Scientometrics (2020) 124:1945–2008
https://doi.org/10.1007/s11192-020-03547-w

First systematic review on PM-bound water: exploring the existing knowledge domain using the CiteSpace software

Kamila Widziewicz-Rzońca[1] · Malwina Tytła[1]

Received: 30 September 2019 / Published online: 18 June 2020

Abstract

Aerosol water is a master component of atmospheric aerosols and a medium that enables all aqueous-phase reactions occurring in the atmosphere. This integral chemical compound of suspended aerosol particles (PM) has become one of the hottest issues in recent years. To look for scientific productivity in the area of PM-bound water research a bibliometric analysis was performed. Most actual literature regarding aerosol and particulate bound water and implications of the research in this field was downloaded from WOS database using 1996–2018 timespan. Different bibliographic statistics were used to get a general profile of leading authorships, institutions, countries and mainstream journals providing most highly cited articles in the field. Using the CiteSpace software it was possible to identify past trends and possible future directions in measuring aerosol bound water. The search terms used in the database were {"aerosol" AND "water" OR "chemical mass balance"} AND {"particulate matter" OR "PM-bound water" OR "hygroscopic"}. The answers to the following questions were found: which authors, countries, institutions and aerosol journals to the greatest degree influenced PM-bound water research?. The network of co-occurring noun phrases was extracted from the set of publications, followed by co-citation analysis. The network was also clustered by top terms which gave a clear picture of topics most often undertaken. Finally the publication meeting eligibility criteria were looked for chemical compounds most frequently determined in PM-bound water research, which help to indicate works where quantitative assessment of PM-bound water was performed. Obtained results indicate that the paper with the greatest citation burst was Tang and Munkelwitz (J Geophys Res Atmos 99(D9):18801–18808, 1994). The largest number of articles in this specific field was published in Atmospheric Chemistry and Physics. An absolute leader in the quantity of publications among all research institutions is National Aeronautics Space Administration NASA. Meteorology and Atmospheric sciences is the discipline most occupied by highly cited journals in this field. Clustering results indicate that the research has mainly focused on hygroscopic measurement of aerosol, hygroscopic growth of particles;

✉ Kamila Widziewicz-Rzońca
kamila.widziewicz@ipis.zabrze.pl

1 Institute of Environmental Engineering, Polish Academy of Sciences, 34 M. Skłodowska-Curie St., 41-819 Zabrze, Poland

aerosol liquid water, and hygroscopic behavior. Most articles rather points PM-bound water as an artifact in organic carbon and ions measurements without detailed analysis of its contents or probable origin. The number of publications in each cluster of the build network is relatively high, which indicate that scholars have formed a rather consistent studies in the theme of aerosol-bound water. Despite a relevant role played by aerosol-bound water in atmospheric processes a quantitative description of its contents is rather rarely found in the literature (with the total number of only 23 papers concerning PM-bound water contents). In terms of yield, USA, China and Italy ranked highest, playing a propelling role in the research on PM-bound water. Future trends in PM-bound water research should be directed to a quantitative measurements of its contents; source apportionment, chemical composition of PM—modulating its hygroscopicity and therefore cloud formation processes, and the assessment of artefacts influencing the quality of PM-bound water measurements. Those areas should be especially developed in future studies and scientific projects concerning atmospheric water.

Keywords Systematic review · Atmospheric water · PM-bound water · PM hygroscopicity · CiteSpace · Knowledge domain

Introduction

Coal is the fossil fuel, which to the greatest extent influence the load and number of PM particles of anthropogenic origin. Particles released during combustion processes may bring serious environmental hazards, but also pollute the atmosphere and have adverse impacts on human health. Although the chemical composition of PM is rather well known, one of the PM compound has aroused special interest only in recent years. The latter is the presence of the PM-bound water, both the loosely adsorbed one and chemically bound to the structure of the PM particles (Canepari et al. 2017; Rogula-Kozłowska et al. 2017; Su et al. 2018). The strength of this bounding will vary depending on chemical composition of PM, but also on the location (PM origin) and can be easily delimited when testing thermal behavior of PM particles. The mass ratio between weakly and strongly bound water as well as PM hygroscopicity can be described by two key parameters: the deliquescence relative humidity (DRH) and the crystallization relative humidity (CRH) (Casati et al. 2015), crucial for a correct parameterization of the aerosol hygroscopic growth, used in different practical applications likewise remote sensing (D'Angelo et al. 2016). These parameters defines the relative humidity thresholds at which aqueous solid phase changes occurs—from solid to liquid saturated solution at DRH and CRH, respectively (Casati et al. 2015; Seinfeld and Pandis 2006). As RH increases PM compounds like crystalline soluble salts $(NH_4)_2SO_4$ or NH_4NO_3 undergo phase transition and become aqueous solution particles. Under decreasing relative humidity solution particle follows the equilibrium curve to the deliquescence point and remains dissolved in a supersaturated solution. When RH is still decreasing solution particle abruptly loses water vapor and return to initial crystalline form. Particles in the atmosphere are present as a supersaturated solution droplets (liquid particles) as well as solid particles. Generally the particle-bound water consist of weakly-bonded (vapor) water, condensing on aerosol particles when the relative humidity (RH) increases, and bounded-water remaining enclosed in PM compounds. Constitutional water—embedded in the compound undergo removal only under higher temperatures, or under the influence of dehydrating agents. Strongly bound (crystalline) water can be released only during heating in a staggered manner; resulting in new solid phases formation (Widziewicz et al. 2018). Significant portions of water can be still present in PM particles even after equilibration, which means that simple conditioning before gravimetric measurements do not guarantee water removal. The amount of PM-bound water can vary from few to several tens of percent of the PM mass (Tang 1979). Many previously conducted studies tried to assess the hygroscopic properties of PM under different humidity conditions, however taking into account variable chemical composition of PM those properties will also vary from site to site. Many works focuses on estimation of thermodynamic properties of model (pure or mixed) aerosol solutions (mostly salts) (Tang 1979, 1997); much less studies conducted experimental measurements of particulate matter deliquescence and crystallization based on real PM samples (Casati et al. 2015). Another methods used for the assessment of PM-bound water contents are based on mathematical modelling methods (Tsyro 2005; Meng et al. 1995). According to the model estimates made by Tsyro (2005), the fraction of $PM_{2.5}$-bound water at 50% RH (relative humidity) varied across Europe between 20 and 35%. Much lower water contents 10.6% for PM_{10} and 13–23% for $PM_{2.5}$ were found in Switzerland under 50% RH conditions when using most popularly used mass closure method. Information regarding contribution of retained water to the unaccounted mass of PM is well described in the literature (Hueglin et al. 2005; Ho et al. 2006; Putaud et al. 2010; Perrino et al. 2013, 2014; Taiwo 2016); however its quantitative determination rarely done. The abundance of secondary inorganic components like nitrates and sulfates is one of the most important factors determining aerosol hygroscopicity (Świetlicki et al. 2008). PM-bound water also accelerate formation of secondary inorganic and organic aerosol and under high ambient RH levels could promote haze events frequency (Wang et al. 2019). The observational and theoretical analysis of the relationship between particulate-bound water and/or secondary aerosol formation under smog episodes or haze events has been infrequently reported (Cheng at al 2016; Wu et al. 2018; Wang and Chen 2019; Ge et al. 2019).

In order to master the characteristics of PM-bound water this study adopts the CiteSpace bibliometric software to analyze the publications panning the time period of 1996–2018 in this field. In recent years many publications has appeared in the scientific market regarding PM- or more generally aerosol-bound water (Perrino et al. 2016; Rogula-Kozłowska et al. 2019). Many of them touch these issues indirectly. This strictly means that information regarding PM-bound water appears for example in articles related to physical and chemical characteristics of particulate matter including water-soluble ions (El-Sayed et al. 2018; Tsai and Kuo 2005) and water soluble carbon (Decesari et al. 2001; Duplissy et al. 2011), chemical mass balance (Tsyro 2005), thermodesorption of aerosol matter (Wittmaack and Keck 2004; Perrino et al. 2012), positive and negative artifacts in particulate organic carbon measurements (Subramanian et al. 2004; Canepari et al. 2013) and others. The least works in a manner remarkably describes a qualitative and quantitative methods for the determination of PM-bound water (Canepari et al. 2013, 2017; Perrino et al. 2016), forms of water occurrence in PM and its origin (Perrino et al. 2012). At present, there are many software used for bibliometric (scientometric) analysis of bibliographic records of relevant publications. Among those most popular are HistCite, CiteSpace, Pajek, Sci2, BibExcel and Thomson Data Analyzer (TDA). Due to the user-friendliness, fast-computations result, a wide range of graphic tools CiteSpace is probably most often used. CiteSpace was designed to answer the questions about the structure and dynamics of a knowledge domain and its visualization. Through co-occurrence analysis and co-citation analysis on a large number of bibliographic records, it can explore the trends and patterns identified in the knowledge domain and found some development trends of a particular study field (Chen 2013, 2016).

Due to the growing public awareness regarding PM, its behavior in the atmosphere, the sources of its origin and health hazards the research on chemical composition of PM, including also its water contents has been growing in recent years (Tan et al. 2017; Canepari et al. 2017; Rogula-Kozłowska et al. 2017; Su et al. 2018). On the one hand it's important to measure the chemical components of atmospheric PM to estimate the climatic effects but also to know to which extent the presence of PM-bound water (non-hazardousness regarding human health) adds to the gravimetric mass of PM particles (Tsyro 2005). Such a knowledge would assist in formulating pollution control strategies for areas not in compliance with the PM standards.

This study aims to investigate current and most actual literature regarding aerosol and particulate bound water and implications of the research in this field from 1996 till 2018 based on the bibliometric technique. Different bibliographic statistics were used to get a general profile of leading authorships, institutions, countries and mainstream journals providing most highly cited articles in the field of PM-bound water.

Data and methods

Data description and CiteSpace analysis

The systematic review presented in this article followed the PRISMA guidelines. The search was performed using all databases in the Web of Science platform, including:

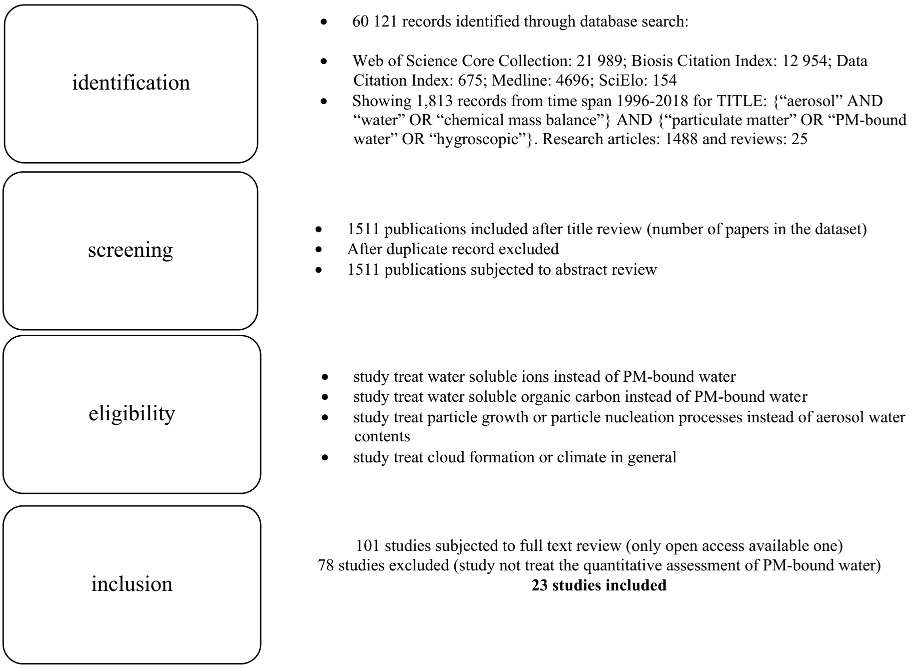

Fig. 1 Flow chart illustrating selection process of bibliographic records and selection criteria

SciELO, Science Direct, Scopus, and few others databases. WoS is currently the most relevant scientific platform regarding systematic review needs, since it allows for accurate retrieval of records during successive and repeated searches, which means that search results are reproducible and reportable. The search terms used in the databases were {"aerosol" AND "water" OR "chemical mass balance"} AND {"particulate matter" OR "PM-bound water" OR "hygroscopic"} (Fig. 1). The search was started using TOPIC search, which gave the overall number of 60,121 records. The effectiveness of our search was checked by comparing the number and quality of database outputs under different searching schemes and seeing how much overlaps there were in our findings. The used keywords "filter" in the TOPIC search narrowed the results to 1513 records (subjectively) most relevant to the research question. Records were divided into 6 groups for analysis: "mass closure", "artefacts", "qualitative and quantitative methods for water determination", "water soluble-ions", "Karl Fischer titration" and "other". Only original articles and reviews were included without short reports or letters, case studies, methodologies or books. The search was restricted only to English-language publications. The time span includes 1996–2018 years. Putting restriction regarding time span was based on a clear and strong reasoning. When looking into air quality criteria for Particulate Matter—some kind of gold standard in aerosol literature it can be easily noticed that most influential works regarding experimental measurements of particulate matter hygroscopicity and processes influencing particle hygroscopic growth but also condensational and dissolutional growth equations development were performed in the late 90' (Seinfeld and Pandis 1998; Lee et al. 1999; Ohta et al. 1998). Therefore 1996 was used as a starting point for bibliometric analysis.

There were only 101 records which meet an eligibility criterion (Fig. 1, Table 8). The final database was created on 14 January 2019 and it includes articles, which can be generally described as those concerning aerosol-bound water topic. This database was generally treated as the output for the scientific domain and for organization purposes will be called "the dataset" or the "network".

The records creating "the network" were subjected to full text review. The aim was to extract from the network works that strictly concerned the issues of quantitative estimation of water contents in PM in the form of a percentage, mass or concentration units. This was started by looking into titles and abstracts before reading full texts of articles. During this process only publications with the term "water" in title, abstract or keywords were selected, which in fact met the final inclusion criteria. Flow chart (Fig. 1.) illustrates the databases searched in this review, the resulting number of potential studies identified by this search; and the number and reasons for excluding studies based our pre-determined criteria. Final database include only 23 studies concerning the quantitative assessment of PM-bound water contents.

Each piece of finally selected data (from the network) was downloaded into EndNote database and converted into full-record text format. The analyses at the literature level were based on CiteSpace V. The starting parameters were as follows: (1) Time Slicing: 1996–2018; (2) Years Per Slice: "1"; (3) Term Source: Title, Abstract, Author Keywords, and Keyword Plus; (4) Node Type: select the corresponding one each time; (5) Selection Criteria: the top 50, (6) Pruning: Minimum Spanning Tree and Pruning Sliced Networks; and (7) Visualization: Cluster View-Static and Show Merged Network.

Few parameters are used in this work in order to present the structure and distribution of scientific knowledge in terms of scientific metrics, visualizations and data summaries. The *Centrality* parameter is used to find and measure the importance of the term and mark the key point of node in purple circle in the knowledge graph. *Burst* identifies emergent interest in a domain exhibited by the surge of citations and refers to terms, publications, authors, journals which is marked in red in CiteSpace. The *TimeLine* is an important indicator used to reflect the frontier and the trend in the knowledge domain and finally the publication records are being mapped in the form of *Dual-map overlay* showing the entire dataset in the context of a global map of major disciplines. Additionally this study conducts some basic and simple analysis on the annual quantity of papers, authors, disciplines, countries, journals, keywords and other research impact metrics related to atmospheric water and specifically PM-bound water topic.

Results and discussion

The starting number of publications in the interesting field sources from the Web of Science database (extracted by TOPIC search) was 60,121. After TITLE review only 1513 were included.

Data description by web of science metrics

The number distribution of publications through the period 1996–2018 is shown in Fig. 2. It is possible to observe how the publishing trend increased from 32 publications in 1996 to 128 publications in 2018, highlighting the actual interest on the topic. Over the past 23 years, it is possible to distinguish two stages. The first took place between 1996 and 2005, which shows rather slow increase reflected by the increase rate equal 1.5 compared to starting year. The second phase shows some acceleration which ran from 2006 up to 2018, with a higher growth rate, indicating the growing interest in this specific research domain. The second increase in the number of generated papers coincides well with the expansion phase in scientific development of mass closure models used for determining inconsistencies between chemical characterization and gravimetric PM mass (Tsyro 2005; Rees et al. 2004).

Approximately 33% of the publications in the dataset were published in the top 7 international aerosol journals (Fig. 3). The greatest number of papers was published in

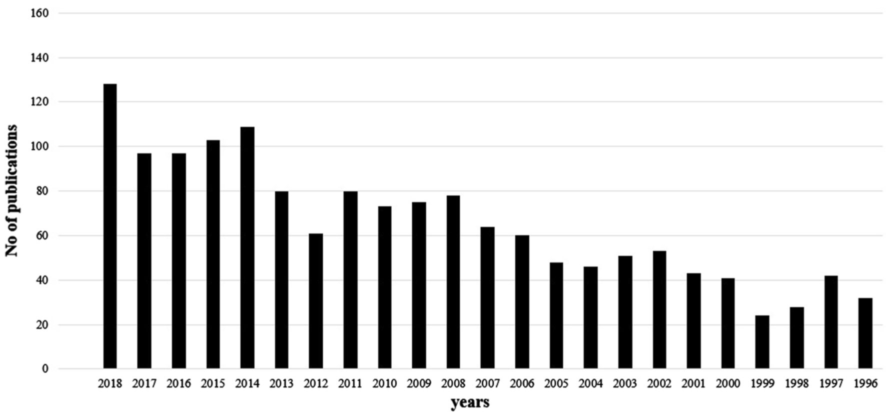

Fig. 2 Distribution of the bibliographic set concerning aerosol and PM-bound water measurements over the time span 1996–2018

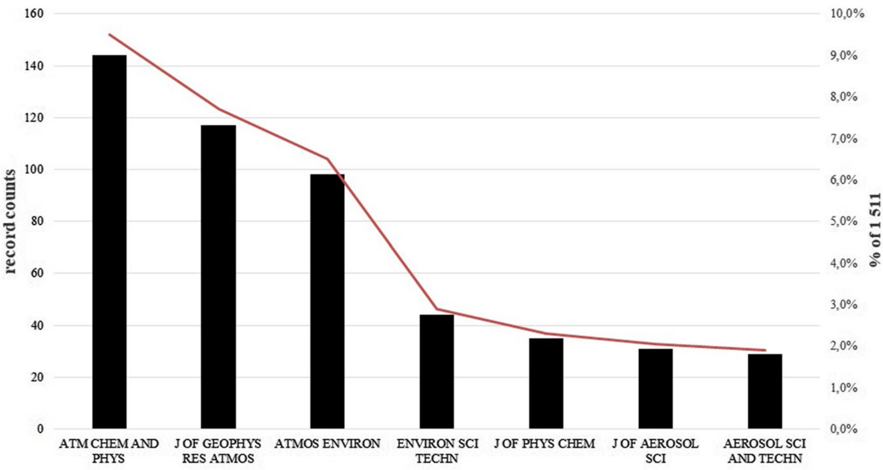

Fig. 3 Top 7 Journals with the highest number of publications

Atmospheric Chemistry and Physics with the total number of papers equal 144 (more than 9% of total papers in the dataset as reported by the red-line trend). This gives an overview on the distribution of potential research interests in the topic of aerosol bound water. Atmospheric Chemistry and Physics is dedicated to the publication of high-quality studies investigating the Earth's atmosphere and the underlying chemical and physical processes occurring in the atmosphere (5-year IF = 5.689). Such great number of studies published in most top and reputable journals (taking into account journal ranking on atmospheric sciences) confirms the importance of aerosol-bound water for both—the scientists but also the scientific audience. It must be however remembered that the influence of journal impact is not directly proportional to the number of published papers, therefore the influence of the journal in the interesting field cannot be judged based on IF factor or number of papers alone.

