Introduction to Atmospheric Simulation Chambers and Their Applications

Astrid Kiendler-Scharr, Karl-Heinz Becker, Jean-Francois Doussin, Hendrik Fuchs, Paul Seakins, John Wenger, Peter Wiesen

Chapter 1
Introduction to Atmospheric Simulation Chambers and Their Applications

Astrid Kiendler-Scharr, Karl-Heinz Becker, Jean-François Doussin, Hendrik Fuchs, Paul Seakins, John Wenger, and Peter Wiesen

Abstract Atmospheric simulation chambers have been deployed with various research goals for more than 80 years. In this chapter, an overview of the various applications, including emerging new applications, is given. The chapter starts with a brief historical overview of atmospheric simulation chambers. It also provides an overview of how simulation chambers complement field observations and more classical laboratory experiments. The chapter is concluded with an introduction to the different aspects requiring consideration when designing an atmospheric simulation chamber.

Atmospheric simulation chambers, such as those in the EUROCHAMP network, are highly valuable research tools for investigating chemical and physical processes that occur in air. They are used in a large number of applications, ranging from air quality and climate change to cloud microphysics, cultural heritage and human health. Chambers were originally developed as laboratory-based systems to investigate the formation of clouds or photochemical smog and hence, were called cloud chambers or smog chambers, respectively. Their ability to provide a controlled environment to study the formation and evolution of atmospheric pollutants, by isolating

Astrid Kiendler-Scharr passed away before publication of this chapter.

A. Kiendler-Scharr · H. Fuchs
Forschungszentrum Jülich, Jülich, Germany
e-mail: a.kiendler-scharr@fz-juelich.de

K.-H. Becker · P. Wiesen
Bergische Universität Wuppertal, Wuppertal, Germany

J.-F. Doussin (✉)
Centre National de la Recherche Scientifique, Paris, France
e-mail: jean-francois.doussin@lisa.ipsl.fr

P. Seakins
University of Leeds, Leeds, UK

J. Wenger
University College Cork, Cork, Ireland

J.-F. Doussin et al. (eds.), *A Practical Guide to Atmospheric Simulation Chambers*,
https://doi.org/10.1007/978-3-031-22277-1_1

specific compounds of interest and controlling the oxidizing environment, made them especially useful in elucidating the key factors governing photochemical smog formation on a local to regional scale. Within EUROCHAMP-2020 and across the world, chambers dedicated to the exploration of atmospheric chemistry outnumber the atmospheric physics and cloud chambers. For this reason, this guide has an emphasis on atmospheric chemistry related aspects of simulation chambers.

Initially, smog chamber experiments were focused on elucidating the processes responsible for the observed increase in atmospheric secondary pollutants such as ozone and peroxyacyl nitrates (PAN-type compounds). This approach was later broadened to include studies of the kinetics and mechanisms of gas phase atmospheric oxidation and chambers have been extremely useful in producing kinetic data, branching ratio and product distributions (Becker 2006). Together with data arising from flow tubes and flash photolysis experiments, this knowledge allowed the scientific community to build complex numerical chemical codes that have led to the development of the models used to predict ozone formation. Nowadays, chambers are also essential tools for evaluating these chemistry models and for predicting the formation of secondary pollutants in the absence of uncertainties associated with emissions, meteorology and mixing effects (Carter and Lurmann 1991; Dodge 2000; Hynes et al. 2005). Experimental chamber data have been key to the development and optimisation (e.g. Gery et al. 1989; Carter 2010; Bloss et al. 2005a), as well as the evaluation (e.g. Saunders et al. 2003; Goliff et al. 2013; Jenkin et al. 2012; Bloss et al. 2005b; Metzger et al. 2008; McVay et al. 2016) of chemical mechanisms used in a wide range of science and air quality policy models. Today, chamber-derived data remains a key component in the development and evaluation of future atmospheric chemical mechanisms (Kaduwela et al. 2015; Stockwell et al. 2020).

In the past few decades, chamber facilities have been increasingly used to investigate processes leading to secondary organic aerosol (SOA), an important component of atmospheric aerosol (Finlayson-Pitts and Pitts 1986; Dodge 2000; Finlayson-Pitts and Pitts 2000; Kanakidou et al. 2005; Barnes and Rudzinski 2006; Hallquist et al. 2009). The general methodology which has been (and still is) useful for gaseous pollutants is now providing valuable data related to SOA formation (e.g. Hatakeyama et al. 2002; Pankow 1994; Odum et al. 1996; Cocker et al. 2001; Pun et al. 2003; Takekawa et al. 2003; Martin-Reviejo and Wirtz 2005; Baltensperger et al. 2005; Donahue et al. 2005; Pathak et al. 2007; McFiggans et al. 2019; Zhao et al. 2018, Ciarelli et al. 2017) as well as the physico-chemical properties of aerosols and their changes during atmospheric transport and processing (De Haan et al. 1999; Kalberer et al. 2006; Field et al. 2006; Linke et al. 2006; Meyer et al. 2009; D'Ambro et al. 2017; Huang et al. 2018; Zhao et al. 2017).

Furthermore, due to the wide range of experimental requirements, simulation chamber designs vary considerably. As pointed out by Finlayson-Pitts and Pitts (2000), although the general aims of all chamber studies are similar–i.e. to simulate processes in ambient air under controlled conditions–the chamber designs and capabilities to meet these goals vary widely. This in turn means that chambers and their associated measurement technologies are being adapted to a growing number of applications.

This chapter provides a short history of atmospheric simulation chambers Sect. 1.1, investigations of atmospheric processes Sect. 1.2, approaches for bridging the gap between laboratory and field studies Sect. 1.3, emerging new applications Sect. 1.4, and considerations on the design and instrumentation of atmospheric simulation chambers Sect. 1.5. Respective references to the more detailed discussion in Chaps. 2–8 are provided in each of the subsections.

1.1 A Short History of Atmospheric Simulation Chambers

Atmospheric simulation chambers have been used for more than 80 years. As early as the 1930s, Findeisen performed studies on cloud droplet size distributions and conducted cloud chamber experiments, which was a highly novel approach at the time. Findeisen's cloud chamber was approximately 2 m^3 in volume and connected to a vacuum pump, which allowed the process of adiabatic expansion and atmospheric cloud formation to be mimicked in the chamber (Storelvmo and Tan 2015).

Photochemical smog formation, first observed in the Los Angeles area in the 1940s and 1950s stimulated study in large chambers to simulate plant damage and health effects such as eye and lung irritation (Haagen-Smit 1952). Europe followed suit in chamber construction and application to atmospheric processes and through a range of national and European Union funding streams, Europe now leads the world in the use of large, highly instrumented chambers for atmospheric model development and evaluation. These large facilities are complemented by a range of smaller chambers that have been designed for specific purposes.

The first large European chamber was the "Große Bonner Kugel" (Groth et al. 1972), constructed at the University of Bonn and completed in 1968. The programme led by Groth and Harteck initially focused on air glow reactions at the low pressures pertaining to the *upper* atmosphere. However, studies of tropospheric interest were also undertaken, but at a very basic level and without the use of photolytic sources. Radicals were generated by discharge flow techniques, and this limited the range of conditions that could be used.

The facility, which was operated by Becker, Fink, Kley and Schurath for several years (Groth et al. 1972), had the following properties as indicated in Table 1.1.

At that time dark OH radical sources and the importance of OH reactions were not known. Figures 1.1 and 1.2 show the facility installed at the Institute of Physical Chemistry, Bonn University. The chamber has not been used since the mid-1980s because of its enormous operational cost and has since been completely dismantled.

In the mid-1970s, as our understanding of the basics of tropospheric chemistry increased and particularly the role of photolysis, the Pitts group at Riverside (Finlayson-Pitts and Pitts 1986, 2000) started to construct an indoor chamber with the objective of exploring photochemical smog formation. Advances in the understanding of photochemical processes had been slow because appropriate analytical techniques still had to be developed at that time. However, activity soon increased with the construction of a similar chamber in Japan (Akimoto et al. 1979a, b), while

Table. 1.1 Key properties of the "Bonner Kugel"

Volume	221 m^3
Surface	177 m^2
Inner diameter	7.5 m
Heatable	$T_{max} = 350$ °C with 233 kW power, cooling of baffles between pumps and chamber with liquid hydrogen
Material	Stainless steel, 10 mm wall thickness
Pumping speed	240 000 l/s with 8 diffusion pumps
Lowest pressure	10^{-12} bar

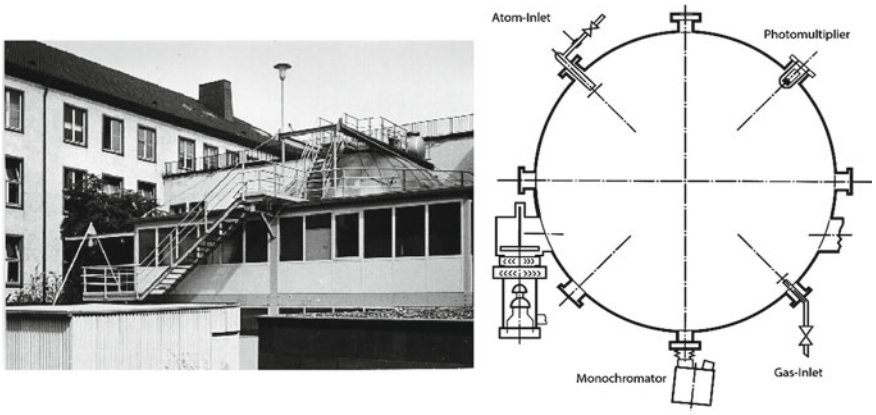

Fig. 1.1 The housing of the "Große Bonner Kugel" (left) and cross-section through the spherical reaction chamber "Große Bonner Kugel" (right). Courtesy of K.H. Becker, Bonn, Germany

Atkinson in the Pitts group started to successfully investigate the kinetics of the initiation reactions of OH, O_3 and NO_3 with volatile organic compounds (VOC). Concurrently, other groups used Teflon bags to study smog-forming reactions under irradiation by natural sunlight, but their results were limited to the Los Angeles conditions.

The importance of the OH radical in atmospheric chemistry had been promoted by Weinstock (1969), working at the Ford Motor Company research laboratories at Dearborn. In this laboratory, Niki used a relatively small photoreactor to develop the application of FTIR spectroscopy for quantitative investigation of atmospheric reactions (Niki et al. 1972, 1981; Wu et al. 1976). IR absorption spectroscopy had been used for a number of years to study atmospherically relevant chemical reactions (Stephens 1958; Hanst 1971), based mainly on mirror systems which allowed long path light absorption (White 1942, 1976; Herriott et al. 1964; Herriott and Schulte 1965). However, it was the use of FTIR methods by Niki et al. (1981) and additional work in the Pitts' group to quantitatively measure rate coefficients and products in photoreactors by long path FTIR absorption spectroscopy that really accelerated and

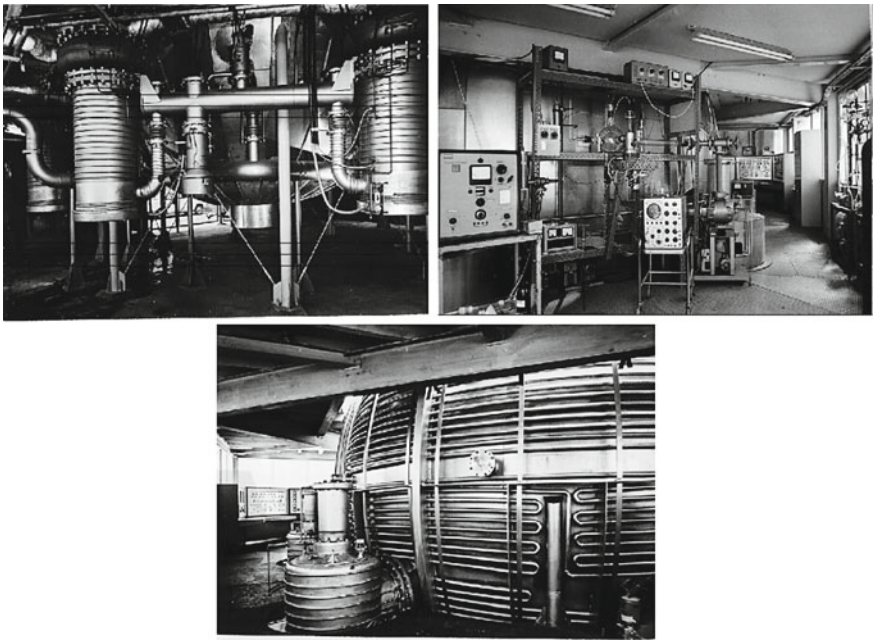

Fig. 1.2 The pipe system by which the chamber could be heated to 300 °C (left), enormous pumping capacity needed to reach the vacuum of 10–9 Torr (middle), the platform at which the experiments were prepared and carried out (right). Courtesy of K.H. Becker, Bonn, Germany

promoted the use of the technique and FTIR has been one of the work-horses of chemical simulation chambers ever since.

In the 1960s and '70s, the understanding of atmospheric reactions developed as first the key role of the OH radical was recognised as the dominant oxidizing agent in the troposphere, based on the analysis of the CO budget (Heicklen et al. 1969; Weinstock 1969; Stedman et al. 1970; Levy 1971), and the measurement of the OH + CO rate coefficient two years earlier (Greiner 1967). The propagation of an OH radical chain was understood 10 years later when the rate coefficient of the fast reaction $HO_2 + NO \rightarrow OH + NO_2$ was measured by several groups (Howard and Evenson 1977; Leu 1979; Howard 1979, 1980; Glaschick-Schimpf et al. 1979; Hack et al. 1980; Thrush and Wilkinson 1981), initiated by studies of Crutzen and Howard (1978) that showed the importance of this reaction in stratospheric ozone chemistry.

In Europe in the 1970s, several groups e.g., Becker and co-workers in Bonn and Cox and co-workers in Harwell, started studies on tropospheric chemistry based on either the technique of long path FTIR absorption spectroscopy in simulation chambers by Becker and co-workers in Wuppertal or molecular modulation studies focusing more on elementary reactions by Cox. Becker and co-workers constructed a multiple reflection mirror system in a 420 L photoreactor, which could be operated between 223 and 323 K to determine the OH reaction rate coefficients in combination with product analyses in the ppm range. Subsequent developments involved the

construction of a 6 m long quartz glass reactor of 1000 L volume, the QUAREC chamber, which enabled measurements to be extended down to the ppbV level. Over the years, other European laboratories started to use indoor chambers of larger volume irradiated by a range of photolysis sources (Baltensperger et al., in Villigen/Zürich, Carlier and Doussin in Paris, Hjorth et al., in Ispra, Herrmann et al., in Leipzig, Le Bras et al., in Orléans, Treacy et al., in Dublin, Wenger et al., in Cork). Tables 1.2 and 1.3 lists the larger indoor and outdoor reactors, respectively, that have been built up to 2000.

Large outdoor simulation chambers have many advantages in terms of photochemical smog simulation and several large outdoor chambers have been built in the US, with support from the EPA. A major objective of these studies was to determine ozone formation isopleths under chemical conditions representative of conditions observed in major US cities. These chambers were made from FEP Teflon foil, with volumes up to 25 m^3. Whilst they lead to improvements in the empirical understanding of smog formation, the results could not be generalised because of the limited range of conditions requested by the US EPA. In Riverside, Carter and co-workers developed a method to define the ozone formation potential of VOCs by determining maximum incremental reactivity (MIR) factors using chamber data and chemical modelling (Carter 1994). A similar method was introduced by Jeffries in Chapel Hill, who also used an outdoor chamber (Fox et al. 1975).

Other approaches involved the injection of real engine exhaust directly into a smog chamber and studying the formation of ozone. However, the data were still very US specific in terms of the VOC/NO_X ratios and so could not be generalised and applied in other countries. In parallel, with the simulation studies mentioned above, Atkinson and co-workers refined their method to determine the OH reactivity from relative rate measurements in chambers and developed structure reactivity relationships to calculate rate coefficients for OH radical reactions with VOCs (Atkinson 1986, 1987; Kwok and Atkinson 1995). Further developments in simulation work included work by Seinfeld and co-workers in the mid-1980s, to study secondary organic aerosol formation from the oxidation of aromatic and biogenic hydrocarbons via the use of a 65 m^3 outdoor chamber made of FEP Teflon (Pandis et al. 1991).

In Europe, the first development of a large, highly instrumented chamber was led in the mid-1990s, by Becker, Millán and co-workers who built the EUPHORE (European Photoreactor) outdoor chamber in Valencia, Spain. In fact, EUPHORE consists of two chambers made of FEP Teflon foil, each of which has a volume of 200 m^3 (Becker 1996). This facility became a centre for European laboratories to work co-operatively on mechanistic, kinetic and ozone formation studies using either controlled starting materials or real exhaust gases from gasoline and Diesel engines. The EUPHORE chambers were equipped with a comprehensive suite of analytical instrumentation, including in situ detection of the key radicals HO_2 and OH using laser-induced fluorescence measurements.

In 2000, the group of Wahner at Forschungszentrum Jülich, Germany, built a new double walled outdoor chamber called SAPHIR (Brauers et al. 2003), which has a volume of 280 m^3, see Fig. 1.3. The double wall made of FEP Teflon foil allows studies of oxidation processes at low NO_x concentrations (below 1 ppbV). The Jülich

Table 1.2 Indoor chambers without light sources or irradiated by black lamps or solar simulators up to the year 2000

Year	References and location	Description	Application
1968	Groth et al. (1972) Bonn	Dark chamber 220 m^3, stainless steel (high vacuum)	Without light sources, for low pressure studies
1972	Niki et al. (1972), Dearborn	150 l Pyrex	Kinetic and mechanistic studies
1975	e.g. Doyle et al. (1975), Riverside	6 m^3, evacuable, thermostated, FEP[a] coated aluminium	Photooxidant and kinetic studies
1979	Akimoto et al. (1979a), Tsukuba	6 m^3 evacuable, thermostated, FEP coated aluminium	Photooxidant studies
1980	Winer et al. (1980), Los Angeles	6 m^3 evacuable, thermostated, FEP coated aluminium	Photooxidant studies
1981	Barnes et al. (1979), Wuppertal	420 l Duran glass, evacuable, thermostated − 50 to + 50 ℃	Gas phase studies
1982	Joshi et al. (EPA), Research Triangle Park	440 glass reactor	Photooxidant studies
1986	Barnes et al., Wuppertal	Quartz glass 1100 l, evacuable, thermostated 0 to + 25 °C	Gas phase and aerosol kinetic and mechanistic studies
1986	Evans et al. (1986), Australia	4 × 200 l FEP bags	Photooxidants studies
1988	Behnke et al. (1988), Germany, Hannover, now Bayreuth	ca. 3000 l, Duran glass, thermostated −25 °C to ambient temperature	Aerosol studies
1997	Möhler et al. (2001), Karlsruhe	84 m^3, thermostated –90 to + 60 ℃, *AIDA*	For trace gas, aerosol and cloud studies
1996	Wahner et al. (1998), Jülich	256 m^3, FEP wall cover of a lab room	Without light source, for NO_Y chemistry
1997	Doussin et al. (1997), Paris	977 l, glass	Gas phase mechanistic studies
1998	Cocker et al. (2001), Pasadena	2 × 28 m^3, 10–40 ℃	Aerosol studies
2000	Carter et al. (2005), Riverside	FEP, double wall	Low NO_x studies

[a] FEP fluorinated ethylene propylene

Table 1.3 Outdoor chambers irradiated by sunlight up to the year 2000

Year	References and location	Volume, wall material
1976	Jeffries et al. (2013), Chapel Hill	25 m^3, FEP
1981	Fitz et al. (1981)	40 m^3, FEP
1983	Spicer (1983)	17.3 m^3, FEP
1985	Kelly (1982)	450–2000 l, FEP bags
1985	Jeffries et al. (1976), Chapel Hill	25 m^3, FEP
1985	Leone et al. (1985), Pasadena	65 m^3, FEP
1995	Becker (1996), Valencia	2 × 200 m^3, FEP, *EUPHORE*
2000	Wahner (2002), Jülich	270 m^3, FEP, double wall, *SAPHIR*

group did pioneering work in field measurements of OH and HO_2 concentrations (Hofzumahaus et al. 2009), so SAPHIR is fully equipped with the most advanced in situ radical measurement techniques (Fuchs et al. 2012a, b). A smaller double wall indoor chamber was recently built by Carter in Riverside, to study tropospheric oxidation processes at low NO_x concentrations.

Two other chambers were built in Germany, at the same time, for the study of aerosol processes. In 1986, Zetzsch and co-workers built a 3000 l Duran glass indoor chamber in Hannover, covered inside with FEP, and irradiated by solar simulators. This facility has been moved to Bayreuth. In 1987, Schurath and co-workers started to

Fig. 1.3 The double wall outdoor chamber SAPHIR in Jülich, Germany (© "Forschungszentrum Jülich/Sascha Kreklau")

operate the 84 m^3 aluminium chamber AIDA (Aerosol Interaction and Dynamics in the Atmosphere) in Karlsruhe, which has homogeneous temperature control between + 60 °C and −90 °C for trace gas, aerosol and cloud process studies. Other groups also now operate medium sized chambers.

A milestone for the European landscape of atmospheric simulation chambers was the implementation of the EUROCHAMP initiative, which started in May 2004 with the goal of joining together the existing European facilities into one integrated infrastructure of atmospheric simulation chambers.

The integration of all these chamber facilities within the framework of EUROCHAMP, followed by the EUROCHAMP-2 and EUROCHAMP-2020 projects, promoted the retention of Europe's international position of excellence in this area and it is unique in its kind worldwide. The mobilization of a large number of stakeholders dealing with environmental chamber techniques provided an infrastructure to the research community at a European level, which offers maximum support for a broad community of researchers from different disciplines. Overall, the EUROCHAMP projects fostered the structuring effect of atmospheric chemistry activities performed in European chambers and initiated wider international collaborations by supporting transnational access activities. Nowadays these facilities are fully available for the whole European scientific community and are exploratory platforms within the new Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS). The following tables summarize current chambers across the world (Table 1.4) starting with the chambers of the EUROCHAMP consortium.

1.2 Investigations of Atmospheric Processes

1.2.1 Reaction Kinetics and Product Studies

Being the building blocks of the general atmospheric chemical mechanism, the study of the kinetics of elementary steps and the related product distribution has been the main application of simulation chambers. Involving pure gas phase conditions this has been–and is still–often carried out in small photoreactors of a few hundred litres or in small indoor simulation chambers. In the case of kinetics studies, Teflon bags of several litres to a few cubic-meters working under atmospheric pressure and ambient temperature under artificial irradiation (generally UV fluorescent tube) were often used to apply relative rate methods (Brauers and Finlayson-Pitts 1997). Nevertheless, the atmospheric fate of hundreds of various volatile organic compounds (VOC) was also studied–and is still–in rigid chambers such as the one displayed in Fig. 1.4 (Barnes et al. 1987; Doussin et al. 1997; Etzkorn et al. 1999; Picquet-Varrault et al. 2001; Atkinson 2000). This systematic kinetic and mechanistic work has produced over time a comprehensive database that has established the foundations of most chemical schemes used in numerical models.

Table 1.4 List of current chambers across the world; The chambers of the EUROCHAMP consortium are listed in alphabetic order of chamber acronym, and chambers across the world outside the EUROCHAMP consortium are listed in alphabetic order of country

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
EUROCHAMP chambers							
AIDA KIT, Karlsruhe, Germany	Indoor	Aluminium	85	LED	+ 60 °C to − 90 °C	Evacuable and developed for aerosol and cloud simulation	Möhler et al. (2003), Wagner et al. (2006)
CESAM CNRS-UPEC, Créteil, France	Indoor	Stainless steel	4,2	Xenon arc lamps	−10 to + 50 °C	Evacuable and developed multiphase atmospheric processes	Wang et al. (2011)
CHAMBRe INFN, Genoa, Italy	Indoor	Stainless steel	3	Arc	Ambient	Evacuable and suitable for bioaerosols	Massabò et al. (2018)
CSA CNRS-UPEC, Créteil, France	Indoor	Pyrex	0,97	Fluorescent Tubes	Ambient	Evacuable Gas phase chemistry	Doussin et al. (1997)
ESC-Q-UAIC CERNESIM, Iaisi, Romania	Indoor	Quartz	0,76	Fluorescent Tubes	Ambient	Gas phase chemistry	
EUPHORE CEAM, Paterna, Spain	Outdoor	FEP	200	Sun	Ambient	Dual chambers gas phase and aerosol	Zádor et al. (2006)
FORTH-ASC FORTH, Patras, Greece	Indoor	FEP	10	Fluorescent tubes	Ambient	Indoor simulation chamber	Kostenidou et al. (2013), Kaltsonoudis et al. (2017)
FORTH, Patras, Greece	Outdoor	FEP	2	Sun/Fluorescent tubes	Ambient	Mobile	Kaltsonoudis et al. (2019)

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
HELIOS CNRS_Orléans, Orléans, France	Outdoor	FEP	90	Sun	Ambient		Ren et al. (2017)
CNRS_Orléans, Orléans, France	Indoor	FEP	16	Fluorescent tubes	Ambient		Le Person et al. (2008)
HIRAC Unversity of Leeds, Leeds, UK	Indoor	Stainless steel	2	Fluorescent tubes	−25 to + 70 °C	Evacuable gas phase chemistry and radicals	Glowacki et al. (2007)
IASC UCC, Cork, Ireland	Indoor	FEP	27	Fluorescent tubes	15–25 °C	Atmospheric chemistry	
ILMARI University of Eastern Finland, Kuopio, Finland	Indoor	FEP	29	Fluorescent tubes	16–25 °C	Combustion emission and health	Leskinen et al. (2015)
ISAC CNRS-IrceLyon, Villeurbanne, France	Indoor	FEP	2	Fluorescent tubes	Ambient		Bernard et al. (2016)
ACD-C TROPOS, Leipzig, Germany	Indoor	FEP	19	Fluorescent tubes	Ambient	Dual chamber	

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
MAC University of Manchester, Manchester, UK	Indoor	FEP	18	Xenon arc lamp	Ambient	Can be coupled with the MICC cloud chamber	Alfarra et al. (2012)
QUAREC Wuppertal University, Wuppertal, Germany	Indoor	Quartz	1.1	Fluorescent tubes	298 ± 5 K	Evacuable	Barnes et al. (1994)
RvG- ASIC University of East Anglia, Norwich, UK	Indoor	FEP and borosilicate glass	3.3	Fluorescent tubes	−55 to + 30 °C:	Atmosphere–ocean–sea-ice–snow simulation chamber	Thomas et al. (2021)
PACS-C3 PSI, Villigen, Switzerland	Indoor	FEP	27	Arc	Range 15–30 °C		Paulsen et al. (2005)
PACS-C3 PSI, Villigen, Switzerland	Indoor	FEP	9	Fluorescent tubes	Ambient	Mobile	Platt et al. (2013)
PACS-C3 PSI, Villigen, Switzerland	Indoor	FEP	9	Fluorescent tubes	Range 10–30 °C		Platt et al. (2013)
SAPHIR FZJ, Jülich, Germany	Outdoor	FEP	270	Sun	Ambient	Atmospheric chemistry at low concentrations, radical budgets	Rohrer et al. (2005a)

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
SAPHIR-PLUS FZJ, Jülich, Germany	Indoor	FEP	9	LED	0–50 °C	Plant chamber	Hohaus et al. (2016)
SAPHIR-STAR FZJ, Jülich, Germany	Indoor	Quartz	2	Fluorescent tubes	Ambient	Continuous stirred reactor	
Large Aerosol Chamber FZJ, Jülich, Germany	Indoor	Teflon	250	None	Ambient		Zhao et al. (2010)
Other chambers worldwide							
CSIRO, Sidney, Australia	Indoor	FEP	25	Fluorescent tubes	Ambient		Hynes et al. (2005)
Fudan University, Shanghai, China	Indoor	Teflon coated Stainless steel	4.5	No	Ambient		Li et al. (2015, 2017), Zhang et al. (2011a, b)
IAP, Beijing, China	Indoor	FEP	1	Fluorescent tubes	Ambient		Zhang et al. (2019)
CRAES, Beijing, China	Outdoor	FEP	56	Sun	Ambient		Li et al. (2021)

