



OUTDOOR AIR POLLUTION

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TO HUMANS

Table 1.4 Gaseous and particle air pollutants and their measurement methods

Observable	Measurement method	References
<i>Individual gases (Common gases can also be measured with instruments shown in the “Multiple gases” category below)</i>		
Carbon monoxide (CO)	Passive: • Chemical reagent impregnated on silica gel, based on colorimetric dosimeter or solid absorber such as Na-Y-zeolite (LZY-S²) using chemisorption or physisorption, followed by TD-GC-FID Continuous: • NDIR detector • Electrochemical sensor	McConnaughey et al. (1985) ; Lee et al. (1992) , Jantunen (1998) , Monn (2001) , Lodovici et al. (2003) , Orr (2003) , Abi Esber et al. (2007) , Bhoga & Singh (2007)
Nitrogen dioxide (NO ₂)	Passive (methods often applied to NO and NO _x): • Often use TEA- or sodium iodide-/sodium hydroxide-impregnated filter; also use passive colorimetric dosimeter with strip of impregnated paper Integrated: • Saltzman impinger or bubblers with colorimetric detection using a mixture of sulfanilic acid, N-(1-naphthyl)ethylenediamine dihydrochloride, and acetic acid • Sampling with front filter to remove particles, followed by TEA-impregnated cellulose-fibre filters for IC analysis of nitrite (NO₂⁻) as NO₂ Continuous (some absorbents can be used for NO and NO _x): • Chemiluminescence (catalytic reduction of NO₂ to NO; reaction of NO with O₃), including: (1) photolysis: photolytic converter to reduce NO₂ to NO, followed by chemiluminescence, and (2) luminol (5-amino-2,3-dihydro-1,4-phthalazinedione): reaction with NO₂, followed by chemiluminescence methods • Electrochemical sensor to detect NO₂ by an amperometric method • Photoacoustic spectroscopy • Long-path absorption photometer	Saltzman (1954) , Clyne et al. (1964) , Clough & Thrush (1967) , Ridley & Howlett (1974) , Palmes et al. (1976) , Ohtsuka et al. (1978) , Kley & McFarland (1980) , Maeda et al. (1980) , Kring et al. (1981) , Wendel et al. (1983) , Atkins et al. (1986) , Mulik et al. (1986) , Schiff et al. (1986) , Chang & Stetter (1990) , Kelly et al. (1990) , Parrish (1990) , Blatter et al. (1992) , Ferm & Sjodin (1993) , Willems (1993) , Spicer et al. (1994) , Pisano et al. (1996) , Gaffney et al. (1999) , Cohen et al. (2000) , Demerjian (2010) , Cox (2003) , Marley et al. (2004) , Bhoga & Singh (2007) , Dunlea et al. (2007) , Mitravanya et al. (2007) , Steinbacher et al. (2007) , Deshler et al. (2008) , EPA (2010) , Sluis et al. (2010) , Villena et al. (2011)
Nitrogen oxide/ nitrogen oxides (NO/NO _x)	See: Nitrogen dioxide (NO ₂)	
Sulfur dioxide (SO ₂)	Passive: • Huey sulfation plate: Petri dish with glass-fibre filter layered with lead peroxide; other absorbents include sodium tetrachloromercurate (Na₂HgCl₄), potassium carbonate (KCO₃), sodium bicarbonate (NaHCO₃) and sodium carbonate (Na₂CO₃), sodium hydroxide (NaOH), and TEA • Colorimetric dosimeter with strip of impregnated paper Integrated: • Gas-wash-bottle method using cellulose-fibre filters to remove particles (gas bottle containing an acidified peroxide solution, gas meter, restrictor, and pump), followed by IC analysis of sulfate as SO₂	Orr et al. (1967) , Huey (1968) , Reiszner & West (1973) , Kring et al. (1981) , Beghi et al. (1987) , Hallberg & Rudling (1989) , Mari et al. (1990) , Krochmal & Kalina (1997) , Ferm & Svanberg (1998) , Bogue (2008)

