understand the complex physical and chemical characteristics of aerosols. These include the aerosol size distributions in three-dimensional (3D) space, the aerosol dynamics, and the aerosol shape, phase, surface, and chemical composition. Many instrumental techniques exist to analyze aerosols' physical and chemical properties, including real-time aerosol sizing and counting using optical and electrical mobility techniques have provided limited knowledge of the aerosol particle size distribution in 3D space, orientation, shape, phase, chemical composition, and dynamic processes that control the formation and transformation of aerosols in the atmosphere. This thesis aims to develop aerosol measurement techniques that can give real-time, in situ 3D physicochemical properties of aerosols and operate in both cold and warm climate conditions.

The first project of this research focuses on studying the physicochemical properties of aerosols in cold climatic conditions in the city of Montreal. Later, we developed the Nano-Digital In-line Holographic Microscopy (Nano-DIHM) system, a new approach to investigating the 3D size distribution, 3D orientation, phase, roughness, and shape of airborne particles from the nanoscale to the millimeter scale with a time resolution on the order of milliseconds. The Nano-DIHM setup consists of a point source (pinhole), a camera, a flow tube, and an optical cuvette system, through which aerosol-charged air samples flow into Nano-DIHM sample volume. The results obtained by the Nano-DIHM were validated with multiple aerosol sizers and high-resolution electron microscopy. Addressing pressing needs in infectious bioaerosols research, we parallelly tested the Nano-DIHM setup for bioaerosol measurements. In these measurements, we observed bacteriophage viruses MS2 and SARS-CoV-2 and their interaction with various metals and organic molecules in air and water. We developed an algorithm for reconstructing holographic images, enabling us to use the Nano-DIHM to measure and automatically distinguish SARS-CoV-2 aerosols in mixed biological aerosol samples or heterogeneous samples. Lastly, we paired the

newly developed optical detection system (Nano-DIHM) with the newly developed McGill Realtime Ice Nucleation Chamber (MRINC) for ice nucleation studies. This system is capable of recreating ice nucleation processes taking place in the atmosphere and allows observations of ice crystals, supercooled water droplets, and other aerosol particles in situ.

Mixed-phase clouds represent a substantial uncertainty in climate model predictions of radiative forcing, despite significant advancements in the fundamental understanding of ice formation processes over the last decades. This uncertainty is partly due to limited knowledge of the physicochemical properties of aerosol particles responsible for ice nucleation (INPs) and partly to limited observational data in the atmosphere for quantifying their spatial and temporal distribution. Using the Nano-DIHM with MRINC allows distinguishing between ice crystals and supercooled water droplets under conditions pertinent to mixed-phase cloud temperatures, from about 0 °C to -38 °C.

This dissertation contributes to fundamental advancements in aerosol science by introducing a novel analytical technique for measuring the 3D physicochemical properties of nano aerosol particles that are impossible to measure in situ otherwise. The Nano-DIHM system has the potential for making breakthroughs in determining the physicochemical characteristics of aerosols, which cannot be achieved with existing analytical techniques, e.g., real-time measurements of 3D size, shape, surface area, and roughness of aerosol particles. All these properties of atmospheric aerosol particles directly impact cloud formation and, thus, climate change. The novel data generated using Nano-DIHM can provide critical information for health studies by determining the surface characteristics of aerosols in situ and in real-time. Understanding the additional particle properties using Nano-DIHM will help predict atmospheric phenomena more accurately under increasing amounts of aerosols released by anthropogenic sources.

Résumé

La plupart des aérosols atmosphériques sont trop petits pour être vus à l'œil nu, mais leur impact sur la santé et le climat est immense. L'Organisation mondiale de la santé et le Groupe d'experts intergouvernemental sur l'évolution du climat désignent ainsi l'étude détaillée des aérosols atmosphériques comme étant une priorité de recherche. Pour comprendre l'impact des aérosols sur le climat mondial, la santé des populations et la chimie de l'atmosphère, nous devons comprendre les caractéristiques physiques et chimiques complexes des aérosols. Il s'agit notamment de la distributions des tailles d'aérosols dans l'espace tridimensionnel (3D), de la dynamique des aérosols, ainsi que de la forme, de la phase, de la surface et de la composition chimique des aérosols. Il existe plusieurs techniques instrumentales pour analyser les propriétés physiques et chimiques des aérosols, notamment la taille et le nombre d'aérosols en temps réel, à l'aide de techniques de mobilité optique et électrique, de microscopie optique et électronique et de spectrométrie de masse. Cependant, ces techniques traditionnelles apportent une connaissance limitée de la distribution de la taille des particules d'aérosols dans l'espace 3D, de leur orientation, de leur forme, de leur phase, de leur composition chimique et des processus dynamiques qui contrôlent la transformation des aérosols dans l'atmosphère. De plus, ces méthodes traditionnelles ne permettent pas d'obtenir des informations en temps réel sur les propriétés détaillées des aérosols. Cette thèse vise à développer des techniques servant à mesurer les propriétés physicochimiques 3D complètes des aérosols en temps réel, et qui peuvent fonctionner dans des conditions climatiques froides et chaudes.

Nous étudions d'abord les propriétés physico-chimiques des aérosols dans les conditions climatiques froides de la ville de Montréal, et développons un système de microscopie holographique numérique en ligne (Nano-DIHM), une nouvelle approche pour étudier la distribution de taille 3D, l'orientation 3D, la phase, la rugosité et la forme des particules en suspension dans l'air, à des échelles spatiales de l'ordre du nanomètre au millimètre, et avec une résolution temporelle de l'ordre de la milliseconde. Le Nano-DIHM est composée d'une source ponctuelle (sténopé), d'une caméra, d'un tube d'écoulement et d'un système de cuvettes optiques, à travers lesquels circulent des échantillons d'air chargés d'aérosols. Les résultats obtenus par le Nano-DIHM sont validés à l'aide de différentes méthodes, incluant la microscopie électronique à haute résolution. Pour répondre aux besoins pressants de la recherche sur les bioaérosols

infectieux, nous testons la configuration du Nano-DIHM pour les virus bactériophages MS2 et SARS-CoV-2, ainsi que leur interaction avec une série de métaux et de molécules organiques dans l'air et l'eau. Nous développons un algorithme pour reconstruire les images holographiques, ce qui nous permet d'utiliser le Nano-DIHM pour mesurer avec succès et distinguer automatiquement les aérosols de SARS-CoV-2 dans des échantillons d'aérosols biologiques mixtes, ou des échantillons hétérogènes. Enfin, nous combinons le nouveau système de détection optique (Nano-DIHM) à la nouvelle chambre de nucléation de glace de McGill (MRINC). Ce système permet de recréer les processus de nucléation de glace qui ont lieu dans l'atmosphère et permet d'observer les cristaux de glace, les gouttelettes d'eau en surfusion et d'autres aérosols.

Les nuages en phase mixte représentent une incertitude considérable dans les prévisions de forçage radiatif des modèles climatiques, et ce malgré les progrès significatifs réalisés dans la compréhension fondamentale des processus de formation de glace au cours des dernières décennies. Cette incertitude est attribuable en partie à une connaissance limitée des propriétés physico-chimiques des aérosols responsables de la nucléation de la glace, et en partie à une disponibilité limitée de données d'observation dans l'atmosphère permettant de quantifier la distribution spatiale et temporelle des particules de nucléation de glace (INP). À ce jour, aucune étude n'a permis de quantifier les propriétés de nucléation de glace des nanoparticules en suspension dans l'air. L'utilisation du détecteur Nano-DIHM avec la chambre de refroidissement MRINC permet de distinguer les cristaux de glace des gouttelettes d'eau en surfusion dans des conditions représentatives des températures de nuages en phase mixte, d'environ -10 °C à -38 °C.

Cette thèse propose une avancée fondamentale de la science des aérosols en introduisant une nouvelle technique analytique pour mesurer les propriétés physicochimiques 3D des nanoparticules et des fines particules d'aérosols, impossibles à mesurer autrement. Le système Nano-DIHM a le potentiel de contribuer à des percées dans la compréhension des caractéristiques physico-chimiques des aérosols, qui ne peuvent pas être réalisées avec les techniques analytiques existantes, par exemple, les mesures en temps réel de la taille, de la forme, de la surface et de la rugosité des aérosols en 3D. Toutes ces propriétés des aérosols atmosphériques ont un impact direct sur la formation des nuages et, par conséquent, sur le changement climatique. Les nouvelles données générées par le Nano-DIHM sont des informations essentielles pour les études sur la santé, en déterminant les caractéristiques de surface des aérosols en temps réel. La compréhension de propriétés supplémentaires des aérosols à l'aide du Nano-DIHM aidera à prévoir les phénomènes atmosphériques avec plus de précision dans le contexte d'une augmentation des quantités d'aérosols émis par des sources anthropique.

Table of Contents

Chapter	r 1 Introduction	1
1.1	Atmospheric Aerosols	1
1.2	Importance of atmospheric aerosols	
1.3	Sources, classification, and physicochemical characteristics of aerosols	4
1.3.	1 Natural sources	4
1.3.	2 Anthropogenic sources	6
1.3.	3 Physical properties of aerosols	7
1.3.4	4 Chemical properties of aerosols	7
1.4	Health effects and regulation of aerosols (PM _{2.5})	
1.4.	1 Global regulatory measures of PM _{2.5} standards	9
1.4.	2 Regulation of nanoparticles (ultrafine particles)	11
1.5	Role of aerosols in climate	
1.5.	1 Direct radiative effect/Scattering-absorption effect	
1.5.	2 Indirect radiative effect/Aerosol-cloud interaction	16
1.5.	3 Ice formation in the atmosphere: role of aerosols	17
1.6	Air quality and aerosols in an urban cold climate	
1.7	Are aerosols good or bad for the global economy?	
1.8	Aerosol measurement methods	22
1.8.	1 Laboratory-based aerosol measurement techniques	
1.8.	2 Remote sensing and model-interpolated aerosol measurement	
1.9	Outstanding questions	
1.10	Dissertation outline	
Chapter	r 2 Aerosols in an Urban Cold Climate: Physical and Chemical Characteris	tics of
Nanopa	urticles	
2.1	Introduction	
2.2	Experimental section	
2.2.	1 Sampling and measurement site	
2.2.	2 Number-size distribution measurement	
2.2.	3 Micro-Orifice Uniform Deposit Impactor (MOUDI)	
2.2.4	4 High-Resolution S/TEM and FE-ESEM imaging with Energy Dispersive X-Ray Spectro 37	oscopy (EDS)
2.2.	5 Trace metal analysis	
2.2.	6 Complementary ion analysis	
2.2.	7 Total organic carbon (TOC)	
2.2.	8 Meteorology and auxiliary air quality data	
2.2.	9 Statistical analysis and classification	
2.3	Results and discussion	
2.3.	1 Seasonal particle number-size distribution	40
2	.3.1.1 Winter seasons: The highest observed nanoparticle number density	42
2.3.	2 Comparison with previous research on airborne particle distribution	43

2.3.3	Chemical analysis of airborne particles	44
2.3	.3.1 Trace metal concentration	44
2.3	.3.2 Ions in aerosols	45
2.3	.3.3 TOC observations	46
2.3.4	HR-S/TEM and FE-ESEM observation of airborne particles: Focus on nanoparticles	47
2.3.5	Distinct trend of weekday and weekends of nanoparticles distribution in summer and winter	49
2.3.6	Day-night variation of aerosols	50
2.3.7	Seasonal and diurnal variations: Rush hours effect	
2.3.8	Anthropogenic sources of nanoparticles	
2.3.9	Snow impact on nanoparticles	54
2.4	Importance of emerging metal contaminants observations in the atmosphere	55
2.4.1	Potential environmental implications of airborne metal-containing nanoparticles	55
2.4.2	The Importance of this metadata to improve cold-climate air quality modelling	56
2.5	Conclusions and future directions	56
Acknow	vledgments	57
Chapter 3	3 Advancing the Science of Dynamic Airborne Nanosized Particles using Nano)-
<i>DIHM</i>		58
3.1	Introduction	
3.2	Results	62
3.2.1	Detection of airborne nanosized objects using Nano-DIHM: Beyond the diffraction barrier	63
3.2.2	4D trajectories of airborne PSL spheres	69
3.2.3	PSL spheres in aqueous mode: confirmation with S/TEM	71
3.2.4	Distinguishing PSL spheres from Iron oxide mixture: S/TEM	74
3.2.5	Tracking ambient airborne particles	76
3.3	Discussion	77
3.4	Methods	79
3.4.1	Digital in-line holographic Microscopy	79
3.4	.1.1 Recording of holograms	80
3.4	.1.2 Resolution of Nano-DIHM: Beyond the diffraction limit	82
3.4.2	Phase shift and refractive index calculation	86
3.4.3	SMPS and OPS	86
3.4.4	Experimental Setup	
Acknow	vledgment	
Chapter 4	4 Four-dimensional in situ real-time physicochemical tracking of virus-laden a	lroplets
and aeros	sols in the air	89
4.1	Introduction	91
4.2	Results and Discussion	94
4.2.1	Validation of the MS2 bacteriophage shape and size obtained by nano-DIHM with S/TEM	
4.2.2	Tracking of aerosolized MS2 characteristics in dynamic air	
4.2.3	4D trajectories of MS2 particles and droplets in air	104
4.2.4	In situ real-time SARS-CoV-2 detection, classification, and physicochemical characteristics	105
4.2	.4.1 SARS-CoV-2 detection in dynamic mode	105
4.2	.4.2 SARS-CoV-2 detection in stationary mode	108
4.2.5	Building a library and classifiers for fully automated SARS-CoV-2 detection (Yes/No)	

4.2.6	5 Physicochemical characteristics of MS2 with TiO ₂ and organic coating	111
4.2.7	7 Surface properties of SARS-CoV-2, MS2, and metal oxide particles	
4.3	Outlook and potential applications	
4.4	Methods	
4.4.1	Digital in-line holographic microscopy	114
4.4.2	2 Building library: automation and classification process	116
4.4.3	3 SARS-CoV-2 sample information	
4.4.4	4 Experimental setup	
4.4.5	5 Aerosol sizers	
4.4.6	5 High-resolution electron microscopy	
4.4.	/ Litesizer particle analyzer	
4.4.0	wledgment	120
Chapter Phase C	owedginent 5 Deciphering Supercooled Droplets from Ice Crystals: MRINC Simulate Cloud Regime	ed Mixed-
5.1	Introduction	
5.2	Experiment and methods	
5.2.1	McGill Real-time Ice Nucleation Chamber (MRINC)	
5.	2.1.1 Novel optical detection unit	
5.	2.1.2 Aerosol generation unit	
5.	2.1.3 Growth section of INPs	
5.2.2	2 Sample preparation and CCN, IN experiments	
5.3	Results and discussion	
5.3.1	Validation of MRINC	
5.3.2	2 Distinction of ice crystals and supercooled droplets in mixed-phase cloud regime	
5.3.4	Example of MRINC operation in CCN mode	
5.3.5	5 Advantages and limitations of MRINC	
5.4	Conclusion and proposed future steps	
Ackno	owledgement	140
Chapter	6 Conclusions and Future Work	
6.1	Conclusions	141
6.2	Future work	145
A Cha	apter 2 Supplementary Information	
A1	Supplementary methods	
A1.1	MOUDI	148
A1.2	2 Meteorology and auxiliary air quality data	148
A1.3	Geometric mean and geometric standard deviation	
A2	Supplementary figures	150
A3	Supplementary tables	154
B Cha	upter 3 Supplementary Information	
B1	Supplementary methods	159

B1.1	Analysis of the size and phase of snow-borne particles in dynamic and stationary modes	159
B1.2	Refractive index measurement	159
B1.3	Synthetic materials	
B1.4	Automation of stingray software	
B2	Supplementary figures	
B3	Supplementary tables	
C Cha	pter 4 Supplementary Information	173
C1	Supplementary figures	
C2	Supplementary tables	
D Cha	pter 5 Supplementary Information	187
D1	Supplementary text	
D1.1	Existing continuous flow diffusion chamber	
D2	Supplementary figures	
D3	Supplementary tables	190
Chapter	7 References	192

List of Figures

Figure 1.1	Sketch of aerosol size, number and mass distribution in the atmosphere and their primary associated
F ! 1 0	sources. The blue line represents the aerosol number, and the red line represents the mass
Figure 1.2	Schematic of aerosol's relevance in the atmosphere and their impact on air quality, health, and climate
Figure 1.3	PM_{25} standards worldwide. (a) Population and the total area covered by different annual PM_{25} ambient
	air quality standards worldwide, and (b) Annual ambient PM _{2.5} air quality standards worldwide. The data
	and plot have been adopted from Nazarenko et al., 2021 (Co-authored paper)10
Figure 1.4	Airborne nanoparticles and PM _{2.5} in the rue University, McGill University, cold climate city of Montreal.
	(a) Time series of hourly average nanoparticles and PM2.5. The green line represents the threshold of
	considered nanoparticles exposure in the ambient atmosphere, and the gray line is a PM _{2.5} standard by
	WHO. (b) direct correlation between nanoparticles and PM _{2.5} . The data used in panels (a-b) was obtained
	from Pat et al. (2021). (c) Total average particle number concentration (PNC) in multiple worldwide
	cities in different time periods. The blue and green lines represent the considered WHO nanoparticle
	exposure in the ambient atmosphere. (This Figure is part of the manuscript by Pal et al. (2023), which
	will be submitted to the Bulletin of the World Health Organization). The blue and green lines correspond
Figure 1 5	to 24 hr and 1 hr mean concentration thresholds, respectively.
rigure 1.5	Summary of radiative forcing (EPE) and (b) global surface temperature change from component
	(a) effective radiative forcing (ERF) and (b) global surface temperature change from component emissions for 1750 - 2019 based on Counled Model Intercomparison Project Phase 6 (CMIP6) models
	and (c) net aerosol ERE for 1750 - 2014 from different lines of evidence. The intent of this is to show
	advances since AR5 in the understanding of (a) emissions-based ERF. (b) global surface temperature
	response for short-lived climate forcers, and (c) aerosol ERF from different lines of evidence. The figure
	was adopted from the Technical Summary (TS 15) of Climate Change 2021: The Physical Science Basis
	[106, 109]
Figure 1.6	Schematic of the ice nucleation processes in the atmosphere as a function of ice saturation Si (RHi/100),
	and temperature T. The solid slope line represents saturation with respect to water and the solid
	horizontal line with respect to ice. The dashed sloped line is the homogeneous freezing line of solution
	droplets (Koop et al., 2000). The plot was adapted from Hoose and Mohler[137]18
Figure 1.7	Schematic of aerosol measurement methods
Figure 2.1	Size aggregated particle number densities (#/cm ³). (a) Seasonal variation of geometric mean, arithmetic
	mean, and median particle number densities, and (b) Monthly box plots of size aggregated particle
	number densities data from May 2017 to May 2019. The horizontal line through each whisker box
	represents that month's median value, and the lower and upper edges of the whisker boxes present the 25^{th} and 75^{th} percentiles values, respectively. Whickers above and below the boxes are maximum and
	25 and 75 percentiles values, respectively. Whisters above and below the boxes are maximum and minimum values, respectively. The outliers are not shown. The rectangular shapes inside the box present
	monthly mean number density 41
Figure 2.2	High-resolution transmission electron microscopy images (a-d) with EDS of airborne particles (a)
0	Represents the crystalline structure of TiO_2 and close-up (a1) represents titanium nanostructure, (b) and
	(c) represents the secondary organic particles with multiphase morphological structures, (d) represents
	spherical shaped organic-inorganic particles mixed with emerging metals. (e) Scanning electron
	microscopy with EDS represents biological particles. This figure rearranged with permission49
Figure 2.3	Diurnal time series of weekdays to the weekend from May 2017 to May 2019. Particle number densities
	$(\#/ \text{ cm}^3)$ in different size aggregated ranges (a) < 100 nm and CO on weekdays, (b) < 200 nm, (c) < 1
	μ m, (d) < 100 nm and CO on weekends. (a,d): The left-hand scale on Y-axis represents the nanoparticle's
	number density, and the right-hand Y-axis shows the CO mixing ratios
Figure 2.4	Seasonal, diurnal plot for nanoparticle number density (#/cm ³). (a) Summer months from 2017 and
	winter from 2017-2018., (b) Summer months from 2018 and winter from 2018-2019., (c) Spring and fall month from 2018
Figure 2.1	Iail month from 2017 and (d) Spring and fail month from 2018.
r igure 3.1	keconstruction of the intensity information for 100 nm PSL particles in the aerosol phase. (a) Kaw hologram recorded for airborne PSL particles: (b) background hologram recorded without PSL particles:
	norogram recorded for an oorne r SL particles, (b) background horogram recorded without PSL particles;
	xviii

(c) contrast hologram obtained after subtracting the background hologram from the raw hologram. (d) Zoomed-in area of c1 at $z=3109 \mu m$. (e) Particles in focus from (d). (f) Zoomed-in area of (e) showing the precise recovery of nanosized PSL particles and their shape. (g, h) Phase reconstruction of PSL particles. The line across the numbers 1 and 2 in Figures f and h shows the crosscut across the particles. (i, j) The phase profile of the PSL particle crosscut. (k, l) The intensity profile of PSL particles across the particle crosscut. (m, n) The size distribution of PSL particle aerosols measured by the SMPS and the OPS, respectively. The red dashed line and the black line correspond to the two repeats of the experiments. The Blue dotted line is a Gaussian peak fit for the data. The validation of the holographic reconstruction of 100 nm PSL particles are provided in Movie 1 and Movie 2. The background holograms recorded for zero air and particle concentration tested by the SMPS and the OPS are shown in Appendix Figure B3.

- Figure 3.6 Holographic reconstruction of 200 nm PSL particles deposited on a microscope slide and their validation by S/TEM images. (a) Intensity reconstruction at 2318 μm. (b) Zoomed-in area of (a). (c) In-focus, high-resolution reconstruction at Z=2321 μm. (d-f) S/TEM images of same 200 nm PSL samples. Circle 1 and 2 in image (c) show the good agreement with S/TEM images shown in (d, e). (g) Intensity crosscut of particles in (c) with a diameter of 205 nm. (h, i) Intensity and phase crosscut of particles with the confirmation of existing clusters of PSL particles. Similar confirmation by S/TEM image in (e) suggested the presence of a cluster of PSL particles. Phase reconstruction of 200 nm PSL particles shown in Figure B6.
- Figure 3.7 Holographic reconstruction of a mixed sample of 200 nm PSL particles and iron oxide nanoparticles deposited on a microscope slide and the validation by S/TEM images. (a) Intensity reconstruction at 905 µm. (b) Zoomed-in area circle 1 of (a). (c, d) Zoomed-in area circles 2 and 3 of (a). (e) S/TEM images of the same sample confirming the presence of both PSL and iron oxide nanoparticles. Circles 1, 2 and 3 are shown in Figure (a) and highlighted in Figure (b-d), respectively. (f) Selected area diffraction pattern and (g, h) EDS data for Spot A and Spot B, respectively. Phase reconstruction of the same samples and more S/TEM images are provided in the Supplementary Figure S7.

- **Figure 4.2** Intensity and phase reconstruction of airborne MS2. Panel (a-c) is the intensity reconstruction and panel (d-f) presents phase reconstructions. (a) Intensity reconstruction of airborne MS2 viruses at Z= 627 μ m, (b) Z= 687 μ m, and (c) Z= 1570 μ m. (d-f) Phase results of the same particles as (a-c). (g-i) Intensity crosscut profiles of particles in sections (a-c) and (j-l) phase crosscut profiles of particles in panel (d-f). (m-n) Airborne MS2 particle size distribution obtained by the SMPS and the OPS, respectively, and (o-p) size distribution of mixed samples of MS2 and TiO₂. The two-colored line corresponds to two repetitions of an experiment. The 4D dynamic trajectories of the particles are provided in Movie 1, and Movie 2. The background holograms recorded for zero air and particle concentrations tested by the SMPS and the OPS are shown in Figure C3. The automated detection of airborne MS2 by Stingray software is shown in Figure C4.

- Figure 4.6 MS2 viruses coated with TiO₂ and olive oil. (a-b) Intensity and phase reconstruction of TiO₂ particles. (c-d) Intensity and phase results of MS2 viruses coated with TiO₂ particles obtained by nano-DIHM. (e-f) High-resolution electron microscopy images of TiO₂-coated MS2 viruses. (g-h) Intensity and phase images of olive oil. (i-j) Intensity and phase results of MS2 viruses coated with olive oil obtained by

	nano-DIHM. (k-l) High-resolution electron microscopy images of oil-coated MS2 viruses. (m) Intensity response of particle 1 in panel (a). (n-p) Intensity response of particles 1 and 2 in panel (c), respectively.
Figure 4.7	Schematic of nano-DIHM setup. a) SARS-CoV-2 transmission by an infected human via airborne transmission. The viral droplets pass through the flow tube cuvette to the nano-DIHM sample volume and SMPS. Furthermore, Octopus/Stingray software (artificial intelligence) was used to detect and characterize viral particles. b) Working principle of holography microscopy. c) Deep learning for SARS-CoV-2 analysis. d) Particle tracking analysis and sample collection method for field data. e) Experimental setup of airborne particle characterization
Figure 5.1	Schematic of McGill Real-Time Ice Nucleation Chamber (MRINC). The bottom side inserted image shows the cylindrical geometry and experimental setup at McGill University127
Figure 5.2	Aerosol size distribution in ambient conditions with and without chamber. (a-b) The size distribution of different aerosols inside the chamber, and (c-d) shows the size distribution without the chamber. (a,c) and (b,d) measured by SMPS and OPS, respectively
Figure 5.3	Temperature response inside the MRINC at a different length. The temperature gradient was ≤ 2 °C from the inlet at 10 cm to 97 cm at the end of chamber length (3 cm from the outlet, where the optical detection unit was installed). At the current stage, MRINC reached ~ 25 °C, though it can reach a much colder temperature by changing the cooling bath or colling the circulator
Figure 5.4	Activated fraction of AgI at different temperatures and constant supersaturation. At T = 0 °C, RH = 104 %; T = - 6.2 °C, RH ~ 143%; T = - 9.6 °C, RH ~ 143%
Figure 5.5	Intensity and phase reconstruction images of AgI aerosol particles in situ in real time. (a) Intensity reconstruction of dry AgI particles at reconstruction distance $z = 1378 \mu m$ (T = 22.5 °C, RH $\leq 1\%$). (b) Intensity images of a cloud droplet of AgI at $z = 1410 \mu m$ (T = -0.2 °C, RH ~ 104 %). (c,d) Intensity reconstruction AgI ice crystals and cloud droplets at $z = 2644 \mu m$ (T = -6.2 °C, RH ~ 143%). The red rectangles are cloud droplets, and the green circle shows the ice crystals. (e) Phase images of the same particles in panels (c,d). (f,g) zoom-in image of the panel (c,d) shows the cloud droplet and ice crystal. (h) After the 1-minute phase image clearly shows the signature of fog
Figure 5.6	MRINC operation in CCN mode. The aerosol particles' growth determined at room temperature (~22.5 °C) at different humidity conditions; RH1 ~ 52%; RH2 ~ 68%; RH3 ~ 78 %; RH4 ~ 89%. (a,b) NaCl, (c,d) (NH ₄) ₂ SO ₄ , and (e,f) 200 nm PSL, respectively. (a,c,e) and (b,d,f) are SMPS and OPS measurements, respectively
Figure 5.7	Intensity and phase reconstruction images of airborne NaCl and 200 nm PSL aerosol particles in situ in real time. (a) Intensity reconstruction of dry NaCl particles at reconstruction distance $z = 985 \ \mu m$ (T = 22.5 °C, RH $\leq 1\%$). (b) Intensity images of NaCl after water uptake at $z = 962 \ \mu m$ (T = 22 °C, RH $\sim 89 \ \%$). (c) Phase image of same particles as panel (b) at $z = 1350 \ \mu m$. (d) Intensity reconstruction of dry 200 nm PSL particles at reconstruction distance $z = 968 \ \mu m$ (T = 22.5 °C, RH $\leq 1\%$). (e) Intensity images of PSL after water uptake at $z = 958 \ \mu m$ (T = 22 °C, RH $\sim 89 \ \%$). (f) Phase image of same particles as panel (e) at $z = 958 \ \mu m$
Figure 6.1	Schematic chart summarizing the distinct research contributions realized during my doctoral studies in the McGill University Atmospheric & Interfacial Chemistry Research Group
Figure A1	Airborne particle observation location Otto Maass Building, McGill University, Montreal Canada (45.5048° N, 73.5742° W). 150
Figure A2	Particle size distribution with HEPA filter. (a) Particle size distribution from 10 nm to 400 nm using SMPS. And (b) Particle size distribution from 0.3 μ m to 10 μ m using OPS. The duplicate experiment has been done
Figure A3	Size aggregated particles number densities. Each point represents one-minute temporal resolution from May 2017 to May 2019. Different colors represent different size ranges of particles (a) < 100 nm, (b) < 200 nm, (c) < 1 μ m, (d) < 2.5 μ m and (e) < 10 μ m

- **Figure B3** Background intensity holograms (a) zero air (crosscut size plotted with horizontal line 1 and vertical line 2. (b, c) particle size distribution of zero air and the air filter with a HEPA filter......163

- Figure B7 2D and 3D view of holographic reconstruction of a mixed sample of 200 nm PSL particles and iron(III) oxide nanoparticles (size <50 nm) deposited on microscopy slide and their validation by S/TEM images. (a) 2D view of phase reconstruction at 925 μm. (b) Zoomed in area circle (a). The red arrow in figure (b) displayed the PSL particles while green arrow shows attachment of PSL on iron particles (c) 3D view of phase reconstruction at 562 μm. (d) Zoomed in area ranctangle shows in figure (c). (e-f) S/TEM images of the same sample confirmed the existence of both PSL and iron oxide nanoparticles. 3D view of phase reconstruction clearly indicates the attchement of PSL on iron oxide particles. 165
 Figure B8 Phase image. (a, b) Phase reconstruction of particles in ambient air. (c-f) Phase profiles of particles
- Figure B10 A simple example of fast and automated reconstruction by stingray software of large volume of images, which were produced in xls file and individual images part of it is shown here. Automated detection of airborne 100 nm PSL particles by using stingray software. (a) As an example from number 1 to number 21 and so on shows the object Id, and (b) Exported results in xls format with the numerical values. Excel

	data sheet carried the information of particle orientation, particle size, perimeter, area, roughness and
Figure B11	other morphology component of particles, momentum and spectrum of particles
-	recorded with PSL particles; (b) Background hologram recorded without PSL particles; (c) Contrast
	hologram obtained after subtracting the background hologram from the raw hologram.(d-i)
	Reconstruction of particles at different reconstruction position Z. It shows the small changes in Z
Figure R1 2	Hologram reconstruction for aerosolized snow meltwater (a) Intensity reconstruction of particles (b, c)
I Igui e Di 2	Intensity profile through the crosscut of particles. (d) Phase reconstruction of particles. (e, f) Phase shift
	across the crosscut of particles through the line 1 and line 2. (g-i) Intensity reconstructions of particles
	in the snow meltwater in the liquid phase. The image in the selected area in (d) shows the same particles'
	intensity reconstruction. The red lines are the Gaussian quadratic fits for particles in (b, c)169
Figure B13	Morphology of snow meltwater in the liquid phase (a) visualized by STEM, and (b) visualized by Nano-
E' D14	DIHM
Figure B14	Glycerine drops in the suspension of type F microscope immersion oil. (a, b) Intensity and phase
	(d) drop height. The blue and red lines are the Gaussian guadratic fits.
Figure B15	Shape size and morphology of synthetic materials (a) Iron oxide (b, c) Iron oxide in the highlighted
I igui e Die	regions of Image (a). (d) Zinc oxide. (e, f) Zinc oxide in the box of image (d)
Figure C1	BLASTN using the betacoronavirus genomic database, result of the sequence genome of the $SARS_{-}$
Figure C1	CoV-2 sample The GenBank ID for the sequence is MN908947 3
Figure C2	Intensity and phase profiles of MS2 in aqueous mode. (a-f) Intensity and phase profiles across the
8	particle crosscuts (Fig 1c), respectively. The size of the particles is represented in terms of the full width
	half maximum (FWHM). (g) MS2 particle size distribution obtained by a particle sizer analyzer (PSA,
	Anton Paar) matched with the size obtained by nano-DIHM. (h) Calibration curve of PSA with 200 nm
	PSL spheres
Figure C3	Nano-DIHM control experiment. (a) Background intensity hologram recorded for zero air. (b) Intensity
	profile across the crosscut of horizontal line 1. (c) Intensity profile along vertical line 2. (d, e) Particle
Figure C4	size distribution of zero air and the air with a HEPA filter. The total particle count was $< 5 \text{ #.cm}^{-1.175}$ Automated detection of MS2- and LIVB-exposed MS2 particles using Stingray software (a-d) Shape
Figure C4	and morphology of MS2 particles and (e-h) shape and morphology of UVB-exposed MS2 particles.
	Nano-DIHM clearly shows the change in the structure of MS2 and successfully determines the UV
	impact
Figure C5	3D orientation and size distribution of bacteriophage MS2 viruses. (a-b) Orientation and size distribution
	of airborne MS2 particles (dry aerosols). (c-d) Orientation and size distribution of a mixture of MS2 and
T! O(TiO2 particles. (e-f) Orientation and size distribution of viral MS2 varus-laden droplets
Figure C6	3D orientation and size distribution of SARS-CoV-2 viral droplets at different velocities. (a-b) Orientation and size distribution of SARS CoV-2 viral droplets at 10 m/ α and (a d) 20 m/ α and and
	(e-f) 30 m/second
Figure C7	Intensity and phase cross-section of SARS-CoV-2 viruses in aqueous mode (a-b) Intensity profiles
- guite of	across the particle crosscuts. (c-d) Phase profiles across the particle crosscuts. The intensity and phase
	profiles indicate the SARS-CoV-2 viral particle size from nano- to micronsized
Figure C8	Distinction between SARS-CoV-2 vs. SARS-CoV-2 RNA. (a-d) Intensity and phase reconstruction of
	SARS-CoV-2 and (e-h) intensity and phase reconstruction of SARS-CoV-2 RNA178
Figure C9	TiO ₂ coating impact on MS2. (a-b) Intensity reconstruction of TiO2-coated MS2 viruses and (d, e) phase
	reconstruction of identical particles. (c, f) High-resolution electron microscopy images, (g, i) intensity
Element O10	response, and (h, j) particle phase response
rigure C10	Onve on coaung impact on MS2. (a-c) intensity reconstruction of onve on-coated MS2 viruses and (d- a) phase reconstruction of identical particles (a i) High resolution electron microscopy impact. The
	c) phase reconstruction of identical particles. (g-1) High-resolution electron incroscopy images. The shape of the oil-coated particles obtained by pano-DIHM is identical to that obtained by S/TEM 180
	shape of the on concerptations obtained by nano-Diffixing is identical to that obtained by 5/1EWI160

Figure C11	Natural organic coating material coating impact on MS2. (a-b) Intensity reconstruction of alpha-pinene	
	coated MS2 viruses and (c-d) phase reconstruction of identical particles. (e-f) Intensity and phase	
	responses of natural honey-coated MS2 particles	
Figure C12	Deciphering MS2 from a mixed sample of MS2 and PSL. (a-b) Phase images of MS2 mixed particles	

with PSL. The red arrow in panel (a) indicates MS2, and the green arrow in panel (b) indicates PSL. 182

Figure D1	Temperature and humidity response of MRINC at inlet point. Where a, b, c, and d are steps, constant
	moist air is supplied to MRINC
Figure D2	Relative humidity inside the chamber at different constant temperatures. The short peaks for a few
	seconds come due to external flow fluctuation
Figure D3	Temperature, humidity, and flow calibration of RINC at cooling conditions. Cooling is achieved by
	using Dry Ice

List of Tables

Table 1.1	Estimated emissions flux of the main types of primary and secondary aerosols in Tg= 10^{12} g. Data obtained from Boucher 2015 [5]
Table 2.1	Mass concentrations (ng/m ³) of trace metals, ions and TOC in different size-fractionated ranges of airborne particles during 24, and 48h sampling periods. The size fraction ranges were based on instrument limitation and the interest of research. The mass concentration also presents in μ g/L in Table
Table 2.2	Nanoparticle number density (number/cm ³). Geometric mean (GM), arithmetic mean (AM), standard deviation (Std), median 99 th and 1 st percentile values were given for winter and summer weekdays and weekends.
Table 2.3	Particle number density (#/cm ³). Median, 25 th and 75 th percentile values during weekday-daytime (09:00-18:00h), weekday-nighttime (22:00-05:00h), weekend-daytime, weekend-nighttime. Also, Median, 25 th and 75 th percentile values calculated for during the weekday (24h) and weekends (24h) from May 2017 - 2019
Table 2.4	Snow impact on nanoparticles. Three snow events were analyzed. Mean, median number densities of nanoparticles were calculated the day before, during and the day after a snowfall in each event. The averages temperatures, relative humidity, total precipitation, and snow on the ground data are also given.
Table 3.1	Detailed experimental parameters for the matrices used
Table 3.2	3D size distribution of 100 nm PSL spheres in the aerosol phase. Descriptive statistics for the dimension distributions of the PSL spheres in 3D space in a single hologram
Table 4.1	Automated physical characteristics of SARS-CoV-2, MS2, and several natural and synthetic materials in dynamic and stationary modes over 31.25 ms. The detailed automation processes of the virus and particle detection and classification procedures are discussed in the Methods section. These images are reconstructed images of objects/particles that show the shape/morphology of particles. *shows clusters.
Table 4.2	3D size distribution of MS2 and mixed samples with TiO ₂ in dry aerosols. The MS2 samples were also analyzed in the form of droplets or the coughed-sneezed phase. Std means standard deviation
Table 4.3	Yes/No detection of SARS-CoV-2 from mixed samples. A mixed sample of SARS-CoV-2 and MS2 particles was analyzed. "YES" indicates SARS-CoV-2, and "NO" indicates MS2 particles. This automated classification is in progress, and we have built full automation for SARS-CoV-2 and will develop it for future viruses, metals, plastics, and bacteria. Table 4.1 discusses the surface properties of multiple sample matrices
Table A1	Seasonal size aggregated geometric mean (GM) number densities (#/cm3), geometric standard deviation (σ g), arithmetic mean number densities, standard deviation (σ), medians, and top 99 th and 1 st percentile values from May 2017 - 2019154
Table A2	Comparisons of particle number density (geometric mean $\pm \sigma_g$) cm ⁻³ in worldwide studies
Table A3	Mass concentrations (μ g/L) of trace metals, ions and total organic carbon (TOC) in different d ₅₀ cut off size ranges of airborne particles during 24, and 48h sampling periods The size fraction ranges were based on instrument limitation and the interest of research
Table A4	Correlation coefficients between nanoparticles (<100 nm) and <200 nm particle number densities, and gaseous co-pollutants
Table B1	Descriptive statistics of the distributions of dimensions of the aerosolised Milli-Q water in 3D space in a single hologram
Table B2	Descriptive statistics of the distributions of dimensions of the 100 nm PSL spheres, 200 nm PSL spheres
	deposited on the microscopy slide in 3D space in a single hologram

Table B3	Changing refractive indices for different sizes of glycerine drops. Comparison of glycerin drop size as determined from phase shifts and from intensity reconstructions
Table C1	SARS-CoV-2 virus detection techniques based on polymer chain reaction, optical-based and industrialized techniques
Table C2	Detailed experimental parameters for the matrices used. The hologram size was 2048 * 2048 pixels, and
	the camera pixel size was 5.5 µm during each experiment
Table C3	3D size distribution of SARS-CoV-2 particles in the droplet phase with different velocities. Previous
	studies for droplet sizes based on a transmission mode
Table D1	Direct processing ice nucleation measurements based on CFDC
Table D2	Operating conditions of RINC191

Lists of Acronyms and Symbols

Acronyms

AERONET	Aerosol Robotic Network
AMS	Aerosol Mass Spectrometer
APS	Aerodynamic Particle Sizer
BAM	Beta Attenuation Mass Monitor
BC	Black Carbon
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CCD	Charge-coupled device
CCN	Cloud Condensation Nuclei
CMOS	Complementary Metal-Oxide-semiconductor
CPC	Condensation Particle Counter
DIHM	Digital In-Line Holography Microscopy
DMA	Differential Mobility Analyzers
DMPS	Differential Mobility Particle Sizer
EARLINET	European Aerosol Research Lidar Network
EC	Elemental Carbon
ECCC	Environment and Climate Change Canada
EDS	Energy-dispersive X-ray spectroscopy
EU	European Union
FEG-TEM	Field emission gun transmission electron microscope
FEMR	Facility for Electron Microscopy Research
FID	Flame Ionization Detector
FPD	Flame Photometric Detector
FRQNT	Fonds de Recherche du Quebec Nature et Technologies
GC	Gas Chromatography

GDP	Gross Domestic Product	
GHG	Greenhouse Gases	
HNMR	Proton Nuclear Magnetic Resonance	
HPLC	High-Performance Liquid Chromatography	
HR-TEM	High-Resolution Transmission Electron Microscopy	
IAM	Integrated Assessment Model	
IC	Ion Chromatography	
IN	Ice Nuclei	
IPCC	Intergovernmental Panel on Climate Change	
LALINET	Latin American Lidar Network	
LWP	Liquid Water Path	
MPLNET	Micro-Pulse Lidar Network	
MRINC	McGill Reat-time Ice Nucleation Chamber	
NAPS	National Air Pollution Surveillance Program	
NASA	National Aeronautics and Space Administration	
NPs	Nanoparticles	
NSERC CREATE PURE	National Sciences and Engineering Council of Canada - Collaborative Research and training Experience Program - Pollution in Urban Environments	
NSERC CREATE	National Sciences and Engineering Research Council of Canada Collaborative Research and Training Experience Program	
OC	Organic Carbon	
OECD	Organization for Economic Co-operation and Development	
OPC	Optical Particle Counter	
OPS	Optical Particle Sizer	
PAX	Photoacoustic Extinctiometer	
PM	Particulate Matter	
PM ₁₀	Particulate matter with aerodynamic diameter less than 10 μ m	

PM _{2.5}	Particulate matter with aerodynamic diameter less than 2.5 μ m
PNC	Particle Number Concentration
PRIMA Quebec	Pôle de recherche et d'innovation en matériaux avancés du Québec
PSL	Polystyrene Latex spheres
PV	Photovoltaic
SD	Standard deviation
SEM	Scanning Electron Microscopy
SIMS	Secondary Ion Mass Spectrometry
SMPS	Scanning Mobility Particle Sizer
SO2	Sulphur dioxide
SSA	Single-Scattering Albedo
TOEM	Tapered Element Oscillating Microbalances
UFP	Ultrafine Particles
US	United State
UV	Ultra-violet
VOCs	Volatile Organic Compounds
WHO	World Health Organisation
Symbols	
$A_{ref}(r,t)$	Reference Amplitudes
$A_{scat}(r,t)$	Scattered Amplitudes
k	Wave Vector
r	Position Vector
λ	Wavelength
ψ	Phase Shift

Chapter 1 Introduction

1.1 Atmospheric Aerosols

Atmospheric aerosols (also referred to as particulate matter, PM) are tiny complex solids, liquids, or mixed-phase particles suspended in the atmosphere [1, 2]. They are emitted from natural and anthropogenic (human-related activities) sources [3, 4]. Atmospheric aerosols exist widely, from a few nanometers to several tens of micrometers [2, 4]. The size of aerosols alters their behaviour and is a significant factor in deciding the lifetime of particles or how long they remain suspended in the air [2]. Aerosols are mainly divided/classified into two groups based on their formation mechanism [3, 4].

- (a) <u>Primary particles</u>: Primary particles are emitted directly into the atmosphere from mechanical processes or natural sources. For example, windblown dust aerosols are directly emitted from the Earth's surface, sea-salt aerosols from wind-swept seas/oceans and biological aerosols (in short, bio-aerosols). The latter originated from various sources, including solid plant debris, pollens, bacteria, and spores [4, 5].
- (b) <u>Secondary particles (gas-to-particle conversion)</u>: Secondary atmospheric particles are the product of gas-to-particle transformation, where chemical or physical reactions of gases like sulphur dioxide (SO₂), nitric oxide, and nitrogen dioxide (NO_x), and volatile organic compounds (VOCs) lead to either the nucleation of new particles or the condensational growth of existing particles [4, 5].

In the environment at the global scale, aerosols exhibit large spatiotemporal variability in their size distribution but generally represent approximately tri-modal size distribution [6-8]. An example of aerosol mode distribution is shown in Figure 1.1. The aerosol particle aerodynamic diameter (d_p) is less than 100 nm $(d_p < 100 nm)$ referred to as nanoparticles (ultrafine particles as a combination of nucleation $(d_p < 10 nm)$ and Aitken mode (10 nm < $d_p < 100 nm$); fine particle or accumulation mode (0.1 $\mu m < d_p < 1 \mu m$); and coarse mode particles (1 $\mu m < d_p < 10 \mu m$). However, aerosol size distribution modes can be shifted

based on the seasons, type of emissions, local meteorological conditions, and measurement location.



Figure 1.1 Sketch of aerosol size, number and mass distribution in the atmosphere and their primary associated sources. The blue line represents the aerosol number, and the red line represents the mass.

Nanoparticles (NPs) are a combination of both nucleation and Aitken modes. The nucleation mode results from the nucleation events of particle formation from precursor gases [9-11]. In contrast, Aitken mode results from condensation or self-coagulation of particles from nucleation mode, which are emitted from primary emissions during combustion [12, 13]. The nanoparticles contain the highest number but almost negligible mass compared to the total aerosol mass burden (Fig. 1.1). The accumulation mode particles typically result from the coagulation and aggregation of the nanoparticles [14, 15] and primarily play a part in cloud chemistry. Direct emissions from industries, biomass burning, fossil fuel combustion, and sea salt spray significantly contribute to fine particles [2, 4]. Coarse mode particles usually comprise road dust, soil or mineral dust, sea salt, plant debris, and volcanic erupted particles. Although the coarse mode particles rapidly settle down from the air due to their large mass, together with the accumulation mode, they make up most of the atmospheric aerosol mass [4, 5].

1.2 Importance of atmospheric aerosols

Aerosols are very complex. They are highly size distributed and undergo many chemical and physical processes that can cause them to evaporate, recondense, and alter their composition and surface characteristics. These complexities make it challenging to predict and model aerosol properties and assess their impact on air quality, adverse human health, climate, and atmospheric chemistry [16-19]. Depending on size and composition, aerosols can absorb and reflect solar radiation, which in turn impacts the Earth's radiative budget [18, 20]. Aerosols are also necessary for cloud formation as they play as cloud condensation nuclei (CCN) or ice nuclei (IN) [21-23].

Aerosol influences on air quality, health, and climate are interconnected (Fig. 1.2) due to the nature and complexity of aerosol sizes, chemical compositions, and their sources. For a complete understanding of all three effects, an understanding of the aerosol physicochemical processes and sources is needed.



Figure 1.2 Schematic of aerosol's relevance in the atmosphere and their impact on air quality, health, and climate change.

1.3 Sources, classification, and physicochemical characteristics of aerosols

Aerosol size distribution and their physicochemical characteristics vary regionally and globally [2, 5, 24]. Factors that significantly influence this variability are types of sources, meteorological conditions (temperature, wind, humidity, precipitation and boundary layer height), precursor gases for gas-to-particle conversion, and transport of pollutants and their wet and dry removal [25-28]. Chemical characterization is one of the most acceptable processes for identifying aerosol sources [3, 29]. The major challenge is that the aerosols are generally composed of a mixture of species from several sources, which makes it hard to pinpoint the exact sources [29-31].

1.3.1 Natural sources

Globally, natural aerosols dominate total aerosol mass loading in the atmosphere (Table 1.1). Mineral dust contributes a massive fraction of the primary aerosols from natural sources [5]. The desert, volcanic eruptions, oceans, and wildfires are the major natural emitters of aerosols in the atmosphere [1, 4]. The foremost dust regions include the Sahara Desert, Gobi Desert, and other deserts located around middle east Asia. These are configured in a chain of dust belts in arid areas extending over North Africa, South Africa, and high-altitude desert regions in South America [4, 8, 32]. In addition, dry lakes, lakebeds, and wet areas are also efficient sources of atmospheric dust particles [33] due to physical, mechanical, or chemical weathering and re-suspension of soil dust [34]. Dust mobilization occurs when the surface wind speed exceeds a threshold value, a function of surface roughness elements, grain size, soil moisture, and surface geological characteristics [34-36]. Human activities' disturbance of such surfaces enhances dust mobilization. Later, winds drives and mobilize the dust over long distances, like thousands of kilometres from their source areas [34, 36]. The annual emission flux of mineral dust made over the global scale varies from 10^3 to 5×10^3 Tg per year [5, 37]. The main chemical composition of mineral dust are Si, Ca, Fe, Al, Mg, K, and O, like road dust or Earth's crust elements [38, 39].

Globally, sea-salt aerosols are the second most abundant primary naturally emitted aerosol (Table 1.1), originating mainly from wind-swept saline water bodies such as oceans [40, 41]. The chemical compositions of sea-spray aerosols are salts; sodium chloride (NaCl), potassium chloride (KCl), calcium sulphate (CaSO₄), and ammonium sulphate ((NH₄)₂SO₄) and organics like fatty

acids covering the ocean surface (monolayer) [41, 42]. Sea-salt aerosols are the product of numerous physical processes, particularly by exploding entrained air bubbles to the sea surface during whitecap formation, which depends on wind speed [41, 43, 44]. Due to their high hygroscopic properties, sea-salt aerosols act as very efficient CCNs [20, 45-47].

Biogenic aerosols, which are solid and liquid particles released into the atmosphere from plants and animals, are another major natural aerosols [6]. They consist of plant debris, microbial particles such as living and dead viruses, bacterial cells, fungi, spores, pollen, algae, seeds, insects, humic matter, marine colloids, and pieces of animal skins [6, 48]. Due to their different origins, biological aerosol particles exhibit several shapes and vary in size from ~ 10 nm to ~ 300 μ m [49-51]. Bioaerosols comprise up to 1% of the total aerosol concentration in remote oceanic regions and typically around 2–3% in continental environments [52, 53]. However, it can reach up to ~25% in continental aerosol [54] and 35% in Amazonia [55], indicating the wide variations related to the source and particle type [6, 22, 56].

Table 1.1	Estimated emissions flux of the main types of primary and secondary aerosols in $Tg=10^{12}$
	g. Data obtained from Boucher, 2015 [5].

Type of aerosols	Natural sources	Anthropogenic sources		
Primary emission				
Mineral dust	1000-3000 Tg	40-130 Tg		
Seasalt	1000-6000 Tg			
Biomass burning aerosols	20-35 Tg	50-90 Tg		
Biogenic aerosols	Order of 1000 Tg	-		
Including bacteria	0.04-1.8 Tg	-		
Including spores	30 Tg	-		
Black carbon (from fossil fuel)	-	6-10 Tg		
Organic carbon (from fossil fuel)	-	20-30 Tg		
Secondary emission				
Dimethylsulphide (DMS)	20-40 Tg S	-		
Volcanic SO2	6-20 Tg S	-		
Terpenes	40-400 Tg	-		
SO2	-	70-90 Tg S		
VOCs	-	100-560 Tg C		
NOx	-	20-50 Tg N		
NH3	-	30-40 Tg N		

C: carbon, S: sulphur, N: nitrogen

Volcanic eruptions are major sources of both primary and secondary aerosols, including primarily dust/ash particles and sulphates aerosols (secondary) formed from gaseous sulphur into

the troposphere, even with moderate intensity [4]. Intense eruptions inject considerable amounts of sulphate aerosol and gases into the lower stratosphere [57]. These alter the atmospheric radiation budget and stratospheric chemistry, acting as IN and forming cirrus clouds [57-59]. Sulphate, nitrate, and organic matter are the main chemical compositions of naturally occurring secondary aerosols [39, 60, 61]. Two significant sulphate gaseous precursors are sulphur dioxide (SO₂) and dimethyl sulphide ((CH₃)₂S; DMS) from volcanic and biogenic sources, respectively. Nitrate aerosols are mainly formed by oxidizing nitrogen oxides (NO_x), which can occur naturally due to soil transpiration and atmospheric lightning [62, 63].

1.3.2 Anthropogenic sources

Anthropogenic aerosols are emitted into the atmosphere from various sources and consist of both primary particles occurring due to human activities such as energy production from fossil fuels, vehicular traffic exhaust and secondary particles formed from the gases emitted by urban, industrial, and also agricultural activities [4]. In indoor environments, cigarettes, cooking stoves, fireplaces, washing machines, dryers, and candles are the sources of aerosols other than the infiltrations of outdoor pollution [64]. However, we cannot underestimate the anthropogenic emissions from rural areas due to not having access to clean energy for cooking [65]. The estimated flux of anthropogenic aerosols is shown in Table 1.1.

The most significant anthropogenic sources in urban and industrial environments can be divided into four categories: (1) fossil fuel combustion, (2) industrial processes and activities, (3) nonindustrial sources such as road dust, construction, and wind erosion of cropland/crop residue burning etc., and (4) transportation activities with cars, ships, airplanes, incinerators, smelters, and power plants. Consequently, anthropogenic aerosols chemically contain sulphate, ammonium, nitrate, trace metals (rare earth metals), and carbonaceous material [1, 4]. Aerosols' carbonaceous component comprises elemental carbon (EC) and organic carbon (OC). The EC, black carbon (BC), graphitic carbon, or soot, is emitted directly into the atmosphere from predominantly combustion processes. OC can be emitted directly into the atmosphere from biomass burning and combustion processes or formed through atmospheric condensation of volatile organic compounds [66-68]. The total aerosol mass loading by anthropogenic sources is approximately 15-20% in the atmosphere, but their influence on the climate system is not precisely known [69-71].

1.3.3 Physical properties of aerosols

Understanding aerosols' physical and chemical characteristics are essential due to their interaction with the climate system and their impact on human health [3]. Aerosols exist in the atmosphere with wide size ranges and multi-phased morphologies [72, 73], and can be internally and externally mixed particles [2, 27]. If the aerosol particles arise from multiple sources and have different chemical compositions, they are externally mixed aerosol. While internally mixed particles are a uniform mixture of components [1, 3]. The number, concentration, size, shape, phase, and morphology of aerosol particles are the main physical properties of consideration. Particle size and shape can affect its surface, aerodynamic behaviour, and optical properties such as single scattering albedo and absorption cross section that are important to climate [74] and human anatomy [75]. Aerosol particles usually have variable shapes, including aggregate, fractal, and chain-like, and exist in both amorphous and crystalline states [1, 2]. Generally, aerosol concentration is mainly reported in terms of mass or number of particles in a unit volume of sampling air. The standard units of aerosol mass concentration [76] are $\mu g/m^3$, and for number concentration [72] is $\#/cm^3$.

