

## Supplementary Materials:

# A Decade of Poland-AOD Aerosol Research Network Observations

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### S1. Poland-AOD Research Stations

The RTLab and the RSLab at the University of Warsaw (52.21°N, 20.98°E, 110 m a.s.l.; [www.igf.fuw.edu.pl](http://www.igf.fuw.edu.pl)) comprise research platforms installed on the roof of the university building and at a ground site located at Ochota University Campus. The location of this station, close to several main roads but also to a large park (Pole Mokotowskie), is typical for the agglomeration of Warsaw (2,000,000 population). It is approximately 3 km from the city centre and 4 km from the largest airport in Poland (Warsaw Chopin Airport with 125,000 operations annually). Since 2013, the RSLab has been a part of the PollyNET lidar network. Since 2015, it has regularly provided EARLINET lidar observations, and since 2018, it has also provided continuous photometer measurements for AERONET. Continuous measurements at this site include standard meteorological parameters, radiation fluxes, in situ and columnar aerosol optical and microphysical properties, and vertical profiles from lidar.

The Sopot station is installed on a platform on the roof of the Institute of Oceanology, Polish Academy of Sciences (54.45°N, 18.56°E, 10 m a.s.l.; [www.iopan.gda.pl](http://www.iopan.gda.pl)), except for the lidar and ceilometer, which are installed on the ground close to the Institute building. It is a coastal station located in the vicinity of the beach and surrounded by a residential area and parks. Sopot borders two large towns: Gdansk to the south (about 10 km) and Gdynia to the north (about 7 km). This station can be characterized as a coastal-urban location. Significant pollution is emitted in Gdansk (580,000 population) and Gdynia (240,000 population) but also locally in Sopot (40,000 population). Measurements at this station consist of radiation fluxes, columnar aerosol properties, and vertical profiles by ceilometer and lidar. In addition, aerosol observation onboard s/v Oceania is conducted in the southern Baltic Sea. The marine research is focused on sea-salt emission and water-air interaction.

The Central Geophysical Observatory in Belsk (51.83°N, 20.80°E, 180 m a.s.l.; [www.igf.edu.pl](http://www.igf.edu.pl)) is located about 45 km south of Warsaw in a rural area away from urban and industrial developments. It is situated on the edge of a larch reserve and surrounded by orchards, approximately 2 km away from the nearest village and 6 km from the motorway. Equipment for aerosol and sun radiation observations is installed on the roof of a dedicated building for atmospheric measurements, where a lidar is also placed. This station, due to its location, can be described as a monitoring background station. The Belsk site is part of the EARLINET (since 2000) and the AERONET (since 2002) networks.

The Raciborz station (50.08°N, 18.19°E, 230 m a.s.l.; [www.igf.edu.pl](http://www.igf.edu.pl)) is located in Southern Poland in Upper Silesia. The measurement site is approximately 2 km southwest of the town centre (54,000 population) and 65 km southwest from the centre of the Upper Silesian metropolitan area, which is a highly industrialized and populated area (4,300,000 population). The location of the site is typically urban. Measurement equipment is located

on the roof of the historical building of the Silesian Geophysical Observatory. This site has been a part of the AERONET network since 2015.

Observatory in Torun is located at the main Campus of Nicolaus Copernicus University (53.02°N, 18.57°E, 58 m a.s.l.; <https://www.geo.umk.pl/obsmeteo/> accessed on 24 November 2021) at the Department of Meteorology and Climatology, Faculty of Earth Sciences and Spatial Management. The station consists of a standard meteorological garden located in front of the faculty building and an observation platform located on its roof. It is a typical urban site (3 km from the old town) but close to forests. The population of Torun is about 200,000. Observation at this site includes standard meteorological parameters (Vaisala MAWS 301), radiation fluxes, and AOD from handheld measurements. The radiation equipment (two CMP22 pyranometers, CHP1 pyrhelimeter) is mounted on a Solys 2 sun tracker. In addition, a CSD3 sensor is used to measure sunshine duration.

The Rzecin site (52.76°N, 16.31°E, 54 m a.s.l.) belongs to Poznan University of Life Sciences (PULS) and is located in a rural area in the north-western part of the Greater Poland Region. The site is surrounded mainly by the Notecka Primeval Forest complex, and the observations are carried out in the middle of a peatland area that is classified as a fen. The following observations are carried out at the station: net heat/mass exchange by means of eddy covariance (R3-100 sonic anemometer [Gill Instruments Ltd., UK] and LI-7200 enclosed CO<sub>2</sub>/H<sub>2</sub>O gas analyser [LI-COR, Inc., USA]), standard meteorological measurements (e.g., radiation, air temperature, and air humidity), as well as observations of the optical properties of the atmosphere. The Rzecin site has been part of the AERONET network since 2016, known as POLWET\_Rzecin, where the sun photometer (CE318, CIMEL Electronique, Paris, France) is operating.