Table 1.4 (continued)

Observable	Measurement method	References
Sulfur dioxide (SO ₂) (cont.)	• Sampling with front filter to remove particles, followed by potassium carbonate (KCO₃)-impregnated cellulose-fibre filters for IC analysis of sulfate as SO₂ - Continuous: • UV fluorescence • Electrochemical sensor	
Hydrogen sulfide (H ₂ S)	Passive: • Colorimetric dosimeter with strip of impregnated paper Integrated: • Sampling with front filter to remove particles, followed by silver-nitrate-impregnated cellulose-fibre filters for XRF analysis of sulfur as H₂S Continuous: • UV fluorescence: catalytic oxidation to SO₂	Kring et al. (1981) , McConnaughey et al. (1985)
Ammonia (NH ₃)	Passive: • Impregnated boric acid (H₃BO₃), sodium potassium tartrate (KNaC₄H₄O₆·4H₂O), tartaric acid (2,3-dihydroxybutanedioic acid), sulfuric acid (H₂SO₄), ethylene glycol (C₂H₆O₂)/hydrochloric acid (HCl), or citric acid (C₆H₈O₇); Nessler's reagent (50 g of manganese iodide [MgI₂] and 35 g of potassium iodide [KI]) Integrated: • Sampling with front filter to remove particles, followed by citric-acid-impregnated cellulose-fibre filters for automated colorimetric analysis of ammonium as NH₃ Continuous: • Chemiluminescence: conversion to NO	Sigsby et al. (1973) , Benedict et al. (1983) , Tang et al. (2001)
Ozone (O ₃)	Passive: • Impregnated nitrite (NO₂⁻) or nitrate (NO₃⁻), followed by IC analysis; other absorbents include indigo, indigo carmine, or KI • Treated strips that react with O₃ and comparison with colour scale • KI-impregnated filter Integrated: • Sampling with front filter to remove particles, followed by KI-impregnated cellulose-fibre filters for automated colorimetric analysis of KOH Continuous: • Chemiluminescence • UV absorption (continuous long path or satellite)	Clyne et al. (1964) , Clough & Thrush (1967) , Werner (1989) , Kanno & Yanagisawa (1992) , Kleindienst et al. (1993) , Koutrakis et al. (1993) , Brauer & Brook (1995) , Grosjean et al. (1995) , Hangartner et al. (1996) , Lutter & Wolz (1997) , Cox et al. (1999) , Cox & Malcolm (1999) , Tang & Lau (2000) , Boss & Day (2001) , Bytnerowicz et al. (2002) , Carmichael et al. (2003)

Table 1.4 (continued)