1.3.4 Chemical properties of aerosols

Understanding the chemical composition of aerosols is useful in identifying their sources of origin and foreseeing their effect on various complex atmospheric processes. Aerosols emitted from combustion processes contain thousands of organic/inorganic compounds such as black and brown carbon, heavy metals, cations, anions, and salts aerosols [1, 4]. Organic aerosol (OA) matter typically contains semi-volatile material that can partition between the gas-liquid-solid phases, a process controlled by dynamic equilibrium or interfacial mass transfer [66-68]. Volatile and semi-volatile organic compounds can undergo photooxidation in the atmosphere and further form secondary particles, which grow via condensation [66-68]. Although organic compounds typically compose 10 - 70% of the total dry mass of the fine particle in the atmosphere [77], their concentration variations, composition and physical processes involved in their formation and transformation in the atmosphere are not very well understood [78, 79].

Sulphates, nitrates, and organic are the main chemical constituents of secondary aerosols from anthropogenic sources. A large portion of SO₂, precursor gas of sulphate aerosols, originates
from coal combustion, industrial activities, and vehicular traffic. The oxidation of SO₂ produces sulphuric acid (H₂SO₄), which is later neutralized by the formation of ammonium products such as (NH₄HSO₄, (NH₄)₂SO₄). Gaseous nitric acid (HNO₃) is formed by the oxidation of NO_x and can be transformed into particulate nitrate [3, 5, 80]. Most NO_x gases are emitted into the atmosphere by traffic [81]. Atmospheric chloride particles enter the atmosphere due to ammonia-neutralizing hydrochloric acid (HCl) vapour emitted from incinerators and power stations. However, the primary source of chlorides is natural sea spray, even at locations that are hundreds of kilometres away from the coast [82-84]. The diverse chemical and physical processes of aerosols generate distinct particle morphologies and nano/micro-structures that are heterogeneous in composition. This, in turn, affects the optical properties, aerodynamic nature, transport and removal of aerosols [3, 30]. Determination of the chemical composition of size-distributed aerosols requires various advanced analytical measurement techniques. Both field and laboratory-based instrumentation are needed to characterize such complexity (Section 1.8).

1.4 Health effects and regulation of aerosols (PM_{2.5})

Since at least the 1990s, health studies have shown that particulate matter (PM) has caused cardiopulmonary disease, increasing mortality and morbidity [85-87]. In 2005, the WHO issued a global update arguing for implementing the air quality standard guidelines worldwide and expressing concern for the public health threat posed by increased air pollution, particularly exposure to aerosols [85]. Aerosols are the leading environmental risk factor worldwide and cause almost ~5 million deaths [19]. The burden of disease caused by air pollution was in the top five out of 87 risk factors in a recent global health assessment and comparable to other major global health risk factors such as unhealthy diet and smoking [88].

It has become evident that PM_{2.5} is associated with several health issues, like mortality, acute lower respiratory infections, chronic obstructive pulmonary disease, ischaemic heart disease, lung cancer, and stroke [89]. PM_{2.5} can penetrate the respiratory system by inhaling through the mouth or nose and is likely to trigger respiratory or cardiovascular disease [85, 90]. They can also interact with the human body through dermal contact and cause eye irritation and skin-related health problems. The health impact caused by inhaled PM particles depends on their size, phase, shape, concentration, chemical compositions, and the active site at which they are deposited within

the respiratory system [75, 91]. Aerosol trace metal components, such as zinc, copper, cadmium, mercury, nickel, lead, etc., in the $PM_{2.5}$ fraction are of concern for their potential impact on human health and ecological systems [92, 93]. Studies have suggested that trace metals can catalyze the formation of lung oxidants, which can cause tissue damage. Mineral dust and wildfire smoke also cause severe human respiratory health issues [19, 93].

1.4.1 Global regulatory measures of PM_{2.5} standards

In 2015, \sim 5 million global premature mortality deaths per year were caused by PM_{2.5} alone [76, 94]. During 2010, China was leading the premature deaths with around 1.33 million, followed by India with 575 thousand and Pakistan with 105 thousand by PM_{2.5} [76, 95]. The 28 European Union (EU) member countries had 173 thousand, and the United States reported 52 thousand premature deaths in 2010 [95]. In 2016, an assessment projected that if the world implements the $PM_{2.5}$ EU annual mean standard concentration of 25 μ g/m³, global premature mortality could drop up to 17%. If the revised US PM_{2.5} concentration of 12 μ g/m³ were implemented worldwide, premature mortality could drop by 46 % globally; 4 % in the US, 20 % in the EU, 69 % in China, 49 % in India, and 36 % in Pakistan [95]. The ultimate challenge for policymakers or regulators is implementing harmonized PM2.5 regulations worldwide. Exposure to PM2.5 heavily depends on PM_{2.5} concentrations, which vary substantially from country to country and within regions and seasons [72, 73, 76, 81]. Almost 90% of the global population in 2019 lived in areas where PM_{2.5} concentrations exceeded the WHO PM_{2.5} standard limit of 10 µg/m³ [19]. Among all countries with standards for 24-hour averaging times for PM_{2.5}, only 21% met the air quality standard guidelines [19, 76], and only seven countries (2%) embraced the WHO annual mean air quality guidelines for $PM_{2.5}$ [19, 76].

Nazarenko *et al.*, 2021 (co-authored paper, [76]) studied PM_{2.5} ambient concentration standards from 62 jurisdictions in 58 countries (Fig. 1.3). The study found that 136.06 million km² of land covered under national jurisdictions and 71.70 million km² (52.7%) lacked an official PM_{2.5} air quality standard shown in Figure 1.3. The current PM_{2.5} standards range from 8 to 75 μ g/m³, which is mostly higher than the WHO annual limit of < 10 μ g/m³. While 3.17 billion people live in areas without PM_{2.5} standard measures (Fig. 1.3).



Figure 1.3 PM_{2.5} standards worldwide. (a) Population and the total area covered by different annual PM_{2.5} ambient air quality standards worldwide, and (b) Annual ambient PM_{2.5} air quality standards worldwide. The data and plot have been adopted from Nazarenko *et al.*, 2021 (Co-authored paper).

A current problem with worldwide $PM_{2.5}$ standards is that different countries or jurisdictions have different time intervals over which they average the observed $PM_{2.5}$ concentrations, such as 20 minutes, 24 hours, annually, and three-year periods. Besides, there is uncertainty in reporting the $PM_{2.5}$ standards values based on countries that used the 98th or 99th percentile, and some used the arithmetic mean of all $PM_{2.5}$ measurements over a prescribed period. For example, the annual arithmetic means were calculated in the USA for the annual $PM_{2.5}$

standard, and the 98th percentile was used for 24-hour arithmetic means standards of concentrations over 3 years. The Russian Federation used the 99th percentile of 24-hour arithmetic means of concentrations over 1 year. The EU countries used a 3-year running annual mean $PM_{2.5}$ concentration averaged over selected monitoring stations in urban areas [76]. China used different $PM_{2.5}$ standards for the first-class (residential) and the second-class (commercial) zones. Both the annual and the 24-hour standards differed substantially for the two zones: 15 µg/m³ annual and 35 µg/m³ 24-hour for the first-class zones and 35 µg/m³ annual and 75 µg/m³ 24-hour for the second-class zones. In the Eastern Mediterranean Region, only Egypt, Pakistan, and Saudi Arabia had $PM_{2.5}$ standards [96, 97]. At the same time, South Africa was the only African region with a $PM_{2.5}$ standard (Fig. 1.3).

Standards and air quality monitoring data cannot be accurately compared between jurisdictions when data collection and processing methods are different [76]. The differences in these metrics (averaging periods, exceedances, and percentiles) result in potential discrepancies between PM_{2.5} ambient air pollution levels and standards [76]. Currently, there are no universal set of metrics used in PM_{2.5} ambient air quality standards that would ensure the comparability of monitoring data globally [76]. Without a universal metric, the same absolute PM_{2.5} mass concentration limit can permit different levels of PM_{2.5} pollution and create a challenge for health risk assessment studies, where the differences in metrics can introduce errors [76].

1.4.2 Regulation of nanoparticles (ultrafine particles)

The airborne particles with a diameter less than or equal to 100 nm are called nanoparticles or ultrafine particles [98]. Nanoparticles are tiny particles with very little mass compared to $PM_{2.5}$ (Fig. 1.4). Their concentrations are most commonly measured and expressed in terms of particle number concentration per unit volume of air [1]. The nanoparticles are emitted into the environment through combustion, fossil fuel, vehicles and other forms of transportation (aviation and shipping), industrial and power plants, cooking, washing/drying clothes and residential heating [1]. The major problem of nanoparticle measurements is the instrumental uncertainty based on the standardized methodology that varies up to 30% for lower concentrations. At the same time, instruments are also limited to higher concentrations [24, 99]. Most of the studies report the number concentration of nanoparticles [24, 72] while lacking information on nanoparticle

physicochemical properties such as phases (solid/liquid), compositions (e.g. organic carbon/elemental carbon, metals), and their toxicity.

No evidence supports controlling PM_{2.5} will necessarily lead to a nanoparticle reduction [99]. Very little or no relationship exists between nanoparticles number concentration and PM_{2.5} concentration. Thus, the nanoparticles and PM_{2.5} matrix can not be treated as a single matrix in the atmosphere. The quantitative knowledge of nanoparticles is needed since focusing only on PM_{2.5} may result in overlooking the impact of nanoparticles number concentration. Growing evidence suggests that short-term exposure to nanoparticles affects respiratory systems and pulmonary/systemic inflammation, heart rate variability, and blood pressure [100]. Also, evidence indicates that long-term exposure to nanoparticles is linked to mortality (all-cause, cardiovascular, and pulmonary) and several types of morbidity [99-101].



Figure 1.4 Airborne nanoparticles and PM_{2.5} in the rue University, McGill University, cold climate city of Montreal. (a) Time series of hourly average nanoparticles and PM_{2.5}. The green line represents the threshold of considered nanoparticles exposure in the ambient atmosphere, and the gray line is a PM_{2.5} standard by WHO. (b) direct correlation between nanoparticles and PM_{2.5}. The data used in panels (a-b) was obtained from Pat *et al.* (2021). (c) Total average particle number concentration (PNC) in multiple worldwide cities in different time periods. The blue and green lines represent the considered WHO nanoparticle exposure in the ambient atmosphere. (This Figure is part of the manuscript by Pal *et al.* (2023), which

will be submitted to the Bulletin of the World Health Organization). The blue and green lines correspond to 24 hr and 1 hr mean concentration thresholds, respectively.

Continuous nanoparticle monitoring will provide additional information for evaluating the effects of pollution. It could be used in studies of the health effects of nanoparticles and to distinguish these effects from the impact of other pollutants. It will also allow us to see the human health benefits of changing an air quality policy or applying a more stringent standard. Note that nanoparticle measurements should not hinder the existing measures of air pollutants for which guidelines currently exist. A global data bank for nanoparticles is also required to study the full-scale public health burden associated with current levels of air pollution. In 2021, a WHO report mentioned that nanoparticle exposure guidelines in the environment could be considered 10 000 particles/cm³ for a 24-hour mean and 20 000 particles/cm³ for a 1-hour mean [19]. Though, none of the jurisdictions have any standard guidelines for nanoparticles.

Here we show a case study for 2-year long-term data (Rue University, McGill University) set for aerosol size ranging from 10 nm to 10 μ m for a clean cold climate city of Montreal [72]. The aerosol size number concentration is converted into $PM_{2.5}$ metrics, and their direct correlation is estimated and shown in Figure 1.4 (a-b). The results suggest no direct correlation between nanoparticles and PM_{2.5}, indicating that both metrics must be treated separately. As shown in Figure 1.4(a), hourly nanoparticle concentration exceeds the recommended WHO exposure nanoparticle concentration (20 000 particles/cm³1-hour mean) for several hours each day. Several studies worldwide observed the total particle number concentration in different periods and geographical locations (Fig. 1.4 (c)). As a snapshot, nanoparticle concentration data were obtained from published studies [102, 103]. We assumed that total particle number concentration (PNC) was almost equivalent to nanoparticle number concentration [72] and generated the graph of nanoparticle data taken from different cities and their respective countries (Fig. 1.4 (c)). Please note that the PNC data was not consistent in the measurement environment and their duration of observation (we used this data as a snapshot to show why nanoparticles should be considered differently than $PM_{2.5}$). In Figure 1.4 (c), PNC was observed in 80 cities in 25 countries covering Asia, Europe, North America, South America, and Australia. The preliminary analysis suggested that most cities' average PNC exceeded the WHO limit (Fig. 1.4 (c)). Thus, we recommend designing a proper global data acquisition system for nanoparticle number density, and policymakers should rethink to regulate them in future. However, some jurisdictions, particularly

in Europe, are starting to implement monitoring programs in preparation for implementation of likely future regulations of particle number concentration. There is no concrete protocol or regulation for monitoring nanoparticles anywhere in the world yet. However, the EU has a vehicle emissions regulator body adapted to control particle number concentration based on EURO 6 vehicle emission standard set at 6×10^{11} particles/km travelled.

1.5 Role of aerosols in climate

The uncertainty in climate due to aerosols depends on their spatial and temporal distribution, hygroscopicity, optical properties, and abilities of aerosols to act as CCN and IN [18]. The particle number size distribution, chemical composition, mixing state, and morphology are fundamental for aerosol optical and cloud-forming properties [104]. The Intergovernmental Panel on Climate Change (IPCC) assessment has conducted that the emissions of greenhouse gases (GHGs) and aerosols due to anthropogenic activities continue to alter atmospheric processes, and their impacts are influencing the climate [17, 18, 104-106]. Anthropogenic aerosols have cooled global surface temperatures up to 0.8 °C over the last century [17, 106]. Aerosols are somewhat masking global warming and are one of the main sources of uncertainty in understanding humandriven impacts on present-day climate [18, 106]. Aerosols absorb and scatter incoming solar radiation and outgoing terrestrial infrared radiation (direct radiative forcing). Aerosols act as CCN or IN in cloud and precipitation formation, thus altering the indirect radiative forcing of climate [106]. The direct and indirect effects of aerosols influence the radiative transfer in the atmosphere, thus changing the Earth's radiative budget [106, 107] and climate. Both direct and indirect Earth's radiative forcing by aerosols has been accepted in the last two decades as having great importance for understanding climate change [105, 106, 108]. The radiative forcing component from aerosols and GHS are shown in Figure 1.5.

1.5.1 Direct radiative effect/Scattering-absorption effect

The IPCC reports indicating aerosols have had a negative impact on the Earth's radiative forcing (ERF) of around -1.3 (-2.0 to -0.6) W/m² between the years 1750 and 2014, with medium confidence [106, 109]. The most significant factor contributing to ERF (high confidence) is the interaction between aerosols and clouds (ERFaci), which is estimated to be around -1.0 (-1.7 to - 0.3) W/m², with medium confidence. The remaining impact is due to aerosol-radiation interactions

(ERFari), which are estimated to be around -0.3 (-0.6 to 0.0) W/m², with medium confidence [106, 109]. The overall negative impact of aerosols on ERF has increased since the AR5 assessment [110], but there is now less uncertainty around this estimate due to an increased understanding of the processes involved and better modelling and observational analyses [109]. The estimates from different sources of evidence are now in agreement, and the total aerosol ERF is likely negative. The impact of aerosol-cloud interactions has increased, while the impact of aerosol-radiation interactions has decreased compared to the AR5 assessment [106, 109, 110]. Though, the radiative forcing of greenhouse gases is substantially stable spatially and temporally uniform (Fig. 1.5).

The radiative forcing component by individual aerosols is given in Figure 1.5. Most aerosols either scatter or absorb the radiation, frequently coexisting in the atmosphere, making the radiative forcing more complicated and uncertain. The aerosols such as sulphate, nitrate, and sea salt scatter the solar radiation in the atmosphere [111], meaning changing the direction [112]. As a result, their scattering effect is most potent for shortwave radiation and negligible for longwave radiation, except for some large dust particles [113]. The scattering process of aerosols sends a fraction of solar radiation back to space, cooling the climate system. Yet, high surface albedo and the presence of clouds tend to reduce the net effect [114, 115].

BC aerosols absorb the radiation [116], causing atmospheric warming, which means positive radiative forcing [5, 117]. The atmospheric heating occurs higher in the atmosphere [118], which increases atmospheric stability. It slows the hydrological cycle [104, 108, 115, 118] and may induce positive feedback of aerosol climate effects by decreasing aerosol wet deposition. Non-absorbing aerosol (sulphate, OA nitrate) coating on an absorbing core such as soot (BC) increases the absorption properties by ~ 2 times, depending on the structure and morphology of the mixed aerosols [119, 120]. At the same time, during the vertical distribution, the organic coating on the hygroscopic core, such as sulphate/nitrate, decreases the rate of water uptake of particles. Overall, aerosol complexity and their mixing properties result in a combined direct forcing that may differ from the direct forcing of individual aerosols [121]. The negative radiative forcing component was calculated for sea-spray aerosol from the range - 0.6 to -2.0 W/m² for low wind speed and -1.5 to -4 W/m² during the high wind speed case [122]. Mineral dust is still a mystery because it can warm and cool the climate due to its composition/mineralogy, concentration, particle size, albedo, and temperature of the underlying surfaces [115, 118, 122].



Figure 1.5 Summary of radiative forcing by atmospheric drivers and emissions from preindustrial. Contribution to (a) effective radiative forcing (ERF) and (b) global surface temperature change from component emissions for 1750 - 2019 based on Coupled Model Intercomparison Project Phase 6 (CMIP6) models and (c) net aerosol ERF for 1750 - 2014 from different lines of evidence. The intent of this is to show advances since AR5 in the understanding of (a) emissions-based ERF, (b) global surface temperature response for short-lived climate forcers, and (c) aerosol ERF from different lines of evidence. The figure was adopted from the Technical Summary (TS 15) of Climate Change 2021: The Physical Science Basis [106, 109].

1.5.2 Indirect radiative effect/Aerosol-cloud interaction

Atmospheric aerosols serve as CCNs and alter cloud microphysics [104]. The effective CCNs in the atmosphere are water-soluble aerosols such as sulphate, nitrate, sea salt, and secondary organic aerosols. In contrast, insoluble aerosols, like dust and organic aerosols (high BC content), are critical players in aerosol-cloud interaction [108]. An increase in CCN

concentration leads to a rise in smaller cloud droplets that take longer to precipitate, thereby increasing the cloud reflectivity and cloud lifetime, resulting in a cooling effect [18, 123]. The smaller cloud droplets quickly evaporate, which enhances the mixing of clouds with dry air and reduces the liquid water path (LWP), causing a warming effect [117, 124]. Overall, the aerosol-cloud interaction cooling effect at the surface (negative radiative forcing) is relatively higher.

Aerosols also act as INPs and impact ice and mixed-phase clouds, notably in the case of intermediate-absorbing species of dust and organic aerosols [125-127]. Absorbing aerosols can interact with clouds and heat the atmosphere, resulting in clouds' evaporation [126]. The aerosol-ice-cloud interaction processes are very complex because of the competition between homogeneous freezing from liquid-phase particles and heterogeneous freezing by INPs [128, 129]. For example, adding INPs into ice clouds followed by a heterogeneous path leads to an increase in ice crystals, which possibly causes a warming effect. Alternatively, if the cloud process is dominated by homogeneous freezing, adding INPs decreases the ice cloud's optical depth and potentially induces a cooling effect (mostly cirrus) [114, 130]. Both global and regional models have shown that the INPs influence the current and future Earth's climate [108, 129, 131-133]. For example, in remote areas such as the Southern Ocean, the overestimation of INPs foresees a rapid glaciation and removal of clouds, leading to warm biases in surface temperatures [133].

1.5.3 Ice formation in the atmosphere: role of aerosols

Without clouds, we cannot think of having life on Earth. Clouds are essential for producing fresh water that human-ecological life relies on. Clouds are aggregates of tiny water droplets and/or ice crystals and are the most uncertain components of the Earth's climate [110]. Global climate models involve significant uncertainties in their predictions because the microphysical processes occurring in these clouds are not well represented by these models [114, 134, 135], especially for the ice clouds. The formation of ice crystals in the Earth's atmosphere involves complex processes that primarily depend on the ambient temperature, supersaturation with respect to ice (Si), and aerosols [21, 128]. Due to the importance of ice formation in the atmosphere, ice nucleation studies have been ongoing since the early 1950s [136]. Recently, several fundamental theories and advances in technology have been established. Yet the physicochemical properties that make aerosol particles efficient INPs and the variability in INP concentrations remain uncertain [6, 21,

128, 137]. Ice nucleation in the atmosphere can either happen through 1) homogeneous freezing of water cloud droplets or 2) through heterogeneous freezing in the presence of INPs. INPs affect the formation and determination of mixed-phase and cirrus clouds [128, 130]. Only a small fraction (fewer than 1 in 1000) of ambient particles participate in the ice nucleation process [128, 130]. Homogeneous ice nucleation requires a high supersaturation ($S_i \ge 1.4$) with respect to ice and low temperature (T < 235 K) without the presence of any foreign particles [138]. Heterogeneous ice nucleation is initiated by the presence of INPs [21, 129, 137-141]. It follows one of the four modes of the ice nucleation process via deposition nucleation, immersion freezing, condensation freezing, or contact freezing, as shown in Figure 1.6.



- **Figure 1.6** Schematic of the ice nucleation processes in the atmosphere as a function of ice saturation Si (RHi/100), and temperature T. The solid slope line represents saturation with respect to water and the solid horizontal line with respect to ice. The dashed sloped line is the homogeneous freezing line of solution droplets (Koop *et al.*, 2000). The plot was adapted from Hoose and Mohler[137].
 - **Deposition nucleation:** An ice nucleation process in which supersaturated water vapor nucleates on the INPs surface directly from the gaseous to the solid state is known as deposition nucleation [138].
 - **Immersion freezing:** Immersion freezing is triggered by an INP which is already immersed in the droplet [138].

- **Condensation freezing:** Condensation freezing occurs at supersaturation with respect to liquid water and a temperature below the melting point of water. Here, an aerosol particle acts as a cloud condensation nuclei (CCN) and directly triggers the freezing of the condensing water [138].
- **Contact freezing:** Contact freezing describes the ice formation process where the collision of an INP with a supercooled water droplet initiates freezing, which starts from the contact point [138].

To evaluate the impact of ice nucleation processes in the atmosphere, it is crucial to recognize the role of INPs in cloud formation [128, 129]. Therefore, INP formation has been studied both in the field and under controlled laboratory experiments [23, 127, 140, 142]. The recent reviews are focused on many laboratory studies to assess the ice nucleation ability of selected size (> 0.5μ m) and the composition of aerosols, such as soot particles, mineral dust, and biological particles [21, 137, 143, 144]. In contrast, earlier heterogeneous ice nucleation parameterizations did not include aerosols-specific dependencies in cloud-resolving models to global climate models [132, 145]. Nowadays, the results of ice nucleation due to the aerosols are often used in atmospheric models on different scales, from regional to global climate models [129, 134, 146-149]. Almost no study or measurement of nanosized ice nuclei in the atmosphere exists either computationally or in laboratory or field experiments. Also, distinguishing supercooled water droplets from ice crystals in clouds is an ongoing challenge in the mixed-phase cloud regime that requires better observational techniques.

1.6 Air quality and aerosols in an urban cold climate

The abundance, structure, and dynamics of aerosols impacted by snow and ice interfaces are expected to be different than in the air, where snow is not present [150]. In a cold environment, snow/ice crystals and the liquid water phase of the snowpack provide a large surface area and a medium for physical transformations and chemical reactions of air pollutants [151]. However, snow precipitation scavenges the air pollutants in the atmosphere but results in impurities directly interacting with the snowflake surface through adsorption processes [152, 153]. The enhanced partitioning of gas-phase chemicals to the snow surface at cold temperatures makes snow an excellent scavenger of semi-volatile organic chemicals from the atmospheric gas phase [72, 151]. Snow can be an efficient scavenger for contaminants; a large snow cover during winter provides a

substantial exchange of organic chemicals between snow and the atmosphere affecting atmospheric chemistry in cold climatic conditions [154]. A recent laboratory study confirmed that the aerosol size distribution and their chemistry were different in-vehicle exhaust-exposed snow than in cold ambient air [23, 153, 155]. During winter in cold climates, the chemical reaction between aerosols and NO_x/SO_x , O_3 , and VOCs happens along with temperature inversions, when warm air aloft traps cold air below, concentrating pollutants and creating favourable conditions for fog/smog [156]. Air pollutant concentration increases in two ways. The first is the most obvious when the air volume remains constant, but the amount of pollutants increases in the atmosphere[112]. The second process is complex and mainly happens during winter because suppression of the boundary layer height enhances the concentration of pollutants even having the same emission sources throughout the years [112]. This mixing in cold climate cities becomes more hazardous to health, visibility and frequent haze/smog episodes[112, 157].

In the presence of snow/ice surfaces, the air-surface exchange processes can dramatically influence near-surface air quality due to temperature inversion and suppression of the atmospheric boundary layer height [150]. In cold climatic conditions, the winter air quality often becomes hazardous, and it is crucial to understand the reduction and formulation mechanism of vehicle exhaust particulates and the optimization of engines or the urban green environment.

1.7 Are aerosols good or bad for the global economy?

Aerosols, directly and indirectly, impact economics, which is still an extremely niche area. Several countries worldwide have started implementing their GHG reduction targets under the Paris climate agreement; thus, the co-emissions of aerosols and their precursors will also change [158]. Subsequently, the co-emissions of aerosols vary from country to country, and by economic sector, each country will face different trade-offs between aerosol-driven health or temperature co-benefits. The 21st century is the era of modern technology, where the world faces climate/global warming and frequent natural disasters each year. These tiny mysterious aerosol particles affect the global economy collectively, mainly in three ways.

(1) Economic burden by health issues: Aerosols significantly damage global economies due to the cost of adverse health effects. These are due to increased healthcare costs due to enhanced incidence of diseases such as cardiovascular, respiratory disease, cancers and mortality [19].

These health issues are enormous and lead to correspondingly large economic damages. Organization for Economic Co-operation and Development (OECD) estimated that the financial burden due to outdoor air pollution in OECD countries (including deaths and illnesses) was USD 1.7 trillion in 2010. In comparison, China faced an economic burden due to aerosol pollution to be around USD 1.4 trillion and USD 0.5 trillion in India. A recent study estimated that aerosol pollution shortened life expectancy by ~0.64 yr for each 10 μ g/m³ increase in concentration [159]. A second economic impact of aerosols is through lost labour productivity: In 2013, the World Bank estimated a global economic impact of USD 143 billion due to lost labour income and USD 3.55 trillion in welfare payments resulting from exposure to PM_{2.5} [160]. Besides the health-related burden, air pollution causes additional economic costs, such as its impact on crops or damage to buildings and infrastructure. In addition, there are costs associated with air pollution-related climate change and environmental degradation.

- (2) Economic impact by changing climate: Changing climate and global warming are expected to affect economies by influencing labour productivity, crop yields, and more extended extreme weather events, which majorly damage regional infrastructure, thus, economies [161, 162]. Aerosols are known to have uncertainty in climate projection and are somewhat masking greenhouse gas-induced warming. A recent case study performed climate simulations and projected results suggesting that with an anthropogenic aerosol emissions scenario, anthropogenic aerosols caused the cooling of the Earth by 0.72 ± 0.02 °C comparative to a case without anthropogenic aerosols emissions [163]. Considering this baseline of temperature change by aerosol cooling, it was estimated that countries in tropical and subtropical regions benefit, with the highest economic benefits observed over the Arabian Peninsula and South Asia. They pointed out that 109 countries (65%), encompassing about 21% of the global Gross Domestic Product (GDP) and 59% of the worldwide population, exhibit very likely positive economic impacts from aerosol-induced cooling [161, 163, 164]. In contrast, in higher latitudes regions, 30 countries (18%), encompassing about 21% of the global GDP and 8% of the global population, exhibit likely negative economic impacts due to aerosols inducing cooling [161, 163, 164]. Note that high-latitude regions could benefit economically from warmer temperatures, even if those warming substantially disrupted natural systems [165, 166].
- (3) **Economic impact due to aerosol attenuation:** Atmospheric aerosols are a massive obstacle to efficient solar energy production due to the aerosol's attenuation effect. Additionally,

aerosols often get dry deposited on the surface of solar panels and affect their photovoltaic (PV) performances, termed the 'soiling effect' [160, 167]. Due to the aerosol's attenuation and soiling effect, India alone faces an average loss of 12% (horizontal) to 41% (dual) in solar energy across the country, and this loss costs approximately 245–835 million USD annually [168]. At the same time, China experienced a loss of ~ 10 - 34% in PV potential between 1960 and 2015 [169, 170]. Recently, a global study estimated a more than 50% reduction in solar power by aerosols over highly polluted regions like northern India, northern China, and global desert regions [167]. Recent studies estimated the loss in revenue to the economy above 20 million USD just losing solar energy due to pollution in New Delhi. While the estimated damage in Kolkata is 16 million dollars, China faces an annual loss in revenue of around 10 million USD for Beijing and 9 million USD for Shanghai [171-173]. However, cities like Los Angeles, where air quality is better, still face notable economic damage [173, 174]. These numbers indicate that global losses in revenue could quickly sum up to hundreds of millions, if not billions, of dollars annually.

It is fair to say that even due to opposing economic impacts in different regions, the net economic effects of aerosol-induced cooling are likely to be small on a global scale. However, aerosols pose severe threats to air quality and public health. Therefore, international efforts must continue reducing aerosol emissions to protect public health and improve urban air quality in the future.

1.8 Aerosol measurement methods

Atmospheric aerosol size, shape, and chemical characteristics vary by orders of magnitude; thus, not a single instrument or technique can complete the physicochemical characterization of aerosols. Hence, the choice of an aerosol measurement technique/method solely depends on the application type and scientific research questions. Aerosol measurements can be divided into four categories 1) surface in situ, 2) surface-based remote sensing, 3) space-borne remote sensing, and 4) airborne (aircraft, balloons) in situ or remote sensing categories.

In situ aerosol measurement techniques require ambient air sampling. They can accurately measure the mass concentration, chemical composition, shape, mixing, scattering and/or absorbing properties, hygroscopicity, and particle size distribution that determine the efficiency of CCN and

INPs [5, 104, 175]. When similar or slightly modified instruments are deployed on aircraft or tethered balloons, the vertical distribution of aerosols can be measured [176]. It is essential to consider that the high accuracy and comprehensiveness of in situ measurements often serve as benchmarks for remote-sensing observation and model simulations [177, 178]. Figure 1.7 describes the detailed information for aerosol measurement techniques. Multiple methods are used to cover the aerosol physicochemical characteristics in real-time and offline.



Figure 1.7 Schematic of aerosol measurement methods.

1.8.1 Laboratory-based aerosol measurement techniques

In a brief overview, real-time and offline techniques are used to study aerosol particles in the field and in laboratories. Generally, differential mobility analyzers (DMAs) or electrostatic classifiers are used to measure the smaller particles (2 - 1000 nm). DMAs classify airborne particles according to their electrical mobility, which depends on particle charge, gas properties and the geometric particle size but is independent of the density of the particle [1, 179]. Several DMA-based commercial instruments are available in the market, namely Scanning Mobility Particle Sizer (SMPS), and Differential Mobility Particle Sizer (DMPS) [179]. The measurement of larger particles, from submicron to several tens of microns in diameter, was measured based on optical analyzers. They are commercially available, and Optical Particle Sizer (OPS) and Optical Particle Counter (OPC) are among the favourite ones. The basic principle of optical particle counters is to measure the amount of light scattered by individual particles as they traverse a tightly focused beam of light. A fraction of the scattered light is directed to a photodetector and converted to a voltage pulse. Particle size is determined from the magnitude of this voltage pulse by using a calibration curve usually obtained from measurements using spherical particles of known dimensions and refractive index [1, 179]. A disadvantage of light-scattering and electric mobility instruments is that they can provide the particle surfaces and volume but fail to provide real-time shape, refractive index, and morphology. The aerodynamic particle sizers (APSs) are another method of simultaneously counting and sizing particles. As an aerosol rapidly accelerates through a nozzle into a partially evacuated chamber, particles tend to lag behind the carrier gas due to inertia [1, 179]. Aerodynamic particle size is inferred from particle velocity, which is determined by measuring the time of flight the particle takes to travel a known distance. Unlike optical counters, which determine particle size from the intensity of the scattered light, aerodynamic particle sizers use the scattered light to detect particles at both ends of the flight distance. The smallest reported size that can be measured with these instruments varies with instrument design and ranges from 0.2 - 0.5 µm in diameter. The condensation particle counter (CPC) is traditionally used to measure the total aerosol number concentration.

Measurements of aerosol mass concentrations are vital for regulating PM_{2.5} and PM₁₀ standards to protect public health [19, 93]. The most common methods/techniques to measure aerosol mass concentrations are collecting air samples on filters [179, 180] and weighing them under control temperature and humidity conditions [179]. The significant issues with these techniques are unavoidable factors such as adsorption/desorption of water and reactive species, particle loss associated with the air sampling period [179], and operating cost. During past decades, commercial instruments such as (Beta Attenuation Mass) BAM monitors and Tapered Element Oscillating Microbalances (TOEM) have been available for online measurement of PM_{2.5} and PM₁₀ [1, 179]. These instruments have a significant advantage over filter sample gravimetric techniques due to real-time data delivery with high resolution. Beta gauges measure the attenuation of β -radiation through an aerosol particle-laden filter, and the degree of attenuation is proportional to the entire sample mass. TEOM is a tapered tube with a narrow-wide end. The aerosol particles are collected by

impaction on a replaceable filter mounted on the narrow end of the tapered tube, free to oscillate. These changes in the tube oscillations are measured and related to the mass of the aerosol sample.

The most common methods for size-distributed chemical characterization of aerosols typically involve offline techniques, which require the collection of aerosol particles on substrate/filters using impactors (Fig. 1.7). The collected aerosol samples are then dissolved or digested in water or acids in the laboratory, and the extracted sample chemically analyzed using several analytical techniques. These techniques include: atomic absorption, Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), high-performance liquid chromatography (HPLC), gas chromatography (GC), ion chromatography (IC), proton nuclear magnetic resonance (HNMR), secondary ion mass spectrometry (SIMS), inductively coupled plasma mass spectrometry (ICPES or MS), and laser microprobe mass spectrometry [1, 179, 180]. Although impactors and filters are one of the standard methods to collect aerosol samples for chemical analysis, there are drawbacks. They require long sampling periods, which precludes observing short-time chemical changes in the atmosphere. During analysis at the laboratory, the offline analysis methods suffer from possible contamination during analytical procedures and sample handling, time consumption, and possible decomposition of labile compounds during analysis. Consequently, moving toward online aerosol chemical composition measurements is desirable whenever possible.

In-situ real-time monitoring techniques for analyzing aerosol chemical composition increase sample frequency and decrease operating costs. The aerosol mass spectrometer (AMS) measures the real-time selective size and chemical mass loading for non-refractory constitute (ammonium, total nitrate, total sulphate, total organics, and non-sea-salt chloride) in sub-micron aerosol particles [181-186]. However, AMS alone cannot provide all atmospheric chemical species information. Aethalometer and Photoacoustic Extinctionometer (PAX) are online instruments to measure BC concentration in ambient air based on light absorption/scattering [187, 188]. The carbonaceous aerosol generally contains hundreds of mixed compounds, so instruments usually report the total carbon. This total carbon is often fractionated into OC and EC. Thermal-optical analysis (TOA) has been widely used to determine total aerosol carbon and its components OC and EC [189]. The basic principle of these thermal-optical techniques is that organic carbon is volatilized when the sample is heated without oxygen. At the same time, oxygen is required for

the combustion of elemental carbon [179, 190]. In thermal-based techniques, the sample is generally heated in a temperature-programmed chamber in the presence of one or more gases (He, N_2). OC is quantified under a heating cycle in either He or N_2 . EC is quantified as the fraction of the same sample gas mixture containing mainly oxygen, which is subsequently quantified by an IR or a flame ionization detector (FID). The lack of standards for OC/EC analysis suitable for ambient measurements is a disadvantage of these methods. Flame photometric detectors (FPD) are commonly used techniques for in situ measurements of particulate sulphate concentrations [179, 190, 191]. Inductively coupled plasma mass spectrometers (ICP-MS) are the most common technique at present for real-time measurements of particulate metal concentrations in ambient air [72, 192-194]. While these methods offer a higher time resolution than offline methods (minutes are possible), they do not provide size-resolved data.

1.8.2 Remote sensing and model-interpolated aerosol measurement

Atmospheric aerosols have a complicated vertical distribution with various layered structures of different types and sizes [195, 196]. Remote-sensing-based instruments (Sun photometers and Lidar) measure the transmitted or scattered radiances containing aerosol scattering and absorption properties and can explore the vertical distribution of aerosols. These techniques provide the total column loading of aerosols from the surface, referred to as aerosol optical depth (AOD), and can be inferred from the attenuation of direct solar radiation from the top of the atmosphere to the surface. The National Aeronautics and Space Administration (NASA) operates a global surface network using sky-scanning photometers configured in remote sensing fashion called the Aerosol Robotic Network (AERONET), which covers almost 800 measurement stations covering several aerosol source regions [197]. The aerosol retrievals from AERONET provide essential quantitative insights into aerosol single-scattering albedo (SSA) and particle size distribution of ambient aerosols [197, 198]. Similarly, regional Sun photometer networks, such as the SKYNET in Asia and Europe, and CARSNET in China, offer insightful information on regional aerosol optical properties [199, 200]. The vertical profiles of aerosol scattering/absorption and size information can be retrieved using multi-wavelength Raman scattering, high-spectralresolution techniques, or a combination of backscattering lidar and Sun photometers [201]. Few established lidar networks include MPLNET (Micro-Pulse Lidar Network), EARLINET

(European Aerosol Research Lidar Network), and LALINET (Latin American Lidar Network) that are operated in different parts of the world [202-204].

The vertical distribution of aerosols is challenging to retrieve from passive sensors and is usually prescribed in retrieval algorithms [205]. The active space-borne Lidar is the only reliable method to obtain the vertical profiles of aerosols on large scales, although with limited areal coverage. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is a two-wavelength backscattering lidar with depolarization measurement capability. It can obtain aerosol extinction profiles from backscatter measurements and some information about aerosol type based on depolarization sensitivity, surface type, and prior knowledge of aerosol type from surface measurements [206, 207].

Global information on aerosols relies on analyzing global satellite measurements in combination with global aerosol models. An enormous effort has been made for aerosol measurement using active and passive space-borne instruments such as MODIS, MISR, GOCI, SEVERI, POLDER, CALIPSO and ALADIN etc. Several aerosol retrieval algorithms have been developed to retrieve aerosol type, AOD, and size distribution at different atmospheric settings, such as land to ocean, but they require prior aerosol information [205, 208-211]. Passive satellite sensors use the visible-near-infrared spectrum (400 to 900 nm) to detect the aerosols based on the scattered solar radiation back to space by the Earth-atmosphere. Usually, the satellite provides the column AOD, column-averaged SSA, and column-effective particle single-scattering information of aerosols [70, 212, 213]. Fine and coarse mode aerosols can be retrieved from the spectral dependence of AOD, but it is only reliable over the ocean and not applicable globally [70, 175].

The satellite observations are evaluated and validated using surface-based AOD observations such as AERONET and SKYNET [214]. The global aerosol product of the Copernicus Atmosphere Monitoring Service (CAMS) uses satellite observations, and the ECMWF global weather model with aerosols is a leader in such activities [214, 215]. Further evaluation of the CAMS forecast is done with surface-based lidar and routine aircraft observations of IAGOS [216]. CAMS also produces a global aerosol reanalysis evaluated with non-satellite observations. The significant limitation of aerosols' present measurement methods (in situ, surface-based and remote sensing) is the trade-off between accuracy, comprehensiveness, and spatial representation.

1.9 Outstanding questions

Undoubtedly, atmospheric aerosol concentration, composition, spatial distribution, and dynamics have changed since 1750; the date typically represents the start of the Industrial Revolution. A challenge in understanding aerosol-cloud-climate interactions is untangling the role of aerosol physical and chemical properties and meteorological processes in clouds and precipitation form. One pitfall is that aerosols are sometimes assumed to be homogeneous spheres. In fact, they are much more complicated, with vastly varying particle size, morphology, orientation, surface roughness and chemical composition. Current satellite and remote sensing data provide long-term, global coverage of a wide range of aerosol and cloud properties. Still, they cannot sufficiently constrain aerosol microphysical, optical, and chemical properties to estimate CCN/IN concentrations. Thus, in situ observations are vital for establishing the necessary process-level understanding to include the essential physics and chemistry in global/regional climate models. Therefore, three outstanding long-term persistent questions guide this research work and are presented in this thesis:

- 1. How are changes in physical and chemical properties of aerosols in cold climate conditions affecting air quality and aerosol-cloud interactions?
- 2. What kind of in-situ measurement technique can be developed to retrieve comprehensive information on the aerosol number, size, shape, phase, and indices of refraction under a range of atmospheric meteorological conditions that would be useful in better understanding and modelling aerosol-cloud interactions useful in weather and climate prediction?.
- 3. Observationally, how can supercooled water droplets be better distinguished from ice crystals in a mixed-phase cloud regime?

1.10 Dissertation outline

This thesis focuses on the questions above by presenting four original research projects realized over my doctoral degree. These projects are incorporated into five chapters as follows:

Chapter 2 discusses the aerosol's microphysical properties in cold conditions of the urban atmosphere of Montreal, Canada. Montreal is a perfect metropolitan (> 1M people) model cold climate city with a five-month-long winter season and more than a 2-meter fresh snowfall in which to evaluate changes the aerosol physics and chemistry. This study provides a 2-year dataset of realtime aerosol number and size distribution measurements. The impact of meteorology on aerosol distributions was also investigated. Several traditional techniques were deployed, such as aerosol particle sizers, a Micro Orifice Uniform Deposit Impactor (MOUDI), High-Resolution Electron Microscopy Imaging (HR-S/TEM-EDS), Triple Quad inductively coupled Plasma Mass Spectrometer (QQQ-ICP-MS), Ion Chromatography (IC), and Total Organic Carbon (TOC) analyzers to study the aerosol physicochemical properties. We observed the highest aerosols (nanoparticles) number concentration in the winter. This chapter has been published in the peerreviewed journal Urban Climate (**Pal et al. 2020**).

Chapter 3 demonstrates the newly developed Nano-Digital In-line Holographic Microscopy (Nano-DIHM) technique with an integrated flow tube. Nano-DIHM enables the first-time, in-situ, and real-time phase, shape, and size distribution of aerosols, including those smaller than 200 nm (here we call nanosized) measurements directly in airflow, without any need for particle traps. This technique enables promising technology for analyzing macroscale and nanoscale particles in dynamic and stationary phases, namely gas, liquid, solid, and heterogeneous matrices. The Nano-DIHM facilitates time-dependent direct observation of the size, phase, and shape of airborne aerosols, which has never been previously achieved. This chapter has been published in Communication Chemistry (**Pal et al., 2021**).

Chapter 4 presents an application of Nano-DIHM to bioaerosol detection in real time. As a proof of concept, we used Nano-DIHM to detect the SARS-CoV-2 and Bacteriophage MS2 viruses in air and water media. Nano-DIHM successfully observed the SARS-CoV 2 viruses' size, phase and shape in real-time. We automatized the Stingray software to detect and distinguish the SARS-CoV-2 viruses from mixed biological samples, metal and organics. This chapter has been accepted in Communication Engineering (**Pal et al., 2023, in press**).

Chapter 5 presents the development of McGill Real-time Ice Nucleation Chamber (MRINC) to study ice nucleation by airborne nanosized particles. The coupling of MRINC with Nano-DIHM successfully demonstrated the distinction between ice crystals and supercooled water

droplets in real time. This chapter is a manuscript under preparation and will be submitted to the Journal of Geophysical Research (**Pal et al., 2023, in preparation**).

Chapter 6 summarizes the findings of this dissertation and discusses the future research plan.

Chapter 2 Aerosols in an Urban Cold Climate: Physical and Chemical Characteristics of Nanoparticles

It was discovered that aerosols might impact Earth's climate and the measurements of aerosols needed to establish the magnitude of these effects [1]. Even though many studies have focused on the aerosol impact on climate, health and air quality, aerosols are one of the key sources of uncertainty in climate forecasts in many climate models that continue to revolve around atmospheric aerosols and their interactions with clouds [110]. While aerosol optical characteristics in climate models were the main emphasis, influences of aerosol particle number size distribution were not considered significant and needed a complete examination [217]. It was due to the lack of observations of aerosol number distribution in different environmental conditions and geographical locations [72]. In addition, aerosols significantly impact air quality and human health. Thus, the direct measurement of aerosols in different environments, such as cold vs warm climate, ocean to continental or global observation, is essential. Immediate measures of the amount and type of aerosols in a specific location can provide information about how factors like wildfires and pollution episodes impact air quality.

Aerosol measurements can be used to assist researchers in finding the origins of new aerosol formation and understanding how they are distributed in the atmosphere. There may be significant variations at the measurement site due to the closeness of the observation spot to emission sources, variations in the local wind speed and direction, and the dynamics of the boundary layer [218]. In this chapter, we had two aims: (1) to study the size classification trends of aerosol particle number concentrations for 5-size aggregated bins; <100 nm, <200 nm, <1 μ m, < 2.5 μ m and < 10 μ m in a cold urban climate, in downtown Montreal Canada. (2). We provide unique long-term (~ 2 years) observations of aerosol number size distribution analysis for cold urban climate settings from May 2017 to June 2019. The diurnal, seasonal analysis of aerosol particle number concentration, we share our data set with Environment Canada for model evaluation. The observational data assembled in this study could also facilitate reflections on how the aerosol size distributions have evolved during previous years and how they have changed, e.g. the cloud activation capability of different sizes of aerosols.

This Chapter consists of the following published article in peer-reviewed journals:

Pal, Devendra, Ashu Dastoor, and Parisa A. Ariya^{*}(2020). *Aerosols in an urban cold climate: Physical and chemical characteristics of nanoparticles. Urban Climate 34 (2020): 100713*. Doi: <u>https://doi.org/10.1016/j.uclim.2020.100713</u>

*Corresponding author

Aerosols in an Urban Cold Climate: Physical and Chemical Characteristics of Nanoparticles

Devendra Pal¹, Ashu Dastoor³ and Parisa A. Ariya^{1, 2}

¹ Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montreal, QC, H3A 0B9, Canada.

² Department of Chemistry, McGill University, 801 Sherbrooke Street West, Montréal, QC H3A 2K6, Canada.

³Air Quality Research Division, Environment and Climate Change Canada, 2121 Trans-Canada Highway, Dorval, QC H9P 1J3, Canada

© 2020 Elsevier B.V. All rights reserved. Used with permission.

Abstract

Atmospheric aerosols are of significant importance in climate change and health research. This study provides a 2-years meta dataset of real-time aerosol number and size distribution measurements in a model cold-climate city of Montreal (Canada). We provide selected information on the chemical composition and morphology of aerosols (~10 nm to 10 µm). We deployed a suite of complementary techniques such as aerosol particle sizers, MOUDI, S/TEM imaging, EDS, triple quad ICP-MS, IC, and TOC analyzers. The highest geomean nanoparticles (<100 nm) number density (9260 \pm 1.6 number/cm³) was observed in the winter. A broad range of metals, including emerging contaminants, was quantified in all aerosol sizes include Pb, Cd, Ni, Zn, As, Al, Mn, Co, and Se, with concentrations ranging from 0.01 to 67.64 ng/m³. Nanosize particles included Ni, Cd, Pb, Zn. Iron exhibited the highest concentrations consistently in two modes (<180 nm and > 1 micron). S/TEM-EDS confirmed the abundance of nanoparticles, single and clusters, with multifaceted morphologies and compositions. We identified (a) emerging nanoparticles, (b) secondary organic aerosols, (c) bioaerosols, and (d) combustion particles. Diurnal, weekly, monthly, seasonal, and yearly variations of aerosols are provided. We herein discuss the implications of these results on air quality and climate modelling.

2.1 Introduction

Aerosols (airborne particles) are identified as key players in climate change and health by the Inter-governmental Panel for Climate Change [110] and the World Health Organization [94]. Aerosol and their interactions with clouds and radiation "continue to contribute the major

uncertainty to assessments and understandings of the Earth's changing energy budget," thereby affecting the assessment of the Earth's climate [110, 219]. The uncertainty in the global radiation budget associated with aerosol-cloud interactions is of the same order of magnitude as the estimated radiative impact of the increase in atmospheric concentrations of major greenhouse gases associated with human activities [110]. Air pollution, particularly aerosols, has been directly linked to an increase in respiratory and cardiovascular diseases, as well as cancer [94]. Air pollution is now explicitly named "*the biggest cause of early childhood mortality*" [94]. Airborne nanoparticles are aerosols with an aerodynamic diameter of less than 100 nm. There are currently no regulatory measures for nanoparticles, which are far smaller than the regulated particles with aerodynamic diameters of less than 2.5 μ m (PM_{2.5}) and 10 μ m (PM₁₀). The physical and chemical properties of nanoparticles, such as size, surface tension, active sites, surface properties, volatility, and photochemistry, are essential parameters in both climate and health research [75, 220].

Cities are the leading emission sources of air pollutants (e.g., PM_{2.5}, PM₁₀, CO, SO₂, CO₂ and NO_x) [221] and are the locations where most humans reside. Airborne particles are emitted into the atmosphere from various sources, both natural and anthropogenic [12], and include a diverse composition of compounds such as organic, inorganic, and emerging metal contaminant species [51, 73]. The primary sources of airborne nanoparticles in urban areas have been identified as vehicle exhaust, airport, thermal plants, industries, and hospital combustion process [14, 222, 223]. The combustion process is also a significant source of CO, and it can be used as a tracer for anthropogenic emissions of nanoparticles in the atmosphere [224, 225]. Furthermore, secondary aerosol formation, gas-to-particle conversion, and condensation of vapours on pre-existing particles lead to the formation of nanoparticles in both urban and suburban regions [61, 226, 227].

Emerging contaminants are defined as synthetic or naturally occurring chemicals or materials that have the potential to enter the environment and have adverse ecological and human health impacts, but are currently inadequately regulated because of the lack of contaminants characterization in the environment and insufficient toxicological data on their effects [73, 228, 229]. The rapid urbanization and the enlargement of the number of vehicles and industries are vital parameters of elevating the level of emerging metal contaminants in the ambient air [38, 230]. In the cold-climate urban regions [231] during the winter months, the height of the planetary boundary layer is lower than during the summer months due to colder temperatures and a higher

air density. This phenomenon and the additional possibility of a winter inversion layer can suppress vertical mixing, leading to entrapment of pollutants close to the Earth's surface [1]. Further need for the additional heating in winter, increased emission of pollutants is also anticipated from the transport sector (i.e., idling cars and planes) to energy usage for heating buildings. Recent health studies have shown that an enhanced PM10 (< 10 μ m diameter) number density causing health hazards in winter [232], notwithstanding that many major cities in the world receive various levels of frozen precipitation [231].

In this study, we aimed to (a) provide real-time self-consistent in-situ measurements of the number-size distribution of particles (~10 nm to 10 μ m), focusing on nanoparticles (< 100 nm) in a cold-urban site, where there are limited real-time aerosol data; (b) determine complementary chemical/elemental composition of size-aggregated aerosols, (c) understand the morphology of aerosols at different sizes, and (d) the effects of selected distinct environmental conditions such as seasons, diurnal, daytime vs. nighttime and weekdays vs. weekend days aerosol number-size distribution were also evaluated. We herein focused on airborne nanoparticles and emerging nano-contaminants. We further discuss unique aerosol patterns in a model city Montreal, which receives, on average, 2.1 m of snow per year (vs. Moscow 1.2 m snow per year).

2.2 Experimental section

We performed real-time in-situ particle size distribution measurements as well as sampled aerosol particles using an Impactor. The samples were analyzed to characterize the morphology and chemical compositions of aerosols. The complementary methodologies for each measurement are discussed in detail below, as well as in the supporting information (Appendix A).

2.2.1 Sampling and measurement site

Real-time measurements of airborne particle number-size distribution were performed at McGill University, downtown campus in Montreal, Canada (Fig. A1). The in-situ observations of aerosols were performed ~ 4 m above from the ground at the intersection of University and Sherbrooke streets. A conductive tube (2 feet long) inlet was used to direct the ambient air into a NanoScanTM Scanning Mobility Particle Sizer (SMPS) model 3910 (TSI Inc.) and an Optical Particle Sizer (OPS) model 3330 (TSI Inc.). Significant anthropogenic sources of aerosols and

other pollutants are the local traffic emissions along with the nearby industrial and hospital combustion processes. Besides, Mount Royal Park is not far from the sampling site, and thus the sampling site receives biogenic aerosols.

2.2.2 Number-size distribution measurement

The real-time aerosols measurements were performed using an SMPS and an OPS. The SMPS measures the particle size distribution of ambient particles in the range of 10 - 400 nm in terms of the electrical mobility diameter. The OPS determines the particle size distribution from a size range of 0.3 - 10 μ m in terms of optical diameter. These instruments are factory-calibrated every year with Polystyrene Latex spheres (PSL) for all the internal and external flow rates. The particles are considered spherical, and size distribution determined by the optical counters is very close to the actual physical (or geometric) diameter [233-235]. The OPS measurements are intensely dependent on the aerosol's appearances, such as the refractive index and dynamic shape factor. Based on the assumption that the aerosol particles are spherical and the particle density is 1 g/cm³, the optical diameter is considered to be equivalent to the aerodynamic diameter [1]. We performed routine quality assurance procedures for the SMPS and OPS to ensure the accuracy of the measured data, including the measurement of the aerosol number density, passing the air with HEPA filter, as shown in Figure A2(a-b). The particle number density was observed < 1 particle/cm³ for both SMPS and OPS.

2.2.3 Micro-Orifice Uniform Deposit Impactor (MOUDI)

MOUDI (model 100-R, MSP Corp., Shoreview, MN, USA) was used to collect sizefractionated aerosol particle samples for subsequent analysis of chemical compositions, organic carbon, and morphology of particles. The unit has eight impaction stages and is comprised of five assemblies: rotator impactor, Magnehelic gage, rotator unit, shelter, and a blower motor. The stages of MOUDI are calibrated to the following d_{50} cut-off points: 18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, and 0.18 µm, equivalent to aerodynamic diameters. Further information provides in the appendix section A1.1. We operated the MOUDI on the roof of the laboratory with an inlet airflow rate of 30 L/min. Aerosol samples were collected on Teflon quartz substrate (MSP Corp., Shoreview, MN, USA) during different days of sampling periods. The 24 hours sampling period was from 19/07/2017 to 20/07/2017, and the longer-term sampling (i.e., 48 hours) was conducted between 14/07/2017 and 16/07/2017. These aerosol samples were used for chemical analysis and determination of the morphology of particles discussed in the subsequent sections.