The second PULS station, the Debrzyna site (53.78°N, 16.59°E, 158 m a.s.l.), is located in a rural area (a meadow in a deciduous forest) in north-western Poland, in Western Pomerania. It is at a distance of 63 km south of the Baltic coast. This station has been operating since 2020 when the sun photometer (CE318-T, CIMEL Electronique, Paris, France) was installed and incorporated into the AERONET network (site ID Debrzyna\_PULS). These measurements are carried out along with meteorological (e.g., radiation, air temperature, and air humidity) and micrometeorological observations (e.g., the eddy covariance observations [Gill WindMaster Pro sonic anemometer, Gill Instruments Ltd., UK and LI-7500DS open path CO<sub>2</sub>/H<sub>2</sub>O gas analyser LI-COR, Inc., USA]) that are taken at the Kusowo bog site located 3.8 km north of the Debrzyna site.

The Research Station of the University of Gdansk (52.27°N, 17.97°E, 163 m a.s.l.; [klimat.ug.edu.pl](http://klimat.ug.edu.pl)) is located in Borucino, a rural area 60 km southwest of Gdansk, on the bank of the post-glacial Lake Radunskie Gorne. This station has been in operation since the early 1960s and conducts meteorological observations according to the CLIMATE standard and evaporation measurements. For several years, evaporation measurements have also been carried out at the station on a raft anchored on the lake. Actinometric equipment is installed at the station, and elements of solar radiation are recorded. A sun tracker Solys-2 with sun spectrometer (PGS-100), pyrhelimeter (SHP-1), and pyranometer (SMP-11) is installed on a tower 14 m high. A digital sunshine sensor (CSD4) is also installed next to it. Other instruments measuring the components of solar radiation include the following: net radiometer Kipp and Zonen CNR-1, UVS-AB-T UV Radiometer, and Phytophotometer (PQS 1 PAR).

The Meteorological Observatory of the University of Wroclaw (51.10°N, 17.09°E, 116 m a.s.l.; <https://www.meteo.uni.wroc.pl/> accessed on 24 November 2021), operating at the Department of Climatology and Atmospheric Protection, has been operating continuously since 1946. At present, the following measuring units operate within the observatory: standard meteorological measurements unit (temperature, humidity, pressure, precipitation, and wind), actinometric measurements unit (total, diffuse solar flux, and sunshine duration), air quality measurement unit (PM<sub>2.5</sub>, PM<sub>10</sub>, TEOM, O<sub>3</sub>, dust meters, and bioaerosol concentrations), measurements of the vertical structure of the atmosphere unit

(SODAR measurements, vertical temperature profile, height 15 m), and mobile measurement unit—mobile station: two cars as station measurement platforms, equipped with optical dust meters with heated measurement paths, autonomous meteorological stations, a UAV with an environmental head enabling measurement of PM concentrations, and a mobile monostatic SODAR.

The Radiative Transfer Station SolarAOT in Strzyzow (<http://www.igf.fuw.edu.pl/~kmark/stacja/> accessed on 24 November 2021) is located on the Niebylecka Hill in the south-east part of Poland (49.878°N, 21.861°E, 444 m a.s.l.) in the Carpathian region. The SolarAOT site is elevated approximately 200 m above small villages and towns, at background conditions, with relatively low anthropogenic emission. The site is about 4 km from the centre of a small town, Strzyzow (8000 population), and 25 km from Rzeszow (180,000 population). Since August 2013 this station has also been a part of the AERONET network with the polarized CIMEL. Continuous measurements at this site include standard meteorological parameters, radiation fluxes, in situ and columnar aerosol optical properties, and vertical profiles from the ceilometer. In addition, 4 km from this station and 180 m below, there is a second site, where meteorological and air-quality observations are conducted. Data from both sites are used to determine the surface temperature inversion and vertical transport of air pollution.

## S2. Instrumentation

Table S1 lists instrumentation of Poland-AOD stations. The equipment can be divided into the following categories of observations: radiation, sun photometry, active remote sensing, in situ aerosol properties, and weather.

**Table S1.** Instruments used within the Poland-AOD network. Index N indicates instruments to be purchased in 2021–2023 within the ACTRIS-PL infrastructure development (allocated funds).