Observable	Measurement method	References
Volatile organic compounds (VOCs and SVOCs), including carbonyls, organic acids, alcohols, PAHs, and pesticides (present in gas phase and/or particle phase)	Passive: - Activated charcoal, Tenax, or other thermally desorbed sorbent, followed by GC-MS; can be used to analyse HCs and chlorinated HCs - POPs: started with semipermeable membrane devices (SPMDs), now primarily using PUF disks or XAD-2 resin filled into stainless steel mesh cylinders; samples are extracted in organic solvent before chemical analyses; can be used for PCBs, PBDEs, and other POPs - Pesticides: PUF disk or XAD resin; applied to organochlorine, organophosphate, pyrethrin, triazine, and other PCBs - SVOCs: PUF disks or XAD resin, for PAHs and other organic compounds Integrated: - Canister, bag, or Carbotrap sampling for HCs including CH₄, C₂–C₃, and C₄–C₁₀, and Tenax for C₁₁–C₂₀ - Filter/PUF or filter/Tenax (US EPA method TO-13) for volatile PAHs - Filter impregnated with DNPH or cryogenic traps for carbonyls - HCHO: mostly with DNPH-coated substrate to form hydrazones, followed by HPLC analysis, or using a Palmes-type tube coated with sodium bisulfite (NaHSO₃); method also applied to acetaldehyde, propionaldehyde acetone aldehydes, amines, etc. - Quartz-fibre filters or base-coated filters for organic acids - Charcoal, canister, impinger with water, cryogenic trap, or condensation sampling for alcohols (C₁–C₄) - Filter/XAD or filter/Tenax (US EPA methods TO-4 and TO-10) for semivolatile pesticides Continuous: - HCs by auto GC-FID for CH₄, speciated C₂–C₇ (including 1,3-butadiene), NMHCs including isoprene, CH₃OH, (CH₃)₂CO, CH₃CHO, CO, aldehydes, ketones, alcohols, halocarbons, N₂O, PAN, and organic nitrates - Oxygenated HCs by automated GC-FID using selective column - PAN and its homologues (PANs) by CIMS - Carbonyls by electrochemical sensor - NMHCs and oxidized HCs by proton transfer reaction-MS (PTR-MS) - Organic acids by negative-ion CIMS - Organic peroxides by CIMS	NIOSH (1984), Andreae et al. (1987), Shields & Weschler (1987), EPA (1988, 1991), Levin et al. (1988), Cohen et al. (1990), Druzik et al. (1990), Pierotti (1990), Weschler et al. (1990), Zielinska et al. (1990), Zielinska & Fung (1992), Tang et al. (1993), Tanner (1993), Ockenden et al. (1998), Boss & Day (2001), Shoeib & Harner (2002), De Gouw et al. (2003), Rivett et al. (2003), Pozo et al. (2004), Slusher et al. (2004), Crounse et al. (2006), Hamilton et al. (2006), Heard (2006), Santiago & Cayetano (2007), Bohlin et al. (2008), Chaemfa et al. (2008), Gouin et al. (2008), Veres et al. (2008), Chaemfa et al. (2009), He & Balasubramanian (2010), Holzinger et al. (2010), Yatavelli & Thornton (2010), Gebicki et al. (2013)

Table 1.4 (continued)

Observable	Measurement method	References
<i>Multiple gases</i>		
	• Laser-induced fluorescence (LIF) for OH, NO, NO₂, NO₃⁻, N₂O, SO₂, CO, and HCHO • Differential optical absorption spectroscopy (DOAS) for NO, NO₂, HONO, NH₃, SO₂, CS₂, NMHCs, benzene, toluene, phenol, HCHO, ClO, BrO, I₂, etc. • Cavity ring-down spectroscopy (LAS) for CH₄, HCs, NO, NO₂, NO₃, N₂O₅, HONO, Hg, I₂, and O₂ • Tunable diode LAS including IR absorption (LAS) for CO, CO₂, CH₄, HCs, liquid water (H₂O), H₂O₂, NO, NO₂, nitric acid (HNO₃), N₂O, NH₃, halocarbons, HCHO, and O₃ • Integrated cavity output spectroscopy (ICOS; LAS) for NO, CO, and CH₄ • FTIR spectroscopy: a vibrational spectroscopy technique for molecular structure and functional groups like HONO₂ and HCHO • LIDAR or differential absorption LIDAR (DILA) for NMHCs, NO₂, and O₃ • CIMS for OH, HO₂, HONO, and HONO₂	Thornton et al. (2000), Matsumoto et al. (2001), Cleary et al. (2002), Day et al. (2002), Thornton et al. (2003) Alicke et al. (2002), Dunlea et al. (2007), Platt et al. (1980), Pundt et al. (2005) Evertsen et al. (2002), Mazurenka et al. (2003), Kebabian et al. (2005), Osthoff et al. (2006) Eng et al. (1980), Li et al. (2004) Behrentz et al. (2004), Clemmitshaw (2004), Larkin (2011) Clemmitshaw (2004) Huey et al. (1995), Edwards et al. (2003), Huey (2007)
<i>Particulate matter (PM) for mass and chemical components</i>		
Mass	Passive: • Dust sampler: collects particles electrostatically with a charged electret; requires knowledge of particle electrical mobility and electret charge • Dust monitor: uses light extinction to estimate index of mass concentration • UNC passive aerosol sampler: developed by the University of North Carolina, USA; based on deposition velocity model; collects particles on a stub by gravity, diffusion, and convective diffusion; followed by SEM or TEM and auto-image analyses to get PM concentration and particle size distribution; may exhibit errors when sampling volatile aerosols; used carbon substrate for SEM or TEM analyses or glass substrate for PM_{10-2.5} (coarse particles) by optical microscopy; uncertainties include assumption of particle density and shape factors, wind speed, turbulence, etc. Integrated: • Peaked-roof sampler for TSP without size-selective inlet for particles of 30–50 µm; integrated samplers for PM include inlet, sampling surfaces, substrates, flow controllers, and pump • PM₁₀: using a size-selective inlet with a 50% collection efficiency of 10 µm • PM_{2.5}: using a size-selective inlet with a 50% collection efficiency of 2.5 µm	Watson & Chow (1984), Brown & Hemingway (1995), Arashiro & Leith (2013), Brown et al. (1996), Vinzents (1996), Jayne et al. (2000), Wagner & Leith (2001a, b, c), DeCarlo et al. (2006), Leith et al. (2007)