Table 1 presents the top 15 contributing institutes. National Aeronautics Space Administration NASA with the number of records 59 (3.9% of all papers in the dataset) lead the list, followed by University of California System (3.7%) and the Chinese Academy of Sciences (3.6%). Among the top 15 institutions, 9 are American, followed by 4 European and 2 Chinese. However, more than 29% of the total records belong to the USA.

Table 2 ranks countries that contribute the most to the aerosol—bound water research. In terms of publications number USA is at the forefront accounting the 29.8% of the total dataset, with 450 records, followed by China with 205 records (13.6%). Germany, England and Japan occupy, respectively, the 3rd, 4th, and 5th place, with a cumulative number of publication equal to 370. The institutions with more publications in this topic mainly consist on research institutes and universitiesm which ensure high level of study on aerosol bound water.

Every journal covered by Web of Science core collection is assigned to at least one of the subject categories. The top 10 most-cited subject categories for aerosol-bound water topic are reported in Table 3. The most important research fields are Meteorology Atmospheric Sciences; Environmental Sciences and Engineering Chemical with the record count: 61; 50 and 9 respectively.

Table 1 Top 15 contributing institutions

Nos.	Institution	No. of records	Country
1	National Aeronautics Space Administration NASA	59	USA
2	University of California System	57	USA
3	Chinese Academy of Sciences	55	China
4	Leibniz Institut fur Tropospharenforschung Tropos	55	European
5	Centre National de la Reherche Scientifique CNRS	46	European
6	United States Department of Energy DOE	42	USA
7	University System of Georgia	37	USA
8	Georgia Institute of Technology	34	USA
9	Max Planck Society	33	European
10	National Oceanic Atmospheric Admin NOAA USA	33	USA
11	California Institute of Technology	32	USA
12	Lund University	32	European
13	NASA Goddard Space Flight Center	32	USA
14	Peking University	31	China
15	University of Manchester	31	USA

Table 2 Top 10 contribution countries

Nos.	Field: countries/regions	Record count	% of 1513
1	USA	450	29.782
2	China	205	13.567
3	Germany	164	10.854
4	England	106	7.015
5	Japan	100	6.618
6	France	97	6.420
7	Canada	70	4.633
8	South Korea	66	4.368
9	India	62	4.103
10	Russia	62	4.103

Table 3 Top 10 categories

Nos.	Field	Record count
1	Meteorology Atmospheric Sciences	61
2	Environmental Sciences	50
3	Engineering Chemical	9
4	Geosciences Multidisciplinary	9
5	Engineering Environmental	7
6	Chemistry Physical	6
7	Materials Science Multidisciplinary	6
8	Physics Applied	6
9	Engineering Civil	5
10	Engineering Mechanical	5

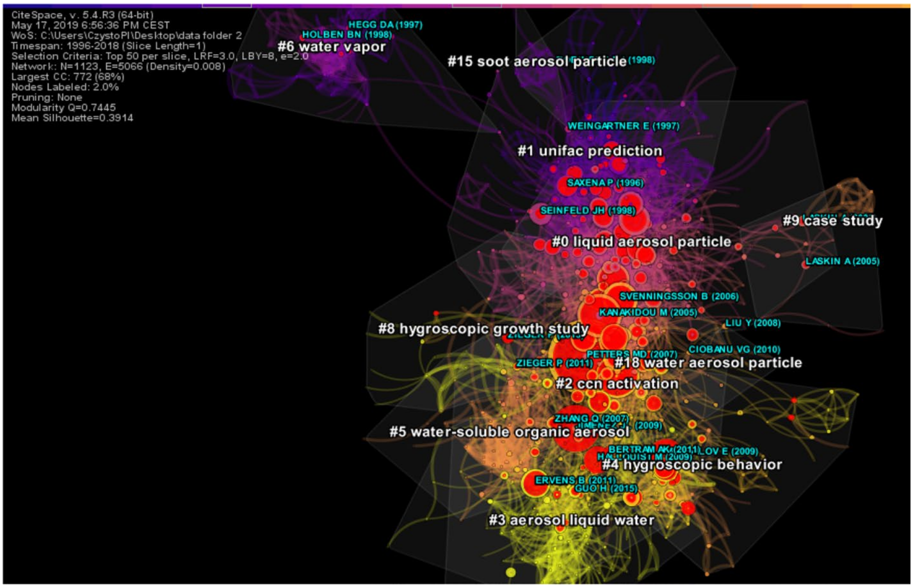

Fig. 4 The node-link diagram of authors co-occurrence together with marked author burst (red nodes) (different colors on the map indicate different year of the first cooperation between authors, where purple color indicate longer cooperation). Node size represents the overall amount of citations (by author) and colored rings show author citation by time-slice. The network is clustered by top terms founded in the publication titles. The link strength between two nodes refers to the frequency of terms co-occurrence. (Color figure online)

The most cited authors by the number of citations (year of publication, number of counts) were Tang and Munkelwitz (1994, counts 223); Seinfeld and Pandis (1998, 207), Saxena and Hildemann (1997, 150), Petters and Kreidenweis (2008, 141), Gysel et al. (2003; 140) (Fig. 4). As presented in Fig. 4 there is a strongly cooperative relationship between most cited authors; for example Saxena P. and Seinfeld J.H; Svenningson and Kanakidou. This collaboration is reflected by measuring co-occurrence of pairs of top-terms in the article titles. For example Svenningson is affiliated with Lund University (Sweden) and undertake many research studies regarding particulates hygroscopicity, cloud formation and Po Valley fog, together with the researchers from Italian National Research Council; while Kanakidou works in the Department of Environmental Chemistry, in University of Crete (Greece) and her research interests focus mostly chemical and physical aspects of aerosols composition. Despite the geographical distance that separates Sweden and Greece the cooperative relationship between those authors regarding PM-bound water interests is rather strong. The more two authors are co-cited the more they are related. This is also a simply measure of authors occurrence in the same articles as a co-authors. A red marks on Fig. 4 indicate that all those authors have a burst of terms with relatively great impact and high level of attention from the scientific audience in a certain period of the study process like for example in case of articles: Seinfeld and Pandis (1998) "Atmospheric Chemistry and Physics from air pollution to climate change" and Saxena and Hildemann (1996) "Water-soluble organics in atmospheric particles: A critical review of the literature and application of thermodynamics to identify candidate compounds". The key nodes in this network are "hygroscopic growth study"; "water aerosol particle"; "liquid aerosol particle"; "water soluble organic aerosol"; "hygroscopic behavior"; "aerosol liquid water"' "soot aerosol particle" and "water vapor", indicating that they have strong influence in the whole network.

When comparing information included in Table 4 and one presented in Fig. 4 we came to the conclusion that the influence of the author on the study on aerosol bound water should not be determined by the number of publications or citations alone.

One of the most important factor reflecting the overall success of the paper is its authorship by author with the strong citation burst (Fig. 5). The list of the most cited authors in terms of citation burst does not necessarily correspond with the list of most references with the highest burst (see Fig. 8). Speaking other words the author with the greatest burst is Zhang (burst = 11.47) (Fig. 5), while the most cited authors (in terms of number of citations) are Saxena and Hildemann (1996) (Table 6).

Categories of co-occurring subject categories founded in the database

In order to compared results presented by WOS citation and journal metrics we created the map of co-citation network at category (discipline) level (Fig. 6). The database includes 76 nodes and 337 links (purple links indicate longer cooperation between disciplines), which generally could be categorized into 5 groups: meteorology and atmospheric-related (on the left); environmental and ecology (plant)-related (left bottom); physical chemistry and physics-related (center); chemistry-related (center); pharmacology and pharmacy related (right bottom) and material science-related (upper right). This categorization corresponds well with WOS metrics presented in Table 3. The biggest nodes correspond to the categories occupied by most cited journals and characterized by greatest centrality—for example soil related journals on the left; atmospheric chemistry and physics journals (center). Other words they are the hottest disciplines in terms of aerosol bound water research.

Table 4 Top 15 authors (by number of papers)

Nos.	Author name	Record counts
1	Wiedensohler A	32
2	Reid JP	26
3	Zhang YH	24
4	Weingartner E	22
5	Baltensperger U	21
6	Massling A	21
7	Weber RJ	20
8	Seinfeld JH	19
9	Chan CK	18
10	Gysel M	18
11	Stratmann F	17
12	Świetlicki E	17
13	Flagan RC	15
14	Kreidenweis SM	15
15	Martin ST	14

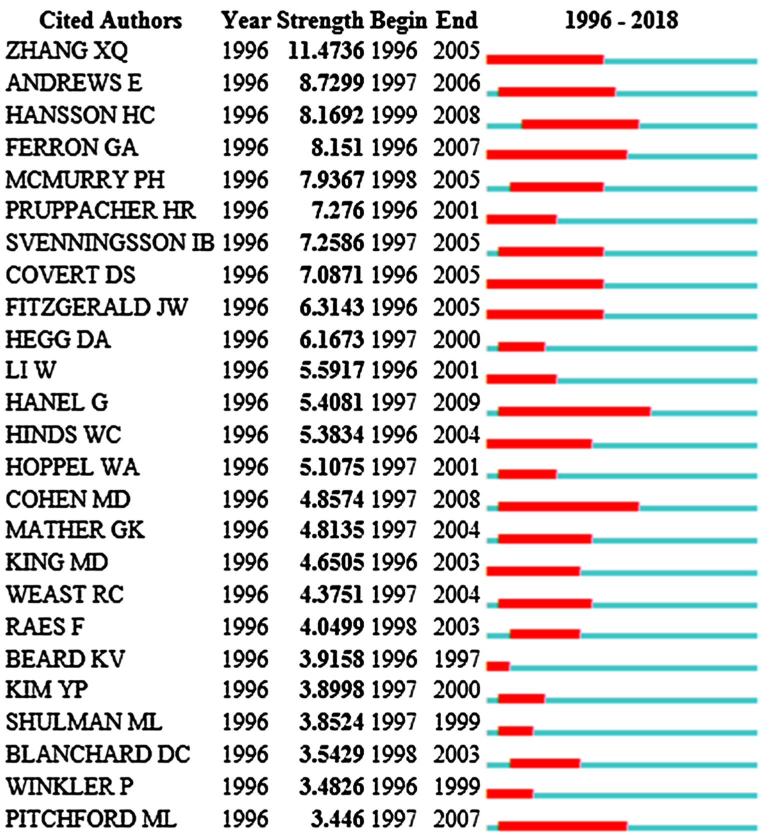

Fig. 5 Information of highly cited authors in the topic of aerosol bound water

Meteorology and Atmospheric Sciences (cluster #4) together with Environmental Sciences (cluster #9 and #22) and Chemistry (cluster #5 and #6) are a key disciplines in terms of relevant publications about the study on aerosol bound water, and the connections with chemistry and physics indicate that PM-bound water topic will be widely applied among those categories in the future studies, with strong interactivity among different disciplines (Fig. 6). However connections between thermodynamics (cluster #7), optics (cluster #15) and plant sciences (#21) is rather weak. For example articles building cluster #15 ("optics") only points atmospheric water presence as an artifact when measuring PM concentration by means of optical sensors.

Figure 7 presents the citation history of Journals. The most cited journals are: Journal of Geophysical Research Atmospheres; Atmospheric Environment and Geophysical Research Letters (most colored nodes in the network). As one can easily noticed, the number of publications in the Journal (Fig. 3) does not perfectly correspond to the number and frequency of their citations (Fig. 7).

Based on the ranks of articles according to WOS statistical metrics the highest cumulated number of citations were assigned to the following papers (Table 5).

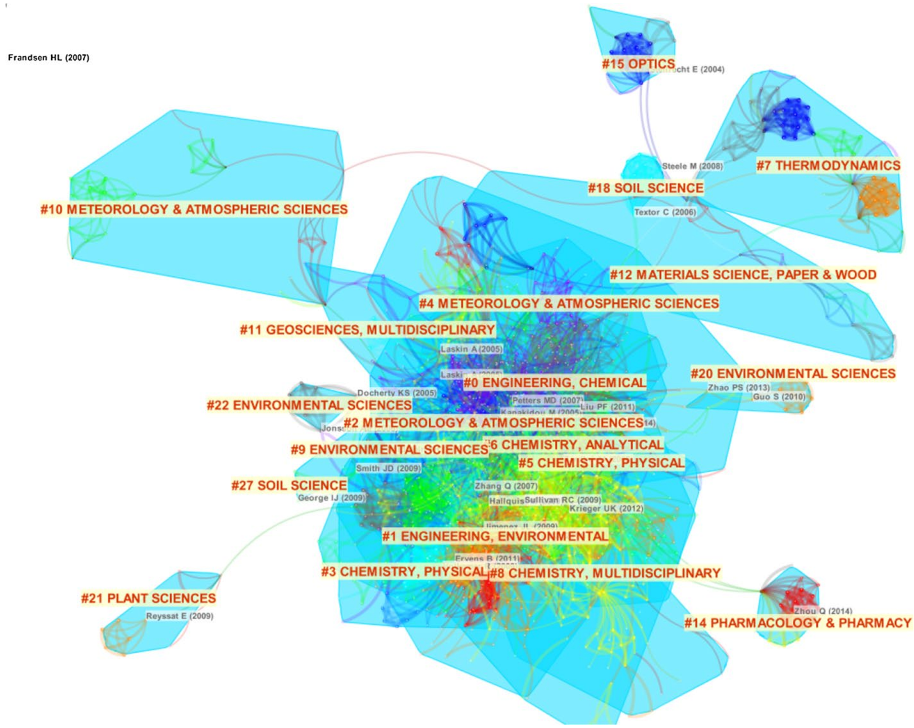

Fig. 6 Network of co-occurring subject categories

The most active area of the research: citation burst

Table 6 shows top 25 references with strongest citation bursts during the period between 1996 and 2018. The reference characterized by strong citation burst refers to the situation when a sudden increase in the cited frequency of the reference occurs at a time point or time period. This strictly means that citation burst is an indicator of extraordinary degree of attention from the scientific community. Citation burst contains two dimensions: the burst strength and the bursting time. Papers characterized by high values in the "*Strength*" column can be considered as relevant in the aerosol bound water field. The "*Topic*" column was filled by hand and it summarizes the content of each publication. "*Burst period*" column is the period when citation burst evolves. Our analysis found that the article with the strongest citation burst (12.854) is Saxena P. and Hildeemann L.M. "Water-soluble organics in atmospheric particles: A critical review of the literature and application of thermodynamics to identify candidate compounds", 1996, which was one of the few landmark papers published by this author. Its burst lasted for 5 years from 1999 to 2004. Tang In. and Munklewitz H.R. "Water activities, densities, and refractive indices of aqueous sulfates and sodium nitrate droplets of atmospheric importance", 1994, has the second strongest burst of 11.904 from 1996 to 2002. Usually the most recent papers have weaker citation bursts. Several articles like for example Zappoli et al. 1999; Shulman et al. 1996started their citation bursts just 1 year after publication. It is also worth noting that eight over 25

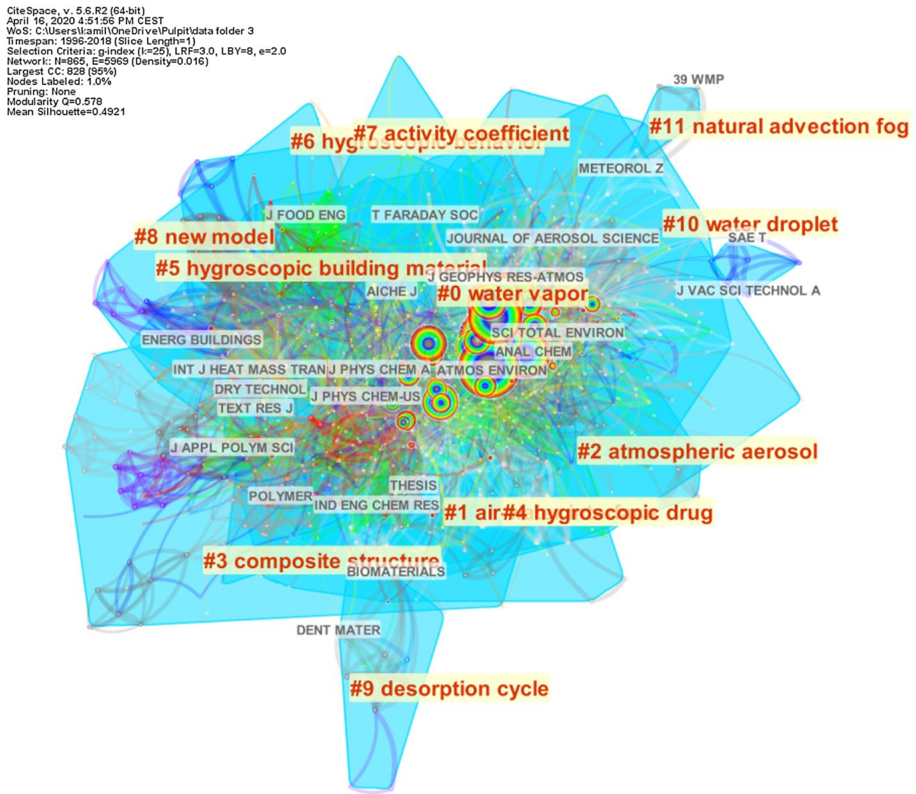

Fig. 7 Journal citation tree rings. Citation tree-rings represent the citation history articles in the Journal. The color of a citation ring denotes the time of corresponding citations. The thickness of a ring is proportional to the number of citations in a given time slice, where red color is most recent one. The network is clusterized by terms in the titles of the articles. While the labels next to the nodes are most highly cited journals. (Color figure online)

publications, reported in Table 6, are related to the hygroscopic properties of atmospheric aerosols and hygroscopic growth, and this constitutes a major topic.

Networks of co-occurring terms

The word *term* refers to noun phrases extracted from the text of a bibliographic record or a full text document. We therefore generate a series of networks of co-occurring terms (nouns, keywords, title words); those terms are one appearing in the same document, keywords section, title, respectively and connected in the network.

