Atmospheric
Chemistry
and Physics

Supplement of

Urban population exposure to NO$_x$ emissions from local shipping in three Baltic Sea harbour cities – a generic approach

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Supplement I: Urban Atlas 2012 Land Use Classification and Mapping to microenvironments in this study.

The following table is based on the Urban Atlas 2012 Land Use Classification by Copernicus and the descriptions of the different classifications are taken from Copernicus (2016). The mapping of UA2012 classifications to Microenvironments used in this study are in column three of table SI-1.

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Table SI-1: Model performance statistics of CityChem for NO_2 based on hourly concentration at stations with sufficient data availability in 2012 in all Baltic Sea urban domains.

Nomenclature: Continuous urban fabric (S.L. > 80%)	Code: 11100	ME Classification: 30% WORK ME Classification: 70% HOME
Land Use Description: Predominant residential usage. Contains more than 20% non-sealed areas, independent of their housing scheme (single family houses or high-rise dwellings, city centre or suburb). Included are downtown areas and city centres, and Central Business Districts (CBD) as long as there is partial residential use.		
Nomenclature: Discontinuous dense urban fabric (S.L. 50%-80%)	**Code:** 11210	**ME Classification:** HOME
Description: Residential buildings, roads and other artificially surfaced areas. The non-sealed areas might be private gardens or common green areas.		
Nomenclature: Discontinuous medium density urban fabric (S.L. 30%-50%)	**Code:** 11220	**ME Classification:** HOME
Description: Residential buildings, roads and other artificially surfaced areas.		
Nomenclature: Discontinuous low dens. urban fabric (S.L. 10%-30%)	**Code:** 11230	**ME Classification:** HOME
Description: Residential buildings, roads and other artificially surfaced areas. The vegetated areas are predominant, but the land is not dedicated to forestry or agriculture.		
Nomenclature: Discontinuous very low density urban fabric (S.L.<10%)	**Code:** 11240	**ME Classification:** HOME
Description: Residential buildings, roads and other artificially surfaced areas. The vegetated areas are predominant, but the land is not dedicated to forestry or agriculture. Example: exclusive residential areas with large gardens.		
Nomenclature: Isolated structures	**Code:** 11300	**ME Classification:** HOME
Description: Isolated artificially structures with a residential component, such as (small) individual farm houses and related buildings. The mapping unit will never be surrounded by any urban class other than transportation network. The mapping unit is no larger than 2 ha. It must not contain more than 4 houses, otherwise it should be included in class Urban Fabric.		
Nomenclature: Industrial, commercial, public, military & private units	**Code:** 12100	**ME Classification:** WORK
Description: Industrial, commercial, public, military or private units. The administrative boundaries of the production or service unit are mapped, including associated features larger than the MMU (e.g. sports areas or transport structures). Industrial uses and related areas: Sites of industrial activities, including their related areas; Production sites; Energy plants: nuclear, solar, hydroelectric, thermal, electric and wind farms; Sewage treatment plants; Farming industries (farms with large buildings and / or greenhouses); Antennas, even with predominant vegetated areas. The vegetated areas may be predominant, but the land is not dedicated to forestry or agriculture; Water treatment plants; Sewage plants; Seawater desalination plants.		

The industrial units can be distinguished from residential built-up areas by the type of buildings, their access to transport features and the surroundings: Buildings with large surface areas (inside, not all rooms need daylight, as in dwelling houses); Good access to roads and parking for customers; Industrial areas are often outside the historical city centre.

The commercial units can be distinguished from residential built-up areas by the type of large buildings, their access to transport features and the surroundings: Buildings with large surface areas (inside, not all rooms need daylight, as in dwelling houses); Good access to roads and parking for customers; Pure commercial areas are often outside the historical city centre.

Not included are: Petrol stations along fast transit and main roads with access only from these roads. They are mapped together with the road transport system

Public, military and private services not related to the transport system. Surfaces purely occupied by general government, public or private administrations including their related areas (access ways, lawns, parking areas). Included are: Schools and universities; Hospitals and other health services or buildings; Places of worship (churches / cathedrals / religious buildings); Archaeological sites and museums; Administration buildings, ministries; Penitentiaries; Military areas including bases and airports; Military exercise areas fenced and under current use; Castles, etc. not primarily used for residential purposes (building management, gardeners, etc. living there is not residential use in this sense); Private storage areas without a residential component, such as compounds of garages. Not included are: Public parks; Holiday resorts including their hotels; Sport centres or bathing centres; Cemeteries.