2.2.4 High-Resolution S/TEM and FE-ESEM imaging with Energy Dispersive X-Ray Spectroscopy (EDS)

The airborne particles were collected onto Cu grids (SPI. Supplies, West Chester, PA USA). The TEM-grids were fixed on the filter substrate using double-sided adhesive tape and placed in the following d_{50} cut-off points: 0.18 µm and 1µm. The field emission gun transmission electron microscope (FEG-TEM) has an operating voltage in the range of 50 to 300 kV. The high-brightness, high-coherency gun permits large electron probe currents to focused on nanometer-sized areas of the specimen (sample). The capabilities of this gun include energy-dispersive X-ray spectroscopy (EDS), S/TEM imaging and mapping, and a CCD camera that allows magnification of thin samples (<500 nm) up to >1 million times [236]. The TEM grids were analyzed using a high-resolution FEI. Tecnai G²F20 S/TEM microscope with a field emission gun [236]. Images were acquired using an Advanced Microscopy Technique, Corp. (AMT) XR80C CCD Camera System, which was previously also used for snow particles [23]. In this study, the AMT was adapted for the collection of atmospheric aerosols directly on the grid. It allowed us to study the size, morphology, and composition (with EDS) of airborne single and aggregated nanoparticles at high resolution. The cut-off d₅₀ (= 1 µm) TEM grids were subjected to the FEI. Quanta 450 Environmental Scanning Electron Microscope (FE-ESEM).

2.2.5 Trace metal analysis

Collected samples for each fractionated size range were digested in a combination of 2% nitric acid (Omni trace ultra- nitric acid) and ultrapure Milli-Q water in a sealed microwave vessel. Digested samples were then introduced to Triple Quad Inductively Coupled Plasma Mass Spectrometry (QQQ)ICP-MS/MS) [model - Agilent technology – 8900] to determine the concentrations of the trace metals Ni, Cr, Zn, Pb, As, Se, Sr, Co, Cu, Ag, Al, V, Mn, Fe, Cd, Ba, and U. The instrument was optimized using a standard solution containing 10 μ gmL⁻¹ of each metal to ensure that inherent interfering species constituted less than 2% of the signal. Calibration was achieved using a multi-element standard (SPEX, USA ISO 9001 certified) made of a 2% nitric acid solution matrix matched to the samples. Analytical drift was monitored using a 10 μ g/L multi-

element standard, which was repeatedly analyzed throughout the procedure, and then was subsequently used to normalize the data. The quantitative results of metals are calculated based on the sampling flow rate of 30 L/min for both the 24h and 48h sampling periods. The lower limit of detection of the (QQQ)ICP-MS/MS) analysis was calculated as 3σ for each element measured in the ten procedural blanks. The detection limits for individual elements were: Ni - 0.0046, Cr - 0.00766, Zn - 0.08764, Pb - 0.00302, As - 0.00577, Sr - 0.00242, V - 0065, Mn - 0.00594, Fe - 0.02939, Co - 0.00208, Cu - 0.00413, Ag - 0.00203, Cd - 0.00417, Ba - 0.00851, and U - 0.00147 μ g/L.

2.2.6 Complementary ion analysis

The ICS-5000 AS-DP Dionex Thermo Scientific Ion Chromatography (IC) system was used to measure the ions. We analyze both the anion species (F^- , Cl^- , NO_2^- , Br^- , NO_3^- , PO_4^{3-} , and SO_4^{2-}) and cation species (Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+}). The Dionex column AS18–4 was used to separate the anions, and the Dionex column CS16–4 was deployed for the cations. Before introducing samples into the IC, we dissolved all fractionated individual aerosol samples in 5 mL of ultrapure Milli-Q water. An un-used substrate was always analyzed for blank, and concentration was observed below the instrument detection limit < 1 ppm.

2.2.7 Total organic carbon (TOC)

We dissolved fractionated individual aerosol samples in 40 mL of ultrapure Milli-Q water, and the resulting samples were subjected to an Aurora 1030 W TOC Analyzer. A 5 mL aliquot of water was used from each sample. To detect total inorganic carbon, 0.5 mL of 5% phosphoric acid was added to the subsample and combusted at 700 °C. Afterwards, to detect organic carbon, 2 mL of 10% sodium persulfate was added and combusted at 980 °C. The resulting CO₂ gas from these two reactions was detected separately by a nondispersive infrared sensor.

2.2.8 Meteorology and auxiliary air quality data

The complementary meteorological (T, RH, wind speed) and air pollution (O₃, NO_x, CO, SO₂, and PM_{2.5}) data were obtained from the City of Montreal's Air Quality Surveillance Network (RSQA), which described in detail in the appendix A1.2.

2.2.9 Statistical analysis and classification

In this study, the geometric mean and geometric standard deviation were used for data interpretation to minimize outlier effects. We also performed the arithmetic average, standard deviation, median, 99th, and 1st percentile values along with geometric mean, geometric standard deviation, during the advanced data analysis, which presented in appendix Table A1. The details of the geomean equations were discussed in appendix A1.3. Recent metadata analysis has justified the usage of geometric error analysis [237, 238]. This meta dataset of two years provides a one-minute temporal resolution of particle number density (numbers/cm³) with each of five sizes aggregated ranges of particles, as shown in Figure A3. Statistical analysis were carried out in each five size range i.e., < 100 nm (10 - 100 nm), < 200 nm (100 - 235 nm), < 1 μ m (0.3 - 0.9 μ m), < 2.5 μ m (0.9 - 2.6 μ m), and <10 μ m (2.6 - 10 μ m), of airborne particles for several temporal regimes: seasonal, monthly, weekdays (Monday - Friday), weekend days (Saturday - Sunday), daytime (09:00 - 18:00 h), nighttime (22:00 - 05:00 h), weekday-daytime, weekday-nighttime, weekend-daytime, weekend-nighttime, and snow precipitation events.

In cold-climate cities such as Montreal, cold months are not confined only to winter. We followed the classification from Environment and Climate Change Canada (https://weather.gc.ca/forecast/canada/index_e.html?id=QC). Thereby, the seasons are classified as Spring (April, 21st to June, 20th), Summer (June, 21st to Sept, 20th), Fall (Sept, 21st to Nov, 30th), and Winter (Dec, 1st to April, 20th) in different days of months. Correlations between various environmental variables (i.e., gaseous pollutants, meteorological parameters) and particle number densities were assessed by Spearman's correlation coefficients [239]. The independent Student ttest was used to explore the differences between different size groups aggregated by month, weekdays, weekend days, daytime, nighttime, and snow episodes. In the correlation test, a p-value lower than 0.05 and in the independent t-test, p-values lower than 0.001 were considered to be statistically significant.

2.3 Results and discussion

2.3.1 Seasonal particle number-size distribution

The geometric mean, arithmetic means, median, 99th percentile, and 1st percentile values of aerosol number densities were provided for a comprehensive statistical representation of the data set presented in Table A1. Seasonally geometric mean, arithmetic mean, and median number densities of each of five size range particles are providing a clear depiction of the long-term variability, as shown in Figure 2.1(a).





Figure 2.1 Size aggregated particle number densities (#/cm³). (a) Seasonal variation of geometric mean, arithmetic mean, and median particle number densities, and (b) Monthly box plots of size aggregated particle number densities data from May 2017 to May 2019. The horizontal line through each whisker box represents that month's median value, and the lower and upper edges of the whisker boxes present the 25th and 75th percentiles values, respectively. Whiskers above and below the boxes are maximum and minimum values, respectively. The outliers are not shown. The rectangular shapes inside the box present monthly mean number density.

We observed a multimodel seasonal variation of each five-size range of particles over two years (Fig. 2.1a). Notably, nanoparticle (< 100 nm) number density revealed a periodic pattern with the high geometric mean number density (number/cm³) were observed during winter (9260.2 \pm 19), followed by Spring (7562.4 \pm 2.0), Summer (6278.6 \pm 1.8), and in Fall (5547.6 \pm 1.9) during the year 2018 – 2019 (Table A1). In contrast, submicron (< 200 nm) and micron (< 1µm and < 2.5 µm) size particle geometric mean number densities were observed higher during summer. Several

factors impact the seasonal distribution of nanoparticles in urban cold-climate. For instance, during winter, the combination of cold temperature and suite of meteorological conditions and anthropogenic activities in cities (e.g., heating building and vehicles, etc.), lead to lowering the mixing layer height, favour the concentration of pollutants near the surface. The peak in the summer is due to the increased photochemical processes that lead to the net production of particles, including larger particles (> 1 μ m).

In this study, we observed the highest nanoparticle number density during the winter season. This observation is in contrast to previous studies [240-242], rather than the cold-urban climate such as Montreal. These researchers have observed higher aerosol number density during spring [240-242] and summer [243]. Other studies have confirmed that the seasonal differences in aerosol number densities differ in the northern hemisphere to the southern hemispheres [24, 244]. They had concluded that the observed seasonal trends in the northern hemisphere [24, 224, 245, 246], contrary to the southern hemisphere [32, 244]. The northern hemisphere contains approximately 90% of the global population and about 68 % of earth landmass, while the southern hemisphere is mainly occupied by oceans [247]. This means that the northern hemisphere required more energy and resources, which elevated the anthropogenic deeds. Besides that, the differences in vegetation/agriculture between the northern hemisphere and the Southern Hemisphere [248], along with significant meteorological differences [244], are likely to result in different aerosol properties in the southern hemisphere [249]. This study is one of the very few studies in cold-urban regions with specific characteristics of aerosols. Thus the observed systematic winter maximum of aerosols is likely a specific characteristic of this climatic region. Hence, more studies are required to understand the characteristics of aerosols in various hemispherical, topographical, and climatic regions.

2.3.1.1 Winter seasons: The highest observed nanoparticle number density

During the peak winter months (Dec, Jan, and Feb), as shown in Figure 2.1(b), the highest nanoparticles number density was observed throughout the years (2017 - 2019). The geometric mean number density of nanoparticle during Dec 2017 and Feb 2018 was observed 8447.6 \pm 1.9 and 7463.3 \pm 2.3 number/ cm³, and during Dec 2018, Jan, and Feb 2019 were observed 8137.7 \pm 2.1, 10174.5 \pm 1.8, and 10935.6 \pm 1.7 number/cm³, respectively. Along with nanoparticle number

density, the CO mixing ratio also observed higher during winter seasons (Dec, Jan and Feb) compared to other seasons (See Fig. A4). The monthly averages of CO mixing ratios (ppbv) during Dec 2017, Jan and Feb 2018 were observed 235.8, 271.4 and 262.9 ppbv, respectively. While CO missing ratios during Dec 2018, Jan and Feb 2019 were observed 257.6, 247.6 and 239.5 ppbv, respectively. The higher concentration of both nanoparticles and CO in the winter is associated with an increase in anthropogenic activity, higher traffic density, along with lower traffic circulation due to the snow removal operation in Montreal. Additionally, lower atmospheric boundary layers in winter allow more accumulation of pollutants, particularly nanoparticles, where the deposition rate is much lower than larger particles [26, 250]. Besides the lower boundary layer, the cold temperature (Monthly average temperature: Dec 2017 (-8.1 °C), Jan 2018 (-8.7 °C), Feb 2018 (-3.2 °C), Dec 2018 (-4.4 °C), Jan 2019 (-9.8 °C), and Feb 2019 (-7.5 °C), respectively (Fig. A5)) induced inversion or kind of inversion (leaking inversion) which again allow to preconcentration of particles. Thus, it increases in the emission of particles due to idling in cold climate.

Higher number densities of submicron and micron-size particles were found during summer. Such a phenomenon has been attributed to enhanced photochemistry in the summer and elevated biological activities [51, 222], which release directly micron-sized particles (e.g., bio-aerosols like bacteria) or produce precursors for coagulations processes resulting in the high concentrations of submicron and micro-aerosols [240, 251]. The nanoparticle's geometrical yearly mean, geometric standard deviation, and median values (given in parenthesis) were observed to be 5516.2 ± 2.1 (5822.6) number/cm³ from May 2017 to May 2018 and 6979.3 \pm 1.84 (7514.8) number/cm³ in May 2018 to May 2019. These observations concluded that the nanoparticle's geometric mean number density elevated up to ~ 25 % from the year 2017 to 2019 in the cold urban setting of Montreal. Several factors can affect the aerosols observations as herein report, such as (a) meteorological impact of the lower height of boundary layer, suppression of vertical mixing, and cold temperature in Montreal, and (b) potential increase in anthropogenic emission.

2.3.2 Comparison with previous research on airborne particle distribution

We compared the measured particle number densities in this study to previous studies, which have been conducted worldwide. These results are given in Table A2. In this study, the total
geometric mean number density (10 nm - 10 μ m) during the two years of observation was 6776 ± 1.8 cm⁻³. This value is the second-lowest number density compared to other worldwide studies, shown in Table A2. The contribution from the number densities of larger particles (1 μ m to 10 μ m) was small relative to the total particle number density. The number density of particles within the range of 10 nm to 1 μ m in downtown Montreal was comparable to the particle number densities from Santiago (Chile), Helsinki (Finland), and Prague (Czech Republic). Number densities in other regions were 2 to 4 times higher than this study.

2.3.3 Chemical analysis of airborne particles

2.3.3.1 Trace metal concentration

The trace metal concentration (ng/m³) determined by the triple quad ICP-MS/MS shown in Table 2.1. In this study, different groups of airborne metals were observed, namely; alkaline earth metals (Mg, Ca, Sr, and Ba), transition metals (V, Cr, Mn, Fe, Co, Ni, Cu, Zn, and Cd), posttransition metals (Al and Pb), metalloids (As, Sb) and other nonmetals (Se) (Table 1).

The observations revealed that the emerging metal contaminants, namely: Ni, Cr, Zn, Pb, As, Co and Cd were abundant in the 180 nm size particles (nanosized particles) and then in 320 nm and 560 nm size particles, respectively. Whereas the concentrations of elements such as Cr (2.8 ng/m^3) , Ni (1.48 ng/m^3) , and V (0.05 ng/m^3) were found to be maximum in the 0.18 - 0.32 μ m fraction size range. Al and Fe showed the highest concentrations in each fraction size range particles. Since these data can be of interest to urban biogeochemical researchers, we have also provided in the supplementary data, per unit of aqueous volume. The observations have shown that the metals are not only abundant in micron-sized particles but are also ubiquitous in airborne nanoparticles, which are considered as emerging contaminants (Table 2.1). Notwithstanding, even in one nanosized particle, showed several metal elements (e.g., Fe, Al, Ni, Cr, and Ti), as confirmed by HR-S/TEM analysis, presented in section 2.3.4.

Table 2.1Mass concentrations (ng/m^3) of trace metals, ions and TOC in different size-fractionated
ranges of airborne particles during 24, and 48h sampling periods. The size fraction ranges
were based on instrument limitation and the interest of research. The mass concentration
also presents in $\mu g/L$ in Table A3.

Unit	19-20 July 2018 (24 h) 14 - 16 July 2018 (48 h)									
ng/m ³	0.18 µm	0.32 μm	0.56 µm	1.0 µm	0.18 - 0.32 μm	0.56 - 1 μm	1.8 - 3.2 μm	5.6 - 18 µm		
Alkali metals										
Na	5.71	5.17	3.19	3.61						
Κ	14.38	3.64	15.71	9.35						
Cs	176.39	14.19	284.13	163.4						
Alkaline earth metal										
Mg	7.53	1.46	6.67	5.58						
Ca	54.42	69.44	20.63	37.5						
Sr	Nd	Nd	Nd	Nd	0.01	0.15	0.14	Nd		
Ba	Nd	Nd	Nd	Nd	Nd	0.25	1.01	0.37		
				Т	ransition metal					
V	Nd	Nd	Nd	Nd	0.05	0.1	0.05	0.03		
Cr	0.07	0.35	Nd	0.28	2.8	Nd	Nd	Nd		
Mn	0.56	0.25	0.29	0.44	0.31	Nd	0.22	0.17		
Fe	27.11	9.86	23.46	16.61	8.74	Nd	12.2	7.74		
Со	0.03	0.03	Nd	0.04	0.03	0.01	0.01	0.01		
Ni	0.85	0.69	0.11	0.13	1.48	0.06	0.03	0.03		
Си	1.4	0.64	1.11	0.76	0.02	0.19	0.74	0.29		
Zn	0.6	Nd	Nd	1.10	Nd	Nd	0.56	Nd		
Cd	1.4	0.64	1.11	Nd	0.02	0.19	0.74	Nd		
Post transition metal										
Al	9.79	35.83	67.64	28.56	0.21	1.98	7.49	3.81		
Pb	0.74	0.1	0.28	0.39	0.06	0.02	0.02	0.02		
Metalloids 0102										
As	0.08	Nd	0.11	Nd	0.05	0.02	0.01	0.01		
Sb	Nd	0.04	0.08	0.08						
Se	0.21	Nd	0.14	0.13	0.03	0.01	0.01	Nd		
					Ions					
Cl^{-}					1637.5	76.39	111.11	979.17		
NO_2^-					13.89	465.28	1569.44	458.33		
SO_4^{2-}					1520.83	1111.11	354.17	854.17		
NO_3^-					88.19	263.89	847.22	347.22		
Na^+					1060.42	1131.94	1138.89	1798.61		
NH_4^+					10.42	277.78	34.72	34.72		
$K^{\scriptscriptstyle +}$					160.42	222.22	250	263.89		
Mg^{2+}					413.89	69.44	118.06	236.11		
Ca^{2+}					2062.5	Nd	1027.78	1798.61		
				Tota	l organic carbon					
TOC	240.28	836.11	50.21	57						

• Nd represents the below filter blank

• Blank space represents no data (No measurements) on that particular day

2.3.3.2 Ions in aerosols

The concentrations of the anions, Cl⁻ (1637 ng/m³), and SO₄²⁻ (1520 ng/m³), and the cations, Mg²⁺ (414 ng/m³), and Ca²⁺ (2062 ng/m³), were observed maximum in 0.18 - 0.32 μ m size particles (Table 2.1). While the concentrations of NO₃⁻, NO₂⁻ and K⁺ were observed higher in the

1.8 - 3.2 µm particle size range, as shown in Table 2.1. The concentrations of nitrate (88 ng/m³) and ammonium ions (10 ng/m³) in the size fraction 0.18 - 0.32 µm were observed considerably lower than in size fractions 0.56 - 1.0 µm, (264 and 278 ng/m³, respectively) and 1.8 - 3.2 µm, (847 and 35 ng/m³, respectively) respectively. The previous study has also confirmed that the concentrations of nitrate and ammonium ions were at a maximum in the submicron to micron size range 0.45 -1.09 µm of aerosols [62]. The concentrations of ions, F^- , Br^- , PO_4^{3-} , and Li^+ , were observed to be below the detection limit (< 0.1 ppm). The conversions of gaseous pollutants such as SO₂, NO_x, and NH₃ into ions, namely; SO₄²⁺, NO₃⁻, and NH₄^{+,} are vital for increasing secondary aerosol formation. The abundance of SO₄²⁻ and NO₃⁻ in nanosized particles may indicate the contribution of secondary aerosols [63].

2.3.3.3 TOC observations

In this study, TOC concentration is dominant in the nanosized and sub-micron size aerosols. The TOC concentration in nanosized particles, submicron and micron-sized particles were 240 ng/m³, 836 ng/m³, and 57 ng/m³, respectively (Table 2.1). The existence/presence of TOC in the nanosized particles indicates that carbon-containing compounds are constituents of nanoparticles. These observations were further validated by the morphology and elemental analysis of particles using S/TEM coupled with EDS (section 2.3.4), which provided the evidence for organic and inorganic carbonaceous compounds as well as mixed organic-inorganic carbon-containing particles.

More than half of the total organic carbon in atmospheric aerosols has been estimated to be secondary [252, 253]. However, the mechanisms of secondary organic aerosol (SOA) formation are not fully understood, leading to difficulties in the modelling of SOA in air quality models [254]. Pre-existing metal-containing aerosol particles in urban air have been found to either suppress or enhance SOA formation via metal-mediated pathways for aerosol-phase oxidation of organics [253, 255, 256]. These studies have suggested that the effects of transition metals in aerosol particles on SOA formation must be considered in modelling urban air quality[254, 257]. The concurrent physical and chemical data on different sizes of the particle can be parameterized in air quality models, particularly those focusing on cold-climate regions.

2.3.4 HR-S/TEM and FE-ESEM observation of airborne particles: Focus on nanoparticles

Analysis of particle morphology is essential for determining the impacts and possible sources of airborne particles. In this study, the insights on particle size, morphology, and surface crystallinity, along with concurrent elemental analysis, are discussed below in four groups:

(a) Emerging contaminants (TiO₂)

Figure. 2(a, a1) are the nanostructures related to titanium-containing complexes, and EDS analysis confirmed that the particle is emerging metal or metal oxide nano-contaminants. Selected area electron diffraction (SAED) of particles in Fig.2.2a confirmed a crystalline nature of titanium oxide nanoparticles. As previously shown in the literature [258], such morphologies are likely related to synthetic nanoparticles of titanium compounds or nanocrystals of TiO₂. Since the reactivity of various titanium oxides in the presence of light and various atmospheric compounds have been previously studied [259], further research on the atmospheric chemistry of these emerging anthropogenic nanoparticles and their potential impacts on health is recommended.

(b) Secondary organic aerosols

Figure 2.2(b, c) depicts likely secondary organic particles with multiple phases. The EDS revealed that the particles in Fig. 2.2(b, c) contained a significant carbon and oxygen peaks followed by elements S, K, Ca along with other metals. SAED analysis confirmed that the particle in Fig. 2.2(b) has an amorphous nature. Particles in Fig. 2.2(c) represents the multiphase dendrite structures with diverse elemental compositions (EDS spots A, B and C). Although the morphologies of particles A, B, and C are similar, their elemental compositions were found to be quite distinct, suggested that the complexity of emission sources in an urban environment.

(c) Bio-aerosols

Bioaerosols are referred to as airborne living organisms (such as bacteria, viruses, algae) and remnants of biological activities such as natural polymers or semi-volatile organic compounds. The morphology of the particle in Figure 2.2(e) depicts a likely biological particle. The elemental composition of particles is contained an abundance of C, O, and minor traces of K, Mg, and P. Previous studies have shown that the similar elemental composition of biological particles [6, 51, 260].



Figure 2.2 High-resolution transmission electron microscopy images (a-d) with EDS of airborne particles (a) Represents the crystalline structure of TiO₂ and close-up (a1) represents titanium nanostructure, (b) and (c) represents the secondary organic particles with multiphase morphological structures, (d) represents spherical shaped organic-inorganic particles mixed with emerging metals. (e) Scanning electron microscopy with EDS represents biological particles. This figure rearranged with permission.

(d) Combustions particles

Figure 2.2(d) displays the nearly spherical or non-regular shape particle of organic, inorganic, and mixed-phase organic-inorganic components, containing the peak amount of carbon and oxygen followed by metals Si, Fe, Ni, and Cr, which indicate industrial and combustion sources. As shown in Table 2.1, the highest carbon content (TOC) was not observed only in nanosized particles, but also observed in micron-sized particles (SEM images in Fig. A6 (a-f)), indicate the existence of soot particles and carbonaceous materials. EDS analysis confirmed that these carbonaceous particles could be soot, black carbon, or related carbon nanotubes and graphitic matter [261-263].

Based on the morphology and elemental composition analysis of airborne particles, we identified multiphase organic, inorganic, and biological particles in the atmosphere with different shapes and sizes, namely single and clusters, spherical and non-spherical, and chain-like aggregated particles as shown in Fig. 2.2(a-e), and Fig. A6(a-f). The elemental composition analysis of these particles by EDS was consistent with the chemical analysis of the same samples by using (QQQ)ICP-MS/MS, IC and TOC analyzers (Table 2.1).

2.3.5 Distinct trend of weekday and weekends of nanoparticles distribution in summer and winter

The geometrical mean and median number density of nanoparticle was observed consistently higher during weekdays compared to weekends in both winter and summer seasons (Table 2.2). For instance, the geometric mean number density of nanoparticles was observed 7384.9 and 10466.5 number/cm³ during winter weekdays in 2017 - 2018 and 2018 - 2019, respectively. Whereas the geometric mean nanoparticle number densities during the summer weekdays 2017 and 2018 were observed to be 5427.7 and 6518 number/cm³, respectively. The observation indicates the ~ 40% higher values in winter weekdays in comparison to the summer weekdays. However, nanoparticle number density was up to ~ 30% higher in winter weekends

than in summer weekends. This observation reveals that the colder meteorological conditions (average monthly temperature in winter months < -9 °C, Fig. A5) in combination with higher emission of nanoparticles (heating, car operation, etc.) likely leads to an enhancement nanoparticle's number density during winter.

Table 2.2Nanoparticle number density (number/cm³). Geometric mean (GM), arithmetic mean
(AM), standard deviation (Std), median 99th and 1st percentile values were given for
winter and summer weekdays and weekends.

Cold/warm*	GM	AM	Std	Median	99 th per.	1 st per.			
2017-2018									
Summer Weekdays	5427.7	6179.3	3222.4	5539.5	17650.7	1429.6			
Winter weekdays	7384.9	9146.2	6117.1	7714.8	29056.8	1163.4			
Summer weekend	3479.4	4996.1	3775.4	4025.8	20387.4	564.5			
Winter weekend	4620.6	5815.9	3611.7	5129.2	16651.5	908.9			
2018-2019									
Summer Weekdays	6518	8527.4	6161.3	7285	30667	673.7			
Winter weekdays	10466.5	12721.4	7637.8	11619.2	37474.7	1404.6			
Summer weekend	5738.1	6550.9	4095.3	5627	24511.2	2243.5			
Winter weekend	6508.7	8384.9	5542.6	7090.9	25072.5	844.5			

2.3.6 Day-night variation of aerosols

The statistical summary of each of the five-size ranges particle number densities during weekdays, weekends, daytime and nighttime, are presented in Table 2.3. The 25th, median, and 75th percentile values of number densities of < 100 nm, < 200 nm, < 2.5 μ m, and < 10 μ m particle sizes were observed consistently higher during the weekday-daytime to weekday-nighttime (independent t-test, p < 0.001) except the < 1 μ m size particles (p = 0.009). In contrast, the number densities of particle sizes < 1 μ m, <2.5 μ m, and <10 μ m, did not exhibit significant statistical differences (p=0.81, p=0.31 and p=0.43 respectively) during weekend-daytime to weekend-nighttime. It could be due to the coagulation and condensational growth of particles emitted or formed during the daytime [264, 265]. The number densities for particles in other size ranges, < 1 μ m, < 2.5 μ m and < 10 μ m, did not change significantly from weekdays to weekends; this suggests a vehicle exhaust emission consist of predominantly smaller particles [266-268].

Table 2.3Particle number density (#/cm³). Median, 25th and 75th percentile values during weekday-
daytime (09:00-18:00h), weekday-nighttime (22:00-05:00h), weekend-daytime,
weekend-nighttime. Also, Median, 25th and 75th percentile values calculated for during
the weekday (24h) and weekends (24h) from May 2017 - 2019.

Group	Group	Median	25%	75%	P-value
		Weekday	/S		
Daytime	< 100 nm	8887.697	5757.574	13354.743	P = <0.001
Night-time	< 100 nm	5236.058	3272.673	8202.243	P = <0.001
Daytime	< 200 nm	690.243	419.453	1060.625	P = <0.001
Night-time	< 200 nm	548.097	304.800	862.963	P = <0.001
Daytime	< 1.0 µm	25.054	13.614	52.352	P = 0.009
Night-time	$< 1.0 \mu m$	23.144	13.476	47.780	P = 0.009
Daytime	$< 2.5 \mu m$	1.808	1.109	3.186	P = <0.001
Night-time	$< 2.5 \mu m$	1.567	0.928	2.726	P = <0.001
Daytime	< 10 µm	0.119	0.0565	0.221	P = <0.001
Night-time	< 10 µm	0.0666	0.0311	0.118	P = <0.001
Daytime	CO (ppb)	204.170	173.994	242.571	P = <0.001
Night-time	CO (ppb)	188.457	158.511	224.839	P = <0.001
		Weekend	ls		
Daytime	< 100 nm	6377.403	3682.225	10366.979	P = <0.001
Night-time	< 100 nm	5184.072	3116.472	7749.686	P = <0.001
Daytime	< 200 nm	569.866	315.020	974.525	P = <0.001
Night-time	< 200 nm	598.601	330.042	1047.595	P = <0.001
Daytime	< 1.0 µm	23.393	13.094	50.786	P = 0.813
Night-time	$< 1.0 \mu m$	24.876	12.249	52.308	P = 0.813
Daytime	$< 2.5 \mu m$	1.476	0.931	2.634	P = 0.314
Night-time	$< 2.5 \ \mu m$	1.457	0.860	2.472	P = 0.314
Daytime	< 10 µm	0.0701	0.0337	0.111	P = 0.438
Night-time	$< 10 \mu m$	0.0651	0.0371	0.103	P = 0.438
Daytime	CO (ppb)	188.266	158.533	224.672	P = <0.001
Night-time	CO (ppb)	204.745	166.262	247.678	P = < 0.001
		Weekdays-Weel	kends		
Group	Size	Median	25%	75%	P-value
Weekdays	< 100 nm	7369.8	4585.0	11416.5	P = <0.001
Weekends	< 100 nm	5843.1	3517.9	9131.1	P = < 0.001
Weekdays	< 200 nm	644.2	378.9	1015.5	P = <0.001
Weekends	< 200 nm	589.9	331.0	996.3	P = <0.001
Weekdays	$< 1 \mu m$	24.6	13.8	51.2	P = 0.015
Weekend	$< 1 \ \mu m$	24.1	12.8	50.5	P = 0.015
Weekdays	CO (ppb)	202.3	170.9	241.9	P = <0.001
Weekends	CO (ppb)	195.6	162.5	235.5	P = <0.001

2.3.7 Seasonal and diurnal variations: Rush hours effect

The diurnal pattern of particle number densities during weekdays and weekends shown in Figure 3.3(a-d). On weekdays, the first peak of nanoparticle's number density is observed between 6:00 to 9:00 a.m. linked with the morning rush hour (Fig 2.3(a)). The second peak of nanoparticle number density is observed around noon from 11:00 a.m. to 1:00 p.m., suggesting aerosols formation from photochemical pathways [12, 269]. On weekends, the nanoparticle number density increased later in the morning from 08:00 to 10:00 a.m. due to late vehicle circulation. The second peak was likely to correspond to the photochemical production of nanoparticles was observed at the same time as weekdays (11:00 a.m. to 1:00 p.m.). Nevertheless, we observed higher nanoparticle density at the weekend during the late night to early morning period from 10:00 p.m. to 05:00 a.m. in contrast to the same hours during weekdays, as shown in Figure 2.3(a, d). This could be associated due to the late-night activities in downtown Montreal.



Figure 2.3 Diurnal time series of weekdays to the weekend from May 2017 to May 2019. Particle number densities (#/ cm³) in different size aggregated ranges (a) < 100 nm and CO on weekdays, (b) < 200 nm, (c) < 1 μ m, (d) < 100 nm and CO on weekends. (a,d): The left-hand scale on Y-axis represents the nanoparticle's number density, and the right-hand Y-axis shows the CO mixing ratios.

We also explored the diurnal pattern based on the seasons. Nanoparticle number densities exhibited the three-peak pattern in all seasons, as shown in Figure 2.4(a-d). These three peaks were observed corresponding to morning, midday, and evening hours, respectively. The first peak of nanoparticles was observed consistently with morning rush hours in all seasons, which reflects a higher traffic density. The highest number density of nanoparticles was observed in winter morning rush hours compared to the other seasons, partly due to the idling of cars, more energy to heat the cars at subzero temperatures, and more extended circulation period due to snow/ice coverage on the roads. The midday peak of nanoparticles was observed from 12:00 - 01:00 p.m. in all seasons, suggesting that the formation of new particles by the photochemical process [269, 270]. The night peak was observed around 08:00 p.m. in winter, while the peaks shifted around 09:00 p.m. to 10:00 p.m. during summer seasons. This is attributed to longer daytime hours in the summer. Besides, the late-night activity starts in the summer bit later than the winter months shift the local traffic later in the night.



Figure 2.4 Seasonal, diurnal plot for nanoparticle number density (#/cm³). (a) Summer months from 2017 and winter from 2017-2018., (b) Summer months from 2018 and winter from 2018-2019., (c) Spring and fall month from 2017 and (d) Spring and fall month from 2018.

2.3.8 Anthropogenic sources of nanoparticles

The spearmen correlation coefficient values (Table A4) and closely correlated diurnal time series of particle number densities with CO during weekdays and weekends, as shown in Figure 2.3(a-d). The monthly time series of co-pollutants such as CO, O_3 , NO_x , SO_2 , and $PM_{2.5}$ are shown in Fig. A4. On weekdays, the mixing ratios of CO and nanoparticle concentrations are increasing simultaneously during morning rush hours and evening rush hours, as shown in Figure 2.3(a), hinting at the similar emission sources and the predominance of anthropogenic activities. Whereas during the afternoon from 12:00 to 02:00 p.m., the nanoparticle number density increases, but CO concentration decreases. The nanoparticles peak at noon comes due to the photochemical pathways, while the lower mixing ratios of CO are associated with less traffic in the afternoon. The positive correlation (r = 0.74) was observed between the nanoparticle number density and CO during weekdays morning rush hours (Fig. 2.3a). It suggested that nanoparticle number densities are likely associated with a strong influence of traffic emissions in urban environments [223, 265]. CO and nanoparticles also showed a positive correlation on weekends during early evenings to late-night, as shown in Figure 2.3d, which indicates the combined effect of traffic along with late-night outings/activities in the downtown area.

2.3.9 Snow impact on nanoparticles

Table 2.4 illustrates the statistical analysis of snow impact on nanoparticle distributions. We classified three snowfall events. We provided the nanoparticles number densities in the day before, during, and next day to a snowfall event (Table 2.4). The meteorological information (T, RH, total precipitation and total snow on the ground) are also shown in Table 2.4. We observe that the snowfall affected the nanoparticle number densities. The impact of snow on nanoparticles is dependent on several factors, such as the wind speed, frequency, duration and intensity of precipitation, humidity, etc. For instance, in events 1 and 2, the mean number densities of nanoparticles during snowfall were observed to be 5627.8 cm⁻³ and 21397.7 cm⁻³, respectively. While, the next day to a snowfall, nanoparticles number densities were observed 5075.5 cm⁻³, 15685.8 cm⁻³, respectively. These observations suggested that the snowfall enhanced the nanoparticle number densities. It could be due to the deposition of exhaust vapour on the snowflakes. In contrast, during event 3, the average nanoparticle number densities were observed

a slightly higher day after snowfall than during snowfall, as shown in Table 2.4. The behavioural differences of the snow event 3 in comparison to the snow events 1 and 2, might be due to the colder day temperature (average temperature -15.7 °C), associated with the increase in the vehicle density and the higher requirement of local heating. In addition, the clear sky on that particular day may have elevated the photochemical production of nanoparticles. Snowmelt contains various organic and inorganic contaminants. Thereby, it is vital for future study to consider the concurrent physicochemical measurements of snow/ice/air interfaces, as well as understanding the snow photochemistry during and after snowfall/snowmelt process, are essential parameters to model and assess their impacts on cold-climate urban air quality [150, 271, 272].

Table 2.4Snow impact on nanoparticles. Three snow events were analyzed. Mean, median number
densities of nanoparticles were calculated the day before, during and the day after a
snowfall in each event. The averages temperatures, relative humidity, total precipitation,
and snow on the ground data are also given.

Snowfall events	Days	Total	Snow on	Number density		CO	Ave.	Ave.		
(MM/DD/YYYY)		prec.	the	(number/cm ³)			Temp	RH		
			ground							
		(mm)	(cm)	Mean	Median	(ppb)	(°C)	(%)		
	Event 1									
Before	12/2/2018	17.6	9	9604.2	7606.3	268.2	1.8	93.7		
During	12/3/2018	8.9	6	5627.8	4510.1	294.7	1.4	87.8		
after	12/4/2018	-	7	5075.5	4702	177	-4.5	61		
Event 2										
Before	1/28/2019	-	61	18558.1	16600.1	210.8	-17.4	44.3		
During	1/29/2019	8	60	21397.7	21285.6	269.5	-12.5	79		
after	1/30/2019	0.2	71	15685.8	13610.2	210.1	-10.9	59.9		
Event 3										
Before	2/25/2019	0.2	84	5508.8	4187.5	182.7	-4.5	63		
During	2/26/2019	0.2	82	16371	16476.2	203.5	-14.5	49.1		
after	2/27/2019	-	82	19856.4	18107	260.8	-15.7	53.4		

2.4 Importance of emerging metal contaminants observations in the atmosphere

2.4.1 Potential environmental implications of airborne metal-containing nanoparticles

The extensive usage of anthropogenic nanoparticles/nanomaterials in diverse domains such as construction, pharmaceutical, cosmetic, health, and electronics industries can add to the complexity of urban atmospheric chemistry [259]. The production and the usage of nanomaterials have been suggested to increase metallic-nanoparticles into the Earth's environment, including in the atmosphere [229, 273]. Once the nanoparticles enter the environment, they can undergo complex processes. These particles can interact with other particles or gases compounds and alter the aerosol numbers. Size distribution, and their chemical composition, and optical properties are influencing urban air quality [274]. Examples of other chemical reactions, including the interactions, include reactions with halogens in cities [275, 276]. There is now increasing evidence that halogen oxidation is not only crucial in polar or marine environments but also coastal cities [276, 277]. Additional reactions include the transformation of organic compounds [278], interactions with trace metals such as mercury [259, 277, 279], and composite reactions with ozone. Several of these processes can furthermore be influenced by surfaces, such as snow/ice [153, 271]. It is noteworthy that urban chemistry is closely linked with meteorology and urban built, and thus increasingly complex. There are also feedbacks between biogeochemical processes and atmospheric chemistry [49]. We recommend future integrative studies to understand these emerging aspects of urban chemistry in an evolving chemical environment.

2.4.2 The Importance of this metadata to improve cold-climate air quality modelling

An inherent assumption in most air quality and climate models is that within a specific size range, the aerosols are internally mixed concerning composition and morphology. However, observations in this study demonstrate various compositional and morphological mixing states within a single size range. The assumption of complete internal mixing can lead to the inaccurate prediction of gas-particle partitioning and climate-relevant aerosol properties such as cloud condensation nuclei concentrations and optical properties in models [280]. The findings in this study will motivate improved representation of mixing state in models, and the measurement data will facilitate the detailed evaluation of modelled aerosols in simulations of urban air quality.

2.5 Conclusions and future directions

- We herein provided self-consistent 2-years real-time metadata on number density, distribution and selected physical and chemical characterization of airborne particles for a model cold climate urban site of Montreal.
- We observed distinct seasonal variations of aerosols in this cold-climate city, namely the highest nanoparticle density in winter.

- We demonstrate that in the cold-climate urban regions, the combination of winter meteorology (lowering of the boundary layer and suppression of vertical mixing) and higher pollution emission due to the enhanced usage of energy (transport sector and heating building) enhance nanoparticle density in the lower troposphere, which is currently not considered. Nevertheless, it is of potential significance in human health and air quality.
- We provided evidence that nanoparticle formation is of anthropogenic origin during the rush hours. The high-resolution S/TEM confirmed that airborne nanoparticles are not ubiquitously spherical; the nanoparticles exhibited varied structures single/cluster, chain-like, regular, and irregular. We observed a suite of emerging contaminants such as Ni, Cd, Zn, Pb, and As in particles of all sizes, including in nanosize particles. Diverse anthropogenic sources of precursors, ever-increasing emission of emerging contaminants further complicating the urban atmospheres.
- Cold temperature, snow/ice surfaces, in addition to Urban built, are likely factors that can alter the atmospheric chemistry of cold climate. Various salts are being used for the deicing of urban surfaces in cold-climate cities. These salts have been recently shown to produce tropospheric oxidants such as photolabile chlorine [281]. We recommend that air quality and climate models adapt to the unique features of cold-climate urban regions.
- Further physical, chemical, biogeochemical, and health studies are required for better understanding and modelling of urban air quality in a changing climate and increasingly complex chemical emissions.

Acknowledgments

We acknowledge the Natural Science and Engineering Research Council of Canada (NSERC), Environment and Climate Change Canada (ECCC), as well as NSERC Create Mine of Knowledge for their financial support. Dominic Bélanger and Dr.Marc Amyot (Université de Montréal, Canada) for their help with the ICP-MS/MS measurements. David Liu (McGill University, Canada) for the TEM measurements. We also thank Kelly Kong and Nafisa Islam for their help in proofreading the manuscript.

Chapter 3 Advancing the Science of Dynamic Airborne Nanosized Particles using Nano-DIHM

There is an immediate need to develop a comprehensive understanding of atmospheric aerosols, which play a critical role in air quality, climate change, and human health. Currently, various measurement techniques are available to measure atmospheric aerosols, including directsampling techniques such as impactors and filters, real-time aerosol sizers, and remote-sensing techniques such as lidar and satellite-based measurements (as discussed in section 1.8). However, these methods cannot retrieve the three-dimensional (3D) size, shape, phase, and surface properties as a whole in real-time. In this Chapter, we developed a new approach based on digital in-line holography microscopy (DIHM) to integrate with a flow tube (Nano-DIHM), allowing for the realtime, 3D characterization of particles in the atmosphere, shape, phase, and surface properties which is particularly useful for understanding the properties of non-spherical particles. This method uses a laser to illuminate particles in the air and a camera to capture the resulting holographic image. The image is then processed using computational numerical methods to extract information about the particles' size, shape, phase, and surface properties in real-time. One of the main advantages of Nano-DIHM is that it can measure a wide range of particle sizes and types, including spherical and non-spherical particles and particles with diameters as small as a few nanometers. In addition, this technique can be used to simultaneously measure multiple particle populations, which is vital for understanding the complex nature of atmospheric aerosols. The advances in holographic microscopy will provide a low-cost, portable, easy-to-use instrument option to deploy in different regions and environments.

This Chapter consists of the following published article in peer-reviewed journals:

Pal, D., Nazarenko, Y., Preston, T. C., & Ariya, P. A. (2021). Advancing the science of dynamic airborne nanosized particles using Nano-DIHM. *Communications Chemistry*, *4*(1), 170.

DOI: https://doi.org/10.1038/s42004-021-00609-9

Advancing the Science of Dynamic Airborne Nanosized Particles using Nano-DIHM

Devendra Pal¹, Yevgen Nazarenko¹, Thomas C. Preston^{1,2}, and Parisa A. Ariya^{1,2}

¹Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 0B9, Canada.

²Department of Chemistry, McGill University, 801 Sherbrooke Street West, Montréal, QC H3A 2K6, Canada.

© The Author(s) 2021. Used with permission.

Abstract

In-situ and real-time characterization of aerosols is vital to several fundamental and applied research domains including atmospheric chemistry, air quality monitoring, or climate change studies. To date, digital holographic microscopy is commonly used to characterize dynamic nanosized particles, but optical traps are required. In this study, a novel integrated digital in-line holographic microscope coupled with a flow tube (Nano-DIHM) is demonstrated to characterize particle phase, shape, morphology, 4D dynamic trajectories, and 3D dimensions of airborne particles ranging from the nanoscale to the microscale. We demonstrate the application of Nano-DIHM for nanosized particles (≤ 200 nm) in dynamic systems without optical traps. The Nano-DIHM allows observation of moving particles in 3D space and simultaneous measurement of each particle's three dimensions. As a proof of concept, we report the real-time observation of 100 nm and 200 nm particles, i.e. polystyrene latex spheres and the mixture of metal oxide nanoparticles, in air and aqueous/solid/heterogeneous phases in stationary and dynamic modes. Our observations are validated by high-resolution scanning/transmission electron microscopy and aerosol sizers. The complete automation of software (Octopus/Stingray) with Nano-DIHM permits the reconstruction of thousands of holograms within an hour with 62.5 millisecond time resolution for each hologram, allowing to explore the complex physical and chemical processes of aerosols.

3.1 Introduction

In-situ and real-time characterization of airborne particle (aerosol) size, phase, and morphology is vital to several fundamental and applied research domains, including atmospheric chemistry and physics [282], air quality [283, 284], climate change [108, 285, 286], and human health [94]. Aerosols are diverse and are emitted from anthropogenic or natural sources. Aerosols undergo physicochemical transformations in the atmosphere on a wide range of spatial and

temporal scales [10, 284]. Aerosols can contain biological particles such as bacteria and viruses [287]. Airborne Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) virion-containing aerosols are significant in the COVID-19 transmission [288-290].

Nano-objects that comprise nanomaterials refer to matter dispersed into individual objects with one or more external dimensions, or an internal structure, on a scale from 1 to 100 nm [98]. The most abundant airborne particles in the atmosphere are nanosized (< 200 nm diameters) [1, 72, 73]. Nanosized particles have a large surface-to-volume ratio. They can be photoreactive and serve as cloud condensation nuclei [286, 291, 292] or ice nuclei [23, 293]. Nanoparticles are also involved in coagulation [291, 294] and phase transition processes [295], which are vital to understanding aerosol-cloud interactions [285, 286, 292]. Prior to this study, to our knowledge, the phase of nanoparticles has never been determined in situ in dynamic ambient air.

There has been significant progress in in-situ aerosol analysis during the last decade, including in-situ analysis of nanoparticles in air [1, 2, 24, 38, 39, 72, 73, 267, 279, 282, 283, 296]. Yet, no existing technique allows the determination of airborne particles' phase in situ and in real time; and so in-situ phase determination, despite its importance, remains a key challenge [297]. There are various real-time aerosol characterization techniques, including in-situ optical/laser or condensation-based and electron mobility analysis [23, 73, 279]. However, these techniques fail to provide information on the behaviour or dimensions of aerosols. Offline analysis following the collection of aerosols using impactors [72, 73], impingers, precipitators, and filters is often more informative yet does not provide real-time data or information regarding aerosol dynamics. Significant advances in microscopy during the recent decades have enabled researchers to observe individual nanoparticles [298, 299], using techniques such as near-field optical microscopy [300-302], super-resolution microscopy [303-305], atomic force microscopy [306], electron microscopy [307] and other more recently developed imaging techniques [308-312]. Among them, Scanning Transmission Electron Microscopy (S/TEM) enables acquiring accurate information on particle phase and morphology in stationary mode [23]. Bright-field and dark-field optical microscopy provide two-dimensional information on particles, albeit in a limited depth interval within samples [309, 313]. A challenge with conventional light microscopy methods is that these methods work in fixed imaging planes [313], which precludes determining aerosol dynamics, phase, and 3D morphology of aerosols [313]. However, the 3D structure information can be obtained using

Fourier ptychography [314], optical diffraction tomography [315] or by scanning the whole sample/particle volume using confocal imaging [316]. All these existing microscopy techniques have significant advantages, yet they cannot track moving particles in situ or in real time, precluding their application to dynamic media, such as air.

Here, we provide an alternative approach of Nano-DIHM. The Nano-DIHM consists of a holographic microscope[317] and a gas flow tube that allows airborne particles to pass through the imaging volume of the DIHM and exit or circulate inside the volume, allowing observation of single particles or ensembles of particles in real time. Nano-DIHM directly acquires data on interference patterns of the incident and scattered light with a light-sensitive matrix, without any lenses or objective [318]. The recorded interference pattern referred to as a hologram is numerically reconstructed using an Octopus/Stingray software based on a patented algorithm [319] to recover the object information [318, 320]. To date, digital holography setups could merely characterize particles held in electrodynamic [321, 322] or optical traps [323, 324] or particles deposited on a substrate [310, 318, 320, 325-327]. It is noteworthy that optical trapping of airborne particles requires optical tweezers, trapping only a single particle confined to the field of view [324, 328, 329]. The Nano-DIHM has a larger field of view up to several square centimetres (~ 1.27 cm², 2048×2048 pixels, 5.5 µm each pixel size). In this study, the Nano-DIHM field of view of up to $\sim 40 \text{ mm}^2$ enables observation of moving objects, in contrast to conventional optical microscopy that uses lenses and has smaller fields of view (a few micrometres) [309, 310]. Until now, investigations of airborne particles by DIHM have been confined to relatively large particles (> 1 µm) [330-335]. We show that Nano-DIHM can detect nanosized objects in 2D and 3D space for dynamic (air), aqueous (water) and solid (powder) media. We were able to track individual airborne nanoparticles directly and quantify each particle's dimensions in situ and in real time. The Nano-DIHM enabled us to record six-dimensional spatial motion of aerosol particles (3D for the position of each particle in 3D space) and the dimensions of each particle as it is orientated in 3D space [325, 336]. A critical advantage of Nano-DIHM is that, during reconstruction, a single 2D hologram can produce a 3D image of the objects without any loss of resolution [318, 325]. The Octopus/Stingray software allows real-time or offline reconstruction with a temporal resolution on the order of milliseconds (62.5 ms), and it can be improved to microsecond-scale temporal resolution, depending on the framerate of the camera [324, 332, 337, 338].

3.2 **Results**

We demonstrated that the developed Nano-DIHM detects single and cluster aerosols in situ and in real time, in dynamic and stationary media such as air, water and heterogeneous matrices. We further performed intercomparison of the aerosol size distribution measured using a Scanning Mobility Particle Sizer (SMPS) and an Optical Particle Sizer (OPS) and S/TEM with the observation made by the Nano-DIHM. The SMPS and OPS can only measure particle size distributions and cannot track particle position in space or individual particle dimensions in 3D, in contrast to Nano-DIHM. In the following section, we demonstrate: (1) the observation of airborne PSL particles (100 nm and 200 nm) and their dynamic trajectories; (2) the detection of the 100 nm and 200 nm PSL particles in colloid solution deposited on a microscope slide; (3) distinguishing the PSL and mixed metal oxide nanoparticles; (4) semi-automation of the software (Octopus/Stingray), which allows the reconstruction of thousands of holograms within an hour; and (5) the observation of ambient particles in the air and snow in real time and in situ (Appendix B1.1). Finally, the demonstration of the accuracy of measurement of refractive index is presented (Appendix B1.2). The experimental parameters for each experiment are given in Table 3.1. More details are provided in the Methods section.

Sample matrix	SSD (mm)	Flow rate	Hologram size	Camera pixel
		(L/min)	(pixels)	size (µm)
PSL (air) ¹	5	1.7, 0.7	2048×2048	5.5
Snow meltwater (air)	5	1.7, 0.7	2048×2048	5.5
Ambient air	5	1.7, 0.7	2048×2048	5.5
Snow meltwater	5	Stationary	2048×2048	5.5
PSL (liquid) ²	5	Stationary	2048×2048	5.5
100-fold PSL (liquid) ³	5	Stationary	2048×2048	5.5
PSL+Iron oxide (liquid)	5	Stationary	2048×2048	5.5
Glycerin+oil (liquid) ⁴	5	Stationary	2048×2048	5.5
Zinc oxide (powder)	5	Stationary	2048×2048	5.5
Iron oxide (powder)	5	Stationary	2048×2048	5.5

Table 3.1 Detailed experimental parameters for the matrices used.

Both 100 nm and 200 nm PSL spheres aerosolized (see method section) and analyzed by Nano-DIHM 1 The original colloid solution of PSL spheres (100 nm and 200 nm) 2

100 µL of the original colloid solution of the PSL spheres mixed with 10 mL of Milli-Q water 3

4 100 µl of glycerin in 1 ml of type F microscope oil

3.2.1 Detection of airborne nanosized objects using Nano-DIHM: Beyond the diffraction barrier

One of the significant limitations of optical microscopy, including digital holography, is overcoming the diffraction barrier of the system to detect nanosized objects with visible wavelengths. To mitigate this challenge, recently, different experimental and numerical focusing approaches have been developed [310, 327, 339-341]. In this study, an ensemble of three routines is used to overcome the diffraction barrier: (1) keeping a minimum distance between the pinhole and the sample, (2) numerical reconstruction using Octopus/Stingray software [342, 343] based on Kirchhoff–Helmholtz transform to achieve the high resolution [319, 344, 345], and (3) several holograms are formed in an aqueous medium (water), and thus the wavelength of the laser is reduced [318, 346] from $\lambda = 405$ nm to ~ 300 nm, which creates favourable conditions to achieve the high resolution. More details are provided in the Methods section. We thereby successfully demonstrated the first-time in-situ real-time observation of airborne nanosized objects using the Nano-DIHM (Figs. 3.1-3.4) and validated the results using aerosol sizers.

The Nano-DIHM effectively resolved the size and shape of airborne nanosized PSL particles with dimensions ranging from nano- to microscale. Figure 3.1(a-n), Figure 3.2(a-c), Appendix Figure B1, and Table 3.2 provide information on the aerosolized 100 nm PSL particles, and Figure 3.3(a-o) and Figure B2(a-f) provide information on the 200 nm aerosolized PSL particles. The PSL particle size and spherical shape determined by the Nano-DIHM matched the standard PSL particles' specifications (standard diameter, 101 ± 7 nm) for 100 nm and 200 nm PSL (standard diameter, 188 ± 4 nm). The size data also aligned with the results of simultaneous analysis of the aerosol size distribution in the outflow from the Nano-DIHM optical cuvette performed using the SMPS and the OPS instruments, measuring the aerosol size distribution in the particle size range from 10 nm to 10 µm (Fig. 3.1(m, n)).

Table 3.23D size distribution of 100 nm PSL spheres in the aerosol phase. Descriptive statistics for
the dimension distributions of the PSL spheres in 3D space in a single hologram.

Statistics	Width (µm)	Height (µm)	Length (µm)
Mean values	0.264	0.265	0.739
Standard deviation	0.287	0.274	0.672
Median values	0.177	0.174	0.643
99 th percentile	1.362	1.316	3.347
1 st percentile	0.014	0.013	0.016



Figure 3.1 Reconstruction of the intensity information for 100 nm PSL particles in the aerosol phase. (a) Raw hologram recorded for airborne PSL particles; (b) background hologram recorded without PSL particles; (c) contrast hologram obtained after subtracting the background hologram from the raw hologram. (d) Zoomed-in area of c1 at $z=3109 \,\mu\text{m}$. (e) Particles in focus from (d). (f) Zoomed-in area of (e) showing the precise recovery of nanosized PSL particles and their shape. (g, h) Phase reconstruction of PSL particles. The line across the numbers 1 and 2 in Figures f and h shows the crosscut across the particles. (i, j) The phase profile of the PSL particle crosscut. (k, l) The intensity profile of PSL particles across the particle crosscut. (m, n) The size distribution of PSL particle aerosols measured by the SMPS and the OPS, respectively. The red dashed line and the black line correspond to the two repeats of the experiments. The Blue dotted line is a Gaussian peak fit for the data. The validation of the holographic reconstruction of 100 nm PSL particles was compared with S/TEM images in Figure 3.4. The 4D dynamic trajectories of the particles are provided in Movie 1 and Movie 2. The background holograms recorded for zero air and particle concentration tested by the SMPS and the OPS are shown in Appendix Figure B3.