Table 1.4 (continued)

Observable	Measurement method	References
Mass (cont.)	- Using filter sampler for TSP, PM₁₀, and PM_{2.5} samplers following Federal Reference Method used by US EPA for compliance monitoring. Filters are equilibrated in a temperature-controlled (20–23 °C) and relative humidity-controlled (30–40%) environment for a minimum of 48 hours before pre- and post-gravimetric analysis of filter substrate for mass - Continuous: - Measurement by beta attenuation monitor (BAM): based on beta attenuation - Filter dynamics measurement system (FDMS) and tapered element oscillating microbalance (TEOM): based on inertial microbalance - Particle light scattering by nephelometer, a surrogate for PM₁₀ or PM_{2.5} mass: particle scattering of visible light, relates scattered intensity to concentration (nephelometer; most often single-wavelength [$\lambda = 530$ nm] or 3-wavelength [e.g. $\lambda = 450, 5258$ (or 550), and 635 (or 700) nm]); DustTrak) - AMS for mass of particles with aerodynamic diameters < 1 μm (PM₁) - Optical particle counter: measures intensity of individual particle scattering, surrogate for PM mass	
Light absorption coefficient (b_{abs}); also called absorbance (abs), light absorption, or light transmission	Integrated: Sampling onto Teflon-membrane filters, usually after gravimetric analysis; densitometer measurement of filter light absorption/light transmission (2-wavelength [$\lambda = 370$ and 880 nm] transmissometer); or by reflectometer; used as a surrogate for BC	Butterfield et al. (2010) , Heal & Quincey (2012)
Elements	Integrated (preferably on thin-film Teflon-membrane filter): - XRF: measures ~50 elements from sodium to uranium, except beryllium - Particle-induced X-ray emission (PIXE); part of accelerator-based ion beam analysis (IBA) - Instrumental neutron activation analysis (INAA) - Inductively coupled plasma atomic emission spectroscopy (ICP-AES) or ICP-MS - Flame or graphite AAS (FAAS or GAAS) - Lead by high-volume sampling, followed by acid block or hot plate extraction and AAS analysis (US EPA method 40 CFR Part 50) - Lead by cold trap sampling, followed by analysis by GC-AAS Continuous: - Laser-induced breakdown spectroscopy (LIBS) - XRF filter tape (commercially available, used mostly by industry), measures a limited number of elements - Electron ionization high-resolution MS for elemental species: (C, H, N, S, and O) to determine organic-matter-to-OC ratios	EPA (1982, 2006) , Biegalski (1999) , Cohen (1999) , Grohse (1999) , Kasahara (1999) , Landsberger & Creatchman (1999) , Watson et al. (1999) , Lithgow et al. (2004)