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
Zhejiang University Smog chamber (CAPS-ZJU), Hangzhou, China	Indoor	FEP	3	Fluorescent tubes	Ambient	Dual	Li et al. (2020)
Guangdong University of Technology–dual-reactor chamber (GDUT-DRC), Guangzhou, China	Indoor	FEP	2	Fluorescent tubes	Ambient	Dual	Luo et al. (2020)
CAS, Guangzhou, China	Indoor	FEP	30	Fluorescent tubes	−10 to 40 °C		Wang et al. (2014)
RCEES, Beijing, China	Indoor	FEP	30	Fluorescent tubes	Controlled		Chen et al. (2019)
SHUSC, Shanghai University Smog Chamber, Shanghai, China	Indoor	FEP	1.2	Fluorescent tubes	Ambient		Qi et al. (2020)

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
Tsinghua University, Beijing, China	Indoor	FEP	2	Fluorescent tubes	10–60 °C,		Wu et al. (2007)
Aarhus University, Aarhus, Denmark	Indoor	FEP	2	Fluorescent tubes	−15 to 26 °C		Kristensen et al. (2017)
Toyota, Aichi, Japan	Indoor	FEP	5	Fluorescent tubes	Ambient		Takekawa et al. (2003)
NIES, Tsukuba, Japan	Indoor	Teflon coated Stainless steel	6	Xenon arc lamps	0–40 °C	Evacuable and bakable up to 200 °C	Akimoto et al. (1979a, b, c)
NIES, Tsukuba, Japan	Indoor	FEP	0.7	Fluorescent tubes	−5 to 40 °C		Deng et al. (2021)
KIST, Korea Institute of Science and Technology, Seoul, Korea	Indoor	FEP	5.8	Fluorescent tubes	Ambient	Dual	Lee et al. (2009)
CLOUD, CERN, Geneva, Switzerland	Indoor	Stainless steel	26	LED	Controlled		Duplissy et al. (2010)
Carnegie Mellon, Pittsburg, USA	Indoor	FEP	16	Fluorescent tubes	Controlled		Donahue et al. (2012)

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
GeorgiaTech, Atlanta, USA	Indoor	FEP	12	Fluorescent tubes	Controlled	Dual	Boyd et al. (2015)
CalTech, Pasadena, USA	Outdoor	FEP	28	Fluorescent tubes	18–50 °C		Cocker et al. (2001)
CalTech, Pasadena, USA	Outdoor	FEP	65	Sun	Ambient		Leone et al. (1985)
UC Irvine, Irvine, USA	Indoor	Stainless steel	0.5	Hg and flouorescent tubes	Controlled	−10 to 70 °C	De Haan et al. (1999)
UC Irvine, Irvine, USA	Indoor	FEP	5		Controlled		Nguyen et al. (2011)
UC Riverside, Riverside, USA	Indoor	FEP	90	Ar-Xe arc lamp	5–45 °C		Carter et al. (2005)
UC Riverside, Riverside, USA	Indoor	FEP	6.6	Fluorescent tubes	Ambient		Lim and Ziemann (2005)
UC Riverside, Riverside, USA	Indoor	Teflon coated aluminium	5.6	Xenon arc	Ambient	Evacuable	Beauchene et al. (1973), Winer et al. (1980)
UNC, Pitsboro, USA	Outdoor	FEP	135	Sun	Ambient	Half-cylinder-shaped dual chambers	Lee et al. (2004)

(continued)

Table 1.4 (continued)

Chamber name and location	Indoor/Outdoor	Wall material	Volume (m^3)	Light source	Temperature	Comment	References
Pacific Northwest National Laboratory, Richland, USA	Indoor	FEP	10.6	Fluorescent tubes	Controlled		Liu et al. (2012)
UNC, Chappel Hill, USA	Indoor	FEP	9	Fluorescent tubes	Ambient		Smith et al. (2019)
CU Boulder, Boulder, USA	Indoor	FEP	8	Fluorescent tubes	Ambient		Krechmer et al. (2016, 2017)
Harvard/HEC, USA	Indoor	FEP	4.7	Fluorescent tubes	Ambient		King et al. (2009)
NCAR, Boulder, USA	Indoor	FEP	10	Fluorescent tubes	Ambient		Fry et al. (2014)
University of Florida UF-APHOR, USA	Outdoor	FEP	52	Sun	Ambient	Half-cylinder-shaped dual chambers	Im et al. (2014)

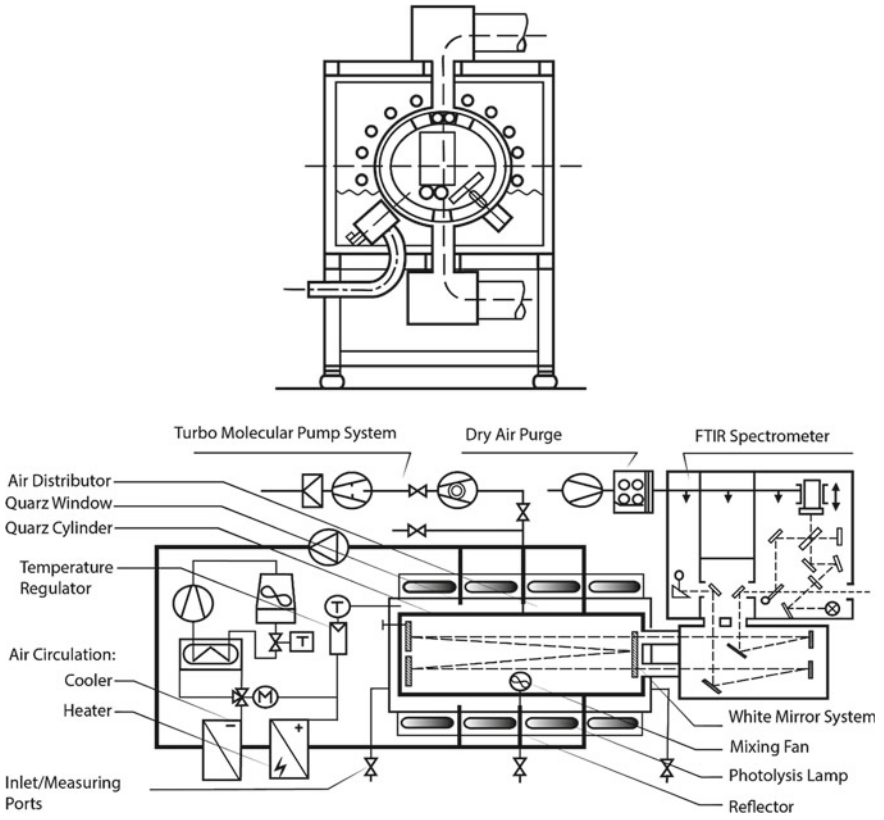

Fig. 1.4 Example of a 1 m^3 indoor quartz chamber irradiated with UV fluorescent tube–the QUAREC chamber from the Bergische Universität Wuppertal–Germany. (© Bergische Universität Wuppertal)

1.2.2 Simulating Gas Phase Mechanism, Radical Cycles and Secondary Pollutant Formation

Studies on the formation of secondary pollutants are generally conducted in large outdoor chambers to avoid potential artefacts linked to a lack of realism in the irradiation and to minimize radical losses or conversion on the walls. Tropospheric ozone production studies were hence the first to benefit from chamber application. Nevertheless, for those studies to be of use for general modelling it is necessary to disentangle chamber effects from directly applicable results. Such an approach has led as early as the late 1970s to the first ozone isopleth diagrams, linking precursor levels to ozone production (Dodge 1977; Jeffries et al. 2013). Interestingly, because of the focus on photooxidants which is mostly driven by air quality legislation, operational model evaluation is often conducted by comparison with the results arising

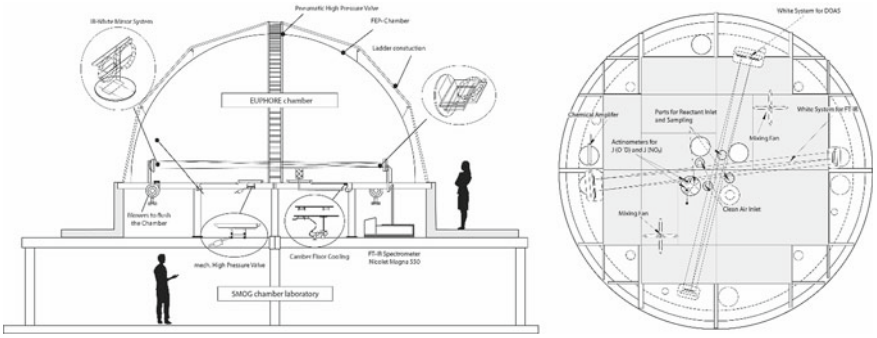

Fig. 1.5 Example of a large outdoor Teflon® chamber: the EUPHORE chamber–Valencia, Spain. (© EUPHORE)

from experiments conducted in these types of large chambers (Carter et al. 1979; Wagner et al. 2003; Bloss et al. 2005a, b; Carter 2008; Parikh et al. 2013).

Such chambers are made of FEP Teflon film, generally, several hundreds of cubic-meters in volume and are often installed on the roof of a dedicated laboratory (e.g. EUPHORE in Valencia, Spain Fig. 1.4 or Helios in Orleans, France) or in dedicated shelter structures (e.g. SAPHIR in Jülich, Germany Fig. 1.9 or UNC in North Carolina, USA). Because of their size and their outdoor installation, these facilities generally involve through-wall connections and inlets to connect the chamber with a measurement laboratory often located below. They also include devices such as a retractable roof to protect them from rain and wind. Temperature control cannot be achieved in such chambers and air inside the chamber may be heated by metal plates underneath the chamber when they are exposed to sunlight during the experiment. This effect is reduced if there is no direct contact of the metal plate with the chamber film and can be further reduced if the metal plate is cooled. Interestingly, even if their size is a significant advantage to minimize wall effects (on both gas phase and particulate phase), wind induced movements of the Teflon film lead to charge build-up that has the tendency to strongly reduce the physical lifetime of particle by drawing them to the wall (McMurry and Grosjean 1985) (Figs. 1.5 and 1.6).

1.2.3 Aerosol Processes

Originally considered as a technical problem during early smog simulation experiments, secondary organic aerosol (SOA) formation has since attracted very large interest from the scientific community. The availability of instruments such as Scanning Mobility Particle Sizers (SMPS), for the determination of particle number and size distribution with a time resolution of minutes, helped to promote the rapid development of experimental studies of SOA formation. This trend was further increased when mathematical formalisms were proposed to extrapolate the SOA yield from the

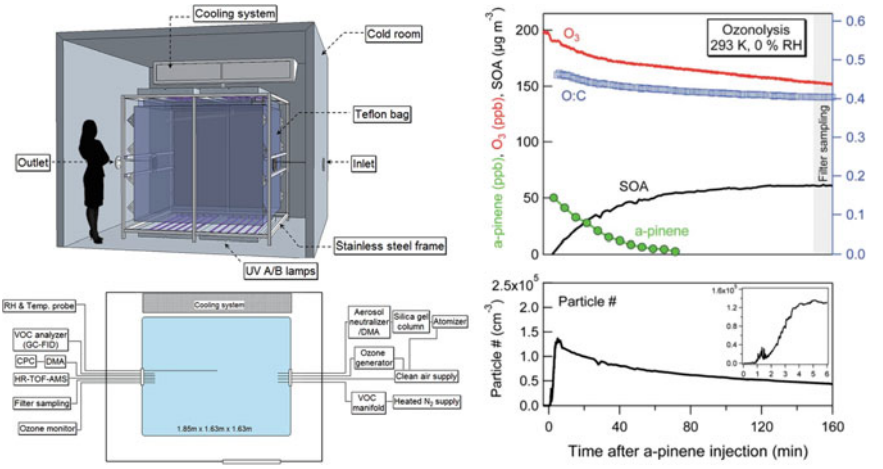

Fig. 1.6 Left: Example of a medium size indoor Teflon® chamber irradiated with UV fluorescent tubes/Right: Typical SOA production from terpene ozonolysis experiment (adapted from Kristensen et al. 2017)

high precursor concentrations used in chamber experiments to atmospheric conditions (Odum et al. 1996). The volatility basis set (VBS) formalism proposed by Donahue et al. (2006) was especially successful in providing a parameterization that could be inserted in models (3D included) and has triggered a renewed interest for chamber experiments from the modelling community. Both medium size and large chambers, as well as indoor and outdoor facilities, are regularly used for SOA experiments. Due to the multiphase nature of the processes studied and their even greater non-linearity, there is a general effort to reduce the starting concentration of the precursor to the ppb range (and sometimes below) in order to perform experiments at atmospherically relevant chemical conditions. These low concentrations make the results of these experiments very sensitive to wall effects on the gaseous species, such as wall loss of compounds that could normally participate in the aerosol mass or, on the other hand, the release of semi-volatile species. Further, physical wall losses of particles can also be significant. The quantitative characterization of these wall effects is still an open topic that requires a widely applicable formulation (see Chap. 2). It also depends highly on the properties of the wall (conductivity, permeability, reactivity, porosity…) in a context where the mechanisms involved are not yet well understood. Consequently, the combined use of several types of chambers, different in size but also made from different materials (Teflon film, glass, steel, aluminium…), is highly desirable for SOA experiments conducted at more realistic atmospheric concentrations of precursor gases. In parallel, a significant quantity of work has been conducted to better represent semi-volatile wall losses in this diversity of chambers (La et al. 2016; Krechmer et al. 2017; Lamkaddam 2017).

The contribution of simulation chambers to the understanding and quantification of SOA and related impacts is not limited to yield measurements. A wide body of

work has focused on both online and offline chemical characterization with the aim of understanding the chemical composition of the SOA fraction but also the chemical processes that govern the formation and aging of organic aerosol. As a result of the amount of work carried out in medium size chambers, important breakthroughs have been made in these topics such as the identification of oligomerization processes in the aerosol phase (Kalberer et al. 2006), the chemical trends followed by oxidation during SOA aging (Jimenez et al. 2009; Ng et al. 2011a, b; Kourtchev et al. 2016), or the importance of auto-oxidation processes for the formation of SOA precursors (Ehn et al. 2014).

New particle formation was long considered as a barely controllable step in the formation of SOA during simulation chamber experiments. For reproducibility purposes, in most of the studies focusing on aerosol yield, it is hence recommended to use seed aerosol as a condensation medium in order to avoid nucleation. Nevertheless, dedicated chambers–often exhibiting a very low level of electrostatic charges on the wall–have been used to investigate this important process that is possibly controlling the number of cloud condensation nuclei in some parts of the atmosphere (Bonn et al. 2002; Kiendler-Scharr et al. 2009a, b; Kirkby et al. 2011, Boulon et al. 2012). One of the challenges in studying the early steps of nucleation in simulation chambers is, on the one hand, the ability to measure clusters and particles in the range of 1 to 3 nm and, on the other hand, the reduced lifetime of particles smaller than 20 nm in enclosed vessels (see Sect. 2.5 for particle wall losses analysis). Indeed, simulation chambers easily allow for aerosol lifetimes of several hours to a few days for particles in the range of a few hundreds of nanometers but due to their very high diffusivity, particles in the range of a few nanometer exhibit lifetimes in the range of a few minutes only.

Because of the importance of nucleation related processes, a dedicated facility was set-up at CERN: the CLOUD (Cosmics Leaving OUtdoor Droplets) experiment. The CLOUD chamber is a stainless steel atmospheric simulation chamber of 26.1 m^3 (Duplissy et al. 2010; Voightländer et al. 2012) operating under drastically clean conditions and installed in the T11 beamline at the CERN Proton Synchrotron. In order to study the effect of cosmic rays on nucleation, the chamber can be exposed to a 3.5 GeV/c positively-charged pion (π+) beam from a secondary target. The results from this atmospheric simulation chamber have led to significant advances in the understanding of nucleation including the elimination of the role of sulfuric acid alone as a nucleating agent, some insight on the effect of cosmic rays and the role of low volatility products from biogenic oxidation in initial cluster formation.

As aerosols refer to the particulate and gas phase, the investigation of aerosol processes in atmospheric simulation chambers also includes studies of heterogeneous processes. Prominent examples of systems studied include the chemical aging of aerosols and formation of brown carbon (e.g. Laskin et al. 2015) and the uptake of ozone on organic aerosol such as SOA formed from limonene ozonolysis (Leungsakul et al. 2005; Zhang et al. 2006). The N_2O_5 uptake coefficient on different particle types and the influence on gas phase oxidant levels were excessively studied in the Jülich indoor aerosol chamber (Mentel et al. 1996; Folkers et al. 2003; Anttila et al. 2006). More recently it was shown in atmospheric simulation chambers that levoglucosan,

traditionally utilized as a source tracer for biomass burning aerosol, is reactive in the atmosphere (Hennigan et al. 2010, 2011; Sang et al. 2016; Bertrand et al. 2018; Pratap et al. 2019).

1.2.4 Cloud Processes

While "cloud chambers" have existed for a very long time, mostly to study the microphysics of fog and clouds, the past few decades have seen emerging chamber facilities which can generate clouds and fog under sufficiently clean conditions that multiphase chemistry, transformation at the droplet interface and cloud microphysical processes can be studied (Stehle et al. for the DRI chamber 1981; Hoppel et al. for the CALSPAN chamber 1994; Möhler et al. 2001 for the AIDA chamber; Duplissy et al. 2010 for the CLOUD chamber; Wang et al. 2011 for the CESAM chamber; Chang et al. 2016 for the Pi Chamber). All of these chambers are made of metal–mostly stainless steel (except for AIDA where the walls are made of aluminium)–because one of the most common protocols to generate a cloud is to perform a quasi-adiabatic expansion through a relatively fast decrease of the total pressure (from a few second to a few minutes) with or without controlling the wall temperature. For instance, the AIDA chamber allows for generating liquid droplets, mixed-phase (droplet and ice) and pure ice clouds. Further details can be found in Sect. 8.1 (Fig. 1.7).

These facilities have opened the door for realistic studies of cloud microphysics in the laboratory. The studies, which have been enabled due to careful control of the initial and boundary conditions, include investigations into the cloud condensation nuclei (CCN) and ice nucleation activity of various aerosol particles (Wagner et al. 2011; Henning et al. 2012; Hoose and Möhler 2012), homogeneous freezing of supercooled solution droplets (Möhler et al. 2003), scattering properties of ice crystals (Järvinen et al. 2014; Schnaiter et al. 2016), and the effects of non-precipitating water clouds on aerosol size distributions (Hoppel et al. 1994).

In parallel, a whole field of activity has been opened with the ability to study chemical transformations at the interface of droplets or even in the suspended aqueous phase. Using this approach, sulfate formation from the multiphase oxidation of SO_2 has clearly attracted the most attention (Stehle et al.1981; Miller et al. 1987; Lamb et al. 1987; Hoyle et al. 2016), but more recently, aqueous SOA formation from isoprene oxidation products (Brégonzio-Rozier et al. 2016) and brown carbon formation from fog processes of functionalized organics (De Haan et al. 2018) have also been investigated.

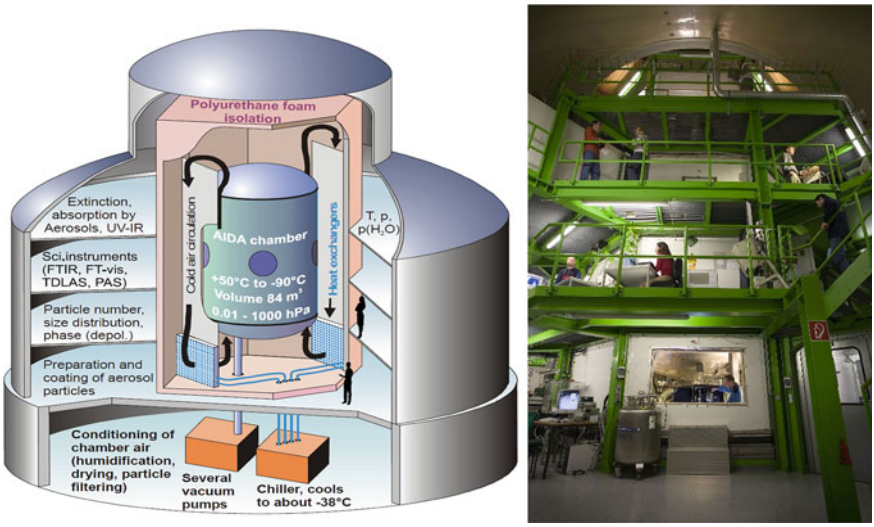

Fig. 1.7 Left: The AIDA facility at the Karlsruhe Institute of Technology with an 84 m^3 aluminium chamber. Trace gas, aerosol and cloud experiments can be performed in a wide range of atmospheric temperatures (+60 °C to −90 °C), pressure (1–1000 hPa) and humidity (sub- and supersaturated with respect to liquid water and ice) conditions). Right: Typical evolution of pressure, temperature, relative humidity, and cloud droplet diameter for an adiabatic expansion experiment in AIDA

1.2.5 Characterization and Processing of Real-World Emissions

The development of atmospheric chemical mechanisms has been based on chamber studies of atmospheric oxidation of individual compounds. Hundreds of species have been studied following this approach and have contributed to the building of detailed chemical schemes, such as the Master Chemical Mechanism MCM (website: mcm.york.ac.uk). This effort is still ongoing to take into account new emissions and refine the chemical module of large-scale models. Nevertheless, in parallel, chamber studies that represent more realistic and more complex conditions are required to close the gap between well controlled but simplified laboratory experiments and observations in the real atmosphere.

Chamber studies, previously described here, have focused on chemical processes occurring in the gas and aerosol phases and have usually been limited to the simplified oxidation conditions and systems of selected precursors. More recent studies on real emissions from combustion sources such as engines and wood-burning stoves, or from natural emission sources such as plants or mineral dust, raise interesting possibilities for more relevant investigations of atmospheric processes.

In these studies, chambers are coupled to real emission sources (plant chambers, engines, wood burners, cooking stoves…) to study systems of real-world complexity. As much as one loses the ability to fully understand processes because of the

complexity of the starting mixtures, one gains in the realism of the impact and the enhanced comparison with field measurements.

Experiments using real-world emissions involve complex sources that are either so intense that they need to be diluted before being added to chambers (e.g. engines, wood burners, cooking stoves) or do not require dilution (e.g. plants, sea spray, air fresheners and other household products). Approaches to ensure the quantitative transfer of all compounds of such complex emission blends into atmospheric chambers are described in detail in Chap. 5.

Concerning the first category, these experiments involve primary pollution sources whose aging is studied because of a potential formation of secondary pollution worsening their primary effect. The experimental challenges here are to

a. reproduce the atmospheric dilution of primary emission (both gaseous and particulate matter) while remaining in measurable concentrations: generally, a dilution factor ranging between 100 and 1000 are used (Platt et al. 2013, 2017; Gentner et al. 2017; Pereira et al. 2018)
b. establish a chemical system mimicking atmospheric aging over a few days.

Large and medium size chambers can be used for these studies. For example, Geiger et al. (2002) have connected a diesel engine fuelled with various diesel fuel formulations and mounted on a motor test bed directly to the EUPHORE chamber. In the dual outdoor simulation chambers, VOC mixtures containing a fixed ratio of *n*-butane, ethene and toluene were irradiated by natural sunlight in the presence and the absence of diesel exhaust. In this case, the large volume of the EUPHORE chamber (ca. 200 m^3) removed the need for a dilution system. For smaller simulation chambers (Chirico et al. 2010; Pereira et al. 2018; Platt et al. 2013) a conservative dilution system is needed to reduce the concentrations while keeping constant the various ratios between gaseous and particulate species, volatile and semi-volatile species. To do so, a specific aerosol diluter and heated lines are used. To preserve the efficiency of the atmospheric processes, prescribed VOC-to-NO_x ratios are used which often require the addition of a VOC such as ethene, which is chosen for its ability not to add to the particulate mass during its oxidation. Aging is, for example, evaluated using the OH exposure index, defined as the cumulative OH concentration over the course of the experiment. The calculation of OH exposure requires the use of an OH tracer such as deuterated butanol-d_9 (Barmet et al. 2011) or the direct measurement of OH (e.g. Zhao et al. 2018) (Fig. 1.8).

These studies have demonstrated that, when considering car emission related fine particles, secondary pollution was as important as primary pollution and sometimes larger (Geiger et al. 2003; Bahreini et al. 2012; Platt et al. 2013, 2017; Gentner et al. 2017). In particular, the content of intermediate volatility organic compounds (IVOC) has been identified as critical in the ability to produce SOA (Pereira et al. 2018). The work in simulation chambers has allowed testing of the various types of vehicles, engines or fuel formulations that were already available on the market but, the interest that this methodology has raised among car manufacturers, allows one to hope for testing of future technology before its widespread deployment in vehicles.

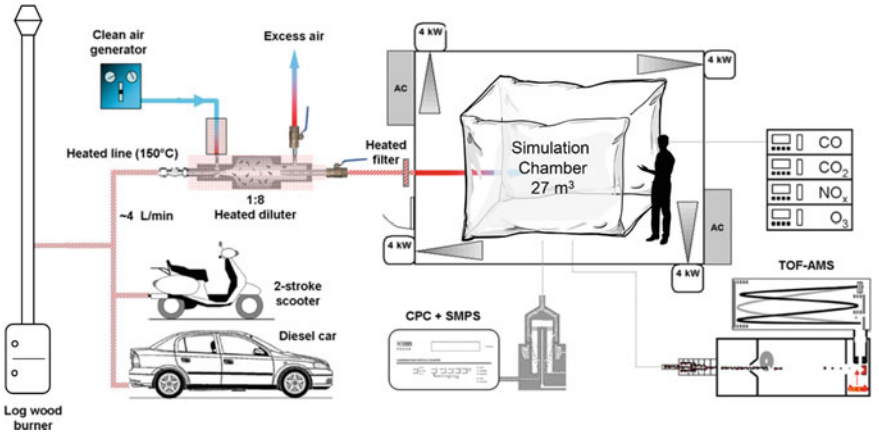

Fig. 1.8 Use of the PSI 27 m^3 Teflon chamber for investigating various real-world emissions transformation in the atmosphere. (Figure reused with permission from Heringa et al. (2012) Open access under a CC BY 3.0 license, https://creativecommons.org/licenses/by/3.0/)

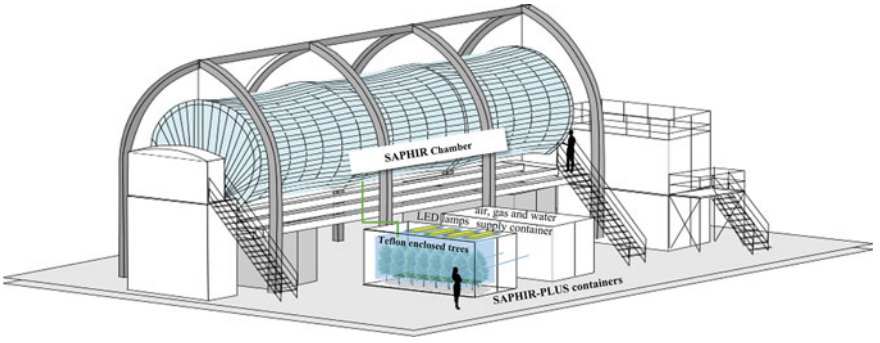

Fig. 1.9 SAPHIR-PLUS the combination of one of the largest outdoor simulation chamber (SAPHIR–Forschungszentrum Jülich, volume: ca. 270 m^3) with a controlled plant growing unit

A similar methodology can be applied to biomass combustion emissions. Considering the importance of this family of emissions, sources such as in-house open fires, agricultural burning, modern stoves or even barbecue emissions have been injected in a simulation chamber and aged in order to better quantify the extent of secondary pollution relatively to primary emission (Tiitta et al. 2016; Bertrand et al. 2017; Bhattu et al. 2019). Not only do these studies allow evaluation of the environmental impacts of combustion of various fuels (e.g. logwood, pellet, straw), types of combustion technology (e.g. stoves) and the various burning regimes (such as flaming or smouldering), but they also allow identification of molecular tracers and mass spectral signatures that can be monitored in the field to improve emissions inventories.

For experiments involving the atmospheric processing of plant emissions, the key challenge is not the dilution as these emissions are diffuse enough, but rather the preservation of their representativeness. Indeed, as living organisms, plants are sensitive to their environmental condition and any unwanted factors such as water stress, mechanical stress, biotic stress, oxidative stress or other abiotic stress from air composition may affect the composition and amount of their emissions (e.g. Kleist et al. 2012; Mentel et al. 2013; Wu et al. 2015; Yli-Pirilä et al. 2016; Zhao et al. 2017). Consequently, for studies involving plants, the plant growing facility as well as the emission transfer system have to be the subject of extreme care.