Equipment	Wavelength (nm) & Additional Information	Belsk	Bo-	Debr	Raci-	Rze-	Sopot	Strzy	To-	War-	Wroc
<b>Passive sun photometers</b>											
Sun photometer Microtops	5 channels within 340–1020	-	-	-	-	1	4	-	2	2	-
Radiometer MFR-7	415, 500, 610, 675, 870 940	-	-	-	-	-	1	1	-	1	-
Sun photometer CIMEL	Several channels within 340–1640	1	-	1	1	1	-	1	-	1	N
<b>Radiation sensors</b>											
Pyranometer	300–4000	1	1	-	1	1	2	2	2	2	2
Pyrheliometer	300–4000	1	1	-	-	-	-	-	1	1	-
Pyrgeometer	4000–50000	-	-	1	-	1	-	1	-	1	-
Albedometer	285–2800	1	-	-	-	1	-	1	-	-	-
Net radiometer	300–2800 & 4500–42000	-	1	-	-	1	-	1	-	1	1
UV Radiometer	315–400	1	1	-	1	-	-	-	1	-	-
Sunshine sensor		1	1	1	-	-	-	-	1	-	1
Sun Spectrometer	350–1050	-	1	-	-	-	-	1	-	1	-
Sun Tracker	STR22/Solys2	-	1	-	-	-	-	1	1	1	-
<b>Active remote sensors</b>											
Ceilometer CHM15K	1064	-	-	-	1	-	1	1	-	-	-
Aerosol Lidar	532	-	-	-	-	-	1	-	-	-	-
Raman polarization lidar	355(s), 387, 407, 532(s), 607, 1064	1	-	-	1	-	-	N	-	1	N

Doppler Lidar		-	-	-	-	-	-	-	-	-	N	-
<b>Aerosol in situ</b>												
Aethelometer AE-31	370, 470, 520, 590, 660, 880, 950	-	-	-	-	-	-	1	1	-	N	N
Aethalometr AE-51	880	-	-	-	-	-	-	-	1	-	-	-
Nephelometer	450, 525, 635	-	-	-	-	-	-	1	1	-	1	N
Photoacoustic Extinction.	532 or 870	-	-	-	-	-	-	1	-	-	2	-
PM <sub>10</sub> /PM <sub>2.5</sub> sensor		-	-	-	-	-	-	1	1	-	1	3
Aerosol size distribution		-	-	-	-	-	-	1	-	-	1	-
<b>Additional instruments</b>												
Weather station		1	1	1	1	1	1	1	1	1	1	1
Whole sky camera		1	-	1	-	1	1	1	1	1	1	-
Microwave Radiometer	K-Band, V-Band	-	-	-	-	-	-	-	-	-	1	-
Eddy covariance system		-	-	1	-	1	1	-	-	-	1	-
Unmanned aerial vehicle	Payload up to 1 kg/4 kg	1	-	-	-	-	-	-	-	-	1	1
Radiosonde system	RS92SGP, RS42	-	-	-	-	-	-	-	1	-	-	-
Acoustic Sounding System		-	-	-	-	-	-	-	-	-	-	2

### S2.1. Radiometers

For monitoring of shortwave (SW) and longwave (LW) surface radiation several radiometers from Kipp and Zonen ([www.kippzonen.com](http://www.kippzonen.com)) are used. The total and diffuse SW radiation is measured by the first-class pyranometers (CMP11, CMP21, and CPM22). At Rzecin station the second class pyranometer (CMP6) is used. The diffuse and direct SW broadband flux is measured respectively by a pyranometer and pyrliometer (CHP1) mounted on the sun tracker. The LW radiation is measured by CGR3 and CGR4 pyrgeometers and by CNR4 net radiometer (see Table 2).

### S2.2 Sun Photometers

The columnar aerosol optical properties are measured by three types of devices: CIMEL and Microtops sun photometers and Multi-Filter Rotating Shadowband Radiometers (MFR-7). The MFR-7 ([www.yesinc.com](http://www.yesinc.com)) is a six narrowband channels (415, 500, 615, 675, 870, 940 nm) and 1 broadband channel device to measure the total, direct, and diffuse solar flux [S1]. The rotating arm-band allows to make four types of measurements: the first measures total radiation, the second is made with the sun completely blocked to measure diffuse horizontal flux, and the other two are done with the arm-band rotated to 9° on either side of the sun to estimate diffuse radiation around the sun aureole, which is removed in the second scan. A single complete cycle takes 15 s. The CIMEL sun photometer (<https://www.cimel.fr> accessed on 24 November 2021) is used in the AERONET network [S2]. A few versions of this instrument are installed in Poland. The standard CIMEL is used at Belsk, Warsaw, Rzecin, and Debrzyna, the polarised model (CE 318–2) at Strzyzow, and sun sky-lunar (CE319-T, [S3]) at Raciborz site. The instrument measures direct solar radiation at eight or nine wavelengths (typically 340, 380, 440, 500, 675, 870,

936, 1020, and 1640 nm). The AOD, Ångström exponent (AE), and precipitable water (PW) aerosol direct radiative forcing (RF) are calculated from direct flux. In addition, the almucantar and principal plane measurements of diffuse radiation are used to retrieve among others the aerosol size distribution and SSA [S4].