Figure 8 presents the network of co-occurring noun phrases. Only terms related to articles with a number of counts greater than 10 were included. The terms are labeled by crosses, while most important articles by nodes (for better visualization the most hot terms were moved onto right). More "violet" crosses and nodes are those characterized by higher burst. Its therefore easily to observe that the initial "relative humidity"; "hygroscopic

Table 5 The most influential articles in the merged network. The ranking was done based on normalized citations for the interesting time span 1996–2018

Title	First author	Source title	Publication date	Volume	Issue	Total citations	Average per year
Hygroscopic properties of submicrometer atmospheric aerosol particles measured with H-TDMA instruments in various environments—a review	Świetlicki	Tellus Series B-Chemical and Physical Meteorology	2008	60	3	243	20.25
Amorphous and crystalline aerosol particles interacting with water vapor: conceptual framework and experimental evidence for restructuring, phase transitions and kinetic limitations	Mikhailov	Atmospheric Chemistry and Physics	2009	9	24	236	21.45
Reactive nitrogen chemistry in aerosol water as a source of sulfate during haze events in China	Cheng	Science Advances	2016	2	12	187	46.75
A decadal regional and global trend analysis of the aerosol optical depth using a data-assimilation grade over-water MODIS and Level 2 MISR aerosol products	Zhang	Atmospheric Chemistry and Physics	2010	10	22	182	18.20
Water-Soluble Organic Aerosol material and the light-absorption characteristics of aqueous extracts measured over the Southeastern United States	Hecobian	Atmospheric Chemistry and Physics	2010	10	13	177	17.70

Table 6 Top 25 references with the strongest citation bursts over the period between 1996 and 2018

References	Topic	Year	Burst strength	Burst period	No of citation by WOS database (checked on 26 may 2019)
Saxena and Hildemann (1996)	**Water-soluble organics in atmospheric particles: A critical review**	**1996**	**12.854**	**1999–2004**	**808**
Tang and Munkelwitz (1994)	Dynamic behavior, visibility reduction, and radiative effects of atmospheric sulfate and nitrate aerosols	1994	11.904	1996–2002	605
Saxena et al. (1995)	**Hygroscopic behavior of atmospheric particles**	**1995**	**11.2948**	**1997–2003**	**498**
Zhang et al. (1993)	Water content of submicron aerosols	1993	8.8704	1996–2001	146
Tang (1997)	Thermodynamic and optical properties of mixed-salt aerosols	1997	7.4346	2000–2005	212
Berg et al. (1998)	**Hygroscopic** growth of aerosol particles	1998	7.4346	2000–2005	89
Zappoli et al. (1999)	**Macromolecular components of fine aerosol in relation to their water solubility**	**1999**	**7.0546**	**2000–2007**	**368**
Andrews and Larson (1993)	Size changes of aerosol particles as a function of relative humidity	1993	6.6848	1997–2001	133
Novakov and Penner (1993)	**Contribution of organic aerosols to cloud-condensation-nuclei concentrations**	**1993**	**6.09**	**1996–2001**	**534**
Saxena and Hildemann (1997)	Water absorption behavior of multifunctional oxygenated organic compounds in atmospheric particles	1997	5.5473	2000–2004	84
Rogge et al. (1993)	**Quantification of urban organic aerosols at a molecular level**	**1993**	**5.3821**	**2000–2001**	**723**
Virkkula et al. (1999)	**Hygroscopic** properties of aerosol	1999	5.11	2000–2005	127
Pitchford and McMurry (1994)	Relationship between measured water vapor growth and chemistry of atmospheric aerosol	1994	5.0094	1997–2001	79
Shulman et al. (1996)	Dissolution behavior and surface tension effects of organic compounds in nucleating cloud droplets	1996	4.4915	1997–1999	328
Svenningsson et al. (1992)	**Hygroscopic** growth of aerosol particles	1992	4.2201	1997–2000	112
Hegg et al. (1997)	Chemical apportionment of aerosol column optical depth	1997	3.7122	2000–2003	207
Weingartner et al. (1997)	**Hygroscopic** properties of carbon and diesel soot particles	1997	3.7092	2000–2005	312
Svenningsson et al. (1994)	**Hygroscopic** growth of aerosol particles and its influence on nucleation scavenging in cloud	1994	3.63	1997–2002	57
Kotchenruther et al.(1999)	Humidification factors for atmospheric aerosols	1999	3.5851	2000–2001	179

Table 6 (continued)

References	Topic	Year	Burst strength	Burst period	No of citation by WOS database (checked on 26 may 2019)
Novakov and Corrigan (1996)	Cloud condensation nucleus activity of the organic component of biomass smoke particles	1996	3.5135	1999–2001	142
Weingartner et al. (1995)	**Growth** and structural change of combustion aerosols at high relative humidity	1995	3.4754	1998–2001	72
McMurry et al. (1996)	Individual particles separated by size and **hygroscopicity** with the TDMA	1996	3.3369	1997–2001	74
Covert and Heintzenberg (1993)	Size distributions and chemical properties of aerosol	1993	3.2638	1997–1999	76
Charlson et al. (1992)	**Climate forcing by anthropogenic aerosols**	**1992**	**3.2474**	**1996–1999**	**2391**
Russell et al. (1999)	Aerosol induced radiative flux changes	1999	3.181	2000–2003	142

Bold font: papers characterized by high citation burst (> 5) and large number of citations

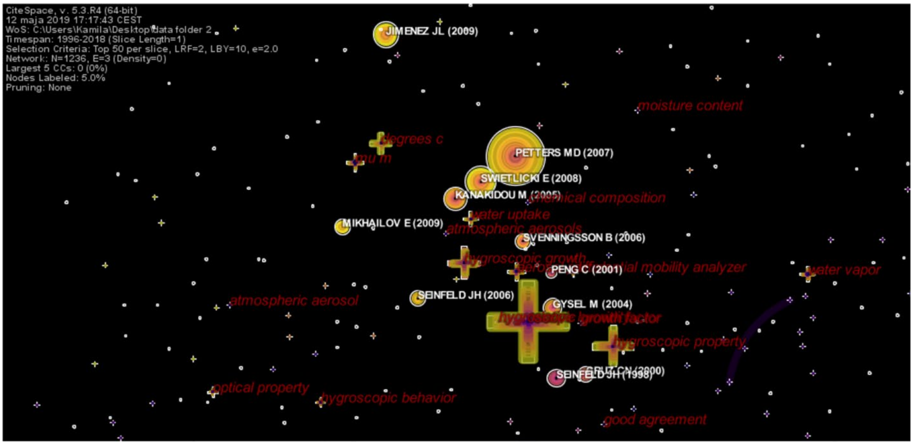

Fig. 8 Network of co-occurring noun phrases extracted from the set of publications

properties”; “hygroscopic growth” and “aerosol particles” phrases occurs in the paper written by Petters MD and Kreidenweis SM., Atmos. Chem. Phys., 7, 1961–1971, 2007, entitled “A single parameter representation of hygroscopic growth and cloud condensation nucleus activity”; but also in Kanakidou et al. Atmos. Chem. Phys., 5, 1053–1123, 2005 “Organic aerosol and global climate modelling: a review”, and coincidence with the following phrases “water vapor”, “degree”, “(m^3 air μg^{-1})”, “water uptake”, “differential mobility analyzer”, “hygroscopic behavior” and “hygroscopic growth factor”. Hygroscopic properties of sub-micrometer atmospheric aerosol particles measured with HTDMA instruments in various environments—a review published by Świetlicki et al. Tellus (2008), 60B, 432–469 is additionally enriched by “chemical composition” phrase. First studies concerning hygroscopic properties of aerosols were conducted in early 80’s (Deliquescence properties and particle-size change of hygroscopic aerosols By: Tang In, ISSN: 0065-7727 Issue: APR, Published: 1979) and in the late 80’s they were strongly developed together with the development of devices/methods used for measuring aerosols hygroscopicity and liquid water mass of aerosols like for example: tandem differential mobility analyzers (TDMA), aerodynamic particle seizers (APS), particle into liquid samplers, mist chambers, Karl Fischer titrators, cloud condensation nuclei counters (CCN), Droplet Measurement Technologies (DMT) CCN counters, and finally satellite methods (Table 9).

In this last time interval, pollutants with a strong, still active burst are related to the fine particulate matters ($PM_{2.5}$) and size fractionated PM suggesting the shift of the attention by the academic from the coarse particle nodes to submicrometer one.

Co-citation network

Such network represents a number of references that have been co-cited by a set of papers. A time period is divided into 23 1-year time slices, and an individual co-citation network is derived from each time slice. Every single time-slice network is very complex. In order to reduce the dimension of every slice, the top 50 most cited publications in each year are used to build a network of co-cited references in that particular year. Subsequently, individual networks are combined into single visualization (merged network). The publications in the presented visualization extend from early 70’s to the present. Figure 9 presents

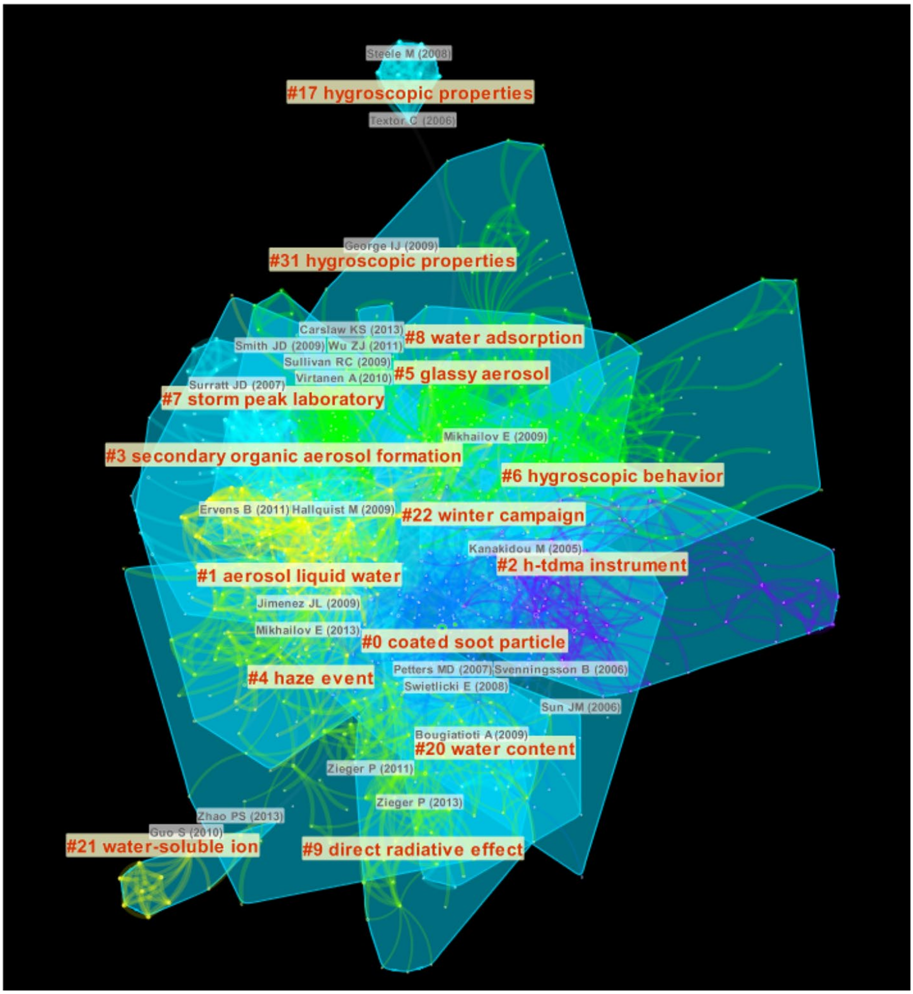

Fig. 9 Co-citation analysis of publications from 1996 to 2018

the resulting network of co-occurring co-citations and additionally the development of the aerosol-bound water topic over time, showing the most important footprints of the related research activities. Each node marked by concentric rings represents a cited reference. The thickness of a ring is proportional to the number of publication citation in a given time slice, while nodes color represents the year of the first co-citation. In presented network the dominant color is yellow corresponding to citations which were first made in the time frame 1996–2018. As can be observed from Fig. 9 the most important publications corresponding to the biggest nodes on the graph with the highest citation frequency from Petters and Kreidenweis (2007) and Kanakidou et al. (2005).

In the next step we make some sense of the nature of major clusters in merged network that may inform us about the stage of the underlying specialties. In the interesting example, a total of 262 clusters of co-cited references are identified. The modularity

Q of 0.8025 is rather high, which means that the network is reasonably divided into loosely coupled clusters or in other words the specialties in aerosol bound water domain are clearly defined in terms of co-citation clusters. The mean silhouette score of 0.3102 suggests that the homogeneity of these clusters on average is not very high. It's mainly due to the presence of numerous small clusters. The major clusters that we will focus on in the review are sufficiently high. In this study, we consider a cluster as the embodiment of an underlying specialty. Thus, science mapping consists of multiple specialties that contribute to various aspects of the domain. The areas of different colors indicate the time when co-citation links in those areas appeared for the first time. Areas in violet were generated earlier than areas in yellow. The links depict co-citations. More prominent links are from the original search (Fig. 9).

Figure 10 represents the map of the merged network, which in fact reflects the development of aerosol bound water topic over time, showing the most important footprints of the related research activities. This analysis focuses on a network of cited authors connected by co-citation links (more information: Chen et al. 2010). Each node represents a cited reference. To characterize the nature of an identified cluster, we extract noun phrases from the titles. Each term represent some specialties in a scientific field, which nature is a fundamental challenge for gathering information regarding aerosol water science. This analysis indicate that "mixing state"; "internal mixture"; "water-soluble organic carbon" and "inorganic salt aerosol" have largest nodes and therefore are some kind of focuses in this field. This analysis also shown that the study focus has changed over time from "water solubility"; "liquid aerosol particles" and "water vapor" into "hygroscopic behavior"; "water soluble organic carbon" and "hygroscopic growth studies" and broadly understood diverse chemical "mixing state" of aerosols.

For better visual reception the merged network was clusterized (Fig. 11) Top-terms were used to extract information, and the LSI algorithm was used as the calculation method to obtain clustering results; all information regarding single clusters were summarized in Table 7. The table was divided into 5 columns. The "size" column refers to the number of publications within the cluster, the "silhouette" value tells about the homogeneity of a

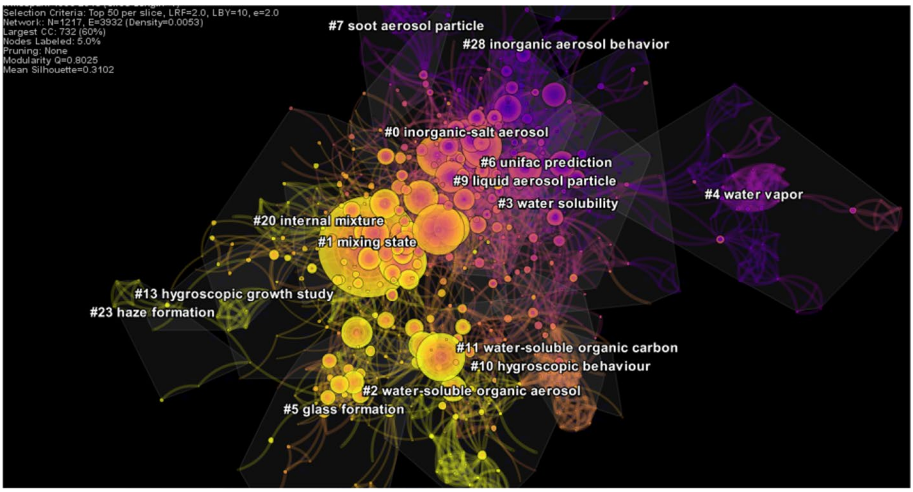

Fig. 10 Landscape view of the resulted network

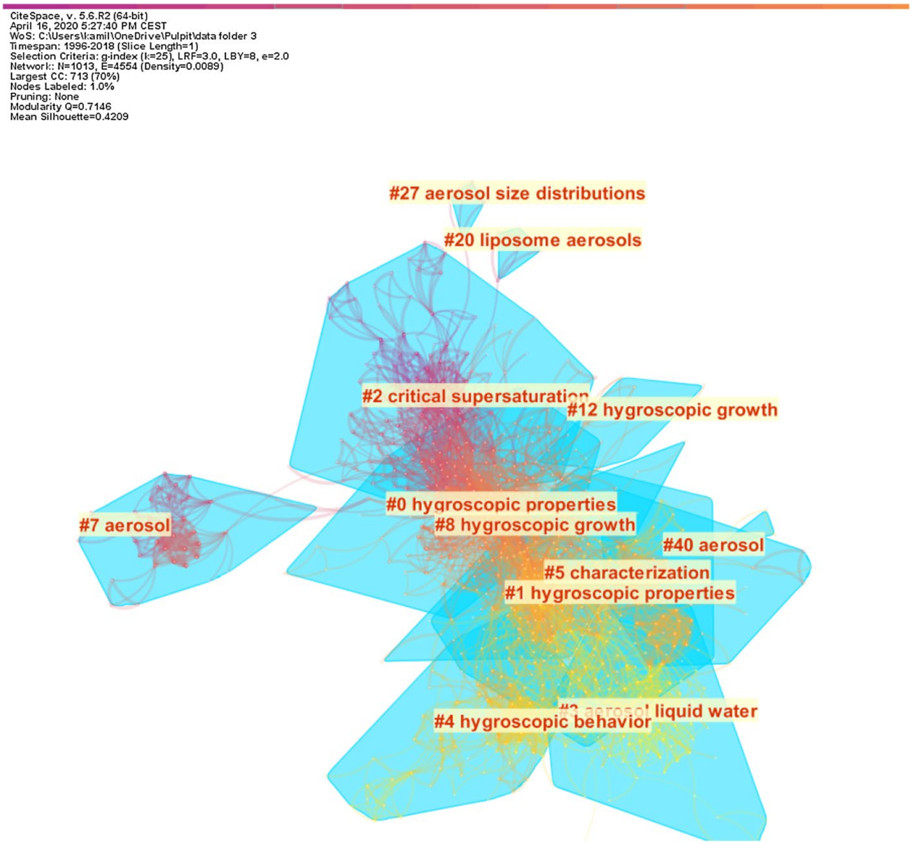

Fig. 11 Merged network clusterization. Clusters labeled by top terms using LSI

cluster (it ranges between − 1 and 1; higher values indicate meaningful clusters), "the mean year" is the period in which the cluster evolves.

Among 63 clusters found, 13 effective clustering tags were obtained (with silhouette score 0.71–0.99). Cluster #0 (hygroscopic properties) was the largest one, followed by cluster #1 (hygroscopic properties), cluster #2 (critical supersaturation), cluster #3 (aerosol liquid water) and cluster #4 (hygroscopic behavior). The terms used in last column (Table 7) gives us a clear picture of what the cluster is about. The terms find indicate that biggest clusters are about processes of hygroscopic measurement of PM, which is not surprising considering that one of the leading searching quotes during articles acquisition from WoS was keyword: "hygroscopic". To create a better picture of cluster character the last column should be extended by other representative terms with the numbers of LLR (log-likelihood ratio) next to them. Configuration of clusters on Fig. 11 indicate that airborne aerosol size distribution or liposome aerosols creates some thematically (or semantically) separated areas while hygroscopic growth; hygroscopic properties; aerosol liquid water are thematically related areas.