Table 1.4 (continued)

Observable	Measurement method	References
Ions	Integrated (preferably on quartz-fibre filter): • IC for anions (e.g. F^-, Br^-, Cl^-, NO_2^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}) and cations (e.g. Na^+, Mg^{2+}, K^+, Ca^{2+}, and NH_4^+), can be used to measure ClO_3^-, ClO_2^-, and BrO_3^- • Ion-selective electrode, mainly for NH_4^+ • Automated colorimetry, mainly for NH_4^+; can be analysed for NO_3^- and SO_4^{2-}; often on chemically impregnated filters • AAS or GAAS for Na^+, Mg^{2+}, K^+, and Ca^{2+} Continuous (measures precursor gases as well as ions): • Field IC: grow particles with steam, then collect precursor gases and multiple ions (e.g. ambient ion monitor [AIM]; PILS; wet annular denuder/steam-jet aerosol collector [MARGA]; gas-particle IC [GPIC]; gas-collector IC; or flash volatilization for SO_4^{2-} and NO_3^- [R&P 8400S and 8400N, respectively; no longer commercialized]); and AMS	Mullin & Riley (1955), Weatherburn (1967), Mulik et al. (1976), Small (1978), Hoffer et al. (1979), Lodge (1989), Chow et al. (1999, 2005, 2008), Grohse (1999), Finlayson-Pitts & Pitts (2000), Jayne et al. (2000), Stolzenburg & Hering (2000), Al-Horr et al. (2003), Weber et al. (2003), Wittig et al. (2004), Trebs et al. (2005), ten Brink et al. (2007), Thomas et al. (2009), Yao et al. (2009), Schaap et al. (2011), Dong et al. (2012)
Carbon	Integrated (on quartz-fibre filter): • Thermal methods for OC and EC and their thermal fractions with NDIR detection of CO_2; Switzerland two-step method, Lawrence Berkeley Laboratory (LBL) method, Brookhaven National Laboratory (BNL) method, and General Motors (GM) method • Coulometric titration for CO_2 by VDI 2465/1, VDI 2465/2, and Centre National de la Recherche Scientifique-Commissariat à l'énergie atomique et aux énergies alternatives (CNRS-CEA) method • Thermal magnesium oxide (TMO) method • Thermal/optical methods for OC and EC; FID detection of CH_4; including thermal/optical reflectance (TOR) following the Interagency Monitoring of Protected Visual Environments (IMPROVE_A) protocol that has been applied in long-term non-urban (IMPROVE) and urban (Chemical Speciation Network; CSN) networks in the USA, National Institute for Occupational Safety and Health (NIOSH) thermal/optical transmittance (TOT) protocol, and European Supersites for Atmospheric Aerosol Research (EUSAAR-2) TOT protocol	Cadle et al. (1980), Geisling et al. (1982), Novakov (1982), Cadle et al. (1983), Ellis et al. (1984), Gaffney et al. (1984), Levin et al. (1985), Cachier et al. (1989a), Cachier et al. (1989b), Fung (1990), Chow et al. (1993, 2001, 2004, 2007a, 2011), Birch & Cary (1996a, b), NIOSH (1996), VDI (1996, 1999), Gilpin et al. (1997), Birch (1998), Lavanchy et al. (1999), Kirchstetter et al. (2001), Fung et al. (2002), Watson et al. (2005), Andreae & Gelencser (2006), Seethapathy et al. (2008), Yang et al. (2009), Cavalli et al. (2010), Chakrabarty et al. (2010)
Brown carbon	• Various origins at blue or near-UV wavelengths, commonly found in the smouldering phase of biomass burning (e.g. humic-like substances); see: Bioaerosols	