The Microtops II (<http://www.solarlight.com> accessed on 24 November 2021) is a handheld device used as additional equipment to measure AOD and AE at five narrow-band (approx 10 nm) channels between 340 and 1020 nm [S5]. It is mainly used during field campaigns to support our research on the spatial variability of AOD and AE, including the vertical extent if installed on moving platforms [S6].

### *S2.3 Active Remote Sensing*

Profiles of aerosol optical properties are measured by ceilometer and lidar systems. Polly<sup>XT</sup> Raman Polarization Lidar (<https://polly.tropos.de/> accessed on 24 November 2021) mounted in July 2013 at RSLab in Warsaw is a 12-channel new-generation system [S7]. The transmission module consists of an Nd-YAG laser which emits light 20 Hz pulses at 355, 532, and 1064 nm. The receiving system was developed for the far and near-range detection by two Newtonian-type telescopes (300 mm and 50 mm). The far range detection is used to determine the elastic scattering at 355, 532, and 1064 nm, the elastic cross-polarized scattering at 532 and 355 nm, the vibrational Raman scattering for N<sub>2</sub> at 607 and 387 nm, and for H<sub>2</sub>O at 407 nm. The near-range optics detects elastically scattered radiation at 355, and 532 nm and N<sub>2</sub> Raman scattering at 387 and 607 nm. The signals are acquired with 600 MHz using photon counters (providing 7.5 m height resolution). The overlap depends on the user settings, and it is between 400–800 m for far and 120–300 m for near range.

The LB-10 D-200 Raymetrics lidar (<http://www.raymetrics.gr/> accessed on 24 November 2021) is located at the Sopot site [S8]. The light pulses (20 Hz) at 532 nm with an energy of 20 mJ are generated by Nd:YAG laser. The laser beam diameter is 10 mm with a divergence of less than 0.1 mrad. The detection system is based on a Cassegrainian reflecting telescope with a primary mirror of 200 mm of diameter. The acquisition system consists of both analogue detection of the photomultiplier current and single photon counting. The receiving system which is a combination of an A/D converter (12 Bit at 40 MHz) with a 250 MHz photon counting system, which shows a high dynamic range of the acquired signal and provides a spatial resolution of 7.5 m. The lidar overlap height is about 400 m.

The construction of lidar in Belsk is based on the Nd:YAG laser which generates three wavelengths (1064, 532, and 355 nm). Energies of light pulses are about 320 mJ while their repetition rate is 15 Hz. The receiver consists of two systems: near range (150 mm parabolic mirror, 150 m overlap distance) for observations in the planetary boundary layer and far range (600 mm mirror, 1500 m overlap distance) for observations of aerosols in the free troposphere and lower stratosphere. In the Belsk lidar, a polychromator based on dichroic beam splitters and a set of narrow bandpass filters is used to separate wavelengths. Acquisition of the analogue lidar echoes is performed by photomultipliers (at 355 and 532 nm) and the avalanche photodiode (at 1064 nm).

The luft CHM-15k (Warsaw until 2013, Strzyzow since 2013) and CHM-15k Nimbus (Sopot and Raciborz) ceilometers (<https://www.lufft.com/> accessed on 24 November 2021) are used to derive aerosol backscatter profile [S9], cloud base height, cloud penetration depth, aerosol layer height [S10], cloud cover, and vertical visibility. Data from the ceilometer is acquired with 30 s time and 15 m vertical resolution. The active remote system works with Nd:YAG solid-state laser diode at 1064 nm, which emits energy pulses (8 µJ), at a high frequency (5–7 kHz). The detection system is based on a single lens (100 mm in diameter), which, in comparison to the traditional biaxial design, is characterized by a shorter overlap range. In the CHM-15k overlap is reduced to about 650 m due to a custom-designed change of the optics aperture done by the manufacturer. The overlap height for the CHM-15k Nimbus is around 1 km. Markowicz et al., [S11] show that the overlap in

ceilometers can be reduced to about 250 m by applying a correction function, which is computed from the horizontal measurements.