In SAPHIR-PLUS for example (see Fig. 1.9, Hohaus et al. 2016), the photo-oxidation of Pinus sylvestris L. (Scots pine) emissions were reacted and aged by ozonolysis in the presence of sunlight (Gkatzelis et al. 2018) which has allowed parameterization of the SOA production from these real plant emissions following the volatility basis set (VBS) formalism (Donahue et al. 2006). In a 9 m^3 temperature controlled Teflon simulation chamber, run in batch mode at the University of Eastern Finland, Failo et al. (2019) studied SOA formation from healthy Scots pine emissions and from the same plants infected with aphids. The aphid stressed pine were shown to emit more linear sesquiterpenes than healthy ones with significant effects on the SOA yields. Wyche et al. (2014) investigated in the Manchester Aerosol Chamber (MAC), the differences in SOA formed from predominantly terpene versus predominantly isoprene emitters. So far only very few studies have examined SOA production from the full range of VOCs made by plants. Since it was shown that the individual contributions of VOC in mixtures interact in non-linear ways in SOA formation mechanisms (Kiendler-Scharr et al. 2009a, b; McFiggans et al. 2019), there is a strong need for more studies exploring plant emissions.

1.2.6 Mineral Dust

aerosols are another key player in the atmospheric system. These particles contribute to the aerosol radiative effect and can act as cloud condensation nuclei (CCN) as well as ice nucleating particles (INPs). Mineral dust particles can deliver soluble elements needed for the development of oceanic life and eventually modify the CO_2 content of the atmosphere. Altogether, these kinds of aerosol particles affect Earth's weather and climate. Desert dust also affects human health, as an irritating agent at high concentrations causing respiratory diseases, as well as a vector for bacteria, viruses and possibly for severe infections like meningitis.

During transport, mineral dust can mix with air pollution and undergo chemical transformations that may affect their basic properties (composition, optical properties, CCN/IN activities, solubility…) and therefore their atmospheric impacts. Further, the multiphase chemistry occurring at their surface may also affect air composition. All these reasons have recently led a small number of research groups in the chamber community to apply the experimental simulation methodology to this science topic. This application implies solving various issues.

The first issue is the representativeness of the generated dust aerosol with respect to the atmosphere. Airborne mineral dust is a mixture of several minerals whose proportions change depending on the properties of the parent soil and wind speed. It forms an aerosol of an extended size distribution (extending from hundreds of nanometers to tenths of micrometers) that does not necessarily reflect the mineralogy of the soil due to the size-dependence fractionation between the soil and the aerosol phases that occurs at emission. There is hence a technological challenge in reproducing the dust generation from the soil process so that both the mineralogical composition and the size distribution are realistic (see Sect. 5.2). The global diversity of the mineralogical composition of natural parent soil is not reproduced by the commercially available minerals or standard mixtures. As much as possible, research tries to face this diversity by generating dust from natural soil collected across the world (Linke et al. 2006; Möhler et al. 2008a; Connolly et al. 2009; Wagner et al. 2012; Di Biagio et al. 2014, 2017a, b, 2019; Caponi et al. 2017), complementing and augmenting the many studies with model mineral dust such as Arizona Test Dust (Möhler et al. 2006, 2008a, b; Connolly et al. 2009; Vlasenko et al. 2006) or pure minerals such as illitte (Möhler et al. 2008a, b) kaolinite (Tobo et al. 2012), hematite (Hiranuma et al. 2014) or Feldspar (Mogili et al. 2006, 2007; Atkinson et al. 2013).

Another critical issue for the study of mineral dust in simulation chambers is the reduced lifetime of these aerosols. Indeed, simulation chambers easily allow for aerosol lifetimes of several hours to a few days for particles in the range of a few hundreds of nanometers, but particles in the range of several micrometers undergo rapid sedimentation. As a consequence, in the absence of active resuspension processes, their lifetime in enclosed vessels is reduced to a few minutes only. This makes it difficult to study chemistry at the surface of the coarse fraction of mineral dust, but it is an advantage when one tries to reproduce the physical aging of dust plumes in the atmosphere. In fact, chamber experiments of a couple of hours duration can reproduce modifications to the size distribution of airborne dust that takes place over 2–3 days of transport (Di Biagio et al. 2017a, b). Chambers are therefore an emerging tool of choice to study the hygroscopicity and optical properties of mineral dust or the chemistry in the presence of the fine fraction only.

To date, most of the published results from chamber studies involving mineral dust have focused on their direct and indirect radiative effect. A large number of ice nucleation studies have been carried out at the AIDA chamber and LACIS (Leipzig Aerosol Cloud Interaction Simulator) on surrogate dust left bare (Möhler et al. 2006, 2008a, b; Tobo et al. 2012; Hiranuma et al. 2014; DeMott et al. 2015; Niedermeier et al. 2011, 2015; Hartmann et al. 2016) or covered with inorganic (Augustin-Bauditz et al. 2014; Niedermeier et al. 2011; Wex et al. 2014) and organic layers (Möhler et al. 2008a, b). In the CESAM chamber, most of the research to date has focused on optical properties and the derivation of complex refractive indexes in the long wave spectral ranges (Di Biagio et al. 2014, 2017a, b) and in the UV–visible (Di Biagio et al. 2019, Caponi et al. 2017).

To date, the number of studies of chemical reactivity at the surface of mineral dust in simulation chambers is rather limited due to the above-mentioned difficulties. They mostly involved ozone loss on the particles (Mogili et al. 2006) or SO_2 uptake and reactivity (Zhou et al. 2014).

1.3 Bridging the Gap Between Laboratory and Field Studies

Simulation chambers have been also used for the benefit of field experiments and long-term atmospheric monitoring (Kourtchev et al. 2016). These cross-community activities have first concerned instrumental development with a number of high technology new techniques being developed or tested at simulation chambers (see also 1.5). Prominent among these types of studies is the development of new techniques dedicated to atmospheric radical measurement (Schlosser et al. 2007; Onel et al. 2017), new techniques involving advanced optical setups such as optical cavities (Varma et al. 2009, 2013), the development of new advanced mass spectrometry instruments (Docherty et al. 2013) and chromatographic procedures for the elucidation of the aerosol organic fraction (Rossignol et al. 2012a, b).

1.3.1 Tracers and Sources of Fingerprint Studies

The use of simulation chambers for the benefit of field studies also includes the identification of specific signatures for emission sources (especially for aerosol mass spectrometry–see Aiken et al. 2008; Mohr et al. 2009; Kiendler-Scharr et al. 2009a, b; Zhang et al. 2011a, b; Schwartz et al. 2010). It also involves the identification of molecular tracers characteristic of specific processes. In this case, the ability of chambers to study specific processes is valuably used to separate the effect of the various potential oxidants or conditions. When well characterized, and found to be sufficiently unreactive in the atmosphere, these tracers are then searched for in the field to apply advanced apportionment procedures with the aims of not only elucidating the extent of primary sources but also of secondary processes (Jaoui et al. 2007; Kleindienst et al. 2007, 2012; Zhang et al. 2012).

In addition, important work has been carried out in characterizing the atmospheric tracers of primary sources such as levoglucosan or guaiacol (Hennigan et al. 2010; Bertrand et al. 2018; Pratap et al. 2019) that were initially thought fairly unreactive. This includes the use of stable isotopes as tracers for the extent of chemical processing (Sang et al. 2016; Gensch et al. 2014).

1.3.2 Instrument Comparison Campaigns

In addition to activities which involve generally one or only a few groups, large instrument comparison campaigns gather the wider atmospheric science community around chambers to characterize both established and emerging techniques using the ability of simulation chambers to precisely control the environmental conditions, while allowing different instruments to simultaneously sample from the same air mass. Suspected artefacts can hence be intentionally amplified and the sensitivity of the related techniques can be investigated and quantified. High precision water vapor measurement (Fahey et al. 2014), NO_x and NO_y measurements (Fuchs et al. 2010), oxygenated species measurements (Wisthaler et al. 2008; Apel et al. 2008; Thalman et al. 2015; Munoz et al. 2019), radical measurements (Schlosser et al. 2007; Fuchs et al. 2010; Fuchs et al. 2012a, b; Ródenas et al. 2013; Onel et al. 2017) or radical reactivity measurements (Fuchs et al. 2017) have been compared in large campaigns at chambers during the last 15 years.

1.3.3 Field Deployable Chamber

Recently a very innovative approach which combines the use of a simulation chamber with field studies has been developed both in Patras (Greece) and in Carnegie Mellon Institute (USA). It involves the use of portable simulation chambers directly in the field. This strategy is based upon a concept experiment: use ambient air as a starting point and allow the study of the evolution of atmospheric particulate matter at timescales longer than those achieved by traditional laboratory experiments (Kaltsonoudis et al. 2019).

This type of study can take place under more realistic environmental conditions but they could appear as being contrary to the whole simulation chamber experiment concept i.e. simplify and control the chemical system to better understand it. To solve this apparent contradiction, the group that is developing this new approach has developed a dual chamber strategy: after careful characterization of both chambers and so after verifying that they are producing comparable results, both are filled with the ambient being studied but one is "perturbed". The perturbation can consist of an additional oxidant injection such as ozone, addition of OH sources such as HONO or H_2O_2, or the addition of a compound potentially modifying the aerosol formation scheme such as α-pinene (Kaltsonoudis et al. 2019). The information on the chemical state of the sampled air is then deduced from the differential analysis of the results from the perturbed and control chambers (Fig. 1.10).

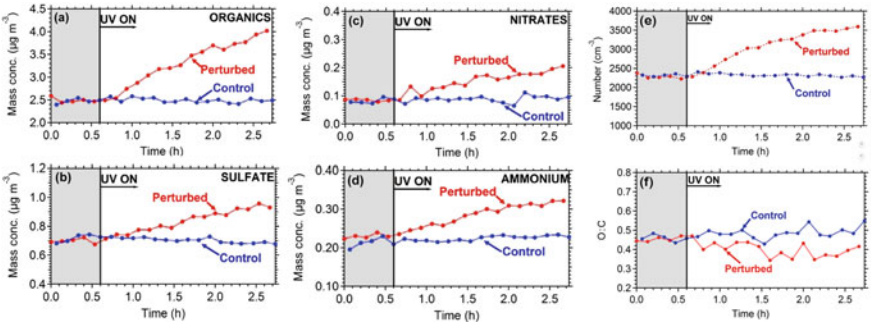

Fig. 1.10 Results from the operation of a dual field deployable simulation chamber during a campaign in Pittsburg (USA). One chamber is perturbed with the addition of HONO as an addition OH sources **a** submicronic aerosol mass **b** Sulfate content of sampled aerosol in both chambers as measured by an AMS **c** Nitrate aerosol content **d** Ammonium aerosol content **e** submicronic particle number concentration **f** Oxygen-to-carbon ratio in the organic fraction of the aerosol as measured by an AMS. (Reused with permission from Kaltsonoudis et al. 2019, open access under a CC BY 4.0 license, https://creativecommons.org/licenses/by/4.0/)

1.4 Emerging Applications

1.4.1 Air-Sea/Ice Sheet Interaction

Recently, even more specific installations have been developed across the simulation chamber community: a chambers dedicated to the elucidation of processes occurring at the air-sea interface. It consists of chambers that include a reservoir at their bottom where artificial or real sea water is kept under controlled conditions and in exchange with the atmosphere above. In Lyon (France) such a chamber has been developed and used to study the processes occurring in an organic film deposited at the water surface and potentially affecting the simulated atmosphere composition. From a modelled sea water containing, humic acid ($1-10$ mg L^{-1}) as a proxy for dissolved organic matter, and nonanoic acid ($0.1-10$ mM), a fatty acid proxy which formed an organic film at the air–water interface, this work has shown that a photosensitized production of marine secondary organic aerosol could occur (Bernard et al. 2016). These new results suggest that in addition to biogenic emissions, abiotic processes could be of importance for the marine boundary layer. In East Anglia (UK), the *Roland von Glasgow* Air-Sea-Ice Chamber (RvG-ASIC), named in honour of its late founder, allows users to simulate sea ice growth and decay in a controlled environment. The tank can be filled with artificial or natural seawater and can be capped with a Teflon sheet to reproduce an experimental atmosphere. Here the main challenge is to produce a realistic sea-ice from the cooling of the seawater tank (the whole facility can be temperature controlled from $+30$ to -55 °C). This new facility has allowed investigating the mechanisms governing the fate of persistent organic contaminants in sea ice. It has shown that sea ice formation results in the entrainment of chemicals

from seawater, and concentration profiles in bulk ice generally showed the highest levels in both the upper (ice–atmosphere interface) and lower (ice–ocean interface) ice layers making them available from transit toward other compartments or interface reactivity.

1.4.2 Health Impacts

Even though the need to understand atmospheric chemistry has always been significantly motivated by public health issues and solving these issues has been part of the rationale for building many simulation chambers, until very recently, studies directly focused on health were rather scarce. In early investigations, the carcinogenicity and mutagenicity of chamber products were mostly evaluated after sampling of the contents and applying rather targeted offline in-vitro tests such as the Salmonella typhimurium plate-incorporation test (Claxton and Barnes 1981; Pitts 1983). In the past ten years, important progress has been made with the rise of surrogate indicators to qualify and quantify the potential health impact of particles such as the Reactive Oxygen Species content (ROS) (Fuller et al. 2014). The development of the corresponding instrumentation (Campbell et al. 2019) operating at high time resolution (on-line) now opens the way to building links between these indicators and the detailed chemical analysis often performed in the chamber. The goal is a better chemical characterization of the actual molecules or molecular functions involved in the oxidative stress.

In parallel, many groups have connected their simulation chambers with online samplers to expose living organisms such as lung cells or epithelial cells to the secondary pollutants produced in chambers (Savi et al. 2008; Mertes et al. 2013) in an attempt to understand the mechanisms that link cell toxicity with smog chemical and physical composition. This approach has led to important advances, especially when coupled with chamber experiments involving real world emissions (Künzi et al. 2013, 2015; Nordin et al. 2015). New directions have been explored by a few groups (Coll et al. 2018) which involve the use of simulation chambers for the long-term exposure (several days to several weeks) of living organisms such as murine models while complying with ethical standards. This new development requires overcoming substantial technical issues such as the stable and controlled production of secondary pollution over several days in a chamber. Their methodological research is pointing toward the use of indoor simulation chambers operated in batch mode. Development of such platforms in full cooperation with colleagues in the toxicology and medical communities may bring this health-related research to a better integration of the living body's functioning in the understanding of its response to air pollution.

1.4.3 Bioaerosols

Bioaerosols have been studied for over a decade in cloud chambers to investigate their potential ice nuclei activity (Möhler et al. 2008b). Given the public health problems associated with bioaerosol contamination and the many unknowns about the survival and transformation of bioaerosols, such as bacteria, in the atmospheric environment, innovative chamber work has recently started to address these issues (Amato et al. 2015; Brotto et al. 2015). These studies have led to the development of an indoor simulation chamber at the University of Genoa (Italy) where viable bioaerosol can be directly collected using Petri dishes without perturbing the course of the experiments while, in parallel, being online monitored by more classical techniques such as WIBS (Massabò et al. 2018). The goal is to derive parameterization of survival and activity of bioaerosols to eventually model the geographical extent of their contamination area.

1.4.4 Cultural Heritage

Works of art, with highly sensitive colours and materials, may be exposed to harmful levels of particulate matter in both indoor and ambient (i.e. outdoor) environments. Over time, these particles can deposit onto the surface of the artwork, which may influence the perceived colour. Reports over the concern of colour degradation to paintings, buildings, and other pieces of cultural heritage due to exposure to air pollution, acid rain, and other environmental factors have existed since at least the late 1800s due to London smog events (Brommelle 1964). However, the physical processes that connect exposure to particulate matter and the corresponding change in perceived colour are unknown, and first attempts to experimentally quantify the impact of particulate matter on painted works of art are only now emerging. The FORTH art exposure facility makes such an approach by developing protocols for the exposure of artwork to known levels of air pollutants and quantifying the effects of exposure using a portable colourimeter model WR-10 (FRU). Further developments in this emerging field will benefit from combining the expertise of exposure chamber approaches and atmospheric simulation chambers.

1.5 Considerations on the Design of an Atmospheric Simulation Chamber

The main objective of the guide is to serve as a reference for both new and current users of atmospheric simulation chambers. However, some readers may be considering the construction of a new chamber and this section is aimed at them. Additionally, it will provide to the new user, some insights into the design rationale of the chambers they will be working with.

This section mainly deals with the scientific issues and objectives that drive a particular chamber construction, but of course, practical limitations such as space, personnel and money will also influence chamber design. A particular focus is put on the requirements for the design of chambers dedicated to the exploration of atmospheric chemistry processes.

Atmospheric simulation chambers have several uses; firstly, they may be used to provide a controlled and realistic environment to simulate aspects of the real atmosphere or to test and compare field instrumentation. Secondly, chambers can be used as extended laboratory apparatus. For example, several hundreds of elementary reactions are involved in the complete oxidation of complex volatile organic compounds (VOC) such as isoprene (C_5H_8) or aromatic hydrocarbons. Some of these processes, particularly those occurring in the initial stages, can be studied individually by techniques such as laser flash photolysis or discharge flow, but many cannot. Atmospheric simulation chambers equipped with a wider range of instrumentation may either be able to directly measure rate coefficients, provide information on the yields of stable first-generation products, test entire chemical mechanisms or investigate aerosol chemistry. The main purpose of the experiments also strongly influences the design of the chamber.

1.5.1 Chemical Regime of Simulation Experiments

Whatever the objective of the chamber, the primary applications are to processes in the Earth's *troposphere* (extending from surface to the tropopause, where tropopause height varies with latitude from ~10 km in polar regions to ~18 km in the tropics). In the troposphere temperatures range from ~220–320 K and pressures of ~100–1000 mbar are found. In addition, we are often interested in the interactions of emissions (biogenic or anthropogenic) with the atmosphere and the interactions of atmospheric pollutants with humans, animals, plants and the ocean. Most of these interactions take place within the *boundary layer*, typically the first kilometre or so of the troposphere and therefore for many applications, operation at pressures close to 1000 mbar is appropriate. However, there is obviously still a wide range of temperature variation within the boundary layer and so temperature variation may be an important goal in chamber design. Relative humidity also varies over a wide range in the troposphere and affects many physical and chemical processes in the atmosphere. Therefore, depending on the application of the chamber, precise control of humidity is also vital.

Besides variations in physical parameters, there are also significant variations in the chemical composition desired in the simulation experiments that will influence the chamber design. Most studies focus on regions of the atmosphere with significant VOC emissions. The chemical oxidation of VOCs often includes the same initial reaction steps; the reaction of a radical species, X, (where X = OH, NO_3, Cl etc.) leads via abstraction or addition of the oxidant to an organic radical, R, which then rapidly adds O_2 to lead to an organic peroxy radical RO_2.

$$\text{e.g. } OH + RH \rightarrow H_2O + R \tag{R1}$$

$$R + O_2 \rightarrow RO_2 \tag{R2}$$

The atmospheric fate of the organic peroxy radicals depends on the relative abundance of concentrations of reaction partners such as nitric oxide ([NO]) and other peroxy radicals ([RO_2/HO_2]). In regions with high NO_x concentrations, the loss of RO_2 is typically dominated by the reaction with NO, generating an alkoxy radical (RO). The exact fate of the RO depends on its structure, but most often products are a carbonyl compound and hydroperoxyl radicals (HO_2). Further reaction of HO_2 with NO regenerates OH completing a reaction cycle (Fig. 1.10)

$$RO_2 + NO \rightarrow RO + NO_2 \tag{R3}$$

$$\text{e.g. } RO + O_2 \rightarrow \text{Carbonyl} + HO_2 \tag{R4}$$

$$HO_2 + NO \rightarrow OH + NO_2 \tag{R5}$$

The by-product of the NO to NO_2 conversion in reactions (R3) and (R5) is ozone, a significant secondary pollutant. This radical reaction chain is the only relevant chemical source for ozone in the troposphere.

However, in environments with low NO_x concentrations (typically [NO] < 50 pptv) such as the marine boundary layer or remote tropical or boreal forests, radical recombination reactions become the dominant RO_2 loss channel.

$$RO_2 + RO_2 \rightarrow ROH + R'CHO + O_2 \text{ or } 2RO \tag{R6}$$

$$RO_2 + HO_2 \rightarrow ROOH + O_2 \text{ or } RO + OH + O_2 \tag{R7}$$

These reactions terminate the radical chain. For specific RO_2 radicals, isomerization reactions can be competitive. Products can be again RO_2 radicals that may decompose and thereby form other radical species such as HO_2 or highly oxygenated molecules could be eventually formed. For example, significantly enhanced OH concentrations are observed in high isoprene and low NO_x environments that can be explained by radical production from isomerization reactions of isoprene derived RO_2 (Peeters et al. 2014; Novelli et al. 2020).

Due to the importance of the fate of RO_2 radicals for the chemical reaction system that should be investigated in the simulation experiments, considerations about the NO_x concentration that can be achieved in the chamber is important and can have implications on the chamber design (Fig. 1.11).

The chemical composition of the troposphere is also impacted by surface interactions such as bulk and aerosol surfaces. The interaction with bulk solid surfaces

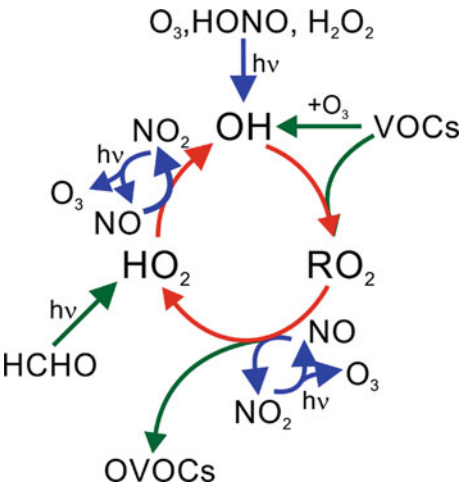

Fig. 1.11 Scheme of the radical reactions involved in atmospheric photochemical VOC oxidation and ozone production

can be easily replicated in many chambers. Some chambers (e.g. ISAC) are specifically designed to investigate interactions with liquid surfaces and sea-ice like the Roland Van Glasow Air-Sea-Ice Chamber at the University of East Anglia. Aerosols, primary or secondary, organic or inorganic, are the other main surfaces in the troposphere and studies involving aerosols and gas/aerosol/cloud interactions may require specific design criteria and instrumentation.

1.5.2 Chamber Size

Whilst there may be specialized chambers for the investigation of interactions with bulk surfaces, often bulk surfaces and their associated heterogeneous chemistry are minimized to avoid that experiments are impacted by chamber wall effects. Minimizing the surface to volume ratio (S/V) helps and might be the only way to suppress chamber wall effects, if experiments are performed at atmospheric concentrations of trace gases. For example, the large chambers EUPHORE (200 m^3) and SAPHIR (270 m^3) have spherical and cylindrical shapes, respectively, to minimize the surface to volume ratio and are advantageous compared to cuboid structures. Cuboid shapes are commonly used for Teflon chambers as they can be easily mounted, illuminated and physically accessed.

Most chambers have capabilities to inject reagents and maintain a homogeneous mixture by operating fans. Clearly, the specifications of fans need to match the chamber size to ensure efficient operation. The practical issues concerning logistics are beyond the scope of this chapter, but it is worth highlighting that large chambers such as AIDA, EUPHORE and SAPHIR have significant numbers of dedicated personnel and additional infrastructure facilities for example for clean air generation and power requirements.

As well as providing a more realistic environment for simulations, large chambers are ideal tools for field instrument comparisons. The volumes of gas sampled by some instruments make comparisons in small chambers impossible and generally there is more space for instruments. In situ comparisons in the real atmosphere have their advantages, but instrument comparisons in large chambers ensure, that all instruments sample the same chemical composition in a controlled environment and conditions can be systematically varied (e.g. Dorn et al. 2013; Fuchs et al. 2010, 2017; Fuchs et al. 2012a, b).

Whilst a small surface to volume ratio helps in ensuring that the chemical processes studied are indeed dominated by gas phase chemistry and ensures the best representation of atmospheric processes, this may not be required for other purposes of environmental chambers. For mechanistic or relative rate reaction kinetic studies, the rapid turnaround time of smaller chambers, where several experiments can be run per day, is far more efficient than performing such experiments in large chambers where studies may only be possible for good weather conditions in the case of outdoor chambers and may be limited to one experiment per day. Smaller chambers (particularly if made from glass or metal) can be rapidly evacuated (and in some cases heated) to clean the surfaces or can be even physically cleaned. Surfaces can be coated to minimize wall effects. Furthermore, many small chambers are operated in steady state conditions contrary to the batch mode operation of large chambers.

1.5.3 Materials

In general, there are three types of materials used in chambers: Teflon (or equivalent), borosilicate glass, quartz, or stainless steel (see Table 1.4). All materials have their advantages and disadvantages with respect to surface properties and physical parameters (e.g. *T, p*) that can be regulated in the chamber. Depending on the purpose of the chamber, the possibility to simulate e.g. pseudo-adiabatic cloud expansion, ultra-clean air conditions, or photolytic conditions representative of the troposphere is a key driver of choices of material used.

Teflon (or equivalent). Due to their large size, all large (> ~80 m^3) chambers are constructed from fluoro-polymer plastics mounted on a metal frame. Such structures are light but fragile and need to be protected. Outdoor chambers like SAPHIR and EUPHORE have retractable protection, protecting the film from bad weather conditions, but also allow for experiments in the dark. The Helios chamber (~90 m^3) at CNRS-Orleans can be rapidly moved in and out of a permanent shelter. All of these chambers have a solid metal floor that can be used to place equipment such as FTIR mirrors and fans. In EUPHORE this forms part of the chamber surface and is cooled to prevent significant heating from solar radiation. In SAPHIR it is covered with Teflon and can be lowered for experiments such that the Teflon film does not have contact with the metal to avoid radiative transfer heating.

Teflon is also used in the construction of smaller chambers where glass or metal would be alternatives. Teflon has significant advantages in terms of cost. Additionally, as it is transparent, it is easy to fully illuminate the entire chamber with either solar or artificial light. Although Teflon is chemically inert, it is commonly observed that compounds can adhere to the wall and released in later experiments even if the chamber had been cleaned in between. For example, nitrous acid (HONO) is released, if humidified air is illuminated in Teflon chambers. The photolysis of HONO serves as a source of OH radicals, but also leads to an increase of nitrogen oxide species over the course of an experiment (Rohrer et al. 2005). The radical production from the chamber HONO source can be sufficiently high for performing OH oxidation experiments in large chambers as EUPHORE and SAPHIR (Fuchs et al. 2013). Smaller chambers can be manually cleaned, but this is not possible for larger chambers. As non-rigid structures, Teflon type chambers cannot be evacuated and are limited to operation at ambient pressures. Rather than evacuation, residual trace gases are removed by flowing clean gas through the chamber. For large chambers, this is typically done overnight. Smaller chambers can be enclosed in air-conditioned rooms to provide some degree of temperature control and variation.

Pyrex/Quartz Pyrex or quartz chambers are used for volumes of ~1 m^3 or less. Within EUROCHAMP, the chambers at Wuppertal and Iasi are of cylindrical shape (~0.5 m diameter) and have a volume of approximately 1 m^3. The end flanges of both chambers are metal allowing for easy access to instrumentation and provide a fixed framework for mounting FTIR mirrors (similar structures are also used in some Teflon type chambers too). Due to the fragility of glass, the chambers are mounted on a vibration resistant framework. The advantage of quartz is that it allows for the transmission of shorter wavelength UV radiation compared to Teflon (e.g. radiation from mercury lamps emitting at 254 nm) which can be useful for specific radical generation methods.

Whilst pyrex/quartz chambers are limited in size, their small size allows to uniformly distribute artificial light sources around the chamber. The rigid construction also allows to evacuate the chambers, so that the chamber can be cleaned within a short time between experiments and it can be operated at sub-ambient pressure. Smaller chambers such as those at the National Centre for Atmospheric Research (NCAR) in Boulder, US, are surrounded with air-conditioned liquid baths to perform studies in which the temperature is varied. Quartz and pyrex are well characterized and reasonably inert surfaces. Evacuation (in combination with heating if available), provides rapid and efficient cleaning, in extremis, the end flanges of large chambers can be removed to allow for physical cleaning.

Metal Chambers are typically of cylindrical shapes and have volumes of the order of 1–6 m^3, with the exception of the 84 m^3 large AIDA chamber at Karlsruhe Institute of Technology. Metal chambers are typically constructed from stainless steel and have significant advantages in their robustness compared to other materials allowing for rapid evacuation/operation at reduced pressure. Several systems are also equipped with a temperature control system. Temperature control can be useful for two main purposes; firstly, simulating the temperature variation both within the boundary

layer at various latitudes/seasons and across the vertical extend of the troposphere; Secondly, elucidating the temperature dependence of chemical mechanisms.