Civil protection and supply infrastructure: Dams, dikes, irrigation and drainage canals and ponds and other technical public infrastructure, to be mapped with the roads, embankments and associated land included; Includes also breakwaters, piers and jetties, sea walls and flood defences; (Ancient) city walls, other protecting walls, bunkers.

Nomenclature: Fast transit roads and associated land	**Code:** 12210	**ME Classification:** TRAFFIC
Description: Roads defined as "motorways" in the navigation data, including motorway rest, service areas, tolls, parking areas, only accessible from the motorways. Areas surrounded by highway or railway junctions have to be included in the corresponding network. Motorways that are not included in the navigation data are to be mapped by the service provider.		

Nomenclature: Other roads and associated land	**Code:** 12220	**ME Classification:** TRAFFIC
Description: Roads, crossings, intersections and parking areas, including roundabouts and sealed areas with "road surface".		

Nomenclature: Railways and associated land	**Code:** 12230	**ME Classification:** n.a.
Description: Railway facilities including stations, cargo stations and service areas.		

Nomenclature: Port Areas	**Code:** 12300	**ME Classification:** PORT
Description: Administrative area of inland harbours and sea ports. Infrastructure of port areas, including quays, dockyards, transport and storage areas and associated areas.		

Nomenclature: Airports	**Code:** 12400	**ME Classification:** n.a.
Description: Administrative area of airports, mostly fenced. Included are all airport installations: runways, buildings and associated land. Military airports are also included		

Nomenclature: Mineral extraction and dump sites	**Code:** 13100	**ME Classification:** WORK
Description: Open pit extraction sites (sand, quarries) including water surface, if < MMU, open-cast mines, inland salinas, oil and gas fields; Their protecting dikes and / or vegetation belts and associated land such as service areas, storage depots; Public, industrial or mine dump sites, raw or liquid wastes, legal or illegal, their protecting dikes and / or vegetation belts and associated land such as service areas.		

Nomenclature: Costruction sites	**Code:** 13300	**ME Classification:** WORK

Description: Spaces under construction or development, soil or bedrock excavations for construction purposes or other earthworks visible in the image. Clear evidence of actual construction needs to be identifiable in the data, such as actual excavations and machinery on site, or ongoing construction of any stage, etc.

Nomenclature: Land without current use	**Code:** 13400	**ME Classification:** n.a.

Description: Areas in the vicinity of artificial surfaces still waiting to be used or re-used. The area is obviously in a transitional position, "waiting to be used".

Nomenclature: Green urban areas	**Code:** 14100	**ME Classification:** OTHER

Description: Public green areas for predominantly recreational use such as gardens, zoos, parks, castle parks and cemeteries Suburban natural areas that have become and are managed as urban parks. Forests or green areas extending from the surroundings into urban areas are mapped as green urban areas when at least two sides are bordered by urban areas and structures, and traces of recreational use are visible. Not included are: Private gardens within housing areas; Buildings within parks, such as castles or museums; Patches of natural vegetation or agricultural areas enclosed by built-up areas without being managed as green urban areas.

Nomenclature: Sports and leisure facilities	**Code:** 14200	**ME Classification:** OTHER

Description: All sports and leisure facilities including associated land, whether public or commercially managed: e.g. Theresienwiese (Munich), public arenas for any kind of sports including associated green areas, parking places, etc.: Golf courses; Sports fields (also outside the settlement area); Camp grounds; Leisure parks; Riding grounds; Racecourses; Amusement parks; Swimming resorts etc.; Holiday villages ("Club Med"); Allotment gardens; Glider or sports airports, aerodromes without sealed runway; Marinas.

Nomenclature: Arable land (annual crops)	**Code:** 21000	**ME Classification:** n.a.

Description: Fields under rotation system. Can be non-irrigated or permanently irrigated. Also includes rice fields; Fields laid in fallow are included.

Nomenclature: Permanent crops	**Code:** 22000	**ME Classification:** n.a.

Description: Fruit orchards, scattered fruit trees with pasture; Vineyards and their nurseries; Roses; Olive groves; Berries and hop plantations.

Nomenclature: Pastures	**Code:** 23000	**ME Classification:** n.a.

Description: Pasture and meadow under agricultural use, grazed or mechanically harvested, Wooded meadows.