Table 1.4 (continued)

Observable	Measurement method	References
Water-soluble organic carbon (WSOC)	- Total organic carbon (TOC) analyser: speciated WSOC classes by HPLC-UV/VIS; IC-pulsed amperometric detection (IC-PAD) for carbohydrates; IC-conductivity detection (IC-CD) for organic acids - Continuous: - Semicontinuous real-time carbon aerosol analysis instrument for OC and EC by thermal/optical method - Electron ionization high-resolution MS for non-refractory fraction of OC - PILS for WSOC: combining PILS with total carbon (TC) analyser; can use XAD-8 resin as preceding denuder to separate hydrophobic and hydrophilic carbon fractions - British Smoke/coefficient of haze (COH) for BC: British Smoke quantifies filter darkness by reflectance as air is drawn through; called COH in the USA, light transmission measured based on optical density of filter deposit; reported as COH/1000 linear feet - Filter transmittance (e.g. aethalometer; $\lambda = 370\text{--}880$ nm for 2-wavelength, also $\lambda = 370\text{--}950$ nm for 7-wavelength); multi-angle absorption photometer (MAAP; $\lambda = 670$ nm) - Single-particle soot absorption photometer ($\lambda = 565$ nm, also $\lambda = 466, 520$, and 660 nm for 3-wavelength) by laser incandescence	Hill (1936) , Ingram & Golden (1973) , Thornes (1978) , Hansen et al. (1984) , Brimblecombe (1987) , Horvath (1993) , Jayne et al. (2000) , Weber et al. (2003) , Li et al. (2003, 2009) , Petzold & Schönlinner (2004) , Petzold et al. (2005) , DeCarlo et al. (2006) , Miyazaki et al. (2006) , Park et al. (2006) , Sullivan et al. (2006) , Sullivan & Weber (2006) , Peltier et al. (2007) , Slowik et al. (2007) , Chow et al. (2009) , Kreissberg et al. (2013) , Hansen & Mccnic (2010) , Lambe et al. (2010) , Müller et al. (2011)
Reactive oxygen species (ROS)	Aerosol oxidative activity: couples PILS with microfluidic electrochemical sensor; the oxidative activity is based on dithiothreitol (TDD) assay that assesses the capacity of PM to catalyse ROS generation	
Organic speciation	Integrated: - Using filter/PUF/XAD sampling system, followed by solvent extraction-GC (SE-GC) with FID, electron capture detector (ECD), photoionization detector, flame photometric detector (FPD), MS, or TOF-MS for both polar and non-polar organic compounds and volatile halocarbons, NMHCs, aromatics, and PAN; also speciated PAHs - Using an aliquot of filter, followed by direct injection with thermal extraction- or TD-GC-MS for non-polar alkanes, alkenes, cycloalkanes, hopanes, steranes, and PAHs - FTIR for molecular structure and functional groups - HPLC coupled with MS detection, or UV fluorescence: based on water or organic solvent extraction for polar organic compounds or macromolecules - LC with MS detection, or UV fluorescence: for organic fractions such as PAHs, peroxides, carbonyls, and derivatives of organic acids, polymers, and proteins Continuous: - TD aerosol GC/MS-FID (TAG); or auto GC-FID for speciated organic composition of non-polar and polar organic compounds - CIMS for non-polar and polar organic compounds	Vairavamurthy et al. (1992) ; Rogge et al. (1993) ; Burtcher & Siegmann (1994) , Schauer et al. (1996) , Glasius et al. (1999) , Schauer & Cass (2000) , Sin et al. (2001) , Graham et al. (2002) , Russell (2003) , Welthagen et al. (2003) , Ho & Yu (2004) , Ward & Smith (2004) , William et al. (2006) , Chow et al. (2007) , Hamilton & Lewis (2007) , Hays & Lavrich (2007) , Courty & Dillner (2008) , Winterhalter et al. (2009) , Holzinger et al. (2010) , Yatavelli & Thornton (2010)