Examples of intensity and phase reconstructions for the 100 nm PSL spheres in the moving air are depicted in Figure 3.1(a-h). The raw hologram in Figure 3.1(a) was recorded for the airborne PSL spheres, which carried the information of phase, size, and shape, while the background hologram (Fig. 3.1(b)) was recorded without PSL particles and only dry air purified used with three HEPA filters, leading to a particle-free spectrum, and the contrast hologram (Fig. 3.1(c)) is a result of subtraction of the background hologram from the raw hologram. Subtracting the background from the raw hologram removes the possible contamination due to the source (pinhole imperfections) and the object holder (a cuvette or microscope slide). Thus, this process significantly improves the reconstruction of an image, as discussed in numerous publications [318, 325, 347]. The reconstruction of the cropped area (c1) in Figure 3.1(c), as displayed in Figure 3.1(d), is of interest. Figure 3.1(e) is an example of high-resolution images of Figure 3.1(d); this high resolution is achieved by performing deconvolution and in-focus reconstruction, thus enhancing image quality, and reducing noise [318, 325, 336, 341, 344, 348-350]. Figure 3.1(f) is a zoomed-in area of Figure 3.1(e), revealing information on nanosized objects and their shape.

Phase reconstruction of the identical hologram exemplified in Figure 3.1(g, h) yields the replicate size and shape of airborne PSL particles as intensity images (Fig. 3.1(e)). The intensity profiles along the crosscut of particles (1 and 2) are shown in Figure 3.1(k, l) while their phase response in Figure 3.1(i, j), respectively. The particle size determined by the Nano-DIHM along the crosscut through particle 1 is 160 nm and 200 nm, and 119 nm through particle 2 (Fig. 3.1(f and h)), expressed as the full width at half maximum (FWHM) (Fig. 3.1(i-l)). As shown in Figure

3.1(I and k), the Nano-DIHM successfully recovered the particle images within a lateral dimension of ~ 200 nm in agreement with the previous study [341, 344], which stated the lateral resolution is achievable on the scale of a half of the wavelength (λ /2). The diameters of the PSL spheres determined by the Nano-DIHM vary from nano- to submicrometer-scale and are validated by the SMPS and the OPS data for the same samples (Fig. 3.1(m, n)). The 100 nm airborne PSL particle size determined by the Nano-DIHM agreed well with the particle size simultaneously measured using the SMPS and the OPS. During the numerical reconstruction process, many particles can be in focus at a given Z value. Previous literature has shown similar results at a given Z value, and many particles were detected [310, 318, 325, 327, 332, 346, 347]. For example, Xu et al. [325] in Figure 6 showed that several particles could be detected at a particular Z value.



Figure 3.2 3D size distribution of 100 nm PSL spheres in the aerosol phase. (a) The orientation of PSL particles. (b) Width, height, and length distribution of PSL particles in a single hologram over 62.5 ms. (c) Highlighted PSL particle size distribution from (b) within the nanosized width of particles. Another 3D reconstruction of different holograms is shown in Figure B1.

Figure 3.2(a, b) displays the 3D orientation/position of particles and the individual dimensions (width, height, and length) of PSL aerosol particles. The descriptive statistics of 100 nm PSL spheres in 3D space are provided in Table 3.2. The median values of the width, height and length determined by the Nano-DIHM are 177 nm, 174 nm, and 672 nm, respectively. The first percentile of the observed particle dimensions is 14 nm (width), 13 nm (height), and 16 nm (length), which is evidence that Nano-DIHM can be used for nanoparticle measurements. Furthermore, the SMPS size distribution of airborne PSL particles exhibits a good agreement with the width and height of particles observed by the Nano-DIHM and suggests that the most abundant PSL particle size peaks between 100 nm and 160 nm.

Another confirmation for positive observation of 200 nm airborne PSL particles measured in real time in situ by Nano-DIHM is shown in Figure 3.3. The intensity and phase reconstructions of airborne PSL particles are displayed in Figure 3.3(a-i), and their intensity responses across the crosscut of particles are shown in Figure 3.3(j-m). Nano-DIHM reveals the ~200 nm particles as well as particles of larger diameter ~ 1.4 μ m (Fig. 3.3(e)). In addition, intensity and phase profiles through the crosscut of the PSL particles were determined for the ~ 400 nm, ~ 500 nm, and ~ 2 μ m particles (Fig. B4(a-d)). Nano-DIHM and the SMPS/OPS confirmed that the PSL spheres include a wide range of particle sizes ranging from 10 nm to 10 μ m in the airborne state. The recovery of the shape and size information for a single PSL particle (Fig. 3.3(c, f)) unveils that Nano-DIHM can also be used for single-particle detection. The Nano-DIHM worked effectively not only for single aerosol particle detection but also allowed the multiparticle scanning of the total aerosol sample (Fig. 3.2(a-d), Fig. B2(a-f)).

The particle's orientation and dimensions are shown in Appendix Figure B2(a-f), and the tabular form of Figure B2(c and f) provides the statistics for the 200 nm PSL spheres in 3D space. The median values of the width, height and length determined by the Nano-DIHM were: 319 nm, 319 nm, and 678 nm, respectively. The 1st percentile of the observed particle dimensions was 23 nm (width), 23 nm (height), and 15 nm (length). The length of the PSL spheres was observed to equal almost twice the width and height. It may be because two or more particles in different planes were closer than the depth resolution (362 nm); the Nano-DIHM could not distinguish them and observed them as a single particle. This limitation should be considered in future studies. We



recommend the usage of further length correction methods along other routes to reduce or eliminate this limitation.

Figure 3.3 Holographic reconstruction of 200 nm PSL airborne particles. (a) Raw hologram; (b) zoomed-in region of (a) at Z=1547 μ m. (d, e) Phase and intensity reconstruction of the region of box b1 in (b). The arrow mark indicating the airborne PSL particles from nanosized to the larger diameter of particles. (g-i) Phase, intensity, and amplitude

reconstruction of PSL particles in the region of box b2 in (b), respectively. (c and f) are zoomed-in intensity and amplitude images of the PSL particle clearly showing the spherical shape. (j-n) intensity crosscut of particles 1, 2, 3, and 4 levels in panel (e), respectively. (n, o) The airborne PSL particle size distribution confirmation by the SMPS and the OPS. Various other S/TEM and their holographic reconstruction comparisons are included in Figure 3.5. More intensity crosscuts of particles are shown in Figure B4.

As seen, in both cases, the particle size distributions of the 100 nm and the 200 nm PSL spheres in the airborne state obtained by the Nano-DIHM agreed with the particle size distributions measured by the SMPS and the OPS (Fig. 3.1(m, n) and Fig. 3.3(n, o)). The observed size distribution of airborne PSL spheres obtained by both the Nano-DIHM and the SMPS and OPS was bimodal. This size distribution had a broader peak between 100 nm and 160 nm for the 100 nm PSL particles (Fig. 3.1(m)) and between 150 nm and 300 nm for the 200 nm PSL (Fig. 3.2(n)) corresponding to the 150 and 300 nm, consistent with the particles' median dimensions determined by the Nano-DIHM (Fig. 3.2(c), Appendix Fig. B1(c) and Fig. B2(c and f)).

The aerosolized Milli-Q water peak was observed by the SMPS and the OPS between 30 nm and 50 nm (Fig. B5). At the same time, the following median values for the same water sample were observed by the Nano-DIHM (Appendix Table B1): 41 nm (width), 43 nm (height). They aligned well with the SMPS and OPS measurements (Fig. B5(a-d)). The Milli-Q water peak at around 30 - 50 nm is typical of various aqueous dispersions and arises from condensed dissolved compounds in the solution [1, 351] or may arise during aerosolization [1]. The median and mean particle dimensions varied within \pm 5 % from one hologram to the next during reconstructions of several holograms (Fig. B1 and Fig. B2). This uncertainty likely arises during hologram reconstruction due to the input digital image data that includes noise during the recording process.

3.2.2 4D trajectories of airborne PSL spheres

The dynamic 4D trajectories (3D positions and 1D time) of 100 nm PSL spheres are provided in Figure 3.4(a-d), <u>Movie 1 and Movie 2</u> with a temporal resolution of 62.5 ms. The <u>Movie 1</u> is a zoomed-in image of <u>Movie 2</u>. To obtain high-resolution trajectories of the airborne nanoparticles in this study, we used the following procedure: (1) A sequence of holograms was recorded at 16fps. (2) The background contaminations were eliminated by subtraction of consecutive holograms, and (3) the resultant holograms were reconstructed at a given plane and summed to obtain the final trajectories (16 holograms summed in Figure 3.4(a) and 9 holograms

summed in Figure 3.4(c)). Subtracting holograms ensured that the dynamic range was not exceeded and only the object-related information (moving PSL particles information) was retained [318, 352]. Figure 3.4(a and c) shows the sequential positions at successive recording times of the airborne 100 nm PSL particles contained in the sample volume in two reconstructions planes separated by 200 μ m. Figure 3.4(b) depicts the zoomed-in crop area of trajectories given in Figure 3.4(a) to provide the confirmation of the size of 100 nm PSL airborne particles. Sixteen sequential positions clearly define the trajectory of airborne PSL particles (Fig. 3.4(a)), which moving in a random fashion confined to a plane parallel to the flow tube cuvette.



Figure 3.4 Trajectories of 100 nm airborne PSL particles in motion within the flow tube cuvette. (a) Sum of 16 holograms with 62.5 ms temporal resolution. (b and e) The intensity response

of selected particles and their diameters are 180, 110 nm (FWHM), respectively. (c) Sum of 9 holograms with 62.5 ms temporal resolution. (d) reconstruction of summed hologram (c) in one plane with the trajectory of circled data in focus. The red arrows indicate the directions of particles motion.

All the reconstructions of the holograms were performed at the same reconstruction distance (z) and then processed to create the Giff movies. As depicted in <u>Movie 1</u>, the dark red particles are in the focus of the reconstruction plane, whereas some of the particles (green/blue) are slightly out of focus at the exact reconstruction distances due to the finite depth of field of the objective. As seen in Figure 3.4(a-d), some PSL particles are in the focus reconstruction plane, yet some are progressively out of focus, indicating that the motion direction also has a component perpendicular to the reconstruction plane. To overcome the out-of-focus reconstruction in-complete trajectories analysis, several reconstructions from the same hologram in many planes are necessary [318, 352]. As such, we demonstrated the ability of the Nano-DIHM to visualize particle trajectories.

3.2.3 PSL spheres in aqueous mode: confirmation with S/TEM

To evaluate whether Nano-DIHM can determine shapes, size, and morphology of individual PSL spheres in an aqueous state, we investigated the same samples of 100 nm PSL and 200 nm PSL particles using Nano-DIHM (Fig. 3.5(a-f) and Fig. 3.6(a-c)) and S/TEM (Fig. 3.5(j and i) and Fig. 3.6(d-f)). Figure 3.5(a-f) shows the reconstruction of the holograms in all three modes: intensity, amplitude, and phase. Figure 3.5(d-f) is a high-resolution image of Figure 3.5(a-c) and illustrates the PSL size, shape, and phases. The red circles and rectangles marked in Figure 3.5(d-f) highlight an example showing the consistency of the existence of 100 nm PSL particles in all three reconstruction modes and the alignment of these Nano-DIHM measurements with the particle size and shape determined by S/TEM (Fig. 3.5(g and i)).



Figure 3.5 Holographic detection of 100 nm PSL particles deposited on a microscope slide. (a-c) Intensity, amplitude, and phase reconstructions at reconstruction distance Z=1353 µm. (d-f) In-focus high-resolution reconstructions of images at Z=1347 µm corresponding to (a-c), respectively. (g and i) S/TEM images of the same 100 nm PSL samples. (h) Intensity reconstructions at Z= 1650 µm. Circle 1 and rectangular box 1 in the image (g) are similar to the holographic reconstruction (d-f). (j-k) Intensity crosscut of particles shown in (h). And (l) EDS data of PSL particles. The Blue dotted curve in (j, k) presents the Gaussian peak fitting of the data.

As shown in the S/TEM images (Fig. 3.5(g)), the red circle 1 and rectangle 2 revealed the similarity to the PSL particle shape obtained by Nano-DIHM (Fig. 3.5(d-f)). The S/TEM image (Fig. 3.5(i)) confirmed that the PSL particle size ~ 100 nm is in a good agreement with the observed

median values of PSL particle width (110 nm) and height (120 nm) obtained in 3D space by Nano-DIHM (Table B2). Thus, the observations of PSL particle size and shape made by S/TEM and Nano-DIHM are well-matched with the size of the manufactured PSL spheres (standard diameter 101 ± 7 nm). The intensity response of particles along the crosscut is shown in Figure 3.5(j, k). The energy-dispersive X-ray spectroscopy (EDS) data for PSL particles presented in Figure 3.5(i) confirmed the PSL sample quality.



Figure 3.6 Holographic reconstruction of 200 nm PSL particles deposited on a microscope slide and their validation by S/TEM images. (a) Intensity reconstruction at 2318 μm. (b) Zoomed-in area of (a). (c) In-focus, high-resolution reconstruction at Z=2321 μm. (d-f) S/TEM images of same 200 nm PSL samples. Circle 1 and 2 in image (c) show the good agreement with S/TEM images shown in (d, e). (g) Intensity crosscut of particles in (c) with a diameter of 205 nm. (h, i) Intensity and phase crosscut of particles with the confirmation of existing clusters of PSL particles. Similar confirmation by S/TEM image in (e) suggested the presence of a cluster of PSL particles. Phase reconstruction of 200 nm PSL particles shown in Figure B6.

We also show another example of validation of particle size and their shape made by Nano-DIHM with S/TEM (Fig. 3.6). Here, we examined a 200 nm PSL particle deposited on a microscope slide. The size and shape determined by Nano-DIHM (Fig. 3.6(a-c)) are complemented with S/TEM images (Fig. 3.6(d-f)). In Figure 3.6(c), circles 1 & 2 show PSL particles imaged by Nano-DIHM are parallel to images made by S/TEM shown in Figure 3.6(d, e). The intensity response along the crosscut of the PSL particle shown in Figure 3.6(g) indicates a single particle with a diameter of ~ 198 nm, which is similar to the size provided by the manufacturer (standard diameter 188 \pm 7 nm) and the size measured by the S/TEM (Fig. 3.6(e, f)). The S/TEM images (Fig. 3.6(e)) confirmed that PSL particles existed as agglomerates or clusters. The Nano-DIHM also confirmed the presence of agglomerates or clusters (Fig. 3.6(h, i)). Although the Nano-DIHM identified the overall shape of particles, it did not decipher the precise cluster shape of particles as the S/TEM did. The Nano-DIHM thereby provides promising results to determine the phase, shape, and size of the particles, yet high-resolution electron microscopy is a valuable tool for determining the refined shape, at this stage, despite the lacking in-situ and real-time imaging capabilities that Nano-DIHM offers.

3.2.4 Distinguishing PSL spheres from Iron oxide mixture: S/TEM

The shape, size, and morphology of PSL and iron oxide particles within the mixed sample of PSL particles and iron oxide particles have been successfully determined using Nano-DIHM. Figure 3.7(a) shows the reconstructed intensity image of mixed PSL and iron oxide particles on a microscope slide. The zoomed-in area in Figure 3.7(a) is shown in Figure 3.7(b-d). As depicted in Figure 3.7(b), the red arrows indicate the PSL particles, and the white arrows show the iron oxide particles or the iron oxide particles to which PSL particles are attached. The mixture of the same samples was also analyzed using S/TEM. The S/TEM images (Fig. 3.7(e)) confirmed the size, shape, and morphology of the PSL, and iron oxide particles determined by Nano-DIHM (Fig. 3.7(a-d)). The EDS data for Spot A and Spot B (Fig. 3.7(e)) shown in Figure 3.7(g, h) confirmed the identity of the PSL and iron oxide particles. The Selected Area Electron Diffraction (SAED) pattern is shown in Figure 3.7(f). High-resolution images in Figure 3.7(c, d) (zoomed-in areas 1 and 2 in Fig. 3.7(a)) depicted the different sizes and shapes of iron oxide particles and confirmed

the attachment of the PSL particles. The phase reconstruction of the same samples shown in the Figure B7 complements the S/TEM images. As discussed in this example, Nano-DIHM showed the capability to determine the size, shape, and morphology of the synthetic materials within the mixed samples and successfully distinguish the nanosized particles.



Figure 3.7 Holographic reconstruction of a mixed sample of 200 nm PSL particles and iron oxide nanoparticles deposited on a microscope slide and the validation by S/TEM images. (a)

Intensity reconstruction at 905 μ m. (b) Zoomed-in area circle 1 of (a). (c, d) Zoomed-in area circles 2 and 3 of (a). (e) S/TEM images of the same sample confirming the presence of both PSL and iron oxide nanoparticles. Circles 1, 2 and 3 are shown in Figure (a) and highlighted in Figure (b-d), respectively. (f) Selected area diffraction pattern and (g, h) EDS data for Spot A and Spot B, respectively. Phase reconstruction of the same samples and more S/TEM images are provided in the Supplementary Figure S7.

3.2.5 Tracking ambient airborne particles

Figure 3.8 illustrates examples of the capability of the real-time analysis of ambient airborne particles using Nano-DIHM.



Figure 3.8 Hologram reconstruction for ambient air showing different airborne particles' sizes, shapes, and morphologies. (a) Intensity reconstruction of airborne particles. (b, c) High-resolution intensity images. (d) Phase reconstruction of image a. (e) Phase image. The phase of particles through a cross-section were shown in appendix Figure B8(a-f). Simultaneously aerosol size distribution obtained from the SMPS, and the OPS were shown in Figure B9(a, b).

For instance, the intensity and phase reconstruction of real-time Nano-DIHM measurements of particles in ambient air is shown in Figure 3.8(a, d). Figure 3.8(b, c) shows two selected areas of Figure 3.8(a), identifying particles of two different sizes and shapes in the ambient air. The morphology of the particle in Figure 3.8(c) confirmed the presence of agglomerates. It is noteworthy that while the intensity image in Figure 3.8(b) does not indicate the particle's precise structure, the phase image of the same particle in Figure 3.8(c) resolves the particle's structure and morphology clearly. The morphology of the particle in Figure 3.8(b, e) suggests its biological origin. Particles with a similar morphology have been observed in previous studies using transmission electron microscopy [279, 353], which supports this particle's organic or biological origin. Yet, further genomic confirmation will be required for the positive determination of airborne microbiological entities. We observed the changing phase shift of the particle in Figure 3.8 (e) across crosscuts, and this is shown in Figure B8(a-f). Quantitatively, changing phase shifts of 2.4 to 4.2 radians were observed across particle crosscuts (Fig. B8(c-f)), suggesting the presence of multiple layers or particle heterogeneity.

3.3 Discussion

This study demonstrates the first real-time acquisition of size, shape, phase, and morphology information for free-flowing spherical and non-spherical particles in moving air in situ using Nano-DIHM. The successful use of the developed technique was also demonstrated for non-gaseous environmental matrices: water samples from the ambient environment and solid synthetic materials (zinc oxide and iron oxide) (Appendic B1.3). Nano-DIHM efficiently resolves the size and shape of PSL particles in moving air, demonstrating the newly developed technique's ability to describe aerosol dynamics with rapid sequential hologram acquisitions. The real-time dynamic trajectories of aerosols in atmospherically relevant conditions open the vast potential to investigate physicochemical properties of nanosized or micron-sized particles and their impact on climate and human health [324, 354]. Nano-DIHM successfully observed the original spherical shape and size of airborne PSL particles ~ 119 nm (Fig. 3.1(f)) in 2D space, while in 3D space, it detected nanoparticles ~ 10 nm (first percentile; Table 3.2 and Fig. B1(c)). Previous studies suggested that in holographic microscopy, in the volumetric reconstruction (3D space), particles/objects can be localized within 1 nm [355] in all three dimensions. Besides the detection of smaller particles, Nano-DIHM also determined the larger diameter particles (Fig. 3.3 and Fig.

B4(a-d)). The size distribution of PSL particles in the aerosol phase obtained by Nano-DIHM was validated by the SMPS and the OPS techniques (Fig. 3.1(m, n) and Fig. 3.3(n, o)).

In the ambient air, our results indicate that the Nano-DIHM technique can distinguish a broad range of particle sizes (nanosized to submicron-sized), resolving spherical, irregularly shaped particles and particles of varying morphology. The measurement of the real-time phase shift of ambient air particles was also achieved (Fig. B8(a-f)). The ability to accurately measure the real-time phase shift and the refractive index is significant in the characterization of ambient air particles. Furthermore, it allows distinguishing between particles of different compositions, liquid vs. solid particles, such as water droplets and ice crystals in real time and in situ. For example, the analysis of the size and phase of snow-borne particles in the dynamic and stationary mode has been discussed in the Appendix B1.1. Nano-DIHM successfully recovered the phase and size of snow-borne particles (Fig. B12), and S/TEM validated their morphology (Fig. B13).

The Nano-DIHM accurately determined the refractive indices of moving aerosols in the gas phase. We determined the refractive indices of particles in a liquid suspension (Appendix B1.2). The reconstructions at different crosscuts through particles validate that Nano-DIHM effectively distinguishes refractive index variations of 0.001. Such results are consistent with the past studies [346, 356]. Prior to this study, only optical trapping techniques enabled refractive index measurements for aerosols. Accurate determination of the refractive index allows inferences about particle composition [357, 358]. For instance, optical chromatography has been previously used to identify the chemical composition of particles based on their size and refractive index [357-359]. The combination of theoretical and experimentally measured refractive index values has also been used to distinguish particle types [358, 360]. The considerable improvement of the resolution and the lower size limit of particles amenable to analysis by Nano-DIHM opens a range of new applications for the technique in future by permitting real-time and in-situ measurements of the phase, size, shape, and refractive indices of particles.

The attained temporal resolution of 62.5 ms can still be improved to the level of microseconds through further optimization, such as changing the frame rate of image acquisition, the shutter speed, or using a detector with a higher resolution [332, 337, 346]. Furthermore, the successful implementation of fully automated Stingray software with Nano-DIHM would allow

the reconstruction of thousands of holograms within an hour's interval time, allowing the exploration of the aerosol's complex physical and chemical processes in the future [337]. We have started to train the Stingray software[343], and some preliminary results of the airborne PSL spheres are shown in Figure B10. However, significant further progress is required. The ability of Nano-DIHM to visualize the motion of nanoscale and microscale particles in 3D space opens opportunities in multiple facets of fundamental and applied aerosol science. The capability of Nano-DIHM to probe aerosols in situ will allow exploring physicochemical processes under atmospherically relevant conditions.

The potential of Nano-DIHM in the atmospheric sciences is in the context of investigating the dynamics of phase transitions: particle freezing processes, [293, 361] and efflorescence and deliquescence [336, 362] in fine aerosol particles, which are poorly understood processes critical to unravelling the effects of aerosols on climate [70, 108]. Recent evidence shows that phase transitions in atmospheric particles are more complex than predicted earlier, and these processes can happen through multiple unknown pathways [10, 362, 363]. We expect that the direct imaging of fast temporal changes in the morphology of particles with Nano-DIHM will prove invaluable for understanding the complex mechanisms of ice nucleation phenomena. Furthermore, the broad applicability of this new experimental technique is expected to open new directions in applied and fundamental particle research. Next-generation software and more advanced hardware will likely advance the performance of Nano-DIHM for remote and automated observation of complex matrices, such as planetary atmospheres.

3.4 Methods

3.4.1 Digital in-line holographic Microscopy

Digital in-line Holographic Microscopy (DIHM) is a two-stage process. At the first stage, holograms are recorded. At the second stage, the reconstruction of holograms is performed, yielding a visualization of the object(s). With the current setup, holograms were recorded using the 4Deep Desktop Holographic Microscope [317]. The numerical reconstruction of the holograms was performed using the Octopus software package, version 2.2.2 [342].
3.4.1.1 Recording of holograms

The schematic of the DIHM is shown in Figure 3.9(a). A laser (L) emits at the wavelength of $\lambda = 405$ nm. The laser beam is focused on the pinhole (P) that has an aperture diameter approximately matching the wavelength of the laser source. The resulting wave illuminates object(s) under observation from a distance of a few micrometres from the pinhole, producing a highly magnified diffraction pattern, the hologram, on the screen (photosensitive matrix, model MV1-D2048-96-G2-10, Photonfocus AG 00140622, version 2.1) [318, 325]. We used the CMOS matrix that allowed recording holograms that are 2048 × 2048 pixels (5.5 µm camera pixels), stored as digital images for subsequent reconstruction.

As shown in Figure 3.9(a), the light emitted from the point source (the pinhole) propagates towards the screen and is scattered by the objects in its path, resulting in a hologram. The wave amplitude of the hologram at the screen, A(r, t), is given by Equation 3.1.

$$A(r,t) = A_{ref}(r,t) + A_{scat}(r,t)$$
(3.1)

where $A_{ref}(r,t)$ and $A_{scat}(r,t)$ are the reference and scattered amplitudes, respectively. The intensity of the hologram recorded on the photosensitive matrix screen, I(r,t), is $A(r,t)A^*(r,t)$ and can be expanded to yield

$$I(r,t) = A_{ref}(r,t)A_{ref}^{*}(r,t) + [A_{ref}(r,t)A_{scat}^{*}(r,t) + A_{scat}(r,t)A_{ref}^{*}(r,t)] + A_{scat}(r,t)A_{scat}^{*}(r,t)$$
(3.2)

In Equation 3.2, the first term is the intensity of the beam in the absence of a scatterer, and the last term is the intensity of the scattered wave. The second term in the square brackets in Equation 3.2 signifies the interferences between the reference and the scattered waves, referred to as holograms.

$$A_{scat}(r) = \frac{iA_{ref}}{r\lambda} \iint I(r) \frac{\exp\left(ik\frac{rr'}{r}\right)}{|r-r'|} ds$$
(3.3)



Figure 3.9 Digital in line holography microscopy setup. (a) Schematic showing the operational principle of DIHM and a recorded hologram. (b) Schematic of the experimental setup for holographic imaging in moving airflows, stationary liquid, and solid samples by Nano-DIHM.

The distance between the source (pinhole) and the camera sensor (screen) is ~ 5 mm, the wavelength of light is 405 nm, and the camera pixel size 5.5 µm. These are the input parameters for the reconstruction. No other information is required to retrieve images, which yield the position, orientation, and shape of the observed objects. The 3D morphology and the 3D position of the object(s) can be determined from the reconstructions at different image planes. The proper reconstruction position is essential to obtain sharp images (Fig. B11). Figure B11 shows that merely small changes of reconstruction position Z can significantly enhance image quality, including its resolutions. The aim was not to focus on the dimension of the particles. The reconstruction plane is defined as the plane between the laser source's focus and the camera sensor parallel to the YZ- plane [318, 324, 364]. These distances are found manually by systematically changing the reconstruction positions, i.e., the distance between the focus of the laser and the reconstructed plane [318, 324]. The absolute dimensions of the observed object(s) in the reconstructed image are calculated during the resultant hologram's inversion. No further calibration is needed for the determination of the dimensions of the observed object(s). We show the quality of background holograms with our experiment in Figure B3(a). The mean values of background intensity along the different crosscuts of holograms are 8.05 ± 6.56 arbitrary units (Fig. B3(a)). The background hologram was recorded with zero air. The air or aerosol exiting the gas cuvette is passed into the SMPS and the OPS. The data obtained with the SMPS and the OPS for zero air showed a particle count of fewer than 1 particle/cm³ (Fig. B3(b, c)).

3.4.1.2 Resolution of Nano-DIHM: Beyond the diffraction limit

The resolution of reconstructed DIHM images depends on the information recorded in the hologram. In turn, the information captured in the hologram depends on numerous factors, such as (1) the pinhole size, controlling spatial coherence and illumination cone; (2) the numerical aperture, given by the size and positioning of the recording photosensitive matrices, i.e., a CCD or a CMOS chip; (3) the pixel density and the dynamic range, controlling fringe resolution and the noise level in the hologram; and (4) the wavelength [318].

The lateral resolution is represented in terms of the geometric parameters of DIHM. The recording screen is perpendicular to the optical axis connecting the light source with the center of the screen. The lateral resolution of DIHM can be calculated using Equation 3.2. A detailed

description of the lateral criteria of DIHM has been reported in previous studies [318, 325]. The holographic term in Equation (3.2) can be rewritten as

$$|r2 - r1| \ge \frac{\lambda}{2NA} \tag{3.4}$$

Where NA is the numerical aperture of the microscope, and it can be defined as:

$$NA = \frac{W}{2\left[\sqrt[2]{\left(\frac{d}{2}\right)^2 + (d)^2}\right]}$$
(3.5)

where W is the width of the screen and d is the distance between the point source and the screen. Depth resolution in holographic reconstruction is harder to achieve which improves with the increasing size of the screen [318]. The depth resolution of the holographic microscope is given by Equation 3.6.

$$|r2 - r1| \ge \frac{\lambda}{2(NA)^2} \tag{3.6}$$

The theoretical lateral resolution calculated for the setup used in this study was 271 nm, while the depth resolution was 362 nm. However, applying the experimental approach and the numerical process can bring a much lower resolution. In this study, these are the three processes used to overcome the diffraction barrier of the setup and detect the nanosized objects.

1) Improved experimental approach:

In this study, we do not need to add any additional physical objects, and there is no need for external filtering for the recording/reconstruction of holograms [318, 342, 343, 347]. The holograms were recorded near the pinhole and bring the camera closer to the quartz flow tube cuvette for dynamic mode or quartz microscopic slide for stationary mode. This configuration is possible because the Octopus software [342] still allows us to record the hologram in the size of 2048×2048 -pixel with a pixel size of 5.5 µm given the source to camera distance (5 mm). Hence, we achieved a larger field of view, allowing tracking both single-particle and multiple particles. The pinhole and the flow tube (cuvette) for dynamic experiments or microscopy slides for the

stationary experiment nearly touched each other. In DIHM, the shorter the source-to-sample distance, the higher the magnification, and hence a higher resolution can be achieved [318, 347, 365]. By using this process, the numerical aperture (NA) of the Nano-DIHM increases substantially (NA = 0.7428) (Eqn. 3.3). Thus, following the steps below, the nano-DIHM resolution can go below this theoretical threshold [318, 344, 346, 347, 349, 365] and allow nano-size particle detection.

Keeping the cuvette near the source and bringing the camera to near the cuvette collectively increases the Nano-DIHM magnification [318, 347]. Previously, the only way to increase the resolution was by numerical approaches because the low numerical aperture was one of the major issues in achieving the high resolution in digital holography [318, 344, 346]. Another advantage of the current experimental setup shown in Figure 3.9(a) is that the single pinhole can work with multiple virtual illumination sources. Thereby, we do not need multiple illumination sources to record the hologram. To obtain such short distances, the sample flow tube is introduced between the pinhole and CMOS so that the sample is facing the pinhole, as illustrated in Figure 3.9(a, b). The pinhole emits the light, and the bottom of the surface of the sample carrier will partially reflect this light to the pinhole. In turn, this light is reflected to the sample carrier, where it is partially reflected backward, multiple times. As a result, the light coming directly from the pinhole is superposed upon the reflected light, which appears to come from several virtual pinholes [365]. This experimental recording process of holograms enabled us to overcome the diffraction barrier, allowing measurement of the nanosized particles ≤ 200 nm. It is noteworthy that several studies using near-field optical microscopy have successfully captured the nanoscale objects, overcoming the diffraction limit of the optical system [298-302, 304, 309].

In digital holography, recent studies achieved detection of nanoparticles using an on-chip microscope where each nanoparticle served as a nucleus for self-assembled deposition of refractive materials (Polyethylene Glycol (PEG)-based solution) around each particle (nanolenses), thus increasing each particle's size and scattering cross-section, effectively helping it's the detection on a chip [310, 311, 327, 339, 366, 367]. Several theoretical numerical methods based on the deconvolution algorithm on the sensor chip and point source are used to detect the nanoparticles [312, 355, 368-370].

As the distance between the source and the sample gets shorter, the object vibrations and noise are getting more extensive due to the higher magnification [341, 348]. It blurs out the fine interference fringes and reduces the potentially achievable high resolution. Indeed, it is a challenge, and we agree with it. However, experimentally, to overcome this significant challenge and compensate for the vibrations and noise, a short-time acquisition sequence of the holograms and a thin sample carrier (compared to the distance between the pinhole and the image sensor) was used and recorded [348, 371]. Such numerical reconstruction methods with deblurring techniques have been demonstrated that in the motion-deblurring photo-image analysis permits achieving a higher resolution by a factor of 2 or more [341, 342, 348].

2) Numerical reconstruction process:

The Octopus/Stingray software [342, 343] was used to reconstruct the recorded holograms in this study. The software is based on a patented algorithm [319], which can effortlessly achieve the lateral resolution on the order of half-wavelength (λ /2) of source and depth resolution on the order of one wavelength (λ) [344]. Furthermore, as shown in detail elsewhere,[341, 344, 348, 349] a higher resolution was achieved using multiple deconvolutions routines during the reconstruction: (1) illumination system (pinhole) and (2) the finite numerical aperture of the recording screen (CCD/CMOS) [341, 344, 348, 349]. Implementing an instant 3D-deconvolution routine in our reconstruction method allowed us to reach the desire resolution [340, 342, 344, 348, 349]. The importance is that to find the plane where the phase/intensity image is accurately focused. Thereby, if we are aimed to measure the PSL for 200 nm size, as an example, the plane must be within 0.01 micron. Otherwise, the dots will be only a few pixels and do not look like quality images. For that reason, increasing the precision with 0.001 in Octopus software allowed us to achieve high resolution. Finally, we accurately focus on blurred objects by adjusting reconstruction position (z) to up to three decimal places (0.001).

The advantage of the deconvolution routines is to remove white noise from final reconstructed images and enhance the resolution by a factor of 2, as discussed in detail in previous studies [340, 341, 344, 348]. By employing the 3D-deconvolution routines, the out-of-focus signal is brought back to its scatterer, and the twin images are automatically removed as they are not part of the scattered wave. Thus, spatially well-localized parts of an object are recovered free from artifacts

and noise-free. For example, Nickerson et al. [344] in Figure 5 shows how implementing the twofold deconvolution mechanism removes the white noise from reconstructed images.

3) Aqueous medium:

In addition to air, several holograms are formed in an aqueous medium (water), and thus the wavelength of the laser is reduced [318, 346] from $\lambda = 405$ nm to ~ 300 nm.

3.4.2 Phase shift and refractive index calculation

The recorded holograms provided the information on the phase, size, and morphology of objects. The holograms were reconstructed using the Octopus software (version 2.2). The relative phase shift (rad) has been measured for the objects. Suppose the refractive index of objects is n_{obj} and the refractive index of fluid or medium is n_m ; the phase shift depends on the distance that light travels in each medium. In this study, the light with wavelength λ (405 nm) travelling a distance of t in the object, results in the relative phase shift given by

$$\Delta \psi = \left(n_{obj} - n_m \right) \frac{2\pi t}{\lambda} \tag{3.7}$$

Further, the optical path difference is:

$$OP = (n_{obj} - n_m)t = \frac{\lambda\Delta\psi}{2\pi}$$
(3.8)

The crosscuts (phase shift vs. position of the object) through a phase reconstruction image of an object determine the optical path as a function of position within the objects. If the size of the particles/objects in the light propagation direction is known, the changing refractive index can be calculated from the measured phase shifts using Eq. (3.7). Otherwise, information on the refractive indices of the objects/particles and the medium allows determining the object/particle size in the light propagation (object height).

3.4.3 SMPS and OPS

A NanoScanTM SMPS model 3910 (TSI Inc.) and an OPS model 3330 (TSI Inc.) were used to measure the real-time size distributions of airborne particles. The SMPS measures the size of

the airborne particles in the range of 10 nm to 400 nm in terms of the electrical mobility diameter. The sampling flow rate of the SMPS was 0.75 L/min. The OPS determines the particle size distribution in a size range of 0.3 μ m – 10 μ m in terms of optical diameter with a sampling flow rate of 1 L/min. A more detailed description of the SMPS and the OPS is provided elsewhere [72].

3.4.4 Experimental Setup

The experimental setup (Fig. 3.9(b)) for measurement of airborne particles consists of the following components: the DIHM instrument, a gas flow cuvette (ES Quartz Glass, volume of 700 μ L, path Length 2 mm), a microscope slide (Quartz Glass), the aerosol generator unit, and the aerosol sizers (SMPS and OPS). Each experiment has been triplicated (repeated thrice). During each repeat, we generally recorded 1000 holograms. The details of the aerosol generation unit and the particle sizers have been described elsewhere [23, 72].

Several sample matrices have been tested (Table 3.1): ambient air, snow meltwater, aerosolized 100 nm and 200 nm size polystyrene latex spheres (PSL), a mixture of PSL with iron oxide powder, synthetic materials such as zinc oxide (powder, < 60 nm particle size, Sigma-Aldrich, Inc. Ontario, Canada) and iron oxide (iron (III) oxide, nano-powder, < 50 nm particle size, Sigma Aldrich Inc.). For in-situ real-time measurements of ambient aerosols, an electrically conductive tube \sim 122 cm in length was used to direct the ambient air through the gas flow cuvette placed on the stage of the DIHM instrument. The outflow (1.7 L/min) from the cuvette passed to the SMPS and the OPS. The coupling of the SMPS and the OPS with the DIHM allowed determining the aerosol size distribution of the particles imaged by DIHM in real time.

The original colloid solution of 100 nm PSL spheres (2% wt) was provided with a calibrated diameter of 101 ± 7 nm, and the size of 200 nm PSL (10% wt) standard particles with a calibrated diameter of 188 ± 4 nm, supplied by Sigma-Aldrich, respectively. The original colloid solution was diluted for aerosolization and imaging in the moving airflow stream by mixing 100 μ L of the original colloid solution of the PSL spheres with 10 mL of Milli-Q water. The resultant solution was aerosolized using the aerosol generation unit (solution flow rate of 0.25 ml/minute) and passed through the gas flow cuvette installed in the DIHM instrument with a final flow rate of 1.7 L/minute.

We investigated the size and shape of the PSL spheres in the colloid solution of PSL standard particles and 1:100 mixtures with Milli-Q water at room temperature. In addition, the mixture of iron oxide nanoparticles and 200 nm standard PSL particles were analyzed by directly using DIHM. A 20 μ L aqueous solution of PSL particles (100 nm and 200 nm) and mixed samples were deposited on the microscope slide to record the direct holograms by DIHM, respectively. Next, standard-size synthetic powder materials (zinc oxide and iron oxide) were imaged by DIHM directly on a microscope slide. To validate the size, shape, and morphology of the PSL, mixed samples and particles in the snow were visualized in the holograms and compared with the morphology visualized using S/TEM. Half of the liquid samples were analyzed by S/TEM at the Facility of electron microscopy at McGill University, and the remaining half samples were studied using Nano-DIHM. The S/TEM imaging techniques are discussed in our previous papers [72, 73]. The additional details of each experiment, such as sample information, flow rates, and the recording parameters of DIHM, are given in Table 3.1.

We evaluated the changing refractive index measurement of the suspended solution. Glycerin drops were prepared by adding 100 μ l of glycerin (refractive index, 1.4729, Sigma-Aldrich, Inc.) to 1 ml of type F microscope oil (refractive index, 1.518 at 23 °C, Olympus, immoil-f30cc, Tokyo, Japan). This mixture was then vortexed for 15 min, and a small sample of the resulting suspension was placed on a microscope slide. A previous study suggests that this method produced glycerin drops in the range of 1 μ m to 10 μ m in diameter [346].

Acknowledgment

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), National Research Council (NRC), NSERC CREATE Mine of Knowledge, NSERC CREATE Pure, and Environment and Climate Change Canada (ECCC). The authors are thankful to Dr. Jim Avik Ghoshdastidar, University of Toronto and Dr. Amit Kumar Pandit, National Institute of Aerospace, Hampton Virginia, USA for his critical review of the manuscript and Mr. Ryan Hall for proofreading our manuscript. We also thank Dr. Justin Jacquot and Dr. Deokhyeon Kwon for their help in installing the Holography setup in the laboratory. Finally, we are very grateful to Professor Hans Juergen Kreuzer, Dalhousie University, for his guidance in hologram reconstruction and verification of our results.

Chapter 4 Four-dimensional in situ real-time physicochemical tracking of virus-laden droplets and aerosols in the air

We showed the capability of Nano-DIHM to measure aerosols in situ in real in Chapter 3. In this Chapter, Nano-DIHM is applied to measuring, identifying and classifying bioaerosols, including viruses, in real time. As proof of concept, Nano-DIHM was successfully used to measure SARS-CoV-2 and bacteriophage MS2 in air and water. It also successfully automatically detected and classified the SARS-CoV2 virus in a mixture of SARS-CoV-2 and MS2 samples. We showed the interaction of MS2 with metallic (TiO₂) aerosols, which is essential to understand the surfactant effect on viruses. In the era of COVID-19, real-time airborne virus measurement techniques are vital and can provide valuable information on the dynamics of the disease, including the number of infections, the rate of transmission, and the impact of interventions. [372]. However, there are many techniques to measure bioaerosols or viruses, as summarized in Table C1. But most techniques require sample collection and cannot scan large spaces such as homes, workplaces, schools, and public spaces. Nano-DIHM can be used to understand the physical and chemical properties of viruses and provide information on the virus's size, phase, number, and surface properties in air and water, which can help to understand how the virus is transmitted and inform interventions to reduce transmission.

This chapter consists of a manuscript in a press in Communications Engineering:

Pal, Devendra; Amyot, Marc; Liang, Chen; and Ariya, P.A. (2022): Four-dimensional in situ realtime physicochemical tracking of virus-laden droplets and aerosols in the air. Communications Engineering: accepted. (In press)

Four-dimensional in situ real-time physicochemical tracking of virus-laden droplets and aerosols in the air

Devendra Pal¹, Marc Amyot², Chen Liang³, and Parisa A. Ariya^{1,4}

Short title: Detecting viruses in the blink of an eye

¹Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 0B9, Canada.

²Department of Biological Sciences, Univerité de Montréal, Complexe des Sciences, 1375 Avenue Thérèse-Lavoie-Roux, Montréal QC, Canada, Montreal, Quebec, Canada H2V 0B3

³Department of Medicine, Division of Experimental Medicine, McGill University and Jewish General Hospital, 3755 Cote Sainte Catherine Rd., Montreal, Quebec, Canada, G3T 1 E2

⁴Department of Chemistry, McGill University, 801 Sherbrooke Street West, Montréal, QC H3A 2K6, Canada.

Abstract

There is currently no real-time in situ airborne virus tracking method, hindering the understanding of rapid virus changes and associated health impacts. Here, we provide evidence for 4-dimensional physicochemical tracking of virus-laden droplets and aerosols in the air using automated next-generation label-free Nano-digital in-line holographic microscopy (Nano-DIHM). We characterize time-dependent live/inactivated viruses as a single particle or ensemble of particles, phases, morphologies, 4D dynamic trajectories, and surface area/roughness/edge gradients with 32.5 ms resolution. We present proof of concept for the selective detection of active MS2 bacteriophages (MS2), inactivated SARS-CoV-2 and RNA fragments, and an MS2 mixture with metallic and organic materials. MS2 aerosolization experiments confirm the bimodal size distribution of viral-laden particles peaking at ~ 60-200 nm and 2-3 microns. These experiments revealed the evaporation-condensation process in air. Aerosol addition confirms that the airborne viral-laden MS2 particle distribution shifts toward larger sizes, changing settling velocities and affecting transmission processes. High-resolution scanning/transmission electron microscopy and aerosol analyzers confirm the nano-DIHM data. We also present a portable remotely controlled prototype that instantaneously detects SARS-CoV-2 (Yes/No) in air, water, and heterogeneous matrices. Nano-DIHM can become a revolutionary tool in health and environmental crises, providing rapid multidimensional virus detection to improve transmission management now and in the future.



TOC Simplified schematic of 4D physicochemical tracking and validation

4.1 Introduction

A recent study has identified a significant knowledge gap is the in-situ and physicochemical characterization technology of airborne viruses [372] to better model viral transmission. Until now, no in situ and real-time technology for physicochemical airborne virus characterization exists. The existing technologies are insufficient for detecting a single airborne virus or even clusters of them in the air and cannot be used to decipher transmission mechanisms accurately [373]. We present a robust imaging technology addressing the expressed knowledge gap by providing much-needed in-situ and real-time capability and tracking viruses in the air.

The transmission mechanism(s) of SARS-CoV-2 is(are) still debated. However, almost all studies point to the fact that SARS-CoV-2 is transmitted by exposure to infectious respiratory fluids [374-378]. Three major transmission pathways for respiratory diseases are the (a) inhalation of viral droplets and airborne particles or bioaerosols [288, 379], (b) deposition of exhaled aerosols and droplets onto exposed mucous membranes [290, 380], and (c) physical contact of exhaled viral aerosols and droplets on surfaces [381, 382]. The best current non-in-situ technologies, such as real-time polymerase chain reactions, have poor detection limits and require approximately 100 copies of viral RNA per milliliter of transport media [373]. These transmission pathways can take place simultaneously and are multifactorial processes affected by factors such as viral load,

duration of contact, concentration [374], multiple exposures, environmental conditions, host receptor age, immune system, etc. [383-385]. Numerous research studies worldwide agree that facial masks show a systematic decrease in SARS-CoV-2 transmission, demonstrating the importance of air as a significant transmission pathway [386-388], but little is known about it [372].

Air is in motion, as are airborne virus-laden particles. Airborne viral droplet or aerosol detection and quantification methods have generally included collecting samples into liquids or onto solid surfaces that are not in situ or real-time [389-392]. Various conventional techniques exist to observe, collect, and quantify viruses, such as molecular assays, immunoassays, multistage collectors, fluorescent sensors, and several types of polymerase chain reactions, as shown in Appendix C Table C1. However, despite their advantages, these techniques are neither real-time nor in situ techniques [390-395] and therefore cannot provide a physicochemical understanding of dynamic air. Suspensions of virus-laden droplets in the air are classified as a subset of bioaerosols [396], containing microbiological entities such as bacteria, pollens, fungi, dead or alive viruses, and biological activity markers [397]. During recent decades, it has become clear that bioaerosols can undergo physicochemical transformations [22, 50, 398]. Bioaerosols interact with gases and airborne particles, forming complex mixed structures [72, 279] that transform under different environmental conditions, such as temperature, humidity, radiation and air dynamics, and at various atmospheric interfaces, such as built surfaces, snow/ice, water, and soil [399]. The lack of physicochemical transformation of airborne viruses precludes scientists from foreseeing even viral aerosol evaporation and condensation process [372], which are pivotal for primary and secondary viral transmission [372, 384].

This study used Nano-Digital in-line Holographic Microscopy (Nano-DIHM) to investigate viruses in air and water in situ in real time. The Nano-DIHM comprises a desktop holographic microscope (4Deep, Halifax, Nova Scotia)[317] and a gas flow tube that allows airborne particles to travel through the imaging volume of the DIHM, enabling real-time observation of single or ensembles of viral particles or other objects. Nano-DIHM is a lensless technology that directly records interference patterns called holograms of the incident and scattered light using a light-sensitive matrix/digital camera[317, 318, 325]. The object information was recovered from the recorded holograms by performing numerical reconstruction using

Octopus/Stingray[342, 343] software based on a patented algorithm [319, 400]. We observed the in situ and real-time physicochemical transformation of the virus-laden droplets and aerosols of two viruses, SARS-CoV-2 and MS2 bacteriophage (MS2), which is widely used as a surrogate for viruses in the air. Using artificial intelligence, nano-DIHM enables 4D tracking of viruses in air and water and has the capability for surface measurement (e.g., roughness and surface areas) in situ and in real time. It does not require particle trapping, collection, or virus particle deposition, and no strong laser is needed. The Methods section provides a schematic, experimental procedure and workflow of nano-DIHM. The experimental parameters for each experiment are shown in Table C2. We used SARS-CoV-2 particles with confirmed whole genome sequencing (Figure C1). Inactivated SARS-CoV-2 was provided by the Contaminant Level 3 Platform in the Faculty of Medicine at McGill University.

We first provide evidence for the observation of live MS2 virus particles (3D size, phase, intensity, surface properties and their dynamic trajectories), and we present the validation of nano-DIHM results with scanning/transmission electron microscopy (S/TEM) as a single virus particle and an ensemble of them. Second, we demonstrate the nano-DIHM capability of detecting and classifying SARS-CoV-2 particles and their physiochemical properties in dynamic (sneezing-coughing) and static modes (SARS-CoV-2 deposited on a microscope slide). Photochemical experiments are performed to confirm the detection accuracy and physicochemical characteristics of observed viruses even after deactivation. Then, we present a library of individual classifiers for automated software in YES/NO format, which allows SARS-CoV-2 particle identification in dynamic air. In addition, we establish that we can clearly distinguish specific viruses in inorganic mixtures by identifying SARS-CoV-2, SARS-CoV-2 RNA, MS2, and metals such as TiO₂ and Fe₂O₃ in the mixed samples. We establish that we can selectively detect viruses in organic mixtures (MS2, alpha-pinene, oil, and honey). Finally, we discuss this technology's potential in various research domains, including non-invasive medical imaging.

4.2.1 Validation of the MS2 bacteriophage shape and size obtained by nano-DIHM with S/TEM

Our first step was to validate the potential of nano-DIHM to detect virus characteristics using a commonly used airborne virus surrogate: MS2. MS2 was purchased from ZeptoMetrix (Buffalo, NY, USA), and detailed information is described in the Methods section. In the current setup, laser light (405 nm) illuminates particles suspended in the air or water as they flow through a flow tube cuvette or are placed on a microscope slide, and holograms of the particles are recorded onto a screen. A fast image-processing software, Octopus/Stingray[342, 343], based on a patented algorithm [319, 400], analyzes the holograms to extract individual dimensions, phases, shapes, and surfaces of individual particles (33). The virus sizes, phase, morphology, surface area, and roughness in dynamic and stationary media are given in Table 4.1. The active MS2 virus size, shape, and morphology measurements made by nano-DIHM were validated using high-resolution determined by nano-DIHM was confirmed with a scanning mobility particle sizer (SMPS), optical particle sizer (OPS), and particle size analyzer (PSA) (Fig. 4.2). The electron microscopy and particle sizer details are given in the Methods section.



Figure 4.1 Size and morphology of MS2 particles obtained by nano-DIHM in a stationary manner and results validated by Talos-S/TEM and S/TEM. The top panel (a-c) shows the intensity reconstruction obtained by nano-DIHM. (a) Intensity reconstruction of MS2 viruses at a reconstruction distance of $Z = 2844 \mu m$, (b) intensity reconstruction at $Z = 1132 \mu m$, with the inserted image in panel (b) showing the magnified MS2 virus shape, and (c) reconstruction performed $Z = 702 \ \mu m$ and nanosized MS2 viruses observed in highresolution images. Zoomed-in images in white dotted circles in panel (c) show an example of the MS2 virus shape and size. The green arrows indicate that several nano- to microsized MS2 viruses existed at the same reconstruction distance. Panel (d-f) shows the Talos-S/TEM images of MS2 viruses exhibiting the shape and size. The results in panels (a-e) were obtained with negatively stained MS2 samples. (g-i) Intensity reconstruction of 100X diluted MS2 samples without negative staining reconstructed at reconstruction distances of $Z = 3267 \mu m$, $Z = 496 \mu m$, and $Z = 367 \mu m$ using nano-DIHM. (j-l) S/TEM images from the same samples. Both the nano-DIHM and S/TEM results confirmed the agglomeration of MS2 viruses without negatively stained samples.

Observations of MS2 viruses in aqueous mode were obtained by nano-DIHM and validated with independent results obtained by S/TEM and Talos-S/TEM with the same sample shown in Figure 4.1. The intensity reconstruction of the MS2 viruses obtained by nano-DIHM is displayed in Figure 4.1(a-c), and Figure 4.1(d-f) presents the MS2 images obtained by Talos-S/TEM. The MS2 virus samples were negatively stained (see the Methods section) as shown in Figure 4.1(a-f). In Figure 4.1(b, c), the circles and green arrow indicate MS2 virus sizes of ~ 90 nm, 110 nm, 130 nm, 160 nm, 180 nm, 1 μ m, and 2 μ m. The size and shape determined by nano-DIHM (Fig. 4.1(b, c)) were validated by the Talos-S/TEM images, as shown in Figure 4.1(d-f). The intensity and phase profiles across the crosscut of the MS2 particles shown in Figures 4.1(b, c) are shown in Figure C3(a-f). During the reconstruction process, the background holograms recorded in the presence of the sample to remove any experimental/optical impurities [401]. More detailed hologram recordings/reconstruction and automatic virus detection and classifications are given in the method section.

To reproduce a more realistic situation of measuring viruses in a natural environment, we diluted the original MS2 samples in Milli-Q water by 100 X volume. Furthermore, we mixed the MS2 viruses with several organics and metal oxides (see below, metal coating section). An example of MS2 virus detection in the 100 X diluted sample by nano-DIHM is shown in Figure 4.1(g-i)), and the corresponding S/TEM images are displayed in Figure 4.1(j-l). The hydrodynamic size peak of MS2 in water was observed at ~ 200 nm and 700 nm by PSA (Fig. C2(g-h)) and was aligned with the size data determined by nano-DIHM (Table 4.2). Interestingly, the morphology of MS2 in the 100 X diluted samples changed from spherical to aggregate, suggesting that water uptake and/or MS2 coagulation occurred [402, 403]. The negatively stained MS2 samples did not show the aggregated morphology because the stained materials created a dark border around the MS2 viruses [404], which is unlikely in the atmosphere. Nano-DIHM not only detected single virus particles but also confirmed the presence of agglomerates/clusters (Fig. 4.1(g-i)). The nano-DIHM determined and classified the overall shape of virus particles, but it did not decipher the precise cluster shape of MS2 as compared to the high-resolution S/TEM. Nano-DIHM offers promising results for determining the phase, shape, size, and surface properties of airborne/waterborne particles. Currently, high-resolution electron microscopy is a powerful measurement tool for determining virus shape/morphology, [72, 390, 405]. But electron

microscopy does not have the in situ and real-time imaging capabilities [72, 390, 405] that nano-DIHM offers [401] on the millisecond time scale.

Table 4.1Automated physical characteristics of SARS-CoV-2, MS2, and several natural and
synthetic materials in dynamic and stationary modes over 31.25 ms. The detailed
automation processes of the virus and particle detection and classification procedures are
discussed in the Methods section. These images are reconstructed images of
objects/particles that show the shape/morphology of particles. *shows clusters.