Nomenclature: Complex and mixed cultivation	**Code:** 24000	**ME Classification:** n.a.

Description: Annual crops associated with permanent crops; Complex cultivation patterns; Land principally occupied by agriculture, with significant areas of natural vegetation; Agro-forestry areas.

Nomenclature: Orchards	**Code:** 25000	**ME Classification:** n.a.

Description: Orchards at the fringe of the urban classes or in the rural classes if > 1 ha.

Nomenclature: Forests	**Code:** 31000	**ME Classification:** n.a.

Description: Broad leaved forest, coniferous forest and mixed forest; Transitional woodland and shrub (clear cut, new plantations and regeneration, or damage forest); With ground coverage of tree canopy > 30%, tree height > 5 m, including bushes and shrubs at the fringe of the forest; Included are plantations such as Populus plantations, Christmas tree plantations; Forest regeneration / re-colonisation: clear cuts, new forest plantations. Not included are: Forests within urban areas and/or subject to high human pressure.

Nomenclature: Herbaceous vegetation associations	**Code:** 32000	**ME Classification:** n.a.

Description: Vegetation cover more than 50%, ground coverage of trees with height >5 m: <30%, areas with minor / without artificial or agricultural influence: Sclerophyllous vegetation; Bushy sclerophyllous vegetation (e.g. maquis, garrigue); Abandoned arable land with bushes; Woodland degradation: storm, snow, insects or air pollution; Areas under power transmission lines inside forest; Fire breaks; Steep bushy slopes of eroded areas; Abandoned vineyards or orchards, arable land and pasture land under natural colonisation; Dehesas with bush proliferation indicating no agricultural or farming use for a rather long time; Bushy areas along creeks. Bushes, shrubs and herbaceous plants, dwarf forest in alpine or coastal regions (Pinus Mugo forests). Height is maximum 3 m in climax stage. Natural grassland.

Nomenclature: Open spaces with little or no vegetation	**Code:** 33000	**ME Classification:** n.a.

Description: Beaches, dunes, sand: < 10% vegetation cover; Beaches, dunes and sand plains, (coastal or inland location), gravel along rivers; Seasonal rivers, if water is characteristic for a shorter part of the year (< 2 months). Bare rocks:
 > 90% of the land surface of bare rocks, (i.e. < 10% vegetation); Rocks, gravel fields, landslides; Scree (fragments resulting from mechanical and chemical erosion. Weathering rocks forming heaps of coarse debris at the foot of steep slopes), cliffs, rocks. Sparsely vegetated areas: Steppes, tundra, badlands, scattered high altitude vegetation. Bare soils inside military training areas. Vegetation cover 10 - 50%. Burnt areas: Recently burnt forest or shrubs (but not natural grassland), still mainly black on EO data. Snow and ice: Glacier and perpetual snow.

Nomenclature: Wetlands	**Code:** 40000	**ME Classification:** n.a.

Description: Inland wetlands: Areas flooded or liable to flooding during a large part of the year by fresh, brackish or standing water with specific vegetation coverage made of low shrub, semi-ligneous or herbaceous species; Water fringe vegetation, reed beds of lakes, rivers and brooks. Sedge and fen-sedge beds, swamps; Peat bogs, with or without peat extracting areas; Shallow water areas covered with reed; Seasonal rivers, if water course is not visible in the EO data. Coastal wetlands: Areas, flooded or liable to flooding during a large part of the year by brackish or saline water, susceptible to flooding by sea water. Often in the process of fi in and gradually being colonised by halophytic plants; Specific vegetation coverage made of low shrub, semi-ligneous or herbaceous species; Alluvial planes, marshes and intertidal flats: Salinas (salt production sites by evaporation). Not included are: Military exercise areas fenced and under current use; Greenhouses; Inland salinas.

Nomenclature: Water	**Code:** 50000	**ME Classification:** n.a.

Description: Sea; Lakes; Fish ponds (natural, artificial); Rivers, including channelled rivers; Canals; Reservoirs; Water courses or ponds with a strongly variable surface level. All water bodies and watercourses visible in the imagery are mapped as long as they exceed an extent of 1 ha. Water courses are mapped continuously also when water surface is covered by vegetation. If the water is partly obscured, e.g. by vegetation, the delineation shall be oriented to other parts of the water where it is not obscured.

Nomenclature: No data	**Code:** 91000 **Code:** 92000	**ME Classification:** n.a.