For metal chambers, flanges with inlets for instruments are easy to install either in the main end flanges or elsewhere at the chamber. Although the end flanges of chambers can be large, they typically bow slightly if the chamber is operated at reduced pressure and therefore thought needs to be given on how to mount equipment requiring high spatial precision (e.g. multi-pass mirror) onto the end flanges.

The two significant disadvantages of metal as the construction material (besides the high S/V associated with the relatively small volume of most chambers) is the potential reactivity of the surface and the difficulty in generating a uniform light field. Surface effects can be accounted for (see Sects. 2.4 and 2.5) and efficient evacuation combined with overnight heating and/or oxidant exposure (e.g. O_3) ensures that the surface remains uniform over the course of an experimental campaign (see Chap. 3). Illumination issues are discussed in the next section.

1.5.4 Light Sources

Photochemistry is one of the main driving forces for atmospheric processes, so that whilst there are important dark reactions such as ozonolysis or nitrate radical (NO_3) initiated chemistry, light is required for most experiments.

The most obvious source, particularly if atmosphere-like conditions are simulated, is solar radiation and for large chambers such as Helios, EUPHORE and SAPHIR it is the only feasible option. Certain small/medium sized Teflon type chambers can be operated with either solar or artificial radiation.

The transmission of solar radiation by Teflon is good over the entire solar spectrum. Spectral radiometers inside the chamber can be used to measure the actinic flux (see also Sect. 2.3), both of the incoming solar radiation and of light reflected/emitted by the chamber floor. The disadvantage of outdoor chambers using sunlight is that experiments are dependent on the weather, because large chambers made of Teflon cannot be operated in windy conditions. Like in the atmosphere, the radiation field in the chamber changes over the course of a day-long experiment, both due to the change of the solar zenith angle and also due to short-term, transient variations caused by clouds.

Artificial radiation is used for a majority of smaller Teflon chambers and all glass and metal chambers. Depending on the main purpose of the chamber, light with a broad radiation distribution, including simulation of the solar spectrum, can be used or alternatively lamps with narrow outputs for example in the UV region (e.g. mercury lamps with emission lines at 254, 308, 365 nm) can be used. For many chambers it is possible to swap between different types of lamps.

For Teflon chambers lamps are often mounted on one side and the bank of lamps is directed into the chamber. The often cuboid nature of such chambers makes it easy to establish a uniform radiation field across the chamber. For glass chambers banks

Fig. 1.12 QUAREC chamber, Wuppertal, the lights are mounted outside the chamber providing a uniform radiation field in the actual chamber

of tubular lamps surround the cylindrical chamber. Carefully arranged, the radiation field inside the chamber can be very uniform.

The chamber construction determines the UV cut-off wavelength for example quartz is transmissive for wavelengths higher than ~200 nm. Arranging lamps around the chamber such that a uniform radiation field is obtained is clearly not possible for a metal chamber. Two approaches are typically used. For example in the CESAM chamber, radiations from xenon arc lamps are directed into the chamber through windows, whereas in the HIRAC chamber quartz tubes mounted inside the chamber are used as a light source (Figs. 1.12, 1.13, 1.14, and 1.15). Radiation fields in these chambers are less uniform; variations can be measured with a spectral radiometer (Sect. 2.3) and instruments can be designed to sample from various locations to test for significant spatial variations of trace gas and radical concentrations.

1.5.5 Instrumentation

The type of instruments installed at the chamber depends on the primary purpose of the individual study, for example, aerosol and gas phase experiments will require different measurements. Table 1.5 summarizes typical instrumentation and measurement approaches utilized in chambers. Table 1.5 is structured into groups of instruments according to measurement parameters. Specialized and custom-built instrumentation may require significant technical support to ensure their operation. In some cases, high costs for commercial systems can balance low, long-term running costs.

It is important to consider what instrumentation is going to be applied to the chamber in advance of the construction, e.g. to allow for sufficient space and air conditioning. Although most commercial instruments and equipment that take samples for later offline analysis can be easily placed at the chamber, some components that are directly attached to the chamber (e.g. mirrors used for FTIR spectroscopy or special

Fig. 1.13 CESAM Chamber, LISA, the chamber is illuminated from above

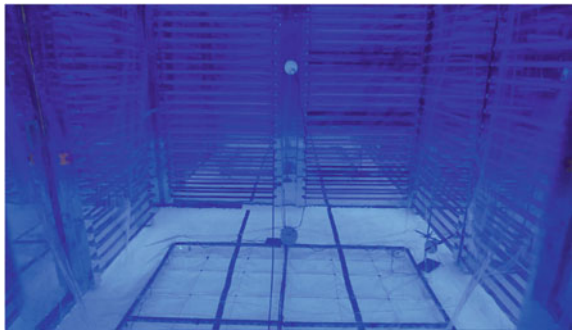

Fig. 1.14 FORTH chamber, a Teflon chamber with side wall illumination

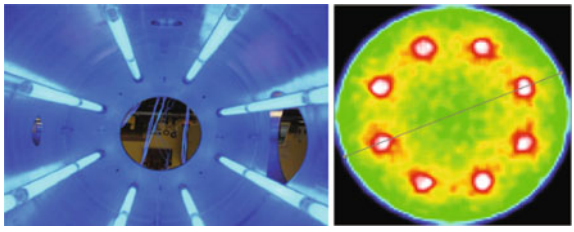

Fig. 1.15 HIRAC chamber showing internal illumination and modelling of resultant radiation field across the chamber. Reproduced from Seakins (2010)

cavity ring-down systems) have to be considered in the early planning of the chamber construction. Mirrors need to be mounted where they are unaffected by vibrations from fans or pumps and the mounting needs to be rigid with respect to changes in pressure or they need to be easily adjustable. Purge gas flows may be needed for

Table 1.5 Summary of typical instrumentation and measurement approaches utilized in chambers, structured in order to group the instrumentation according to measurement parameter

Gas phase concentration			
Parameter	**Instrument type**	**Online/offline/in situ**	**References**
NO concentration	Chemiluminescence NO_x analyser Mo converter	Online	Dunlea et al. (2007)
NO and NO_2 concentration	Chemiluminescence NO_x analyser blue light Converter	Online	NO_2: Ryerson et al. (2000)
NO_2 concentration	NO_2 cavity-based absorption spectroscopy	Online	Fuchs et al. (2010), Kebabian et al. (2005)
Ozone concentration	UV absorption O_3 Analyser,	Online	Parrish and Fehsenfeld (2000)
Ozone concentration	Chemiluminescence		Ridley et al. (1992)
SO_2 concentration	fluorescence SO_2 Analyser	Online	Krechmer et al. (2016), Krechmer et al. (2017)
CO_2, CO, H_2O, CH_4 concentration	CRDS	Online	https://www/picarro.com/products/g2401_gas_concentration_analyzer
HCHO	Hantzsch reaction	Online	Junkermann and Burger (2006)
HONO	Chemical derivatization; HPLC or photometer absorption	Online	Kleffmann et al. (2002), Afif et al. (2016)
VOC, OVOC concentration	PTR-MS, CIMS	Online	DeGouw and Warneke (2007), Taipale et al. (2008), Barber et al. (2012), Cappellin et al. (2012), Duncianu et al. (2017)
VOC concentration	Sorbent cartridges + GC–MS	Offline	Rossignol et al. (2012a, b)
VOC concentration	Automatic GC- FID	Online	De Blas et al. (2011)
VOC, NO_x, NO_y, Ozone	long path FTIR	In situ	Barnes et al. (1985), Doussin et al. (1997)

(continued)

Table 1.5 (continued)

OH Reactivity	Flash-photolysis combined with laser-induced fluorescence Comparative Reactivity Method CRM	Online	Fuchs et al. (2017) and references therein
NO_3 Reactivity	CRDS	Online	Dewald et al. (2020)
Water mixing ratio	Hygrometer gage, chilled mirror	In situ	Fahey et al. (2014)
Relative humidity	polymer sensors	In situ	Fahey et al. (2014)
Chamber physical properties			
Parameter	**Instrument type**	**Online/offline/in situ**	**References**
Temperature	Thermocouple resistance thermometer	in situ	Dias et al. (2017)
Pressure	Capacitance manometer	in situ	Blado et al. (1970)
Irradiation spectrum/actinic flux	spectral radiometer	in situ	Bohn et al. (2008)
Radical measurements			
Parameter	**Instrument type**	**Online/offline/in situ**	**References**
OH	Long Path DOAS Laser-induced fluorescence Chemical-ionization mass spectrometry	Online, in situ	Schlosser et al. (2009)
OH	Faraday Rotation Spectroscopy	Online	Zhao et al. (2018)

(continued)

Table 1.5 (continued)

HO_2	NIR-CRDS	Online, in situ	Onel et al. (2017)
HO_2	Chemical conversion and Laser-induced fluorescence	Online	Fuchs et al. (2010)
HO_2	CIMS(Br-)	Online	Albrecht et al. (2019)
CH_3O_2	NIR-CRDS	Online, in situ	Onel et al. (2020)
CH_3O_2	Laser-induced fluorescence	Online	Onel et al. (2017)
RO_2	CIMS	Online	Nozière and Hanson (2017)
RO_2	ROx-LIF	Online	Fuchs et al. (2008), Whalley et al. (2018)
Rox	ROx-MAS, PerCIMS	Online	Hanke et al. (2002), Edwards et al. (2003)
Rox	PERCA	Online	Cantrell et al. (1984)
Hydroperoxides, peroxides	HPLC with FLD detector	Offline	Lazrus et al. (1986)
NO_3	DOAS, cavity-based absorption spectroscopy	Online	Dorn et al. (2013), Fouqueau et al. (2020)
N_2O_5	FTIR, cavity-based absorption spectroscopy		Fuchs et al. (2012a, b)
Particulate matter physical properties			
Parameter	**Instrument type**	**Online/offline/in situ**	**References**
Total concentration/Size distribution	Particle Size Magnifier (PSM)	Online	Vanhanen et al. (2011)
Total concentration	Diethylene Glycol–Condensation Particle Counter (DEG CPC)	Online	Jiang et al. (2011), Wimmer et al. (2013)

(continued)

Table 1.5 (continued)

Size distribution, Ion size distribution	Neutral and Air Ion Spectrometer (NAIS)	Online	Mirme and Mirme (2013)
Ion size distribution	Cluster Ion Counter (CIC)	Online	
Ion size distribution	Air Ion Spectrometer	Online	Mirme et al. (2007)
Total concentration	Condensation Particle Counter (CPC)	Online	Stolzenburg and McMurry (1991), Hering et al. (2005)
Total concentration/Size distribution	Condensation Particle Counter Battery (CPCb)	Online	Kulmala et al. (2007)
Size distribution	Differential Mobility Analyzer Train (DMA train)	Online	Stolzenburg et al. (2017)
Size distribution	Scanning Mobility Particle Sizer (SMPS/MPSS)	Online	Wang and Flagan (1990), Gaie-Levrel et al. (2020)
Size distribution	OPC–single wavelength (eg. Grimm)	Online	Heim et al. (2008)
Size distribution	OPC–white light	Online	Heim et al. (2008)
Size distribution	APS	Online	Pfeifer et al. (2016)
Aerosol spectral absorption	Photoacoustic spectrometer	Online	Arnott et al. (1999)
Aerosol spectral absorption	Aethalometer	Online	Arnott et al. (2005), Di Biagio et al. (2017a, b)
Aerosol spectral scattering	Nephelometer	Online	Andersoin and Ogren (1998)
Aerosol spectral extinction/scattering/SSA	External CRDS–Optical cavities	Online	Massoli et al. (2010)

(continued)

Table 1.5 (continued)

Aerosol spectral absorption	Filter sampling–Multi-Wavelength Absorbance Analyzer (MWAA)	Offline	Massabò et al. (2018)
Particle morphology/shape distribution	filter sampling–Electron microscopy	Offline	Chou et al. (2006)
Mass concentration	Online tapered element oscillating microbalance (TEOM)	Online	Tortajada-Genaro and Borrás (2011), Roberts and Nenes (2005)
Aerosol hygroscopicity	Hygroscopic Tandem Differential Mobility Analyser (HTDMA)	Online	Denjean et al. (2014), Good et al. (2010)
Cloud condensation Nucleous counter	CCN counter	Online	Wex et al. (2009)
Ice Nucleous Counter	IN counter	Online	DeMott et al. (2018), Mölher et al. (2021)
Particulate matter concentration and composition			
Parameter	**Instrument type**	**Online/ offline/in situ**	**References**
Organic aerosol chemical composition	Filter sampling - derivatization - GC–MS	Offline	Chiappini et al. (2006)
Elemental carbon and organic fraction of particle	EC/OC (Sunset)	Offline	Massabò et al. (2016)
Aerosol composition	ACSM-ToF Aerodyne		Ng et al. (2011a, b)
size segregated Aerosol composition	AMS		Kiendler-Scharr et al. (2009a, b)

(continued)

Table 1.5 (continued)

Surface state and composition	Filter sampling–X–ray induced photoelectron spectroscopy (XPS)	Offline	Denjean et al. (2015)
Refractory black carbon	Single Particle Soot Photometer (SP2)	Online	Laborde et al. (2012)
Inorganic/organic soluble fraction	Particle into Liquid Sampler (PILS)	Online	Pereira et al. (2015), Behera and Sharma (2012)
Inorganic soluble fraction	Filter sampling–Ion Chromatography (IC)	Offline	Chen and Jang (2012)
Organic aerosol chemical composition	filter sampling–UPLC-QTOF-MS	Offline	Nizkorodov et al. (2011), Hamilton et al. (2008)

optical systems to keep mirrors clean. Access to important equipment that may need regular cleaning or service must be assured. Some instruments will extract significant volumes of gas posing requirements on the chamber volume to ensure that dilution does not become a major loss term. A mechanism of regulating the replenishment flow to maintain a certain pressure or volume may be required.

There is a very strong synergy between chamber and field communities in terms of instrumentation, with chambers being used to design, develop, validate and compare field instruments. In general, instruments that work well in the field will be suitably sensitive and robust to ensure efficient use within chambers.

Homogeneous mixing within the chamber has to be ensured. This can be tested through a comparison of measurements that derive average concentrations across the pathlength of the system and point measurements at a single location, as well as through sampling from different locations. In addition, careful design of sampling systems (material, residence time, heating) and location of the instrumentation to minimize transfer distance limits the effect of sampling losses or transformation of reactive or instable species during the sampling process.

Making sensitive measurements of complex systems is a challenging task and even if carefully operated, systematic errors or inferences can occur. Having multiple, complementary methods (or regularly participating in inter-comparisons) can help identify these problems.

The above discussion focused on how scientific objectives and considerations influence the chamber design, construction and instrumentation. This section can only give a brief outline on considerations. This section can be used as an overall introduction, but details can be found in technical papers and reports. There is no perfect chamber design; each system has its own advantages in meeting particular objectives, but also disadvantages. In fact, having a variety of chamber designs and performing comparisons (i.e. reference experiments as detailed in Sects. 2.4 and 2.5, Donahue et al. 2012) highlights issues that would easily be missed in standardized approaches.

1.6 Conclusion

The original use of “smog chambers” for investigating chemical transformations in the atmosphere, for quantification of the rate, extent and relevance of the various possible pathways, for the identification of secondary pollutants remains just as relevant today as it did many decades ago. Indeed, the models that utilise chamber-derived data are still far from explicit, i.e. they do not include all of the processes that are required to represent and forecast the actual atmospheric composition, and there is still room for improvement, as well as the possibility of incorporating new chemistry to address future challenges. At the same time, the field of experimental atmospheric simulations has been extremely active over the past 15 years and considering the number of new facilities around the world, there is little doubt about its vitality over the next 15 years. A number of new methodologies and applications have risen,

and they will bring the operational capacity of simulation chambers to a new level. This community effort will allow a much broader range of scientific and societal needs to be addressed, including the direct and indirect climate effect of atmospheric pollutants, the impact of air composition on health and cultural heritage, as well as on the various compartments of the Earth system. The application of simulation chambers in some of these areas is still in the early stages, but rapid progress is being made and already producing data that will help to open new ways of considering the complex interplays between atmospheric transformation and impacts.

References

Afif, C., Jambert, C., Michoud, V., Colomb, A., Eyglunent, G., Borbon, A., Daële, V., Doussin, J.-F., Perros, P.: NitroMAC: an instrument for the measurement of HONO and intercomparison with a long-path absorption photometer. J. Environ. Sci. **40**, 105–113 (2016). https://doi.org/10.1016/j.jes.2015.10.024

Aiken, A.C., DeCarlo, P.F., Kroll, J.H., Worsnop, D.R., Huffman, J.A., Docherty, K.S., Ulbrich, I.M., Mohr, C., Kimmel, J.R., Sueper, D., Sun, Y., Zhang, Q., Trimborn, A., Northway, M., Ziemann, P.J., Canagaratna, M.R., Onasch, T.B., Alfarra, M.R., Prevot, A.S.H., Dommen, J., Duplissy, J., Metzger, A., Baltensperger, U., Jimenez, J.L.: O/C and OM/OC ratios of primary, secondary, and ambient organic aerosols with high-resolution time-of-flight aerosol mass spectrometry. Environ. Sci. Technol. **42**, 4478–4485 (2008). https://doi.org/10.1021/es703009q

Akimoto, H., Hoshimo, M., Inoue, G., Sakamaki, F., Washida, N., Okuda, M.: Design and caracterization of the evacuable and bakable photochemical smog chamber. Environ. Sci. Technol. **13**, 471–475 (1979a)

Akimoto, H., Hoshino, M., Inoue, G., Sakamaki, F., Washida, N., Okuda, M.: Design and characterization of the evacuable and bakable photochemical smog chamber. Environ. Sci. Technol. **13**, 471–475 (1979b)

Akimoto, H., Sakamaki, F., Hoshino, M., Inoue, G., Okuda, M.: Photochemical ozone formation in propylene-nitrogen oxide-dry air system. Environ. Sci. Technol. **13**, 53–58 (1979c). https://doi.org/10.1021/es60149a005

Albrecht, S.R., Novelli, A., Hofzumahaus, A., Kang, S., Baker, Y., Mentel, T., Wahner, A., Fuchs, H.: Measurements of hydroperoxy radicals (HO2) at atmospheric concentrations using bromide chemical ionisation mass spectrometry. Atmos. Meas. Tech. **12**, 891–902 (2019). https://doi.org/10.5194/amt-12-891-2019

Alfarra, M.R., Hamilton, J.F., Wyche, K.P., Good, N., Ward, M.W., Carr, T., Barley, M.H., Monks, P.S., Jenkin, M.E., Lewis, A.C., McFiggans, G.B.: The effect of photochemical ageing and initial precursor concentration on the composition and hygroscopic properties of β-caryophyllene secondary organic aerosol. Atmos. Chem. Phys. **12**, 6417–6436 (2012). https://doi.org/10.5194/acp-12-6417-2012

Amato, P., Joly, M., Schaupp, C., Attard, E., Möhler, O., Morris, C.E., Brunet, Y., Delort, A.M.: Survival and ice nucleation activity of bacteria as aerosols in a cloud simulation chamber. Atmos. Chem. Phys. **15**, 6455–6465 (2015). https://doi.org/10.5194/acp-15-6455-2015

Anderson, T.L., Ogren, J.A.: Determining aerosol radiative properties using the TSI 3563 integrating nephelometer. Aerosol Sci. Technol. **29**, 57–69 (1998). https://doi.org/10.1080/02786829808965551

Anttila, T., Kiendler-Scharr, A., Tillmann, R., Mentel, T.F.: On the reactive uptake of gaseous compounds by organic-coated aqueous aerosols: theoretical analysis and application to the heterogeneous hydrolysis of N2O5. J. Phys. Chem. A **110**, 10435–10443 (2006). https://doi.org/10.1021/jp062403c

Apel, E.C., Brauers, T., Koppmann, R., Bandowe, B., Boßmeyer, J., Holzke, C., Tillmann, R., Wahner, A., Wegener, R., Brunner, A., Jocher, M., Ruuskanen, T., Spirig, C., Steigner, D., Steinbrecher, R., Gomez Alvarez, E., Müller, K., Burrows, J.P., Schade, G., Solomon, S. J., Ladstätter-Weißenmayer, A., Simmonds, P., Young, D., Hopkins, J.R., Lewis, A.C., Legreid, G., Reimann, S., Hansel, A., Wisthaler, A., Blake, R.S., Ellis, A.M., Monks, P.S., Wyche, K.P.: Intercomparison of oxygenated volatile organic compound measurements at the SAPHIR atmosphere simulation chamber. J. Geophys. Res. Atmos. **113** (2008). https://doi.org/10.1029/2008jd009865

Arnott, P.W., Moosmüller, H., Rogers, F.C., Tianfeng, J., Reinhard, B.: Photoacoustic spectrometer for measuring light absorption by aerosol: instrument description. Atmos. Environ. **33**, 2845–2852 (1999). https://doi.org/10.1016/S1352-2310(98)00361-6

Arnott, W.P., Hamasha, K., Moosmüller, H., Sheridan, P.J., Ogren, J.A.: Towards aerosol light-absorption measurements with a 7-wavelength aethalometer: evaluation with a photoacoustic instrument and 3-wavelength nephelometer. Aerosol Sci. Technol. **39**, 17–29 (2005). https://doi.org/10.1080/027868290901972

Atkinson, R.: Kinetics and mechanisms of the gas-phase reactions of the hydroxyl radical with organic compounds under atmospheric conditions. Chem. Rev. **86**, 69–201 (1986). https://doi.org/10.1021/cr00071a004

Atkinson, R.: A structure-activity relationship for the estimation of rate constants for the gas-phase reactions of OH radicals with organic compounds. Int. J. Chem. Kinet. **19**, 799–828 (1987). https://doi.org/10.1002/kin.550190903

Atkinson, R.: Atmospheric chemistry of VOCs and NO_x. Atmos. Environ. **34**, 2063–2101 (2000)

Atkinson, J.D., Murray, B.J., Woodhouse, M.T., Whale, T.F., Baustian, K.J., Carslaw, K.S., Dobbie, S., O'Sullivan, D., Malkin, T.L.: The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds. Nature **498**, 355–358 (2013). https://doi.org/10.1038/nature12278

Augustin-Bauditz, S., Wex, H., Kanter, S., Ebert, M., Niedermeier, D., Stolz, F., Prager, A., Stratmann, F.: The immersion mode ice nucleation behavior of mineral dusts: a comparison of different pure and surface modified dusts. Geophys. Res. Lett. **41**, 7375–7382 (2014). https://doi.org/10.1002/2014GL061317

Bahreini, R., Middlebrook, A.M., de Gouw, J. A., Warneke, C., Trainer, M., Brock, C.A., Stark, H., Brown, S.S., Dube, W.P., Gilman, J.B., Hall, K., Holloway, J.S., Kuster, W.C., Perring, A.E., Prevot, A.S.H., Schwarz, J.P., Spackman, J.R., Szidat, S., Wagner, N.L., Weber, R.J., Zotter, P., Parrish, D.D.: Gasoline emissions dominate over diesel in formation of secondary organic aerosol mass. Geophys. Res. Lett. **39** (2012). https://doi.org/10.1029/2011GL050718

Baltensperger, U., Kalberer, M., Dommen, J., Paulsen, D., Alfarra, M.R., Coe, H., Fisseha, R., Gascho, A., Gysel, M., Nyeki, S., Sax, M., Steinbacher, M., Prevot, A.S.H., Sjögren, S., Weingartner, E., Zenobi, R.: Secondary organic aerosols from anthropogenic and biogenic precursors. Faraday Discuss. **130**, 265–278 (2005). https://doi.org/10.1039/b417367h

Barber, S., Blake, R.S., White, I.R., Monks, P.S., Reich, F., Mullock, S., Ellis, A.M.: Increased sensitivity in proton transfer reaction mass spectrometry by incorporation of a radio frequency ion funnel. Anal. Chem. **84**, 5387–5391 (2012). https://doi.org/10.1021/ac300894t

Barmet, P., Dommen, J., DeCarlo, P., Tritscher, T., Praplan, A., Platt, S., Prevot, A., Donahue, N., Baltensperger, U.: OH clock determination by proton transfer reaction mass spectrometry at an environmental chamber. Atmos. Meas. Tech. Discuss. **4**, 7471–7498 (2011). https://doi.org/10.5194/amtd-4-7471-2011

Barnes, I., Becker, K.H., Fink, E.H., Kriesche, V., Wildt, J., Zabel, F.: Studies of atmospheric reaction systems in a temperature controlled reaction chamber using Fourier-Transform-spectroscopy. In: First European symposium on Physico-Chemical Behaviour of Atmospheric Pollutants, JRC-Ispra (Italy) (1979)

Barnes, I., Becker, K.H., Fink, E.H., Reimer, A., Zabel, F., Niki, H.: FTIR spectroscopic study of the gas-phase reaction of HO2 with H2CO. Chem. Phys. Lett. **115**, 1–8 (1985). https://doi.org/10.1016/0009-2614(85)80091-9

Barnes, I., Becker, K.H., Carlier, P., Mouvier, G.: FTIR study of the DMS/NO_2/I_2/N_2 photolysis system: the reaction of IO radicals with DMS. Int. J. Chem. Kinet. **19**, 489–501 (1987). https://doi.org/10.1002/kin.550190602

Barnes, I., Becker, K.H., Mihalopoulos, N.: An FTIR product study of the photooxidation of dimethyl disulfide. J. Atmos. Chem. **18**, 267–289 (1994). https://doi.org/10.1007/bf00696783

Barnes, I., Rudzinski, K.J.: Environmental Simulation Chambers: Application to Atmospheric Chemical Processes, Nato Science Series: IV, vol. 62, pp. 458. Springer Netherlands (2006)

Beauchene, J., Bekowies, P., Winer, A., McAfee, J., Zafonte, L., Pitts, J., Jr.: A Novel 20 KW Solar Simulator Designed for Air Pollution Research (1973)

Becker, K.H.: The European Photoreactor "EUPHORE", European Community, Final report (1996)

Becker, K.H.: Overview on the development of chambers for the study of atmospheric chemical processes. In: Environmental Simulation Chambers: Application to Atmospheric Chemical Processes, pp. 1–26. Dordrecht (2006)

Behera, S.N., Sharma, M.: Transformation of atmospheric ammonia and acid gases into components of PM2.5: an environmental chamber study. Environ. Sci. Pollut. Res. **19**, 1187–1197 (2012). https://doi.org/10.1007/s11356-011-0635-9

Behnke, W., Holländer, W., Koch, W., Nolting, F., Zetzsch, C.: A smog chamber for studies of the photochemical degradation of chemicals in the presence of aerosols. Atmos. Environ. **1967**(22), 1113–1120 (1988). https://doi.org/10.1016/0004-6981(88)90341-1

Bernard, F., Ciuraru, R., Boréave, A., George, C.: Photosensitized formation of secondary organic aerosols above the air/water interface. Environ. Sci. Technol. **50**, 8678–8686 (2016). https://doi.org/10.1021/acs.est.6b03520

Bertrand, A., Stefenelli, G., Bruns, E., Pieber, S., Temime-Roussel, B., Slowik, J., Prevot, A., Wortham, H., Haddad, I., Marchand, N.: Primary emissions and secondary aerosol production potential from woodstoves for residential heating: Influence of the stove technology and combustion efficiency. Atmos. Environ. **169** (2017). https://doi.org/10.1016/j.atmosenv.2017.09.005

Bertrand, A., Stefenelli, G., Pieber, S., Bruns, E., Temime-Roussel, B., Slowik, J., Wortham, H., Prevot, A., Haddad, I., Marchand, N.: Influence of the vapor wall loss on the degradation rate constants in chamber experiments of levoglucosan and other biomass burning markers. Atmos. Chem. Phys. **18**, 10915–10930 (2018). https://doi.org/10.5194/acp-18-10915-2018

Bhattu, D., Zotter, P., Zhou, J., Stefenelli, G., Klein, F., Bertrand, A., Temime-Roussel, B., Marchand, N., Slowik, J.G., Baltensperger, U., Prévôt, A.S.H., Nussbaumer, T., El Haddad, I., Dommen, J.: Effect of stove technology and combustion conditions on gas and particulate emissions from residential biomass combustion. Environ. Sci. Technol. **53**, 2209–2219 (2019). https://doi.org/10.1021/acs.est.8b05020

Blado, L.D., Lilienkamp, R.H.: In Situ Vacuum Gauge Calibration by the Reference Transfer Method. In: ASTM/IES/AIAA Space Simulation Conference (1970)