Image	Size	Edge gradient	Roughness	Surface area (µm ²)		
SARS-CoV-2						
6	1.35	90.90	1.12	31.80		
	12.74*	91.03	1.55	48.66		
0	1.24	90.64	1.06	28.41		
	0.14	101.63	1.22	8.55		
	•	MS2 bacteriophage				
	4.33	108.62	1.67	11.15		
	0.92	109.23	1.34	6.27		
	0.12	107.38	1.61	19.24		
	1.72	103.98	1.43	11.54		
MS2 bacteriophage (UVB)						

	2.37	56.44	2.12	18.06		
	0.58	64.23	1.99	13.74		
	1.77	76.08	1.33	8.85		
ale	2.25	64.53	2.34	20.59		
		PSL				
9	0.36	104.97	1.91	14.80		
0	0.37	105.02	1.81	15.23		
	0.94	108.37	1.90	57.99		
	0.96	97.76	2.01	58.86		
Iron oxides (Fe ₂ O ₃)						
No.	2.11	26.66	1.21	7.08		
	5.76	27.46	1.31	21.18		

Analay	10.61*	27.51	1.27	12.05
and a	5.43	28.32	1.25	20.99
		Olive oil (C88H164O10)		<u>.</u>
	0.87	106.19	1.01	6.93
	1.0	108.43	1.01	5.26
	0.75	97.40	1.01	5.73
	0.79	126.27	1.06	7.46

4.2.2 Tracking of aerosolized MS2 characteristics in dynamic air

Nano-DIHM efficiently determined the phase, size, shape, and surface properties of airborne MS2 particles with dimensions ranging from nano- to micrometers in dynamic media (Fig. 4.2, Table 4.2). Table 4.2 provides detailed experimental setup and statistical information on three aerosolization types of MS2 particle size distributions, and <u>Movie 1</u>, and <u>Movie 2</u> provide the 4D (time and 3D positions) dynamic trajectories.

Table 4.23D size distribution of MS2 and mixed samples with TiO2 in dry aerosols. The MS2
samples were also analyzed in the form of droplets or the coughed-sneezed phase. Std
means standard deviation.

Bacteriophage MS2 (dry aerosol) ¹						
Statistics (µm)	Mean	Std	Median	99 th	1 st	
Width	0.25	0.97	0.18	1.40	0.04	
Height	0.25	0.97	0.18	1.40	0.03	
Length	0.50	0.40	0.38	1.74	0.06	

Bacteriophage MS2+TiO ₂ (dry aerosol) ²						
Width	0.46	0.43	0.34	2.00	0.02	
Height	0.45	0.43	0.33	1.99	0.02	
Length	0.83	0.67	0.66	2.90	0.06	
	Bac	cteriophage MS2	c (droplet) ³			
Width	1.20	3.70	0.77	6.29	0.07	
Height	1.09	2.15	0.73	5.82	0.06	
Length	1.40	1.11	1.12	4.76	0.10	
SARS-CoV-2 (Sneezed/viral droplets) ⁴						
$Q1 = 10 \text{ m.sec}^{-1}$						
Width	0.63	0.68	0.45	3.15	0.03	
Height	0.59	0.69	0.41	3.15	0.02	
Length	0.72	0.72	0.60	3.89	0.01	
$Q2 = 20 \text{ m.sec}^{-1}$						
Width	0.75	0.90	0.51	4.23	0.03	
Height	0.72	0.85	0.49	3.79	0.03	
Length	0.72	0.74	0.61	3.54	0.01	
$Q3 = 30 \text{ m.sec}^{-1}$						
Width	0.82	1.32	0.56	4.18	0.04	
Height	0.82	1.43	0.55	4.29	0.04	
Length	1.99	1.73	1.58	5.51	0.04	

1. MS2 Bacteriophage samples aerosolized with a C-flow atomizer and aerosol stream pass through two diffusion dryers before passing to a nano-DIHM sample volume (flow tube cuvette) and the SMPS/OPS. The humidity was less than 4%.

2. A mixed solution of MS2 and TiO₂ was aerosolized, and the aerosol stream passed through a diffusion dryer.

3. A bubbler was used to generate MS2 droplets. The droplets directly passed through a flow tube cuvette during nano-DIHM. No dryer was used.

4. SARS-CoV-2 droplets were generated by using a c-flow atomizer. The droplets directly passed through a flow tube cuvette into the nano-DIHM sample volume. This experiment was modeled with sneezing/coughing velocities.

• Figure 4.7 shows the integrated experimental setup.

MS2 samples were aerosolized with a C-flow atomizer. Afterward, the aerosol stream passed through two diffusion dryers to the nano-DIHM sample volume (flow tube cuvette), and outlet connected to the SMPS/OPS (method section, schematic Figure). The aerosolized MS2 viral particle size distribution determined by nano-DIHM varied from the nano- to microscale (Table 4.2). This result was consistent with the simultaneous analysis performed using the SMPS and OPS in the particle size range from 10 nm to 10 μ m (Fig. 4.2(m-p)). The SMPS and OPS only measure particle size distributions in real time [72] and unable tracking virus/particle trajectories in 3D space and individual virus particle dimensions in 3D, in contrast to nano-DIHM [401]. Nano-

DIHM is very versatile and can easily be coupled to various particle analyzers, PCR equipment, or a wide range of electronic microscopy units.





Figure 4.2 Intensity and phase reconstruction of airborne MS2. Panel (a-c) is the intensity reconstruction and panel (d-f) presents phase reconstructions. (a) Intensity reconstruction of airborne MS2 viruses at Z= 627 μ m, (b) Z= 687 μ m, and (c) Z= 1570 μ m. (d-f) Phase results of the same particles as (a-c). (g-i) Intensity crosscut profiles of particles in sections (a-c) and (j-l) phase crosscut profiles of particles in panel (d-f). (m-n) Airborne MS2 particle size distribution obtained by the SMPS and the OPS, respectively, and (o-p) size distribution of mixed samples of MS2 and TiO₂. The two-colored line corresponds to two repetitions of an experiment. The 4D dynamic trajectories of the particles are provided in Movie 1, and Movie 2. The background holograms recorded for zero air and particle concentrations tested by the SMPS and the OPS are shown in Figure C3. The automated detection of airborne MS2 by Stingray software is shown in Figure C4.

The phase and intensity results of airborne MS2 viral particles shown in Figure 4.2(a-f) indicate that the MS2 particles existed in varied shapes and morphologies, from spherical to irregular. It is unlikely that the virus/material would maintain uninterrupted morphologies during aerosolization without attaching to the suspending matrix [1, 2]. The intensity profiles for the particle crosscuts in Figure 4.2(a-c) are illustrated in Figure 4.2(g-i), while their phase response is shown in Figure 4.2(j-l). Negative and positive phase shifts across the MS2 particle crosscuts were

observed, varying from 2.6 to 4 radians. This could be due to MS2 particle coagulation or aggregation during the aerosolization process [1, 2] or self-interaction among the MS2 particles that enlarged the size of the particles. The MS2 particle sizes determined by the nano-DIHM in Figure 4.2(a) are 80 and 290 nm, and those in Figure 4.2(b) are 130, 80, and 210 nm, while the particles in Figure 4.2(c) are submicron to 2 and 3 μ m, expressed as the full width at half maximum (FWHM) (Fig. 4.2(g-i)).

The 3D orientation (XYZ positions) and individual dimensions (width, height, and length) of airborne MS2 viral particles in a single hologram with a temporal resolution of 31.25 ms in moving air are shown in Figure C5. The detailed statistics of airborne MS2 particles (dry aerosols), MS2 samples mixed with TiO₂ (dry aerosols), and MS2 particles in sneezed/drop form in 3D space are given in Table 4.2. The median values of width, height, and length of the airborne MS2 particles/vesicles (dry aerosols) determined by nano-DIHM are 180 nm, 180 nm, and 380 nm, respectively. The median size distributions of a mixed suspension of MS2 with TiO₂ are 340 nm, 330 nm, and 660 nm, respectively. The median size distribution of MS2 viruses in the droplet (sneezing-coughing) form increased toward a more prominent size, and values were observed at 770 nm, 730 nm, and 1.12 μ m, respectively. This may be due to the moist envelope across the MS2 virus vesicles.

Nano-DIHM and SMPS/OPS observations indicated that the airborne MS2 viral particle (dry aerosol) size peaks were between 60 and 200 nm. The size distribution of MS2 particles in the TiO₂ suspension is shown in Figure 4.2(o-p). The mixed TiO₂ and MS2 suspension exhibited a shifted size distribution to 150-350 nm. This could be due to attachment or coagulation/aggregation between MS2 and TiO₂ particles [402, 403]. The high-resolution electron microscopy images in Figure 4.6 and Figure C9 confirmed the attachment of TiO₂ on MS2 viral particles. The mixing/coating of TiO₂ in MS2 samples suggested physicochemical transformation and is essential to consider for the secondary transmission of airborne viruses. This interesting phenomenon between MS2 (as a surrogate of virus or viral analog) and TiO₂ (abundant cosmetic material) indicates the physicochemical transformation of airborne viruses, which potentially occurs in the of SARS-CoV-2 [399, 402, 406-408].

4.2.3 4D trajectories of MS2 particles and droplets in air

The dynamic 4D trajectories (3D positions and 1D time) of MS2 viruses were obtained by nano-DIHM of both dry MS2 aerosols and MS2 viral droplets in moving air, as shown in Figure 4.3 and <u>Movie 1</u>, and <u>Movie 2</u>. Movie 1 presents the dynamic trajectories of MS2 viral droplets (sneezing model), and Movie 2 displays the trajectories of dry MS2 aerosols in moving air. As depicted in <u>Movie 1</u>, and <u>Movie 2</u>, the dark red MS2 particles were in the focus of the reconstruction plane, while some of the particles (green/blue) were slightly out of focus for a given reconstruction position. This occurred due to the finite depth of field of the objective [401]. Multiple reconstructions of the same hologram in many planes are required to bring those out-offocus particles were focused. However, many particles were progressively out of focus, indicating that the particles were also moving perpendicular to the reconstruction plane. This indicates that MS2 particles were in random motion, which also occurs in the case of aerosol particles [1]. The dynamic trajectories of MS2 particles aggregated or coagulated after some time. This may be related to the MS2 particle interactions with water or the self-assembly of MS2 particles.



Figure 4.3 Trajectory analysis of MS2 particles in droplet form and dry aerosols. (a) MS2 viral-laden droplet particle trajectories. The trajectories were obtained by the sum of 13 holograms with 31.25 ms temporal resolution. (b) Trajectories of MS2 particles in dry aerosols

obtained with the sum of 10 holograms with 31.25 ms temporal resolution. (c, d) Zoomedin particles from their trajectories. The white arrows indicate the directions of particle motion. The blue interference pattern suggests that particles are not focused.

4.2.4 In situ real-time SARS-CoV-2 detection, classification, and physicochemical characteristics

Next-generation nano-DIHM [401] is innovated through the development of libraries and classifiers for several airborne nonvirus airborne particles as controls. Thus, we implemented artificial intelligence to distinguish and improve the accuracy of the physicochemical characterization of viral droplets and aerosols from other aerosols in the matrix [401, 409]. Figures 4.4&4.5 present for the first time in situ real-time observations of airborne SARS-CoV-2 detection using nano-DIHM. SARS-CoV-2 samples were obtained from the Department of Medicine at McGill University and were heat-inactivated (see Methods). PCR analysis was performed at the Department of Medicine, McGill University, to confirm the SARS-CoV-2 particles in the samples. BLASTN, using the beta coronavirus genomic database, is the result of the sequenced genome of the SARS-CoV-2 sample, as shown in Figure C1. The RIM-1 viral stocks were whole-genome sequenced, and the GenBank accession number is MW599736. The physicochemical properties of these samples are presented in the next section.

4.2.4.1 SARS-CoV-2 detection in dynamic mode

Previously, in the literature, the transmission of viral droplets and aerosols produced during coughing and sneezing upon microbial infections has been studied [410, 411], and lifetimes of virus-laden droplets have been assessed. We performed experiments using these literature studies [411, 412] to mimic three different sneezing/coughing types: air velocities ~10 m/sec, 20 m/sec, and 30 m/sec. SARS-CoV-2-laden droplets were generated by using a c-flow atomizer. The droplets directly passed through the flow tube cuvette into the nano-DIHM sample volume, and holograms were recorded. The size data of the SARS-CoV-2 droplets are given in Table 4.2. Figure 4.4(a-l) displays the intensity and phase results of SARS-CoV-2 droplets in dynamic mode, while Figure 4.5(a-i) depicts the SARS-CoV-2 viral particle results in a stationary manner.



Figure 4.4 Inactivated SARS-CoV-2 droplet detection by nano-DIHM. (a) Raw hologram recorded for SARS-CoV-2 viral droplet particles. (b) Background hologram recorded without particles. (c) Contrast hologram obtained after subtracting the background hologram from the raw hologram. (d) Zoomed-in area of (c) at $Z = 2109 \ \mu$ m. (e) Zoomed-in area of (d) revealing the precise recovery of SARS-CoV-2 viral droplets and their shape. (f) A more focused zoomed-in image of (e) clearly demonstrates the SARS-CoV-2 droplet structure. (g-i) Phase reconstruction of identical SARS-CoV-2 particles. (j, k) Intensity profile of PSL particles across the particle crosscut in (e). (l) Phase profile of the SARS-CoV-2 particle crosscut in panel (h)

Examples of the intensity and phase reconstruction for airborne droplets of SARS-CoV-2 are shown in Figure 4.4(a-1). Figure 4.4(a) shows that a raw hologram was recorded for the airborne droplets of SARS-CoV-2 particles. In contrast, the background hologram (Fig. 4.4(b)) was recorded without SARS-CoV-2 particles, and only purified dry air was used with three HEPA filters to serve as a control. Before processing the final reconstruction, the background hologram was subtracted from the raw hologram. This process is performed to remove possible contamination due to the pinhole and sample holders, such as a flow tube cuvette or microscope slide [401]. The contrast hologram shown in Figure 4.4(c) is a product of subtracting the background hologram from the raw hologram. The intensity and phase reconstruction performed on the rectangular cropped area in Figure 4.4(c), as shown in Figure 4.4(d), is of interest. Figure 4.4(e, f) is an example of the high-resolution intensity images in Figure 4.4(d), which was achieved by performing in-focus reconstruction, thus enhancing image quality and reducing noise [401]. Figure 4.4(f) is a zoomed-in area of Figure 4.4(e), revealing a SARS-CoV-2 shape that is well matched to that of prior studies using high-resolution microscopy [408, 413, 414]. Phasereconstructed images of the identical hologram exemplified in Figure 4.4(g-i) yield a similar form of SARS-CoV-2 particles as the intensity images (Fig. 4.4(d-f)). The intensity and phase reconstruction showed that the SARS-CoV-2 cluster size was 400, 600 nm, 1.2 µm and 3.4 µm.

As depicted in Figure 4.3(a, b), under similar experimental conditions, the coagulation of several viral particles was observed, or, more likely, the vesicles were covered with moist water vapor (since the experiment was performed in droplet form). Previous studies suggested that SARS-CoV-2 viral-laden particles vary from submicron to several-micrometer particles [381, 415] due to water or organic/inorganic compound uptake in the environment [399]. Nano-DIHM provided a similar size trend and trajectory analysis <u>Movie 3</u>, confirming the water uptake and morphological change.

The 3D size distribution (Table 4.2), 3D orientation and individual dimensions of SARS-CoV-2 viral particles are shown in Figure C6. The 3D size data of SARS-CoV-2 depicted variations from ~300 nm to several micrometers (Table 4.2). The 3D size data of the SARS-CoV-2-laden vesicles/droplets/aerosols obtained by nano-DIHM were in agreement with the virus sizes found due to coughing, sneezing, and breathing in previous studies (Table C3). The mean/median values

of the SARS-CoV-2 viral droplet width increased with higher velocities (Table 4.2). This is due to SARS-CoV-2 droplet aggregation or coagulation.

The 4D dynamic trajectories of the SARS-CoV-2 droplet motion are shown in <u>Movie 3</u>. The trajectory analysis successfully illustrated the morphological evolution of SARS-CoV-2 particles over time. The SARS-CoV-2-laden particles moved randomly. The morphological changes of the SARS-CoV-2 vesicle/droplet/aerosols were well aligned with the existence of multiple variants of SARS-CoV-2 [407, 413, 416-418]. Observing real-time surface properties and their morphological changes is vital to quickly responding to not only SARS-CoV-2 but also any future pandemics caused by unknown viruses or other microbial entities.



4.2.4.2 SARS-CoV-2 detection in stationary mode

Figure 4.5 SARS-CoV-2 detection in stationary mode by nano-DIHM. (a-c) Intensity images of SARS-CoV-2 particles and (d-f) phase reconstruction. (g-i) Images were taken with a 10X

magnification AMG Evos XL core microscope at the Medicine Department, McGill University.

The confirmation of SARS-CoV-2 particle size, phase, shape, and morphology in a stationary manner is displayed in Figure 4.5. The observation of SARS-CoV-2 particles made by nano-DIHM (Fig. 4.5(a-f)) were in agreement with the images made by the 10X magnification AMG Evos XL core microscope (Fig. 4.5(g-i)). The intensity and phase results showed that the SARS-CoV-2 particle size varied from 1 micron to several micrometers (Fig. 4.5 and Fig. C7). Additional intensity and phase profiles along the crosscut of the particle crosscuts are shown in Figure C7. The positive phase shift varied from 3.1 to 4.1 radians across the particles (Fig. C7(d)), suggesting water uptake. In contrast, the negative phase shifting from 3.2 to 2.6 rad may indicate the different sites of SARS-CoV-2 particles (Fig. C7(c)). In this study, nano-DIHM clearly shows advantages over other optical microscopy methods [414] because of its simple configuration and in situ real-time measurement capabilities in terms of the size, shape, phase, and morphology of viral entities, which is not possible using optical microscopy.

4.2.5 Building a library and classifiers for fully automated SARS-CoV-2 detection (Yes/No)

Stingray software was trained to achieve the real-time in situ automatic detection and physicochemical characterization of SARS-COV-2 by using nano-DIHM. The Stingray software working and training procedure is given in methods. We trained the Stingray software for multiple sample matrices (Table C2) in dynamic and stationary modes. In this study, Stingray software training was performed using over 10000 holograms and 100 K iterations to achieve an accuracy of approximately 99% for identifying SARS-CoV-2 or any targeted particles in a mixed sample in air and water. For instance, Table 3 presents the automated detection of SARS-CoV-2 in the mixed MS2 sample with outcomes of "YES" and "NO" outcome. Table 4.1 provides an example of the physicochemical characteristics (size, shape, and surface morphology) of viruses and metal oxide particles. The accuracy of automated detection and classification by Stingray software may be decreased based on sample matrix complexity. Nevertheless, this can be addressed by building an extensive library of multiple sample matrices. Nano-DIHM may also give false positives. Further improvement of classifiers and surface data will likely reduce this disadvantage.

Table 4.3Yes/No detection of SARS-CoV-2 from mixed samples. A mixed sample of SARS-CoV-2 and MS2 particles was analyzed. "YES" indicates SARS-CoV-2, and "NO" indicates
MS2 particles. This automated classification is in progress, and we have built full
automation for SARS-CoV-2 and will develop it for future viruses, metals, plastics, and
bacteria. Table 4.1 discusses the surface properties of multiple sample matrices.



Flow chart for Automatic detection and classification



4.2.6 Physicochemical characteristics of MS2 with TiO2 and organic coating

We also performed a series of experiments to explore whether nano-DIHM enables deciphering a coating suite of naturally observed organic and inorganic/metallic particles on MS2 viruses. We also examined highly viscous droplets, such as honey ($C_6H_{12}O_6$), olive oil ($C_{88}H_{164}O_{10}$), and alpha-pinene ($C_{10}H_{16}$), mixed with MS2 or with TiO₂ and PSL (mostly C_8H_8)_n). The results of TiO₂ and oil-coated MS2 viruses are shown in Figure 4.6, Figure C9, and Figure C10. The coating impact of alpha-pinene and honey on MS2 viruses is depicted in Figure C11.

The intensity and phase results of TiO_2 particles are shown in Figure 4.6(a, b) and Figure 4.6(c, d), representing the TiO₂-coated MS2 viruses. Figure 4.6(e-f) displays the electron microscopy images of TiO₂-coated MS2 viruses. The intensity crosscuts across particle 1 (Fig. 4.6a) and particles 1 and 2 (Fig. 4.6c) are shown in Figure 4.6(m-p). The intensity profiles of TiO₂-coated MS2 viruses demonstrated the attachment of MS2 viruses on TiO_2 or vice versa and enhanced the size from nanosized to several micrometers (Fig. 4.6(m-p), Fig. C9). The high-resolution electron microscopy images confirmed the attachment of TiO₂ to MS2 viruses, likely due to the high surface tension of the MS2 and TiO₂ particles. More intensity and phase reconstruction images of TiO₂coated MS2 viruses are shown in Figure C9. The intensity and phase reconstruction images of pure olive oil are shown in Figure 4.6(g, h), and those for olive oil-coated MS2 virus particles are shown in Figure 4.6(i-j). High-resolution electron microscopy images of olive oil-coated MS2 virus are displayed in Figure 4.6(k-l). Interestingly, the olive oil-coated MS2 virus tended to adhere to contact-type morphologies more than TiO₂-coated MS2 viruses. This may be due to the adhesive properties of olive oil. More intensity and phase results of olive oil-coated MS2 viruses are shown in Figure C10. Figure C11(a-d) illustrates the intensity and phase images of alpha-pinene (secondary organic aerosols)-coated MS2 viruses. Moreover, the honey-coated MS2 particle intensity and phase results are shown in Figure C11 (e-f). The multimodal intensity and phase shift crosscut distribution observed in the alpha-pinene-coated MS2 particles indicated the surface modification or heterogeneity of the samples. However, honey-coated MS2 particles maintained their original structures with elongated/agglomerated morphologies.

Nano-DIHM successfully distinguished the coating impact on MS2 particles (Fig. 4.6, Fig. C9-11) with distinct pure MS2 particles (Fig. 4.1). It is clear evidence that alpha-pinene had a more vital interaction with the MS2 surface and transformed the MS2 particle structure into a layered structure. In contrast, TiO₂ was attached to the MS2 viruses, enhancing the MS2 size and altering its surfaces and morphologies. The olive oil and honey coatings altered MS2 morphologies due to their strong viscosity and adhesive surfaces. We further provided an example of an iron oxide and PSL coating on MS2 particles, as presented in Figure C12. Overall, nano-DIHM offers promising results for providing real-time in situ physicochemical virus characterization.



Figure 4.6 MS2 viruses coated with TiO₂ and olive oil. (a-b) Intensity and phase reconstruction of TiO₂ particles. (c-d) Intensity and phase results of MS2 viruses coated with TiO₂ particles obtained by nano-DIHM. (e-f) High-resolution electron microscopy images of TiO₂-coated MS2 viruses. (g-h) Intensity and phase images of olive oil. (i-j) Intensity and phase results

of MS2 viruses coated with olive oil obtained by nano-DIHM. (k-l) High-resolution electron microscopy images of oil-coated MS2 viruses. (m) Intensity response of particle 1 in panel (a). (n-p) Intensity response of particles 1 and 2 in panel (c), respectively.

4.2.7 Surface properties of SARS-CoV-2, MS2, and metal oxide particles

To investigate the surface morphology of SARS-CoV-2 particles, we also imaged MS2, 200nm polystyrene latex spheres (PSLs), olive oil, and metal oxide nanoparticles (TiO₂ and iron oxide) by using nano-DIHM. As shown in Table 4.1, the edge gradient and surface roughness of SARS-CoV-2 particles were quite distinct from those of PSL, olive oil, MS2 bacteriophage, and metal oxide particles. Note that reference holograms were obtained between experiments, including those with HEPA filtering. However, we cannot overrule possible contaminants such as impurities in Milli-Q water. However, as we developed classifiers for each item, the contaminants were detected and subtracted. The apparent difference in the edge gradient of SARS-CoV-2 and MS2 is due to their different surface properties. SARS-CoV-2 was heat-inactivated, while MS2 was an active virus. To demonstrate the structured exposure of viruses obtained by nano-DIHM, we exposed the MS2 samples to UV-B light (280-315 nm) for 30 minutes before the experiment. The MS2 particle shape with and without UV-B was similar, but the edge gradient of UV-B-exposed MS2 was observed to be almost half that of the unexposed MS2. Figure C4 shows the automated detection of MS2 particles using Stingray with UV-B and without UV-B. The real-time observation of surface roughness, size, phase, and time-dependent changes in the morphology of the SARS-CoV-2 in an ambient environment could be a significant breakthrough in understanding the physical process for not only SARS-CoV-2 but also future unknown viruses.

4.3 Outlook and potential applications

The currently developed nano-DIHM [401] can detect, classify, and determine the physicochemical properties of SARS-CoV-2 in air and water in the blink of an eye. The portable unit can act as a virus sensor, similar to a breathalyzer or an aerosol analyzer. Nano-DIHM can operate in static/dynamic mode at the site or laboratory to produce results in less than a minute with an accuracy of +90%. In contrast, conventional testing methods for COVID-19 are expensive and time-consuming; none are in situ or real-time methods. (Table C1). A future promising feature of nano-DIHM is that it can allow simultaneous measurements of several types of even more diverse particles that could signal both active and past infections from multiple viruses. An

increase in microbial pandemic occurrences is expected due to climate change [419]. The capability of nano-DIHM to determine the in situ and real-time physicochemical transformation of viruses and other pollutants and contaminants, such as nano- and microplastics and nanometals, would provide an edge over existing technologies. The real-time tracking of SARS-CoV-2 or any future viruses allows policymakers to react swiftly with more knowledge in future epidemic management response.

In brief, nano-DIHM can be used in a broad range of research and technology, from timedependent physical and chemical transformation of viruses and other microbiological entities, biogeochemistry, noninvasive imaging, biophysics, life cycle analysis of environmental pollutants, sustainable technology and pharmaceutical-medicinal applications to space and climate change science.

4.4 Methods

4.4.1 Digital in-line holographic microscopy

Digital in-line holographic microscopy (DIHM) works as a two-stage process: 1) recording the holograms and 2) numerically reconstructing the holograms to yield object(s) information. In the current setup, the holograms are recorded using the 4Deep Desktop Holographic Microscope (Halifax, Nova Scotia) [317], and numerical reconstruction is performed using the improved Octopus software, version 2.2.2 [342, 401] and Stingray software package, version 2.2.2 [343]. The detailed theory of DIHM and the reconstruction process are given in our previous paper [401]. In brief, a schematic of the next-generation nano-DIHM setup is displayed in Figure 4.7. A pinhole (laser (L)) emits a wave at $\lambda = 405$ nm. The resulting wave illuminated objects and produced a highly magnified diffraction pattern (hologram) on a screen [318, 401]. A complementary metaloxide semiconductor (CMOS) sensor is used to record holograms and store them on a computer for subsequent numerical reconstruction [317, 342].

Figure 4.7(b) shows that light emitted from the pinhole propagates toward the screen and is scattered by the particles/objects in its way, resulting in a hologram. The wave amplitude of the hologram on the screen, A(r, t), is given by Equation 4.1.

$$A(r,t) = A_{ref}(r,t) + A_{scat}(r,t)$$
(4.1)

where $A_{ref}(r, t)$ and $A_{scat}(r, t)$ are the reference and scattered amplitudes, respectively. The resultant intensity of the hologram recorded on the screen is:

$$I(r,t) = A(r,t)A^{*}(r,t)$$

$$I(r,t) = A_{ref}(r,t)A_{ref}^{*}(r,t) + [A_{ref}(r,t)A_{scat}^{*}(r,t) + A_{scat}(r,t)A_{ref}^{*}(r,t)]$$

$$+ A_{scat}(r,t)A_{scat}^{*}(r,t) \qquad (4.2)$$

In Equation 4.2, the first term represents the beam's intensity in the absence of an object or scatterer, and the last term represents the intensity of the scattered wave. The second term in the square brackets indicates the interferences between the reference and the scattered waves, referred to as holograms. The amplitude of the scattered hologram is:

$$A_{scat}(r) = \frac{iA_{ref}}{r\lambda} \iint I(r) \frac{\exp\left(ik\frac{rr'}{r}\right)}{|r-r'|} ds$$
(4.3)

.

During the numerical reconstruction of holograms, only three parameters are required to yield the object information: 1) the distance between the source (pinhole) and the screen, 2) the wavelength of light ($\lambda = 405$ nm), and 3) the camera pixel size (5.5 µm) [401]. Our experiment shows the quality of the background holograms in Figure C4(a). The background hologram was recorded with purified air. The airborne particles exiting the gas flow tube cuvette are passed into the SMPS and the OPS through the nano-DIHM sample volume (Fig. 4.7(d)). The particle counts measured with the SMPS and the OPS for purified air are fewer than 2 particles/cm³ (Fig. C4).

The nanosized resolution was obtained using specific experimental and numerical reconstruction approaches[401]. First, the hologram was recorded at the tip of the pinhole, keeping a minimum distance between the sample and the source. This procedure enables higher magnification, and hence a higher resolution can be achieved. Further, we modified the Octopus and Stingray software by implementing the additional convolution-deconvolution route to achieve a higher resolution. The details of those approaches can be found in our previous paper [401].


Figure 4.7 Schematic of nano-DIHM setup. a) SARS-CoV-2 transmission by an infected human via airborne transmission. The viral droplets pass through the flow tube cuvette to the nano-DIHM sample volume and SMPS. Furthermore, Octopus/Stingray software (artificial intelligence) was used to detect and characterize viral particles. b) Working principle of holography microscopy. c) Deep learning for SARS-CoV-2 analysis. d) Particle tracking analysis and sample collection method for field data. e) Experimental setup of airborne particle characterization.

4.4.2 Building library: automation and classification process

The automation and classification of SARS-CoV-2 viral-laden droplets were performed using Stingray software (flow chart in the manuscript). The Stingray software is based on a patented algorithm [319, 400] that was trained to achieve the real-time in situ automatic detection, classification, and physicochemical characterization of SARS-COV-2 in situ in real by using nano-

DIHM. The stingray software workflow follows three main categories: 1) Identify and find objects from recorded or real-time holograms, 2) classify the objects into taxon, and 3) start training the classifiers. The basic algorithm of stingray software follows the Kirchhoff-Fresnel reconstruction approach [319, 400], including robust deep neural network classifiers that extract in-focus objects and classify them within the image volume [343]. The intensity threshold and edge gradient value will be used as input parameters to detect the virus or other objects.

The 10K hologram and 100k iteration were used to train the Stingray software, and 99% accuracy was achieved. The following steps were performed to identify and classify SARS-CoV-2, MS2 and other materials (Table C2): 1) the input of holograms and recording parameters, such as the camera pixel size, laser wavelength and source-to-camera distance; 2) the optimization of intensity threshold values, which is responsible for finding the particles within the threshold domain. A good threshold value can be achieved by reconstructing the hologram manually using Octopus software, and 3) Choosing and selecting SARS-CoV-2-laden particles and classifying them into groups. This classification is based on the shape/morphology, intensity threshold and edge gradient. The flexibility of \pm 5% of their threshold allowed them to be classified or identified as particles/viruses/materials. Once the threshold parameter is optimized, the Stingray software can detect and classify the objects from millions of holograms. The automated outcome results contain object information, including the sizes, roughness, edge gradient, surface area, and shape of the particles. This process can be performed for both static and dynamic samples.

Table 4.1 shows the automated classification and detection of several materials and their associated physical properties, such as their size, shape and surface properties. Table 4.3 shows the ability of Stingray software to classify and identify SARS-CoV-2 from the mixed samples, and the outcome of "YES" indicates SARS-CoV-2 and "NO" indicates MS2. To validate the accuracy, we used seven different types of classifiers to compare the results. They are included: MS2 (dry aerosols), MS2 (moist droplets), TiO₂ (dry aerosols), 200 nm PSL (dry aerosols), SARS-CoV-2 + SARS-CoV-2 RNA + TiO₂ (water), SARS-CoV-2 + MS2 (air and water). The major challenge of the accuracy of Stingray software may decrease depending on the complexity of the sample matrix. A more extensive library of multiple sample matrices is required to overcome this issue. The extended/extensive library also allowed us to identify or target unknown species. Since several known or unknown species exist in the natural environment/atmosphere, Nano-DIHM cannot

extract information on unknown species without information on targeting species. We have shown that Nano-DIHM successfully detected and classified the oil spills in water samples [409]. The next generation nano-DIHM may detect the unknown particles if they are viruses or not. Since even unknown viruses have physicochemical characteristics, we may have the rapid training of the software and confirmation with more conventional PCR techniques in future.

4.4.3 SARS-CoV-2 sample information

We obtained heat-inactivated SARS-CoV-2 samples from the Medicine Department at McGill University. The heat inactivation process was performed at 92 °C for 20 minutes by shaking the samples. To confirm the SARS-CoV-2 particles in the samples, the Facility of Medicine Department at McGill University performed an RT–PCR test, and the genome sequencing results of the SARS-CoV-2 sample are given in Figure C1. The GenBank ID for the sequence is MN908947.3. Furthermore, SARS-CoV-2 sample images were obtained under the 10X magnification of an AMG Evos XL core microscope (Fig. 4.5) before supplying the samples for nano-DIHM measurements. The bacteriophage MS2 samples (1.0×10^9 pfu/ml) were purchased from ZeptoMetrix and stored below -20 °C until they were used for the experiment. MS2 sample preparation, such as dilution and mixing with metal oxides, was performed under a clean biosafety fume hood. Nano-DIHM requires no prior sample preparation for imaging virus particles and measuring combined organics or metal oxide particles. The original bacteriophage MS2 samples were diluted by a volume of 100x before performing the nano-DIHM measurements.

4.4.4 Experimental setup

A schematic of the integrated experimental setup of next-generation nano-DIHM is shown in Figure 4.7. The experimental design (Fig. 4.7) for the measurement of airborne viral particles consisted of the following components: 1) DIHM instrument, 2) gas flow cuvette (ES Quartz Glass, volume of 700 μ L, path length 2 mm), 3) microscope slide (Quartz Glass), 4) aerosol generator unit, 5) aerosol sizes and 6) sample collection unit for further analyses. The airborne/waterborne viruses (bacteriophage MS2 and SARS-CoV-2) passed through the quartz flow tube cuvette, and holograms were recorded by nano-DIHM (Fig. 4.7(a-e)). Several sample matrices were tasted in both dynamic and stationary manners. The detailed sample information and recording parameters are given in Table C2. The holograms were recorded for the moving airflow (containing viral aerosols) stream passed through the gas flow cuvette installed in nano-DIHM with a final flow rate of 1.7 L/minute. The outflow (1.7 L/min) from the cuvette was connected to the SMPS and the OPS. The coupling of the SMPS and the OPS with the DIHM allowed determination of the aerosol size distribution of the particles imaged by DIHM in situ in real time. In addition, the mixed samples with MS2 and TiO₂ were used to examine the heterogeneity and physiochemical transformation of viral particles in the air. We also combined SARS-CoV-2, SARS-CoV-2 RNA and iron oxide particles and analyzed them directly by nano-DIHM. Nano-DIHM determined the size, shape, and morphology of the bacteriophage MS2 compared with the morphology visualized using S/TEM. We also performed the experiments in stationary mode. To do that, 15 μ L sample drops were placed on a microscope slide using a micropipette. Once the sample was placed on the slide, a cover slide was used. Furthermore, sample-loaded microscope slides were placed in a nano-DIHM sample holder, and images were recorded.

4.4.5 Aerosol sizers

In this study, a scanning mobility particle sizer (NanoScanTM SMPS model 3910, TSI Inc.) and an Optical Particle Sizer (OPS, model 3330, TSI Inc.) was used to measure the real-time size distributions of airborne particles [72, 401]. The SMPS measured the particle sizes in the range of 10 nm to 400 nm, and the OPS determined the particle size in a range of 0.3 μ m – 10 μ m. The sample flow rate for the SMPS was 0.75 L/min, while the OPS required a sampling flow rate of 1 L/min. A more detailed description of the SMPS and the OPS system is provided in our previous articles [72, 73].

4.4.6 High-resolution electron microscopy

First, the TEM grid was negatively charged using a 15 MA plasma glowing discharge, and later, 10 μ L drops of pure MS2 bacteriophage solution were applied to the grid. After 5 minutes, the excess MS2 sample was removed using filter paper. Afterward, uranyl acetate (aq. 2%, w/v) was applied for negative staining. One minute later, the excess uranyl acetate was removed with filter paper. Electron microscopy images were taken by using a transmission electron microscope.

Thermo Scientific Talos F200X G2 S/TEM with ChemiSTEM technology, including an X-FEG high brightness Schottky field emission Source, Ceta 16M 4k x 4k CMOS camera, super-x windowless energy dispersive spectrometer, and gatan enfinium ER Model 977 electron energy loss spectroscopy (EELS), were used with a couple of high visibility low-background beryllium double-tilt optimized for EDS. S/TEM (Tecnai G²F20 S/TEM microscope) was used to analyze the 100X diluted MS2 samples in Milli-Q water. For S/TEM analysis, no staining was performed. A 10 μ L drop of 100X MS2 samples was applied to the TEM grid and allowed to remain for 1 minute. Afterward, TEM grids were placed onto the sample holder, and TEM images were acquired. A detailed description of S/TEM is given in our previous paper [72, 401].

4.4.7 Litesizer particle analyzer

A Litesizer 500 (Anton Paar, Canada) particle sizer analyzer (PSA) was used to characterize the active MS2 virus sizes in 100x diluted MS2 samples in aqueous mode. The Litesizer 500 measures the particle size from nm to micrometers. The Litesizer measures the particle sizes via dynamic light scattering at three different measurement angles: side, back, or forward scattering, allowing optimal parameter settings.

4.4.8 Particle trajectory analysis

The following procedure was used to achieve high-resolution trajectories: (a) a series of holograms were recorded at 32 fps for both moving air and flowing water in a quartz cuvette, (b) the experimental/optical impurity of the background was eliminated by subtraction of consecutive holograms, and (c) the resultant holograms were reconstructed at a particular reconstruction position (plane) and summed to obtain the dynamic trajectories [401]. The subtraction of holograms was necessary to ensure that the dynamic range was not exceeded, and only the MS2 virus information was preserved [352, 401]. All the holograms were reconstructed at the same reconstruction position (Z=5409 μ m) for moving viral droplets Movie 1 and Z=1790 μ m for moving air Movie 2. Furthermore, reconstructed results were processed to create the Giff movies.

Acknowledgment

We are very grateful to several colleagues at McGill Faculty of Medicine and Health Sciences, particularly the virologists, including Ms. Fiona McIntosh, Professor Marcel Bher, and Professor Jorg Fritz, who provided us with inactivated viruses and guided us with the procedures. We thank Professor Vali from the McGill Facility of electron microscopy for the S/TEM analysis. The Tomlinson Award and McGill Sustainability supported this work to PAA, Canadian Foundation for Innovation (CFI), Natural Sciences and Engineering Research Council of Canada (NSERC), National Research Council (NRC), NSERC CREATE PURE, and PRIMA Quebec. We also thank Dr. Amit Kumar Pandit, National Institute of Aerospace, Hampton, Virginia, USA, for his critical review of the manuscript and Mr. Ryan Hall for proofreading our manuscript.

Chapter 5 Deciphering Supercooled Droplets from Ice Crystals: MRINC Simulated Mixed-Phase Cloud Regime

The involvement of atmospheric ice-nucleating particles (INPs) in ice or mixed-phase clouds significantly affects how precipitation forms, clouds albedo, weather and climate [128]. Regional and global Earth system models have increasingly started to link cloud ice processes to model-simulated aerosol abundance and the origins of INPs [127, 144, 420]. These latest developments are undoubtedly interesting, but connecting cloud processes to simulated aerosol also makes cloud physics models more subject to uncertainties in the simulation of INPs, which are currently inadequately restricted by observations [132, 149]. An emphasis on research that connects the measuring and modelling communities will be necessary to advance the forecasting of INP abundance with appropriate spatiotemporal resolution [130]. The distinction between ice crystals and supercooled droplets in mixed-phase clouds remains challenging. In this, Chapter, we demonstrated that the implementation of Nano-DIHM with in house built McGill Real-time Ice Nucleation Chamber allow us to distinguish the ice crystals and supercooled droplets in mixed phase cloud regime in situ in real time.

This Chapter consists of a manuscript in preparation that will be submitted to the Journal of Geophysical Research: Atmosphere:

Devendra Pal, Ryan Hall, Yevgen Nazarenko, Jean-Philippe Guay, and Parisa A. Ariya: Deciphering Supercooled Droplets from Ice Crystals: MRINC Simulated Mixed-Phase Cloud Regime.

Deciphering Supercooled Droplets from Ice Crystals: MRINC Simulated Mixed-Phase Cloud Regime

Devendra Pal¹, Ryan Hall², Yevgen Nazarenko¹, Jean-Philippe Guay², and Parisa A. Ariya^{*1,2}

¹ Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 0B9, Canada.

² Department of Chemistry, McGill University, 801 Sherbrooke Street West, Montréal, QC H3A 2K6, Canada.

*Corresponding author: Parisa A. Ariya

Abstract

In real-time, little information on ice nucleation physicochemical properties of airborne nanosized aerosols is available. Likewise, the ice nucleation properties of airborne nanosized emerging metal and nano-micro plastic pollutants are unknown. Here, we present the newly developed portable McGill Real-time Ice Nucleation Chamber (MRINC) operating in real-time in situ to study ice nucleation processes and measure nano to micro-sized ice nucleating particles (INPs). At the current stage, MRINC operates under conditions pertinent to mixed-phase cloud temperatures from approximately 0 °C to approximately -38 °C. The MRINC is coupled with aerosol sizers (6 nm to 10 µm) and a Nano-Digital In-line Holographic Microscope (Nano-DIHM) to record the size distribution, phase, and shape of INPs. The characterization includes determining aerosol particles' size, shape, morphology, phase, and surface properties. As a proof of concept, we show preliminary results, where Nano-DIHM coupled with MRINC successfully distinguished silver iodide nucleated ice crystals and supercooled droplets in real-time. We also provide an example of real-time capturing of the growth of sodium chloride (NaCl) and ammonium sulphate ((NH₄)₂SO₄) aerosol particles in controlled temperature and humidity conditions using MRINC. Our preliminary results suggest that coupling the newly developed optical detection system (Nano-DIHM) with MRINC enabled us to measure and distinguish ice crystals from supercooled droplets in real-time in situ under controlled laboratory conditions. Finally, we demonstrate that MRINC could be used for cloud condensation and ice nucleation studies.

5.1 Introduction

The link between ambient aerosols and the formation of ice-containing clouds is one of the most considerable uncertainties in understanding the Earth's climate [106, 110]. Atmospheric ice nucleating particles (INPs) induce ice formation in atmospheric clouds changing their role in direct and indirect radiative forcing [127, 129], ultimately impacting the Earth's climate. INPs are aerosols, defined as solid or liquid particles suspended in the air ranging in size from 1 nm to several 100 μ m. Several natural sources contribute to atmospheric INPs, like wind-blown dust, sea spray particles, biological particles such as fungal spores, bacteria, pollen, and ash, and particles emitted from biomass burning [128]. Nanosized aerosols (diameter \leq 200 nm) contain a major proportion of total atmospheric particle numbers [72, 73]. Nanosized aerosols have a large surface-to-volume ratio, which can serve as cloud condensation nuclei [286] or ice nuclei [23, 285] and help in cloud formation. However, due to a lack of microphysics process-level understanding, aerosol-cloud-climate interactions remain highly uncertain [108, 110, 114]. To improve climate predictability in the future, a comprehensive knowledge of INPs, including their transportation in the atmosphere, microphysical interactions with atmospheric processes, and effects on clouds, is necessary [130].

Clouds are the aggregates of water and ice crystals, the most uncertain components of the Earth's climate, and essential for the global hydrological cycle [110]. Global climate models involve significant uncertainties in their predictions because microphysical processes occurring in these clouds are not well represented by these models [114, 134, 135], especially for the ice clouds. The formation of ice crystals/ice clouds in the Earth's atmosphere involves complex microphysical processes that primarily depend on the ambient temperature, supersaturation with respect to ice (*S_i*), and availability and type of aerosols [21, 128]. INPs are exceedingly rare in the atmosphere, with concentrations ranging from less than 0.01 to more than 100 L⁻¹ for INPs active at -30 °C [129]. INPs are challenging to quantify and characterize due to their scarcity and intense sensitivity to aerosol chemical and physical properties [127, 128].

Research on atmospheric INPs has witnessed a resurgence in recent decades [127, 128, 421], enhancing the understanding of INPs measurement methods and expanding the range of observations[422, 423]. Field experiments have shown that adding INPs into supercooled clouds

can alter the time and location of precipitation [424, 425]. Ice cloud models have demonstrated significant impacts of INPs on clouds that can explain observed variations in cloud properties [129, 133, 426]. For example, satellites and lidar observations suggest that INPs play a key role in shaping the cloud phase, cloud albedo and their lifetime [427-429]. Yet, significant uncertainties remain in the comprehensive understanding of INPs research. At the same time, several advancements in the experiment, observation, and theory have increased confidence that INPs can influence mixed-phase cloud characteristics and their interactions with solar radiation and precipitation [149, 430]. Recent review articles have discussed challenges associated with INPs measurement methods, the availability of INPs measurements from different environments, and the representation of INPs in cloud microphysical models [21, 128, 130, 134, 137, 420, 431].

Several types of ice nucleation measurement instruments have been developed since the 1960s or 70s. These are direct sampling ice nucleation instruments based on Continuous Flow Thermal Diffusion Chambers (CFDC) and post-processing ice nucleation instruments [430]. For post-processing ice nucleation devices, the sample is collected on a filter or substrate and then measured in the laboratory according to sample requirements [21]. These devices record freezing by particles within liquid droplets or confined liquid volumes. More details on post-processing ice nucleation devices can be found in previous studies [21, 140, 430, 432]. Details of various CFDC instruments being used in different laboratories around the globe are given in Appendix Table D1 and Text D1.

Reviews show that there are many laboratory studies assessing the ice nucleation ability of selected size (> 0.5μ m) and types of aerosols, such as soot particles, mineral dust, and biological particles [21, 129, 130, 137, 143, 144]. However, the measurement of nanosized ice nuclei in the atmosphere has not been studied either computationally or in controlled laboratory experiments. Most parameterization schemes for heterogeneous ice nucleation did not include specific nanosized aerosol dependencies in cloud-resolving models to global climate models [132, 145]. Nowadays, the results of ice nucleation due to the aerosols are often used in atmospheric models on different scales, from regional to global climate models [129, 130, 134, 146-149].

Here, we introduce a newly developed portable ice nucleation system called McGill Realtime Ice Nucleation Chamber (MRINC) to measure the nanosized ice nuclei that are coupled with a newly developed optical detection unit combining Nano-Digital In-Line Holography Microscopy (Nano-DIHM) and aerosol sizers [401]. The novel optical detection system of the MRINC allowed the characterization of nanosized INPs and their physical (size, shape, and phase) and chemical properties. Nano-DIHM will determine the real-time time-dependent morphology of ice nucleation particles in situ and the roughness of INPs. The experimental results of MRINC will help elucidate the role of nanosized particles in the ice nucleation process, including the impact of chemical identity and different size fractions of aerosols on the particles' ice-nucleating ability. In this study, we provided a detailed description of MRINC development for field and laboratory use at McGill University. This MRINC can study cloud condensation nuclei (CCN) and Ice Nuclei (IN). We demonstrate that the MRINC can distinguish ice crystals and supercooled droplets in a mixedphase cloud regime. The MRINC has been calibrated in both ambient and atmospheric conditions. First, we tested the MRINC for CCN mode by passing sodium chloride (NaCl) and ammonium sulphate ((NH₄)₂SO₄) at different temperatures and humidities. At the same time, MRINC tested for IN mode by passing silver iodide (AgI) and polystyrene latex sphere (PSL) at different temperatures and humidities. Finally, we presented the preliminary results of our optical detection system, combining Nano-DIHM and aerosol sizers, which successfully distinguished the ice crystals and supercooled droplets in situ and in real-time.

5.2 Experiment and methods

5.2.1 McGill Real-time Ice Nucleation Chamber (MRINC)

The schematic of MRINC is shown in Figure 5.1. It consists of four components:1) optical detection unit, 2) aerosol generation unit, 3) main sampling tube or the growth section of INPs or CCN, and 4) humidifier. HMT 370 probe (Vaisala Meteorological Instruments Inc., Vantaa, Finland), sentinel next sensors (Aginova Inc., Mason, OH, USA), and k-p type thermocouples were collectively used to measure temperature and supersaturation inside the MRINC.



Figure 5.1 Schematic of McGill Real-Time Ice Nucleation Chamber (MRINC). The bottom side inserted image shows the cylindrical geometry and experimental setup at McGill University.

5.2.1.1 Novel optical detection unit

The optical detection unit coupled with MRINC consists of the Nano-DIHM and an aerosol sizer.

<u>Nano-Digital In-line Holographic Microscopy</u>: The Nano-DIHM involves a two-stage process. 1) recording the holograms and 2) numerical reconstruction of holograms to yield information about the object(s), such as size, phase, shape, morphology, and surface properties [401, 409]. Currently, holograms are recorded using a 4Deep Desktop Holographic Microscope [433]. The numerical reconstruction of the holograms is performed using the Octopus/Stingray software package, version 2.2.0 [342]. The details of the Nano-DIHM setup and working principle can be found in our earlier article [401]. In brief, a laser (L) emits light that passes through a pinhole (Pinhole) at the wavelength λ =405 nm and illuminates the object(s) under observation located at a distance of a few micrometres from the pinhole. As a result, a highly magnified diffraction pattern, the hologram, is produced on the screen [401]. The recorded holograms are 2048×2048 pixels (5.5 µm camera pixels) and numerically reconstructed using Octopus/Stingray software [342, 433]. Numerical reconstruction requires only the distance between the pinhole and the screen, the wavelength of light (405 nm), and the camera pixel size (5.5 µm) [401]. No other information is needed to retrieve images in individual depth planes, which yield the observed objects' position, orientation, and shape [401].

<u>Aerosol Particle Sizer:</u> A Scanning Mobility Particle Sizer (SMPS) model 3789 (TSI Inc.), an Optical Particle Sizer (OPS) model 3330 (TSI), was used to measure the real-time size and number distribution of ice crystals and aerosols particles. The SMPS measures the size of the airborne particles from 6 nm to 320 nm, and OPS counts the larger particle size range of 0.3 - 10 µm. SMPS consists of a differential mobility analyzer (model 3938), the electrostatic classifier (model 3082) and a water-based condensation particle counter (model 3789) from TSI, Shoreview, MN, USA. The SMPS uses a sample flow rate of 0.6 l/min, and OPS requires 1 l/min. The SMPS system was used with a 0.071 cm impactor. For the SMPS, particle density was set as 1.0 g/cm³ as it was impossible to determine the actual density of measured aerosol droplets. In addition, the use of 1.0 g/cm³ density allowed easy comparison of the SMPS particle size distribution, expressed as electric mobility diameter, with the OPS data expressed as aerodynamic diameter. The SMPS data was extracted by using aerosols integrated software version 11.4.0 (TSI) in 32-size bin channels.

5.2.1.2 Aerosol generation unit

The aerosol generation unit consisted of three main components: (1) a C-flow atomizer for aerosol generation, (2) a double diffusion dryer for aerosol drying, and (3) a sampler for airborne particle collection for physical and chemical offline analysis. The whole aerosol generation assembly setup was placed horizontally. Its components were connected using electrically conductive silicone tubing (TSI, Inc.) to minimize electrostatic aerosol particle losses. The suspended liquid samples were drawn into a syringe and installed into a syringe pump (GenieTouch[™], profiles inside Kent Scientific Corp., Torrington, CT, USA). The syringe pump supplied the liquid samples in a continuous flow to C-Flow 700d PFA atomizer (Savillex Corporation, Minnetonka, MN, USA). The fluid feed rate to the nebulizer was set at 0.25 mL/min.

Dry air from a cylinder was passed to the nebulizer through a large high-efficiency particulate air (HEPA) filter, WhatmanTM HEPA-Cap 150 (Little Chalfont, Buckinghamshire, UK). The resulting aerosol contained aqueous droplets with solid suspended particles within the droplets. This aerosol passed through the double diffusion dryer, and the output flow was introduced to the MRINC. Temperature and RH were continuously measured at ≤ 1 % and ~ 22.5 °C in the outflow from the double diffusion dryer.

5.2.1.3 Growth section of INPs

A 1 m long and 5.7 cm inner diameter open cylindrical stainless-steel tube has been used as a sampling tube (type 316, McMaster-Carr, USA) to grow ice crystals and cloud droplets. The copper coiling (1/8-inch inner diameter) was enclosed in the sampling tube for cooling. The copper coil was connected to the cooling bath circulator (ThermoFisher, model: PC200). Ethylene glycol and silicon oil (Sil 100) were used as coolants. A 2-inch inner diameter double layer of neoprene was used for the insulation. Four hygrometers (sentinel), four k-type thermocouples, and an HMT 370 probe were installed at different distances along the sampling tube to monitor the temperature (Fig. 5.1).

The aerosol particles are generated by an atomizer (or direct air sample inserted into the dryer) and passed through the dryer to ensure they do not carry any moisture. A 1.61 L/min dry aerosol sample is introduced into the sampling tube using a honeycomb stainless steel inlet. Once aerosol particles enter the growth section and are exposed to supersaturation, they start activation as INPs or CCN and grow to a broad range of ice crystals or supercooled cloud droplets. These ice crystals or supercooled cloud droplets are then detected with our novel detecting system (DIHM, SMPS, and OPS); it is possible to distinguish between supercooled droplets and ice crystals and to measure the number size concentration of CCN and IN. MRINC can be used in horizontal and vertical orientations with varying sample flow rates (Table D2). The fraction of aerosol particles that nucleated ice is called the activated fraction (AF), defined as the ratio of the number concentration of ice particles entering the chamber, n_{total} , as determined by the SMPS and OPS in parallel to MRINC (equation 5.1):

$$AF = \frac{n_ice_{ch}}{n_{total}} \tag{5.1}$$

5.2.2 Sample preparation and CCN, IN experiments

The MRINC has been tested and calibrated for both CCN and IN modes. We used the 1 g/L AgI, 0.2 g/L NaCl and $(NH_4)_2SO_4$ suspended solutions for CCN and IN investigation. The ultrapure Milli-Q water 18.2 M Ω ·cm was obtained with the Milli-Q Synergy UV system (Millipore Sigma, USA) and used for sample preparation throughout the experiment. Further, using a syringe pump, each sample was aerosolized using a C-flow atomizer. In the control experiment for SMPS and OPS, we used the PSL spheres (100 and 200 nm, Sigma-Aldrich) 1: 100 mixtures with Milli-Q water at room temperature; the later same sample was also used for CCN and IN experiments (as a proxy of plastic), respectively. At the current stage, the MRINC can operate from room temperature to -25 °C but can reach colder conditions by changing the cooling reagent or replacing the cooling circulator (Fig. 5.3). The schematic of the experimental setup (Fig. 5.1) for measurement of ice crystals and supercooled water droplets in a mixed-phase cloud regime. Each experiment has been repeated thrice.