#### *S2.4 In Situ Aerosol Optics*

Aerosol optical properties are measured by nephelometers and aethalometers, in the second of which the filter must be changed manually. Both aethalometer measured the time variability of light attenuation (transmission) through quartz filter (Pallflex, type Q250F) with the aerosol deposit in it. Aerosol properties are calculated from photoacoustic extinctions (PAX) devices. Two types of nephelometers are used to obtain the aerosol scattering coefficient. The first integrates a nephelometer 3563 from TSI (<https://tsi.com/home/>, accessed on 24 November 2021; Sopot site) and an Aurora 4000 (Warsaw, Strzyzow site) from Ecotech (<http://ecotech-research.com/>, accessed on 24 November 2021). The most important difference between both nephelometers is the light source, which in the TSI is halogen, while in the Aurora 4000 is a matrix of LED [S12]. In addition, the Aurora 4000 allows measurement of the scattering coefficient up to 16 scattering angle sectors at 450, 525, and 635 nm, while the TSI only the total and back-scatter coefficient at 450, 550, and 700 nm. The equivalent of BC and the aerosol absorption coefficient is measured by the AE-31 (Magee Scientific; <https://mageesci.com/> accessed on 24 November 2021), AE-51 (AethLabs; <https://aethlabs.com/> accessed on 24 November 2021) aethalometers. The first one is fully automatic therefore can be used for long-term observation attenuation coefficient derivatives at 370, 470, 520, 590, 660, 880, 950 nm for AE-31 and at 880 for AE-51.

The PAX devices (Droplet Measurement Technologies, Inc.; <https://www.droplet-measurement.com/> accessed on 24 November 2021) are used to measure both scattering and absorption coefficient at 532 nm (Sopot, Warsaw) and 870 nm (Warsaw). The scattering properties are obtained from a small nephelometer sensor while the absorption are obtained from the photoacoustic cell. The laser energy absorbed by aerosols is transferred to the surrounding air in the acoustic resonator (resonance frequency about 1500 Hz). The generated pressure wave is measured by microphone and converted to an absorption coefficient [S13]. The PAX also delivers extinction coefficient and SSA as integration of result from both sensor cells.

#### *S2.5 In Situ Aerosol Microphysics*

The equipment to measure aerosol size distribution, particle number concentration at different sizes includes TSI Laser Aerosol Spectrometer LAS3340, MLU TEOM1400a (Thermo Fisher Scientific Inc; <https://www.thermofisher.com> accessed on 24 November 2021), TSI DustTrack II Aerosol Monitor 8530. The LAS3340 uses wide-angle optics to detect size (between 0.09 and 7.5  $\mu\text{m}$ ) and number concentration at 100 bins [S14]. For the type of optics, the intensity of scattered light is a monotonic function of particle size in contrast to narrow-angle optics, which is characterized by a more complicated Mie-resolved function. This device uses the novel intercavity He–Ne laser design to obtain high sensitivity of particle detection.

MLU TEOM1400a is used to measure particulate matter mass concentration. Depending on the inlet, it can measure  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_1$ , or total suspended particle mass concentration. This device uses the tapered element oscillating microbalance technology to measure the mass of the aerosol. The DustTrack II Aerosol Monitor 8530 is a handheld optical device to measure the  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  mass concentration during field campaigns. In addition, miniaturized low-cost particle counters such as OPC-N2/OPC-N3 (Alphasense; <https://www.alphasense.com/> accessed on 24 November 2021), SPS30, PMS7003, and SEN0177 are used. Such devices are used mostly during field campaigns for vertical profiling by the UAV, tethered balloon or cable cars.

#### *S2.6 Additional Instrumentation*

The atmospheric parameters are monitored using a few types of weather stations. For this purpose, the Vaisala WXT520 and other automatic weather stations (MAWS 301, MetPak, HMP45C, GILL, and Young ultrasonic anemometer, OTT Parsivel 2 disdrometer) are used. Vertical profiles (soundings) of thermodynamic parameters in Poland are measured at three WMO stations (Legionowo, Leba, Wrocław) operated by Institute of Meteorology and Water Management National Research Institute. The Poland-AOD network is equipped with a radiosonde system to launch free and tethered weather balloons. This system is used only during field campaigns.

Two hexacopter drones are used to soundings the lower troposphere. The FUW UAV [S15] quipped with Vaisala RS42 (or RS92SGP) radiosonde, miniaturized aethalometer AE-51, and particle optical counter (e.g., PMS7003, SPS30, SEN0177) is used to profile to lower troposphere (up to 1 km). Such measurement delivers profiles of thermodynamic parameters, eBC, PM<sub>2.5</sub>/PM<sub>10</sub> mass concentration, and aerosol scattering coefficient [S16]. The second drone (UW<sub>r</sub>) is a customized Matrice 600 Pro hexacopter, with an environmental head that enables the measurement of PM concentration, air temperature, and relative humidity. Due to its technical parameters (lifting capacity about 6 kg, flight time up to 45 minutes), the device with the installed head is primarily used to measure air quality parameters in vertical profiles, up to 350 m a.g.l as standard (the range of these measurements corresponds to the range of SODAR measurements). Thanks to the time resolution of the measurement of 1 sec and the ascent/descend speed of 1 m/s, the vertical data resolution is about 1 m.