A dual-map of journals was also displayed (Fig. 12), where left map depicts cited journals while the right map—citing ones (the journal in which a source article is published is called a "citing journal; while the journal in which a reference is published

Table 7 Cluster descriptors for five biggest clusters

Cluster ID	Size	Silhouette	Mean (year)	Top terms (LSI)
0	145	0.713	2002	Hygroscopic properties; measurements; multifunctional acids; unifac predictions; ozone system; gas–particle partitioning; secondary organic aerosol; humic acid aerosol particles; laboratory; modelling study | hygroscopic growth; organic compounds; mixed aerosol particles; critical supersaturations; atmospheric relevance; dicarboxylic acids; ammonium; hygroscopic properties; hygroscopic cycles; California aerosol
1	142	0.732	2008	Hygroscopic properties; aerosol particles; chemical; zotino; tall tower observatory; summer campaign; central European aerosol; aerosol; aerosol particle light; influence | hygroscopic growth; cloud condensation nucleus activity; size-segregated measurements; spring; liquid water content; model; CCN activation; water-soluble aerosol fraction; north china plain; mirage
2	131	0.83	1996	Critical supersaturation; predicting particle; humidified TMDA; hygroscopic growth measurements; theory; sensitivity studies; hygroscopic properties; chemical characterization; inorganic aerosol behavior; hygroscopic growth | hygroscopic properties; unifac predictions; multifunctional acids; measurements; surface-active organic compounds; inorganic-salt aerosol; chemical characterization; inorganic aerosol behavior; hygroscopic growth; different areas
3	83	0.784	2012	Aerosol liquid water; optical thickness; surface fine particle mass; reconciling satellite aerosol; aerosol water; north china plain; hygroscopic growth; ubiquitous contributor; reactive nitrogen chemistry; hydrophilic interaction liquid chromatography | water; isoprene; secondary organic aerosol formation; different roles; toluene; aerosol water; north china plain; hygroscopic growth; ubiquitous contributor; reactive nitrogen chemistry
4	81	0.906	2011	Hygroscopic behavior; efflorescence; nacl–mgcl2 mixture particles; nascent sea-spray aerosol surrogates; observation; humidification; viscous organic aerosol particles; diffusivity-controlled water uptake; upper troposphere; hygroscopic properties | NaCl; hygroscopic properties; chemical compositions; situ Raman microspectrometry; aerosols; real-time investigation; malonic acid mixture solutions; inorganic sea-salt aerosol surrogates; nano3 mixture particles; aerosol water
5	45	0.934	2007	Characterization; mass spectrum analysis; solvent-extractable organics; urban aerosols; hygroscopic growth measurement; size distribution; variations; coastal new England; water-soluble organic aerosol; source apportionment | secondary organic aerosol formation; implications; fine particle; water-soluble organic carbon; states; seasonal variations; water-soluble organic aerosol; source apportionment; mass spectrum analysis; solvent-extractable organics

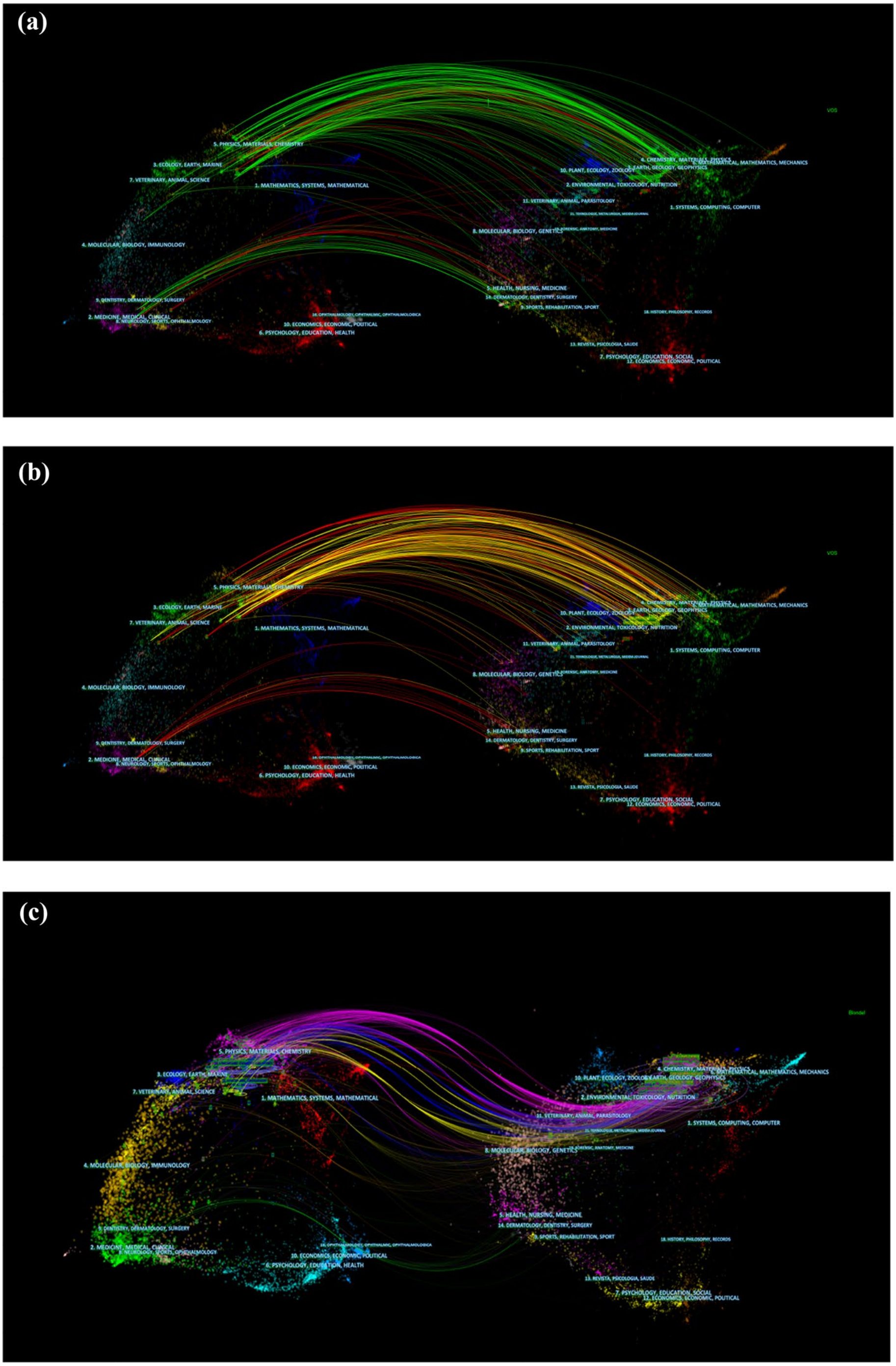

Fig. 12 The dual-map overlay of the science mapping literature regarding aerosol-bound water in time slices 1996–1997 (**a**); 1998–1999 (**b**) and 1996–1998 and 2013–2016 (**c**)

is called a “cited journal”). The lines, which start from left to right, are citation links. This dual map overlay indicate that most articles on PM-bound water were published in physics, materials, chemistry, ecology, earth, marine, veterinary, animal science, mathematics, systems, mathematical journals and they mostly cited works from chemistry, material, physics, environmental, toxicology, nutrition, plant, ecology, geology, geophysics, systems, computer, computing. Dividing time span into single-slice overlays (Fig. 12a–c) indicate that citation years are rather similar regarding disciplines most engaged into PM-bound water research. Two parallel trends can be distinguished when speaking about development of the PM-bound water field—the first concern environmental-chemical approach, the second can be described as health trend (health, nursing, medicine disciplines).

The dataset including 101 publications were subjected to full text review. This analysis outlined the past and present in PM-bound water research. Water content was monitored in 24 studies, although only 23 among them presents results in the form of mass, percentage or concentration values. Among 20 different pollutants selected (Fig. 13), the concentrations of organic carbon/organic matter were most investigated with the number of studies—44 (Table 8) and had the longest history of investigation (1973). Water soluble ions (for example Cl^-, NO_3^-, SO_4^{2-}) take the second place in this ranking with the number of studies—42. PM_{10} and $PM_{2.5}$ were determined in 32 and 29 studies, respectively). Water content treated as unidentified mass of PM but also determined as aerosol water uptake or hygroscopic growth measurement was investigated in 20 studies (water associated with inorganic ions or organic carbon wasn’t included in this summary) (Table 8, Fig. 13). Articles regarding quantitative measurements of PM-bound water were reviewed and used to gather information regarding methodology used for PM-bound water determinations (Table 9). Most of those studies (22) used experimental methods for the assessment of water contents. Since PM-pollution is not randomly assigned across locations, presented experiments do not adequately control for a number of potential confounding determinants of PM-bound water and therefore they cannot be treated as semi (quasi) experiments. Only two works used data from EMEP

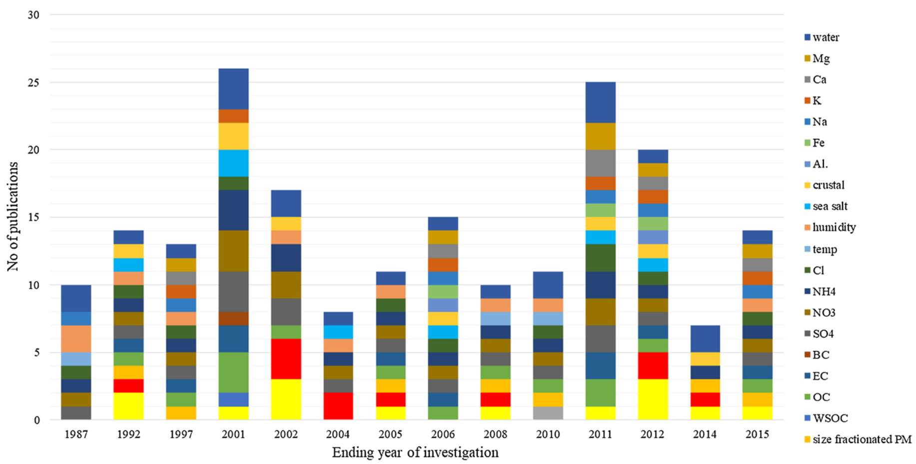

Fig. 13 Investigated pollutants by year (number of studies) based on dataset presented in Table 8. *Note* All articles taken into bibliometric analysis were published in the time-span 1996–2018, however some of them presents data collected before this period; therefore 1987 and 1992 investigations appeared on the graph

Table 8 Number of research studies from the network (without reviews) choose after full text review by pollutants spectrum, place and period of investigation

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
1	Grigoratos et al. (2014)	PM_{10} and $PM_{2.5}$, (Mg, Al, Si, S, Ca, K, Ti, Mn, Fe, Co, Ni, Cu, Zn, Se, Br, Sr, Sn, Te, Pb), NO_3^-, SO_4^{2-}, Cl^-, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, OC, EC	Europe	Thessaloniki, Greece (urban-background)	2011/2012
2	Maenhaut et al. (2011)	$PM_{2.5}$ and PM_{10}, OC and EC, NH_4^+, NO_3^-, SO_4^{2-}, Na, Mg, Al., Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Br, Pb	Europe	One of the 20 stations is the station for measuring forest Ecosystem–atmosphere relations (SMEAR II) Hyytiälä, Finland	2007
3	Marcazzan et al. (2001).	PM_{10} and $PM_{2.5}$, Al, Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Br, Pb, ammonium sulfate, crustal material, heavy metals oxides, others	Europe	Milan, Italy (urban area)	1997/1998
4	Perrino et al. (2008a, b)	$PM_{2.5}$ and PM_{10}, EC, OC, Al, Fe, K, Mg, Ca, Ti, S, Si, NO_3^-, SO_4^{2-}, Cl^-, Na^+, Ca^{2+}, Mg^{2+}, NH_4^+, Al, As, Cd, Cr, Cu, Fe, Mg, Mn, Ni, Pb, S, Sb, Se, Si, Ti, V, Zn	Europe	in Rome (traffic station); Rome (urban background); Latina (urban station), Viterbo (urban station), Fontechiari (regional background)	2004/2005
5	Perrino et al. (2012)	Aerosol mass losses of weakly and strongly bound water	Europe	Montelibretti, Rome Italy, (pri-urban)	2009
6	Perrino et al. (2014)	PM_{10} and $PM_{2.5}$, natural radioactivity, Al, Si, Fe, N, K, Mg, Ca, Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, OC, EC	Europe	Ferrara (suburban)	2010–2012
7	Terzi et al. (2010)	PM_{10}, OC, Cl^-, NO_3^-, SO_4^{2-} and NH_4^+	Europe	Thessaloniki, Greece (urban-background)	2007
8	Vecchi et al. (2009)	PM_{10}, OC and EC, nitrate artefacts, organic artefacts	Europe	Milan (urban background)	2007
9	Viidanoja et al. (2002)	PM_{10} and $PM_{2.5}$, OC and BC, positive quartz filter artefacts	Europe	Helsinki, Finland (urban site)	2000/2001

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
10	Duan et al. (2006)	PM_{10} and $PM_{2.5}$, OC and EC, SO_2, NO_2, CO/10, NO_3^-, SO_4^{2-}, NH_4^+, K^+, Mg^{2+}, Na, Mg, Si, S, Cl, K, Ca, Ti, Fe, Cu, Zn, As, Se, Br, Pb	Asia	Tsinghua Beijing, China (semi-residential)	2001/2002
11	Rees et al. (2004)	$PM_{2.5}$, sulfate, nitrate, and ammonium, OC, EC, crustal matter, water	Europe	PAQS ambient monitoring station located in Schenley Park, Pittsburg, Pennsylvania	2001
12	Harrison et al. (2003)	PM_{10}, sulfate, nitrate, chloride, OC, EC, iron and calcium	Europe	Four pairs of sites, three in London and one in Birmingham (roadside location)	2000–2002
13	Ho et al. (2006)	PM_{10} and $PM_{2.5}$, OC, EC, water-soluble organic carbon (WSOC) and water-insoluble organic carbon (WIOC), Cl^- NO_3^-, SO_4^{2-} and NH_4^+, (Na and K, Al, Ca, Fe and Ti, Mg, Zn, As, Cr and Cu, Sr, V, sea salt, crustal matter, others	Asia	Hong Kong, China (urban and rural)	2000/2001
14	Bardouki et al. (2003)	Size segregated particles, chloride: Cl^-; Br^-; NO_3^-; SO_4^{2-}, oxalate: $C_2O_4^{2-}$ and MS^-, $HCOO^-$, CH_3COO^-, $C_3H_5O^{2-}$, $C_2O_4^{2-}$, $C_4H_4O_4^{2-}$, $C_5H_6O_4^{2-}$, $C_3H_3O_3^-$, Na^+; NH_4^+; K^+; Mg^{2+} and Ca^{2+}, Al, Si, K, Ca, Ti, Mn, Fe, Sr, S, Cl, Ni, V, Cu, Cr, Zn, and Pb.	Europe	Finokalia, Eastern Meditarranean coastal site (the top of a small building)	2000/2001
15	Li et al. (2010)	Particles larger than 1.5 µm ambient diameter, TC/OC, (NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}), total water soluble organic carbon content, neutral compounds, Mono/di-acids, polyacids	Asia	Eastern China, Changbai Mountain Nature Reserve (CB), Chongming Island (CM), Dinghu Mountain Nature Reserve (DH), and Jingfengling Nature Reserve in Hainan Island (HN)	2006/2007

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
16	Decesari et al. (2001)	(d < 1.5 μm) aerosol, TC,/OC, (Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}, total water soluble organic carbon content	Europe	Po Valley, Italy. San Pietro Capofiume	1998/1999
17	Balasubramanian et al. (2003)	$PM_{2.5}$, water-soluble ions nss-SO_4^{2-}, nss-K^+, and nss-Ca^{2+}, water-soluble organic compounds (WSOC), elemental carbon (EC), organic carbon, and trace elements ((Al, Ag, Ba, Cd, Cr, Co, Cu, Fe, Ga, Li, Mn, Ni, Pb, Sr, Zn, V, Si, and Ti)	Asia	Singapore, Atmospheric Research Station	2000
18	Yin et al. (2005)	(PM_{10}, $PM_{2.5}$ and $PM_{2.5-10}$), (SO_4^{2-}, NO_3^-, Cl^-, $CH_3SO_3^-$, NH_4^+, Na^+, K^+, Mg^{2+} and Ca^{2+}), elemental carbon (EC) and organic carbon (OC)	Europe	Ireland, Galway City, Dublin, Ballinasloe (roadside, urban, rural and coastal) monitoring sites	2001–2002
19	Maenhaut et al. (2002)	Size segregated PM, OC and EC, 27 elements (e.g. Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Zr, Nb, Mo and Pb), chemical mass closure	Europe	Belgium, Gent	1999
20	Perrino et al. (2011)	PM_{10} and $PM_{2.5}$, EC, OC, (Na, Mg, Al, Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Br, Sr, Ba, Pb, ions, EC, OC, levoglucosan, Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}. Li, Co, Ga, Rb, Cd, Sn, Sb, Cs, Ce, W, Tl, Bi	Asia	Divali Festival, New Delhi	2008/2009

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
21	Sillanpaa et al. (2006)	$PM_{2.5}$ and coarse $PM_{2.5–10}$, Cl^-, Br^-, NO_3^-, succinate, malonate, SO_4^{2-} and oxalate as well as Na^+, NH_4^+, K^+, Ca^{2+} and Mg^{2+}, (water-soluble plus water-insoluble particulate fractions) of K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Se, Br, Rb, Sr, Pb, Al, Si, S and Cl, The water-soluble fraction of elements, including Al, Cd, Co, Cr, Cu, Mn, Ni, Pb, V, As, Fe and Zn, organic carbon (OC) and elemental carbon (EC)	Europe	Six urban sites in Europe	2002/2003
22	Putaud et al. (2010)	PM_{10} and $PM_{2.5}$, EC, NO_3^-, NH_4^+, organic matter (OM) and carbonaceous matter (CM) concentrations, Cl^-, $nssSO_4^{2-}$, min. dust, EC, TC	Europe	60 sites across Europe (rural, urban, kerbside)	1996–2007
23	Joseph et al. (2012)	$PM_{2.5}$, ions, OC, EC, TC and elemental analysis Al, As, Ba, Ca, Cd, Cu, Cr, Fe, In, K, Mg, Mn Na, Ni, Pb, Se, Si, Sr, Ti, V, Zn, nss-Ca^{2+}, nss-K^+, nss-SO_4^{2-}, ss-Ca^{2+}, ssK^+, ss-SO_4^{2-}, Cl^-, NO_3^-, SO_4^{2-}, K^+, NH_4^+, Na^+, and Ca^{2+}	Asia	Mumbai City India	2007/2008
24	Taiwo (2016)	$PM_{2.5}$ and $PM_{10–2.5}$, Cu, Zn, Fe, Ni, Mn, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, $C_2O_4^{2-}$, Na^+, NH_4^+, K^+, Ca^{2+}, OC and EC	Europe	Birmingham UK	2011
25	Sciare et al. (2005)	PM fine and coarse size fractions, (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, Br^-, SO_4^{2-}, PO_4^{3-}), BC and OC, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Pb, sea salt, dust,	Europe	Eastern Mediterranean	2001