Table 1.4 (continued)

Observable	Measurement method	References
PAHs	• Photoemission aerosol sensor (PAS); photoelectric charging of particles by irradiation with UV light for PAHs of four or more rings	
Bioaerosols	Integrated: • Culturable airborne bacteria and fungi: collected using AGI impingers and Andersen impactors, cultivated, and counted on a solid or in a liquid culture medium • Total airborne bacteria and fungi based on: (1) microscopy, including light microscopy (e.g. fluorescence microscopy), electron microscopy, and Raman microscopy; (2) flow cytometry that measures the number of fluorescent biological particles; and (3) qPCR that determines the quantity of DNA copies • Pollens: light microscopy that identifies and enumerates pollen grains collected via non-volumetric (e.g. Durham microscope slides, hanging slides, flags, passive impactor rods, and sticky cylinders) or volumetric (e.g. impactors, cyclones, whirling arm samplers, and Hirst-type samplers such as Burkard pollen and spore traps) sampling approaches • Viruses: qPCR that quantifies the viral DNA/RNA copies; or plaque assays that quantify viral concentrations by infecting living cells with viruses at different dilution ratios • Proteins using micro bicinchoninic acid (BCA) assay, or by nano-orange protein quantification kit • Endotoxins: based on LAL assays with activating factor C, including gel-clot LAL assay, end-point fluorescence assay, end-point chromogenic LAL assay, kinetic chromogenic LAL assay, and kinetic turbidimetric LAL assay; or by GC-MS that measures 3-hydroxyl fatty acids, a key component of endotoxin molecules • (1→3)-β-D-glucan: using inhibition enzyme immunoassay (EIA) or by LAL assays with activating factor G • Mannitol and arabinol: using GC-MS, GC-FID, or by anion-exchange HPLC with pulsed amperometric detection (HPAEC-PAD) • Ergosterol: using HPLC, or by GC-MS • Muramic acid: using GC-MS • Microbial community: based on denaturing gradient gel electrophoresis (DGGE); terminal restriction fragment length polymorphism (T-RFLP); microarrays; clone library sequencing; or pyrosequencing Continuous: • Concentration and size distribution: based on UV aerodynamic particle sizer (UV-APS) and waveband integrated bioaerosol sensor (WIBS) based on the autofluorescence of biomolecules such as nicotinamide adenine dinucleotide phosphate (NADPH) and riboflavin; or by bioaerosol MS that couples fluorescence-based bioaerosol detection with an AMS	Käpylä & Penttinen (1981), Mielniczuk et al. (1993), Douwes et al. (1995), Rantio-Lehtimäki (1995), Douwes et al. (1996), Fox et al. (1996), Terzieva et al. (1996), Hairston et al. (1997), Miller & Young (1997), Mullins & Emberlin (1997), Nielsen et al. (1997), Saraf et al. (1997), Rylander et al. (1999), Bünger et al. (2000), Pashynska et al. (2002), Shelton et al. (2002), Fang et al. (2005), Hogan et al. (2005), Kaye et al. (2005), Maron et al. (2005), An et al. (2006), Brodie et al. (2007), Caseiro et al. (2007), Menetrez et al. (2007), Bauer et al. (2008), Nehme et al. (2008), Vanhee et al. (2008), Chen & Hildemann (2009), Tripathi et al. (2009), Lee et al. (2010), Lindsley et al. (2010), Bowers et al. (2011)

Table 1.4 (continued)