Doppler mini-SODAR and stationary SODAR measurements (UW<sub>r</sub>) provide information about the vertical thermal structure of the atmosphere as well as about vertical wind profile. The vertical range of mini-SODAR is approximately 350 m with a resolution of 2 m. The device has been in continuous operation since 2008. The stationary three-monostatic Doppler SODAR provides information about structure parameter CT2 of the atmospheric boundary layer up to 1000 m a.g.l. In addition, the SODAR is used to estimate atmospheric boundary layer height (ABLH).

Two mobile laboratories (vehicles) are equipped with instrumentation to measure the spatial distribution of air quality (UW<sub>r</sub>) and aerosol optical properties (FUW) and meteorological background conditions. The UW<sub>r</sub> mobile lab performs periodic measurement transects, mainly in the area of Wrocław, but also in selected places in Lower Silesia, with particular emphasis on the city of Wrocław agglomeration and sub-mountain areas. In non-urban measurements, a mobile monostatic sodar installed on a trailer is also used, enabling acoustic sounding of the atmosphere at the site of measurement campaigns. In the case of the FUW RSlab, the measurements are conducted during field campaigns, especially in the mountain area of the SolarAOT station. The mobile laboratory is usually equipped with weather sensors (e.g., MetPak), radiosonde receiver, particle counters (e.g., OPC-N3 and LAS3340), aethalometer AE-51, and PAX and Aurora 4000 nephelometers to profile the smog and radiation fog in the Carpathian valleys.

### S3. Aerosol Transport Models

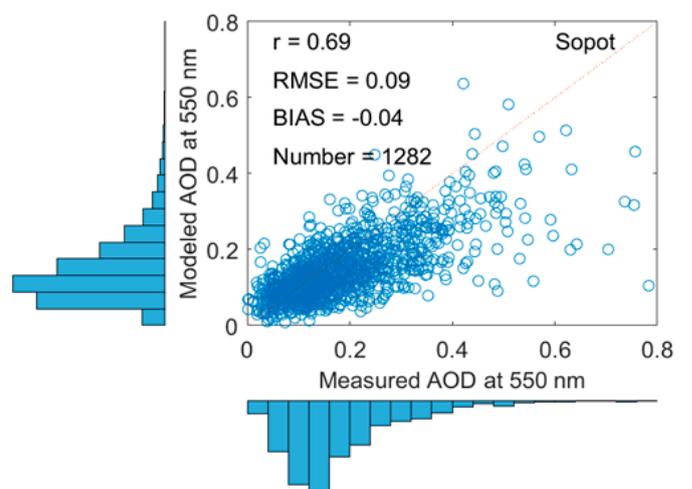
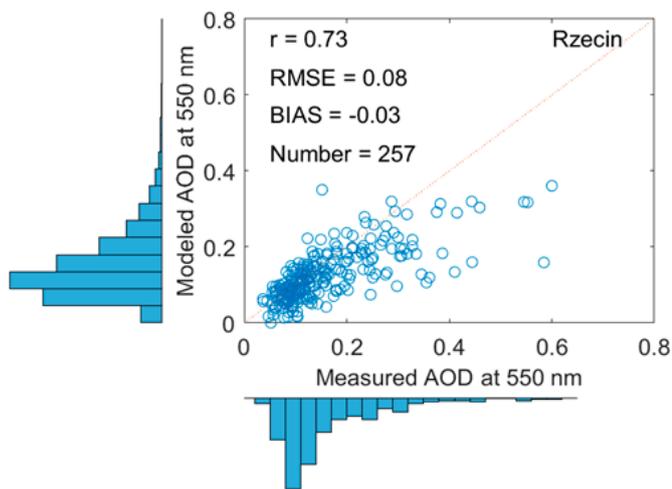
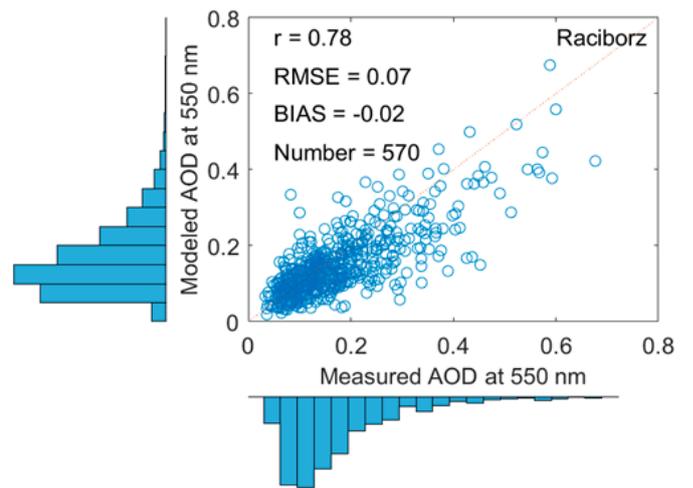
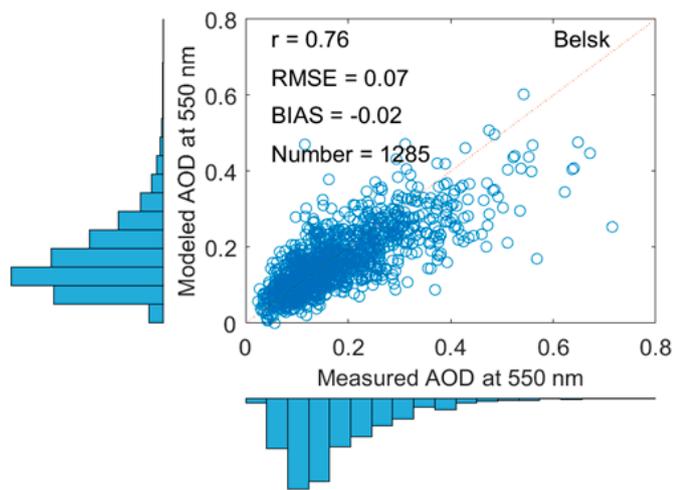
Aerosol transport model simulations were performed by two institutions (EcoFoundation and UW<sub>r</sub>). The GEM-AQ provides a consistent modelling framework for the meteorological and chemistry aspects of the atmospheric system [S17]. The host meteorological model used in this study is the Global Environmental Multiscale (GEM) model developed by Environment and Climate Change Canada for operational weather prediction [S18]. The GEM-AQ model has a unique capability to run in a global variable resolution where a uniform portion of the computational grid can be placed over the region of interest, i.e., northern hemisphere (cf. [S19–S20]). Atmospheric chemistry and tropospheric microphysics modules are implemented online in the host meteorological model. Tracers are advected using the semi-Lagrangian scheme native to the GEM model. The vertical transport includes parameterized subgrid-scale turbulence and deep convection. Dry deposition is implemented as a flux boundary condition in the vertical diffusion equation.