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
26	Shen et al. (2010)	PM_1, OC, and EC, SO_4^{2-}, NO_3^-, Cl^-, and F^-, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}, SOC	Asia	Downtown Xi'an China	2007/2008
27	Maenhaut et al. (2008)	$PM_{2.5}$ and PM_{10}, OC, EC, NH_4^+, NO_3^-, SO_4^{2-}, Na Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn, Pb, unexplained mass, OC, EC, nss-sulphate, sea salt, crustal elements	Europe	K-puszta Hungary	2006
28	Turpin and Lim (2001)	Carbon weight for an urban aerosol	USA	Pasadena, Los Angeles	1973
29	Schaap et al. (2004)	$PM_{2.5}$, PM_{10}, PM_1, NO_3^-, SO_4^{2-}, evaporation artefact	Europe	Melpitz research station Lepizig conurbation, Germany	2000
30	Wittmaack and Keck (2004)	$PM_{2.5}$, PM_{10} and TSP, pure and mixed salts desorption, inorganic ions desorption	Europe	National Research Center Munich, Germany	2002
31	Eatough et al. (1996)	The loss of semi-volatile organic compounds from the particles collected on quartz filters during sampling, carbonaceous material, light extinction	USA	Canyonlands National Park Utah	1990
32	Hering and Cass (1999)	$PM_{2.5}$, the loss of nitrate from PM filters, mass of ammonium nitrate volatilized from Teflon filter	USA	Los Angeles Basin	1987
33	Perrino et al. (2013)	PM_{10} and $PM_{2.5}$, EC, OC, ionic composition, elemental composition, water content	Europe	Po Valley Italy	2008–2011
34	Neususs et al. (2000)	PM_{10}, number size distribution, mass-size distribution, OC, EC, hygroscopicity, NH_4^+, K^+, Ca^{2+}, Na^+, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, N_2O, water (gravimetric versus chemical mass)	Europe	Sagres Portugal	1997

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
35	Subramanian et al. (2004)	PM_{10}, $PM_{2.5}$, ambient particulate organic carbon (POC), positive and negative sampling artifacts	Europe	Pittsburgh Penssylvania	2002
36	Ohta et al. (1998)	Particles (aerosols less than 2 μm in diameter), water content, elemental carbon, organics, sulfate, nitrate, chloride, ammonium, sea-salt cations and soil particles	Asia	Sapporo, Japan	1992
37	Engelhart et al. (2011)	Aged atmospheric aerosol, water, relative humidity	Europe	Finokalia Crete marine station	2008
38	Canepari et al. (2013)	Atmospheric particulate matter (PM_{10}), water	Europe	Rome Italy	2011
39	Mikhailov et al. (2015)	(PM) in the accumulation mode and coarse mode, hygroscopic growth measurements	Asia	Zotino Tall Tower Siberia	2013
40	Canepari et al. (2017)	Mass size distribution of particle-bound water	Europe	Po Valley Italy	2012–2014
41	Meng et al. (1995)	Water content associated with the inorganic fraction of $PM_{2.5}$ and PM_{10} mass	USA	South Coast Air Basin, California's	1987
42	Hueglin et al. (2005)	PM_{10}, $PM_{2.5}$, water soluble ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, NH_4^+, NO_3^-, SO_4^{2-}, Cl^-, trace elements (Na, Mg, Al, K, Ca, V, Mn, Fe, Ni, Cu, Ga, As, Se, Br, Rb, Y, Mo, Rh, Cd, Sb, Ba, La, Ce, Nd, Tl, Pb), as well as elemental and organic carbon, water content associated with the inorganic salts	Europe	Switzerland (urban, near city and rural sites)	1998–1999
43	Tsai and Kuo (2005)	$PM_{2.5}$, relative humidity, water soluble chemical species, water contents	Asia	Taiwan (coastal, metropolitan area)	2002

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
44	Rogula-Kozlowska et al. (2017)	PM_1, water contents, relative humidity, temperature	Europe	Poland (two urban sites)	2010
45	Massling et al. (2009)	Size segregated water uptake of the urban submicrometer aerosol	Asia	Beijing (urban site)	2004/2005
46	Farao (2013/2014)	Secondary inorganic compounds, sea salt, crustal compounds, organic carbon, primary anthropogenic compounds, water content	Europe	Rome (urban background site), Palermo (urban site), Montelibretti (peri-urban site).	2011
47	Perrino et al. (2010)	PM_{10}, NH_4^+, NO_3^-, SO_4^{2-}, Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, EC, OC, natural radioactivity, wind velocity,		Rome (urban site)	2008
48	Perrino et al. (2009)	PM_{10} and $PM_{2.5}$, (Al, Si, Fe, K, Mg, Ca, Ti, S), NH_4^+, NO_3^-, SO_4^{2-}, Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, EC and OC, sea salt, crustal matter	Europe	Lazio region (traffic, urban background, near city, reagional background)	2004/2005
49	Perrino et al. (2008a)	PM_{10}, EC, OC, sulfate, nitrate, natural radioactivity, wind speed	Europe	Rome Italy (traffic, urban background, semi-rural)	2003
50	Perrino et al. (2008a, b)	PM_{10}, $PM_{2.5}$, EC, OC,, Al, Fe, K, Mg, Ca, Ti, S, Si, NH_4^+, NO_3^-, SO_4^{2-}, Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+}	Europe	Lazio region Italy	2004
51	Facchini et al. (2000)	Surface tension of cloud/fog samples and aerosol water extracts	Europe	Po Valley Italy, Puy de Dome central France, Tenerife	2000
52	Duplissy et al. (2011)	Water uptake (hygroscopicity) of secondary organic aerosol (SOA) formed during the chemical and photochemical oxidation of several organic precursors in a smog chamber	USA	Jungfraujoch, Mexico City	2006

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
53	Jung et al. (2009)	Carbonaceous aerosol, water-soluble inorganic ions, ammonium sulfate, $(NO_4)_2SO_4$, ammonium nitrate, NH_4NO_3, organic mass by carbon, sea salt, fine soil, unknown, coarse mass	Asia	Gangzhou (urban site)	2006
54	Cropper et al. (2013)	$PM_{2.5}$, light scattering, relative humidity, OC, EC, sulfate and nitrate, BC	USA	Utah monitoring site	2012
55	Cropper et al. (2018)	$PM_{2.5}$, light scattering, levoglucosan, dehydroabietic acid, stearic acid, pyrene, and anthracene	USA	Brigham Young University Utah Valley	2015
56	Bharti et al. (2017)	PM_{10}, $PM_{2.5}$, relative humidity, wind speed, temp., composition of inorganic mass, composition of organic mass	Asia	Lucknow India	2015/2016
57	Chen et al. (2009)	PM_{10} and $PM_{2.5}$, particulate water, chloride, sodium, nitrate, sulphate, organic matter, and ammonium	USA	California's Central Valley	2000/2001
58	Grimm and Eatough (2009)	PM_{10}, $PM_{2.5}$, light scattering, semi-volatile components	USA	Rubidoux CA, Fresno CA, Lindon UT, California's	2003/2007
59	Graham et al. (2002)	Biomass burning aerosol, WSOC, OC, BC, K, sugar alcohols, sugars	South America	Rainforest Brazil	1999
60	Hegg et al. (1997)	Aerosol optical depth, aerosol volume, total aerosol mass, aerosol light scattering, aerosol light absorption, hygroscopic scattering factor, aerosol chemical composition, relative humidity, aerosol carbon, aerosol sulfate, single scattering albedo	USA	Mid Atlantic Coast US	1996

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
61	Sellegri et al. (2003)	Size segregated aerosol, (Na^+, NH_4^+, K^+, Mg_2^+, Ca_2^+, NO_3^-, SO_4^{2-}, Cl^-) and organic ($HCOO^-$, $CH3COO^-$, and $C_2O_4^{2-}$) ions, organic and elemental carbon (OC and EC), insoluble dust, and total mass	Europe	Puy de Dome, France	2000/2001
62	Su et al. (2018)	Size segregated PM, actual relative humidity in the impactor, NH_4+, NO_3^-, SO_4^{2-}, Cl^-, K^+, OC, and EC, aerosol liquid water content	Asia	Beijing, Institute of Urban Meteorological in the Haidian district	2013–2015
63	Perrino et al. (2016)	PM_{10}, water content of the PM samples, Si, Al, Fe, Na, K, Mg, Ca, chloride, nitrate, sulfate, ammonium, elemental carbon, organics		Chamonix-Mont Blanc, Tunis, Palermo, different sites of the Mediterranean area urban environments, marine atmosphere and rural areas	2005–2015
64	Tsyro (2005)	PM_{10}, sulphate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), elemental (EC) and organic (OC) carbon, sea salt (NaCl) and mineral dust, aerosol water calculated with EQSAM model	Europe	EMEP stations	1999–2001
65	Rogula-Kozłowska et al. (2019)	PM_1, EC, OC, Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-}, F^-, Na^+, NH_4^+, K^+, Ca^{2+}, and Mg^{2+}, PM_1-bound water	Europe	Two urban sites in Poland	2014–2015
66	El-Sayed et al. (2018)	Water-soluble organic carbon in the gas phase (WSOCg) and in the particle phase (WSOCp), VOC, NOx, aqSOA, RH	USA	Baltimore	2014/2015

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
67	Fernandez et al. (2018)	Aerosol backscatter coefficient profiles, relative humidity, the mass of water vapor to the mass of dry air in a certain volume (water vapor mixing ratio (w)), RH, temp.	Europe	Madrid	2012/2014
68	Good et al. (2010)	Hygroscopic growth and CCN (cloud condensation nuclei) activity of atmospheric aerosols, size resolved water uptake at sub- and supersaturation, mean hygroscopic growth factor	Europe	University of Manchester, Manchester, UK	–
69	Guo et al. (2010)	PM_{10} and size-segregated particle mass concentrations, Totally five kinds of cations (Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}), four kinds of anions (F^-, Cl^-, NO_3^- and SO_4^{2-}), and three kinds of low molecular weight water soluble organic compounds (formate, acetate and oxalate), gaseous NH_3 and HNO_3	China	Peking University, PKU) and an upwind rural site Yuta	2006
70	Haywood et al. (2011)	Sulfate, fossil-fuel black carbon, fossil-fuel organic carbon, biomass burning aerosol, biogenic organic aerosol, mineral dust and sea-salt, nitrate, water vapor concentrations	Global	global	1980–1860, 2000–1980
71	Hsieh et al. (2011)	Particle-bound water soluble ions from cooking fume Na^+, K^+, NO_2^-, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-}	Asia	southern Taiwan	2009
72	Huang et al. (2016)	Water-soluble inorganic ions (SO_4^{2-}, $NO_3^-NH_4^+$, Cl^-, K^+, Na^+, Ca_2^+ and Mg^{2+}) in size-segregated PM, relative humidity (RH) and temperature	Asia	Beijing	2013/2014

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
73	Irwin et al. (2011)	Aerosol number size distribution, hygroscopicity in both sub- and supersaturated regimes (Hygroscopic growth factor), aerosol water uptake, the number of cloud condensation nuclei	Asia	Borneo, Malaysia	2008
74	Jung et al. (2009)	Light-extinction coefficient, Light-scattering coefficient, Light-absorption coefficient, PM_{10}, $PM_{2.5}$, $PM_{1.0}$ mass concentration, organic carbon/elemental carbon, water-soluble ions, ammonium sulfates, ammonium nitrates, organic mass by carbon, elemental carbon, sea salt, others	Asia	Guangzhou, Pearl River Delta	2006
75	Kelly and Wexler (2006)	Water activity in supersaturated potassium solutions	USA	California	–
76	Kitamori et al. (2009)	100 and 200 nm particles, aerosol hygroscopic growth, temp, humidity, water content, particle hygroscopicity	Asia	Sapporo Japan	2006
77	Kreidenweis et al. (2008)	Composition-dependent water activities of several aqueous solutions of atmospheric interest	USA	Colorado	–
78	Lee and Hsu (1998)	Aerosol water content as a function of RH for the indicated metastable binary solutions	USA	Colorado	–
79	Lee et al. (1999)	Size segregated PM, SO_4^{2-}, NO_3^- NH_4^+, Cl^-, K^+, Na^+, Ca^{2+} and Mg^{2+}	Asia	Northwestern Taiwan	1994

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
80	Li et al. (2011)	Surface tension of aerosol droplets by performing molecular dynamics simulations on two model systems, the pure water droplets and glycine in water droplets	Europe	Stockholm, Sweden	–
81	Liu et al. (2014)	Water vapor mixing ratios; water vapor gradient, aerosol backscattering coefficients	USA	University of Wyoming King Air (UWKA)	2010
82	Liu et al. (2017)	Size segregated PM, (Cl^-, SO_4^{2-} and NO_3^-) (NO, NO_2, O_3 and SO_2	Asia	Beijing	2010
83	McDow et al. (1995)	Wood smoke samples, Diesel soot samples, the effect of water content on photoreactivity of PAHs, RH	USA	Pittsboro, NC, North Carolina	–
84	Metzger et al. (2018)	The importance of aerosol water for AOD	Europe	The Cyprus Institute, Nicosia, Cyprus	2000–2010, 2000–2013, 2005
85	Metzger et al. (2016)	Aerosol water uptake for mixtures of semi-volatile and non-volatile compounds	Europe	The Cyprus Institute, Nicosia, Cyprus	–
86	Mikhailov et al. (2013)	Concentration-dependent water uptake by atmospheric aerosol particles with complex chemical composition	Asia, South America	Manaus Brazil, Saint Petersburg Russia	2008/2009
87	Rastak et al. (2014)	The impact of water uptake by aerosol particles in ambient atmosphere	Europe	Ny-Ålesund, Svalbard, Sweden	2008
88	Schuster et al. (2009)	Retrieving the aerosol water uptake from the aerosol real refractive index, and applied it to the column-effective AERONET retrievals	global	global	–

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
89	Tham et al. (2018)	N_2O_5 and $ClNO_2$, NO, NO_2, O_3, SO_2, CO, and total odd nitrogen (NOy), Hydroxyl radicals (OH), Hydroxyl radicals (OH), the RH and the aerosol water content	China	Wangdu county of Hebei province, in the northern part of China	2014
90	van Beelen et al. (2014)	The aerosol dry mass, the masses of several aerosol species, and aerosol water	Europe	Cabauw, the Netherlands	2008
91	Wang et al. (2019)	$PM_{2.5}$, The relationship among SIA, pH, gas-phase precursors, and meteorological conditions, Na^+, Ca^{2+}, Mg^{2+}, K^+, NH_4^+, SO_4^{2-}, NO^{3-}, Cl^-), OC, EC, Si, Al, Fe, pH, water content	China	Hohhot, a major city in China	–
92	Wozniak et al. (2015)	PM_{tot}, Aerosol water soluble organic carbon (WSOC) and iron (Fe)	USA	North Atlantic Ocean	2011
93	Berg et al. (1998)	Particles with diameters 35, 50, 75, and 150 (or 165) nm. Hygroscopic properties of submicrometer aerosol particle, RH, relative hygroscopic growth, temperatures, humidity, and flow line pressures	USA, Australia	Pacific and Southern Oceans (from Seattle, United States to Hobart, Tasmania, Australia) and Southern Ocean south and south west of Tasmania	1995
94	Hegg et al. (1997)	Aerosol optical depth, aerosol volume, total aerosol mass, the contributions of various chemical species to the aerosol optical depth, aerosol light-scattering and aerosol light-absorption coefficients, hygroscopic scattering factor and aerosol chemical composition	USA	The mid-Atlantic coast of the United-State, between New Jersey and North Carolina	1996

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
95	Kotchenruther et al. (1999)	Aerosol size distribution, light-scattering coefficients of aerosols as a function of relative humidity(RH) and wavelength, aerosol hygroscopic growth, RH, degree of deliquesce	USA	Mid-Atlantic coast of the United States	1996
96	McMurry et al. (1996)	Hygroscopic growth, TDMA, mixing characteristics, chemical composition, aerosol water content	USA	Minneapolis	1993/1994
97	Russell et al. (1999)	Aerosol size distribution, chemical, physical and optical properties of the responsible aerosol particles, optical depth, radiative flux changes,	USA	Mid-Atlantic coast	1996
98	Tang (1997)	Extensive water activity, density and refractive index data at 25øC for mixed-salt solution (the light scattering properties of both internal and external mixtures of the chloride, sulfate, and nitrate aerosol, RH	USA	New York	1995
99	Virkkula et al. (1999)	Hygroscopic properties of aerosol formed by oxidation of three monoterpenes, hygroscopic growth factor, RH	Europe	Valencia, Spain	–
100	Weingartner et al. (1997)	Hygroscopic properties of freshly produced carbon and diesel soot particles at subsaturations (i.e. at relative humidity < 100%), RH, chemical analysis of aerosol	Europe	Zurich, Switzerland	–

Table 8 (continued)

Nos.	References	Pollutant, parameter	Continent	Site	Period of investigation
101	Zappoli et al. (1999)	Mass balance of aerosol ((1.5 µm AED) collected at three European sites was performed with reference to the water solubility of the different aerosol classes of components	Europe	Aspvreten background site in central Sweden, K-puszta rural site in the Great Hungarian Plain and San Pietro CapoÞume Po Valley, northern Italy	1996

When the paper is based on modelling results or experiments performed in laboratory conditions (without any field measurements) usually the column “period” cannot be filled

Table 9 Methodological analysis of studies regarding PM-bound water measurement

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
1	Su et al. (2018)	Size-segregated PM samples: 0.056, 0.10, 0.18, 0.32, 0.56, 1.0, 1.8, 3.1, 6.2, 9.9 and 18 µm	Micro-Orifice Uniform-Deposit Impactor (MOUDI-120)	Quartz fiber filters (Pallflex, 47 mm)	Average mass concentration of aerosol liquid water content—0.02 to 369.12 (µg m^{-3})	ISORROPIA II model	E	July 12–18, 2013, January 13–19, 2014, July 3–5, 2014, October 9–20, 2014, January 26–28, 2015	Residential area in the Haidian district in the northern urban area of Beijing: unpolluted site; polluted site and heavily polluted site	$PM_{2.5}$ mass concentrations and the ambient relative humidity; water soluble inorganic ions (Na^+, NH_4^+, K^+, Mg_2^+, Ca_2^+, Cl^-, NO_3^-, and SO_4^{2-}); OC; EC
2	Rogula-Kozłowska et al. (2017)	PM_1 fraction	Low volume sampler (2.3 m^3/h, Zambelli twin dust) with a PM_1 sampling head (TSI)	Quartz fiber filters	0.3–68%; in average 19% in Warsaw 20% in Zabrze	Coulometric titration. A set consisted of a Karl Fischer 831 coulometer with an 874 oven sample processor	E	2014–2015	Two urban sites in Poland—Zabrze and Warsaw cities	–

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
3	Canepari et al. (2017)	Size-segregated PM samples: 0.18, 0.32, 0.56, 1.0, 1.8, 3.2, 5.6, 10 and 18 µm	Two colocated Micro-Orifice Uniform Deposition Impactors (MOUDI)	Teflon filters, TEFLO, 47 mm, 2.0 µm pore size, PALL Life Sciences	SOP1 (5.6–35% H_2O)]; SOP2 (1.5–6.8% H_2O)]; SOP3 (1.2–4.4% H_2O); SOP4 (1.8–11% H_2O)	The size distribution of water by Karl Fischer coulometric titration by using a 831 KF Coulometer (Metrohm AG, Herisau, CH) equipped with a programmable oven (874 Oven Sample Processor; Metrohm)	E	Daily collection: Ist SOP (February 16th to March 1st, 2012); IInd SOP (February 13th to 26th, 2014); IIIrd SOP (May 16th to 27th, 2014); IVth SOP (December 3rd to 17th)	Areas subjected to different environmental conditions (protracted atmospheric stability, desert dust intrusion, urban atmosphere	The size distribution of water, PM mass, the content of inorganic ions and soluble and residual fractions of elements
		PM_{10} samples	Dual channel beta attenuation automatic monitor (SWAM 5a Dual Channel Monitor, FAI Instruments, Fonte Nuova, Rome, IT)	–	–	–				A complete chemical analysis of the samples (not reported in the cited paper