Bloss, C., Wagner, V., Bonzanini, A., Jenkin, M.E., Wirtz, K., Martin-Reviejo, M., Pilling, M.J.: Evaluation of detailed aromatic mechanisms (MCMv3 and MCMv3.1) against environmental chamber data. Atmos. Chem. Phys. **5**, 623–639 (2005a). https://doi.org/10.5194/acp-5-623-2005a

Bloss, C., Wagner, V., Jenkin, M.E., Volkamer, R., Bloss, W.J., Lee, J.D., Heard, D.E., Wirtz, K., Martin-Reviejo, M., Rea, G., Wenger, J.C., Pilling, M.J.: Development of a detailed chemical mechanism (MCMv3.1) for the atmospheric oxidation of aromatic hydrocarbons. Atmos. Chem. Phys. **5**, 641–664 (2005b). https://doi.org/10.5194/acp-5-641-2005b

Bohn, B., Corlett, G.K., Gillmann, M., Sanghavi, S., Stange, G., Tensing, E., Vrekoussis, M., Bloss, W.J., Clapp, L.J., Kortner, M., Dorn, H.P., Monks, P.S., Platt, U., Plass-Dülmer, C., Mihalopoulos, N., Heard, D.E., Clemitshaw, K.C., Meixner, F.X., Prevot, A.S.H., Schmitt, R.: Photolysis frequency measurement techniques: results of a comparison within the ACCENT project. Atmos. Chem. Phys. **8**, 5373–5391 (2008). https://doi.org/10.5194/acp-8-5373-2008

Bonn, B., Schuster, G., Moortgat, G.K.: Influence of water vapor on the process of new particle formation during monoterpene ozonolysis. J. Phys. Chem. A **106**, 2869–2881 (2002). https://doi.org/10.1021/jp012713p

Boulon, J., Sellegri, K., Katrib, Y., Wang, J., Miet, K., Langmann, B., Laj, P., Doussin, J.F.: Sub-3 nm particles detection in a large photoreactor background: possible implications for new particles formation studies in a smog chamber. Aerosol Sci. Technol. **47**, 153–157 (2012). https://doi.org/10.1080/02786826.2012.733040

Boyd, C.M., Sanchez, J., Xu, L., Eugene, A.J., Nah, T., Tuet, W.Y., Guzman, M.I., Ng, N.L.: Secondary organic aerosol formation from the β-pinene+NO_3 system: effect of humidity and peroxy radical fate. Atmos. Chem. Phys. **15**, 7497–7522 (2015). https://doi.org/10.5194/acp-15-7497-2015

Brauers, T., Finlayson-Pitts, B.J.: Analysis of relative rate measurements. Int. J. Chem. Kinet. **29**, 665–672 (1997). https://doi.org/10.1002/(SICI)1097-4601(1997)29:9%3c665::AID-KIN3%3e3.0.CO;2-S

Brauers, T., Bohn, B., Johnen, F.-J., Rohrer, R., Rodriguez Bares, S., Tillmann, R., Wahner, A.: The atmosphere simulation chamber SAPHIR: a tool for the investigation of photochemistry (2003)

Brégonzio-Rozier, L., Giorio, C., Siekmann, F., Pangui, E., Morales, S.B., Temime-Roussel, B., Gratien, A., Michoud, V., Cazaunau, M., DeWitt, H.L., Tapparo, A., Monod, A., Doussin, J.F.: Secondary organic aerosol formation from isoprene photooxidation during cloud condensation–evaporation cycles. Atmos. Chem. Phys. **16**, 1747–1760 (2016). https://doi.org/10.5194/acp-16-1747-2016

Brommelle, N.S.: The Russell and Abney report on the action of light on water colours. Stud. Conserv. **9**, 140–152 (1964). https://doi.org/10.2307/1505213

Brotto, P., Repetto, B., Formenti, P., Pangui, E., Livet, A., Bousserrhine, N., Martini, I., Varnier, O., Doussin, J.F., Prati, P.: Use of an atmospheric simulation chamber for bioaerosol investigation: a feasibility study. Aerobiologia **31**, 445–455 (2015). https://doi.org/10.1007/s10453-015-9378-2

Campbell, S.J., Utinger, B., Lienhard, D.M., Paulson, S.E., Shen, J., Griffiths, P.T., Stell, A.C., Kalberer, M.: Development of a physiologically relevant online chemical assay to quantify aerosol oxidative potential. Anal. Chem. **91**, 13088–13095 (2019). https://doi.org/10.1021/acs.analchem.9b03282

Cantrell, C.A., Stedman, D.H., Wendel, G.J.: Measurement of atmospheric peroxy radicals by chemical amplification. Anal. Chem. **56**, 1496–1502 (1984). https://doi.org/10.1021/ac00272a065

Caponi, L., Formenti, P., Massabo, D., Di Biagio, C., Cazaunau, M., Pangui, E., Chevaillier, S., Landrot, G., Andreae, M.O., Kandler, K., Piketh, S., Saeed, T., Seibert, D., Williams, E., Balkanski, Y., Prati, P., Doussin, J.F.: Spectral- and size-resolved mass absorption efficiency of mineral dust aerosols in the shortwave spectrum: a simulation chamber study. Atmos. Chem. Phys. **17**, 7175–7191 (2017). https://doi.org/10.5194/acp-17-7175-2017

Cappellin, L., Karl, T., Probst, M., Ismailova, O., Winkler, P.M., Soukoulis, C., Aprea, E., Märk, T.D., Gasperi, F., Biasioli, F.: On quantitative determination of volatile organic compound concentrations using proton transfer reaction time-of-flight mass spectrometry. Environ. Sci. Technol. **46**, 2283–2290 (2012). https://doi.org/10.1021/es203985t

Carter, W.P.L., Lloyd, A.C., Sprung, J.L., Pitts, J.N., Jr.: Computer modeling of smog chamber data: progress in validation of a detailed mechanism for the photooxidation of propene and n-butane in photochemical smog. Int. J. Chem. Kinet. **11**, 45–101 (1979). https://doi.org/10.1002/kin.550110105

Carter, W.P.L., Lurmann, F.W.: Evaluation of a detailed gas-phase atmospheric reaction mechanism using environmental chamber data. Atmos. Environ. Part A Gen. Top. **25**, 2771–2806 (1991). https://doi.org/10.1016/0960-1686(91)90206-M

Carter, W.P.L.: Development of ozone reactivity scales for volatile organic compounds. Air Waste **44**, 881–899 (1994). https://doi.org/10.1080/1073161x.1994.10467290

Carter, W.P.L., Cocker, D.R., III., Fitz, D.R., Malkina, I.L., Bumiller, K., Sauer, C.G., Pisano, J.T., Bufalino, C., Song, C.: A new environmental chamber for evaluation of gas-phase chemical mechanisms and secondary aerosol formation. Atmos. Environ. **39**, 7768–7788 (2005)

Carter, W.P.L.: Development of the SAPRC-07 chemical mechanism. Atmos. Environ. **44**, 5324–5335 (2010). https://doi.org/10.1016/j.atmosenv.2010.01.026

Carter W.P.L.: Development of the SAPRC-07 chemical mechanism and updated ozone reactivity scales. Final Report to the California Air Resources Board Contract No. 03-318 (2008)

Chang, K., Bench, J., Brege, M., Cantrell, W., Chandrakar, K., Ciochetto, D., Mazzoleni, C., Mazzoleni, L.R., Niedermeier, D., Shaw, R.A.: A laboratory facility to study gas–aerosol–cloud interactions in a turbulent environment: the Π chamber. Bull. Am. Meteor. Soc. **97**, 2343–2358 (2016). https://doi.org/10.1175/bams-d-15-00203.1

Chen, T., Jang, M.: Chamber simulation of photooxidation of dimethyl sulfide and isoprene in the presence of NO_x. Atmos. Chem. Phys. **12**, 10257–10269 (2012). https://doi.org/10.5194/acp-12-10257-2012

Chen, T., Liu, Y., Chu, B., Liu, C., Liu, J., Ge, Y., Ma, Q., Ma, J., He, H.: Differences of the oxidation process and secondary organic aerosol formation at low and high precursor concentrations. J. Environ. Sci. **79**, 256–263 (2019). https://doi.org/10.1016/j.jes.2018.11.011

Chiappini, L., Perraudin, E., Durand-Jolibois, R., Doussin, J.F.: Development of a supercritical fluid extraction-gas chromatography-mass spectrometry method for the identification of highly polar compounds in secondary organic aerosols formed from biogenic hydrocarbons in smog chamber experiments. Anal. Bioanal. Chem. **386**, 1749–1759 (2006)

Chirico, R., DeCarlo, P.F., Heringa, M.F., Tritscher, T., Richter, R., Prévôt, A.S.H., Dommen, J., Weingartner, E., Wehrle, G., Gysel, M., Laborde, M., Baltensperger, U.: Impact of aftertreatment devices on primary emissions and secondary organic aerosol formation potential from in-use diesel vehicles: results from smog chamber experiments. Atmos. Chem. Phys. **10**, 11545–11563 (2010). https://doi.org/10.5194/acp-10-11545-2010

Chou, C., Formenti, P., Maille, M., Ausset, P., Helas, G., Harrison, M., Osborne, S.: Size distribution, shape, and composition of mineral dust aerosols collected during the African Monsoon Multidisciplinary Analysis Special Observation Period 0: Dust and Biomass-Burning Experiment field campaign in Niger, January 2006. J. Geophys. Res. Atmos. **113** (2008). https://doi.org/10.1029/2008JD009897

Ciarelli, G., Aksoyoglu, S., El Haddad, I., Bruns, E.A., Crippa, M., Poulain, L., Äijälä, M., Carbone, S., Freney, E., O'Dowd, C., Baltensperger, U., Prévôt, A.S.H.: Modelling winter organic aerosol at the European scale with CAMx: evaluation and source apportionment with a VBS parameterization based on novel wood burning smog chamber experiments. Atmos. Chem. Phys. **17**, 7653–7669 (2017). https://doi.org/10.5194/acp-17-7653-2017

Claxton, L.D., Barnes, H.M.: The mutagenicity of diesel-exhaust particle extracts collected under smog-chamber conditions using the Salmonella typhimurium test system. Mutat. Res. Genet. Toxicol. **88**, 255–272 (1981). https://doi.org/10.1016/0165-1218(81)90037-9

Cocker, D.R., Flagan, R.C., Seinfeld, J.H.: State of the art chamber facility for studying atmospheric aerosol chemistry. Environ. Sci. Technol. **35**, 2594–2601 (2001)

Coll, P., Cazaunau, M., Boczkowski, J., Zysman, M., Doussin, J.-F., Gratien, A., Derumeaux, G., Pini, M., Di Biagio, C., Pangui, É., Gaimoz, C., HÜE, S., Relaix, F., Der Vartanian, A., Coll, I., Michoud, V., Formenti, P., Foret, G., Thavaratnasingam, L., Lanone, S.: Pollurisk: an innovative experimental platform to investigate health impacts of air quality, pp. 557–565 (2018)

Connolly, P.J., Möhler, O., Field, P.R., Saathoff, H., Burgess, R., Choularton, T., Gallagher, M.: Studies of heterogeneous freezing by three different desert dust samples. Atmos. Chem. Phys. **9**, 2805–2824 (2009). https://doi.org/10.5194/acp-9-2805-2009

Crutzen, P.J., Howard, C.J.: The effect of the HO2+NO reaction rate constant on one-dimensional model calculations of stratospheric ozone perturbations. Pure Appl. Geophys. **116**, 497–510 (1978). https://doi.org/10.1007/bf01636903

D'Ambro, E.L., Møller, K.H., Lopez-Hilfiker, F.D., Schobesberger, S., Liu, J., Shilling, J.E., Lee, B.H., Kjaergaard, H.G., Thornton, J.A.: Isomerization of second-generation isoprene peroxy radicals: epoxide formation and implications for secondary organic aerosol yields. Environ. Sci. Technol. **51**, 4978–4987 (2017). https://doi.org/10.1021/acs.est.7b00460

de Blas, M., Navazo, M., Alonso, L., Durana, N., Iza, J.: Automatic on-line monitoring of atmospheric volatile organic compounds: Gas chromatography–mass spectrometry and gas chromatography–flame ionization detection as complementary systems. Sci. Total Environ. **409**, 5459–5469 (2011). https://doi.org/10.1016/j.scitotenv.2011.08.072

de Gouw, J., Warneke, C.: Measurements of volatile organic compounds in the earth's atmosphere using proton-transfer-reaction mass spectrometry. Mass Spectrom. Rev. **26**, 223–257 (2007). https://doi.org/10.1002/mas.20119

De Haan, D. O., Brauers, T., Oum, K., Stutz, J., Nordmeyer, T., Finlayson-Pitts, B.J.: Heterogeneous chemistry in the troposphere: experimental approaches and applications to the chemistry of sea salt particles. Int. Rev. Phys. Chem. 343–385 (1999)

De Haan, D.O., Tapavicza, E., Riva, M., Cui, T., Surratt, J.D., Smith, A.C., Jordan, M.-C., Nilakantan, S., Almodovar, M., Stewart, T.N., de Loera, A., De Haan, A.C., Cazaunau, M., Gratien, A., Pangui, E., Doussin, J.-F.: Nitrogen-containing, light-absorbing oligomers produced in aerosol particles exposed to methylglyoxal, photolysis, and cloud cycling. Environ. Sci. Technol. **52**, 4061–4071 (2018). https://doi.org/10.1021/acs.est.7b06105

DeMott, P.J., Prenni, A.J., McMeeking, G.R., Sullivan, R.C., Petters, M.D., Tobo, Y., Niemand, M., Möhler, O., Snider, J.R., Wang, Z., Kreidenweis, S.M.: Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles. Atmos. Chem. Phys. **15**, 393–409 (2015). https://doi.org/10.5194/acp-15-393-2015

DeMott, P.J., Möhler, O., Cziczo, D.J., Hiranuma, N., Petters, M.D., Petters, S.S., Belosi, F., Bingemer, H.G., Brooks, S.D., Budke, C., Burkert-Kohn, M., Collier, K.N., Danielczok, A., Eppers, O., Felgitsch, L., Garimella, S., Grothe, H., Herenz, P., Hill, T.C.J., Höhler, K., Kanji, Z.A., Kiselev, A., Koop, T., Kristensen, T.B., Krüger, K., Kulkarni, G., Levin, E.J.T., Murray, B.J., Nicosia, A., O'Sullivan, D., Peckhaus, A., Polen, M.J., Price, H.C., Reicher, N., Rothenberg, D.A., Rudich, Y., Santachiara, G., Schiebel, T., Schrod, J., Seifried, T.M., Stratmann, F., Sullivan, R.C., Suski, K.J., Szakáll, M., Taylor, H.P., Ullrich, R., Vergara-Temprado, J., Wagner, R., Whale, T.F., Weber, D., Welti, A., Wilson, T.W., Wolf, M.J., Zenker, J.: The fifth international workshop on ice nucleation phase 2 (FIN-02): laboratory intercomparison of ice nucleation measurements. Atmos. Meas. Tech. **11**, 6231–6257 (2018). https://doi.org/10.5194/amt-11-6231-2018

Deng, Y., Inomata, S., Sato, K., Ramasamy, S., Morino, Y., Enami, S., Tanimoto, H.: Temperature and acidity dependence of secondary organic aerosol formation from α-pinene ozonolysis with a compact chamber system. Atmos. Chem. Phys. **21**, 5983–6003 (2021). https://doi.org/10.5194/acp-21-5983-2021

Denjean, C., Formenti, P., Picquet-Varrault, B., Katrib, Y., Pangui, E., Zapf, P., Doussin, J.F.: A new experimental approach to study the hygroscopic and optical properties of aerosols: application to ammonium sulfate particles. Atmos. Meas. Tech. **7**, 183–197 (2014). https://doi.org/10.5194/amt-7-183-2014

Denjean, C., Formenti, P., Picquet-Varrault, B., Pangui, E., Zapf, P., Katrib, Y., Giorio, C., Tapparo, A., Monod, A., Temime-Roussel, B., Decorse, P., Mangeney, C., Doussin, J.F.: Relating hygroscopicity and optical properties to chemical composition and structure of secondary organic aerosol particles generated from the ozonolysis of α-pinene. Atmos. Chem. Phys. **15**, 3339–3358 (2015). https://doi.org/10.5194/acp-15-3339-2015

Dewald, P., Liebmann, J.M., Friedrich, N., Shenolikar, J., Schuladen, J., Rohrer, F., Reimer, D., Tillmann, R., Novelli, A., Cho, C., Xu, K., Holzinger, R., Bernard, F., Zhou, L., Mellouki, W., Brown, S.S., Fuchs, H., Lelieveld, J., Crowley, J.N.: Evolution of NO_3 reactivity during the oxidation of isoprene. Atmos. Chem. Phys. **20**, 10459–10475 (2020). https://doi.org/10.5194/acp-20-10459-2020

Di Biagio, C., Formenti, P., Styler, S.A., Pangui, E., Doussin, J.-F.: Laboratory chamber measurements of the longwave extinction spectra and complex refractive indices of African and Asian mineral dusts. Geophys. Res. Lett. **41**, 6289–6297 (2014). https://doi.org/10.1002/2014gl060213

Di Biagio, C., Formenti, P., Balkanski, Y., Caponi, L., Cazaunau, M., Pangui, E., Journet, E., Nowak, S., Caquineau, S., Andreae, M.O., Kandler, K., Saeed, T., Piketh, S., Seibert, D., Williams, E., Doussin, J.F.: Global scale variability of the mineral dust long-wave refractive index: a new

dataset of in situ measurements for climate modeling and remote sensing. Atmos. Chem. Phys. **17**, 1901–1929 (2017a). https://doi.org/10.5194/acp-17-1901-2017

Di Biagio, C., Formenti, P., Cazaunau, M., Pangui, E., Marchand, N., Doussin, J.F.: Aethalometer multiple scattering correction Cref for mineral dust aerosols. Atmos. Meas. Tech. **10**, 2923–2939 (2017b). https://doi.org/10.5194/amt-10-2923-2017

Di Biagio, C., Formenti, P., Balkanski, Y., Caponi, L., Cazaunau, M., Pangui, E., Journet, E., Nowak, S., Andreae, M.O., Kandler, K., Saeed, T., Piketh, S., Seibert, D., Williams, E., Doussin, J.-F.: Complex refractive indices and single-scattering albedo of global dust aerosols in the shortwave spectrum and relationship to size and iron content. Atmos. Chem. Phys. **19**, 15503–15531 (2019). https://doi.org/10.5194/acp-19-15503-2019

Dias, A., Ehrhart, S., Vogel, A., Williamson, C., Almeida, J., Kirkby, J., Mathot, S., Mumford, S., Onnela, A.: Temperature uniformity in the CERN CLOUD chamber. Atmos. Meas. Tech. **10**, 5075–5088 (2017). https://doi.org/10.5194/amt-10-5075-2017

Docherty, K.S., Jaoui, M., Corse, E., Jimenez, J.L., Offenberg, J.H., Lewandowski, M., Kleindienst, T.E.: Collection efficiency of the aerosol mass spectrometer for chamber-generated secondary organic aerosols. Aerosol Sci. Technol. **47**, 294–309 (2013). https://doi.org/10.1080/02786826.2012.752572

Dodge, M.C.: Chemical oxidant mechanisms for air quality modeling: critical review. Atmos. Environ. **34**, 2103–2130 (2000)

Dodge M.: Combined use of modeling techniques and smog chamber data to derive ozone–precursor relationships. In: International Conference on Photochemical Oxidant Pollution and its Control Proceedings, Raleigh, NC (1977)

Donahue, N.M., Hartz, K.E.H., Chuong, B., Presto, A.A., Stanier, C.O., Rosenhorn, T., Robinson, A.L., Pandis, S.N.: Critical factors determining the variation in SOA yields from terpene ozonolysis: a combined experimental and computational study. Faraday Discuss. **130**, 295–309 (2005)

Donahue, N.M., Robinson, A.L., Stanier, C.O., Pandis, S.N.: Coupled partitioning, dilution, and chemical aging of semivolatile organics. Environ. Sci. Technol. **40**, 2635–2643 (2006). https://doi.org/10.1021/es052297c

Donahue, N.M., Henry, K.M., Mentel, T.F., Kiendler-Scharr, A., Spindler, C., Bohn, B., Brauers, T., Dorn, H.P., Fuchs, H., Tillmann, R., Wahner, A., Saathoff, H., Naumann, K.-H., Möhler, O., Leisner, T., Müller, L., Reinnig, M.-C., Hoffmann, T., Salo, K., Hallquist, M., Frosch, M., Bilde, M., Tritscher, T., Barmet, P., Praplan, A.P., DeCarlo, P.F., Dommen, J., Prévôt, A.S.H., Baltensperger, U.: Aging of biogenic secondary organic aerosol via gas-phase OH radical reactions. Proc. Natl. Acad. Sci. **109**, 13503–13508 (2012). https://doi.org/10.1073/pnas.1115186109

Dorn, H.P., Apodaca, R.L., Ball, S.M., Brauers, T., Brown, S.S., Crowley, J.N., Dubé, W.P., Fuchs, H., Häseler, R., Heitmann, U., Jones, R.L., Kiendler-Scharr, A., Labazan, I., Langridge, J.M., Meinen, J., Mentel, T.F., Platt, U., Pöhler, D., Rohrer, F., Ruth, A.A., Schlosser, E., Schuster, G., Shillings, A.J.L., Simpson, W.R., Thieser, J., Tillmann, R., Varma, R., Venables, D.S., Wahner, A.: Intercomparison of NO_3 radical detection instruments in the atmosphere simulation chamber SAPHIR. Atmos. Meas. Tech. **6**, 1111–1140 (2013). https://doi.org/10.5194/amt-6-1111-2013

Doussin, J.F., Ritz, D., DurandJolibois, R., Monod, A., Carlier, P.: Design of an environmental chamber for the study of atmospheric chemistry: new developments in the analytical device. Analusis **25**, 236–242 (1997)

Doyle, G.J., Lloyd, A.C., Darnall, K.R., Winer, A.M., Pitts, J.N.: Gas phase kinetic study of relative rates of reaction of selected aromatic compounds with hydroxyl radicals in an environmental chamber. Environ. Sci. Technol. **9**, 237–241 (1975). https://doi.org/10.1021/es60101a002

Duncianu, M., David, M., Kartigueyane, S., Cirtog, M., Doussin, J.F., Picquet-Varrault, B.: Measurement of alkyl and multifunctional organic nitrates by proton-transfer-reaction mass spectrometry. Atmos. Meas. Tech. **10**, 1445–1463 (2017). https://doi.org/10.5194/amt-10-1445-2017

Dunlea, E.J., Herndon, S.C., Nelson, D.D., Volkamer, R.M., San Martini, F., Sheehy, P.M., Zahniser, M.S., Shorter, J.H., Wormhoudt, J.C., Lamb, B.K., Allwine, E.J., Gaffney, J.S., Marley, N.A.,

Grutter, M., Marquez, C., Blanco, S., Cardenas, B., Retama, A., Ramos Villegas, C.R., Kolb, C.E., Molina, L.T., Molina, M.J.: Evaluation of nitrogen dioxide chemiluminescence monitors in a polluted urban environment. Atmos. Chem. Phys. **7**, 2691–2704 (2007). https://doi.org/10.5194/acp-7-2691-2007

Duplissy, J., Enghoff, M.B., Aplin, K.L., Arnold, F., Aufmhoff, H., Avngaard, M., Baltensperger, U., Bondo, T., Bingham, R., Carslaw, K., Curtius, J., David, A., Fastrup, B., Gagné, S., Hahn, F., Harrison, R.G., Kellett, B., Kirkby, J., Kulmala, M., Laakso, L., Laaksonen, A., Lillestol, E., Lockwood, M., Mäkelä, J., Makhmutov, V., Marsh, N.D., Nieminen, T., Onnela, A., Pedersen, E., Pedersen, J.O.P., Polny, J., Reichl, U., Seinfeld, J.H., Sipilä, M., Stozhkov, Y., Stratmann, F., Svensmark, H., Svensmark, J., Veenhof, R., Verheggen, B., Viisanen, Y., Wagner, P.E., Wehrle, G., Weingartner, E., Wex, H., Wilhelmsson, M., Winkler, P.M.: Results from the CERN pilot CLOUD experiment. Atmos. Chem. Phys. **10**, 1635–1647 (2010). https://doi.org/10.5194/acp-10-1635-2010

Edwards, G.D., Cantrell, C.A., Stephens, S., Hill, B., Goyea, O., Shetter, R.E., Mauldin, R.L., Kosciuch, E., Tanner, D.J., Eisele, F.L.: Chemical ionization mass spectrometer instrument for the measurement of tropospheric HO2 and RO2. Anal. Chem. **75**, 5317–5327 (2003). https://doi.org/10.1021/ac034402b

Ehn, M., Thornton, J.A., Kleist, E., Sipilä, M., Junninen, H., Pullinen, I., Springer, M., Rubach, F., Tillmann, R., Lee, B., Lopez-Hilfiker, F., Andres, S., Acir, I.-H., Rissanen, M., Jokinen, T., Schobesberger, S., Kangasluoma, J., Kontkanen, J., Nieminen, T., Kurtén, T., Nielsen, L.B., Jørgensen, S., Kjaergaard, H.G., Canagaratna, M., Maso, M.D., Berndt, T., Petäjä, T., Wahner, A., Kerminen, V.-M., Kulmala, M., Worsnop, D.R., Wildt, J., Mentel, T.F.: A large source of low-volatility secondary organic aerosol. Nature **506**, 476–479 (2014). https://doi.org/10.1038/nature13032

Etzkorn, T., Klotz, B., Sorensen, S., Patroescu, I., Barnes, I., Becker, K.H., Platt, U.: Gas-phase absorption cross sections of 24 monocyclic aromatic hydrocarbons in the UV and IR spectral ranges. Atmos. Environ. **33**, 525–540 (1999)

Evans, L.F., Weeks, I.A., Eccleston, A.J.: A chamber study of photochemical smog in Melbourne, Australia—present and future. Atmos. Environ. **1967**(20), 1355–1368 (1986). https://doi.org/10.1016/0004-6981(86)90006-5

Fahey, D.W., Gao, R.S., Möhler, O., Saathoff, H., Schiller, C., Ebert, V., Krämer, M., Peter, T., Amarouche, N., Avallone, L.M., Bauer, R., Bozóki, Z., Christensen, L.E., Davis, S.M., Durry, G., Dyroff, C., Herman, R.L., Hunsmann, S., Khaykin, S.M., Mackrodt, P., Meyer, J., Smith, J.B., Spelten, N., Troy, R.F., Vömel, H., Wagner, S., Wienhold, F.G.: The AquaVIT-1 intercomparison of atmospheric water vapor measurement techniques. Atmos. Meas. Tech. **7**, 3177–3213 (2014). https://doi.org/10.5194/amt-7-3177-2014

Faiola, C.L., Pullinen, I., Buchholz, A., Khalaj, F., Ylisirniö, A., Kari, E., Miettinen, P., Holopainen, J.K., Kivimäenpää, M., Schobesberger, S., Yli-Juuti, T., Virtanen, A.: Secondary organic aerosol formation from healthy and aphid-stressed scots pine emissions. ACS Earth Space Chem. **3**, 1756–1772 (2019). https://doi.org/10.1021/acsearthspacechem.9b00118

Field, P.R., Möhler, O., Connolly, P., Krämer, M., Cotton, R., Heymsfield, A.J., Saathoff, H., Schnaiter, M.: Some ice nucleation characteristics of Asian and Saharan desert dust. Atmos. Chem. Phys. **6**, 2991–3006 (2006). https://doi.org/10.5194/acp-6-2991-2006

Finlayson-Pitts, B.J., Pitts, J.N., Jr.: Atmospheric chemistry: fundamentals and experimental techniques. John Wiley and Sons, New-York (1986). (edited by: Publication, W. I.)