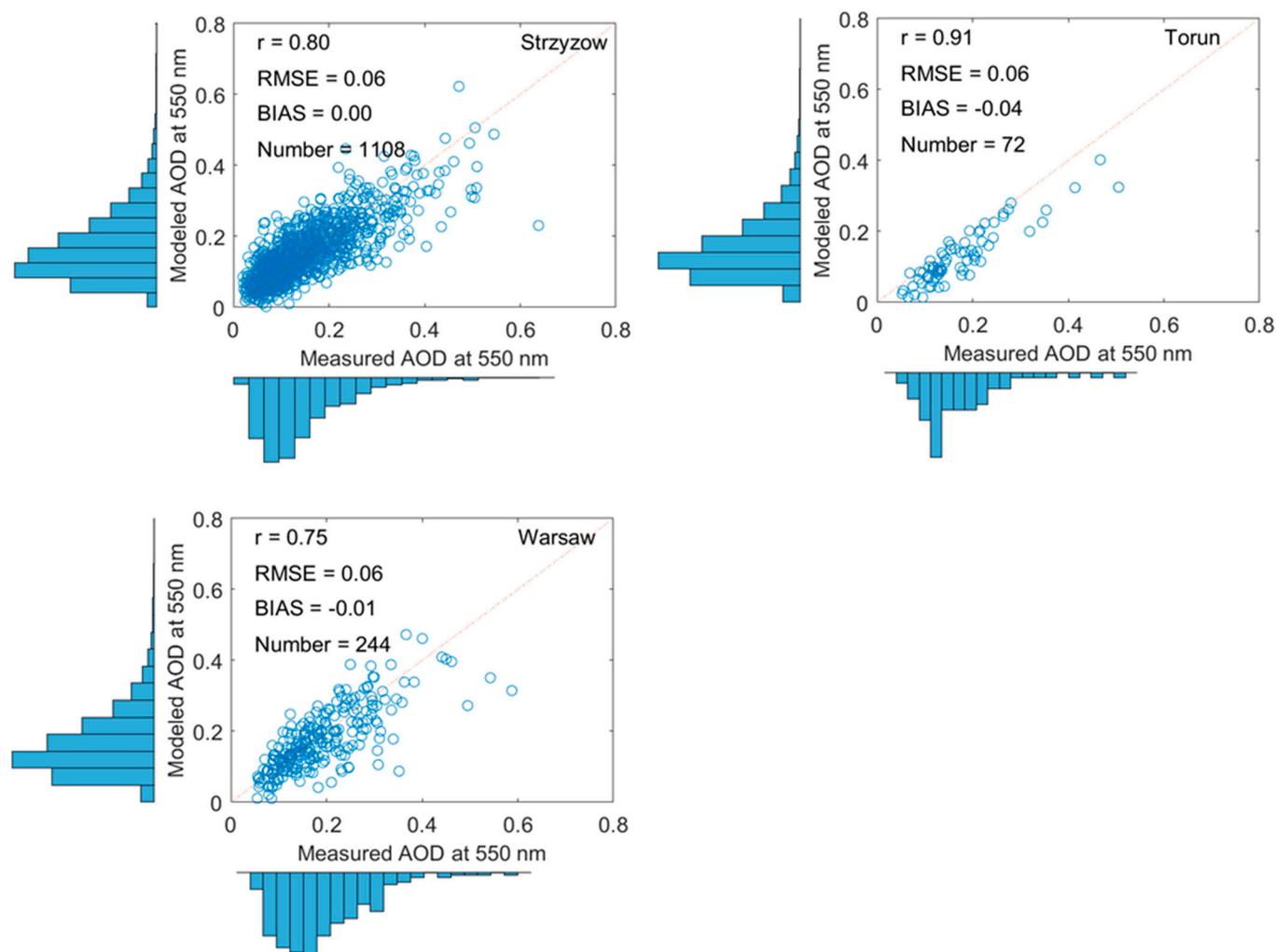
The ISORROPIA thermodynamic equilibrium model is used to calculate gas-aerosol partitioning. Thermodynamically driven heterogeneous reactions are included for sulphate aerosols, liquid ternary solutions, and water ice [S21]. The aerosol module implemented in the GEM-AQ model includes five size-resolved types of aerosols: sulphates, black carbon, organic carbon, sea salt, and mineral dust. Aerosol mass is distributed into 12 logarithmically spaced bins. The AOD module was implemented on-line in the GEM-AQ model. Extinction cross-sections from the AODSEM model—which is based on the same aerosol module as GEM-AQ—were implemented. In the Poland-AOD framework the GEM-AQ model provided operational forecast from March 2016 to June 2021. The forecast products included maps of AOD at 500 and 550 nm, the cloud cover mask, the total cloud cover, and radiation flux at the ground for 12-hour forecast. The time series of the parameters mentioned above for 72-hour forecast were available for seven grid point corresponding to the Poland-AOD stations location. Also, extinction profiles were calculated up to 3 km. Forecast results were made available via the Poland-AOD web portal.