Observable	Measurement method	References
<i>Particle number and size</i>		
Single particle and particle numbers	Integrated: • Sampling onto polycarbonate paper, followed by SEM • Sampling onto TEM grid, followed by TEM	Fruhstorfer & Niessner (1994) , Adachi et al. (2007) , Tumolva et al. (2010)
Particle size distribution	• Use cascade impactors such as micro-orifice uniform deposit impactor (MOUDI) or electrical low-pressure impactor (ELPI) for particle size distribution on filter substrates Continuous: • Condensation particle counter (CPC) • Scanning mobility particle sizer (SMPS), aerosol particle sizer, or optical particle counters for particle size distribution • AMS uses single particle laser ablation based on laser vaporization, laser-induced plasma, or multiphoton ionization • Aerosol TOF-MS	Watson & Chow (2013) Noble & Prather (1996) , McMurry (2000b) , Gebhart (2001) , DeCarlo et al. (2006) , Binnig et al. (2007) , Spencer et al. (2007) , Park et al. (2008) , Giechaskiel et al. (2009) , Grimm & Eatough (2009) , Takegawa et al. (2009) , Wang et al. (2009, 2010b) , Farmer & Jimenez (2010) , Giechaskiel & Bergmann (2011)
<i>Mercury</i>		
	Integrated: • Atmospheric mercury is present in three forms: GEM, largely present in the atmosphere; RGM; and reactive Hg-P; sampling train includes quartz-fibre filter for Hg-P, KCl-impregnated filter for RGM, and gold trap for GEM; samples are subjected to thermal mercury analysis: thermal extraction followed by gold amalgamation and cold vapour atomic fluorescence spectroscopy (CVAFS) Continuous: • Total mercury speciated by oxidation: measured by atomic fluorescence and UV photometry	Lin & Pehkonen (1999) , Rutter & Schauer (2007) , Witt et al. (2010)

AAS, atomic absorption spectroscopy; AMS, aerosol mass spectrometer; BC, black carbon; CH₄, methane; CIMS, chemical ionization mass spectrometry; CO, carbon monoxide; CO₂, carbon dioxide; DNPH, 2,4-dinitrophenylhydrazine; EC, elemental carbon; FID, flame ionization detector; FTIR, Fourier transform infrared; GAAS, graphite atomic absorption spectroscopy; GC, gas chromatography; GEM, gaseous elemental mercury; HCHO, formaldehyde; HCs, hydrocarbons; Hg-P, particulate mercury; HONO, nitrous acid; HPLC, high-performance liquid chromatography; IC, ion chromatography; IR, infrared; KI, potassium iodide; LAL, *Limulus* amoebocyte lysate; LAS, laser absorption spectroscopy; LC, liquid chromatography; LIDAR, light detection and ranging; MS, mass spectrometry; NDIR, non-dispersive infrared; NMHCs, non-methane hydrocarbons; NO, nitrogen oxide; NO₂, nitrogen dioxide; NO_x, nitrogen oxides; N₂O, nitrous oxide; O₃, ozone; OC, organic carbon; PAHs, polycyclic aromatic hydrocarbons; PAN, peroxyacetyl nitrate; PBDEs, polybrominated diphenyl ethers; PCBs, polychlorinated biphenyls; PILS, particle-into-liquid sampler; PM, particulate matter; PM₁₀, particulate matter with particles of aerodynamic diameter < 10 µm; PM_{2.5}, particulate matter with particles of aerodynamic diameter < 2.5 µm; POPs, persistent organic pollutants; PUF, polyurethane foam; qPCR, quantitative real-time polymerase chain reaction; RGM, reactive gaseous mercury; ROS, reactive oxygen species; SEM, scanning electron microscopy; SO₂, sulfur dioxide; SVOCs, semivolatile organic compounds; TD, thermal desorption; TEA, triethanolamine; TEM, transmission electron microscopy; TOF-MS, time-of-flight mass spectrometry; TSP, total suspended particles; US EPA, United States Environmental Protection Agency; UV, ultraviolet; VIS, visible; VOCs, volatile organic compounds; WSOC, water-soluble organic carbon; XRF, X-ray fluorescence.

Prepared by the Working Group.

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