Finlayson-Pitts, B.J., Pitts, J.N., Jr.: The Chemistry of the Lower and Upper Atmosphere: Theory, Experiments and Applications. Academic Press, New-York (2000)

Fitz, D.R., Dodd, M.C., Winer, A.M.: Photooxidation of apinene at near-ambient concentrations under simulated atmospheric conditions. In: 74th Annual Meeting, Air Pollution Control Association, Philadeplphia, PA, 21–26 Juen (1981)

Folkers, M., Mentel, T.F., Wahner, A.: Influence of an organic coating on the reactivity of aqueous aerosols probed by the heterogeneous hydrolysis of N2O5. Geophys. Res. Lett. **30** (2003). https://doi.org/10.1029/2003GL017168

Fouqueau, A., Cirtog, M., Cazaunau, M., Pangui, E., Zapf, P., Siour, G., Landsheere, X., Méjean, G., Romanini, D., Picquet-Varrault, B.: Implementation of an incoherent broadband cavity-enhanced absorption spectroscopy technique in an atmospheric simulation chamber for in situ NO3 monitoring: characterization and validation for kinetic studies. Atmos. Meas. Tech. **13**, 6311–6323 (2020). https://doi.org/10.5194/amt-13-6311-2020

Fox, D.L., Kamens, R., Jeffries, H.E.: Photochemical smog systems: effect of dilution on ozone formation. Science **188**, 1113–1114 (1975). https://doi.org/10.1126/science.188.4193.1113

Fry, J.L., Draper, D.C., Barsanti, K.C., Smith, J.N., Ortega, J., Winkler, P.M., Lawler, M.J., Brown, S.S., Edwards, P.M., Cohen, R.C., Lee, L.: Secondary organic aerosol formation and organic nitrate yield from NO_3 oxidation of biogenic hydrocarbons. Environ. Sci. Technol. **48**, 11944–11953 (2014). https://doi.org/10.1021/es502204x

Fuchs, H., Ball, S.M., Bohn, B., Brauers, T., Cohen, R.C., Dorn, H.P., Dubé, W.P., Fry, J.L., Häseler, R., Heitmann, U., Jones, R.L., Kleffmann, J., Mentel, T.F., Müsgen, P., Rohrer, F., Rollins, A.W., Ruth, A.A., Kiendler-Scharr, A., Schlosser, E., Shillings, A.J.L., Tillmann, R., Varma, R.M., Venables, D.S., Villena Tapia, G., Wahner, A., Wegener, R., Wooldridge, P.J., Brown, S.S.: Intercomparison of measurements of NO_2 concentrations in the atmosphere simulation chamber SAPHIR during the NO_3Comp campaign. Atmos. Meas. Tech. **3**, 21–37 (2010). https://doi.org/10.5194/amt-3-21-2010

Fuchs, H., Dorn, H.P., Bachner, M., Bohn, B., Brauers, T., Gomm, S., Hofzumahaus, A., Holland, F., Nehr, S., Rohrer, F., Tillmann, R., Wahner, A.: Comparison of OH concentration measurements by DOAS and LIF during SAPHIR chamber experiments at high OH reactivity and low NO concentration. Atmos. Meas. Tech. **5**, 1611–1626 (2012a). https://doi.org/10.5194/amt-5-1611-2012

Fuchs, H., Simpson, W.R., Apodaca, R.L., Brauers, T., Cohen, R.C., Crowley, J.N., Dorn, H.P., Dubé, W.P., Fry, J.L., Häseler, R., Kajii, Y., Kiendler-Scharr, A., Labazan, I., Matsumoto, J., Mentel, T.F., Nakashima, Y., Rohrer, F., Rollins, A.W., Schuster, G., Tillmann, R., Wahner, A., Wooldridge, P.J., Brown, S.S.: Comparison of N_2O_5 mixing ratios during NO_3Comp 2007 in SAPHIR. Atmos. Meas. Tech. **5**, 2763–2777 (2012b). https://doi.org/10.5194/amt-5-2763-2012

Fuchs, H., Hofzumahaus, A., Rohrer, F., Bohn, B., Brauers, T., Dorn, H.P., Häseler, R., Holland, F., Kaminski, M., Li, X., Lu, K., Nehr, S., Tillmann, R., Wegener, R., Wahner, A.: Experimental evidence for efficient hydroxyl radical regeneration in isoprene oxidation. Nat. Geosci. **6**, 1023–1026 (2013). https://doi.org/10.1038/ngeo1964

Fuchs, H., Novelli, A., Rolletter, M., Hofzumahaus, A., Pfannerstill, E.Y., Kessel, S., Edtbauer, A., Williams, J., Michoud, V., Dusanter, S., Locoge, N., Zannoni, N., Gros, V., Truong, F., Sarda-Esteve, R., Cryer, D.R., Brumby, C.A., Whalley, L.K., Stone, D., Seakins, P.W., Heard, D.E., Schoemaecker, C., Blocquet, M., Coudert, S., Batut, S., Fittschen, C., Thames, A.B., Brune, W.H., Ernest, C., Harder, H., Muller, J.B.A., Elste, T., Kubistin, D., Andres, S., Bohn, B., Hohaus, T., Holland, F., Li, X., Rohrer, F., Kiendler-Scharr, A., Tillmann, R., Wegener, R., Yu, Z., Zou, Q., Wahner, A.: Comparison of OH reactivity measurements in the atmospheric simulation chamber SAPHIR. Atmos. Meas. Tech. **10**, 4023–4053 (2017). https://doi.org/10.5194/amt-10-4023-2017

Fuller, S.J., Wragg, F.P.H., Nutter, J., Kalberer, M.: Comparison of on-line and off-line methods to quantify reactive oxygen species (ROS) in atmospheric aerosols. Atmos. Environ. **92**, 97–103 (2014). https://doi.org/10.1016/j.atmosenv.2014.04.006

Gaie-Levrel, F., Bau, S., Bregonzio-Rozier, L., Payet, R., Artous, S., Jacquinot, S., Guiot, A., Ouf, F.X., Bourrous, S., Marpillat, A., Foulquier, C., Smith, G., Crenn, V., Feltin, N.: An intercomparison exercise of good laboratory practices for nano-aerosol size measurements by mobility spectrometers. J. Nanopart. Res. **22**, 103 (2020). https://doi.org/10.1007/s11051-020-04820-y

Geiger, H., Kleffmann, J., Wiesen, P.: Smog chamber studies on the influence of diesel exhaust on photosmog formation. Atmos. Environ. **36**, 1737–1747 (2002). https://doi.org/10.1016/S1352-2310(02)00175-9

Geiger, H., Becker, K., Wiesen, P.: Effect of gasoline formulation on the formation of photosmog: a box model study. J. Air Waste Manag. Assoc. **1995**(53), 425–433 (2003). https://doi.org/10.1080/10473289.2003.10466173

Gensch, I., Kiendler-Scharr, A., Rudolph, J.: Isotope ratio studies of atmospheric organic compounds: principles, methods, applications and potential. Int. J. Mass Spectrom. **365–366**, 206–221 (2014). https://doi.org/10.1016/j.ijms.2014.02.004

Gentner, D.R., Jathar, S.H., Gordon, T.D., Bahreini, R., Day, D.A., El Haddad, I., Hayes, P.L., Pieber, S.M., Platt, S.M., de Gouw, J., Goldstein, A.H., Harley, R.A., Jimenez, J.L., Prévôt, A.S.H., Robinson, A.L.: Review of urban secondary organic aerosol formation from gasoline and diesel motor vehicle emissions. Environ. Sci. Technol. **51**, 1074–1093 (2017). https://doi.org/10.1021/acs.est.6b04509

Gery, M.W., Whitten, G.Z., Killus, J.P., Dodge, M.C.: A photochemical kinetics mechanism for urban and regional scale computer modeling. J. Geophys. Res. Atmos. **94**, 12925–12956 (1989). https://doi.org/10.1029/JD094iD10p12925

Gkatzelis, G.I., Hohaus, T., Tillmann, R., Gensch, I., Müller, M., Eichler, P., Xu, K.M., Schlag, P., Schmitt, S.H., Yu, Z., Wegener, R., Kaminski, M., Holzinger, R., Wisthaler, A., Kiendler-Scharr, A.: Gas-to-particle partitioning of major biogenic oxidation products: a study on freshly formed and aged biogenic SOA. Atmos. Chem. Phys. **18**, 12969–12989 (2018). https://doi.org/10.5194/acp-18-12969-2018

Glaschick-Schimpf, I., Leiss, A., Monkhouse, P.B., Schurath, U., Becker, K.H., Fink, E.H.: A kinetic study of the reactions of HO2/DO2 radicals with nitric oxide using near-infrared chemiluminescence detection. Chem. Phys. Lett. **67**, 318–323 (1979). https://doi.org/10.1016/0009-2614(79)85170-2

Glowacki, D., Goddard, A., Hemavibool, K., Malkin, T., Commane, R., Anderson, F., Bloss, W., Heard, D., Ingham, T., Pilling, M., Seakins, P.: Design of and initial results from a highly instrumented reactor for atmospheric chemistry (HIRAC). Atmos. Chem. Phys. **7**, 5371–5390 (2007). https://doi.org/10.5194/acpd-7-10687-2007

Goliff, W.S., Stockwell, W.R., Lawson, C.V.: The regional atmospheric chemistry mechanism, version 2. Atmos. Environ. **68**, 174–185 (2013). https://doi.org/10.1016/j.atmosenv.2012.11.038

Good, N., Coe, H., McFiggans, G.: Instrumentational operation and analytical methodology for the reconciliation of aerosol water uptake under sub- and supersaturated conditions. Atmos. Meas. Tech. **3**, 1241–1254 (2010). https://doi.org/10.5194/amt-3-1241-2010

Greiner, N.R.: Hydroxyl-radical kinetics by kinetic spectroscopy. I. Reactions with H2, CO, and CH4 at 300°K. J. Chem. Phys. **46**, 2795–2799 (1967). https://doi.org/10.1063/1.1841115

Groth, W., Becker, K.H., Comsa, G.H., Elzer, A., Fink, E., Jud, W., Kley, D., Schurath, U., Thran, D.: Untersuchungen in der "Großen Bonner Kugel." Naturwissenschaften **59**, 379–387 (1972). https://doi.org/10.1007/bf00623126

Haagen-Smit, A.J.: Chemistry and physiology of Los Angeles smog. Ind. Eng. Chem. **44**, 1342–1346 (1952). https://doi.org/10.1021/ie50510a045

Hack, W., Preuss, A.W., Temps, F., Wagner, H.G., Hoyermann, K.: Direct determination of the rate constant of the reaction NO + HO_2 → NO_2 + OH with the LMR. Int. J. Chem. Kinet. **12**, 851–860 (1980). https://doi.org/10.1002/kin.550121104

Hallquist, M., Wenger, J.C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., Dommen, J., Donahue, N.M., George, C., Goldstein, A.H., Hamilton, J.F., Herrmann, H., Hoffmann, T., Iinuma, Y., Jang, M., Jenkin, M.E., Jimenez, J.L., Kiendler-Scharr, A., Maenhaut, W., McFiggans, G., Mentel, T.F., Monod, A., Prévôt, A.S.H., Seinfeld, J.H., Surratt, J.D., Szmigielski, R., Wildt, J.: The formation, properties and impact of secondary organic aerosol: current and emerging issues. Atmos. Chem. Phys. **9**, 5155–5236 (2009). https://doi.org/10.5194/acp-9-5155-2009

Hamilton, J.F., Lewis, A.C., Carey, T.J., Wenger, J.C.: Characterization of polar compounds and oligomers in secondary organic aerosol using liquid chromatography coupled to mass spectrometry. Anal. Chem. **80**, 474–480 (2008). https://doi.org/10.1021/ac701852t

Hanke, M., Uecker, J., Reiner, T., Arnold, F.: Atmospheric peroxy radicals: ROXMAS, a new mass-spectrometric methodology for speciated measurements of HO2 and ∑RO2 and first results. Int. J. Mass Spectrom. **213**, 91–99 (2002). https://doi.org/10.1016/S1387-3806(01)00548-6

Hanst, P.L.: Spectroscopic methods of air pollution measurement. Adv. Environ. Sci. Technol. **2**, 91–213 (1971)

Hartmann, S., Wex, H., Clauss, T., Augustin-Bauditz, S., Niedermeier, D., Rösch, M., Stratmann, F.: Immersion freezing of kaolinite: scaling with particle surface area. J. Atmos. Sci. **73**, 263–278 (2016). https://doi.org/10.1175/jas-d-15-0057.1

Hatakeyama, S., Akimoto, H., Washida, N.: Effect of temperature on the formation of photochemical ozone in a propene-NO(x)-air-irradiation system. Environ. Sci. Technol. **25**, 1884–1890 (2002). https://doi.org/10.1021/es00023a007

Heicklen, J., Westberg, K., Cohen, N.: Conversion of nitrogen oxide to nitrogen dioxide in polluted atmospheres, pp. 115–169. Pennsylvania State University, University Park, Penn (1969)

Heim, M., Mullins, B.J., Umhauer, H., Kasper, G.: Performance evaluation of three optical particle counters with an efficient "multimodal" calibration method. J. Aerosol Sci. **39**, 1019–1031 (2008). https://doi.org/10.1016/j.jaerosci.2008.07.006

Hennigan, C.J., Sullivan, A.P., Collett, J.L. Jr., Robinson, A.L.: Levoglucosan stability in biomass burning particles exposed to hydroxyl radicals. Geophys. Res. Lett. **37** (2010). https://doi.org/10.1029/2010gl043088

Hennigan, C.J., Miracolo, M.A., Engelhart, G.J., May, A.A., Presto, A.A., Lee, T., Sullivan, A.P., McMeeking, G.R., Coe, H., Wold, C.E., Hao, W.M., Gilman, J.B., Kuster, W.C., de Gouw, J., Schichtel, B.A., Collett, J.L., Jr., Kreidenweis, S.M., Robinson, A.L.: Chemical and physical transformations of organic aerosol from the photo-oxidation of open biomass burning emissions in an environmental chamber. Atmos. Chem. Phys. **11**, 7669–7686 (2011). https://doi.org/10.5194/acp-11-7669-2011

Henning, S., Ziese, M., Kiselev, A., Saathoff, H., Möhler, O., Mentel, T.F., Buchholz, A., Spindler, C., Michaud, V., Monier, M., Sellegri, K., Stratmann, F.: Hygroscopic growth and droplet activation of soot particles: uncoated, succinic or sulfuric acid coated. Atmos. Chem. Phys. **12**, 4525–4537 (2012). https://doi.org/10.5194/acp-12-4525-2012

Hering, S.V., Stolzenburg, M.R., Quant, F.R., Oberreit, D.R., Keady, P.B.: A laminar-flow, water-based condensation particle counter (WCPC). Aerosol Sci. Technol. **39**, 659–672 (2005). https://doi.org/10.1080/02786820500182123

Heringa, M.F., DeCarlo, P.F., Chirico, R., Tritscher, T., Clairotte, M., Mohr, C., Crippa, M., Slowik, J.G., Pfaffenberger, L., Dommen, J., Weingartner, E., Prévôt, A.S.H., Baltensperger, U.: A new method to discriminate secondary organic aerosols from different sources using high-resolution aerosol mass spectra. Atmos. Chem. Phys. **12**, 2189–2203 (2012). https://doi.org/10.5194/acp-12-2189-2012

Herriott, D.R., Kogelnik, H., Kompfner, R.: Off-axis paths in spherical mirror interferometers. Appl. Opt. **3**, 523–526 (1964). https://doi.org/10.1364/ao.3.000523

Herriott, D.R., Schulte, H.J.: Folded optical delay lines. Appl. Opt. **4**, 883–889 (1965). https://doi.org/10.1364/ao.4.000883

Hiranuma, N., Hoffmann, N., Kiselev, A., Dreyer, A., Zhang, K., Kulkarni, G., Koop, T., Möhler, O.: Influence of surface morphology on the immersion mode ice nucleation efficiency of hematite particles. Atmos. Chem. Phys. **14**, 2315–2324 (2014). https://doi.org/10.5194/acp-14-2315-2014

Hofzumahaus, A., Rohrer, F., Lu, K., Bohn, B., Brauers, T., Chang, C.-C., Fuchs, H., Holland, F., Kita, K., Kondo, Y., Li, X., Lou, S., Shao, M., Zeng, L., Wahner, A., Zhang, Y.: Amplified trace gas removal in the troposphere. Science **324**, 1702–1704 (2009). https://doi.org/10.1126/science.1164566

Hohaus, T., Kuhn, U., Andres, S., Kaminski, M., Rohrer, F., Tillmann, R., Wahner, A., Wegener, R., Yu, Z., Kiendler-Scharr, A.: A new plant chamber facility, PLUS, coupled to the atmosphere simulation chamber SAPHIR. Atmos. Meas. Tech. **9**, 1247–1259 (2016). https://doi.org/10.5194/amt-9-1247-2016

Hoose, C., Möhler, O.: Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments. Atmos. Chem. Phys. **12**, 9817–9854 (2012). https://doi.org/10.5194/acp-12-9817-2012

Hoppel, W.A., Frick, G.M., Fitzgerald, J.W., Wattle, B.J.: A cloud chamber study of the effect that nonprecipitating water clouds have on the aerosol size distribution. Aerosol Sci. Technol. **20**, 1 (1994). https://doi.org/10.1080/02786829408959660

Howard, C.J., Evenson, K.M.: Kinetics of the reaction of HO2 with NO. Geophys. Res. Lett. **4**, 437–440 (1977). https://doi.org/10.1029/GL004i010p00437

Howard, C.J.: Temperature dependence of the reaction HO2+NO→OH+NO_2. J. Chem. Phys. **71**, 2352–2359 (1979). https://doi.org/10.1063/1.438639

Howard, C. J.: Kinetic study of the equilibrium HO2 + NO .dblarw. OH + NO_2 and the thermochemistry of HO2. J. Am. Chem. Soc. **102**, 6937–6941 (1980). https://doi.org/10.1021/ja00543a006

Hoyle, C.R., Fuchs, C., Järvinen, E., Saathoff, H., Dias, A., El Haddad, I., Gysel, M., Coburn, S.C., Tröstl, J., Bernhammer, A.K., Bianchi, F., Breitenlechner, M., Corbin, J.C., Craven, J., Donahue, N.M., Duplissy, J., Ehrhart, S., Frege, C., Gordon, H., Höppel, N., Heinritzi, M., Kristensen, T.B., Molteni, U., Nichman, L., Pinterich, T., Prévôt, A.S.H., Simon, M., Slowik, J.G., Steiner, G., Tomé, A., Vogel, A.L., Volkamer, R., Wagner, A.C., Wagner, R., Wexler, A.S., Williamson, C., Winkler, P.M., Yan, C., Amorim, A., Dommen, J., Curtius, J., Gallagher, M.W., Flagan, R.C., Hansel, A., Kirkby, J., Kulmala, M., Möhler, O., Stratmann, F., Worsnop, D.R., Baltensperger, U.: Aqueous phase oxidation of sulphur dioxide by ozone in cloud droplets. Atmos. Chem. Phys. **16**, 1693–1712 (2016). https://doi.org/10.5194/acp-16-1693-2016

Huang, W., Saathoff, H., Pajunoja, A., Shen, X., Naumann, K.H., Wagner, R., Virtanen, A., Leisner, T., Mohr, C.: α-Pinene secondary organic aerosol at low temperature: chemical composition and implications for particle viscosity. Atmos. Chem. Phys. **18**, 2883–2898 (2018). https://doi.org/10.5194/acp-18-2883-2018

Hynes, R.G., Angove, D., Saunders, S., Haverd, V., and Azzi, M.: Evaluation of two MCM v3.1 alkene mechanisms using indoor environmental chamber data. Atmos. Environ. **39**, 7251–7262 (2005). https://doi.org/10.1016/j.atmosenv.2005.09.005

Im, Y., Jang, M., Beardsley, R.L.: Simulation of aromatic SOA formation using the lumping model integrated with explicit gas-phase kinetic mechanisms and aerosol-phase reactions. Atmos. Chem. Phys. **14**, 4013–4027 (2014). https://doi.org/10.5194/acp-14-4013-2014

Jaoui, M., Lewandowski, M., Kleindienst, T., Offenberg, J., and Edney, E.: β-caryophyllinic acid: An atmospheric tracer for β-caryophyllene secondary organic aerosol. Geophys. Res. Lett. **34** (2007). https://doi.org/10.1029/2006gl028827

Järvinen, E., Vochezer, P., Möhler, O., Schnaiter, M.: Laboratory study of microphysical and scattering properties of corona-producing cirrus clouds. Appl. Opt. **53**, 7566–7575 (2014). https://doi.org/10.1364/ao.53.007566

Jeffries, H., Fox, D., Kamens, R.: Outdoor smog chamber studies: light effects relative to indoor chambers. Environ. Sci. Technol. **10**, 1006–1011 (1976). https://doi.org/10.1021/es60121a016

Jeffries, H.E., Kamens, R.M., Sexton, K.: Early history and rationale for outdoor chamber work at the University of North Carolina. Environ. Chem. **10**, 349–364 (2013). https://doi.org/10.1071/EN13901

Jenkin, M.E., Wyche, K.P., Evans, C.J., Carr, T., Monks, P.S., Alfarra, M.R., Barley, M.H., McFiggans, G.B., Young, J.C., Rickard, A.R.: Development and chamber evaluation of the MCM v3.2 degradation scheme for β-caryophyllene. Atmos. Chem. Phys. **12**, 5275–5308 (2012). https://doi.org/10.5194/acp-12-5275-2012.

Jiang, J., Chen, M., Kuang, C., Attoui, M., McMurry, P.H.: Electrical mobility spectrometer using a diethylene glycol condensation particle counter for measurement of aerosol size distributions down to 1 nm. Aerosol Sci. Technol. **45**, 510–521 (2011). https://doi.org/10.1080/02786826.2010.547538

Jimenez, J.L., Canagaratna, M.R., Donahue, N.M., Prevot, A.S.H., Zhang, Q., Kroll, J.H., DeCarlo, P.F., Allan, J.D., Coe, H., Ng, N.L., Aiken, A.C., Docherty, K.S., Ulbrich, I.M., Grieshop, A.P., Robinson, A.L., Duplissy, J., Smith, J.D., Wilson, K.R., Lanz, V.A., Hueglin, C., Sun, Y.L., Tian, J., Laaksonen, A., Raatikainen, T., Rautiainen, J., Vaattovaara, P., Ehn, M., Kulmala, M., Tomlinson, J.M., Collins, D.R., Cubison, M.J., Dunlea, J., Huffman, J.A., Onasch, T.B., Alfarra, M.R., Williams, P.I., Bower, K., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Salcedo, D., Cottrell, L., Griffin, R., Takami, A., Miyoshi, T., Hatakeyama, S., Shimono, A., Sun, J.Y., Zhang, Y.M., Dzepina, K., Kimmel, J.R., Sueper, D., Jayne, J.T.,

Herndon, S.C., Trimborn, A.M., Williams, L.R., Wood, E.C., Middlebrook, A.M., Kolb, C.E., Baltensperger, U., Worsnop, D.R.: Evolution of organic aerosols in the atmosphere. Science **326**, 1525–1529 (2009). https://doi.org/10.1126/science.1180353

Junkermann, W., Burger, J.M.: A new portable instrument for continuous measurement of formaldehyde in ambient air. J. Atmos. Oceanic Tech. **23**, 38–45 (2006). https://doi.org/10.1175/jtech1831.1

Kaduwela, A., Luecken, D., Carter, W., Derwent, R.: New directions: atmospheric chemical mechanisms for the future. Atmos. Environ. **122**, 609–610 (2015). https://doi.org/10.1016/j.atmosenv.2015.10.031

Kalberer, M., Sax, M., Samburova, V.: Molecular size evolution of oligomers in organic aerosols collected in urban atmospheres and generated in a smog chamber. Environ. Sci. Technol. **40**, 5917–5922 (2006). https://doi.org/10.1021/es0525760

Kaltsonoudis, C., Kostenidou, E., Louvaris, E., Psichoudaki, M., Tsiligiannis, E., Florou, K., Liangou, A., Pandis, S.N.: Characterization of fresh and aged organic aerosol emissions from meat charbroiling. Atmos. Chem. Phys. **17**, 7143–7155 (2017). https://doi.org/10.5194/acp-17-7143-2017

Kaltsonoudis, C., Jorga, S.D., Louvaris, E., Florou, K., Pandis, S.N.: A portable dual-smog-chamber system for atmospheric aerosol field studies. Atmos. Meas. Tech. **12**, 2733–2743 (2019). https://doi.org/10.5194/amt-12-2733-2019

Kanakidou, M., Seinfeld, J.H., Pandis, S.N., Barnes, I., Dentener, F.J., Facchini, M.C., Van Dingenen, R., Ervens, B., Nenes, A., Nielsen, C.J., Swietlicki, E., Putaud, J.P., Balkanski, Y., Fuzzi, S., Horth, J., Moortgat, J., Winterhalter, R., Myhre, C.E.L., Tsigaridis, K., Vignati, E., Stephanou, E.G., Wilson, J.: Organic aerosol and global climate modelling: a review. Atmos. Chem. Phys. **4**, 5855–6024 (2005)

Kebabian, P.L., Herndon, S.C., Freedman, A.: Detection of nitrogen dioxide by cavity attenuated phase shift spectroscopy. Anal. Chem. **77**, 724–728 (2005). https://doi.org/10.1021/ac048715y

Kelly, N.A.: Characterization of fluorocarbon-film bags as smog chambers. Environ. Sci. Technol. **16**, 763–770 (1982). https://doi.org/10.1021/es00105a007

Kiendler-Scharr, A., Wildt, J., Maso, M.D., Hohaus, T., Kleist, E., Mentel, T.F., Tillmann, R., Uerlings, R., Schurr, U., Wahner, A.: New particle formation in forests inhibited by isoprene emissions. Nature **461**, 381–384 (2009a). https://doi.org/10.1038/nature08292

Kiendler-Scharr, A., Zhang, Q., Hohaus, T., Kleist, E., Mensah, A., Mentel, T.F., Spindler, C., Uerlings, R., Tillmann, R., Wildt, J.: Aerosol mass spectrometric features of biogenic SOA: observations from a plant chamber and in rural atmospheric environments. Environ. Sci. Technol. **43**, 8166–8172 (2009b). https://doi.org/10.1021/es901420b

King, S.M., Rosenoern, T., Shilling, J.E., Chen, Q., Martin, S.T.: Increased cloud activation potential of secondary organic aerosol for atmospheric mass loadings. Atmos. Chem. Phys. **9**, 2959–2971 (2009). https://doi.org/10.5194/acp-9-2959-2009

Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., Franchin, A., Gagné, S., Ickes, L., Kürten, A., Kupc, A., Metzger, A., Riccobono, F., Rondo, L., Schobesberger, S., Tsagkogeorgas, G., Wimmer, D., Amorim, A., Bianchi, F., Breitenlechner, M., David, A., Dommen, J., Downard, A., Ehn, M., Flagan, R. C., Haider, S., Hansel, A., Hauser, D., Jud, W., Junninen, H., Kreissl, F., Kvashin, A., Laaksonen, A., Lehtipalo, K., Lima, J., Lovejoy, E.R., Makhmutov, V., Mathot, S., Mikkilä, J., Minginette, P., Mogo, S., Nieminen, T., Onnela, A., Pereira, P., Petäjä, T., Schnitzhofer, R., Seinfeld, J.H., Sipilä, M., Stozhkov, Y., Stratmann, F., Tomé, A., Vanhanen, J., Viisanen, Y., Vrtala, A., Wagner, P.E., Walther, H., Weingartner, E., Wex, H., Winkler, P.M., Carslaw, K.S., Worsnop, D.R., Baltensperger, U., Kulmala, M.: Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. Nature **476**, 429 (2011). https://doi.org/10.1038/nature10343. https://www.nature.com/articles/nature10343#supplementary-information

Kleffmann, J., Heland, J., Kurtenbach, R., Lörzer, J.C., Wiesen, P.: A new instrument (LOPAP) for the detection of nitrous acid (HONO). Environ. Sci. Pollut. Res. **9**, 48–54 (2002)

Kleindienst, T.E., Jaoui, M., Lewandowski, M., Offenberg, J.H., Lewis, C.W., Bhave, P.V., Edney, E.O.: Estimates of the contributions of biogenic and anthropogenic hydrocarbons to secondary organic aerosol at a southeastern US location. Atmos. Environ. **41**, 8288–8300 (2007)

Kleindienst, T.E., Jaoui, M., Lewandowski, M., Offenberg, J.H., Docherty, K.S.: The formation of SOA and chemical tracer compounds from the photooxidation of naphthalene and its methyl analogs in the presence and absence of nitrogen oxides. Atmos. Chem. Phys. **12**, 8711–8726 (2012). https://doi.org/10.5194/acp-12-8711-2012

Kleist, E., Mentel, T.F., Andres, S., Bohne, A., Folkers, A., Kiendler-Scharr, A., Rudich, Y., Springer, M., Tillmann, R., Wildt, J.: Irreversible impacts of heat on the emissions of monoterpenes, sesquiterpenes, phenolic BVOC and green leaf volatiles from several tree species. Biogeosciences **9**, 5111–5123 (2012). https://doi.org/10.5194/bg-9-5111-2012