Description: No data (Clouds and shadows): Areas affected by clouds or shadows on the EO data have to be mapped with ancillary data if the cloud or/and shadow overlays with the "CGC_RG_LAEA" layer (priority areas corresponding to the cities and greater cities according to the EC/OECD definition of cities (2011) provided by DG REGIO). An additional layer called "CGC_CLOUD_CAPI" delineating the areas classified by other data sources (Google Earth or other relevant available data sources) than the VHR2 coverage (DWH_MG2b_CORE_03) will be produced. Outside these priority areas, code 91000 will be used for areas covered by clouds and shadows over the satellite images where land use/land cover is not possible to be determined. No data (Missing imagery): This code 92000 includes areas without available satellite image or inadequate imagery (e.g. no STL data can be produced as the image acquisition is outside the vegetation period).

Supplement II: EPISODE-CityChem model performance statistics for Rostock, Riga and Gdansk

This supplement to the main paper contains details for the model performance of EPISODE-CityChem simulation in Rostock, Riga and the Gdansk-Gdynia area in 2012 for NO_2, O_3 and PM_{10}. Table SII-1 shows all measurement stations with sufficient time series, as well as the classification of time series and the measured pollutants. The model performance for Gdansk-Gdynia has already been described in detail in the main paper. Nevertheless, all statistical indicators for model performance of NO_2, PM_{10} and O_3 can be found in Table SII-2, SII-3 and SII-4 respectively.

Appendix B: Statistical Evaluation of modelled versus measured concentrations of NO2, PM10 and O3

Due to an insufficient number of stations with PM2.5 measurements in all cities, we chose PM10 to evaluate the model results in terms of particulate matter. Moreover, there is an insufficient number of valid time series at the measurement stations in 2012 for Rostock and Riga to achieve significant performance indication. Therefore, we focus on a detailed discussion of measurement evaluation in the Gdansk-Gdynia agglomeration, which contains eight valid NO2 and PM10 measurement time series, as well as four O3 measurement time series. In Rostock, there are four stations for NO2 and PM10 as well as four O3 measurement stations, while in Riga there are two stations for NO2 and PM10 but none for O3. Besides this, we will focus on the evaluation of NO2 due to the objectives of this study (Sect. 1). However, statistical indicators for NO2, O3 and PM10 for all available stations in all cities as well as a detailed description of the AQ simulation performance in Rostock and Riga can be found in Supplement II of this paper.

DELTA is an IDL-based statistical evaluation software, which allows performing diagnostics of air quality and meteorological model performance. DELTA works with modelled-observed data pairs at surface level, i.e. temporal series of modelled and monitoring data at selected ground air monitoring locations. Evaluations of hourly concentrations with DELTA in the Gdansk-Gdynia agglomeration show a good spatial correlation of modelled and measured NO2 (). A detailed analysis of spatial correlations has shown an r² of 0.3 for station averaged daily averages in 2012 and an r² of 0.79 for station-specific annual averages (Figure 1). The analysis of temporal correlation for hourly values over one year at single stations shows four urban background stations with r values between 0.3 and 0.35 and four urban background stations with r values between 0.2 and 0.3. The poorer correlation values can be expected due to not-localised information on temporal emissions. In terms of seasonal performance, the model results tend to underestimate the measurements especially in autumn (SON) and winter (DJF). In spring and even more so, in summer (JJA), the model overestimates NO2 concentrations. Modelled NO2 for hourly values over one year is in agreement with observed NO2 with overestimation of NO2 at station Wrzescez (urban background station located in an urban green area, Latitude 54.38028, Longitude 18.62028, height asl 40 m) by 4% and underestimation of NO2 (-1% to – 26%) at all other (urban background) stations. The DELTA tool temporal correlation evaluation confirms the negative NMB and indicates good performance for the normalized standard deviation (StdDev Norm) and normalized correlation (1-R Norm). Nevertheless, the Hperc values do not fulfil the DELTA performance criteria, indicating differences in highest hourly concentrations. While NO2 shows overall good performance, PM10 is underestimated at most of the stations with NMB of up to -62% in maximum and about -30% on average. This high negative bias is probably due to an underestimation of local