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
		PM_{10} samples	Single-channel sampler (Skypost PM, Tecora, Mi, IT).		10% to 33%	Determination of water by Karl Fischer coulometric titration by using a 831 kF Coulometer (Metrohm AG, Herisau, CH) equipped with a programmable oven (874 Oven Sample Processor; Metrohm)	E			Water contents
4	Taiwo (2016)	$PM_{2.5}$, $PM_{10–2.5}$	Two Partisols sequential air sampler (Rupprecht and Patashnick Dichotomous Partisol-Plus Model 2025)	Quartz fibre filters and Teflon filters	Unidentified mass (including water) equal 31% Water bound component in PM (20–30%)	Mass closure model	E	summer period of 2011 (June 2 –18)	Urban background of Elms Road Observatory Site (EROS) in Birmingham, United Kingdom	Cu, Zn, Fe, Ni, Mn, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, $C_2O_4^{2-}$, Na^+, NH_4^+, K^+, Ca_2^+, OC and EC

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
5	Perrino et al. (2016)	Rome (desert dust—PM_{10} fraction) Rome (road dust-PM_{10} fraction) Ferrara Atmospheric stability conditions (PM_{10} samples)	Dual channel beta attenuation automatic monitors (SWAM 5a Dual Channel Monitor, FAI Instruments, Fonte Nuova, Rome, IT) or dual channel samplers (HYDRA Dual Sampler, FAI Instruments, Fonte Nuova, Rome, IT).	Teflon membrane filters (TEFLO, 47 mm, 2.0 micron pore size, PALL Life Sciences) and quartz fiber filters (TISSUQUARTZ 2500QAT, 47 mm, PALL Life Sciences)	Desert dust—Up to 10% Road dust—Up to 8% Ferrara—stability conditions up to 22% of the total PM_{10}	Coulometric Karl Fisher system equipped with a controlled heating device: 831 KF Coulometer (Metrohm AG, Herisau, CH) equipped with a controlled heating device (874 Oven Sample Processor; Metrohm).	E	Water determinations were performed in Ferrara during the winter of 2012 (field study Ferrara winter II), at Rome-ML during the desert dust events of 2012 (Rome-ML II) and 2014 (Rome-ML III), and at Rome-UN during the winter of 2014	7 sampling sites: Chamonix; Palermo; La Spezia; Monfalcone; Tunis; Tel Aviv; Rome MLI; Ferrara; Rome MLII	PM_{10} mass concentration; (macro-components): Si, Al, Fe, Na, K, Mg, Ca, chloride, nitrate, sulfate, ammonium, elemental carbon, organics

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
6	Perrino et al. (2014)	PM_{10} and $PM_{2.5}$	Automated dual channel beta attenuation monitors (SWAM 5a Dual Channel Monitor, FAI Instruments, Fonte Nuova, Rome, Italy	Teflon membrane filters (TEFLO, 47 mm, 2.0-µm pore size, PALL Life Sciences	For PM_{10} fraction the possible water content during the summer SOPs were: 5.2% (year 2011) 7.4% (year 2012) and for summer SOPs: 14.5% (2011) 13.6% (2012)	Mass closure method	E	2-year field study carried out between 2010 and 2012	Ferrara (Po Valley, Northern Italy) An industrial site (A) close to the power plant, the waste incinerator and the SMEs A rural site (B), located as far as feasible from the main emission sources, A residential site (C), located in the hamlet of Cassana, about 6 km from the center of Ferrara	Mass concentration of PM2.5 and PM10; macro-elements, ions, elemental carbon, organic matter

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
7	Canepari et al. (2013)	PM_{10} samples	Dual-channel samplers (HYDRA Dual Sampler, FAI Instruments, Fontenuova, Rome, I) equipped with two independent PM_{10} sampling heads	47 mm diameter PTFE membranes, 1 µm pore size (PALL Corporation, USA)	Rome: 3–4%[l]; Ferrara and in Tel Aviv—over 10%	Water contributions separated by the application of an optimized thermal ramp Karl–Fisher system: 831 KF Coulometer (Metrohm AG, Herisau, CH) equipped with an oven (874 Oven Sample Processor; Metrohm)	E	November–December 2011 in three different geographical areas; additional collection of six parallel samples was carried during the period 14–20 December 2011	Traffic site in Rome; Industrial site in Ferrara; Industrial plant in Tel Aviv	–

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
8	Perrino et al. (2013)	PM_{10} and $PM_{2.5}$	Two co-located dual channel instruments: Dual channel beta attenuation automatic monitor (SWAM 5a Dual Channel Monitor—FAI Instruments, Fonte Nuova, Rome—IT) equipped with quartz fibre filters; Dual channel sampler (HYDRA Dual Sampler, FAI Instruments, Fonte Nuova, Rome—IT) equipped with Teflon filters	Quartz fiber filters and Teflon filters	10–20%	Mass closure method	E	Eight 30-day Special Observation Periods (SOPs) conducted during January and June in the period 2008–2011	Cassana—6 km from the center of Ferrara, a medium-size city in the Po Valley (Northern Italy).	Mass concentration and chemical composition of PM10 and PM2.5, elemental composition, organic and inorganic carbon

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
9	Perrino et al. (2012)	PM_{10} samples; size-segregated samples	Four dual channel samplers side-by-side (HYDRA Dual Samplers, FAI Instruments, Fonte Nuova, Rome, Italy); Three identical 10-stage MOUDI cascade impactors (mod. 110, MSP Co., MN–USA)	47 mm, 1.0 pore size Teflon filters (PTFE, Pall Co, MI-USA)	2–8%	Thermo-gravimetric analysis performed by using a Thermo-gravimetric Analyzer TGA7 (PerkinElmer Inc., CA-USA)	E	PM_{10} samples–April 2009 Size-segregated samples—September 30th–October 18th, 2010	Peri-urban site of Montelibretti, about 25 km from Rome, Italy	Anionic content; organic carbon

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
10	Engelhart et al. (2011)	<PM_{10}	Calculation method based on DAASS results	–	At 20% RH—10% of water At 50% RH—50% of water	Dry-ambient Aerosol Size Spectrometer (DAASS) used to measure the aerosol water content and volumetric growth factor of fine particulate matter. This method was compared with thermodynamic model E-AIM	E	May 2008	remote sampling site on the northern coast of Crete, Greece	sulfate, organics, nitrate, and ammonium, humidity
11	Tsyro (2005)	$PM_{2.5}$, PM_{10}	no measurements	–	Fraction unaccounted for by chemical analysis can comprise as much as 30–40% of gravimetric PM_{10} or $PM_{2.5}$ mass	The EMEP aerosol model	D	2001	EMEP stations	other, dust, SS, OC + EC, NH_4, NO_3, SO_4
12	EMEP (2003)	PM_{10}	Based on EMEP data	–	Fraction unaccounted by chemical analysis can comprise 30–50% of the PM_{10} mass	The EMEP aerosol model	D	–	EMEP stations	–

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
13	Rees et al. (2004)	$PM_{2.5}$	Three different instruments collocated at the PAQS station; a Partisol s-FRM Model 2000 PM2.5 Air Sampler (Rupprecht & Pataschnick Co., Inc.), a Series 241 Dichotomous Sampler for PM10/PM2.5 (Thermo Andersen) (''Dichot'') and a Model 1400a ''TEOMs'' (Rupprecht & Pataschnick Co., Inc.)	Teflon filters	at 35% RH water conteent 3.9 μg/m^3 (16%),	Dry and Ambient Aerosol Size Spectrometer (DAASS)	E	Summer 2001 to the winter 2002	The main PAQS ambient monitoring station was located in Schenley Park within the city of Pittsburgh	Nitrate, sulfate, ammonium, semi-volatile species, EC, OC, crustal components

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
14	Ho et al. (2006)	PM_{10} and $PM_{2.5}$	High volume (hi-vol.) samplers (Andersen Instruments/GMW)	Whatman quartz microfiber filters	13.58%–25.32%	Mass closure method	E	November 2000 to February 2001 and June 2001 to August 2001	Three locations, Hung Hom (where the Polytechnic University campus, or PolyU, is located), Kwun Tong (KT), and Hok Tsui (HT)	Sulfate, nitrate, chloride, sodium and OC, EC, crustal matter, sea salt,
15	Putaud et al. (2010)	PM_{10}, $PM_{2.5}$	Devices equivalent to gravimetric methodology at most sites	Mostly quartz fiber filters	15–40%	Mass closure—with information that at most sites unaccounted mass (calculated as the difference between quantified and gravimetrically determined mass) s in fact attributable to water contents	E	1991–2000	kerbside, urban, rural and background sites in Europe	BC, OM, unacc., NO3, NH4, nssSO4, sea salt, min dust

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
16	Neususs et al. (2000)	PM_{10}	High-flow and low-flow Anderson PM 10 inlet together with impactors	non	mean water content about 35%	Hygroscopic Tandem Differential Mobility Analyzer for hygroscopic growth measurements. Growth factors used for the determination of water content of impactor samples	E	Summer 1997	Sagres-50 site located on a Portuguese Naval Base near Sagres	Organic, and elemental carbon, mass-size distribution, relative humidity, hygroscopicity, number-derived mass distribution, gravimetrically-derived mass distribution
17	Ohta et al. (1998)	TPM	Two low-volume air samplers, arranged apart 1 m, equipped with cyclone separators whose 50% cut-o	Teflon and quartz fiber filters	0.05 to 1.11 μg/m^3, which comprised 0.4–3.2% of TPM.	Water determined by Karl Fischer method by Mayer and Boyd, 1959	E	Nov 1991–Oct 1992	University Campus in Sapporo	Elemental C, organic C, Cl^-, NO_3^-, SO_4^{2-}, NH_4^+, Na^+, Mg^{2+}, Al^{3+} and water.

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
18	Witz et al. (1988)	PM_{10}	Sierra Andersen HiVol sampler	Whatman QM-A quartz fiber filters	2.1–5.0% depending on site	Coulometric titration method selected in our study for determining moisture content with Karl Fischer (KF) reagent	E	Jun–Jul 1987, Sept 1987	South Coast and Southeast Desert Air Basins	–
19	Meng et al. (1995)	$PM_{2.5}$ and PM_{10}	None. measured aerosol composition data from the 1987 Southern California Air Quality Study (SCAQS)	non	Taking into account 50th percentile values of calculated water content the results were in range 1.92–25% (winter) and 0.03–10.2% (summer)	Thermodynamic gas/aerosol equilibrium model (SCAPE)	E	1987	South Coast and Air Basin	pH, relative humidity, acidity, concentrations of sulfate, nitrate, ammonium, sodium, and chloride, relative humidity, and temperature
20	Tsai and Kuo (2005)	$PM_{2.5}$	No access to full text	No access to full text	In winter (coastal 28.9% versus urban 22.4% in the daytime and coastal 33.0% versus urban 27.4 at night). In spring (coastal 32.7% versus urban 28.4% in the daytime and coastal 35.7% versus urban 22.7 at night)	Coulometric titration method selected in our study for determining moisture content with Karl Fischer (KF) reagent	E	January and April 2002	Urban and Coastal site in southern Taiwan	SO_4^{2-}, NH_4^+, NO_3^-, relative humidity

Table 9 (continued)

Nos.	References	PM fraction	PM sampler type	Type of filters	Water content (unit)	Water measurement method	Type of study*	Monitoring duration	Environment	Other PM compounds
21	Massling et al. (2009)	Particle number–size distributions were measured in the diameter range Dp = 3–800 nm	Micro Orifice Uniform Deposit Impactor (MOUDI).	Non	The calculated total hygroscopic volume fractions varied between 16 and 65% depending on size, level of pollution and season	Hygroscopicity-Tandem Differential Mobility Analyzer (H-TDMA)	E	Summer 2004 (June/July) and winter 2005 (January/February)	Beijing, Peoples Republic of China	EC, OC, ionic compounds, relative humidity
22	Duplissy et al. (2011)	Size distributed secondary organic aerosol	PSI smog chamber	Non	A simple empirical linear relation between the hygroscopicity of OA at subsaturated RH, as given by the hygroscopic growth factor (GF) or "κorg" parameter, and f44 was determined and is given by κorg = 2.2 × f44 − 0.13	Hygroscopicity Tandem Differential Mobility Analyzer (HTDMA)	E	–	High-alpine site Jungfraujoch, Switzerland and in Mexico City	Hygroscopic growth factor, relative humidity
23	Rogula-Kozłowska et al. (2019)	PM_1	low volume sampler (2.3 m^3/h, Twin Dust; Zambelli Milan, Italy) and a PM_1 sampling head (TSI; MN, USA)	Whatman QM-A quartz fiber filters	Summer season: 0.2–6.26 ng/m^3 Winter season: 0.2–14.84 ng/m^3	Karl-Fischer 831 coulometer with an 874 Oven Sample Processor	E	24 June to 22 August 2014 (summer period) 8 January to 9 March 2015 (winter period)	two urban sites in Poland: Zabrze (southern Poland) and Warsaw (central Poland)	EC, OC, Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-}, F^-, Na^+, NH_4^+, K^+, Ca^{2+}, and Mg^{2+}

*Design: *E* experimental (also modelling type), *D* descriptive (no measurements)

measurements and therefore they were classified as descriptive one. When speaking about method design—10 studies used modeling methods, mostly mass closure.

There is rather no diversity in pollutants investigated since 1987. However we can easily observe that among $PM_{2.5}$ and PM_{10} most often investigated pollutants are inorganic ions together with EC and OC. Humidity and temperature are rather rarely found parameters (Fig. 13). What is also interesting more intensive PM-bound water measurements started in early 20's and before this times only few single publications were found regarding aerosol water contents. It's probably due to analytical limitations.

Study focuses and frontiers

When comparing the results of highly cited publications (Table 5) in the aerosol water domain with those having strongest citation burst (Table 6) it was possible to distinguished few papers which can be treated as a reference for research focuses and trends. Papers characterized by striking study results and high level of attention were marked by bold font (Table 6). It was found that they are generally groupable into two main categories: chemical compounds contributing to water soluble PM ("Compounds that are likely to contribute to the water-soluble PM fraction" section) and source apportionment of PM-bound water ("Source apportionment of the PM-bound water" section).

Compounds that are likely to contribute to the water-soluble PM fraction

Molecular composition of the water-soluble fraction of PM is rather sparse and incomplete (Saxena et al. 1995). There is whole spectrum of compounds which are likely to contribute to the water-soluble fraction of PM. Compared to inorganic compounds of PM, like sulfates, nitrates or ammonia, the concentrations, composition, and formation mechanisms of its organic compounds are not well understood. It's mostly because no single analytical method is capable of analyzing the entire mirage of those compounds. Since water-soluble organic compounds (WSOC) could account for 20–90% of the total carbon (depending on PM origin and sampling locations) (Karthikeyan and Balasubramanian 2005; Wozniak et al. 2008) proper determination of the relative contribution of individual water soluble organic compounds to the total WSOC mass is very important. To get an in depth information regarding WSOC, these compounds should be isolated from PM. It must be however remembered that not all WSOC compounds could be extracted using single extraction solvent or same extraction method. Gas chromatography-mass spectrometry (GC–MS; Mayol-Bracero et al. 2002; Wang et al. 2006) and a combination of ion chromatography and high performance liquid chromatography (HPLC; Yang et al. 2004) characterized less than 10% and 20% of WSOC, respectively. Therefore only small part of WSOC could be analyzed at the molecular level (Wei et al. 2019). The most frontier research in this area is to know to which extent the water content of atmospheric particles is influenced by the presence of organics and how the aggregate hygroscopic properties of inorganic particles are altered when organics are also present (Saxena et al. 1995). Along with the development of this research area, the new PM-bound organic compounds are gradually discovered. In terms of water soluble PM fraction, the majority of studies are about the Water-soluble Ions (Haywood et al. 2011; Guo et al. 2010; Hsieh et al. 2011).

Source apportionment of the PM-bound water

Generally water solubility of the different classes of aerosol components changes along with the aerosol origin. The percentage of water soluble species with respect to the total soluble aerosol mass is much higher at the locations of air stagnation also influenced by strong anthropogenic emission of gaseous precursors like SO_2 and NO_x. In such conditions a very high fraction (over 70%) of aerosol compounds consisted of polar species (Zappoli et al. 1999; Majewski et al. 2018). Knowing that fact, particle size could be increased by several times through water uptake therefore influencing aerosol formation mechanism, its interaction with radiation, or the human health effects both: the liquid water content of size-resolved aerosol together with its source apportionment are a study focus today. Studies of source apportionment (SA) for PM-bound water have enhanced understanding of dominant pollution sources mostly influencing PM water uptake and quantification of their contribution to overall PM hydrophilicity. The contribution of single emission source to the water mass concentration of PM can be now determined by thermal ramp technique (Canepari et al. 2013).

Factors confounding PM-bound water measurements

There are few unsolved problems regarding PM-bound water measurements reflected by the number of articles focusing on artifacts. It's hard to answer the question which measurements methods and which conditions favors those measuring uncertainties. Among probable sources of uncertainties aerosol scientist lists the following one: water content differs from filter to filter significantly. Therefore, in order to determine water content of a PM sample one must know the water content of this particular filter. Mass closure methods most often used for the quantitative measurements of PM bound water usually underestimates or overestimates the reconstructed mass. The reason for this phenomenon might be attributed to non-inclusion of strongly water-bound component and also the adopted conversion factors for estimating organic matter and crustal material (Harrison et al. 2003; Terzi et al. 2010). The problem of the model overestimation may be directly link to positive sampling artifacts. According to Turpin and Lim (2001), overestimation of particulate OC may result from adsorption of organic vapor onto quartz-fibre filter material. Also approximations in the determination of the OC/OM and metal/metal oxide conversion factors can be a significant sources of uncertainty (Terzi et al. 2010). Estimation of water contents by Karl Fischer titration methods is also non free from generating artifacts. KF method suffers from the interference of some classes of compounds, both organic and inorganic (EPA 2007, Method 9000), some of which are likely found in PM samples (aldehydes, ketones, carbohydrates, Fe(III) and Cu(II) salts). Another confounding factor could be filter material. There is no certainty which material is best for water predictions in PM (Rogula-Kozłowska et al. 2017). In terms of gravimetric analysis with beta attenuation method glass or quartz fiber filters are generally preferred, while Teflon filters are preferred for gravimetric determinations because of their higher insensitivity to relative humidity during the procedure (Brown et al. 2006).

Methods used for the measurement of PM-bound water

Till day no organization has established any guidelines for air quality regarding atmospheric water. Since water compound is treated as non-criteria pollutant its rather obvious. Less understandable is the lack of preferred methodology for determining the water content in PM particles. Water content in PM mass could be on significant level—even 40% of its mass. Therefore to improve the accuracy of the gravimetric analysis it's of great importance to create technical guideline for the measurement of water contents. It's also very important to established most preferable conditions for PM collection, preventing the condensation of liquid in the form of mist or droplets on PM material. In the final network there were 23 no. of studies in the subject of PM-bound water measurement.