Kostenidou, E., Kaltsonoudis, C., Tsiflikiotou, M., Louvaris, E., Russell, L.M., Pandis, S.N.: Burning of olive tree branches: a major organic aerosol source in the Mediterranean. Atmos. Chem. Phys. **13**, 8797–8811 (2013). https://doi.org/10.5194/acp-13-8797-2013

Kourtchev, I., Giorio, C., Manninen, A., Wilson, E., Mahon, B., Aalto, J., Kajos, M., Venables, D., Ruuskanen, T., Levula, J., Loponen, M., Connors, S., Harris, N., Zhao, D., Kiendler-Scharr, A., Mentel, T., Rudich, Y., Hallquist, M., Doussin, J.-F., Maenhaut, W., Bäck, J., Petäjä, T., Wenger, J., Kulmala, M., Kalberer, M.: Enhanced Volatile Organic Compounds emissions and organic aerosol mass increase the oligomer content of atmospheric aerosols. Sci. Rep. **6**, 35038 (2016). https://doi.org/10.1038/srep35038

Krechmer, J.E., Pagonis, D., Ziemann, P.J., Jimenez, J.L.: Quantification of gas-wall partitioning in teflon environmental chambers using rapid bursts of low-volatility oxidized species generated in situ. Environ. Sci. Technol. **50**, 5757–5765 (2016). https://doi.org/10.1021/acs.est.6b00606

Krechmer, J.E., Day, D.A., Ziemann, P.J., Jimenez, J.L.: Direct measurements of gas/particle partitioning and mass accommodation coefficients in environmental chambers. Environ. Sci. Technol. **51**, 11867–11875 (2017). https://doi.org/10.1021/acs.est.7b02144

Kristensen, K., Jensen, L.N., Glasius, M., Bilde, M.: The effect of sub-zero temperature on the formation and composition of secondary organic aerosol from ozonolysis of alpha-pinene. Environ. Sci. Process Impacts **19**, 1220–1234 (2017). https://doi.org/10.1039/c7em00231a

Kulmala, M., Mordas, G., Petäjä, T., Grönholm, T., Aalto, P.P., Vehkamäki, H., Hienola, A.I., Herrmann, E., Sipilä, M., Riipinen, I., Manninen, H.E., Hämeri, K., Stratmann, F., Bilde, M., Winkler, P.M., Birmili, W., Wagner, P.E.: The condensation particle counter battery (CPCB): a new tool to investigate the activation properties of nanoparticles. J. Aerosol Sci. **38**, 289–304 (2007). https://doi.org/10.1016/j.jaerosci.2006.11.008

Künzi, L., Mertes, P., Schneider, S., Jeannet, N., Menzi, C., Dommen, J., Baltensperger, U., Prévôt, A.S.H., Salathe, M., Kalberer, M., Geiser, M.: Responses of lung cells to realistic exposure of primary and aged carbonaceous aerosols. Atmos. Environ. **68**, 143–150 (2013). https://doi.org/10.1016/j.atmosenv.2012.11.055

Künzi, L., Krapf, M., Daher, N., Dommen, J., Jeannet, N., Schneider, S., Platt, S., Slowik, J.G., Baumlin, N., Salathe, M., Prévôt, A.S.H., Kalberer, M., Strähl, C., Dümbgen, L., Sioutas, C., Baltensperger, U., Geiser, M.: Toxicity of aged gasoline exhaust particles to normal and diseased airway epithelia. Sci. Rep. **5**, 11801 (2015). https://doi.org/10.1038/srep11801. https://www.nature.com/articles/srep11801#supplementary-information

Kwok, E.S.C., Atkinson, R.: Estimation of hydroxyl radical reaction rate constants for gas-phase organic compounds using a structure-reactivity relationship: an update. Atmos. Environ. **29**, 1685–1695 (1995). https://doi.org/10.1016/1352-2310(95)00069-B

La, Y.S., Camredon, M., Ziemann, P.J., Valorso, R., Matsunaga, A., Lannuque, V., Lee-Taylor, J., Hodzic, A., Madronich, S., Aumont, B.: Impact of chamber wall loss of gaseous organic compounds on secondary organic aerosol formation: explicit modeling of SOA formation from alkane and alkene oxidation. Atmos. Chem. Phys. **16**, 1417–1431 (2016). https://doi.org/10.5194/acp-16-1417-2016

Laborde, M., Schnaiter, M., Linke, C., Saathoff, H., Naumann, K.H., Möhler, O., Berlenz, S., Wagner, U., Taylor, J.W., Liu, D., Flynn, M., Allan, J.D., Coe, H., Heimerl, K., Dahlkötter, F., Weinzierl, B., Wollny, A.G., Zanatta, M., Cozic, J., Laj, P., Hitzenberger, R., Schwarz, J.P., Gysel,

M.: Single particle soot photometer intercomparison at the AIDA chamber. Atmos. Meas. Tech. **5**, 3077–3097 (2012). https://doi.org/10.5194/amt-5-3077-2012

Lamb, D., Miller, D.F., Robinson, N.F., Gertler, A.W.: The importance of liquid water concentration in the atmospheric oxidation of SO2. Atmos. Environ. **1967**(21), 2333–2344 (1987). https://doi.org/10.1016/0004-6981(87)90369-6

Lamkaddam, H.: Study under simulated condition of the secondary organic aerosol from the photooxydation of n-dodecane: impact of the physical-chemical processes. Université Paris-Est (2017)

Laskin, A., Laskin, J., Nizkorodov, S.A.: Chemistry of atmospheric brown carbon. Chem. Rev. **115**, 4335–4382 (2015). https://doi.org/10.1021/cr5006167

Lazrus, A.L., Kok, G.L., Lind, J.A., Gitlin, S.N., Heikes, B.G., Shetter, R.E.: Automated fluorometric method for hydrogen peroxide in air. Anal. Chem. **58**, 594–597 (1986). https://doi.org/10.1021/ac00294a024

Lee, S., Jang, M., Kamens, R.M.: SOA formation from the photooxidation of α-pinene in the presence of freshly emitted diesel soot exhaust. Atmos. Environ. **38**, 2597–2605 (2004). https://doi.org/10.1016/j.atmosenv.2003.12.041

Lee, S.-B., Bae, G.-N., and Moon, K.-C.: Smog chamber measurements. In: Kim, Y.J., Platt, U., Gu, M.B., Iwahashi, H. (eds.) Atmospheric and Biological Environmental Monitoring, pp. 105–136. Springer Netherlands, Dordrecht (2009)

Leone, J.A., Flagan, R.C., Grosjean, D., Seinfeld, J.H.: An outdoor smog chamber and modeling study of toluene–NO_x photooxidation. Int. J. Chem. Kinet. **17**, 177–216 (1985). https://doi.org/10.1002/kin.550170206

Leskinen, A., Yli-Pirilä, P., Kuuspalo, K., Sippula, O., Jalava, P., Hirvonen, M.R., Jokiniemi, J., Virtanen, A., Komppula, M., Lehtinen, K.E.J.: Characterization and testing of a new environmental chamber. Atmos. Meas. Tech. **8**, 2267–2278 (2015). https://doi.org/10.5194/amt-8-2267-2015

Leu, M.T.: Rate constant for the reaction HO_2+NO→OH+NO_2. J. Chem. Phys. **70**, 1662–1666 (1979). https://doi.org/10.1063/1.437680

Leungsakul, S., Jaoui, M., Kamens, R.M.: Kinetic mechanism for predicting secondary organic aerosol formation from the reaction of d-limonene with ozone. Environ. Sci. Technol. **39**, 9583–9594 (2005). https://doi.org/10.1021/es0492687

Levy, H.: Normal atmosphere: large radical and formaldehyde concentrations predicted. Science **173**, 141–143 (1971). https://doi.org/10.1126/science.173.3992.141

Li, C., Ma, Z., Chen, J., Wang, X., Ye, X., Wang, L., Yang, X., Kan, H., Donaldson, D.J., Mellouki, A.: Evolution of biomass burning smoke particles in the dark. Atmos. Environ. **120**, 244–252 (2015). https://doi.org/10.1016/j.atmosenv.2015.09.003

Li, C., Hu, Y., Zhang, F., Chen, J., Ma, Z., Ye, X., Yang, X., Wang, L., Tang, X., Zhang, R., Mu, M., Wang, G., Kan, H., Wang, X., Mellouki, A.: Multi-pollutant emissions from the burning of major agricultural residues in China and the related health-economic effects. Atmos. Chem. Phys. **17**, 4957–4988 (2017). https://doi.org/10.5194/acp-17-4957-2017

Li, K., Lin, C., Geng, C., White, S., Chen, L., Bao, Z., Zhang, X., Zhao, Y., Han, L., Yang, W., Azzi, M.: Characterization of a new smog chamber for evaluating SAPRC gas-phase chemical mechanism. J. Environ. Sci. **95**, 14–22 (2020). https://doi.org/10.1016/j.jes.2020.03.028

Li, J., Li, H., Wang, X., Wang, W., Ge, M., Zhang, H., Zhang, X., Li, K., Chen, Y., Wu, Z., Chai, F., Meng, F., Mu, Y., Mellouki, A., Bi, F., Zhang, Y., Wu, L., Liu, Y.: A large-scale outdoor atmospheric simulation smog chamber for studying atmospheric photochemical processes: characterization and preliminary application. J. Environ. Sci. **102**, 185–197 (2021). https://doi.org/10.1016/j.jes.2020.09.015

Lim, Y.B., Ziemann, P.J.: Products and mechanism of secondary organic aerosol formation from reactions of n-alkanes with OH radicals in the presence of NO_x. Environ. Sci. Technol. **39**, 9229–9236 (2005). https://doi.org/10.1021/es051447g

Linke, C., Möhler, O., Veres, A., Mohácsi, A., Bozóki, Z., Szabó, G., Schnaiter, M.: Optical properties and mineralogical composition of different Saharan mineral dust samples: a laboratory study. Atmos. Chem. Phys. **6**, 3315–3323 (2006)

Liu, S., Shilling, J.E., Song, C., Hiranuma, N., Zaveri, R.A., Russell, L.M.: Hydrolysis of organonitrate functional groups in aerosol particles. Aerosol Sci. Technol. **46**, 1359–1369 (2012). https://doi.org/10.1080/02786826.2012.716175

Luo, H., Li, G., Chen, J., Wang, Y., An, T.: Reactor characterization and primary application of a state of art dual-reactor chamber in the investigation of atmospheric photochemical processes. J. Environ. Sci. **98**, 161–168 (2020). https://doi.org/10.1016/j.jes.2020.05.021

Martín-Reviejo, M., Wirtz, K.: Is benzene a precursor for secondary organic aerosol? Environ. Sci. Technol. **39**, 1045–1054 (2005). https://doi.org/10.1021/es049802a

Massabò, D., Caponi, L., Bove, M.C., Prati, P.: Brown carbon and thermal–optical analysis: a correction based on optical multi-wavelength apportionment of atmospheric aerosols. Atmos. Environ. **125**, 119–125 (2016). https://doi.org/10.1016/j.atmosenv.2015.11.011

Massabò, D., Danelli, S.G., Brotto, P., Comite, A., Costa, C., Di Cesare, A., Doussin, J.F., Ferraro, F., Formenti, P., Gatta, E., Negretti, L., Oliva, M., Parodi, F., Vezzulli, L., Prati, P.: ChAMBRe: a new atmospheric simulation chamber for aerosol modelling and bio-aerosol research. Atmos. Meas. Tech. **11**, 5885–5900 (2018). https://doi.org/10.5194/amt-11-5885-2018

Massoli, P., Kebabian, P.L., Onasch, T.B., Hills, F.B., Freedman, A.: Aerosol light extinction measurements by cavity attenuated phase shift (CAPS) spectroscopy: laboratory validation and field deployment of a compact aerosol particle extinction monitor. Aerosol Sci. Technol. **44**, 428–435 (2010). https://doi.org/10.1080/02786821003716599

McFiggans, G., Mentel, T.F., Wildt, J., Pullinen, I., Kang, S., Kleist, E., Schmitt, S., Springer, M., Tillmann, R., Wu, C., Zhao, D., Hallquist, M., Faxon, C., Le Breton, M., Hallquist, Å.M., Simpson, D., Bergström, R., Jenkin, M.E., Ehn, M., Thornton, J.A., Alfarra, M.R., Bannan, T.J., Percival, C.J., Priestley, M., Topping, D., Kiendler-Scharr, A.: Secondary organic aerosol reduced by mixture of atmospheric vapours. Nature **565**, 587–593 (2019). https://doi.org/10.1038/s41586-018-0871-y

McMurry, P.H., Grosjean, D.: Gas and aerosol wall losses in Teflon film smog chambers. Environ. Sci. Technol. **19**, 1176–1182 (1985)

McVay, R.C., Zhang, X., Aumont, B., Valorso, R., Camredon, M., La, Y.S., Wennberg, P.O., Seinfeld, J.H.: SOA formation from the photooxidation of α-pinene: systematic exploration of the simulation of chamber data. Atmos. Chem. Phys. **16**, 2785–2802 (2016). https://doi.org/10.5194/acp-16-2785-2016

Mentel, T., Bleilebens, D., Wahner, A.: A study of nighttime nitrogen oxide oxidation in a large reaction chamber-the fate of NO_2, N_2O_5, HNO_3 and O_3 at different humidities. Atmos. Environ. **30**, 4007–4020 (1996)

Mentel, T.F., Kleist, E., Andres, S., Dal Maso, M., Hohaus, T., Kiendler-Scharr, A., Rudich, Y., Springer, M., Tillmann, R., Uerlings, R., Wahner, A., Wildt, J.: Secondary aerosol formation from stress-induced biogenic emissions and possible climate feedbacks. Atmos. Chem. Phys. **13**, 8755–8770 (2013). https://doi.org/10.5194/acp-13-8755-2013

Mertes, P., Praplan, A.P., Künzi, L., Dommen, J., Baltensperger, U., Geiser, M., Weingartner, E., Ricka, J., Fierz, M., Kalberer, M.: A compact and portable deposition chamber to study nanoparticles in air-exposed tissue. J. Aerosol Med. Pulm. Drug Deliv. **26**, 228–235 (2013). https://doi.org/10.1089/jamp.2012.0985

Metzger, A., Dommen, J., Gaeggeler, K., Duplissy, J., Prevot, A.S.H., Kleffmann, J., Elshorbany, Y., Wisthaler, A., Baltensperger, U.: Evaluation of 1,3,5 trimethylbenzene degradation in the detailed tropospheric chemistry mechanism, MCMv3.1, using environmental chamber data. Atmos. Chem. Phys. **8**, 6453–6468 (2008). https://doi.org/10.5194/acp-8-6453-2008

Meyer, N.K., Duplissy, J., Gysel, M., Metzger, A., Dommen, J., Weingartner, E., Alfarra, M.R., Prevot, A.S.H., Fletcher, C., Good, N., McFiggans, G., Jonsson, Å.M., Hallquist, M.,

Baltensperger, U., Ristovski, Z.D.: Analysis of the hygroscopic and volatile properties of ammonium sulphate seeded and unseeded SOA particles. Atmos. Chem. Phys. **9**, 721–732 (2009). https://doi.org/10.5194/acp-9-721-2009

Miller, D.F., Lamb, D., Gertler, A.W.: SO2 oxidation in cloud drops containing NaCl or sea salt as condensation nuclei. Atmos. Environ. **1967**(21), 991–993 (1987). https://doi.org/10.1016/0004-6981(87)90096-5

Mirme, A., Tamm, E., Mordas, G., Vana, M., Uin, J., Mirme, S., Bernotas, T., Laakso, L., Hirsikko, A., Kulmala, M.: A wide-range multi-channel air ion spectrometer. Boreal Env. Res. **12**, 247–264 (2007)

Mirme, S., Mirme, A.: The mathematical principles and design of the NAIS–a spectrometer for the measurement of cluster ion and nanometer aerosol size distributions. Atmos. Meas. Tech. **6**, 1061–1071 (2013). https://doi.org/10.5194/amt-6-1061-2013

Mogili, P.K., Kleiber, P.D., Young, M.A., Grassian, V.H.: Heterogeneous uptake of ozone on reactive components of mineral dust aerosol: an environmental aerosol reaction chamber study. J. Phys. Chem. A **110**, 13799–13807 (2006). https://doi.org/10.1021/jp063620g

Mogili, P.K., Yang, K.H., Young, M.A., Kleiber, P.D., Grassian, V.H.: Environmental aerosol chamber studies of extinction spectra of mineral dust aerosol components: broadband IR-UV extinction spectra. J. Geophys. Res. **112**(D21) (2007). https://doi.org/10.1029/2007JD008890

Möhler, O., Nink, A., Saathoff, H., Schaefers, S., Schnaiter, M., Schöck, W., Schurath, U.: The Karlsruhe aerosol chamber facility AIDA: technical description and first results of homogeneous and heterogeneous ice nucleation experiments, pp. 163–168 (2001)

Möhler, O., Stetzer, O., Schaefers, S., Linke, C., Schnaiter, M., Tiede, R., Saathoff, H., Krämer, M., Mangold, A., Budz, P., Zink, P., Schreiner, J., Mauersberger, K., Haag, W., Kärcher, B., Schurath, U.: Experimental investigation of homogeneous freezing of sulphuric acid particles in the aerosol chamber AIDA. Atmos. Chem. Phys. **3**, 211–223 (2003). https://doi.org/10.5194/acp-3-211-2003

Möhler, O., Field, P.R., Connolly, P., Benz, S., Saathoff, H., Schnaiter, M., Wagner, R., Cotton, R., Krämer, M., Mangold, A., Heymsfield, A.J.: Efficiency of the deposition mode ice nucleation on mineral dust particles. Atmos. Chem. Phys. **6**, 3007–3021 (2006). https://doi.org/10.5194/acp-6-3007-2006

Möhler, O., Benz, S., Saathoff, H., Schnaiter, M., Wagner, R., Schneider, J., Walter, S., Ebert, V., Wagner, S.: The effect of organic coating on the heterogeneous ice nucleation efficiency of mineral dust aerosols. Environ. Res. Lett. **3**, 025007 (2008a). https://doi.org/10.1088/1748-9326/3/2/025007

Möhler, O., Georgakopoulos, D.G., Morris, C.E., Benz, S., Ebert, V., Hunsmann, S., Saathoff, H., Schnaiter, M., Wagner, R.: Heterogeneous ice nucleation activity of bacteria: new laboratory experiments at simulated cloud conditions. Biogeosciences **5**, 1425–1435 (2008b). https://doi.org/10.5194/bg-5-1425-2008

Möhler, O., Adams, M., Lacher, L., Vogel, F., Nadolny, J., Ullrich, R., Boffo, C., Pfeuffer, T., Hobl, A., Weiß, M., Vepuri, H.S.K., Hiranuma, N., Murray, B.J.: The Portable Ice Nucleation Experiment (PINE): a new online instrument for laboratory studies and automated long-term field observations of ice-nucleating particles. Atmos. Meas. Tech. **14**, 1143–1166 (2021). https://doi.org/10.5194/amt-14-1143-2021

Mohr, C., Huffman, J.A., Cubison, M.J., Aiken, A.C., Docherty, K.S., Kimmel, J.R., Ulbrich, I.M., Hannigan, M., Jimenez, J.L.: Characterization of primary organic aerosol emissions from meat cooking, trash burning, and motor vehicles with high-resolution aerosol mass spectrometry and comparison with ambient and chamber observations. Environ. Sci. Technol. **43**, 2443–2449 (2009). https://doi.org/10.1021/es8011518

Munoz, A., Ródenas, M., Borras, E., Brenan, A., Dellen, J., Escalante, J.M., Gratien, A., Gomez, T., Herrmann, H., Kari, E., Michoud, V., Mutzel, A., Olariu, R., Seakins, P., Tillmann, R., Vera, T., Virtanen, A.: Intercomparison of instruments to measure OVOCs: assessment of performance under different relevant controlled conditions (EUPHORE chambers), EGU General Assembly 2019, Vienna, Austria (2019)

Ng, N.L., Canagaratna, M.R., Jimenez, J.L., Chhabra, P.S., Seinfeld, J.H., Worsnop, D.R.: Changes in organic aerosol composition with aging inferred from aerosol mass spectra. Atmos. Chem. Phys. **11**, 6465–6474 (2011a). https://doi.org/10.5194/acp-11-6465-2011

Ng, N.L., Herndon, S.C., Trimborn, A., Canagaratna, M.R., Croteau, P.L., Onasch, T.B., Sueper, D., Worsnop, D.R., Zhang, Q., Sun, Y.L., Jayne, J.T.: An aerosol chemical speciation monitor (ACSM) for routine monitoring of the composition and mass concentrations of ambient aerosol. Aerosol Sci. Technol. **45**, 780–794 (2011b). https://doi.org/10.1080/02786826.2011.560211

Nguyen, T.B., Roach, P.J., Laskin, J., Laskin, A., Nizkorodov, S.A.: Effect of humidity on the composition of isoprene photooxidation secondary organic aerosol. Atmos. Chem. Phys. **11**, 6931–6944 (2011). https://doi.org/10.5194/acp-11-6931-2011

Niedermeier, D., Hartmann, S., Clauss, T., Wex, H., Kiselev, A., Sullivan, R.C., DeMott, P.J., Petters, M.D., Reitz, P., Schneider, J., Mikhailov, E., Sierau, B., Stetzer, O., Reimann, B., Bundke, U., Shaw, R.A., Buchholz, A., Mentel, T.F., Stratmann, F.: Experimental study of the role of physicochemical surface processing on the IN ability of mineral dust particles. Atmos. Chem. Phys. **11**, 11131–11144 (2011). https://doi.org/10.5194/acp-11-11131-2011

Niedermeier, D., Augustin-Bauditz, S., Hartmann, S., Wex, H., Ignatius, K., Stratmann, F.: Can we define an asymptotic value for the ice active surface site density for heterogeneous ice nucleation? J. Geophys. Res. Atmos. **120**, 5036–5046 (2015). https://doi.org/10.1002/2014JD022814

Niki, H., Daby, E.E., Weinstock, B.: Mechanisms of smog reactions. In: Photochemical Smog and Ozone Reactions, Advances in Chemistry, vol. 113, pp. 16–57. American Chemical Society (1972)

Niki, H., Maker, P., Savage, C., Breitenbach, L.: An FTIR study of mechanisms for the HO radical initiated oxidation of C2H4 in the presence of NO: detection of glycolaldehyde. Chem. Phys. Lett. **80**, 499–503 (1981)

Nizkorodov, S.A., Laskin, J., Laskin, A.: Molecular chemistry of organic aerosols through the application of high resolution mass spectrometry. Phys. Chem. Chem. Phys. **13**, 3612–3629 (2011). https://doi.org/10.1039/c0cp02032j

Nordin, E.Z., Uski, O., Nyström, R., Jalava, P., Eriksson, A.C., Genberg, J., Roldin, P., Bergvall, C., Westerholm, R., Jokiniemi, J., Pagels, J.H., Boman, C., Hirvonen, M.-R.: Influence of ozone initiated processing on the toxicity of aerosol particles from small scale wood combustion. Atmos. Environ. **102**, 282–289 (2015). https://doi.org/10.1016/j.atmosenv.2014.11.068

Novelli, A., Vereecken, L., Bohn, B., Dorn, H.P., Gkatzelis, G.I., Hofzumahaus, A., Holland, F., Reimer, D., Rohrer, F., Rosanka, S., Taraborrelli, D., Tillmann, R., Wegener, R., Yu, Z., Kiendler-Scharr, A., Wahner, A., Fuchs, H.: Importance of isomerization reactions for OH radical regeneration from the photo-oxidation of isoprene investigated in the atmospheric simulation chamber SAPHIR. Atmos. Chem. Phys. **20**, 3333–3355 (2020). https://doi.org/10.5194/acp-20-3333-2020

Nozière, B., Hanson, D.R.: Speciated monitoring of gas-phase organic peroxy radicals by chemical ionization mass spectrometry: cross-reactions between CH3O2, CH3(CO)O2, (CH3)3CO2, and c-C6H11O2. J. Phys. Chem. A **121**, 8453–8464 (2017). https://doi.org/10.1021/acs.jpca.7b06456

Odum, J.R., Hoffmann, T., Bowman, F., Collins, D., Flagan, R.C., Seinfeld, J.H.: Gas/particle partitioning and secondary organic aerosol yields. Environ. Sci. Technol. **30**, 2580–2585 (1996)

Onel, L., Brennan, A., Seakins, P.W., Whalley, L., Heard, D.E.: A new method for atmospheric detection of the CH3O2 radical. Atmos. Meas. Tech. **10**, 3985–4000 (2017). https://doi.org/10.5194/amt-10-3985-2017

Onel, L., Brennan, A., Gianella, M., Hooper, J., Ng, N., Hancock, G., Whalley, L., Seakins, P.W., Ritchie, G.A.D., Heard, D.E.: An intercomparison of CH3O2 measurements by fluorescence assay by gas expansion and cavity ring-down spectroscopy within HIRAC (Highly Instrumented Reactor for Atmospheric Chemistry). Atmos. Meas. Tech. **13**, 2441–2456 (2020). https://doi.org/10.5194/amt-13-2441-2020

Pandis, S.N., Paulson, S.E., Seinfeld, J.H., Flagan, R.C.: Aerosol formation in the photooxidation of isoprene and β-pinene. Atmos. Environ. Part A Gen. Top. **25**, 997–1008 (1991). https://doi.org/10.1016/0960-1686(91)90141-S

Pankow, J.F.: An absorption model of the gas/aerosol partitioning involved in the formation of secondary organic aerosol. Atmos. Environ. **28**, 189–193 (1994)

Parikh, H., Jeffries, H., Sexton, K., Luecken, D., Kamens, R., Vizuete, W.: Evaluation of aromatic oxidation reactions in seven chemical mechanisms with an outdoor chamber. Environ. Chem. **10**, 245 (2013). https://doi.org/10.1071/en13039

Parrish, D.D., Fehsenfeld, F.C.: Methods for gas-phase measurements of ozone, ozone precursors and aerosol precursors. Atmos. Environ. **34**, 1921–1957 (2000). https://doi.org/10.1016/S1352-2310(99)00454-9

Pathak, R.K., Presto, A.A., Lane, T.E., Stanier, C.O., Donahue, N.M., Pandis, S.N.: Ozonolysis of-pinene: parameterization of secondary organic aerosol mass fraction. Atmos. Chem. Phys. **7**, 3811–3821 (2007)

Paulsen, D., Dommen, J., Kalberer, M., Prévôt, A.S.H., Richter, R., Sax, M., Steinbacher, M., Weingartner, E., Baltensperger, U.: Secondary organic aerosol formation by irradiation of 1,3,5-trimethylbenzene−NO_x−H_2O in a new reaction chamber for atmospheric chemistry and physics. Environ. Sci. Technol. **39**, 2668–2678 (2005). https://doi.org/10.1021/es0489137

Peeters, J., Müller, J.-F., Stavrakou, T., Nguyen, V.S.: Hydroxyl radical recycling in isoprene oxidation driven by hydrogen bonding and hydrogen tunneling: the upgraded LIM1 mechanism. J. Phys. Chem. A **118**, 8625–8643 (2014). https://doi.org/10.1021/jp5033146

Pereira, K.L., Hamilton, J.F., Rickard, A.R., Bloss, W.J., Alam, M.S., Camredon, M., Ward, M.W., Wyche, K.P., Muñoz, A., Vera, T., Vázquez, M., Borrás, E., Ródenas, M.: Insights into the formation and evolution of individual compounds in the particulate phase during aromatic photo-oxidation. Environ. Sci. Technol. **49**, 13168–13178 (2015). https://doi.org/10.1021/acs.est.5b03377

Pereira, K.L., Dunmore, R., Whitehead, J., Alfarra, M.R., Allan, J.D., Alam, M.S., Harrison, R.M., McFiggans, G., Hamilton, J.F.: Technical note: use of an atmospheric simulation chamber to investigate the effect of different engine conditions on unregulated VOC-IVOC diesel exhaust emissions. Atmos. Chem. Phys. **18**, 11073–11096 (2018). https://doi.org/10.5194/acp-18-11073-2018

Person, A., Eyglunent, G., Daële, V., Mellouki, A., Mu, Y.: The near UV absorption cross-sections and the rate coefficients for the ozonolysis of a series of styrene-like compounds. J. Photochem. Photobiol. A Chem. **195**, 54–63 (2008)

Pfeifer, S., Müller, T., Weinhold, K., Zikova, N., Martins dos Santos, S., Marinoni, A., Bischof, O.F., Kykal, C., Ries, L., Meinhardt, F., Aalto, P., Mihalopoulos, N., Wiedensohler, A.: Intercomparison of 15 aerodynamic particle size spectrometers (APS 3321): uncertainties in particle sizing and number size distribution. Atmos. Meas. Tech. **9**, 1545–1551 (2016). https://doi.org/10.5194/amt-9-1545-2016