The output flow from MRINC has been drawn to the Nano-DIHM, SMPS and OPS using 1/8 inch stainless steel (316 class) tube ~ 3 cm in length insulated with double-layer neoprene. The outflow (1.6 L/min) was used for SMPS and OPS systems, while (1 L/min) was used for Nano-DIHM. The coupling of the SMPS and the OPS with the Nano-DIHM allowed real-time determining and distinguishing ice crystals and supercooled water droplets. Background data were obtained before and after each experiment by operating the C-Flow Nebulizers without any liquid feed and then with ultrapure Milli-Q water feed.

5.3 Results and discussion

5.3.1 Validation of MRINC

MRINC has been tested and calibrated for different temperature and relative humidity (RH) conditions and was validated using particle-free aerosol samples with varying flow rates with and without cooling (Fig. D1 and Fig. D2). The flow rates have been optimized with respect to residence time for particle growth and required supersaturation. We also investigated the aerosol

loss inside the MRINC in ambient conditions (Fig. 5.2). The MRINC realized the mixing principle, and the aerosol stream passed through a honeycomb inlet before entering the chamber, allowing us to maximize the exposure of aerosols in the supersaturation to mimic the actual atmospheric conditions. Inherently, some aerosol particles are deposited on the chamber wall and lost inside the chamber. We aerosolized several synthetic materials to better estimate aerosol loss due to the chamber wall. We found that the mode of the size distribution of each type of aerosol did not changes while the number of each size of aerosol dropped by ~ 30 percent, as shown in Figure 5.2. Figure 5.2 also shows the quality measurement by SMPS, where SMPS measured 100 nm and 200 nm particle size distribution.



Figure 5.2 Aerosol size distribution in ambient conditions with and without chamber. (a-b) The size distribution of different aerosols inside the chamber, and (c-d) shows the size distribution without the chamber. (a,c) and (b,d) measured by SMPS and OPS, respectively.

The MRINC has been calibrated at different flow rates with the mixture of dry air and 100 % humid air generated with the external humidifier (nafiaonTM, MH-Tm series humidifier, New Hampshire, USA) (Fig. D1). The temperature and humidity of mixed air vary within \pm 0.2 °C and \leq 1%, as shown in Figure D1. This variation generally comes due to a slight fluctuation in the flow. The same experiment was performed at controlled temperature conditions at ~ 0, -5, -10 and -15 degrees, as shown in Figure D2. We achieved a temperature and relative humidity variation around $\leq \pm$ 1°C and \leq 2 %, respectively (Fig. D2). However, the temperature gradient across the length of the chamber is observed to be \leq 1.5 °C from inlet to outlet (Figure 5.3). A series of thermocouples were used to measure the temperature inside the MRINC, and \pm 1.5 °C temperature difference was observed between the topmost thermocouple (at 10 cm) and the bottommost thermocouple (3 cm from the outlet). These temperature differences could be due to using different thermocouples and within the uncertainty limit. The supersaturation was calculated based on August-Roche-Magnus, Murphy, and Koop's (2005) approximation [434]. We are currently simulating the MRINC in the FLUENT 3D model to simulate and calculate the supersaturations.



Figure 5.3 Temperature response inside the MRINC at a different length. The temperature gradient was ≤ 2 °C from the inlet at 10 cm to 97 cm at the end of chamber length (3 cm from the outlet, where the optical detection unit was installed). At the current stage, MRINC reached ~ 25 °C, though it can reach a much colder temperature by changing the cooling bath or colling the circulator.

5.3.2 Distinction of ice crystals and supercooled droplets in mixed-phase cloud regime

The MRINC was designed to investigate the ice nucleation features of aerosol particles. More specifically, the microphysical level studies for understanding the role of nanosized aerosols, surface roughness or active sites, and surface elemental composition on ice nucleation. The MRINC enabled investigation of the submicron particles (≤ 500 nm) in ice nucleation, where these size particles are abundant in the atmosphere but, up to now, cannot be studied in real-time in situ. Here, we present the first preliminary results of MRINC using AgI-suspended particles and successfully distinguishing supercooled droplets and ice crystals. The aerosol-charged AgI particle stream was injected into the MRINC, exposing them at various temperatures (0, -5, and -10 °C) at constant supersaturation RH ~143 % (Fig. 5.4).



Figure 5.4 Activated fraction of AgI at different temperatures and constant supersaturation. At T = 0 °C, RH = 104 %; T = -6.2 °C, RH ~ 143%; T = -9.6 °C, RH ~ 143%.

Figure 5.4 (a-d) presents the activated fraction of AgI particles at - 6.2 and -9.7 °C at constant relative humidity at ~ 143 %. We observed that the AgI concentration of 40-100 nm-sized particles decreased as the temperature got colder, suggesting that the nanosized particles started growing either cloud droplets or ice crystals visible in OPS data, where the secondary peak was observed at approximately 1-2 µm. Further, activated fraction analysis for each size channel suggests that the AgI nanoparticles are evidently behaving or participating in ice nucleation processes (Fig. 5.4).

Figure 5.5 shows the results obtained from Nano-DIHM, where the evaluation of dry AgI particles to supercooled AgI or water droplets and ice crystals can be clearly seen. The intensity reconstruction in the top panel of Figure 5.5 (a-d) displays the differences between dry AgI aerosol particles (T = 22.5 °C, RH \leq 1%), supercooled AgI droplets (T = - 0.2 °C, RH ~ 104 %), and ice crystal formation (T = -6.2 °C, RH $\sim 143\%$), respectively. The phase images in Figure 5.5 (e) replicate the intensity image shown in Figure 5.5(c,d). The images shown in panels (f,g) are zoomin images from panels (b,c), displaying distinctly supercooled droplets and AgI ice crystals, respectively. Previous studies also confirmed similar morphology and structure of AgI ice crystals [435]. Figure 5.5 (h) shows the phase reconstruction of the same AgI aerosol stream sample after 1 minute, suggesting clusters of droplets and ice crystals, where Nano-DIHM cannot evidently distinguish ice crystals and supercooled droplets. This may arise due to the enclosed fog on the flow tube cuvette system, which deteriorates the Nano-DIHM resolution. It is one of the current limitations of MRINC to quantify the supercooled droplet and ice crystals for long-term experiments. Although, we can overcome this issue by replacing larger volume and thin wall flow tube cuvette and simultaneously implementing improved numerical reconstruction approaches [401].



Figure 5.5 Intensity and phase reconstruction images of AgI aerosol particles in situ in real time. (a) Intensity reconstruction of dry AgI particles at reconstruction distance $z = 1378 \mu m$ (T = 22.5 °C, RH $\leq 1\%$). (b) Intensity images of a cloud droplet of AgI at $z = 1410 \mu m$ (T = 0.2 °C, RH ~ 104 %). (c,d) Intensity reconstruction AgI ice crystals and cloud droplets at z= 2644 μm (T = -6.2 °C, RH ~ 143%). The red rectangles are cloud droplets, and the green circle shows the ice crystals. (e) Phase images of the same particles in panels (c,d). (f,g) zoom-in image of the panel (c,d) shows the cloud droplet and ice crystal. (h) After the 1-minute phase image clearly shows the signature of fog.

5.3.4 Example of MRINC operation in CCN mode

We also examined the capability of MRINC in Cloud condensation nuclei measurement or explored particle growth studies. We injected aerosolized NaCl, $(NH_4)_2SO_4$, and 200 nm PSL particles into MRINC using a honeycomb inlet and exposed them at room temperature (T ~22.5 °C) at different humidity conditions; RH1 ~ 52%; RH2 ~ 68%; RH3 ~ 78%; RH4 ~ 89%, to determine their size distributions (Fig. 5.6 (a-f)). The SMPS and OPS collectively measured the particle size distribution from 6 nm to 10 µm. For NaCl, at RH1 ~ 52 % relative humidity, the NaCl peak was observed around ~50 nm, while as humidity increases and reaches ~89 %, the size of NaCl particles shifted by two times to initial size and peaked around 100 nm (Fig. 5.6(a)). Figure 5.6 (a) shows that as relative humidity increases, NaCl particles' concentration is observed to increase. It may be due to the process of deliquescence [436-438]. The exact relative humidity at which deliquescence occurs depends on the specific conditions, such as the temperature and the purity of the NaCl; typically, it happens at around 75-80% relative humidity [436, 439]. Similar

trends were observed for ammonium sulphate; as humidity increased, the size of smaller particles shifted towards larger size particles (Fig. 5.6 (c)). We observed that with higher humidity (~90%), the particles' size and concentration increased significantly as compared to lower humidity (~50%). It is because, at higher humidities, water vapour can condense onto ammonium sulphate particles and form droplets. In comparison, fewer droplets will form at lower humidities, and those that do form will likely be smaller as cloud condensation nuclei [436-439]. However, PSL particles did not show significant changes in their size while changing the humidity. It can be understood that the PSL particles are not very soluble in water and have hydrophobic properties. PSL spheres are typically very smooth, with a low surface area, meaning there is less surface area for moisture to adsorb. This combination of hydrophobic properties and low surface area makes PSL spheres poor CCN and require water uptake to form droplets. It should be noted that some PSL spheres are produced with surface modifications to be hydrophilic so that they can act as CCN, but they are not typical [438, 440].

Figure 5.7 presents the real-time NaCl and 200 nm PSL particle growth obtained from Nano-DIHM in situ. Figure 5.7 (a) shows the distribution of dry NaCl particles followed by their growth at relative humidity ~89 % (Fig. 5.7 (b)). The intensity and phase reconstruction images clearly show NaCl particles' water uptake (Fig. 5.7). However, PSL particles did not show evident uptake due to the PSL hydrophobic properties (Fig. 5.7 (e,f)).



Figure 5.6 MRINC operation in CCN mode. The aerosol particles' growth determined at room temperature (~22.5 °C) at different humidity conditions; RH1 ~ 52%; RH2 ~ 68%; RH3 ~ 78 %; RH4 ~ 89%. (a,b) NaCl, (c,d) (NH₄)₂SO₄, and (e,f) 200 nm PSL, respectively. (a,c,e) and (b,d,f) are SMPS and OPS measurements, respectively.



Figure 5.7 Intensity and phase reconstruction images of airborne NaCl and 200 nm PSL aerosol particles in situ in real time. (a) Intensity reconstruction of dry NaCl particles at reconstruction distance $z = 985 \mu m$ (T = 22.5 °C, RH $\leq 1\%$). (b) Intensity images of NaCl after water uptake at $z = 962 \mu m$ (T = 22 °C, RH ~ 89 %). (c) Phase image of same particles as panel (b) at $z = 1350 \mu m$. (d) Intensity reconstruction of dry 200 nm PSL particles at reconstruction distance $z = 1068 \mu m$ (T = 22.5 °C, RH $\leq 1\%$). (e) Intensity images of PSL after water uptake at $z = 958 \mu m$ (T = 22 °C, RH ~ 89 %). (f) Phase image of same particles as panel (e) at $z = 958 \mu m$.

5.3.5 Advantages and limitations of MRINC

The mixing principle realized in MRINC has several advantages over the parallel plates design CFDC-based Ice Nucleation counters. The list of in-house built existing IN counters are given in Appendix Table D1. Generally, in a parallel plate design, temperature and supersaturation are calculated as a function of the wall temperatures. Thus, both temperature and supersaturation can be changed only by changing wall temperatures, which requires time because of the walls' large heat capacity. However, the MRINC temperature and supersaturation can be rapidly changed by varying the warm and cold air flow mixture (Fig. D1 & D2). In the MRINC, temperature and supersaturation are measured and directly controlled without affecting the aerosol flow.

In contrast, in a parallel design, a disturbance or displacement of the aerosol flow (e.g. misalignment) may result in significant errors in the calculated supersaturation, temperature, and INPs concentration. In MRINC, higher sample flow rates of up to 50 L/min can be achieved (Table D1). An optical detection unit coupled with MRINC successfully recovered the ice crystals and supercooled droplets in a mixed-phase cloud regime (Figure 5.5). However, at the current stage, the simultaneous long-term quantification of supercooled droplets and ice crystals is a tricky measurement due to the smaller volume flow tube cuvette. In future, this challenge can be overcome by modifying the outlet detection system, such as installing a larger volume cuvette or installing an optical window from the side of MRINC. These minor changes in MRINC design are underway and will be communicated in our next-generation MRINC.

5.4 Conclusion and proposed future steps

The newly developed MRINC has been designed, constructed, and validated for ice nucleation investigations. The principle of operation of MRINC is very similar to the fast ice nucleation chamber (FINCH) [45] but advanced for coupling with a unique detection system consisting of a combination of Nano-DIHM, SMPS, and OPS. AgI particles were used for preliminary studies of the ice nucleation process. The MRINC successfully captured the ice nucleation behaviour of AgI particles and distinguished supercooled droplets and ice crystals in real-time. The unique capability of the MRINC is that it allows us to visually record individual particles' nucleation events at different temperatures and supersaturation conditions. Additionally, it provides in situ real-time size, shape, surface, and phase information of ice crystals along with supercooled droplets.

The results from MRINC, where the separation of ice crystals and supercooled droplets in a mixed-phase cloud regime is possible, will allow a better understanding of the microphysics of clouds, which can improve the accuracy of weather forecasting models. Ice crystals and supercooled droplets also have different impacts on precipitation formation, so distinguishing between them can improve our understanding of precipitation patterns and the water cycle. In addition, ice crystals and supercooled droplets have different radiative properties and effects on the atmospheric radiation budget, so distinguishing between them can help to improve climate models. Further experiments will be performed to understand the role of nanosized ice nuclei in cloud formation.

- Measurements of ice nuclei for nanosized emerging metal contaminants such as iron oxide and other mineral particles containing Zn, Cu, and Al in their chemical identities at different sizes (≤50 nm, ≤100 nm, ≤150 nm, and ≤200 nm), in a range of temperature and saturation regimes.
- 2. Ice nucleation measurements for most common plastics include low-density polyethylene, high-density polyethylene, and polypropylene. These experiments are proposed in both the airborne and liquid phases.

Acknowledgement

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), National Research Council (NRC), NSERC CREATE Mine of Knowledge, NSERC CREATE Pure, Pôle de recherche et d'innovation en matériaux avancés du Québec (PRIMA Quebec), and Environment and Climate Change Canada (ECCC). We thank Dr. Justin Jacquot for their help in discussions. We are very grateful to several colleagues at McGill Facility of Machine shop, including Mr. Sam, who provided us timely access to the facility to perform work on steel policing and cutting. We also thank our electrical shop colleagues, Mr. Richard Rossi and Mr. Weihua Wang, for their help in installing the power supply.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

With the scope of this thesis work, three prominent missing links in aerosol science were investigated. Distinct contributions to the advancement of aerosol science were made in 1) understanding the behaviour of airborne nanoparticles in a cold urban climate; 2) developing a novel holographic microscopy technology (Nano-DIHM) for measuring 3D physicochemical properties of aerosols and detecting bioaerosols (viruses and bacteria) in air, water, snow and ice; and 3) developing the McGill Real-Time Ice Nucleation Chamber (MRINC) and coupling it with Nano-DIHM to distinguish supercooled droplets from ice crystals in a mixed-phase cloud regime. These contributions and their connections with other scientific work are presented in Figure 6.1.



Figure 6.1 Schematic chart summarizing the distinct research contributions realized during my doctoral studies in the McGill University Atmospheric & Interfacial Chemistry Research Group.

In Chapter 2, we reported on the measurements of size-aggregated particle number concentration distributions in five size ranges: < 100 nm (10 - 100 nm), < 200 nm (100 - 235 nm), < 1 μ m (0.3 - 0.9 μ m), < 2.5 μ m (0.9 - 2.6 μ m), and < 10 μ m (2.6 - 10 μ m) along with selected

chemical and physical properties of aerosols in the cold climate of downtown of Montreal, from May 2017 to May 2019. We discovered that the concentration of aerosol particles exhibited a strong seasonal variation in these cold-climate conditions, with the highest concentration of nanoparticles in winter. Likely, the combination of winter meteorology (low boundary layer and freezing temperature) and higher emissions of pollutants due to a seasonal peak in energy use (transportation and heating) increases aerosol concentrations at this time of year.

High-resolution S/TEM-EDS imaging confirmed the abundance of single nanoparticles and nanoparticle clusters with multifaceted morphologies and compositions. We identified emerging air pollutants, such as synthetic TiO₂ nanoparticles, secondary organic aerosols, bioaerosols, and combustion particles, in addition to sulphate, nitrate, salt, and dust particles of other chemical identities that are ubiquitous in the urban atmosphere. This work served as the basis for the article by Ariya et al. (2018), which recommended monitoring aerosol size distribution in cold urban atmospheric conditions and investigating the effect of snow and ice surfaces on the aerosol size distribution of air pollution [150]. Following these recommendations, we deployed a suite of experimental techniques to measure aerosols. The instruments included aerosol particle sizers, Micro-orifice uniform deposit impactor (MOUDI), high-resolution transmission electron microscopy (S/TEM-EDS) imaging, triple quad inductively coupled plasma mass spectrometry (ICP-MS), ion chromatography (IC), and total organic carbon (TOC) analyzers. We developed a statistical approach to quantify the impact of snow on air pollution, the impact of weekends and weekdays, and highlight the diurnal variations of aerosol concentration in Montreal. These approaches allowed the identification of key physical and chemical properties of aerosol particles and the sources of aerosols. The findings and discussion presented in Chapter 2 motivated to conduct a field campaign around Montreal to identify aerosols and, precisely, high nanoparticle concentration hot spots [73] and perform a comparison of the PM_{2.5} aerosol category with copollutants at three international airports (Montreal, Toronto and Vancouver) in Canada [81]. Complementary work is being done at the moment by colleagues who conduct black-brown carbon measurements [188] and the identification of plastic pollution in snow and water [441] in coldclimate conditions of the City of Montreal.

We developed a novel technique based on holographic microscopy to measure the 3D physicochemical properties of single and ensemble aerosols in situ and real-time (Ch. 3 & 4) that

we called Nano-DIHM. During the recent decade, there has been substantial improvement in situ aerosol analysis, including in situ study of nanoparticles, as discussed in section 1.8. However, no available technique enables the in situ and real-time detection of the phase of airborne nanosized particles; hence in situ phase determination remains a significant challenge [297]. A few holographic instrumental approaches were previously used to study aerosols. Still, they were limited to larger aerosol particles (> 1 μ m in size). They were not suited to small-size aerosol particles (< 200 nm), which are abundant in the atmosphere and require the optical or mechanical trapping of particles [323, 324, 331]. The Nano-DIHM technique enables new high-accuracy observations of aerosols and provides invaluable information on the 3D orientation, 3D size distribution, particle morphology, and surface properties, including roughness, composition, and phase. The Nano-DIHM developed in this work has been extensively characterized, calibrated, and tested in our laboratory in different atmospheric conditions and various fluids like air, water, snow, and solid synthetic materials.

In Chapter 3, as a proof of concept, Nano-DIHM successfully demonstrated the measurement of 100 nm and 200 nm polystyrene latex sphere (PSL) 3D size, phase, and shape in air and water. The Nano-DIHM efficiently resolved the size and shape of PSL particles in the air, demonstrating its promising potential for further studies on aerosol dynamics, including coagulation/evaporation processes in real-time. Our findings show that the Nano-DIHM identified a wide range of particle sizes (from nano to submicron) in ambient air, resolving spherical, irregularly shaped, and particles with variable morphology. The real-time measurement of aerosol dynamics provides an enormous opportunity to examine the physicochemical features of nano to micrometre-sized particles and their impact on climate and human health [442].

The developed Nano-DIHM introduced in Chapter 3 was used in other applications by colleagues: Ryan Hall used it to measure and characterize metal contaminants, including oil spills [409] in water; Zi Wang used the Nano-DIHM to investigate the nano-microplastics [443] in water (manuscript in preparation); Zaki Nasseradin uses it to study the black/brown carbon in the air (manuscript in preparation).

In Chapter 4, we showed that the Nano-DIHM can be a breakthrough in bioaerosol detection in situ in real-time and in a stationary state. We successfully used the Nano-DIHM to

identify and classify active MS2 bacteriophages (MS2), inactivated SARS-CoV-2 and RNA fragments, and an MS2 combination containing metallic and organic components. In addition, we describe a remotely operated portable prototype of the Nano-DIHM instrument that detects SARS-CoV-2 (Yes/No) in air, water, and heterogeneous matrices in real time. The Nano-DIHM has the potential to be a game-changing technology in health and environmental crises, providing quick multidimensional identification of specific species of virions for use in the management of future disease outbreaks.

Chapter 5 focused on the development of a portable and cost-efficient McGill Real time Ice Nucleation Chamber (MRINC) for studying cloud condensation and ice nucleation processes. The MRINC enables the measurement of ice nucleating particle (INPs) concentrations under conditions representative of mixed-phase cloud temperatures from 0 °C to -38 °C. The MRINC is coupled with the Nano-DIHM and aerosol sizers. For selected proof of concept aerosols, this optical detection unit successfully measured and characterized nanosized INPs and their chemical identity and physical properties (size, shape, and phase) in situ and in real-time. The combination of the Nano-DIHM optical system and the MRINC distinguished ice crystals and supercooled water droplets under mixed-phase cloud conditions. The outcome of the MRINC setup highlights the role of nanoparticles in ice nucleation processes, including the impact of chemical identity and different aerosol particle sizes on the particles' ice-nucleating ability. In future, MRINC could be used in experiments and observations, leading to the improvement of existing ice nucleation models and parameterization schemes that include the role of nanosized ice nuclei. These parameterizations will be tested against observed atmospheric ice nucleation particle concentrations at different scales, and they must account for the submicron-scale particles (< 500 nm) [129, 149, 444].

Scope: The focus of this dissertation is embedded in atmospheric science and connected to various fundamental and applied research disciplines or topics, including aerosol science and technology, atmospheric chemistry, air quality monitoring, climate change and medicine. The research completed in this thesis contributes to a broader discussion on novel aerosol measuring technology developments and their applications for future ground-to-space-borne observations. By developing a Nano-DIHM technology and experimental approach to measure aerosol 3D physicochemical properties in air, I am happy to have contributed to incremental advancements in

understanding aerosol behaviour in cold urban settings. By pursuing aerosol research, I recognize that aerosol-cloud interactions are one of the most complicated research topics. Aerosol-cloud interactions are crucial for understanding future climate projections. One takeaway from this research work is that tiny invisible aerosol particles are very complex, biologically active and dynamic, which is critical to determining future climate projections, air quality, and human life expectancy. In the era of SARS-CoV-2, aerosol transmission and dynamics have become more critical than ever [372]. Finally, to comprehensively understand the unique Earth's atmospheric systems, extraordinary efforts are required from experimental, observational, and theoretical scientists. "Environmental pollution is an incurable disease. It can only be prevented" (Barry Commoner).

6.2 Future work

Many outstanding questions in atmospheric aerosol science remain open and require fundamental research to help in explaining the observable phenomena from climate to health, give new areas for fieldwork, and enable better model forecasts for future circumstances and scenarios. Innovative measurement techniques and data analysis methods are required to mitigate air quality issues, better estimate the health and climate impact, and implement air quality policy, especially targeting primary emission sources.

Development of a smart aerosol-cloud sensor for future observations

We need a comprehensive understanding of aerosol physicochemical properties from surface to space to act rapidly and implement appropriate policies to control aerosol emissions. As discussed in Section 1.8, massive efforts have been undertaken to provide comprehensive observations of aerosols from in situ networks for surface measurement, lidar network and aircraft-based experiments for vertical measurement, and satellite observation to cover aerosols globally. The most abundant aerosols in number are submicron (size < 1000 nm) [10, 72], and they are the most critical component in Earth's climate and play an essential role in changing climate [106]. Yet, space-borne observations, including Lidar and satellite, cannot account for their size distribution, shape, topography, surfaces, selected composition, and many other physicochemical characteristics significant in aerosol-cloud interactions [70, 212, 445]. High accuracy in situ observations of atmospheric aerosol characteristics is required to help down the uncertainties of

radiative forcing magnitude for different types of atmospheric aerosol particles and to get essential parameters that cannot be retrieved alone from remote sensing, and satellite/remote sensing-based measurements must be integrated with in situ measurements. An international network with a routinely operating platform is required to observe key 3D physicochemical properties of aerosols that remote sensing cannot or does not constrain for the major aerosol air masses identified by chemical transport models [74, 446]. Such data would improve the model and satellite-retrieval assumptions about aerosol size distributions and CCN/IN characteristics, hygroscopicity, SSA, and the mass extinction efficiencies employed in climate and air quality models to relate satellite-derived aerosol optical depth (AOD) observations.

Here we propose the development of a smart aerosol cloud imager (ACI) based on holographic microscopy, which would allow us to get the 3D size distribution of aerosols, shape, topography and surface properties, including the aerosol surface roughness. The ACI can be deployed on various platforms (e.g. ground-based, aircraft and satellite). The 3D physicochemical data obtained from the ACI can be used to improve aerosol extraction algorithms from satellite observations and Lidar networks as well as the parameterization of aerosol in weather and climate models. Using satellite-based data and surface observations in models allows us to understand the physicochemical processes in aerosol-cloud interactions and more accurately estimate the Earth's radiative budget and future temperature. A combination of the Lidar Network data, multi-angle polarized passive sensor and potentially ACI data can yield invaluable insights into how different types of aerosols interact with radiation, clouds, and the climate system. The focus on in situ observations must be applied and adequately analyzed to define further the roles of dust, BC, and organic aerosols as INPs, which can then be used to improve ice-cloud microphysical methods. As computational resources become more abundant, global cloud-resolving simulations will be possible, avoiding many parameterizations and providing better constraints on aerosol-cloud interaction and climate sensitivity.

Systematic methods to overcome the impact of aerosols on health and air quality

A better understanding of the role of nanoparticle exposure in public health is required to optimize the available tools for improving air quality. Thus, there is a need for (a) a greater emphasis on a multi-pollutant analysis approach that incorporates sampling and analysis strategies providing information on aerosols sources, chemical properties, physical properties, and both particulate and gaseous pollutants, (b) a better understanding of the mechanisms responsible for health effects of aerosols including biological components, (c) enhancing exposure estimates by using microsensors, hybrid models, local-scale observations, and remote sensing, and (d) supporting an interdisciplinary approach that incorporates atmospheric chemistry, global modelling, exposure science, toxicology, and epidemiology.

Appendix A

A Chapter 2 Supplementary Information

A1 Supplementary methods

A1.1 MOUDI

A Micro-Orifice Uniform Deposition Impactor (MOUDI, MSP Corporation) was used to collect the size-fractionated aerosols samples. The MOUDI standard cutoff diameters (d_{50}) are defined by the aerodynamic diameter, at which 50% of the particles will be impacted onto the stage. However, as the cutoff appearances of the instrument are sharp, and d_{50} is almost equal to the minimum diameter of the particles, which will strike onto each impaction stages, the real cutoff diameters (d_{50} *) were calculated from standard cutoff diameters using the conversion formula predicted by Stokesian theory [1] and MSP Corporation, personal communication, 2003 as given below:

$$d_{50}^* = d_{50} * \sqrt{\frac{30}{Flow \, rate}} \tag{A2.1}$$

Since, the MOUDI operated at a flow rate of 30 L/min, the real (d_{50} *) and standard (d_{50}) cutoff were theoretically almost similar.

A1.2 Meteorology and auxiliary air quality data

The complementary meteorological (T, RH) and air pollution (O₃, NOx, CO, SO₂, and PM_{2.5}) data were obtained from the City of Montreal's Air Quality Surveillance Network (RSQA), which is a part of the Environment and Climate Change Canada national air pollution surveillance (NAPS) program. The air pollution data were used from station 31, while meteorology data were obtained from Mctavis street at Mcgill University. The distance between station 31 and the observation location is less than 1 km. Ozone measurements were performed using a UV-photometric Analyzer (model 49i). Nitrogen oxides' [NO_x = (NO + NO₂)] Chemiluminescence was evaluated by a NO-NO₂-NO_x Analyzer (Model 42i). Sulphur dioxide (SO₂) was measured by a pulsed fluorescence analyzer (model 43i). Carbon monoxide (CO) was monitored by a trace level

enhanced gas filter correlation analyzer (Model 48i-TLE). PM_{2.5} was analyzed using synchronized hybrid ambient real-time analyzers (SHARP 5030). All equipment was obtained from Thermo Fisher Scientific (Forge Parkway Franklin).

A1.3 Geometric mean and geometric standard deviation

The geometric standard deviation (GSD) is defined as exp(Slnx), where Slnx is the arithmetic standard deviation of In(x), where x is a value in the dataset. GSD is a multiplicative factor such that the value of x, at n standard deviations below the geometric mean (GM), is $GM/(GSD)^n$. Thus 68.3% of the x's lie between GM/GSD and GM*GSD, 95.5% between $GM/(GSD)^2$ and $GM*(GSD)^2$, etc. This is why the geometric standard deviation in this study is small. In this study, the geometric mean number densities and geometric standard deviation were examined for the interpretation of data. Additionally, the arithmetic means, median, 99th percentile, and 1st percentile provide a comprehensive statistical representation of the data shown in Table S1. The geometric mean and geometric standard deviation are defined as:

$$X = \sqrt{\prod_{i=1}^{n} x_i} = \sqrt[n]{x1 * x2 * \dots xn}....(A2.2)$$
$$S = Exp(\sqrt[n]{\frac{\sum_{i=1}^{n} \ln (xi/X)^2}{n}})....(A2.3)$$

Where **X** represents the geometric mean number density of data set $(x_1, x_2, ..., x_n)$, and **S** represents the geometric standard deviation.

A2 Supplementary figures



Figure A1 Airborne particle observation location Otto Maass Building, McGill University, Montreal Canada (45.5048° N, 73.5742° W).



Figure A2 Particle size distribution with HEPA filter. (a) Particle size distribution from 10 nm to 400 nm using SMPS. And (b) Particle size distribution from 0.3 μm to 10 μm using OPS. The duplicate experiment has been done.



Figure A3 Size aggregated particles number densities. Each point represents one-minute temporal resolution from May 2017 to May 2019. Different colors represent different size ranges of particles (a) < 100 nm, (b) < 200 nm, (c) < 1 μ m, (d) < 2.5 μ m and (e) < 10 μ m.


Figure A4 Monthly box plots of co-pollutants January 2017 to April 2019. The horizontal line through each whisker box represents that month's median value, and the lower and upper edges of the whisker boxes present the 25th and 75th percentiles values, respectively. Whiskers above and below the boxes are maximum and minimum values, respectively. The outliers are not shown. The rectangular shapes inside the box present monthly mean.



Figure A5 Time series of monthy mean concentration of (a) nanoparticles < 100 nm (b) < 200 nm (c) Tempreature (d) Dew point temperature and (e) Relative humidity.



Figure A6 Scanning electron microscopy images with EDS of airborne particles. (a-b) chain-like aggregate particle. (c) Irregularly shaped particles. (d) Spherical particle and (e) Biological particle and (f) Single-particle

A3 Supplementary tables

Table A1Seasonal size aggregated geometric mean (GM) number densities (#/cm3), geometric
standard deviation (σ g), arithmetic mean number densities, standard deviation (σ),
medians, and top 99th and 1st percentile values from May 2017 - 2019.

Statistics		2017		2018				2019		
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	
< 100 nm (10 – 100 nm)										
GM	6499.8	4757.9	6197.4	6559.6	5897.2	6278.6	5547.6	9260.2	7562.4	
σg	1.8	1.8	1.9	1.9	1.9	1.8	1.9	1.9	2.0	
Mean	7583.5	5815.6	7579.1	8304.6	7269.2	7939.4	8041.7	11593.5	9410.7	
σ	4334.0	3429.3	4326.9	5774.3	4818.7	5689.8	6009.1	7376.5	5806.6	
Median	6606.9	5119.1	7139.8	7055.7	6211.4	6719.3	7067.9	10391.8	8667.7	
99 th	23478.3	17859.4	20139.2	27481.3	25180.9	30207.2	25777.0	35091.6	26636.3	
1 st	1449.3	751.2	734.3	1113.1	925.1	1161.1	415.0	1145.7	982.1	
			<	200 nm (1	00 -235 nm	n)				
GM	575.2	618.7	599.7	480.1	587.5	817.2	365.6	572.3	528.1	
σg	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	
Mean	755.7	742.6	801.3	637.1	760.9	1025.9	532.1	810.4	739.0	
σ	474.7	375.9	613.6	607.8	528.6	665.7	496.7	723.3	785.9	
Median	686.4	694.4	639.8	480.2	632.3	922.8	383.5	580.4	523.1	
99 th	2176.3	1787.5	2743.7	2934.9	2441.5	3097.3	2659.8	3577.4	4740.3	
1 st	6.5	76.2	67.1	75.8	65.7	102.1	32.3	55.3	31.6	
			•	< 1 µm (0.	3 -0.9 µm)					
GM	18.7	33.9	22.7	25.3	21.4	43.4	17.0	24.4	16.1	
σg	1.8	2.0	2.0	1.6	1.6	1.6	1.6	1.3	1.6	
Mean	25.7	48.9	33.6	37.9	28.3	66.0	27.8	34.9	23.7	
σ	23.5	39.4	29.7	42.7	24.4	76.6	32.1	33.0	27.5	
Median	16.7	37.6	23.8	22.4	20.1	44.4	15.7	22.9	15.1	
99 th	114.6	165.3	124.7	215.2	134.5	492.5	157.7	167.9	146.9	
1 st	2.7	9.6	2.2	5.1	2.7	4.7	2.0	3.1	3.4	
			<	2.5 µm (0.	9 – 2.6 µm	l)				
GM	1.3	1.8	1.5	1.8	1.3	2.7	1.2	1.9	1.0	

σg	2.3	2.2	1.9	2.0	1.7	2.4	2.0	1.7	2.4
Mean	1.6	2.5	2.1	2.4	1.6	4.2	1.7	2.6	1.8
σ	1.2	2.0	1.9	2.2	1.3	5.7	1.9	2.7	3.8
Median	1.2	1.8	1.6	1.8	1.3	2.5	1.1	1.9	1.0
99 th	6.5	8.7	7.9	12.4	6.3	37.7	9.4	11.1	27.8
1^{st}	0.4	0.6	0.1	0.3	0.2	0.4	0.2	0.2	0.2
			<	10 µm (2.0	5 – 10 μm))			
GM	0.1	0.1	0.2	0.1	0.1	0.1	0.0	0.2	0.1
σg	1.7	2.6	2.3	1.9	15	19	1.7	2.1	2.3
					1.5	1.9			
Mean	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Mean σ	0.1 0.1	0.1 0.1	0.1 0.1	0.2 0.2	0.1 0.2	0.2 0.4	0.1 0.0	0.1 0.2	0.1 0.1
Mean σ Median	0.1 0.1 0.1	0.1 0.1 0.1	0.1 0.1 0.1	0.2 0.2 0.1	0.1 0.2 0.1	0.2 0.4 0.1	0.1 0.0 0.1	0.1 0.2 0.1	0.1 0.1 0.1
Mean σ Median 99 th	0.1 0.1 0.1 1.0	0.1 0.1 0.1 0.3	0.1 0.1 0.1 0.4	0.2 0.2 0.1 0.9	0.1 0.2 0.1 0.8	0.2 0.4 0.1 2.7	0.1 0.0 0.1 0.2	0.1 0.2 0.1 0.7	0.1 0.1 0.1 0.3

•

The size ranges are approximate based on instrumental limitations. The particle size range from 10 to 200 nm measured by SMPS. And, 0.3 to 10 μ m size particles measured • by OPS.

Table A2	Comparisons of particle number density (geometric mean $\pm \sigma_g$) cm ⁻³ in worldwide
	studies.

Size range	Mean number	Study site	Study	Reference
	density (#/cm ³)		period	
< 100 nm	6191 ± 1.9	McGill downtown	2017-2019	This study
(10-100 nm)		campus		
< 200 nm	554 ± 2.2	McGill downtown	2017-2019	This study
(100-235		campus		
nm)				
< 1 µm	29 ± 2.6	McGill downtown	2017-2019	This study
(0.3-0.9 µm)		campus		
< 2.5 μm	1.7 ± 2.1	McGill downtown	2017-2019	This study
(0.9-2.6 µm)		campus		
< 10 µm	0.1 ± 2.5	McGill downtown	2017-2019	This study
(2.6-10 µm)		campus		
	С	omparisons to interna	ational studies	
10-10000 nm	6776 ± 1.8	McGill downtown	2017-2019	This study
		campus		
3 nm-10 μm	32800	Beijing	2004	[240]

20 -100 nm	6320	Helsinki	2003-2004	[241]
20-1000 nm	33867	Toronto	2008	[447]
8–300 nm	19440	Toronto	2006-2010	[448]
10–500 nm	20000	Alkmaar		[449]
10–500 nm	20000	Erfurt		[449]
10–500 nm	18000	Helsinki		[449]
10–300 nm	10000			[450]
25-25000 nm	11600	Prague	2009	[451]
10-700 nm	8020	Las Condes	2006	[452]
		(Santiago; Chile)		
19.2-800 nm	22941	London	2008-2010	[268]
5-1000 nm	64200	Leicester	2005	[453]
20-750 nm	16789	Essen	2008	[454]
7-3000 nm	24000	Athens	2002-2004	[455]
10-10000 nm	19576	Helsinki	1996-1997	[267]
7-3000 nm	31000	Amsterdam	2002-2004	[455]
7-10000 nm	39000	Strasbourg	2003	[456]
3 – 800 nm	21377	Leipzig	4- year	[457]
3 - 2500 nm	21988	Pittsburgh	1- year	[269]

Table A3Mass concentrations (μ g/L) of trace metals, ions and total organic carbon (TOC) in
different d₅₀ cut off size ranges of airborne particles during 24, and 48h sampling
periods The size fraction ranges were based on instrument limitation and the
interest of research.

Unit	1	19-20 July 2	2018 (24 h)			14 - 16 July 2	2018 (48 h)	
μg /L	0.18 µm	0.32 μm	0.56 µm	1.0 µm	0.18 - 0.32 μm	0.56 - 1 μm	1.8 - 3.2 μm	5.6 - 18 µm
				A	Alkali metals			
Na	4.11	3.72	2.3	2.6				
Κ	10.35	2.62	11.31	6.73				
Cs	127	10.22	204.57	117.62				
				Alka	line earth metal			
Mg	5.42	1.05	4.8	4.02				
Ca	39.18	50	14.85	27				
Sr	Nd	Nd	Nd	Nd	0.010	0.220	0.20	Nd
Ba	Nd	Nd	Nd	Nd	Nd	0.360	1.450	0.530
				Tr	ansition metal			
V	Nd	Nd	Nd	Nd	0.06	0.15	0.07	0.04
Cr	0.05	0.25	Nd	0.20	4.03	Nd	Nd	Nd
Mn	0.40	0.18	0.21	0.32	0.45	Nd	0.32	0.24
Fe	19.52	7.10	16.89	11.96	12.58	Nd	17.57	11.15
Со	0.02	0.02	Nd	0.03	0.04	0.005	0.01	0.006
Ni	0.61	0.50	0.08	0.09	2.13	0.08	0.04	0.04
Си	1.01	0.46	0.80	0.55	0.03	0.28	1.07	0.42
Zn	0.60	Nd	Nd	0.85	Nd	Nd	0.56	Nd
Cd	1.01	0.46	1.0	Nd	0.010	0.004	0.01	Nd
Post transition metal								

Al	7.05	25.80	48.7	20.56	0.30	2.850	10.78	5.480			
Pb	0.53	0.074	0.20	0.28	0.08	0.023	0.025	0.030			
	Metalloids										
As	0.06	Nd	0.08	Nd	0.071	0.030	0.015	0.008			
Sb	Nd	0.03	0.06	0.06							
Se	0.15	Nd	0.1	0.09	0.040	0.020	0.002	Nd			
					Ions						
Cl^{-}					2358	110	160	1410			
NO_2^-					20	670	2260	660			
SO_4^{2-}					2190	1600	510	1230			
NO_3^-					127	380	1220	500			
Na^+					1527	1630	1640	2590			
NH_4^+					15	400	50	50			
K^+					231	320	360	380			
Mg^{2+}					596	100	170	340			
Ca^{2+}					2970	Nd	1480	2590			
				Total	l organic carbon						
TOC	173	602	36	41							

• Nd represents the below filter blank

• Blank space represents no data (No measurements) on that particular day

Table A4	Correlation coefficients between nanoparticles (<100 nm) and <200 nm particle number
	densities, and gaseous co-pollutants.

	V		Weeken	ds				
Size	< 100 nm	< 200 nm	< 1µm	СО	< 100 nm	< 200 nm	< 1µm	СО
< 100 nm		0.784	0.596	0.739		0.461	-0.622	-0.626
< 200 nm			0.577	0.685			NO	NO
< 1µm				0.819				0.890

Appendix B

B Chapter 3 Supplementary Information

B1 Supplementary methods

B1.1 Analysis of the size and phase of snow-borne particles in dynamic and stationary modes

We recovered the size and morphology of snow-borne particles in the gas and liquid phase. Figure B12 (a) presents the distribution of particles in the snow meltwater following aerosolization. Figure B12 (b, c) shows the intensity profile along with the particle crosscut. The intensity profiles confirmed that particles' sizes are 180 nm and 2.7 µm, respectively (Fig. B12 (b, c)). The simultaneous size distribution measurements of the same samples made by the SMPS (Fig. 3.5 (b)) confirmed the particle size of 180 nm, and the OPS data (Fig. B5 (d)) confirmed the particle size of 2.7 µm. The phase reconstruction of snow-borne particles in the gas phase across line 1 and line 2 is shown in Figure B12 (d). The quantitative phase shift varies from 2.3 to 3.3 rad (mean value = 3.04 rad) across line 1 (Fig. B12 (e)). Across line 2, the phase shift shows multimodal variances from 0.6 to 4.7 rad (mean value = 3.3 rad) (Fig. B12 (f)). The relationship between phase shift and refractive index (see methods) shows that the refractive index changes by 0.016 across line 1 and from 0.045 to 0.075 across line 2, suggesting that the particles are of polymeric origin [359, 360]. To evaluate whether DIHM can determine various shapes, size, and morphology of individual particles, we investigated the same snow meltwater samples using both DIHM (Fig. B12 (g, h) and Fig. B13 (b)) and STEM (Fig. B13 (a)). STEM images illustrate the non-spherical morphology of particles and agglomerates (Fig. B13 (a)) matching the shapes visualized by Nano-DIHM (Fig. B13 (b)) in the same snow meltwater samples.

B1.2 Refractive index measurement

We determined the changing refractive indices of glycerine drops of different sizes suspended in type F microscope immersion oil. The intensity and phase reconstruction of several glycerin drops suspended in type F microscope oil are shown in Figure B14 (a, b). Two examples of the phase variation through drops 1 and 4 were examined (Fig. B14 (c)). Figure B14 (d) shows

the drop height for drops 1 and 4. The phase examined for glycerine drops showed almost noisefree cross-sections except for a small phase variation of the background (Fig. B14 (c)). From the known refractive index difference between glycerin and type F microscope oil ($\Delta n=0.0451$) and the measured maximum phase shifts for a drop, we can calculate the drop height or vice versa (see Methods)[346]. The quantitative phase, size, and refractive index measurements for the four glycerine drops shown in Figure B14 (a, b) are also presented in Table B3. Table B3 shows the changing refractive index between 0.0443 to 0.0451 and drop heights between 1.5 to 4.15 µm. The determination of the changing refractive index of each drop size varies within ~ 2%. In comparison, the agreement between the drop height calculated from the maximum phase shift and the diameter obtained from intensity reconstructions was observed within ~10%. The small variation in measured refractive index or drop height could be related to substrate adhesion.

B1.3 Synthetic materials

The shape, size, and morphology of synthetic materials (zinc oxide and iron oxide) have been successfully determined using DIHM. Figure B15 (a) shows the reconstructed image of iron oxide powder over the microscope cover slide. Higher resolution images in Figure B15 (b, c) depict the different sizes of iron oxide particles. Similarly, different sizes of zinc oxide particles were determined using DIHM (Fig. B15 (d-f)). DIHM showed the morphology of the synthetic materials and the presence of nanoparticles.

B1.4 Automation of stingray software

An essential stingray software has been bought with the 4deep desktop holography microscope [458, 459]. The octopus software [459] has been used manually to reconstruct the hologram, while stingray software can be automated to detect the objects for millions of holograms. Stingray can be used to analyze holograms both in real-time or offline. The first input is to train the stingray software by providing the recording conditions of holograms (hologram size, camera pixel, source to sensor distance); the second is to optimize the intensity of the holograms or find the threshold intensity values. We used a grayscale and maximum intensity with 250 arbitrary units. Based on the threshold value of intensity, Stingray will start looking to detect the objects. The main issue is to identify the threshold values of intensity. For that, we used octopus software for hundreds of hologram reconstructions and estimated the best threshold values. Here

are some consequences if we choose high or low threshold values, such as a high threshold, for example, 200, which means that the pixel's intensity has to be 200 or more for that pixel to be detected by the software. Thus, a low threshold (ex: 10) would allow many pixels to be detected, while a high threshold (ex: 200), would let fewer pixels be detected. For that, we started with a low threshold (for example, 50) and worked our way up to a higher threshold until we find optimized conditions. The major advantage of fully automated Stingray software is to distinguish the round vs randon shaped particles along with time dependent morphology, roughness and orientation of objects. However, the size obtained by stringray software required further correction. Currently, we are in the process of building the library for different kinds of samples and establishing the size correction methods (Manuscript in under preparation).

B2 Supplementary figures



Figure B1 3D size distribution of 100 nm, PSL spheres in the aerosol phase. (a) The orientation of PSL particles (b) Width, height, and length distribution of PSL particles in a single

hologram over 62.5 ms. (c) Tabular representation of descriptive statistics of the distributions of dimensions of the PSL spheres in 3D space in a single hologram. The results shows the \pm 5% variation from one hologram to another.



Figure B2 3D size distribution of 200 nm, PSL spheres in the aerosol phase. (a) The orientation of PSL particles (b) Width, height, and length distribution of PSL particles in a single hologram. (c) Tabular representation of descriptive statistics of the distributions of dimensions of the PSL spheres in 3D space in a single hologram. (d-f) 3D size distribution

of 200 nm PSL different hologram. The results are very consistent, and the median dimension of PSL varies within 5%.



Figure B3 Background intensity holograms (a) zero air (crosscut size plotted with horizontal line 1 and vertical line 2. (b, c) particle size distribution of zero air and the air filter with a HEPA filter.



Figure B4 Reconstruction of the intensity and phase images for PSL spheres in the moving air. Single particles and small clusters of PSL particles in different positions inside the cuvette. (a-c) Intensity profile of PSL particles across the particle crosscut. (d) Phase profile through a single-particle crosscut (same particle as in 'c'). The red long-dash curve in (c-d) is a

dynamic Gaussian fitting, which suggests a perfect fitting with the experimental results of a single PSL sphere.



Figure B5 Particle size distribution of Zero air; air passes through a HEPA filter and snow-borne particles in moving air (aerosolized snow meltwater). (a, b) Particle size distribution in the range from 10 nm to 350 nm measured by the scanning mobility particle sizer (SMPS). (c, d) Particle size distribution in the range from 0.3 μm to 10 μm, measured by the optical particle sizer (OPS).



Figure B6 Holographic reconstruction of 200 nm PSL particles deposited on microscopy slide and their validation by STEM images. (a) Phase reconstruction at 2352 µm. (b) Zoomed in area



of (a). (c) In focus high-resolution reconstruction at Z=2419 μm (d-f) S/TEM images of same 200 nm PSL samples.

Figure B7 2D and 3D view of holographic reconstruction of a mixed sample of 200 nm PSL particles and iron(III) oxide nanoparticles (size <50 nm) deposited on microscopy slide and their validation by S/TEM images. (a) 2D view of phase reconstruction at 925 μm. (b) Zoomed in area circle (a). The red arrow in figure (b) displayed the PSL particles while green arrow shows attachment of PSL on iron particles (c) 3D view of phase reconstruction at 562 μm. (d) Zoomed in area ranctangle shows in figure (c). (e-f) S/TEM images of the same sample confirmed the existence of both PSL and iron oxide nanoparticles. 3D view of phase reconstruction clearly indicates the attchement of PSL on iron oxide particles.



Figure B8 Phase image. (a, b) Phase reconstruction of particles in ambient air. (c-f) Phase profiles of particles through a crosscut across Lines 1 to 4.



Figure B9 Particle size distribution of ambient air (a) measured by a scanning mobility particle sizer (SMPS) in the range from 10 nm to 350 nm. (b) measured by an optical particle sizer (OPS) in the range from 0.3 µm to 10 µm.



Figure B10 A simple example of fast and automated reconstruction by stingray software of large volume of images, which were produced in xls file and individual images part of it is shown here. Automated detection of airborne 100 nm PSL particles by using stingray software. (a) As an example from number 1 to number 21 and so on shows the object Id, and (b) Exported results in xls format with the numerical values. Excel data sheet carried the

information of particle orientation, particle size, perimeter, area, roughness and other morphology component of particles, momentum and spectrum of particles.



Figure B11 Intensity reconstruction at different depths of PSL particles on a microscopy slide. (a) Raw hologram recorded with PSL particles; (b) Background hologram recorded without PSL particles; (c) Contrast hologram obtained after subtracting the background hologram from the raw hologram.(d-i) Reconstruction of particles at different reconstruction position Z. It shows the small changes in Z position changes the particles from focus to defocused.



Figure B12 Hologram reconstruction for aerosolized snow meltwater. (a) Intensity reconstruction of particles. (b, c) Intensity profile through the crosscut of particles. (d) Phase reconstruction of particles. (e, f) Phase shift across the crosscut of particles through the line 1 and line 2. (g-i) Intensity reconstructions of particles in the snow meltwater in the liquid phase. The image in the selected area in (d) shows the same particles' intensity reconstruction. The red lines are the Gaussian quadratic fits for particles in (b, c).



Figure B13 Morphology of snow meltwater in the liquid phase (a) visualized by STEM, and (b) visualized by Nano-DIHM.



Figure B14 Glycerine drops in the suspension of type F microscope immersion oil. (a, b) Intensity and phase reconstruction of four glycerin drops in type F microscope oil. (c) Phase cuts through drops 1 and 4, and (d) drop height. The blue and red lines are the Gaussian quadratic fits.



Figure B15 Shape, size and morphology of synthetic materials. (a) Iron oxide. (b, c) Iron oxide in the highlighted regions of Image (a). (d) Zinc oxide. (e, f) Zinc oxide in the box of image (d).

B3 Supplementary tables

Table B1Descriptive statistics of the distributions of dimensions of the aerosolised Milli-Q waterin 3D space in a single hologram.

Statistics	Width (µm)	Height (µm)	Length (µm)
Mean values	0.093	0.089	0.554
Standard deviation	0.195	0.170	1.060
Median values	0.041	0.043	0.273
99 th percentile	0.785	0.700	3.873
1 st percentile	0.010	0.010	0.062

Table B2Descriptive statistics of the distributions of dimensions of the 100 nm PSL spheres, 200
nm PSL spheres deposited on the microscopy slide in 3D space in a single hologram.

100 nm PSL								
Statistics	Width (µm)	Height (µm)	Length (µm)					
Mean values	0.158	0.177	0.765					
Standard deviation	0.237	0.284	0.638					
Median values	0.107	0.120	0.732					
99 th percentile	1.096	1.068	3.874					
1 st percentile	0.012	0.012	0.021					
	200 m	m PSL						
Mean values	0.226	0.228	0.767					
Standard deviation	0.220	0.219	0.840					
Median values	0.172	0.154	0.588					
99 th percentile	0.947	1.110	3.887					
1 st percentile	0.013	0.012	0.015					

Table B3Changing refractive indices for different sizes of glycerine drops. Comparison of glycerin
drop size as determined from phase shifts and from intensity reconstructions.

Drops*	Maximum phase	Drop height from	Drop diameter from	Calculated change of
	shift (Rad)	phase shift (µm)	intensity image (µm)	refractive index (Δn)
1	2.8	4.15	4.0	0.0451
2	0.94	1.5	1.4	0.0433
3	2.3	3.3	3.2	0.0449
4	2.35	4.0	3.4	0.0446

* $\Delta n = (n_{glyc} - n_{oil}) = 0.0451$. Changing refractive index between glycerine and type F microscope immersion oil.

Appendix C

C Chapter 4 Supplementary Information

C1 Supplementary figures

Des	criptions	Graphic Summary	Alignments	Taxonomy										
Sec	Sequences producing significant alignments Download V me Select columns V Show 100 V 3													
	select all 10	00 sequences selected				GenBank	Graph	ics [Distanc	e tree o	f results	New	MSA Viewer	1
			Description			Scientific Name	Max Score	Total Score	Query Cover	E value	Per. Ident	Acc. Len	Accession	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2511/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267426.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2967/2020 geno	Severe acute res	. 54983	54983	99%	0.0	99. <mark>9</mark> 9%	29903	OU267425.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2958/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267423.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2978/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267420.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2528/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267419.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2472/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267417.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2484/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267415.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2512/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267414.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2478/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267413.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2488/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267412.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2479/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267411.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2521/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	<u>OU267410.1</u>	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2517/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267409.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2476/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267408.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2487/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267403.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate hCoV-19/S	witzerland/VD-CHUV-	GEN2471/2020 geno	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OU267398.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 genome assembly	, complete genome: m	nonopartite	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OA967097.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 genome assembly	, complete genome: m	nonopartite	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OA964362.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 genome assembly	, complete genome: m	nonopartite	Severe acute res	54983	54983	99%	0.0	99.99%	29903	OA964256.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate Switzerland	J/GE-SNRCI-8301/202	20 genome assembly,	.Severe acute res	54983	54983	99%	0.0	99.99%	29836	FR993513.1	
	Severe acute re	espiratory syndrome coronaviru	us 2 isolate Switzerland	J/GE-SNRCI-9136/202	20 genome assembly,	. <u>Severe acute res</u>	54983	54983	99%	0.0	99.99%	29834	FR993438.1	

Figure C1 BLASTN, using the betacoronavirus genomic database, result of the sequence genome of the SARS-CoV-2 sample. The GenBank ID for the sequence is MN908947.3.



Figure C2 Intensity and phase profiles of MS2 in aqueous mode. (a-f) Intensity and phase profiles across the particle crosscuts (Fig 1c), respectively. The size of the particles is represented in terms of the full width half maximum (FWHM). (g) MS2 particle size distribution obtained by a particle sizer analyzer (PSA, Anton Paar) matched with the size obtained by nano-DIHM. (h) Calibration curve of PSA with 200 nm PSL spheres.