In 80's and 90's PM-bound water measurements were almost completely focused on simple thermo-gravimetric methods. Based on prepared summary (Table 9) in 9 papers the quantitative determination of water was done by means of mass closure method, same number of papers presents aerosol water contents determined by Karl Fischer titration method, 4 papers used well known thermodynamic models like: ISORPIA, EQUSAM or SCAPE. The hygroscopic tandem differential mobility analyzer (H-TDMA) was used in only 3 from 23 found papers.

To better understand the PM-bound water topic an analysis of co-occurring keywords in the final network was performed. This analysis relied on final database including 23 papers. To understand how it is related to other topics a timeline view was used (Fig. 14). It was shown that in addition to top-terms (Fig. 10) the keywords that have the highest centrality and additionally biggest nodes (square shape) were: $PM_{2.5}$; chemical composition, aerosol; atmospheric aerosol; mass closure, PM_{10} and urban. According to the evolution of keywords urban air and aerosol appeared in 1996; while hygroscopic growth in 2018; aerosol water content in 2009; deliquescence in 2004; liquid water in 2018; chemical mass closure 2006. None among these works poses strong burst. It was also evident that 2003–2009 period had a high concentration of nodes.

In next step the keywords were grouped in the synonym categories. For example hygroscopicity/hygroscopic or Karl Fischer titration/analysis/measurement and so on and the final frequency of keyword categories occurrence was calculated (Fig. 14).

The co-occurring keywords reflect research hotspots in PM-bound water research field. As shown in Fig. 15, a simple analysis of co-occurring keyword frequencies was obtained by counting the frequency of specific key word occurrences in the group of all analyzed key words. The keywords with the highest importance were those directly

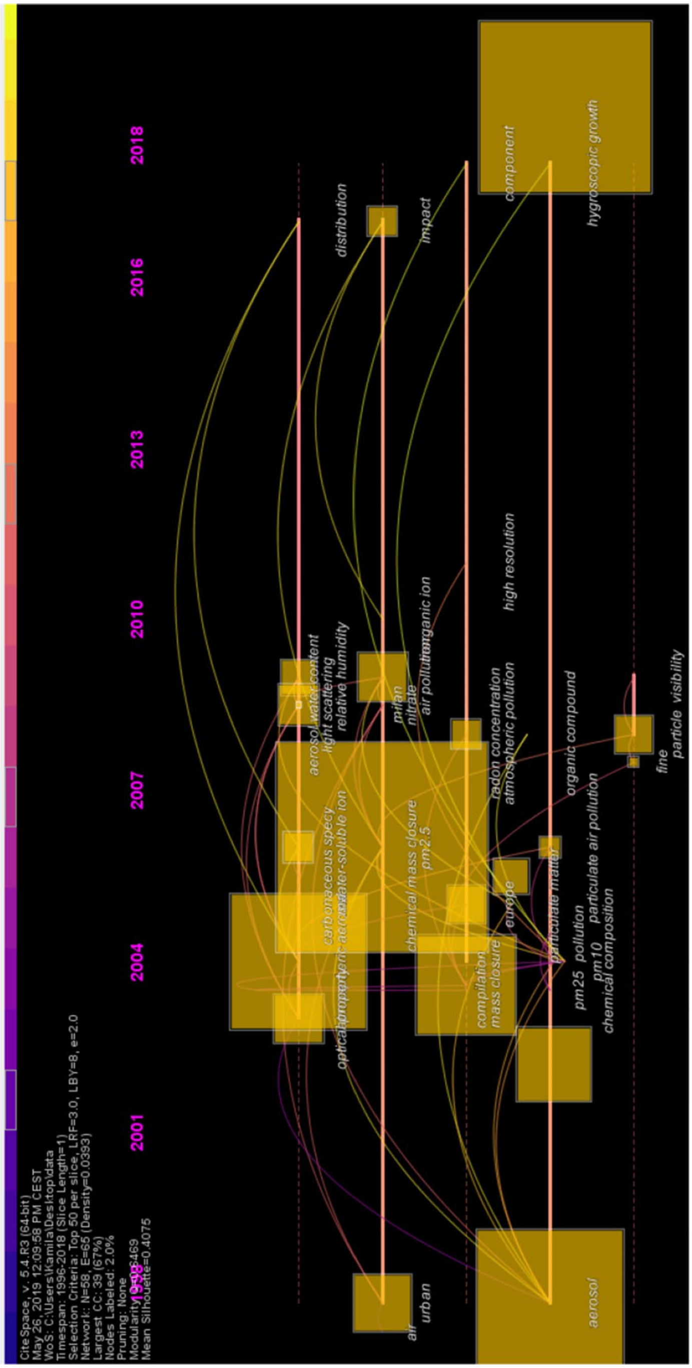

Fig. 14 The timeline of keywords occurrence in the topic of PM-bound water

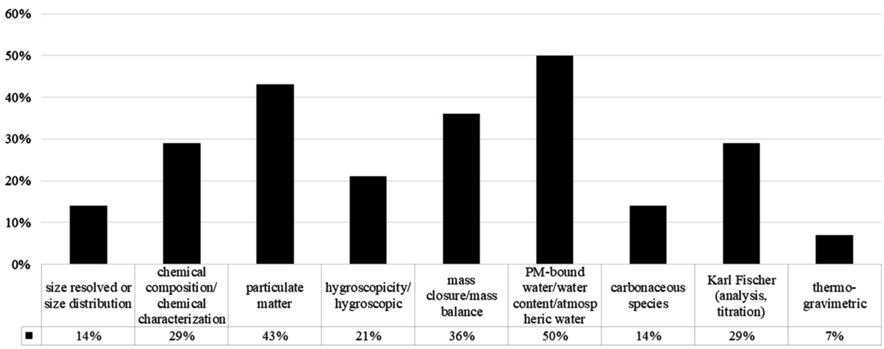

Fig. 15 The frequency of keyword occurrences in the final database regarding PM-bound water measurement

connected to water ("PM-bound water/water content/atmospheric water") (50%); "particulate matter" occupied the second place in this classification (43%). Mass balance and mass closure were also widely studied in PM-bound water research studies (36%).

Conclusions

Presented study provides a systematic bibliographic review for aerosol researchers to achieve a good understanding of how PM-bound water scientific field evolve over last 23 years. Based on visually encoded signs and tabular summaries it recognize potentially insightful patterns concerning atmospheric water, and synthesize various information regarding its presence in the atmosphere, different chemical reactions responsible for particle nucleation and identify past trends and possible future directions in quantitative measurements of aerosol bound water. This study adopts the CiteSpace bibliometric analysis to discuss the most important focuses and trends of aerosol and PM-bound water in terms of publications, authors, countries, institutions, disciplines and type of journals. By using appropriate tools we indicate that the study on aerosol-bound water in this time span has experienced a rather steady and slow development trend and the attention in this field began to rise more rapidly in 2005. In terms of total publications number USA and China have the highest productivity in this field. Zhang XQ.; Andrews E.; Hansson HC.; Ferron GA.; McMurry PH have made comparatively great contributions to the field of study on aerosol—bound water with strong influence reflected by high author citation burst. The most influential article (reflected by the overall number of citations) in the time span 1996–2018 is Świetlicki et al. (2008), which concern the hygroscopic properties of submicron atmospheric aerosol particles measured with H-TDMA instruments. Based on social network analysis (SNA) National Aeronautics Space Administration NASA (USA) together with University of California (USA) and Chinese Academy of Sciences (China) are the most influential institutions in this field, which statement could be reflected by the largest quantity of publications in terms of study on aerosol-bound water and thus they take the leading position. In spite of the relevant role played by aerosol-bound water and its contribution to atmospheric visibility, aerosol optical depth (AOD), climate and health, a quantitative determination of adsorbed water was attempted only in 23 papers. Through the bibliometric analysis and visualization analysis in the field of PM-bound water from 1996 to 2018, it is found that most of these papers are drawn in Italy and China, but there is less cooperation among researchers and among research institutions from USA. In case of atmospheric water this situation is opposite—USA institutions contribute most to the research and encourage domestic research institutions to strengthen the research investment in this discipline. At the same time this means that we should also encourage the cooperation of Polish research institutions to undertake this important topic, as well as try to strengthen a cross regional and transnational cooperation between Italy, China and USA, which are now more advanced in the field of aerosol and PM-bound water. Researchers in Poland should firmly grasp the frontier and hot spot of PM-bound water research, and carry out in-depth research in this advantageous field. The relevant studies on aerosol and PM-bound water mainly focus the disciplines of Meteorology and Atmospheric Sciences together with Environmental Sciences and Ecology and involve Chemistry, Physics and other disciplines, with strong interdisciplinary characteristic. Journal of Geophysical Research Atmospheres; Atmospheric Environment and Geophysical Research Letters are three major journals with the most prominent scientific achievements, largest quantity of publications and highest citation number in the field of PM-bound water. According to the analysis of relevant study indicators (high citation burst and most actual topic) water-soluble organics in atmospheric particles and source apportionment of the PM-bound water are a study focuses today.

There are two main contributions behind this study. The first is information visualization based on CiteSpace, which is an important tool for tracking new advances in the PM-bound water research; the second one is that this article is a good base for future comparative reviews. The contents of atmospheric water understood as both water vapor as well as water bound to solid atmospheric particles has always been a public concern, since its presence in the atmosphere influence the climate and by changing air humidity and particle size it directly affects human health. Analysis of most important keywords or top-terms occurrence indicate that there is still lack of works regarding PM-bound water relations with smog or haze events. Future trends in the discipline of PM-bound water will probably developed in few directions: proper quantitative measurements of its contents; humidity conditions that particles experience in the atmosphere determining their behavior, the chemical composition of aerosol particles determines their ability to take up water, positive or negative errors affecting PM-bound water measurement. Inevitably, the weak points of the study is the data source strongly depending on initial searching criteria selected arbitrary by authors. More number/or different types of keywords might be selected in future research.

Acknowledgements This study was performed within the scope of the Project 2016/23/D/ST10/02705 Atmospheric water as a marker of particulate matter origin financed by National Science Centre Poland.

References

Andrews, E., & Larson, S. M. (1993). Effect of surfactant layers on the size changes of aerosol-particles as a function of relative humidity. *Environmental Science and Technology, 27*(5), 857–865.

Balasubramanian, R., et al. (2003). Comprehensive characterization of PM2.5 aerosols in Singapore. *Journal of Geophysical Research-Atmospheres, 108*(D16), 17.

Bardouki, H., et al. (2003). Chemical composition of size-resolved atmospheric aerosols in the eastern Mediterranean during summer and winter. *Atmospheric Environment, 37*(2), 195–208.

Berg, O. H., et al. (1998). Hygroscopic growth of aerosol particles in the marine boundary layer over the Pacific and Southern Oceans during the first aerosol characterization experiment (ACE 1). *Journal of Geophysical Research-Atmospheres, 103*(D13), 16535–16545.

Bharti, S. K., et al. (2017). Characterization and morphological analysis of individual aerosol of PM10 in urban area of Lucknow, India. *Micron, 103,* 90–98.

Brown, A. S., et al. (2006). Studies of the effect of humidity and other factors on some different filter materials used for gravimetric measurements of ambient particulate matter. *Atmospheric Environment, 40*(25), 4670–4678.

Canepari, S., et al. (2013). Qualitative and quantitative determination of water in airborne particulate matter. *Atmospheric Chemistry and Physics, 13*(3), 1193–1202.

Canepari, S., et al. (2017). Mass size distribution of particle-bound water. *Atmospheric Environment, 165,* 46–56.

Casati, M., et al. (2015). Experimental measurements of particulate matter deliquescence and crystallization relative humidity: Application in heritage climatology. *Aerosol and Air Quality Research, 15*(2), 399–409.

Charlson, R. J., et al. (1992). Climate Forcing by anthropogenic aerosols. *Science, 255*(5043), 423–430.

Chen, C. (2013). *Mapping scientific frontiers: The quest for knowledge visualization* (2nd ed.). Berlin: Springer.

Chen, C. (2016). *CiteSpace: A practical guide for mapping scientific literature*. Hauppauge: Nova Sciene Publishers.

Chen, C. M., et al. (2010). The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. *Journal of the American Society for Information Science and Technology, 61*(7), 1386–1409.

Chen, J. J., et al. (2009). Source apportionment of visual impairment during the California regional PM10/PM2.5 air quality study. *Atmospheric Environment, 43*(39), 6136–6144.

Cheng, Y. F., et al. (2016). Reactive nitrogen chemistry in aerosol water as a source of sulfate during haze events in China. *Science Advances, 2*(12), e1601530.

Covert, D. S., & Heintzenberg, J. (1993). Size distribution and chemical properties of aerosol at NY Alesund, Svalbard. *Atmospheric Environment Part A—General Topics, 27*(17–18), 2989–2997.

Cropper, P. M., et al. (2013). Measurement of light scattering in an urban area with a nephelometer and PM2.5 FDMS TEOM monitor: Accounting for the effect of water. *Journal of the Air and Waste Management Association, 63*(9), 1004–1011.

Cropper, P. M., et al. (2018). Use of a gas chromatography-mass spectrometry organic aerosol monitor for in-field detection of fine particulate organic compounds in source apportionment. *Journal of the Air and Waste Management Association, 68*(5), 390–402.

D'Angelo, L., et al. (2016). Seasonal behavior of PM2.5 deliquescence, crystallization, and hygroscopic growth in the Po Valley (Milan): Implications for remote sensing applications. *Atmospheric Research, 176*, 87–95.

Decesari, S., et al. (2001). Chemical features and seasonal variation of fine aerosol water-soluble organic compounds in the Po Valley, Italy. *Atmospheric Environment, 35*(21), 3691–3699.

Duan, F. K., et al. (2006). Concentration and chemical characteristics of PM2.5 in Beijing, China: 2001–2002. *Science of the Total Environment, 355*(1–3), 264–275.

Duplissy, J., et al. (2011). Relating hygroscopicity and composition of organic aerosol particulate matter. *Atmospheric Chemistry and Physics, 11*(3), 1155–1165.

Eatough, D. J., et al. (1996). Fine particulate chemical composition and light extinction at Canyonlands National Park using organic particulate material concentrations obtained with a multisystem, multichannel diffusion denuder sampler. *Journal of Geophysical Research-Atmospheres, 101*(D14), 19515–19531.

El-Sayed, M. M. H., et al. (2018). The effects of isoprene and NOx on secondary organic aerosols formed through reversible and irreversible uptake to aerosol water. *Atmospheric Chemistry and Physics, 18*(2), 1171–1184.

EMEP Status report 1/2003. (2003). Model performance for particulate matter. Transboundary acidification, eutrophication and ground ozone level, Part II: Unified EMEPmodel performance. EMEP/MSC-W Status report 1/2003 Part II, Norwegian Meteorological Institute, Oslo, Norway, http://www.emep.int.

Engelhart, G. J., et al. (2011). Water content of aged aerosol. *Atmospheric Chemistry and Physics, 11*(3), 911–920.

EPA 2007. Method 9000 Determination of water in waste materials by Karl Fischer Titration.

Facchini, M. C., et al. (2000). Surface tension of atmospheric wet aerosol and cloud/fog droplets in relation to their organic carbon content and chemical composition. *Atmospheric Environment, 34*(28), 4853–4857.

Farao C. (2013). Facoltà di Scienze Matematiche Fisiche e Naturali Dipartimento di Chimica XXVI Ciclo Dottorato in Chimica Analitica e Dei Sistemi Reali. Development of analytical methodologies for the monitoring of the atmospheric particulate matter.

Fernandez, A. J., et al. (2018). Application of remote sensing techniques to study aerosol water vapor uptake in a real atmosphere. *Atmospheric Research, 202,* 112–127.

Ge, B., et al. (2019). Role of ammonia on the feedback between AWC and inorganic aerosol formation during heavy pollution in the north China plain. *Earth and Space Science, 6,* 1675–1693.

Good, N., et al. (2010). Instrumentational operation and analytical methodology for the reconciliation of aerosol water uptake under sub- and supersaturated conditions. *Atmospheric Measurement Techniques, 3*(5), 1241–1254.

Graham, B., et al. (2002). Water-soluble organic compounds in biomass burning aerosols over Amazonia 1. Characterization by NMR and GC-MS. *Journal of Geophysical Research-Atmospheres, 107*(D20), 16.

Grigoratos, T., et al. (2014). Chemical composition and mass closure of ambient coarse particles at traffic and urban-background sites in Thessaloniki, Greece. *Environmental Science and Pollution Research, 21*(12), 7708–7722.

Grimm, H., & Eatough, D. J. (2009). Aerosol measurement: The use of optical light scattering for the determination of particulate size distribution, and particulate mass, including the semi-volatile fraction. *Journal of the Air and Waste Management Association, 59*(1), 101–107.

Guo, S., et al. (2010). Size-resolved aerosol water-soluble ionic compositions in the summer of Beijing: implication of regional secondary formation. *Atmospheric Chemistry and Physics, 10*(3), 947–959.

Gysel, M., et al. (2003). Properties of jet engine combustion particles during the PartEmis experiment: Hygroscopicity at subsaturated conditions. *Geophysical Research Letters, 30*(11), 1566.

Harrison, R. M., et al. (2003). A pragmatic mass closure model for airborne particulate matter at urban background and roadside sites. *Atmospheric Environment, 37*(35), 4927–4933.

Haywood, J. M., et al. (2011). The roles of aerosol, water vapor and cloud in future global dimming/brightening. *Journal of Geophysical Research-Atmospheres, 116,* D20203.

Hecobian, A., et al. (2010). Water-soluble organic aerosol material and the light-absorption characteristics of aqueous extracts measured over the southeastern United States. *Atmospheric Chemistry and Physics, 10*(13), 5965–5977.

Hegg, D. A., et al. (1997). Chemical apportionment of aerosol column optical depth off the mid-Atlantic coast of the United States. *Journal of Geophysical Research-Atmospheres, 102*(D21), 25293–25303.

Hering, S., & Cass, G. (1999). The magnitude of bias in the measurement of PM2.5 arising from volatilization of particulate nitrate from teflon filters. *Journal of the Air and Waste Management Association, 49*(6), 725–733.

Ho, K. F., et al. (2006). Seasonal variations and mass closure analysis of particulate matter in Hong Kong. *Science of the Total Environment, 355*(1–3), 276–287.

Hsieh, L. T., et al. (2011). Removal of particle-bound water-soluble ions from cooking fume using biosolution wet scrubber. *Aerosol and Air Quality Research, 11*(5), 508–518.

Huang, X. J., et al. (2016). Seasonal variation and secondary formation of size-segregated aerosol water-soluble inorganic ions during pollution episodes in Beijing. *Atmospheric Research, 168,* 70–79.

Hueglin, C., et al. (2005). Chemical characterization of PM2.5, PM10 and coarse particles at urban, near-city and rural sites in Switzerland. *Atmospheric Environment, 39*(4), 637–651.

Irwin, M., et al. (2011). Size-resolved aerosol water uptake and cloud condensation nuclei measurements as measured above a Southeast Asian rainforest during OP3. *Atmospheric Chemistry and Physics, 11*(21), 11157–11174.

Joseph, A. E., et al. (2012). Chemical characterization and mass closure of fine aerosol for different land use patterns in Mumbai City. *Aerosol and Air Quality Research, 12*(1), 61–72.