Picquet-Varrault, B., Doussin, J.F., Durand-Jolibois, R., Carlier, P.: FTIR spectroscopic study of the OH-induced oxidation of two linear acetates: ethyl and n-propyl acetates. Phys. Chem. Chem. Phys. **3**, 2595–2606 (2001)

Pitts, J.N.: Formation and fate of gaseous and particulate mutagens and carcinogens in real and simulated atmospheres. Environ. Health Perspect. **47**, 115–140 (1983)

Platt, S.M., El Haddad, I., Zardini, A.A., Clairotte, M., Astorga, C., Wolf, R., Slowik, J.G., Temime-Roussel, B., Marchand, N., Ježek, I., Drinovec, L., Močnik, G., Möhler, O., Richter, R., Barmet, P., Bianchi, F., Baltensperger, U., Prévôt, A.S.H.: Secondary organic aerosol formation from gasoline vehicle emissions in a new mobile environmental reaction chamber. Atmos. Chem. Phys. **13**, 9141–9158 (2013). https://doi.org/10.5194/acp-13-9141-2013

Platt, S.M., El Haddad, I., Pieber, S.M., Zardini, A.A., Suarez-Bertoa, R., Clairotte, M., Daellenbach, K.R., Huang, R.J., Slowik, J.G., Hellebust, S., Temime-Roussel, B., Marchand, N., de Gouw, J., Jimenez, J.L., Hayes, P.L., Robinson, A.L., Baltensperger, U., Astorga, C., Prévôt, A.S.H.: Gasoline cars produce more carbonaceous particulate matter than modern filter-equipped diesel cars. Sci. Rep. **7**, 4926 (2017). https://doi.org/10.1038/s41598-017-03714-9

Pratap, V., Bian, Q., Kiran, S.A., Hopke, P.K., Pierce, J.R., Nakao, S.: Investigation of levoglucosan decay in wood smoke smog-chamber experiments: the importance of aerosol loading, temperature, and vapor wall losses in interpreting results. Atmos. Environ. **199**, 224–232 (2019). https://doi.org/10.1016/j.atmosenv.2018.11.020

Pun, B.K., Wu, S.Y., Seigneur, C., Seinfeld, J.H., Griffin, R.J., Pandis, S.: Uncertainties in modelling secondary organic aerosols: three-dimensional modeling studies in Nashville/Western Tennessee. Environ. Sci. Technol. **37**, 3647–3661 (2003)

Qi, X., Zhu, S., Zhu, C., Hu, J., Lou, S., Xu, L., Dong, J., Cheng, P.: Smog chamber study of the effects of NO_x and NH_3 on the formation of secondary organic aerosols and optical properties from photo-oxidation of toluene. Sci. Total Environ. **727**, 138632 (2020). https://doi.org/10.1016/j.scitotenv.2020.138632

Ren, Y., Grosselin, B., Daële, V., Mellouki, A.: Investigation of the reaction of ozone with isoprene, methacrolein and methyl vinyl ketone using the HELIOS chamber. Faraday Discuss. **200**, 289–311 (2017). https://doi.org/10.1039/c7fd00014f

Ridley, B.A., Grahek, F.E., Walega, J.G.: A small high-sensitivity, medium-response ozone detector suitable for measurements from light aircraft. J. Atmos. Oceanic Tech. **9**, 142–148 (1992). https://doi.org/10.1175/1520-0426(1992)009%3c0142:ashsmr%3e2.0.co;2

Roberts, G.C., Nenes, A.: A continuous-flow streamwise thermal-gradient CCN chamber for atmospheric measurements. Aerosol Sci. Technol. **39**, 206–221 (2005). https://doi.org/10.1080/027868290913988

Ródenas, M., Muñoz, A., Alacreu, F., Brauers, T., Dorn, H.-P., Kleffmann, J., Bloss, W.: Assessment of HONO measurements: The FIONA campaign at EUPHORE, pp. 45–58 (2013)

Rohrer, F., Bohn, B., Brauers, T., Brüning, D., Johnen, F.J., Wahner, A., Kleffmann, J.: Characterisation of the photolytic HONO-source in the atmosphere simulation chamber SAPHIR. Atmos. Chem. Phys. **5**, (2005a). https://doi.org/10.5194/acp-5-2189-2005

Rohrer, F., Bohn, B., Brauers, T., Brüning, D., Johnen, F.J., Wahner, A., Kleffmann, J.: Characterisation of the photolytic HONO-source in the atmosphere simulation chamber SAPHIR. Atmos. Chem. Phys. **5**, 2189–2201 (2005b). https://doi.org/10.5194/acp-5-2189-2005

Rossignol, S., Chiappini, L., Perraudin, E., Rio, C., Fable, S., Valorso, R., Doussin, J.F.: Development of parallel sampling and analysis for the elucidation of gas/particle partitioning of oxygenated semi-volatile organics: a limonene ozonolysis study. Atmos. Meas. Techn. Discuss. **5**, 1153–1231 (2012a)

Rossignol, S., Chiappini, L., Perraudin, E., Rio, C., Fable, S., Valorso, R., Doussin, J.F.: Development of a parallel sampling and analysis method for the elucidation of gas/particle partitioning of oxygenated semi-volatile organics: a limonene ozonolysis study. Atmos. Meas. Tech. **5**, 1459–1489 (2012b). https://doi.org/10.5194/amt-5-1459-2012

Ryerson, T.B., Williams, E.J., Fehsenfeld, F.C.: An efficient photolysis system for fast-response NO_2 measurements. J. Geophys. Res. Atmos. **105**, 26447–26461 (2000). https://doi.org/10.1029/2000JD900389

Sang, X.F., Gensch, I., Kammer, B., Khan, A., Kleist, E., Laumer, W., Schlag, P., Schmitt, S.H., Wildt, J., Zhao, R., Mungall, E.L., Abbatt, J.P.D., Kiendler-Scharr, A.: Chemical stability of levoglucosan: an isotopic perspective. Geophys. Res. Lett. **43**, 5419–5424 (2016). https://doi.org/10.1002/2016GL069179

Saunders, S.M., Jenkin, M.E., Derwent, R.G., Pilling, M.J.: Protocol for the development of the master chemical mechanism, MCM v3 (Part A): tropospheric degradation of non-aromatic volatile organic compounds. Atmos. Chem. Phys. **3**, 161–180 (2003). https://doi.org/10.5194/acp-3-161-2003

Savi, M., Kalberer, M., Lang, D., Ryser, M., Fierz, M., Gaschen, A., Rička, J., Geiser, M.: A novel exposure system for the efficient and controlled deposition of aerosol particles onto cell cultures. Environ. Sci. Technol. **42**, 5667–5674 (2008). https://doi.org/10.1021/es703075q

Schlosser, E., Bohn, B., Brauers, T., Dorn, H.-P., Fuchs, H., Häseler, R., Hofzumahaus, A., Holland, F., Rohrer, F., Rupp, L.O., Siese, M., Tillmann, R., Wahner, A.: Intercomparison of two hydroxyl radical measurement techniques at the atmosphere simulation chamber SAPHIR. J. Atmos. Chem. **56**, 187–205 (2007). https://doi.org/10.1007/s10874-006-9049-3

Schlosser, E., Brauers, T., Dorn, H.-P., Fuchs, H., Häseler, R., Hofzumahaus, A., Holland, F., Wahner, A., Kanaya, Y., Kajii, Y., Miyamoto, K., Nishida, S., Watanabe, K., Yoshino, A., Kubistin, D., Martinez, M., Rudolf, M., Harder, H., Berresheim, H., Elste, T., Plass-Dülmer, C., Stange, G.,

Schurath, U.: Formal blind intercomparison of OH measurements: results from the international campaign HOxComp. Atmos. Chem. Phys. **9**, 7923–7948 (2009). https://doi.org/10.5194/acp-9-7923-2009

Schnaiter, M., Järvinen, E., Vochezer, P., Abdelmonem, A., Wagner, R., Jourdan, O., Mioche, G., Shcherbakov, V.N., Schmitt, C.G., Tricoli, U., Ulanowski, Z., Heymsfield, A.J.: Cloud chamber experiments on the origin of ice crystal complexity in cirrus clouds. Atmos. Chem. Phys. **16**, 5091–5110 (2016). https://doi.org/10.5194/acp-16-5091-2016

Schwartz, R.E., Russell, L.M., Sjostedt, S.J., Vlasenko, A., Slowik, J.G., Abbatt, J.P.D., Macdonald, A.M., Li, S.M., Liggio, J., Toom-Sauntry, D., Leaitch, W.R.: Biogenic oxidized organic functional groups in aerosol particles from a mountain forest site and their similarities to laboratory chamber products. Atmos. Chem. Phys. **10**, 5075–5088 (2010). https://doi.org/10.5194/acp-10-5075-2010

Seakins, P.W.: A brief review of the use of environmental chambers for gas phase studies of kinetics, chemical mechanisms and characterisation of field instruments. In: Boutron, C. (ed.) Erca 9: From the Global Mercury Cycle to the Discoveries of Kuiper Belt Objects. EPJ Web of Conferences, E D P Sciences, Cedex A, pp. 143–163 (2010).

Smith, D.M., Fiddler, M.N., Sexton, K.G., Bililign, S.: Construction and characterization of an indoor smog chamber for measuring the optical and physicochemical properties of aging biomass burning aerosols. Aerosol Air Qual. Res. **19**, 467–483 (2019). https://doi.org/10.4209/aaqr.2018.06.0243

Spicer, C.W.: Smog chamber studies of nitrogen oxide (NO_x) transformation rate and nitrate precursor relationships. Environ. Sci. Technol. **17**, 112–120 (1983). https://doi.org/10.1021/es00108a010

Stedman, D.H.M., Morris, E.D., Jr., Daby, E.E., Niki, H., Weinstock, B.: The role of OH radicals in photochemical smog reactions. In: 160th National Meeting of the American Chemical Society, Chicago, Illinois (1970)

Stehle, R.L., Gertler, A.W., Katz, U., Lamb, D., Miller, D.F.: Cloud chamber studies of dark transformations of sulfur dioxide in cloud droplets. Atmos. Environ. **1967**(15), 2341–2352 (1981). https://doi.org/10.1016/0004-6981(81)90264-X

Stephens, E.R.: Long-path infrared spectrocopy for air pollution research. Appl. Spectrosc. **12**, 80–84 (1958)

Stockwell, W.R., Saunders, E., Goliff, W.S., Fitzgerald, R.M.: A perspective on the development of gas-phase chemical mechanisms for Eulerian air quality models. J. Air Waste Manag. Assoc. **70**, 44–70 (2020). https://doi.org/10.1080/10962247.2019.1694605

Stolzenburg, M.R., McMurry, P.H.: An ultrafine aerosol condensation nucleus counter. Aerosol Sci. Technol. **14**, 48–65 (1991). https://doi.org/10.1080/02786829108959470

Stolzenburg, D., Steiner, G., Winkler, P.M.: A DMA-train for precision measurement of sub-10 nm aerosol dynamics. Atmos. Meas. Tech. **10**, 1639–1651 (2017). https://doi.org/10.5194/amt-10-1639-2017

Storelvmo, T., Tan, I.: The Wegener-Bergeron-Findeisen process-its discovery and vital importance for weather and climate. Meteorol. Z. **24**, 455–461 (2015). https://doi.org/10.1127/metz/2015/0626

Taipale, R., Ruuskanen, T.M., Rinne, J., Kajos, M.K., Hakola, H., Pohja, T., Kulmala, M.: Technical note: quantitative long-term measurements of VOC concentrations by PTR-MS–measurement, calibration, and volume mixing ratio calculation methods. Atmos. Chem. Phys. **8**, 6681–6698 (2008). https://doi.org/10.5194/acp-8-6681-2008

Takekawa, H., Minoura, H., Yamazaki, S.: Temperature dependence of secondary organic aerosol formation by photo-oxidation of hydrocarbons. Atmos. Environ. **37**, 3413–3424 (2003)

Thalman, R., Baeza-Romero, M.T., Ball, S.M., Borrás, E., Daniels, M.J.S., Goodall, I.C.A., Henry, S.B., Karl, T., Keutsch, F.N., Kim, S., Mak, J., Monks, P.S., Muñoz, A., Orlando, J., Peppe, S., Rickard, A.R., Ródenas, M., Sánchez, P., Seco, R., Su, L., Tyndall, G., Vázquez, M., Vera, T., Waxman, E., Volkamer, R.: Instrument intercomparison of glyoxal, methyl glyoxal and NO_2 under simulated atmospheric conditions. Atmos. Meas. Tech. **8**, 1835–1862 (2015). https://doi.org/10.5194/amt-8-1835-2015

Thomas, M., France, J., Crabeck, O., Hall, B., Hof, V., Notz, D., Rampai, T., Riemenschneider, L., Tooth, O.J., Tranter, M., Kaiser, J.: The roland von glasow air-sea-ice chamber (RvG-ASIC): an

experimental facility for studying ocean–sea-ice–atmosphere interactions. Atmos. Meas. Tech. **14**, 1833–1849 (2021). https://doi.org/10.5194/amt-14-1833-2021

Thrush, B.A., Wilkinson, J.P.T.: The rate of reaction of HO2 radicals with HO and with NO. Chem. Phys. Lett. **81**, 1–3 (1981). https://doi.org/10.1016/0009-2614(81)85314-6

Tiitta, P., Leskinen, A., Hao, L., Yli-Pirilä, P., Kortelainen, M., Grigonyte, J., Tissari, J., Lamberg, H., Hartikainen, A., Kuuspalo, K., Kortelainen, A.M., Virtanen, A., Lehtinen, K.E.J., Komppula, M., Pieber, S., Prévôt, A.S.H., Onasch, T.B., Worsnop, D.R., Czech, H., Zimmermann, R., Jokiniemi, J., Sippula, O.: Transformation of logwood combustion emissions in a smog chamber: formation of secondary organic aerosol and changes in the primary organic aerosol upon daytime and nighttime aging. Atmos. Chem. Phys. **16**, 13251–13269 (2016). https://doi.org/10.5194/acp-16-13251-2016

Tobo, Y., DeMott, P.J., Raddatz, M., Niedermeier, D., Hartmann, S., Kreidenweis, S.M., Stratmann, F., Wex, H.: Impacts of chemical reactivity on ice nucleation of kaolinite particles: a case study of levoglucosan and sulfuric acid. Geophys. Res. Lett. **39** (2012). https://doi.org/10.1029/2012GL053007

Tortajada-Genaro, L.-A., Borrás, E.: Temperature effect of tapered element oscillating microbalance (TEOM) system measuring semi-volatile organic particulate matter. J. Environ. Monit. **13**, 1017–1026 (2011). https://doi.org/10.1039/c0em00451k

Vanhanen, J., Mikkilä, J., Lehtipalo, K., Sipilä, M., Manninen, H.E., Siivola, E., Petäjä, T., Kulmala, M.: Particle size magnifier for nano-CN detection. Aerosol Sci. Technol. **45**, 533–542 (2011). https://doi.org/10.1080/02786826.2010.547889

Varma, R., Venables, D., Ruth, A., Heitmann, U., Schlosser, E., Dixneuf, S.: Long optical cavities for open-path monitoring of atmospheric trace gases and aerosol extinction. Appl. Opt. **48**, B159-171 (2009). https://doi.org/10.1364/ao.48.00b159

Varma, R.M., Ball, S.M., Brauers, T., Dorn, H.P., Heitmann, U., Jones, R.L., Platt, U., Pöhler, D., Ruth, A.A., Shillings, A.J.L., Thieser, J., Wahner, A., Venables, D.S.: Light extinction by secondary organic aerosol: an intercomparison of three broadband cavity spectrometers. Atmos. Meas. Tech. **6**, 3115–3130 (2013). https://doi.org/10.5194/amt-6-3115-2013

Vlasenko, A., Sjogren, S., Weingartner, E., Stemmler, K., Gäggeler, H.W., Ammann, M.: Effect of humidity on nitric acid uptake to mineral dust aerosol particles. Atmos. Chem. Phys. **6**, 2147–2160 (2006). https://doi.org/10.5194/acp-6-2147-2006

Voigtländer, J., Duplissy, J., Rondo, L., Kürten, A., Stratmann, F.: Numerical simulations of mixing conditions and aerosol dynamics in the CERN CLOUD chamber. Atmos. Chem. Phys. **12**, 2205–2214 (2012). https://doi.org/10.5194/acp-12-2205-2012

Wagner, V., Jenkin, M.E., Saunders, S.M., Stanton, J., Wirtz, K., Pilling, M.J.: Modelling of the photooxidation of toluene: conceptual ideas for validating detailed mechanisms. Atmos. Chem. Phys. **3**, 89–106 (2003). https://doi.org/10.5194/acp-3-89-2003

Wagner, R., Bunz, H., Linke, C., Möhler, O., Naumann, K.-H., Saathoff, H., Schnaiter, M., Schurath, U.: Chamber Simulations of Cloud Chemistry: The AIDA Chamber, Environmental Simulation Chambers: Application to Atmospheric Chemical Processes, Dordrecht, pp. 67–82 (2006)

Wagner, R., Möhler, O., Saathoff, H., Schnaiter, M., Leisner, T.: New cloud chamber experiments on the heterogeneous ice nucleation ability of oxalic acid in the immersion mode. Atmos. Chem. Phys. **11**, 2083–2110 (2011). https://doi.org/10.5194/acp-11-2083-2011

Wagner, R., Ajtai, T., Kandler, K., Lieke, K., Linke, C., Müller, T., Schnaiter, M., Vragel, M.: Complex refractive indices of Saharan dust samples at visible and near UV wavelengths: a laboratory study. Atmos. Chem. Phys. **12**, 2491–2512 (2012). https://doi.org/10.5194/acp-12-2491-2012

Wahner, A., Mentel, T.F., Sohn, M., Stier, J.: Heterogeneous reaction of N2O5 on sodium nitrate aerosol. J. Geophys. Res. Atmos. **103**, 31103–31112 (1998). https://doi.org/10.1029/1998JD100022

Wahner, A.: SAPHIR: simulation of atmospheric photochemistry in a large reaction chamber: a novel instrument. American Chemical Society 2002, U306–U306.

Wang, S.C., Flagan, R.C.: Scanning electrical mobility spectrometer. Aerosol Sci. Technol. **13**, 230–240 (1990). https://doi.org/10.1080/02786829008959441

Wang, J., Doussin, J.F., Perrier, S., Perraudin, E., Katrib, Y., Pangui, E., Picquet-Varrault, B.: Design of a new multi-phase experimental simulation chamber for atmospheric photosmog, aerosol and cloud chemistry research. Atmos. Meas. Tech. **4**, 2465–2494 (2011). https://doi.org/10.5194/amt-4-2465-2011

Wang, X., Liu, T., Bernard, F., Ding, X., Wen, S., Zhang, Y., Zhang, Z., He, Q., Lü, S., Chen, J., Saunders, S., Yu, J.: Design and characterization of a smog chamber for studying gas-phase chemical mechanisms and aerosol formation. Atmos. Meas. Tech. **7**, 301–313 (2014). https://doi.org/10.5194/amt-7-301-2014

Weinstock, B.: Carbon monoxide: residence time in the atmosphere. Science **166**, 224–225 (1969). https://doi.org/10.1126/science.166.3902.224

Wex, H., Petters, M.D., Carrico, C.M., Hallbauer, E., Massling, A., McMeeking, G.R., Poulain, L., Wu, Z., Kreidenweis, S.M., Stratmann, F.: Towards closing the gap between hygroscopic growth and activation for secondary organic aerosol: Part 1–evidence from measurements. Atmos. Chem. Phys. **9**, 3987–3997 (2009). https://doi.org/10.5194/acp-9-3987-2009

Wex, H., DeMott, P.J., Tobo, Y., Hartmann, S., Rösch, M., Clauss, T., Tomsche, L., Niedermeier, D., Stratmann, F.: Kaolinite particles as ice nuclei: learning from the use of different kaolinite samples and different coatings. Atmos. Chem. Phys. **14**, 5529–5546 (2014). https://doi.org/10.5194/acp-14-5529-2014

Whalley, L.K., Stone, D., Dunmore, R., Hamilton, J., Hopkins, J.R., Lee, J.D., Lewis, A.C., Williams, P., Kleffmann, J., Laufs, S., Woodward-Massey, R., Heard, D.E.: Understanding in situ ozone production in the summertime through radical observations and modelling studies during the Clean air for London project (ClearfLo). Atmos. Chem. Phys. **18**, 2547–2571 (2018). https://doi.org/10.5194/acp-18-2547-2018

White, J.U.: Long optical paths of large aperture. J. Opt. Soc. Am. **32**, 285–288 (1942). https://doi.org/10.1364/josa.32.000285

White, J.U.: Very long optical paths in air. J. Opt. Soc. Am. **66**, 411–416 (1976). https://doi.org/10.1364/josa.66.000411

Wimmer, D., Lehtipalo, K., Franchin, A., Kangasluoma, J., Kreissl, F., Kürten, A., Kupc, A., Metzger, A., Mikkilä, J., Petäjä, T., Riccobono, F., Vanhanen, J., Kulmala, M., Curtius, J.: Performance of diethylene glycol-based particle counters in the sub-3 nm size range. Atmos. Meas. Tech. **6**, 1793–1804 (2013). https://doi.org/10.5194/amt-6-1793-2013

Winer, A.M., Graham, R.A., Doyle, J.G., Bekowies, P.J., Mac Affee, J.M., Pitts, J.N.: An evacuable environmental chamber and solar simulator facility for the study of atmospheric photochemistry. In: Pitts, J.N., Metcalf, R.L., Grosjean, D. (eds.) Advances in Environmental Science and Technology, pp. 461–511. Wiley, New-York (1980)

Wisthaler, A., Apel, E.C., Bossmeyer, J., Hansel, A., Junkermann, W., Koppmann, R., Meier, R., Müller, K., Solomon, S.J., Steinbrecher, R., Tillmann, R., Brauers, T.: Technical note: intercomparison of formaldehyde measurements at the atmosphere simulation chamber SAPHIR. Atmos. Chem. Phys. **8**, 2189–2200 (2008). https://doi.org/10.5194/acp-8-2189-2008

Wu, C.H., Japar, S.M., Niki, H.: Relative reactivities of ho-hydrocarbon reactions from smog reactor studies. J. Environ. Sci. Health Part A Environ. Sci. Eng. **11**, 191–200 (1976). https://doi.org/10.1080/10934527609385765

Wu, S., Lü, Z., Hao, J., Zhao, Z., Li, J., Takekawa, H., Minoura, H., Yasuda, A.: Construction and characterization of an atmospheric simulation smog chamber. Adv. Atmos. Sci. **24**, 250–258 (2007). https://doi.org/10.1007/s00376-007-0250-3

Wu, C., Pullinen, I., Andres, S., Carriero, G., Fares, S., Goldbach, H., Hacker, L., Kasal, T., Kiendler-Scharr, A., Kleist, E., Paoletti, E., Wahner, A., Wildt, J., Mentel, T.F.: Impacts of soil moisture on de novo monoterpene emissions from European beech, Holm Oal, Scots Pine, and Norway Spruce. Biogeosciences **12**, 177–191 (2015). https://doi.org/10.5194/bg-12-177-2015

Wyche, K.P., Ryan, A.C., Hewitt, C.N., Alfarra, M.R., McFiggans, G., Carr, T., Monks, P.S., Smallbone, K.L., Capes, G., Hamilton, J.F., Pugh, T.A.M., MacKenzie, A.R.: Emissions of biogenic

volatile organic compounds and subsequent photochemical production of secondary organic aerosol in mesocosm studies of temperate and tropical plant species. Atmos. Chem. Phys. **14**, 12781–12801 (2014). https://doi.org/10.5194/acp-14-12781-2014

Yli-Pirilä, P., Copolovici, L., Kännaste, A., Noe, S., Blande, J.D., Mikkonen, S., Klemola, T., Pulkkinen, J., Virtanen, A., Laaksonen, A., Joutsensaari, J., Niinemets, Ü., Holopainen, J.K.: Herbivory by an outbreaking moth increases emissions of biogenic volatiles and leads to enhanced secondary organic aerosol formation capacity. Environ. Sci. Technol. **50**, 11501–11510 (2016). https://doi.org/10.1021/acs.est.6b02800

Zádor, J., Turányi, T., Wirtz, K., Pilling, M.J.: Measurement and investigation of chamber radical sources in the European Photoreactor (EUPHORE). J. Atmos. Chem. **55**, 147–166 (2006). https://doi.org/10.1007/s10874-006-9033-y

Zhang, J., Huff Hartz, K.E., Pandis, S.N., Donahue, N.M.: Secondary organic aerosol formation from limonene ozonolysis: homogeneous and heterogeneous influences as a function of NO_x. J. Phys. Chem. A **110**, 11053–11063 (2006). https://doi.org/10.1021/jp062836f

Zhang, H., Hu, D., Chen, J., Ye, X., Wang, S.X., Hao, J.M., Wang, L., Zhang, R., An, Z.: Particle size distribution and polycyclic aromatic hydrocarbons emissions from agricultural crop residue burning. Environ. Sci. Technol. **45**, 5477–5482 (2011a). https://doi.org/10.1021/es1037904

Zhang, Q., Jimenez, J.L., Canagaratna, M.R., Ulbrich, I.M., Ng, N.L., Worsnop, D.R., Sun, Y.: Understanding atmospheric organic aerosols via factor analysis of aerosol mass spectrometry: a review. Anal. Bioanal. Chem. **401**, 3045–3067 (2011b). https://doi.org/10.1007/s00216-011-5355-y

Zhang, H., Worton, D.R., Lewandowski, M., Ortega, J., Rubitschun, C.L., Park, J.-H., Kristensen, K., Campuzano-Jost, P., Day, D.A., Jimenez, J.L., Jaoui, M., Offenberg, J.H., Kleindienst, T.E., Gilman, J., Kuster, W.C., de Gouw, J., Park, C., Schade, G.W., Frossard, A.A., Russell, L., Kaser, L., Jud, W., Hansel, A., Cappellin, L., Karl, T., Glasius, M., Guenther, A., Goldstein, A.H., Seinfeld, J.H., Gold, A., Kamens, R.M., Surratt, J.D.: Organosulfates as tracers for secondary organic aerosol (SOA) formation from 2-methyl-3-buten-2-ol (MBO) in the atmosphere. Environ. Sci. Technol. **46**, 9437–9446 (2012). https://doi.org/10.1021/es301648z

Zhang, Q., Xu, Y., Jia, L.: Secondary organic aerosol formation from OH-initiated oxidation of m-xylene: effects of relative humidity on yield and chemical composition. Atmos. Chem. Phys. **19**, 15007–15021 (2019). https://doi.org/10.5194/acp-19-15007-2019

Zhao, D.F., Buchholz, A., Mentel, T.F., Müller, K.P., Borchardt, J., Kiendler-Scharr, A., Spindler, C., Tillmann, R., Trimborn, A., Zhu, T., Wahner, A.: Novel method of generation of $Ca(HCO_3)_2$ and $CaCO_3$ aerosols and first determination of hygroscopic and cloud condensation nuclei activation properties. Atmos. Chem. Phys. **10**, 8601–8616 (2010). https://doi.org/10.5194/acp-10-8601-2010

Zhao, D.F., Buchholz, A., Tillmann, R., Kleist, E., Wu, C., Rubach, F., Kiendler-Scharr, A., Rudich, Y., Wildt, J., Mentel, T.F.: Environmental conditions regulate the impact of plants on cloud formation. Nat. Commun. **8**, 14067 (2017). https://doi.org/10.1038/ncomms14067

Zhao, D., Schmitt, S.H., Wang, M., Acir, I.H., Tillmann, R., Tan, Z., Novelli, A., Fuchs, H., Pullinen, I., Wegener, R., Rohrer, F., Wildt, J., Kiendler-Scharr, A., Wahner, A., Mentel, T.F.: Effects of NO_x and SO_2 on the secondary organic aerosol formation from photooxidation of α-pinene and limonene. Atmos. Chem. Phys. **18**, 1611–1628 (2018). https://doi.org/10.5194/acp-18-1611-2018

Zhou, L., Wang, W., Gai, Y., Ge, M.: Knudsen cell and smog chamber study of the heterogeneous uptake of sulfur dioxide on Chinese mineral dust. J. Environ. Sci. **26**, 2423–2433 (2014). https://doi.org/10.1016/j.jes.2014.04.005