Figure C3 Nano-DIHM control experiment. (a) Background intensity hologram recorded for zero air. (b) Intensity profile across the crosscut of horizontal line 1. (c) Intensity profile along vertical line 2. (d, e) Particle size distribution of zero air and the air with a HEPA filter. The total particle count was < 3 #.cm⁻³.



Figure C4 Automated detection of MS2- and UVB-exposed MS2 particles using Stingray software. (a-d) Shape and morphology of MS2 particles and (e-h) shape and morphology of UVB-exposed MS2 particles. Nano-DIHM clearly shows the change in the structure of MS2 and successfully determines the UV impact.



Figure C5 3D orientation and size distribution of bacteriophage MS2 viruses. (a-b) Orientation and size distribution of airborne MS2 particles (dry aerosols). (c-d) Orientation and size distribution of a mixture of MS2 and TiO2 particles. (e-f) Orientation and size distribution of viral MS2 varus-laden droplets.



Figure C6 3D orientation and size distribution of SARS-CoV-2 viral droplets at different velocities. (a-b) Orientation and size distribution of SARS-CoV-2 viral droplets at 10 m/second, (c-d) 20 m/second and (e-f) 30 m/second.



Figure C7 Intensity and phase cross-section of SARS-CoV-2 viruses in aqueous mode. (a-b) Intensity profiles across the particle crosscuts. (c-d) Phase profiles across the particle crosscuts. The intensity and phase profiles indicate the SARS-CoV-2 viral particle size from nano- to micronsized.



Figure C8 Distinction between SARS-CoV-2 vs. SARS-CoV-2 RNA. (a-d) Intensity and phase reconstruction of SARS-CoV-2 and (e-h) intensity and phase reconstruction of SARS-CoV-2 RNA.



Figure C9 TiO₂ coating impact on MS2. (a-b) Intensity reconstruction of TiO₂-coated MS2 viruses and (d, e) phase reconstruction of identical particles. (c, f) High-resolution electron microscopy images, (g, i) intensity response, and (h, j) particle phase response.



Figure C10 Olive oil coating impact on MS2. (a-c) Intensity reconstruction of olive oil-coated MS2 viruses and (d- e) phase reconstruction of identical particles. (g-i) High-resolution electron microscopy images. The shape of the oil-coated particles obtained by nano-DIHM is identical to that obtained by S/TEM.

MS2 with alpha-pinene



Figure C11 Natural organic coating material coating impact on MS2. (a-b) Intensity reconstruction of alpha-pinene-coated MS2 viruses and (c-d) phase reconstruction of identical particles. (e-f) Intensity and phase responses of natural honey-coated MS2 particles.



Figure C12 Deciphering MS2 from a mixed sample of MS2 and PSL. (a-b) Phase images of MS2 mixed particles with PSL. The red arrow in panel (a) indicates MS2, and the green arrow in panel (b) indicates PSL.

C2 Supplementary tables

Table C1SARS-CoV-2 virus detection techniques based on polymer chain reaction, optical-based
and industrialized techniques.

Polymer chain reaction-based techniques to detect SARS-CoV-2					
Sample type, collection method	Detection technique	Reference			
Solid/particulate, impactor, filters	ddPCR	[381]			
Solid/particulate, NIOSH sampler	qPCR, RNA	[415]			
Solid/particulate, NIOSH sampler	qRT–PCR	[460]			
Solid/particulate, NIOSH sampler with a gelatin filter	Mean qRT–PCR	[461]			
(<1 µm)					
Solid/particulate, gelatin filter, PC filter, SASS 3100	qRT–PCR	[462]			
	Cryo-EM	[463]			
	Cryo-EM	[416]			
RNA transcripts	RT–PCR	[464]			
Blood	ELISA	[465, 466]			
Throat swabs	RT-LAMP	[382]			
Synthetic RNA	RPA/SHERLOCK assay	[467]			

Nasopharyngeal, oropharyngeal swabs	RT-LAMP/Cas12 DETECTR assay	[468]				
Nasopharyngeal swabs	FET	[469]				
Membrane-engineered Vero cells	Cell-based potentiometric biosensor	[470]				
Synthetic RNA	Plasmonic photothermal (PPT) enhanced	[471]				
	LSPR					
Optical methods for SARS-C	oV-2 detection and investigation					
Optical approach	Virus	References				
SERS	SARS-CoV-2	[472]				
SM-SERS	SARS-CoV-2					
SERS	Spike protein of SARS-CoV-2	[473]				
Fluorescence	Coronavirus diagnosis	[474]				
SPR	SARS-CoV-2	[475]				
SPR	SARS-CoV-2	[476]				
LSPR	SARS-CoV-2	[471]				
SPR	SARS-CoV-2	[477]				
SPR	SARS-CoV-2	[478]				
SERS, SPR	(COVID-19) (SARS-CoV-2)	[479]				
Colorimetric assay	SARS-CoV-2	[480]				
Holography Microscopy	COVID-19 from red blood cell	[481]				
Holography Microscopy	SARS-CoV-2 antibody	[482]				
Holography Microscopy	SARS-CoV-2	[483]				
Holography Microscopy	SARS-CoV-2	[484]				
SERS	SARS-CoV-2	[485]				
Holography Microscopy	SARS-CoV-2	[486]				
Industrialized techniques based on optical methods for SARS-CoV-2 detection						
Technique	Industry	Reference				
SERS	Samsung Strategy and Innovation Center	[487]				

Raman	Botanisol Analytics	[488]
Raman	BioMark Diagnostics Inc.	[489]
Raman	Advanced Nano Technologies	[490]
LSPR	LambdaGen corporation	[491]
SPR	Creative Biostructure Coronavirus	[492]
FTIR	Todos Medical Ltd	[493]
Planar Waveguide	LightDeck Diagnostics	[494]
Holography	Virolens	[495]

Table C2Detailed experimental parameters for the matrices used. The hologram size was
2048 * 2048 pixels, and the camera pixel size was 5.5 µm during each experiment.

Sample matrices	Sample mode	Flow rate (L/min)				
Dynamic						
SARS-CoV-2	Sneezing (aerosol, droplet) ¹	2.5, 1.5, 0.5 ml/min				
MS2	Moist droplet ²	0.5, 0.25 ml/min				
MS2	Airborne (dry aerosols) ³	1.7, 0.7				
MS2+TiO ₂	Airborne (dry aerosols)	1.7, 0.7				
TiO ₂	Airborne (dry aerosols)	1.7,0.7				
100 nm PSL	Airborne (dry aerosols)*	1.7,0.7				
200 nm PSL	Airborne (dry aerosols) *	1.7,0.7				
Stationary						
SARS-CoV-2	Deposition ⁴	Water				
SARS-CoV-2 RNA	Deposition	Water				
MS2	Deposition	Water				
MS2	Deposition	Water				
SARS-CoV-2 + SARS-CoV-2 RNA +	Deposition	Water				
TiO ₂						
SARS-CoV-2 + Iron Oxide	Deposition	Water				

MS2+TiO ₂	Deposition	Water
MS2+PSL	Deposition	Water
Olive oil	Deposition	Water
Honey	Deposition	Water
Alpha-pinene	Deposition	Water
Olive oil + MS2	Deposition	Water
Honey + MS2	Deposition	Water
Alpha-pinene + MS2	Deposition	Water

- 5. MS2 Bacteriophage samples aerosolized with C-flow atomizer and aerosol stream passed through two diffusion dryers before passing to nano-DIHM sample volume (flow tube cuvette) and SMPS/OPS. The humidity was less than 4%.
- 6. A bubbler was used to generate moist droplets of MS2 bacteriophage. The moist droplets directly passed through a flow tube cuvette during nano-DIHM. No dryer was used.
- 7. A mixed solution of MS2 with TIO2 was aerosolized, and aerosol steam was passed through a diffusion dryer.
- 8. SARS-CoV-2 virus droplets were generated by using a c-flow atomizer. The droplets directly passed through a flow tube cuvette into the nano-DIHM sample volume. This experiment was modeled with sneezing/coughing velocities.
 - The schematic diagram in Figure 1 shows the complete experimental setup.

Table C3	3D size distribution of SARS-CoV-2 particles in the droplet phase with different velocities.
	Previous studies for droplet sizes based on a transmission mode.

Droplet size	Droplet generation	Measurement techniques	References
(μm)			
0.8-5.5	Droplet generation through speaking to	Aerosol particle sizer and scanning	[496]
	whispered counting	mobility particle sizer	
9.8-14	Cough data	Liquid impaction	[497]
8.1	Sneeze data	Liquid impaction	[497]
0.63-2.4	Cough/influenza patient	Laser aerosol particle spectrometer	[498]
1.6, 1.7 and 123	Aerosols disease	Aerodynamic particle sizer and	[499]
	(Bronchiolar/Laryngeal/Oral)	droplet deposition analysis	
7-123	Cough and sneeze	High-speed photographic	[500]
		technique	

1-100	Cough and sneeze	Sample collection by using	
		impactor	
< 1	Cough and sneeze via coxsackievirus A	Solid impaction	[501]
85% drops less	Cough	Solid impaction/Optical particle	[502]
than < 1		counter	
Majority of	Cough	Aerosol sampling system and solid	[503]
respirable size		impaction	
0.15-0.19	Breathing	Optical particle counter	[504]
0.62-8.35	Cough	Aerodynamic particle sizer	[505]
		scanning mobility particle sizer	
< 1 (87%)	Influenza cough	Optical particle counter	[506]
13.5	Cough and speech	Interferometric Mie imaging	[507]
		technique	

Appendix D

D Chapter 5 Supplementary Information

D1 Supplementary text

D1.1 Existing continuous flow diffusion chamber

Continuous flow diffusion chamber (CFDC) instruments determine INPs concentrations by drawing dry aerosol particles and exposing them to a controlled temperature and relative humidity environment where they take part in ice nucleation [142, 508, 509]. However, there are instrument-to-instrument differences in geometry and flows (Table D1), such as cylindrical plates [142] and parallel plates [131, 508] wall systems. Even in geometrically different CFDC, aerosols are drawn through an inlet and contained between two sheath flows. These three flows passing between two ice-coated walls are held at different sub-zero temperatures. The temperature difference between both hot and cold walls produces supersaturation with respect to the ice, and maximum supersaturation is observed near the center of the chamber [142, 508, 510]. Particles are constrained to a narrow central lamina by the sheath flows. A sufficiently large temperature gradient between the walls can cause lamina conditions [142, 508, 509, 511], thus producing uncertainty in measuring the size and number concentration of ice nuclei.

CFDC-based ice nucleation chambers measure only the size and number of particles exiting the chamber using an optical particle counter [142, 512, 513]. Though existing chambers generally misinterpreted the counting of ice crystals due to the presence of supercooled droplets, it leads to a higher concentration of ice crystals. The most recent CFDC instrument introduced an "evaporation section" to minimize the impact of droplet formation [508, 509]. These regions are isothermal and ice-coated sections at the bottom of the chamber where supercooled droplets can evaporate. Since most of the CFDC operates with a sufficiently large temperature gradient between the ice-coated walls, which can create droplets large enough to survive evaporation sections, this condition is known as "droplet breakthrough" and is specific to individual CFDC geometry and flow characteristics [142, 508, 509]. This often occurs due to the non-ideal flow and deviations from isothermal conditions [512, 514] and could contribute to a bias in the number of INPs
measured. These chambers are bulky and expensive. However, SPectrometer for Ice Nuclei (SPIN) and Portable Ice Nucleation Experiment (PINE) are commercially available [509, 515]. One of the persistent limitations of the listed chambers (Table D1) is their optical detection system, which is constrained to study the size of INPs smaller than < 200 nm. These chambers can also not determine the real-time time-dependent morphology of INPs in situ. However, we proposed the MRINC, where we can evaluate INPs smaller than 200 nm and distinguish the supercooled droplets and ice crystals in a mixed-phase cloud regime.

D2 Supplementary figures



Figure D1 Temperature and humidity response of MRINC at inlet point. Where a, b, c, and d are steps, constant moist air is supplied to MRINC.



Figure D2 Relative humidity inside the chamber at different constant temperatures. The short peaks for a few seconds come due to external flow fluctuation.



Figure D3 Temperature, humidity, and flow calibration of RINC at cooling conditions. Cooling is achieved by using Dry Ice.

D3 Supplementary tables

Instrument name	Description	Geometry	Institute	Reference
MRINC	Continuous flow	Open cylinder	McGill	In this
	diffusion chamber		University	study
AIDA Expansion	Expansion cloud	-	Karlsruhe Institute	[139, 516]
cloud	Chamber		of Technology	
CFDC-CSU	Continuous flow	Cylindrical plates	Colorado State	[142, 510,
	diffusion chamber		University	517]
CFDCTAMU	Continuous flow	Cylindrical plates	Texas A&M	[513, 518]
	diffusion chamber		University	
INKA	Continuous flow	Cylindrical plates	Karlsruhe Institute	[519]
	diffusion		of	
	Chamber		Technology	
SPIN-MIT	Continuous flow	Parallel plates	Massachusetts	[509]
	diffusion chamber		Institute	
			of Technology	
SPIN-TROPOS	Continuous flow	Parallel plates	Institute for	[509]
	diffusion chamber		Tropospheric	
			Research	
CIC-PNNL	Continuous flow	Parallel plates	Pacific Northwest	[520]
	diffusion chamber		National	
			Laboratory	
ZINC	Continuous flow	Parallel plate	Zurich Ice Nuclei	[508]
	diffusion chamber		Chamber	
UT CFDC	Continuous flow	Parallel plates	University of	[421]
	diffusion chamber		Toronto CFDC	
FINCH	Continuous flow	Open cylinder	University of	[521]
	diffusion chamber		Frankfurt Fast	
			Ice Nuclei	
			Chamber	
MINC	Continuous flow	Cylindrical plates	University of	[522]
	diffusion chamber		Manchester	
PINC	Continuous flow	Parallel plates	ETH Zurich	[131, 523-
PIMCAPINC	diffusion chamber			525]
PINE	Expansion cloud	-	Karlsruhe Institute	[515]
	chamber		of Technology	

Table D1Direct processing ice nucleation measurements based on CFDC.

Flow rate (range) L/min	Temperature (°C)	Reynolds number (range)
5 - 50	-5	~86 to ~830
5 - 50	-10	~90 to ~851
5 - 50	-15	~92 to ~881
5 - 50	-20	~95 to ~912
5 - 50	-30	~103 to ~981
5 - 50	-40	~111 to ~1060

Table D2Operating conditions of RINC.

Chapter 7 References

- 1. Hinds, W.C., *Aerosol Technology*. 1999, Wiley & Sons New York.
- 2. Hinds, W.C., *Aerosol technology: properties, behavior, and measurement of airborne particles.* 2012: John Wiley & Sons.
- 3. Prather, K.A., C.D. Hatch, and V.H.J.A.R.o.A.C. Grassian, *Analysis of atmospheric aerosols.* 2008. **1**(1): p. 485.
- 4. Tomasi, C., et al., *Primary and secondary sources of atmospheric aerosol.* 2017: p. 1-86.
- 5. Boucher, O., *Atmospheric aerosols*, in *Atmospheric Aerosols*. 2015, Springer. p. 9-24.
- 6. Després, V., et al., *Primary biological aerosol particles in the atmosphere: a review.* Tellus B: Chemical and Physical Meteorology, 2012. **64**(1): p. 15598.
- 7. Pöschl, U., *Atmospheric Aerosols: Composition, Transformation, Climate and Health Effects.* Angewandte Chemie International Edition, 2005. **44**(46): p. 7520-7540.
- 8. Prospero, J., et al., *The atmospheric aerosol system: An overview*. 1983. **21**(7): p. 1607-1629.
- 9. Yan, C., et al., *Size-dependent influence of NO_x on the growth rates of organic aerosol particles.* Science Advances, 2020. **6**(22): p. eaay4945.
- 10. Kulmala, M., et al., *Direct Observations of Atmospheric Aerosol Nucleation*. Science, 2013. **339**(6122): p. 943-946.
- 11. Hussein, T., et al., *Observation of regional new particle formation in the urban atmosphere*. Tellus B: Chemical and Physical Meteorology, 2008. **60**(4): p. 509-521.
- 12. Kulmala, M., et al., *Formation and growth rates of ultrafine atmospheric particles: a review of observations.* Journal of Aerosol Science, 2004. **35**(2): p. 143-176.
- 13. Aalto, P., et al., *Physical characterization of aerosol particles during nucleation events.* Tellus B: Chemical and Physical Meteorology, 2001. **53**(4): p. 344-358.
- 14. Kulmala, M., et al., *Formation and growth rates of ultrafine atmospheric particles: a review of observations.* Journal of Aerosol Science, 2004. **35**(2): p. 143-176.
- 15. Asmi, A., et al., *Number size distributions and seasonality of submicron particles in Europe 2008–2009.* Atmos. Chem. Phys., 2011. **11**(11): p. 5505-5538.
- 16. Carslaw, K.S., et al., *A review of natural aerosol interactions and feedbacks within the Earth system.* Atmos. Chem. Phys., 2010. **10**(4): p. 1701-1737.
- 17. Stocker, T.F., et al., *Physical climate processes and feedbacks*, in *IPCC*, 2001: *Climate change 2001*: The scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. 2001, Cambridge University Press. p. 417-470.
- 18. Stocker, T., et al., *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1535 pp. 2013, Cambridge Univ. Press, Cambridge, UK, and New York.*
- 19. World Health, O., *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. 2021, Geneva: World Health Organization.
- 20. Buseck, P.R. and M. Pósfai, *Airborne minerals and related aerosol particles: Effects on climate and the environment.* 1999. **96**(7): p. 3372-3379.
- 21. Murray, B.J., et al., *Ice nucleation by particles immersed in supercooled cloud droplets.* Chemical Society Reviews, 2012. **41**(19): p. 6519-6554.
- 22. Sun, J. and P.A.J.A.E. Ariya, *Atmospheric organic and bio-aerosols as cloud condensation nuclei (CCN): A review.* 2006. **40**(5): p. 795-820.

- 23. Rangel-Alvarado, R.B., Y. Nazarenko, and P.A. Ariya, *Snow-borne nanosized particles: Abundance, distribution, composition, and significance in ice nucleation processes.* Journal of Geophysical Research: Atmospheres, 2015. **120**(22): p. 11,760-11,774.
- 24. Morawska, L., et al., *Ambient nano and ultrafine particles from motor vehicle emissions: Characteristics, ambient processing and implications on human exposure.* Atmospheric Environment, 2008. **42**(35): p. 8113-8138.
- 25. Jamriska, M., L. Morawska, and K. Mergersen, *The effect of temperature and humidity on size segregated traffic exhaust particle emissions.* Atmospheric Environment, 2008. **42**(10): p. 2369-2382.
- 26. Hussein, T., et al., *Meteorological dependence of size-fractionated number concentrations of urban aerosol particles.* Atmospheric Environment, 2006. **40**(8): p. 1427-1440.
- 27. Whiteaker, J.R., et al., *Effects of meteorological conditions on aerosol composition and mixing state in Bakersfield, CA.* 2002. **36**(11): p. 2345-2353.
- Kopeika, N., S. Solomon, and Y.J.J. Gencay, Wavelength variation of visible and near-infrared resolution through the atmosphere: dependence on aerosol and meteorological conditions. 1981.
 71(7): p. 892-901.
- 29. Hopke, P.K., *Review of receptor modeling methods for source apportionment.* Journal of the Air & Waste Management Association, 2016. **66**(3): p. 237-259.
- 30. Belis, C.A., et al., *Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe.* Atmospheric Environment, 2013. **69**: p. 94-108.
- 31. Kim, E., P.K. Hopke, and E.S.J.A.E. Edgerton, *Improving source identification of Atlanta aerosol using temperature resolved carbon fractions in positive matrix factorization.* 2004. **38**(20): p. 3349-3362.
- 32. Mejia, J.F. and L. Morawska, *An investigation of nucleation events in a coastal urban environment in the Southern Hemisphere.* Atmospheric Chemistry and Physics, 2009. **9**(1): p. 2195-2222.
- 33. Prospero, J.M.J.P.o.t.N.A.o.S., Long-range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the southeastern United States. 1999. **96**(7): p. 3396-3403.
- 34. Tegen, I., et al., *Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results.* 1997. **102**(D20): p. 23895-23915.
- 35. Gillette, D.A. and R.J.J.o.G.R.A. Passi, *Modeling dust emission caused by wind erosion*. 1988. **93**(D11): p. 14233-14242.
- 36. Shao, Y.J.J.o.G.R.A., *A model for mineral dust emission*. 2001. **106**(D17): p. 20239-20254.
- 37. Duce, R.J.A.f.o.c., *Sources, distributions, and fluxes of mineral aerosols and their relationship to climate.* 1995. **6**: p. 43-72.
- 38. Sanderson, P., J.M. Delgado-Saborit, and R.M. Harrison, *A review of chemical and physical characterisation of atmospheric metallic nanoparticles.* Atmospheric Environment, 2014. **94**: p. 353-365.
- 39. Kumar, P., et al., *Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment—A review.* Journal of Aerosol Science, 2011. **42**(9): p. 580-603.
- 40. Andreae, M. and D.J.E.-S.R. Rosenfeld, *Aerosol–cloud–precipitation interactions. Part 1. The nature and sources of cloud-active aerosols.* 2008. **89**(1-2): p. 13-41.
- 41. Lewis, E.R., R. Lewis, and S.E. Schwartz, *Sea salt aerosol production: mechanisms, methods, measurements, and models*. Vol. 152. 2004: American geophysical union.
- 42. Gantt, B. and N. Meskhidze, *The physical and chemical characteristics of marine primary organic aerosol: a review.* Atmos. Chem. Phys., 2013. **13**(8): p. 3979-3996.
- 43. Murphy, D.M., et al., *The distribution of sea-salt aerosol in the global troposphere*. 2019. **19**(6): p. 4093-4104.

- 44. Blanchard, D. and A.J.T. Woodcock, *Bubble formation and modification in the sea and its meteorological significance*. 1957. **9**(2): p. 145-158.
- 45. Kulmala, M., et al., *Organic aerosol formation via sulphate cluster activation.* Journal of Geophysical Research: Atmospheres, 2004. **109**(D4).
- 46. Pósfai, M. and P.R. Buseck, *Nature and Climate Effects of Individual Tropospheric Aerosol Particles*. 2010. **38**(1): p. 17-43.
- 47. O'Dowd, C.D., et al., *The relative importance of non-sea-salt sulphate and sea-salt aerosol to the marine cloud condensation nuclei population: An improved multi-component aerosol-cloud droplet parametrization.* 1999. **125**(556): p. 1295-1313.
- 48. Rap, A., et al., *Enhanced global primary production by biogenic aerosol via diffuse radiation fertilization*. 2018. **11**(9): p. 640-644.
- 49. Côté, V., et al., *Microbial and "de novo" transformation of dicarboxylic acids by three airborne fungi.* Science of The Total Environment, 2008. **390**(2): p. 530-537.
- 50. Ariya, P.A., et al., *Bio-Organic Materials in the Atmosphere and Snow: Measurement and Characterization*, in *Atmospheric and Aerosol Chemistry*, V.F. McNeill and P.A. Ariya, Editors. 2014, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 145-199.
- 51. Ariya, P.A., et al., *Physical and chemical characterization of bioaerosols Implications for nucleation processes.* International Reviews in Physical Chemistry, 2009. **28**(1): p. 1-32.
- 52. Pósfai, M., et al., Aerosol bacteria over the Southern Ocean during ACE-1. 2003. 66(4): p. 231-240.
- 53. Winiwarter, W., et al., *Quantifying emissions of primary biological aerosol particle mass in Europe*. 2009. **43**(7): p. 1403-1409.
- 54. Matthias-Maser, S. and R.J.J.o.a.s. Jaenicke, *Examination of atmospheric bioaerosol particles with radii> 0.2 μm.* 1994. **25**(8): p. 1605-1613.
- 55. Elbert, W., et al., *Contribution of fungi to primary biogenic aerosols in the atmosphere: wet and dry discharged spores, carbohydrates, and inorganic ions.* 2007. **7**(17): p. 4569-4588.
- 56. Xie, W., et al., *The source and transport of bioaerosols in the air: A review.* 2021. **15**(3): p. 1-19.
- 57. Andersson, S.M., et al., Significant radiative impact of volcanic aerosol in the lowermost stratosphere. 2015. **6**(1): p. 1-8.
- 58. Solomon, S., et al., *The persistently variable "background" stratospheric aerosol layer and global climate change*. 2011. **333**(6044): p. 866-870.
- 59. Sassen, K.J.S., *Evidence for liquid-phase cirrus cloud formation from volcanic aerosols: Climatic implications.* 1992. **257**(5069): p. 516-519.
- 60. Dall'Osto, M., et al., *Hourly elemental concentrations in PM_{2.5} aerosols sampled simultaneously at urban background and road site during SAPUSS diurnal variations and PMF receptor modelling.* Atmos. Chem. Phys., 2013. **13**(8): p. 4375-4392.
- 61. Wegner, T., et al., *Properties of aerosol signature size distributions in the urban environment as derived by cluster analysis.* Atmospheric Environment, 2012. **61**(Supplement C): p. 350-360.
- 62. Rogula-Kozłowska, W., *Size-segregated urban particulate matter: mass closure, chemical composition, and primary and secondary matter content.* Air Quality, Atmosphere & Health, 2016. **9**(5): p. 533-550.
- 63. Samara, C., et al., *Spatial and seasonal variations of the chemical, mineralogical and morphological features of quasi-ultrafine particles (PM0.49) at urban sites.* Science of The Total Environment, 2016. **553**: p. 392-403.
- 64. Owen, M., D. Ensor, and L.J.A.E.P.A.G.T. Sparks, *Airborne particle sizes and sources found in indoor air.* 1992. **26**(12): p. 2149-2162.
- 65. Abdullahi, K.L., J.M. Delgado-Saborit, and R.M.J.A.E. Harrison, *Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: A review.* 2013. **71**: p. 260-294.

- 66. Odum, J.R., et al., *Gas/particle partitioning and secondary organic aerosol yields.* 1996. **30**(8): p. 2580-2585.
- 67. Hoffmann, T., et al., *Formation of organic aerosols from the oxidation of biogenic hydrocarbons.* 1997. **26**(2): p. 189-222.
- 68. Jang, M. and R.M.J.A.E. Kamens, Newly characterized products and composition of secondary aerosols from the reaction of α -pinene with ozone. 1999. **33**(3): p. 459-474.
- 69. Kaufman, Y.J., et al., Aerosol anthropogenic component estimated from satellite data. 2005. **32**(17).
- 70. Kaufman, Y.J., D. Tanre, and O. Boucher, *A satellite view of aerosols in the climate system*. Nature, 2002. **419**(6903): p. 215-23.
- 71. Lelieveld, J., et al., *Effects of fossil fuel and total anthropogenic emission removal on public health and climate.* 2019. **116**(15): p. 7192-7197.
- 72. Pal, D., A. Dastoor, and P.A. Ariya, *Aerosols in an urban cold climate: Physical and chemical characteristics of nanoparticles.* Urban Climate, 2020. **34**: p. 100713.
- 73. Rahim, M., D. Pal, and P. Ariya, *Physicochemical studies of aerosols at Montreal Trudeau Airport: The importance of airborne nanoparticles containing metal contaminants.* Environmental Pollution, 2018. **246**.
- 74. Seinfeld, J.H., et al., *Improving our fundamental understanding of the role of aerosol–cloud interactions in the climate system*. 2016. **113**(21): p. 5781-5790.
- 75. Grassian, V.H., et al., *Inhalation Exposure Study of Titanium Dioxide Nanoparticles with a Primary Particle Size of 2 to 5 nm.* Environmental Health Perspectives, 2007. **115**(3): p. 397-402.
- 76. Nazarenko, Y., D. Pal, and P.A. Ariya, *Air quality standards for the concentration of particulate matter 2.5, global descriptive analysis.* Bulletin of the World Health Organization, 2021. **99**(2): p. 125-137D.
- 77. Gray, H.A., et al., *Characteristics of atmospheric organic and elemental carbon particle concentrations in Los Angeles.* 1986. **20**(6): p. 580-589.
- 78. Jacobson, M., et al., Organic atmospheric aerosols: Review and state of the science. 2000. **38**(2): p. 267-294.
- 79. Kanakidou, M., et al., *Organic aerosol and global climate modelling: a review.* 2005. **5**(4): p. 1053-1123.
- 80. Tsigaridis, K., et al., *Change in global aerosol composition since preindustrial times.* 2006. **6**(12): p. 5143-5162.
- 81. Rangel-Alvarado, R., D. Pal, and P. Ariya, *PM2.5 decadal data in cold vs. mild climate airports: COVID-19 era and a call for sustainable air quality policy.* Environmental Science and Pollution Research, 2022. **29**(38): p. 58133-58148.
- 82. Wang, H., et al., *Mixed chloride aerosols and their atmospheric implications: a review.* 2017. **17**(4): p. 878-887.
- 83. Faxon, C. and D.J.E.C. Allen, *Chlorine chemistry in urban atmospheres: a review.* 2013. **10**(3): p. 221-233.
- 84. Ten Harkel, M.J.A.E., *The effects of particle-size distribution and chloride depletion of sea-salt aerosols on estimating atmospheric deposition at a coastal site.* 1997. **31**(3): p. 417-427.
- 85. Organization, W.H., *Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*. 2006: World Health Organization.
- 86. Dockery , D.W., et al., *An Association between Air Pollution and Mortality in Six U.S. Cities.* New England Journal of Medicine, 1993. **329**(24): p. 1753-1759.
- 87. Laden, F., et al., *Association of fine particulate matter from different sources with daily mortality in six U.S. cities*. Environmental Health Perspectives, 2000. **108**(10): p. 941-947.

- 88. Murray, C.J., et al., *Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019.* 2020. **396**(10258): p. 1223-1249.
- 89. Cohen, A.J., et al., Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. 2017.
 389(10082): p. 1907-1918.
- 90. Shiraiwa, M., et al., Aerosol health effects from molecular to global scales. 2017. **51**(23): p. 13545-13567.
- 91. Hetland, R., et al., *Release of inflammatory cytokines, cell toxicity and apoptosis in epithelial lung cells after exposure to ambient air particles of different size fractions.* 2004. **18**(2): p. 203-212.
- 92. EPA, Air Quality Criteria for Particulate Matter. 2004.
- 93. EPA, Overview of Airborne Metals Regulations, Exposure Limits, Health Effects, and Contemporary Research. 2010.
- 94. WHO, *World health statistics 2015*. 2015: World Health Organization.
- 95. Giannadaki, D., J. Lelieveld, and A.J.E.H. Pozzer, *Implementing the US air quality standard for PM2.* 5 worldwide can prevent millions of premature deaths per year. 2016. **15**(1): p. 1-11.
- 96. Moridnejad, A., et al., *A new inventory for middle east dust source points*. 2015. **187**(9): p. 1-11.
- 97. Moridnejad, A., N. Karimi, and P.A.J.J.o.A.E. Ariya, *Newly desertified regions in Iraq and its surrounding areas: Significant novel sources of global dust particles.* 2015. **116**: p. 1-10.
- 98. 80004-2:2015(en), I.T., *ISO/TS 80004-2:2015 lists terms and definitions related to particles in the field of nanotechnologies*. 07.120 Nanotechnologies 01.040.07 Natural and applied sciences, 2015.
- 99. Morawska, L., et al., *Ambient ultrafine particles: evidence for policy makers.* 2019.
- 100. Schraufnagel, D.E., *The health effects of ultrafine particles*. Experimental & Molecular Medicine, 2020. **52**(3): p. 311-317.
- 101. Ohlwein, S., et al., *Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence.* 2019. **64**(4): p. 547-559.
- 102. Zhu, Y., et al., Seasonal Trends of Concentration and Size Distribution of Ultrafine Particles Near Major Highways in Los Angeles Special Issue of Aerosol Science and Technology on Findings from the Fine Particulate Matter Supersites Program. Aerosol Science and Technology, 2004. 38(sup1): p. 5-13.
- 103. Kumar, P., et al., *Ultrafine particles in cities*. Environment International, 2014. **66**: p. 1-10.
- 104. McNeill, V.F., *Atmospheric Aerosols: Clouds, Chemistry, and Climate.* 2017. **8**(1): p. 427-444.
- 105. Li, J., et al., *Scattering and absorbing aerosols in the climate system.* Nature Reviews Earth & Environment, 2022. **3**(6): p. 363-379.
- 106. Masson-Delmotte, V., et al., *Climate change 2021: the physical science basis.* 2021. **2**.
- 107. Myhre, G., D. Shindell, and J. Pongratz, *Anthropogenic and natural radiative forcing.* 2014.
- 108. Lohmann, U. and J. Feichter, *Global indirect aerosol effects: a review*. Atmospheric Chemistry Physics, 2005. **5**(3): p. 715-737.
- 109. Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj,, et al., *Climate Change 2021: The Physical Science Basis.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021: p. 33–144.
- 110. IPCC, *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* 2013: edited, Cambridge Sunni. Press, Cambridge, UK, and New York. p. 1535 PP.
- 111. Charlson, R.J., et al., *Climate forcing by anthropogenic aerosols*. 1992. **255**(5043): p. 423-430.
- 112. Seinfeld, J.H. and S.N. Pandis, *Atmospheric chemistry and physics*. From Air Pollution to Climate Change, 1998.
- 113. Dufresne, J.-L., et al., *Longwave scattering effects of mineral aerosols*. 2002. **59**(12): p. 1959-1966.

- 114. Heymsfield, A.J., et al., *Cirrus Clouds*. Meteorological Monographs, 2017. **58**: p. 2.1-2.26.
- 115. Chand, D., et al., *Satellite-derived direct radiative effect of aerosols dependent on cloud cover.* 2009. **2**(3): p. 181-184.
- 116. Bergstrom, R.W., et al., *Spectral absorption properties of atmospheric aerosols.* 2007. **7**(23): p. 5937-5943.
- 117. Bellouin, N., et al., *Bounding global aerosol radiative forcing of climate change.* 2020. **58**(1): p. e2019RG000660.
- 118. Satheesh, S. and V.J.N. Ramanathan, *Large differences in tropical aerosol forcing at the top of the atmosphere and Earth's surface.* 2000. **405**(6782): p. 60-63.
- 119. Jacobson, M.Z., *Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols.* Nature, 2001. **409**: p. 695.
- 120. Cappa, C.D., et al., *Radiative absorption enhancements due to the mixing state of atmospheric black carbon.* 2012. **337**(6098): p. 1078-1081.
- 121. Vuolo, M.R., et al., *A new method for evaluating the impact of vertical distribution on aerosol radiative forcing in general circulation models.* 2014. **14**(2): p. 877-897.
- 122. Satheesh, S. and K.K.J.A.E. Moorthy, *Radiative effects of natural aerosols: A review.* 2005. **39**(11): p. 2089-2110.
- 123. Twomey, S.J.J.o.t.a.s., *The influence of pollution on the shortwave albedo of clouds.* 1977. **34**(7): p. 1149-1152.
- 124. Toll, V., et al., Weak average liquid-cloud-water response to anthropogenic aerosols. 2019. **572**(7767): p. 51-55.
- 125. McGraw, Z., et al., *Global radiative impacts of black carbon acting as ice nucleating particles.* 2020. **47**(20): p. e2020GL089056.
- 126. Kärcher, B., *Cirrus Clouds and Their Response to Anthropogenic Activities.* Current Climate Change Reports, 2017. **3**(1): p. 45-57.
- 127. DeMott, P.J., et al., *Resurgence in Ice Nuclei Measurement Research*. Bulletin of the American Meteorological Society, 2011. **92**(12): p. 1623-1635.
- 128. Kanji, Z.A., et al., *Overview of Ice Nucleating Particles*. Meteorological Monographs, 2017. **58**: p. 1.1-1.33.
- 129. DeMott, P.J., et al., *Predicting global atmospheric ice nuclei distributions and their impacts on climate.* Proceedings of the National Academy of Sciences, 2010. **107**(25): p. 11217.
- 130. Burrows, S.M., et al., *Ice-Nucleating Particles That Impact Clouds and Climate: Observational and Modeling Research Needs.* 2022. **60**(2): p. e2021RG000745.
- 131. Lacher, L., et al., *The Horizontal Ice Nucleation Chamber (HINC): INP measurements at conditions relevant for mixed-phase clouds at the High Altitude Research Station Jungfraujoch.* Atmos. Chem. Phys., 2017. **17**(24): p. 15199-15224.
- 132. Meyers, M.P., P.J. DeMott, and W.R. Cotton, *New primary ice-nucleation parameterizations in an explicit cloud model.* Journal of Applied Meteorology, 1992. **31**(7): p. 708-721.
- 133. Vergara-Temprado, J., et al., *Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles*. 2018. **115**(11): p. 2687-2692.
- 134. Ullrich, R., et al., *Comparison of Modeled and Measured Ice Nucleating Particle Composition in a Cirrus Cloud.* Journal of the Atmospheric Sciences, 2019. **76**(4): p. 1015-1029.
- 135. Field, P.R., et al., *Ice Formation and Evolution in Clouds and Precipitation: Measurement and Modeling Challenges: Chapter 7. Secondary Ice Production-current state of the science and recommendations for the future.* Meteorological Monographs, 2017. **58**: p. 7.1-7.20.
- 136. Vonnegut, B.J.J.o.a.p., *The nucleation of ice formation by silver iodide*. 1947. **18**(7): p. 593-595.
- 137. Hoose, C. and O. Möhler, *Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments.* Atmos. Chem. Phys, 2012. **12**(20): p. 9817-9854.

- 138. Vali, G., et al., *Technical Note: A proposal for ice nucleation terminology*. Atmos. Chem. Phys., 2015. **15**(18): p. 10263-10270.
- 139. Möhler, O., et al., *Experimental investigation of homogeneous freezing of sulphuric acid particles in the aerosol chamber AIDA*. Atmos. Chem. Phys., 2003. **3**(1): p. 211-223.
- 140. Pruppacher, H.R. and J.D. Klett, *Microphysics of clouds and precipitation*. Nature, 1980. **284**(5751): p. 88-88.
- 141. David, R.O., et al., Pore condensation and freezing is responsible for ice formation below water saturation for porous particles. Proceedings of the National Academy of Sciences, 2019. 116(17): p. 8184.
- 142. Rogers, D.C., *Development of a continuous flow thermal gradient diffusion chamber for ice nucleation studies*. Atmospheric Research, 1988. **22**(2): p. 149-181.
- 143. Mahrt, F., et al., *Ice nucleation abilities of soot particles determined with the Horizontal Ice Nucleation Chamber.* Atmos. Chem. Phys., 2018. **18**(18): p. 13363-13392.
- 144. Hoose, C., J. Kristjánsson, and S. Burrows, *How important is biological ice nucleation in clouds on a global scale?* Environmental Research Letters, 2010. **5**(2): p. 024009.
- Young, K.C., A numerical simulation of wintertime, orographic precipitation: Part I. Description of model microphysics and numerical techniques. Journal of the Atmospheric Sciences, 1974. 31(7): p. 1735-1748.
- 146. Knopf, D., et al., *Stimulation of ice nucleation by marine diatoms*. Nature Geoscience, 2011. **4**(2): p. 88-90.
- 147. Kärcher, B., et al., *Insights into the role of soot aerosols in cirrus cloud formation*. 2007.
- 148. Hoose, C., et al., *A classical-theory-based parameterization of heterogeneous ice nucleation by mineral dust, soot, and biological particles in a global climate model.* Journal of the Atmospheric Sciences, 2010. **67**(8): p. 2483-2503.
- Phillips, V.T., P.J. DeMott, and C. Andronache, An empirical parameterization of heterogeneous ice nucleation for multiple chemical species of aerosol. Journal of the atmospheric sciences, 2008.
 65(9): p. 2757-2783.
- 150. Ariya, P.A., et al., *Do snow and ice alter urban air quality?* Atmospheric Environment, 2018. **186**: p. 266-268.
- 151. Lei, Y.D. and F.J.A.E. Wania, *Is rain or snow a more efficient scavenger of organic chemicals*? 2004. **38**(22): p. 3557-3571.
- 152. Bartels-Rausch, T., et al., *Relationship between snow microstructure and physical and chemical processes.* 2012. **12**(11).
- 153. Nazarenko, Y., et al., *Role of snow and cold environment in the fate and effects of nanoparticles and select organic pollutants from gasoline engine exhaust.* Environmental Science: Processes & Impacts, 2016. **18**(2): p. 190-199.
- 154. Grannas, A., et al., *An overview of snow photochemistry: evidence, mechanisms and impacts.* 2007. **7**(16): p. 4329-4373.
- 155. Nazarenko, Y., et al., *Role of snow in the fate of gaseous and particulate exhaust pollutants from gasoline-powered vehicles.* Environmental Pollution, 2017. **223**: p. 665-675.
- 156. Gultepe, I., et al., *Fog research: A review of past achievements and future perspectives.* 2007. **164**(6): p. 1121-1159.
- 157. Hobbs, P.V. and P.V. Hobbs, *Introduction to atmospheric chemistry*. 2000: Cambridge University Press.
- 158. Polonik, P., K. Ricke, and J.J.E.s.F. Burney, *Paris Agreement's ambiguity about aerosols drives uncertain health and climate outcomes.* 2021. **9**(5): p. e2020EF001787.
- 159. Ebenstein, A., et al., *New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy*. 2017. **114**(39): p. 10384-10389.

- 160. 2016, W.B., *The cost of air pollution: strengthening the economic case for action*. 2016: University of Washington Institute for Health Metrics and Evaluation, and Weltbank.
- 161. Burke, M., W.M. Davis, and N.S. Diffenbaugh, *Large potential reduction in economic damages under UN mitigation targets*. Nature, 2018. **557**(7706): p. 549-553.
- 162. Diaz, D. and F.J.N.C.C. Moore, *Quantifying the economic risks of climate change.* 2017. **7**(11): p. 774-782.
- 163. Zheng, Y., et al., *Climate effects of aerosols reduce economic inequality*. 2020. **10**(3): p. 220-224.
- 164. Mastrandrea, M.D., et al., *The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups.* 2011. **108**(4): p. 675-691.
- 165. Šantl-Temkiv, T., et al., *Bioaerosol field measurements: Challenges and perspectives in outdoor studies.* Aerosol Science and Technology, 2020. **54**(5): p. 520-546.
- 166. Field, C.B. and V.R. Barros, *Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects.* 2014: Cambridge University Press.
- 167. Li, X., D.L. Mauzerall, and M.H.J.N.S. Bergin, *Global reduction of solar power generation efficiency due to aerosols and panel soiling.* 2020. **3**(9): p. 720-727.
- 168. CERC, *Calculation of average power purchase cost (APPC) rate at the national level, Petition No. 01/SM/2021.* New Delhi: Central Electricity Regulatory Commission, Government of India), 2021.
- 169. Li, X., et al., *Reduction of solar photovoltaic resources due to air pollution in China.* 2017. **114**(45): p. 11867-11872.
- 170. Sweerts, B., et al., *Estimation of losses in solar energy production from air pollution in China since 1960 using surface radiation data*. 2019. **4**(8): p. 657-663.
- 171. Tongia, R.J.B.I.I.S., *Delhi's household electricity subsidies: highly generous but inefficient.* 2017(042017).
- 172. Guo, S., T.M. Walsh, and M.J.E. Peters, *Vertically mounted bifacial photovoltaic modules: A global analysis.* 2013. **61**: p. 447-454.
- 173. Peters, I., et al., *Urban haze and photovoltaics.* 2018. **11**(10): p. 3043-3054.
- 174. Labor, U.S.D.o., Bureau of Labor Statistics, Average Energy Prices, Los Angeles-Long Beach-Anaheim. 2018.
- 175. Laj, P., et al., A global analysis of climate-relevant aerosol properties retrieved from the network of Global Atmosphere Watch (GAW) near-surface observatories. 2020. **13**(8): p. 4353-4392.
- 176. Ziemba, L.D., et al., *Airborne observations of aerosol extinction by in situ and remote-sensing techniques: Evaluation of particle hygroscopicity.* 2013. **40**(2): p. 417-422.
- 177. Gliß, J., et al., AeroCom phase III multi-model evaluation of the aerosol life cycle and optical properties using ground-and space-based remote sensing as well as surface in situ observations. 2021. **21**(1): p. 87-128.
- 178. Harrison, R.M., et al., *Measurement of number, mass and size distribution of particles in the atmosphere.* Philosophical Transactions of the Royal Society of London. Series A:

Mathematical, Physical and Engineering Sciences, 2000. **358**(1775): p. 2567-2580.

- 179. McMurry, P.H., *A review of atmospheric aerosol measurements*. Atmospheric Environment, 2000. **34**(12): p. 1959-1999.
- 180. Chow, J.C.J.J.o.t.A. and W.M. Association, *Measurement methods to determine compliance with ambient air quality standards for suspended particles*. 1995. **45**(5): p. 320-382.
- 181. Jayne, J.T., et al., *Development of an aerosol mass spectrometer for size and composition analysis of submicron particles*. 2000. **33**(1-2): p. 49-70.
- 182. Canagaratna, M.R., et al., *Chemical and microphysical characterization of ambient aerosols with the aerodyne aerosol mass spectrometer*. 2007. **26**(2): p. 185-222.

- 183. Wang, X., Y. Zhang, and X. Yang, *Investigating aerosol chemistry using Real-Time Single Particle Mass Spectrometry: A viewpoint on its recent development.* Applied Geochemistry, 2023. **149**: p. 105554.
- 184. Li, W., et al., *A review of single aerosol particle studies in the atmosphere of East Asia: morphology, mixing state, source, and heterogeneous reactions.* Journal of Cleaner Production, 2016. **112**: p. 1330-1349.
- 185. Zhou, W., et al., *A review of aerosol chemistry in Asia: insights from aerosol mass spectrometer measurements.* Environmental Science: Processes & Impacts, 2020. **22**(8): p. 1616-1653.
- 186. MacInnis, J., et al., *Measurement report: The chemical composition of and temporal variability in aerosol particles at Tuktoyaktuk, Canada, during the Year of Polar Prediction Second Special Observing Period.* Atmos. Chem. Phys., 2021. **21**(18): p. 14199-14213.
- 187. Hansen, A., H. Rosen, and T.J.S.o.t.T.E. Novakov, *The aethalometer—an instrument for the realtime measurement of optical absorption by aerosol particles.* 1984. **36**: p. 191-196.
- 188. Li, H. and P.A.J.J.o.G.R.A. Ariya, Black Carbon Particles Physicochemical Real-Time Data Set in a Cold City: Trends of Fall-Winter BC Accumulation and COVID-19. 2021. **126**(22): p. e2021JD035265.
- 189. Massabò, D. and P. Prati, *An overview of optical and thermal methods for the characterization of carbonaceous aerosol.* La Rivista del Nuovo Cimento, 2021. **44**(3): p. 145-192.
- 190. Turpin, B., et al., *An in situ, time-resolved analyzer for aerosol organic and elemental carbon.* 1990. **12**(1): p. 161-171.
- 191. Ni, L., et al., *A flame photometric detector with a silicon photodiode assembly for sulfur detection*. 2020. **207**: p. 120283.
- 192. Noble, C.A. and K.A.J.M.S.R. Prather, *Real-time single particle mass spectrometry: A historical review of a quarter century of the chemical analysis of aerosols.* 2000. **19**(4): p. 248-274.
- 193. Yang, K., K. Swami, and L. Husain, *Determination of Trace Metals in Atmospheric Aerosols With Heavy Matrix of Cellulose by Microwave Digestion-Inductively Coupled Plasma Mass Spectroscopy*. Spectrochimica Acta Part B Atomic Spectroscopy, 2002. **57**: p. 73-84.
- 194. Chang, Y., et al., *First long-term and near real-time measurement of trace elements in China's urban atmosphere: temporal variability, source apportionment and precipitation effect.* Atmos. Chem. Phys., 2018. **18**(16): p. 11793-11812.
- 195. Singh, A., et al., *An overview of airborne measurement in Nepal–Part 1: Vertical profile of aerosol size, number, spectral absorption, and meteorology.* 2019. **19**(1): p. 245-258.
- 196. Giles, D.M., et al., Advancements in the Aerosol Robotic Network (AERONET) Version 3 database – automated near-real-time quality control algorithm with improved cloud screening for Sun photometer aerosol optical depth (AOD) measurements. Atmos. Meas. Tech., 2019. **12**(1): p. 169-209.
- 197. Holben, B.N., et al., *AERONET—A federated instrument network and data archive for aerosol characterization.* 1998. **66**(1): p. 1-16.
- 198. Dubovik, O., et al., Variability of absorption and optical properties of key aerosol types observed in worldwide locations. 2002. **59**(3): p. 590-608.
- 199. Takamura, T.J.O.p.y.a., *Overview of SKYNET and its activities.* 2004. **37**(3): p. 3303-3308.
- 200. Che, H., et al., *Ground-based aerosol climatology of China: aerosol optical depths from the China Aerosol Remote Sensing Network (CARSNET) 2002–2013.* 2015. **15**(13): p. 7619-7652.
- 201. Burton, S.P., et al., Information content and sensitivity of the $36 + 2\alpha$ lidar measurement system for aerosol microphysical retrievals. 2016. **9**(11): p. 5555-5574.
- 202. Bösenberg, J., et al., *EARLINET: a European aerosol research lidar network.* 2001. **155**.
- 203. Antuña-Marrero, J.C., et al., *LALINET: The first Latin American–born regional atmospheric observational network.* 2017. **98**(6): p. 1255-1275.

- Lopatin, A., et al., Synergy processing of diverse ground-based remote sensing and in situ data using the GRASP algorithm: applications to radiometer, lidar and radiosonde observations. 2021.
 14(3): p. 2575-2614.
- 205. Chen, C., et al., Validation of GRASP algorithm product from POLDER/PARASOL data and assessment of multi-angular polarimetry potential for aerosol monitoring. 2020. **12**(4): p. 3573-3620.
- 206. Omar, A.H., et al., *The CALIPSO automated aerosol classification and lidar ratio selection algorithm*. 2009. **26**(10): p. 1994-2014.
- 207. Noel, V., et al., *The diurnal cycle of cloud profiles over land and ocean between 51 S and 51 N, seen by the CATS spaceborne lidar from the International Space Station*. 2018. **18**(13): p. 9457-9473.
- 208. Behrenfeld, M.J., et al., *Retrieval of ocean optical and plankton properties with the satellite Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor: Background, data processing, and validation status.* 2022. **281**: p. 113235.
- 209. Zhang, T., et al., A Geometry-Discrete Minimum Reflectance Aerosol Retrieval Algorithm (GeoMRA) for Geostationary Meteorological Satellite Over Heterogeneous Surfaces. 2022. **60**: p. 1-14.
- 210. Arola, A., et al., Aerosol effects on clouds are concealed by natural cloud heterogeneity and satellite retrieval errors. 2022. **13**(1): p. 7357.
- 211. Jin, J., et al., How aerosol size matters in aerosol optical depth (AOD) assimilation and the optimization using the Ångström exponent. 2023. **23**(2): p. 1641-1660.
- 212. Kaufman, Y., et al., *Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect.* 1997. **102**(D14): p. 16815-16830.
- 213. Levy, R., et al., *The Collection 6 MODIS aerosol products over land and ocean.* 2013. **6**(11): p. 2989-3034.
- 214. Gueymard, C.A. and D. Yang, *Worldwide validation of CAMS and MERRA-2 reanalysis aerosol optical depth products using 15 years of AERONET observations.* Atmospheric Environment, 2020. **225**: p. 117216.
- 215. Garrigues, S., et al., Monitoring multiple satellite aerosol optical depth (AOD) products within the Copernicus Atmosphere Monitoring Service (CAMS) data assimilation system. Atmos. Chem. Phys., 2022. **22**(22): p. 14657-14692.
- 216. Petzold, A., et al., *Global-scale atmosphere monitoring by in-service aircraft current achievements and future prospects of the European Research Infrastructure IAGOS.* Tellus B: Chemical and Physical Meteorology, 2015. **67**(1): p. 28452.
- 217. Forster, P., et al., Changes in atmospheric constituents and in radiative forcing. Chapter 2, in Climate Change 2007. The Physical Science Basis. 2007.
- 218. Kulmala, M., et al., *General overview: European Integrated project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI) & ndash; integrating aerosol research from nano to global scales.* Atmos. Chem. Phys., 2011. **11**(24): p. 13061-13143.
- 219. Intergovernmental Panel on Climate, C., *Clouds and Aerosols*, in *Climate Change 2013 The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. Intergovernmental Panel on Climate, Editor. 2014, Cambridge University Press: Cambridge. p. 571-658.
- 220. Rangel-Alvarado, R.B., Y. Nazarenko, and P.A. Ariya, *Snow-borne nanosized particles: Abundance, distribution, composition, and significance in ice nucleation processes.* Journal of Geophysical Research: Atmospheres, 2015. **120**(22): p. 11,760-11,774.
- 221. Satterthwaite, D.J.E. and urbanization, *Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions.* 2008. **20**(2): p. 539-549.