Jung, J., et al. (2009). Aerosol chemistry and the effect of aerosol water content on visibility impairment and radiative forcing in Guangzhou during the 2006 Pearl River Delta campaign. *Journal of Environmental Management, 90*(11), 3231–3244.
Kanakidou, M., et al. (2005). Organic aerosol and global climate modelling: A review. *Atmospheric Chemistry and Physics, 5,* 1053–1123.
Karthikeyan, S., & Balasubramanian, R. (2005). Rapid extraction of water soluble organic compounds from airborne particulate matter. *Analytical Sciences, 21*(12), 1505–1508.
Kelly, J. T., & Wexler, A. S. (2006). Water uptake by aerosol: Water activity in supersaturated potassium solutions and deliquescence as a function of temperature. *Atmospheric Environment, 40*(24), 4450–4468.
Kitamori, Y., et al. (2009). Assessment of the aerosol water content in urban atmospheric particles by the hygroscopic growth measurements in Sapporo, Japan. *Atmospheric Environment, 43*(21), 3416–3423.
Kotchenruther, R. A., et al. (1999). Humidification factors for atmospheric aerosols off the mid-Atlantic coast of the United States. *Journal of Geophysical Research-Atmospheres, 104*(D2), 2239–2251.
Kreidenweis, S. M., et al. (2008). Single-parameter estimates of aerosol water content. *Environmental Research Letters, 3*(3), 035002.
Lee, C. T., & Hsu, W. C. (1998). A novel method to measure aerosol water mass. *Journal of Aerosol Science, 7,* 827–837.
Lee, C. T., et al. (1999). Local circulation and aerosol water-soluble ions—A case study in Taiwan during Mei-yu season. *Chemosphere, 38*(2), 425–443.
Li, L., et al. (2010). Composition, source, mass closure of PM2.5 aerosols for four forests in eastern China. *Journal of Environmental Sciences., 22*(3), 405–412.
Li, X., et al. (2011). Glycine in aerosol water droplets: A critical assessment of Kohler theory by predicting surface tension from molecular dynamics simulations. *Atmospheric Chemistry and Physics, 11*(2), 519–527.
Liu, B., et al. (2014). Compact airborne Raman lidar for profiling aerosol, water vapor and clouds. *Optics Express, 22*(17), 20613–20621.
Liu, Z. R., et al. (2017). Size-resolved aerosol water-soluble ions during the summer and winter seasons in Beijing: Formation mechanisms of secondary inorganic aerosols. *Chemosphere, 183,* 119–131.
Maenhaut, W., et al. (2002). Detailed mass size distributions of elements and species, and aerosol chemical mass closure during fall 1999 at Gent, Belgium. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, 189,* 238–242.
Maenhaut, W., et al. (2008). Chemical composition and mass closure for PM2.5 and PM10 aerosols at K-puszta, Hungary, in summer 2006. *X-Ray Spectrometry, 37*(2), 193–197.
Maenhaut, W., et al. (2011). Chemical composition, impact from biomass burning, and mass closure for PM(2.5) and PM(10) aerosols at Hyytiala, Finland, in summer 2007. *X-Ray Spectrometry, 40*(3), 168–171.
Majewski, G., et al. (2018). Concentration, chemical composition and origin of PM1: Results from the first long-term measurement campaign in Warsaw (Poland). *Aerosol and Air Quality Research, 18*(3), 636–654.
Marcazzan, G. M., et al. (2001). Characterization of PM10 and PM2.5 particulate matter in the ambient air of Milan (Italy). *Atmospheric Environment, 35*(27), 4639–4650.
Massling, A., et al. (2009). Size segregated water uptake of the urban submicrometer aerosol in Beijing. *Atmospheric Environment, 43*(8), 1578–1589.
Mayol-Bracero, O. L., et al. (2002). Water-soluble organic compounds in biomass burning aerosols over Amazonia 2. Apportionment of the chemical composition and importance of the polyacidic fraction. *Journal of Geophysical Research-Atmospheres, 107*(D20), LBA-14.
McDow, S. R., et al. (1995). Combustion aerosol water-content and its effect on polycyclic aromatic hydrocarbon reactivity. *Atmospheric Environment, 29*(7), 791–797.
McMurry, P. H., et al. (1996). Elemental composition and morphology of individual particles separated by size and hygroscopicity with the TDMA. *Atmospheric Environment, 30*(1), 101–108.
Meng, Z. Y., et al. (1995). Contribution of water to particulate mass in the south coast air basin. *Aerosol Science and Technology, 22*(1), 111–123.
Metzger, S., et al. (2016). Aerosol water parameterisation: A single parameter framework. *Atmospheric Chemistry and Physics, 16*(11), 7213–7237.
Metzger, S., et al. (2018). Aerosol water parameterization: Long-term evaluation and importance for climate studies. *Atmospheric Chemistry and Physics, 18*(22), 16747–16774.
Mikhailov, E., et al. (2009). Amorphous and crystalline aerosol particles interacting with water vapor: Conceptual framework and experimental evidence for restructuring, phase transitions and kinetic limitations. *Atmospheric Chemistry and Physics, 9*(24), 9491–9522.

Mikhailov, E., et al. (2013). Mass-based hygroscopicity parameter interaction model and measurement of atmospheric aerosol water uptake. *Atmospheric Chemistry and Physics, 13*(2), 717–740.

Mikhailov, E. F., et al. (2015). Chemical composition, microstructure, and hygroscopic properties of aerosol particles at the Zotino Tall Tower Observatory (ZOTTO), Siberia, during a summer campaign. *Atmospheric Chemistry and Physics, 15*(15), 8847–8869.

Neususs, C., et al. (2000). Size-segregated chemical, gravimetric and number distribution-derived mass closure of the aerosol in Sagres, Portugal during ACE-2. *Tellus Series B-Chemical and Physical Meteorology, 52*(2), 169–184.

Novakov, T., & Corrigan, C. E. (1996). Cloud condensation nucleus activity of the organic component of biomass smoke particles. *Geophysical Research Letters, 23*(16), 2141–2144.

Novakov, T., & Penner, J. E. (1993). Large contribution of organic aerosols to cloud condensation nuclei concentrations. *Nature, 365*(6449), 823–826.

Ohta, S., et al. (1998). Chemical characterization of atmospheric fine particles in Sapporo with determination of water content. *Atmospheric Environment, 32*(6), 1021–1025.

Perrino, C., et al. (2008a). Inorganic constituents of urban air pollution in the Lazio region (Central Italy). *Environmental Monitoring and Assessment, 136*(1–3), 69–86.

Perrino, C., et al. (2008b). Influence of atmospheric stability on the mass concentration and chemical composition of atmospheric particles: A case study in Rome, Italy. *Environment International, 34*(5), 621–628.

Perrino, C., et al. (2009). Influence of natural events on the concentration and composition of atmospheric particulate matter. *Atmospheric Environment, 43*(31), 4766–4779.

Perrino, C., et al. (2010). Time-resolved measurements of water-soluble ions and elements in atmospheric particulate matter for the characterization of local and long-range transport events. *Chemosphere, 80*(11), 1291–1300.

Perrino, C., et al. (2011). Chemical characterization of atmospheric PM in Delhi, India, during different periods of the year including Diwali festival. *Atmospheric Pollution Research, 2*(4), 418–427.

Perrino, C., et al. (2012). Thermal stability of inorganic and organic compounds in atmospheric particulate matter. *Atmospheric Environment, 54,* 36–43.

Perrino, C., et al. (2013). Comparing the performance of teflon and quartz membrane filters collecting atmospheric PM: influence of atmospheric water. *Aerosol and Air Quality Research, 13*(1), 137–147.

Perrino, C., et al. (2014). Seasonal variations in the chemical composition of particulate matter: a case study in the Po Valley. Part I: Macro-components and mass closure. *Environmental Science and Pollution Research, 21*(6), 3999–4009.

Perrino, C., et al. (2016). Assessing the contribution of water to the mass closure of PM_{10}. *Atmospheric Environment, 140,* 555–564.

Petters, M. D., & Kreidenweis, S. M. (2007). A single parameter representation of hygroscopic growth and cloud condensation nucleus activity. *Atmospheric Chemistry and Physics, 7*(8), 1961–1971.

Petters, M. D., & Kreidenweis, S. M. (2008). A single parameter representation of hygroscopic growth and cloud condensation nucleus activity - Part 2: Including solubility. *Atmospheric Chemistry and Physics, 8*(20), 6273–6279.

Pitchford, M. L., & McMurry, P. H. (1994). Relationship between measured water vapor growth and chemistry of atmospheric aerosol for Grand-Canyon, Arizona in winter 1990. *Atmospheric Environment, 28*(5), 827–839.

Putaud, J. P., et al. (2010). A European aerosol phenomenology-3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe. *Atmospheric Environment, 44*(10), 1308–1320.

Rastak, N., et al. (2014). Seasonal variation of aerosol water uptake and its impact on the direct radiative effect at Ny-Alesund, Svalbard. *Atmospheric Chemistry and Physics, 14*(14), 7445–7460.

Rees, S. L., et al. (2004). Mass balance closure and the federal reference method for PM2.5 in Pittsburgh, Pennsylvania. *Atmospheric Environment, 38*(20), 3305–3318.

Rogge, W. F., et al. (1993). Quantification of urban organic aerosols at a molecular level—Identification, abundance and seasonal variation. *Atmospheric Environment Part A-General Topics, 27*(8), 1309–1330.

Rogula-Kozłowska, W., et al. (2017). A simple method for determination of total water in PM1 collected on quartz fiber filters. *Microchemical Journal*. https://doi.org/10.1016/j.microc.2017.02.019.

Rogula-Kozłowska, W., et al. (2019). Seasonal variations of PM1-bound water concentration in urban areas in Poland. *Atmospheric Pollution Research, 10*(1), 267–273.

Russell, P. B., et al. (1999). Aerosol-induced radiative flux changes off the United States mid-Atlantic coast: Comparison of values calculated from sunphotometer and in situ data with those measured by airborne pyranometer. *Journal of Geophysical Research-Atmospheres, 104*(D2), 2289–2307.

Saxena, P., & Hildemann, L. M. (1996). Water-soluble organics in atmospheric particles: A critical review of the literature and application of thermodynamics to identify candidate compounds. *Journal of Atmospheric Chemistry, 24*(1), 57–109.

Saxena, P., & Hildemann, L. M. (1997). Water absorption by organics: Survey of laboratory evidence and evaluation of UNIFAC for estimating water activity. *Environmental Science and Technology, 31*(11), 3318–3324.

Saxena, P., et al. (1995). Organics alter hygroscopic behavior of atmospheric particles. *Journal of Geophysical Research-Atmospheres, 100*(D9), 18755–18770.

Schaap, M., et al. (2004). Artefacts in the sampling of nitrate studied in the "INTERCOMP" campaigns of EUROTRAC-AEROSOL. *Atmospheric Environment, 38*(38), 6487–6496.

Schuster, G. L., et al. (2009). Remote sensing of aerosol water uptake. *Geophysical Research Letters, 36,* L03814.

Sciare, J., et al. (2005). Aerosol mass closure and reconstruction of the light scattering coefficient over the Eastern Mediterranean Sea during the MINOS campaign. *Atmospheric Chemistry and Physics, 5,* 2253–2265.

Seinfeld, J. H., & Pandis, S. N. (1998). *Atmospheric chemistry and physics from air pollution to climate change*. New York: Wiley.

Seinfeld, J. H., & Pandis, S. N. (2006). *Atmospheric chemistry and physics: From air pollution to climate change* (2nd Ed.). New York: Wiley.

Sellegri, K., et al. (2003). Mass balance of free tropospheric aerosol at the Puy de D(o)over-capme (France) in winter. *Journal of Geophysical Research-Atmospheres, 108*(D11), 17.

Shen, Z. X., et al. (2010). Chemical characteristics of fine particles (PM1) from Xi'an, China. *Aerosol Science and Technology, 44*(6), 461–472.

Shulman, M. L., et al. (1996). Dissolution behavior and surface tension effects of organic compounds in nucleating cloud droplets (vol 23, pg 277, 1996). *Geophysical Research Letters, 23*(5), 603.

Sillanpaa, M., et al. (2006). Chemical composition and mass closure of particulate matter at six urban sites in Europe. *Atmospheric Environment, 40,* S212–S223.

Su, J., et al. (2018). Chemical compositions and liquid water content of size-resolved aerosol in Beijing. *Aerosol and Air Quality Research, 18,* 680–692.

Subramanian, R., et al. (2004). Positive and negative artifacts in particulate organic carbon measurements with denuded and undenuded sampler configurations. *Aerosol Science and Technology, 38,* 27–48.

Svenningsson, B., et al. (1994). Hygroscopic growth of aerosol particles and its influence on nucleation scavenging in-cloud experimental results from Kleiner–Feldberg. *Journal of Atmospheric Chemistry, 19*(1–2), 129–152.

Svenningsson, I. B., et al. (1992). Hygroscopic growth of aerosol particles in the Po-Valley. *Tellus Series B-Chemical and Physical Meteorology, 44*(5), 556–569.

Świetlicki, E., et al. (2008). Hygroscopic properties of submicrometer atmospheric aerosol particles measured with H-TDMA instruments in various environments—A review. *Tellus Series B-Chemical and Physical Meteorology, 60*(3), 432–469.

Taiwo, A. M. (2016). Source apportionment of urban background particulate matter in Birmingham, United Kingdom using a mass closure model. *Aerosol and Air Quality Research, 16*(5), 1244–1252.

Tan, H. B., et al. (2017). An analysis of aerosol liquid water content and related impact factors in Pearl River Delta. *Science of the Total Environment, 579,* 1822–1830.

Tang, I. N. (1979). Deliquesence properties and particle-size change of hygroscopic aerosols. Abstracts of Papers of the American Chemical Society(APR) (p. 23).

Tang, I. N. (1997). Thermodynamic and optical properties of mixed-salt aerosols of atmospheric importance. *Journal of Geophysical Research-Atmospheres, 102*(D2), 1883–1893.

Tang, I. N., & Munkelwitz, H. R. (1994). Water activities, densities and refractive indexes of aqueus sulfates and sodium nitrate droplets of atmospheric importance. *Journal of Geophysical Research-Atmospheres, 99*(D9), 18801–18808.

Terzi, E., et al. (2010). Chemical composition and mass closure of ambient PM10 at urban sites. *Atmospheric Environment, 44*(18), 2231–2239.

Tham, Y. J., et al. (2018). Heterogeneous N_2O_5 uptake coefficient and production yield of ClNO2 in polluted northern China: Roles of aerosol water content and chemical composition. *Atmospheric Chemistry and Physics, 18*(17), 13155–13171.

Tsai, Y. I., & Kuo, S. C. (2005). PM2.5 aerosol water content and chemical composition in a metropolitan and a coastal area in southern Taiwan. *Atmospheric Environment, 39*(27), 4827–4839.

Tsyro, S. G. (2005). To what extent can aerosol water explain the discrepancy between model calculated and gravimetric PM10 and PM2.5? *Atmospheric Chemistry and Physics, 5,* 515–532.

Turpin, B. J., & Lim, H. J. (2001). Species contributions to PM2.5 mass concentrations: Revisiting common assumptions for estimating organic mass. *Aerosol Science and Technology, 35*(1), 602–610.

van Beelen, A. J., et al. (2014). Estimation of aerosol water and chemical composition from AERONET Sun-sky radiometer measurements at Cabauw, the Netherlands. *Atmospheric Chemistry and Physics, 14*(12), 5969–5987.

Vecchi, R., et al. (2009). Organic and inorganic sampling artefacts assessment. *Atmospheric Environment, 43*(10), 1713–1720.

Viidanoja, J., et al. (2002). Organic and black carbon in PM2.5 and PM10: 1 year of data from an urban site in Helsinki, Finland. *Atmospheric Environment, 36*(19), 3183–3193.

Virkkula, A., et al. (1999). Hygroscopic properties of aerosol formed by oxidation of limonene, alpha-pinene, and beta-pinene. *Journal of Geophysical Research-Atmospheres, 104*(D3), 3569–3579.

Wang, H. B., et al. (2006). Wintertime organic aerosols in Christchurch and Auckland, New Zealand: Contributions of residential wood and coal burning and petroleum utilization. *Environmental Science and Technology, 40*(17), 5257–5262.

Wang, H. T., et al. (2019). Aerosols in an arid environment: The role of aerosol water content, particulate acidity, precursors, and relative humidity on secondary inorganic aerosols. *Science of the Total Environment, 646,* 564–572.

Wang, Y., & Chen, Y. (2019). Significant climate impact of highly hygroscopic atmospheric aerosols in Delhi, India. *Geophysical Reseach Letters, 46,* 5535–5545.

Wei, N. N., et al. (2019). Size-segregated characteristics of carbonaceous aerosols during the monsoon and non-monsoon seasons in Lhasa in the Tibetan Plateau. *Atmosphere, 10*(3), 157.

Weingartner, E., et al. (1995). Growth and structural-change of combustion aerosols at high relative-humidity. *Environmental Science and Technology, 29*(12), 2982–2986.

Weingartner, E., et al. (1997). Hygroscopic properties of carbon and diesel soot particles. *Atmospheric Environment, 31*(15), 2311–2327.

Widziewicz, K., et al. (2018). Short review on PM-bound water. Its presence in the atmosphere, forms of occurrence and determination by Karl Fischer coulometric titration. In B. Kazmierczak, M. Kutylowska, K. Piekarska & P. Jadwiszczak (Eds.), *10th Conference on Interdisciplinary Problems in Environmental Protection and Engineering* Eko-Dok 2018 (Vol. 44).

Wittmaack, K., & Keck, L. (2004). Thermodesorption of aerosol matter on multiple filters of different materials for a more detailed evaluation of sampling artifacts. *Atmospheric Environment, 38*(31), 5205–5215.

Witz, S., et al. (1988). Water content of collected aerosols in the south coast and southeast desert air basins. *JAPCA, 38*(4), 418–419.

Wozniak, A. S., et al. (2008). Technical Note: Molecular characterization of aerosol-derived water soluble organic carbon using ultrahigh resolution electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry. *Atmospheric Chemistry and Physics, 8*(17), 5099–5111.

Wozniak, A. S., et al. (2015). Aerosol water soluble organic matter characteristics over the North Atlantic Ocean: Implications for iron-binding ligands and iron solubility. *Marine Chemistry, 173,* 162–172.

Wu, Z., et al. (2018). Aerosol liquid water driven by anthropogenic inorganic salts: implying its key role in haze formation over the north China plain. *Environmental Science and Technology Letters, 5,* 160–166.

Yang, H., et al. (2004). Chemical characterization of water-soluble organic aerosols at Jeju Island collected during ACE-Asia. *Environmental Chemistry, 1*(1), 13–17.

Yin, J., et al. (2005). Major component composition of urban PM10 and PM2.5 in Ireland. *Atmospheric Research, 78*(3–4), 149–165.

Zappoli, S., et al. (1999). Inorganic, organic and macromolecular components of fine aerosol in different areas of Europe in relation to their water solubility. *Atmospheric Environment, 33*(17), 2733–2743.

Zhang, J., & Reid, J. S. (2010). A decadal regional and global trend analysis of the aerosol optical depth using a data-assimilation grade over-water MODIS and Level 2 MISR aerosol products. *Atmospheric Chemistry and Physics, 10*(22), 10949–10963.

Zhang, X. Q., et al. (1993). Mixing characteristics and water content of submicron aerosols measured in Los Angeles and at the Grand Canyon. *Atmospheric Environment Part A-General Topics, 27*(10), 1593–1607.