The online integrated meteorological and atmospheric chemistry model WRF-Chem [S22–S23] and offline atmospheric chemistry model EMEP MSC-W [S24–S25] are used for air quality and aerosol transport forecasting for Poland and Central Europe by UW. The forecasting system uses national emission inventory, provided by the Institute of Environmental Protection – National Research Institute, for Poland and EMEP WebDab emission inventory for the rest of the model domain. The forecast is run once per day, with 72h lead time. The system provides information on surface and vertical air concentrations of particulate matter ( $PM_{2.5}$ ,  $PM_{10}$ ) and its chemical components, including secondary inorganic aerosols, elemental carbon, organic matter as well as information on aerosol optical depth. With the online coupled WRF-Chem model it is possible to study the impacts of the direct effect of aerosol particles on radiation and the indirect aerosol effect on meteorological variables and subsequent distribution of, e.g., particulate matter concentrations [S26]. Modelling results are uploaded to the Rasdaman database. Currently, only the WRF-Chem forecasts are available to the broad community through web services ([prognozy.uni.wroc.pl](http://prognozy.uni.wroc.pl)) but the ensemble approach with the application of both models (WRF-Chem and EMEP) is under development. The modelling system uses NCAR GFS forecasts as initial and boundary meteorological conditions. The models are configured using two nested domains covering Europe ( $12\text{ km} \times 12\text{ km}$  grid) and Central Europe ( $4\text{ km} \times 4\text{ km}$ ). Since 2018, the system uses meteorological data assimilation to improve model initial conditions. Recently, there is ongoing work, in cooperation with Met Norway within the PMCOST H2020 project, on the implementation of the uEMEP model for Poland. uEMEP is a gaussian extension of the EMEP model, which allows for very high spatial resolution modelling of gas and aerosols concentrations [S27].

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is being run twice (00 and 12 UTC) a day for Poland-AOD stations to support data analysis, especially for long-range transport. The HYSPLIT model [S28] used the Global Data Assimilation System (GDAS) at  $1^\circ \times 1^\circ$  resolution. The 96-h back trajectories ended at three altitudes (0.5, 1.5, and 3 km) over Warsaw, Sopot, Strzyzow, and Rzecin.

#### S4. AOD Validation





**Figure S1.** Comparison of AOD at 550 nm obtained from Poland-AOD observation with results of numerical simulation from NAAPS reanalysis. Dotted lines show perfect agreement. Measurement data were matched to NAAPS 6 hour AOD product with  $\pm 1$  hour time window. The  $r$  corresponds to Pearson correlation coefficient, RMSE is root mean square error difference, BIAS is mean bias, and Number corresponds to number of data.

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