- 222. Ahlm, L., et al., *Formation and growth of ultrafine particles from secondary sources in Bakersfield, California.* Journal of Geophysical Research: Atmospheres, 2012. **117**(D21): p. n/a-n/a.
- 223. Hitchins, J., et al., *Concentrations of submicrometre particles from vehicle emissions near a major road.* Atmospheric Environment, 2000. **34**(1): p. 51-59.
- 224. Pirjola, L., et al., *Dispersion of particles and trace gases nearby a city highway: Mobile laboratory measurements in Finland.* Atmospheric Environment, 2006. **40**(5): p. 867-879.
- 225. Pirjola, L., et al., *Physical and chemical characterization of real-world particle number and mass emissions from city buses in Finland*. Environmental science & technology, 2016. **50**(1): p. 294-304.
- 226. Dall'Osto, M., et al., *Remarkable dynamics of nanoparticles in the urban atmosphere*. Atmos. Chem. Phys., 2011. **11**(13): p. 6623-6637.
- 227. Sahu, L.K., R. Yadav, and D. Pal, Source identification of VOCs at an urban site of western India: Effect of marathon events and anthropogenic emissions. 2016. **121**(5): p. 2416-2433.
- 228. Sauvé, S. and M.J.C.C.J. Desrosiers, *A review of what is an emerging contaminant.* 2014. **8**(1): p. 15.
- 229. Sýkorová, B., et al., *Heavy metals in air nanoparticles in affected industry area.* 2017. **5**(1): p. 58-68.
- 230. Gallon, C., et al., *Asian industrial lead inputs to the North Pacific evidenced by lead concentrations and isotopic compositions in surface waters and aerosols.* Environmental science & technology, 2011. **45**(23): p. 9874-9882.
- 231. Järvi, L., et al., *Development of the Surface Urban Energy and Water Balance Scheme (SUEWS) for cold climate cities.* Geosci. Model Dev., 2014. **7**(4): p. 1691-1711.
- 232. RJ Januszek, B.S., JB Bartus, KP Plens, AS Surdacki, SB Bartus, DD Dudek, *Increased air pollution expressed as PM10 concentration and winter time are related to the frequency of percutaneous coronary interventions in patients with acute coronary syndromes.* ESC Congress 2019, 2019.
- 233. Chen, G., et al., Observations of Saharan dust microphysical and optical properties from the *Eastern Atlantic during NAMMA airborne field campaign*. Atmos. Chem. Phys., 2011. **11**(2): p. 723-740.
- 234. Hering, S.V. and P.H. McMurry, *Optical counter response to monodisperse atmospheric aerosols*. Atmospheric Environment. Part A. General Topics, 1991. **25**(2): p. 463-468.
- 235. Reid, J.S., et al., *Geometric/aerodynamic equivalent diameter ratios of ash aggregate aerosols collected in burning Kuwaiti well fields.* Atmospheric Environment, 1994. **28**(13): p. 2227-2234.
- 236. FEI, Tecnai G2 F20 High performance in S/TEM imaging and nanoanalysis. 2007.
- 237. Friedrich, J.O., N.K.J. Adhikari, and J. Beyene, *Ratio of geometric means to analyze continuous outcomes in meta-analysis: comparison to mean differences and ratio of arithmetic means using empiric data and simulation.* 2012. **31**(17): p. 1857-1886.
- 238. Georgiadis, P., et al., *Personal exposures to PM2.5 and polycyclic aromatic hydrocarbons and their relationship to environmental tobacco smoke at two locations in Greece*. Journal Of Exposure Analysis And Environmental Epidemiology, 2001. **11**: p. 169.
- 239. Spearman, C.J.T.A.j.o.p., *The proof and measurement of association between two things.* 1904. **15**(1): p. 72-101.
- 240. Wu, Z., et al., *Particle number size distribution in the urban atmosphere of Beijing, China.* Atmospheric Environment, 2008. **42**(34): p. 7967-7980.
- 241. Hussein, T., et al., *Urban aerosol number size distributions*. Atmos. Chem. Phys., 2004. **4**(2): p. 391-411.
- 242. Andronache, C., et al., *Scavenging of ultrafine particles by rainfall at a boreal site: observations and model estimations.* Atmospheric Chemistry and Physics Discussions, 2006. **6**(3): p. 3801-3844.

- 243. Venzac, H., et al., *Seasonal variation of aerosol size distributions in the free troposphere and residual layer at the puy de Dôme station, France.* Atmospheric Chemistry and Physics, 2009. **9**(4): p. 1465-1478.
- 244. Mejía, J.F., et al., *Trends in size classified particle number concentration in subtropical Brisbane, Australia, based on a 5 year study.* Atmospheric Environment, 2007. **41**(5): p. 1064-1079.
- 245. Aalto, P., et al., Aerosol Particle Number Concentration Measurements in Five European Cities Using TSI-3022 Condensation Particle Counter over a Three-Year Period during Health Effects of Air Pollution on Susceptible Subpopulations. Journal of the Air & Waste Management Association, 2005. **55**(8): p. 1064-1076.
- 246. Virtanen, A., et al., *Winter and summer time size distributions and densities of traffic-related aerosol particles at a busy highway in Helsinki.* Atmos. Chem. Phys., 2006. **6**(9): p. 2411-2421.
- 247. Dominick, D., et al., *Particle formation in a complex environment*. Atmosphere, 2019. **10**(5): p. 275.
- 248. Box, E.O., Vegetation analogs and differences in the Northern and Southern Hemispheres: A global comparison. Plant Ecology, 2002. **163**(2): p. 139-154.
- 249. Mitchell, R.M., B.W. Forgan, and S.K. Campbell, *The Climatology of Australian Aerosol*. Atmos. Chem. Phys., 2017. **17**(8): p. 5131-5154.
- 250. Kumar, M., et al., *Wintertime characteristics of aerosols at middle Indo-Gangetic Plain: Impacts of regional meteorology and long range transport.* Atmospheric Environment, 2015. **104**: p. 162-175.
- 251. Ren, Y., et al., Seasonal variation and size distribution of biogenic secondary organic aerosols at urban and continental background sites of China. Journal of Environmental Sciences, 2017.
- 252. Yang, M. and Z.L. Fleming, *Estimation of atmospheric total organic carbon (TOC) paving the path towards carbon budget closure.* Atmos. Chem. Phys., 2019. **19**(1): p. 459-471.
- 253. Chu, B., et al., Influence of metal-mediated aerosol-phase oxidation on secondary organic aerosol formation from the ozonolysis and OH-oxidation of α -pinene. Scientific reports, 2017. **7**: p. 40311.
- 254. Volkamer, R., et al., *Secondary organic aerosol formation from anthropogenic air pollution: Rapid and higher than expected.* Geophysical Research Letters, 2006. **33**(17): p. n/a-n/a.
- 255. Chu, B., et al., The remarkable effect of FeSO4 seed aerosols on secondary organic aerosol formation from photooxidation of α -pinene/NOx and toluene/NOx. Atmospheric Environment, 2012. **55**: p. 26-34.
- 256. Chu, B., et al., *Effects of two transition metal sulfate salts on secondary organic aerosol formation in toluene/NO x photooxidation.* Frontiers of Environmental Science & Engineering, 2013. **7**(1): p. 1-9.
- 257. Stevens, R. and A. Dastoor, *A Review of the Representation of Aerosol Mixing State in Atmospheric Models*. Atmosphere, 2019. **10**: p. 168.
- 258. Banerjee, A.N., V.C. Anitha, and S.W. Joo, *Improved electrochemical properties of morphology-controlled titania/titanate nanostructures prepared by in-situ hydrothermal surface modification of self-source Ti substrate for high-performance supercapacitors.* Scientific Reports, 2017. **7**(1): p. 13227.
- 259. Snider, G. and P. Ariya, *Photo-catalytic oxidation reaction of gaseous mercury over titanium dioxide nanoparticle surfaces*. Vol. 491. 2010. 23–28.
- 260. Coz, E., et al., *Characterization of fine primary biogenic organic aerosol in an urban area in the northeastern United States.* Atmospheric Environment, 2010. **44**(32): p. 3952-3962.
- 261. Buseck, P., et al., *Are black carbon and soot the same?* Atmospheric Chemistry and Physics Discussions, 2012. **12**(9): p. 24821-24846.
- 262. Rangel-Alvarado, R.B., et al., *Athabasca oil sands region snow contains efficient micron and nanosized ice nucleating particles.* Environmental Pollution, 2019. **252**: p. 289-295.

- 263. Shi, J.P., D. Mark, and R.M. Harrison, *Characterization of Particles from a Current Technology Heavy-Duty Diesel Engine.* Environmental Science & Technology, 2000. **34**(5): p. 748-755.
- 264. Rodríguez, S., et al., *A study on the relationship between mass concentrations, chemistry and number size distribution of urban fine aerosols in Milan, Barcelona and London.* Atmos. Chem. Phys., 2007. **7**(9): p. 2217-2232.
- 265. Wang, F., et al., *Particle number, particle mass and NO_xemission factors at a highway and an urban street in Copenhagen*. Atmos. Chem. Phys., 2010. **10**(6): p. 2745-2764.
- 266. Hama, S.M., et al., *Sub-micron particle number size distribution characteristics at two urban locations in Leicester.* Atmospheric Research, 2017. **194**: p. 1-16.
- 267. Putaud, J.-P., et al., A European aerosol phenomenology–3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe. Atmospheric Environment, 2010. **44**(10): p. 1308-1320.
- 268. von Bismarck-Osten, C., et al., *Characterization of parameters influencing the spatio-temporal variability of urban particle number size distributions in four European cities.* Atmospheric Environment, 2013. **77**(Supplement C): p. 415-429.
- 269. Stanier, C.O., A.Y. Khlystov, and S.N. Pandis, *Ambient aerosol size distributions and number concentrations measured during the Pittsburgh Air Quality Study (PAQS).* Atmospheric Environment, 2004. **38**(20): p. 3275-3284.
- 270. Kulmala, M., et al., On the growth of nucleation mode particles: source rates of condensable vapor in polluted and clean environments. Atmos. Chem. Phys., 2005. **5**(2): p. 409-416.
- 271. Ariya, P., et al., *Snow–a photobiochemical exchange platform for volatile and semi-volatile organic compounds with the atmosphere.* Environmental Chemistry, 2011. **8**(1): p. 62-73.
- 272. Schwarz, J.P., et al., *Black carbon aerosol size in snow*. Scientific Reports, 2013. **3**: p. 1356.
- 273. Darlington, T.K., et al., *Nanoparticle characteristics affecting environmental fate and transport through soil.* Environmental Toxicology and Chemistry, 2009. **28**(6): p. 1191-1199.
- 274. Chouvelon, T., et al., *Chemical contaminants (trace metals, persistent organic pollutants) in albacore tuna from western Indian and south-eastern Atlantic Oceans: Trophic influence and potential as tracers of populations.* Science of The Total Environment, 2017. **596-597**: p. 481-495.
- Coquet, S. and P.A. Ariya, *Kinetics of the gas-phase reactions of Cl atom with selected C2–C5 unsaturated hydrocarbons at 283< T< 323 K.* International Journal of Chemical Kinetics, 2000.
 32(8): p. 478-484.
- 276. Sherwen, T., et al., *Effects of halogens on European air-quality*. Faraday Discussions, 2017. **200**(0): p. 75-100.
- 277. Ariya, P.A., et al., *Polar sunrise experiment 1995: hydrocarbon measurements and tropospheric Cl and Br-atoms chemistry.* Atmospheric Environment, 1999. **33**(6): p. 931-938.
- 278. Ryzhkov, A.B. and P.A. Ariya, *A theoretical study of the reactions of carbonyl oxide with water in atmosphere: The role of water dimer.* Chemical physics letters, 2003. **367**(3): p. 423-429.
- Ariya, P.A., et al., Mercury physicochemical and biogeochemical transformation in the atmosphere and at atmospheric interfaces: A review and future directions. Chemical reviews, 2015. 115(10): p. 3760-3802.
- 280. Zaveri, R.A., et al., *Particle-resolved simulation of aerosol size, composition, mixing state, and the associated optical and cloud condensation nuclei activation properties in an evolving urban plume.* 2010. **115**(D17).
- 281. Ryan Hall, O.N., Evguenia Nepotchatyk, and Parisa A. Ariya *Anthropogenic Photolabile Chlorine in the Cold-Climate City of Montreal*. Atmosphere, 2020. **11**(8).
- 282. Kolb, C.E. and D.R. Worsnop, *Chemistry and Composition of Atmospheric Aerosol Particles*. 2012. **63**(1): p. 471-491.

- 283. Fuzzi, S., et al., *Particulate matter, air quality and climate: lessons learned and future needs.* Atmos. Chem. Phys., 2015. **15**(14): p. 8217-8299.
- 284. Murphy, D.M., *Something in the air*. Science, 2005. **307**(5717): p. 1888-1890.
- 285. Carslaw, K., et al., *Large contribution of natural aerosols to uncertainty in indirect forcing*. Nature, 2013. **503**(7474): p. 67.
- 286. Stevens, B. and G. Feingold, *Untangling aerosol effects on clouds and precipitation in a buffered system.* Nature, 2009. **461**(7264): p. 607.
- 287. Deguillaume, L., et al., *Microbiology and atmospheric processes: chemical interactions of primary biological aerosols.* Biogeosciences, 2008. **5**(4): p. 1073-1084.
- 288. Prather, K.A., C.C. Wang, and R.T. Schooley, *Reducing transmission of SARS-CoV-2*. Science, 2020: p. eabc6197.
- 289. Comber, L., et al., *Airborne transmission of SARS-CoV-2 via aerosols*. Reviews in Medical Virology, 2021. **31**(3): p. e2184.
- 290. Chen, B., P. Jia, and J. Han, *Role of indoor aerosols for COVID-19 viral transmission: a review*. Environmental Chemistry Letters, 2021. **19**(3): p. 1953-1970.
- 291. Williamson, C.J., et al., *A large source of cloud condensation nuclei from new particle formation in the tropics*. Nature, 2019. **574**(7778): p. 399-403.
- 292. Yli-Juuti, T., C. Mohr, and I. Riipinen, *Open questions on atmospheric nanoparticle growth*. Communications Chemistry, 2020. **3**(1): p. 106.
- 293. Vortisch, H., et al., *Homogeneous freezing nucleation rates and crystallization dynamics of single levitated sulfuric acid solution droplets.* Physical Chemistry Chemical Physics, 2000. **2**(7): p. 1407-1413.
- 294. Zheng, F., *Thermophoresis of spherical and non-spherical particles: a review of theories and experiments.* Advances in colloid interface science, 2002. **97**(1-3): p. 255-278.
- 295. Martin, S.T., *Phase transitions of aqueous atmospheric particles*. Chemical Reviews, 2000. **100**(9): p. 3403-3454.
- 296. Christian, P., et al., *Nanoparticles: structure, properties, preparation and behaviour in environmental media.* Ecotoxicology, 2008. **17**(5): p. 326-343.
- 297. Huang, Y., et al., *Coexistence of three liquid phases in individual atmospheric aerosol particles.* Proceedings of the National Academy of Sciences, 2021. **118**(16): p. e2102512118.
- 298. Won, R., *Eyes on super-resolution*. Nature Photonics, 2009. **3**(7): p. 368-369.
- 299. Zhuang, X., *Nano-imaging with STORM*. Nature Photonics, 2009. **3**(7): p. 365-367.
- 300. Betzig, E. and R.J. Chichester, *Single Molecules Observed by Near-Field Scanning Optical Microscopy*. Science, 1993. **262**(5138): p. 1422.
- 301. de Lange, F., et al., *Cell biology beyond the diffraction limit: near-field scanning optical microscopy*. J Cell Sci, 2001. **114**(Pt 23): p. 4153-60.
- 302. Ozcan, A., et al., *Differential near-field scanning optical microscopy*. Nano letters, 2006. **6**(11): p. 2609-2616.
- 303. Huang, F.M. and N.I. Zheludev, *Super-resolution without evanescent waves.* Nano letters, 2009. **9**(3): p. 1249-1254.
- 304. Huang, B., H. Babcock, and X. Zhuang, *Breaking the diffraction barrier: super-resolution imaging of cells.* Cell, 2010. **143**(7): p. 1047-1058.
- 305. Kner, P., et al., *Super-resolution video microscopy of live cells by structured illumination*. Nature methods, 2009. **6**(5): p. 339-342.
- 306. Ebenstein, Y., E. Nahum, and U. Banin, *Tapping mode atomic force microscopy for nanoparticle sizing: tip– sample interaction effects.* Nano Letters, 2002. **2**(9): p. 945-950.

- 307. Feinstone, S.M., A.Z. Kapikian, and R.H. Purcell, *Hepatitis A: detection by immune electron microscopy of a viruslike antigen associated with acute illness.* Science, 1973. **182**(4116): p. 1026-1028.
- 308. Hong, X., et al., *Background-free detection of single 5 nm nanoparticles through interferometric cross-polarization microscopy*. Nano letters, 2011. **11**(2): p. 541-547.
- 309. Liu, W., et al., *Breaking the Axial Diffraction Limit: A Guide to Axial Super-Resolution Fluorescence Microscopy.* Laser & Photonics Reviews, 2018. **12**(8): p. 1700333.
- 310. Mudanyali, O., et al., *Wide-field optical detection of nanoparticles using on-chip microscopy and self-assembled nanolenses.* Nature Photonics, 2013. **7**(3): p. 247-254.
- 311. Ray, A., et al., *Holographic detection of nanoparticles using acoustically actuated nanolenses*. Nature Communications, 2020. **11**(1): p. 171.
- 312. Warnasooriya, N., et al., *Imaging gold nanoparticles in living cell environments using heterodyne digital holographic microscopy*. Optics express, 2010. **18**(4): p. 3264-3273.
- 313. Murphy, D.B., *Fundamentals of light microscopy and electronic imaging*. 2002: John Wiley & Sons.
- 314. Tian, L., et al., *Computational illumination for high-speed in vitro Fourier ptychographic microscopy*. Optica, 2015. **2**(10): p. 904-911.
- 315. Horstmeyer, R., et al., *Diffraction tomography with Fourier ptychography.* Optica, 2016. **3**(8): p. 827-835.
- Jeong, H.-j., H. Yoo, and D. Gweon, *High-speed 3-D measurement with a large field of view based on direct-view confocal microscope with an electrically tunable lens.* Optics express, 2016. 24(4): p. 3806-3816.
- 317. imaging, D.i., *Desktop Microscope User Guide*. 2018.
- 318. Garcia-Sucerquia, J., et al., *Digital in-line holographic microscopy*. Applied optics, 2006. **45**(5): p. 836-850.
- 319. Kreuzer, H.J., US. Patent 6411406 B1, Canadian Patent CA 2376395. 2002.
- 320. Berg, M.J. and S. Holler, *Simultaneous holographic imaging and light-scattering pattern measurement of individual microparticles.* Optics letters, 2016. **41**(14): p. 3363-3366.
- 321. Barnes, M.D., et al., A CCD based approach to high-precision size and refractive index determination of levitated microdroplets using Fraunhofer diffraction. Review of Scientific Instruments, 1997. **68**(6): p. 2287-2291.
- 322. Steimer, S.S., et al., *Electrodynamic balance measurements of thermodynamic, kinetic, and optical aerosol properties inaccessible to bulk methods.* Atmos. Meas. Tech., 2015. **8**(6): p. 2397-2408.
- 323. Carruthers, A.E., et al., *Selection and characterization of aerosol particle size using a bessel beam optical trap for single particle analysis.* Physical Chemistry Chemical Physics, 2012. **14**(19): p. 6741-6748.
- 324. David, G., et al., *Digital holography of optically-trapped aerosol particles.* Communications Chemistry, 2018. **1**(1): p. 46.
- 325. Xu, W., et al., *Digital in-line holography of microspheres*. Applied Optics, 2002. **41**(25): p. 5367-5375.
- 326. Davies, N.W., et al., *Evaluating biases in filter-based aerosol absorption measurements using photoacoustic spectroscopy.* Atmos. Meas. Tech., 2019. **12**(6): p. 3417-3434.
- 327. Mudanyali, O., W. Bishara, and A. Ozcan, *Lensfree super-resolution holographic microscopy using wetting films on a chip.* Optics express, 2011. **19**(18): p. 17378-17389.
- 328. Dholakia, K., Spalding, G., & MacDonald, M., *Optical tweezers: The next generation.* Physics World, 2002. **15(10)**: p. 31-35.
- 329. Rafferty, A., et al., *Optical deformation of single aerosol particles*. Proceedings of the National Academy of Sciences, 2019. **116**(40): p. 19880-19886.

- 330. Prodi, F., et al., *Digital holography for observing aerosol particles undergoing Brownian motion in microgravity conditions.* Atmospheric research, 2006. **82**(1-2): p. 379-384.
- 331. Berg, M.J. and G. Videen, *Digital holographic imaging of aerosol particles in flight.* Journal of Quantitative Spectroscopy Radiative Transfer, 2011. **112**(11): p. 1776-1783.
- 332. Kemppinen, O., et al., *Imaging atmospheric aerosol particles from a UAV with digital holography*. Scientific Reports, 2020. **10**(1): p. 16085.
- 333. Bianco, V., et al. *Looking beyond Smoke and Flames by Lensless Infrared Digital Holography*. in *Fringe 2013*. 2014. Berlin, Heidelberg: Springer Berlin Heidelberg.
- 334. Kim, J., T. Go, and S.J. Lee, *Volumetric monitoring of airborne particulate matter concentration using smartphone-based digital holographic microscopy and deep learning.* Journal of Hazardous Materials, 2021. **418**: p. 126351.
- 335. Wu, Y.-C., et al., *Air quality monitoring using mobile microscopy and machine learning.* Light: Science & Applications, 2017. **6**(9): p. e17046-e17046.
- 336. Xu, W., et al., *Digital in-line holography for biological applications*. Proceedings of the National Academy of Sciences, 2001. **98**(20): p. 11301-11305.
- 337. Brunnhofer, G., et al., *Design and Validation of a Holographic Particle Counter*. Sensors (Basel, Switzerland), 2019. **19**(22): p. 4899.
- 338. Laning, J.C. and M.J. Berg, *Orthographic imaging of free-flowing aerosol particles*. OSA Continuum, 2019. **2**(12): p. 3514-3520.
- 339. Bishara, W., et al., *Holographic pixel super-resolution in portable lensless on-chip microscopy using a fiber-optic array*. Lab on a Chip, 2011. **11**(7): p. 1276-1279.
- 340. Latychevskaia, T. and H.-W. Fink, *Holographic time-resolved particle tracking by means of threedimensional volumetric deconvolution.* Optics Express, 2014. **22**(17): p. 20994-21003.
- 341. Latychevskaia, T. and H.-W. Fink, *Resolution enhancement in in-line holography by numerical compensation of vibrations*. Optics express, 2017. **25**(17): p. 20109-20124.
- 342. imaging, D.i., *Octopus Software User Guide*. Copyright © 4Deep inwater imaging 2018, 2018.
- 343. imaging, D.i., *Stingray Software User Guide*. Copyright © 4Deep inwater imaging 2018, 2018.
- 344. Nickerson, B.S. and H.J. Kreuzer, *Deconvolution for digital in-line holographic microscopy*. Advanced Optical Technologies, 2013. **2**(4): p. 337-344.
- 345. Jericho, S., et al., *Submersible digital in-line holographic microscope.* Review of scientific instruments, 2006. **77**(4): p. 043706.
- 346. Jericho, M.H., et al., *Quantitative phase and refractive index measurements with point-source digital in-line holographic microscopy.* Applied Optics, 2012. **51**(10): p. 1503-1515.
- 347. Jericho, M.H. and H.J. Kreuzer, *Point source digital in-line holographic microscopy*, in *Coherent Light Microscopy*. 2011, Springer. p. 3-30.
- 348. Latychevskaia, T., F. Gehri, and H.-W. Fink, *Depth-resolved holographic reconstructions by threedimensional deconvolution.* Optics Express, 2010. **18**(21): p. 22527-22544.
- 349. Kanka, M., R. Riesenberg, and H.J. Kreuzer, *Reconstruction of high-resolution holographic microscopic images.* Optics Letters, 2009. **34**(8): p. 1162-1164.
- 350. Micó, V., et al., *Superresolution digital holographic microscopy for three-dimensional samples*. Optics Express, 2008. **16**(23): p. 19260-19270.
- 351. Nazarenko, Y., et al., *Novel aerosol analysis approach for characterization of nanoparticulate matter in snow*. Environmental Science and Pollution Research, 2017. **24**(5): p. 4480-4493.
- 352. Xu, W., et al., *Tracking particles in four dimensions with in-line holographic microscopy*. Optics Letters, 2003. **28**(3): p. 164-166.
- 353. Mary Ann Clark, J.C., and Matthew Douglas, *OpenStax Biology 2nd Edition, Biology 2e.* 2018.

- 354. Henneberger, J., et al., *HOLIMO II: a digital holographic instrument for ground-based in situ observations of microphysical properties of mixed-phase clouds*. Atmos. Meas. Tech., 2013. **6**(11): p. 2975-2987.
- 355. Dixon, L., F.C. Cheong, and D.G. Grier, *Holographic deconvolution microscopy for high-resolution particle tracking*. Optics Express, 2011. **19**(17): p. 16410-16417.
- 356. Maciel, D., et al., *Quantitative phase measurements of tendon collagen fibres*. J Biophotonics, 2017. **10**(1): p. 111-117.
- 357. Ashkin, A., J.M. Dziedzic, and T. Yamane, *Optical trapping and manipulation of single cells using infrared laser beams*. Nature, 1987. **330**(6150): p. 769-771.
- 358. Knöner, G., et al., *Measurement of the index of refraction of single microparticles.* Physical review letters, 2006. **97**(15): p. 157402.
- 359. Hart, S.J. and A.V. Terray, *Refractive-index-driven separation of colloidal polymer particles using optical chromatography.* Applied Physics Letters, 2003. **83**(25): p. 5316-5318.
- 360. Kudo, H., et al., Novel Materials for Large Change in Refractive Index: Synthesis and Photochemical Reaction of the Ladderlike Poly(silsesquioxane) Containing Norbornadiene, Azobenzene, and Anthracene Groups in the Side Chains. Macromolecules, 2006. **39**(5): p. 1759-1765.
- 361. Lu, J.W., et al., *Low-temperature Bessel beam trap for single submicrometer aerosol particle studies.* Rev Sci Instrum, 2014. **85**(9): p. 095107.
- 362. Davis, R.D., et al., Long Working-Distance Optical Trap for in Situ Analysis of Contact-Induced Phase Transformations. Analytical Chemistry, 2015. **87**(12): p. 6186-6194.
- 363. Lee, S., et al., *Multiple pathways of crystal nucleation in an extremely supersaturated aqueous potassium dihydrogen phosphate (KDP) solution droplet.* Proceedings of the National Academy of Sciences, 2016. **113**(48): p. 13618-13623.
- 364. Cremer, J.W., et al., *Photoacoustics of single laser-trapped nanodroplets for the direct observation of nanofocusing in aerosol photokinetics.* Nature communications, 2016. **7**: p. 10941.
- 365. Kanka, M., et al., *High resolution (NA=0.8) in lensless in-line holographic microscopy with glass sample carriers.* Optics Letters, 2011. **36**(18): p. 3651-3653.
- 366. McLeod, E., et al., *High-Throughput and Label-Free Single Nanoparticle Sizing Based on Time-Resolved On-Chip Microscopy*. ACS Nano, 2015. **9**(3): p. 3265-3273.
- 367. McLeod, E., et al., *Tunable Vapor-Condensed Nanolenses*. ACS Nano, 2014. **8**(7): p. 7340-7349.
- 368. Greenbaum, A., et al., *Increased space-bandwidth product in pixel super-resolved lensfree on-chip microscopy*. Scientific Reports, 2013. **3**(1): p. 1717.
- 369. Wong, A., et al., *Bayesian-based aberration correction and numerical diffraction for improved lensfree on-chip microscopy of biological specimens*. Optics Letters, 2015. **40**(10): p. 2233-2236.
- 370. Tippie, A.E., A. Kumar, and J.R. Fienup, *High-resolution synthetic-aperture digital holography with digital phase and pupil correction.* Optics Express, 2011. **19**(13): p. 12027-12038.
- 371. Germann, M., et al., *Pulsed electron holography.* Applied Physics Letters, 2013. **102**(20): p. 203115.
- 372. Morawska, L., et al., *The physics of respiratory particle generation, fate in the air, and inhalation*. Nature Reviews Physics, 2022. **4**(11): p. 723-734.
- 373. Arnaout, R., et al., SARS-CoV2 Testing: The Limit of Detection Matters. bioRxiv, 2020.
- 374. prevention, C.f.d.c.a., *Scientific Brief: SARS-CoV-2 Transmission*. Updated May 7, 2021.
- 375. Stadnytskyi, V., et al., *The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission*. Proceedings of the National Academy of Sciences, 2020. **117**(22): p. 11875-11877.
- 376. Edwards, D.A., et al., *Exhaled aerosol increases with COVID-19 infection, age, and obesity.* 2021. **118**(8): p. e2021830118.

- 377. Kutter, J.S., et al., SARS-CoV and SARS-CoV-2 are transmitted through the air between ferrets over more than one meter distance. 2021. **12**(1): p. 1-8.
- 378. Shi, J., et al., Susceptibility of ferrets, cats, dogs, and other domesticated animals to SARS– coronavirus 2. 2020. **368**(6494): p. 1016-1020.
- 379. Cheng, V.C.-C., et al., *Outbreak investigation of airborne transmission of Omicron (B.1.1.529) SARS-CoV-2 variant of concern in a restaurant: Implication for enhancement of indoor air dilution.* Journal of Hazardous Materials, 2022. **430**: p. 128504.
- 380. Adhikari, S.P., et al., *Epidemiology, causes, clinical manifestation and diagnosis, prevention and control of coronavirus disease (COVID-19) during the early outbreak period: a scoping review.* Infect Dis Poverty, 2020. **9**(1): p. 29.
- 381. Liu, Y., et al., *Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals*. Nature, 2020. **582**(7813): p. 557-560.
- 382. Huang, Y., et al., *SARS-CoV-2 viral load in clinical samples from critically ill patients*. American journal of respiratory and critical care medicine, 2020. **201**(11): p. 1435-1438.
- 383. Ge, Y., et al., *COVID-19 Transmission Dynamics Among Close Contacts of Index Patients With COVID-19: A Population-Based Cohort Study in Zhejiang Province, China.* JAMA Internal Medicine, 2021. **181**(10): p. 1343-1350.
- 384. Buonanno, G., L. Morawska, and L. Stabile, *Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications.* Environ Int, 2020. **145**: p. 106112.
- 385. Ontario), O.A.f.H.P.a.P.P.H., *COVID-19 Transmission through Short and Long-Range Respiratory Particles.* Toronto, ON: Queen's Printer for Ontario, 2022.
- 386. Arumuru, V., S.S. Samantaray, and J. Pasa, *Double masking protection vs. comfort-A quantitative assessment*. Phys Fluids (1994), 2021. **33**(7): p. 077120.
- 387. Leech, G., et al., *Mask wearing in community settings reduces SARS-CoV-2 transmission.* 2022. **119**(23): p. e2119266119.
- 388. Howard, J., et al., An evidence review of face masks against COVID-19. 2021. **118**(4): p. e2014564118.
- 389. Singh, B., et al., *A comprehensive review on current COVID-19 detection methods: From lab care to point of care diagnosis.* Sensors International, 2021. **2**: p. 100119.
- 390. Bhardwaj, J., et al., *Recent advancements in the measurement of pathogenic airborne viruses*. Journal of Hazardous Materials, 2021. **420**: p. 126574.
- 391. Lukose, J., S. Chidangil, and S.D. George, *Optical technologies for the detection of viruses like COVID-19: Progress and prospects.* Biosensors and Bioelectronics, 2021. **178**: p. 113004.
- 392. Verreault, D., S. Moineau, and C. Duchaine, *Methods for sampling of airborne viruses*. Microbiol Mol Biol Rev, 2008. **72**(3): p. 413-44.
- 393. Pan, M., J.A. Lednicky, and C.Y. Wu, *Collection, particle sizing and detection of airborne viruses*. Journal of applied microbiology, 2019. **127**(6): p. 1596-1611.
- 394. Mainelis, G., *Bioaerosol sampling: Classical approaches, advances, and perspectives.* Aerosol Science and Technology, 2020. **54**(5): p. 496-519.
- 395. Shi, Y., et al., On-Chip Optical Detection of Viruses: A Review. Advanced Photonics Research, 2021.
 2(4): p. 2000150.
- 396. Johnson, T.J., et al., *Viral load of SARS-CoV-2 in droplets and bioaerosols directly captured during breathing, speaking and coughing.* Scientific Reports, 2022. **12**(1): p. 3484.
- 397. Burge, H.A., *Bioaerosols*. Published February 22, 1995 by CRC Press, 1995. **1 edition**(ISBN 9780873717243): p. 332.
- 398. Ariya, P., et al., *Microbiological degradation of organic compounds in the atmosphere*. 2002. **29**: p. 341-344.

- 399. Oswin, H.P., et al., *The dynamics of SARS-CoV-2 infectivity with changes in aerosol microenvironment.* 2022. **119**(27): p. e2200109119.
- 400. Kreuzer, H.J., *HOLOGRAPHIC MICROSCOPE AND METHOD OF HOLOGRAM RECONSTRUCTION.* US. Patent 6411406 B1, Canadian Patent CA 2376395, 2002.
- 401. Pal, D., et al., *Advancing the science of dynamic airborne nanosized particles using Nano-DIHM.* Communications Chemistry, 2021. **4**(1): p. 170.
- 402. Syngouna, V.I., C.V.J.C. Chrysikopoulos, and S.B. Biointerfaces, *Bacteriophage MS2 and titanium dioxide heteroaggregation: Effects of ambient light and the presence of quartz sand.* 2019. **180**: p. 281-288.
- 403. Pan, M., et al., *Determination of the distribution of infectious viruses in aerosol particles using water-based condensational growth technology and a bacteriophage MS2 model.* Aerosol Science and Technology, 2019. **53**(5): p. 583-593.
- 404. Monninger, M.K., et al., *Preparation of viral samples within biocontainment for ultrastructural analysis: Utilization of an innovative processing capsule for negative staining.* Journal of Virological Methods, 2016. **238**: p. 70-76.
- 405. Bhardwaj, J., M.-W. Kim, and J. Jang, *Rapid Airborne Influenza Virus Quantification Using an Antibody-Based Electrochemical Paper Sensor and Electrostatic Particle Concentrator.* Environmental Science & Technology, 2020. **54**(17): p. 10700-10712.
- 406. Oswin, H.P., et al., *Measuring stability of virus in aerosols under varying environmental conditions*. Aerosol Science and Technology, 2021. **55**(12): p. 1315-1320.
- 407. Duffy, S., L.A. Shackelton, and E.C.J.N.R.G. Holmes, *Rates of evolutionary change in viruses: patterns and determinants.* 2008. **9**(4): p. 267-276.
- 408. Laue, M., et al., *Morphometry of SARS-CoV and SARS-CoV-2 particles in ultrathin plastic sections of infected Vero cell cultures.* Scientific Reports, 2021. **11**(1): p. 3515.
- 409. Hall, R., D. Pal, and P.A. Ariya, *Novel Dynamic Technique, Nano-DIHM, for Rapid Detection of Oil, Heavy Metals, and Biological Spills in Aquatic Systems.* Analytical Chemistry, 2022. **94**(32): p. 11390-11400.
- 410. Liu, K., et al., *Peering inside a cough or sneeze to explain enhanced airborne transmission under dry weather.* 2021. **11**(1): p. 1-9.
- 411. Bourouiba, L.J.J., *Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of COVID-19*. 2020. **323**(18): p. 1837-1838.
- 412. El Hassan, M., et al., A review on the transmission of COVID-19 based on cough/sneeze/breath flows. 2022. **137**(1): p. 1.
- 413. Harvey, W.T., et al., *SARS-CoV-2 variants, spike mutations and immune escape*. Nature Reviews Microbiology, 2021. **19**(7): p. 409-424.
- 414. Mondeja, B., et al., *SARS-CoV-2: preliminary study of infected human nasopharyngeal tissue by high resolution microscopy*. Virology Journal, 2021. **18**(1): p. 149.
- 415. Chia, P.Y., et al., *Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients*. Nature communications, 2020. **11**(1): p. 1-7.
- 416. Wrapp, D., et al., *Cryo-EM structure of the 2019-nCoV spike in the prefusion conformation*. Science, 2020. **367**(6483): p. 1260-1263.
- 417. Korber, B., et al., *Tracking changes in SARS-CoV-2 spike: evidence that D614G increases infectivity of the COVID-19 virus.* 2020. **182**(4): p. 812-827. e19.
- 418. Drake, J.W.J.A.o.t.N.Y.A.o.S., *The distribution of rates of spontaneous mutation over viruses, prokaryotes, and eukaryotes.* 1999. **870**(1): p. 100-107.
- 419. Rodó, X., et al., *Changing climate and the COVID-19 pandemic: more than just heads or tails.* Nature Medicine, 2021. **27**(4): p. 576-579.

- 420. Coluzza, I., et al., *Perspectives on the future of ice nucleation research: research needs and unanswered questions identified from two international workshops.* Atmosphere, 2017. **8**(8): p. 138.
- 421. Kanji, Z.A. and J.P.D. Abbatt, *The University of Toronto Continuous Flow Diffusion Chamber (UT-CFDC): A Simple Design for Ice Nucleation Studies.* Aerosol Science and Technology, 2009. **43**(7): p. 730-738.
- 422. Baumgardner, D., et al., *Cloud Ice Properties: In Situ Measurement Challenges %J Meteorological Monographs.* 2017. **58**: p. 9.1-9.23.
- 423. Cantrell, W. and A. Heymsfield, *Production of Ice in Tropospheric Clouds: A Review %J Bulletin of the American Meteorological Society.* 2005. **86**(6): p. 795-808.
- 424. French, J.R., et al., *Precipitation formation from orographic cloud seeding*. 2018. **115**(6): p. 1168-1173.
- 425. Schaefer, V.J.J.S., *The production of ice crystals in a cloud of supercooled water droplets.* 1946. **104**(2707): p. 457-459.
- 426. Prenni, A.J., et al., *Relative roles of biogenic emissions and Saharan dust as ice nuclei in the Amazon basin.* 2009. **2**(6): p. 402-405.
- 427. Zhao, B., et al., *Ice nucleation by aerosols from anthropogenic pollution*. 2019. **12**(8): p. 602-607.
- 428. Stopelli, E., et al., *Ice nucleation active particles are efficiently removed by precipitating clouds.* Scientific Reports, 2015. **5**(1): p. 16433.
- 429. Choi, Y.-S., et al., *Space observations of cold-cloud phase change*. 2010. **107**(25): p. 11211-11216.
- 430. DeMott, P.J., et al., *The Fifth International Workshop on Ice Nucleation phase 2 (FIN-02): laboratory intercomparison of ice nucleation measurements.* Atmos. Meas. Tech., 2018. **11**(11): p. 6231-6257.
- 431. Hiranuma, N., et al., A comprehensive laboratory study on the immersion freezing behavior of illite NX particles: a comparison of 17 ice nucleation measurement techniques. 2015. **15**(5): p. 2489-2518.
- 432. Rangel-Alvarado, R., *Nanosized Particles in North American Snow: Physicochemical Properties of Efficient Ice Nucleating Particles*. 2019, McGill University Libraries.
- 433. imaging, D.i., *Desktop Microscope User Guide*. Copyright © 4Deep inwater imaging 2017, 2017.
- 434. Murphy, D.M., T.J.Q.J.o.t.R.M.S.A.j.o.t.a.s. Koop, applied meteorology, and p. oceanography, *Review of the vapour pressures of ice and supercooled water for atmospheric applications.* 2005. **131**(608): p. 1539-1565.
- 435. Zhang, J., et al., *Preparation of nano-silver iodide powders and their efficiency as ice-nucleating agent in weather modification.* Advanced Powder Technology, 2011. **22**(5): p. 613-616.
- 436. Rissman, T.A., et al., *Cloud condensation nucleus (CCN) behavior of organic aerosol particles generated by atomization of water and methanol solutions.* Atmos. Chem. Phys., 2007. **7**(11): p. 2949-2971.
- 437. Giebl, H., et al., *CCN activation of oxalic and malonic acid test aerosols with the University of Vienna cloud condensation nuclei counter.* Journal of Aerosol Science, 2002. **33**(12): p. 1623-1634.
- 438. Kuwata, M. and Y. Kondo, *Measurements of particle masses of inorganic salt particles for calibration of cloud condensation nuclei counters*. Atmos. Chem. Phys., 2009. **9**(16): p. 5921-5932.
- 439. Rose, D., et al., Calibration and measurement uncertainties of a continuous-flow cloud condensation nuclei counter (DMT-CCNC): CCN activation of ammonium sulfate and sodium chloride aerosol particles in theory and experiment. Atmos. Chem. Phys., 2008. **8**(5): p. 1153-1179.
- 440. Yüce, M. and A.J.T.E.P.J.B. Demirel, *The effect of nanoparticles on the surface hydrophobicity of polystyrene*. 2008. **64**: p. 493-497.

- 441. Wang, Z., N.K. Saadé, and P.A. Ariya, *Advances in Ultra-Trace Analytical Capability for Micro/Nanoplastics and Water-Soluble Polymers in the Environment: Fresh Falling Urban Snow.* Environmental Pollution, 2021. **276**: p. 116698.
- 442. Henneberger, J., et al., *HOLIMO II: a digital holographic instrument for ground-based in situ observations of microphysical properties of mixed-phase clouds.* Atmospheric Measurement Techniques, 2013. **6**(11): p. 2975-2987.
- 443. Wang, Z., et al., *In-situ and real-time nano/microplastic coatings and dynamics in water using nano-DIHM: A novel capability for the plastic life cycle research.* Water Research, 2023. **235**: p. 119898.
- 444. Ullrich, R., et al., *A New Ice Nucleation Active Site Parameterization for Desert Dust and Soot.* Journal of the Atmospheric Sciences, 2017. **74**(3): p. 699-717.
- 445. Paasonen, P., et al., *Warming-induced increase in aerosol number concentration likely to moderate climate change*. Nature Geoscience, 2013. **6**(6): p. 438-442.
- 446. Kahn, R.A., et al., SAM-CAAM: a concept for acquiring systematic aircraft measurements to characterize aerosol air masses. 2017. **98**(10): p. 2215-2228.
- 447. Beckerman, B., et al., *Correlation of nitrogen dioxide with other traffic pollutants near a major expressway*. Atmospheric Environment, 2008. **42**(2): p. 275-290.
- 448. Sabaliauskas, K., et al., *Five-year roadside measurements of ultrafine particles in a major Canadian city*. Atmospheric Environment, 2012. **49**: p. 245-256.
- 449. Ruuskanen, J., et al., *Concentrations of ultrafine, fine and PM2.5 particles in three European cities.* Atmospheric Environment, 2001. **35**(21): p. 3729-3738.
- 450. Väkevä, M., et al., *Effects of meteorological processes on aerosol particle size distribution in an urban background area*. Journal of Geophysical Research: Atmospheres, 2000. **105**(D8): p. 9807-9821.
- 451. Ondráček, J., et al., *Contribution of the road traffic to air pollution in the Prague city (busy speedway and suburban crossroads).* Atmospheric environment, 2011. **45**(29): p. 5090-5100.
- 452. Gramsch, E., et al., *Predominance of soot-mode ultrafine particles in Santiago de Chile: Possible sources.* Atmospheric Environment, 2009. **43**(14): p. 2260-2267.
- 453. Agus, E.L., et al., *Factors influencing particle number concentrations, size distributions and modal parameters at a roof-level and roadside site in Leicester, UK.* Science of the Total Environment, 2007. **386**(1): p. 65-82.
- 454. Weber, S., *Spatio-temporal covariation of urban particle number concentration and ambient noise.* Atmospheric Environment, 2009. **43**(34): p. 5518-5525.
- 455. Puustinen, A., et al., *Spatial variation of particle number and mass over four European cities*. Atmospheric Environment, 2007. **41**(31): p. 6622-6636.
- 456. Roth, E., et al., *Size distributions of fine and ultrafine particles in the city of Strasbourg: Correlation between number of particles and concentrations of NOx and SO 2 gases and some soluble ions concentration determination.* Journal of Environmental Management, 2008. **86**(1): p. 282-290.
- 457. Wehner, B. and A. Wiedensohler, *Long term measurements of submicrometer urban aerosols: statistical analysis for correlations with meteorological conditions and trace gases.* Atmos. Chem. Phys., 2003. **3**(3): p. 867-879.
- 458. imaging, D.i., *Stingray Software User Guide*. 2018.
- 459. imaging, D.i., Octopus Software User Guide. 2018.
- 460. Binder, R.A., et al., *Environmental and aerosolized severe acute respiratory syndrome coronavirus* 2 among hospitalized coronavirus disease 2019 patients. The Journal of infectious diseases, 2020. **222**(11): p. 1798-1806.
- 461. Santarpia, J.L., et al., *The Infectious Nature of Patient-Generated SARS-CoV-2 Aerosol. medRxiv* 2020.07. 13.20041632. Retrieved from doi: <u>https://doi</u>. org/10.1101/2020.07, 2020. **13**.

- 462. Dumont-Leblond, N., et al., *Low incidence of airborne SARS-CoV-2 in acute care hospital rooms with optimized ventilation.* Emerging microbes & infections, 2020. **9**(1): p. 2597-2605.
- 463. Ismail, A.M. and A.A. Elfiky, *SARS-CoV-2 spike behavior in situ: a Cryo-EM images for a better understanding of the COVID-19 pandemic.* Signal Transduction and Targeted Therapy, 2020. **5**(1): p. 252.
- 464. Corman, V.M., et al., *Detection of 2019 novel coronavirus (2019-nCoV) by real-time RT-PCR*. Eurosurveillance, 2020. **25**(3): p. 2000045.
- 465. Krüttgen, A., et al., *Comparison of the SARS-CoV-2 Rapid antigen test to the real star Sars-CoV-2 RT PCR kit.* Journal of virological methods, 2021. **288**: p. 114024.
- 466. Lassaunière, R., et al., *Evaluation of nine commercial SARS-CoV-2 immunoassays.* MedRxiv, 2020.
- 467. Zhang, F., O.O. Abudayyeh, and J.S. Gootenberg, *A protocol for detection of COVID-19 using CRISPR diagnostics*. A protocol for detection of COVID-19 using CRISPR diagnostics, 2020. **8**.
- 468. Broughton, J.P., et al., *CRISPR–Cas12-based detection of SARS-CoV-2*. Nature biotechnology, 2020. **38**(7): p. 870-874.
- 469. Seo, G., et al., *Rapid detection of COVID-19 causative virus (SARS-CoV-2) in human nasopharyngeal swab specimens using field-effect transistor-based biosensor.* ACS nano, 2020. **14**(4): p. 5135-5142.
- 470. Mavrikou, S., et al., *Development of a portable, ultra-rapid and ultra-sensitive cell-based biosensor* for the direct detection of the SARS-CoV-2 S1 spike protein antigen. Sensors, 2020. **20**(11): p. 3121.
- 471. Qiu, G., et al., *Dual-functional plasmonic photothermal biosensors for highly accurate severe acute respiratory syndrome coronavirus 2 detection.* ACS nano, 2020. **14**(5): p. 5268-5277.
- 472. Yan, R., et al., *Structural basis for the recognition of SARS-CoV-2 by full-length human ACE2.* Science, 2020. **367**(6485): p. 1444-1448.
- 473. Jinglin, H., et al., Detection of spike protein of SARS-CoV-2 by surface enhanced Raman spectroscopy. 强激光与粒子束, 2020. **32**(6): p. 069001-1-069001-2.
- 474. Editors, B.W., *Optical method could cut Coronavirus diagnosis time to 15 minutes.* 2020.
- 475. Wang, Q., et al., *Structural and functional basis of SARS-CoV-2 entry by using human ACE2.* Cell, 2020. **181**(4): p. 894-904. e9.
- 476. Shang, J., et al., *Structural basis of receptor recognition by SARS-CoV-2*. Nature, 2020. **581**(7807): p. 221-224.
- 477. Djaileb, A., et al., A rapid and quantitative serum test for SARS-CoV-2 antibodies with portable surface plasmon resonance sensing. 2020.
- 478. Sanchez, J.E., et al., *Detection of SARS-CoV-2 and its S and N proteins using surface enhanced Raman spectroscopy*. Rsc Advances, 2021. **11**(41): p. 25788-25794.
- 479. Cui, F. and H.S. Zhou, *Diagnostic methods and potential portable biosensors for coronavirus disease 2019.* Biosensors and bioelectronics, 2020. **165**: p. 112349.
- 480. Moitra, P., et al., *Selective naked-eye detection of SARS-CoV-2 mediated by N gene targeted antisense oligonucleotide capped plasmonic nanoparticles.* ACS nano, 2020. **14**(6): p. 7617-7627.
- 481. O'Connor, T., S. Santaniello, and B. Javidi, COVID-19 detection from red blood cells using highly comparative time-series analysis (HCTSA) in digital holographic microscopy. Optics Express, 2022.
 30(2): p. 1723-1736.
- 482. Snyder, K., et al., *Holographic immunoassays: direct detection of antibodies binding to colloidal spheres.* Soft Matter, 2020. **16**(44): p. 10180-10186.
- 483. Goswami, N., et al., *Label-free SARS-CoV-2 detection and classification using phase imaging with computational specificity*. Light: Science & Applications, 2021. **10**(1): p. 1-12.
- 484. Potter, C.J., et al., *Point-of-care SARS-CoV-2 sensing using lens-free imaging and a deep learning-assisted quantitative agglutination assay.* Lab on a Chip, 2022.

- 485. Chen, H., et al., *Sensitive Detection of SARS-CoV-2 Using a SERS-Based Aptasensor*. ACS Sensors, 2021. **6**(6): p. 2378-2385.
- 486. Wills, S., *The Search for a Better COVID Test.* Optics and Photonics News, 2021. **32**(9): p. 40-47.
- 487. Devpost, Samsung SARS-CoV-2 detection with SERS spectroscopy research. 2020.
- 488. Optics.org, *Research and Development*. Botanisol Analytics, 2020.
- 489. Newsfile, *BioMark Diagnostics Forms New Company, Bio Stream Diagnostics Inc., for '30-Second' COVID-19 Screening.* BioMark Diagnostics Inc, 2020.
- 490. Ant., Advanced Nano Technologies. 2020.
- 491. Corporation, L., *LamdaGen and COVID-19.* 2020.
- 492. coronavirus, C.B., *Surface Plasmon Resonance (SPR) for Coronavirus Research*. 2020.
- 493. BioWorld, *Todos Medical sets sights on COVID-19 test market.* 2020.
- 494. Diagnostics, L., *LightDeck: Laser Technology for Highly-Accurate, Low-Cost Diagnostics in Minutes.* 2020.
- 495. Virolens, Virolens covid19 detection based on holography microscopy. 2021.
- 496. Morawska, L., et al., *Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities.* 2009. **40**(3): p. 256-269.
- 497. Nicas, M., et al., *Toward understanding the risk of secondary airborne infection: emission of respirable pathogens*. 2005. **2**(3): p. 143-154.
- 498. Lindsley, W.G., et al., *Quantity and size distribution of cough-generated aerosol particles produced by influenza patients during and after illness.* 2012. **9**(7): p. 443-449.
- 499. Johnson, G., et al., *Modality of human expired aerosol size distributions*. 2011. **42**(12): p. 839-851.
- 500. Jennison, M.W.J.A., ATOMIZING OF MOUTH AND NOSE SECRETIONS. 1942. 17: p. 106.
- 501. Gerone, P.J., et al., Assessment of experimental and natural viral aerosols. 1966. **30**(3): p. 576-588.
- 502. Papineni, R.S. and F.S.J.J.o.A.M. Rosenthal, *The size distribution of droplets in the exhaled breath of healthy human subjects.* 1997. **10**(2): p. 105-116.
- 503. Fennelly, K.P., et al., *Cough-generated aerosols of Mycobacterium tuberculosis: a new method to study infectiousness.* 2004. **169**(5): p. 604-609.
- 504. Edwards, D.A., et al., *Inhaling to mitigate exhaled bioaerosols*. 2004. **101**(50): p. 17383-17388.
- 505. Yang, S., et al., *The size and concentration of droplets generated by coughing in human subjects.* 2007. **20**(4): p. 484-494.
- 506. Fabian, P., et al., *Influenza virus in human exhaled breath: an observational study.* 2008. **3**(7): p. e2691.
- 507. Chao, C.Y.H., et al., *Characterization of expiration air jets and droplet size distributions immediately at the mouth opening.* 2009. **40**(2): p. 122-133.
- 508. Stetzer, O., et al., *The Zurich Ice Nucleation Chamber (ZINC)-A New Instrument to Investigate Atmospheric Ice Formation.* Aerosol Science and Technology, 2008. **42**(1): p. 64-74.
- 509. Garimella, S., et al., *The SPectrometer for Ice Nuclei (SPIN): an instrument to investigate ice nucleation.* Atmos. Meas. Tech., 2016. **9**(7): p. 2781-2795.
- 510. Rogers, D.C., et al., *A Continuous-Flow Diffusion Chamber for Airborne Measurements of Ice Nuclei*. Journal of Atmospheric and Oceanic Technology, 2001. **18**(5): p. 725-741.
- 511. Kanji, Z.A., et al., *Results from the University of Toronto continuous flow diffusion chamber at ICIS* 2007: instrument intercomparison and ice onsets for different aerosol types. Atmospheric Chemistry and Physics, 2011. **11**(1): p. 31-41.
- 512. DeMott, P.J., et al., *Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles.* Atmos. Chem. Phys., 2015. **15**(1): p. 393-409.
- 513. Zenker, J., et al., *Using depolarization to quantify ice nucleating particle concentrations: a new method.* Atmos. Meas. Tech., 2017. **10**(12): p. 4639-4657.

- 514. Garimella, S., et al., *Uncertainty in counting ice nucleating particles with continuous flow diffusion chambers.* Atmos. Chem. Phys., 2017. **17**(17): p. 10855-10864.
- 515. Möhler, O., et al., *The portable ice nucleation experiment PINE: a new online instrument for laboratory studies and automated long-term field observations of ice-nucleating particles.* Atmos. Meas. Tech. Discuss., 2020. **2020**: p. 1-43.
- 516. Möhler, O., et al., *Effect of sulfuric acid coating on heterogeneous ice nucleation by soot aerosol particles.* Journal of Geophysical Research: Atmospheres, 2005. **110**(D11).
- 517. Petters, M.D., et al., *Ice nuclei emissions from biomass burning*. Journal of Geophysical Research: Atmospheres, 2009. **114**(D7).
- 518. Glen, A. and S.D. Brooks, *Single Particle Measurements of the Optical Properties of Small Ice Crystals and Heterogeneous Ice Nuclei*. Aerosol Science and Technology, 2014. **48**(11): p. 1123-1132.
- 519. Schiebel, T., *Ice Nucleation Activity of Soil Dust Aerosols*. 2017: Karlsruher Institut für Technologie (KIT).
- 520. Kulkarni, G., et al., *Ice nucleation activity of diesel soot particles at cirrus relevant temperature conditions: Effects of hydration, secondary organics coating, soot morphology, and coagulation.* Geophysical Research Letters, 2016. **43**(7): p. 3580-3588.
- 521. Bundke, U., et al., *The fast Ice Nucleus chamber FINCH.* Atmospheric Research, 2008. **90**(2): p. 180-186.
- 522. Jones, H., et al., Manchester Ice Nucleus Counter (MINC) measurements from the 2007 International workshop on Comparing Ice nucleation Measuring Systems (ICIS-2007). Atmospheric Chemistry and Physics, 2011. **11**(1): p. 53.
- 523. Chou, C., et al., *Ice nuclei properties within a Saharan dust event at the Jungfraujoch in the Swiss Alps.* Atmos. Chem. Phys., 2011. **11**(10): p. 4725-4738.
- 524. Kanji, Z.A., et al., *Laboratory studies of immersion and deposition mode ice nucleation of ozone aged mineral dust particles.* Atmos. Chem. Phys., 2013. **13**(17): p. 9097-9118.
- 525. Kohn, M., et al., *Immersion mode ice nucleation measurements with the new Portable Immersion Mode Cooling chAmber (PIMCA).* Journal of Geophysical Research: Atmospheres, 2016. **121**(9): p. 4713-4733.