particle emissions and low PM10 concentrations in the regional background concentrations. The FAC2 values for NO2 in Gdansk-Gdynia reach from 0.46-0.7 and from 0.33-0.62 for PM10 and are therefore fulfilling the acceptance criteria for urban regions of FAC2 $\geq$ 0.3 as defined by Hanna and Chang (2012).
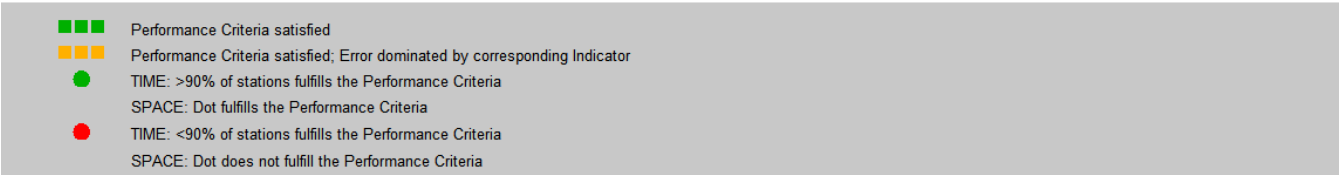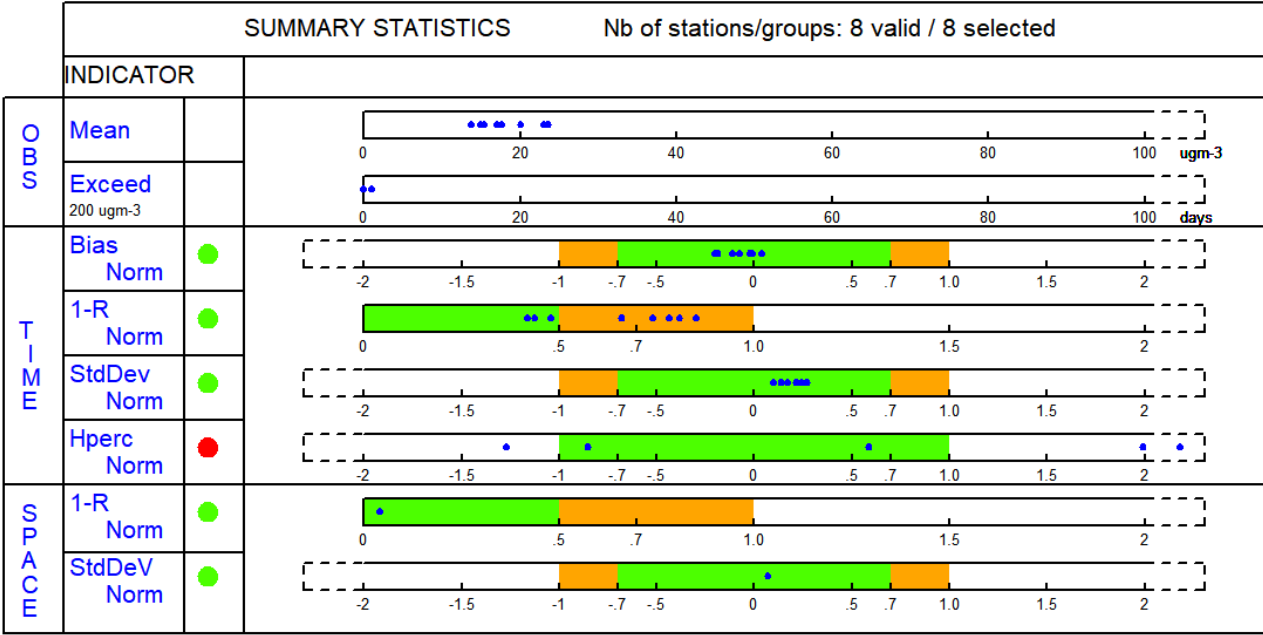
Figure 1: DELTA summary statistics plot for measured vs. modelled NO₂ in Gdansk-Gdynia 2012.

In Rostock NO₂ is highly underestimated at traffic stations with a NMB of -56% but captured better at the rural station and urban station with an NMB -24% and -32%. The underestimation of NO₂ is mostly an effect of the spatially resolved traffic emission totals based on proxy data as described in chapter 2.4. In comparison to Riga and Gdansk-Gdynia, there is no spatial information about traffic emissions or traffic flows and therefore, the created traffic emission inventory for Rostock is inaccurate against measurements, especially at traffic stations. Thus, there is a clear underestimation of NO₂ throughout the whole year in Rostock, which has to be taken into account in the exposure results. The same trend and reasons hold true for

PM_{10}, with high underestimations of PM_{10} at traffic stations with up to -60% but less underestimations with up to -35% at a rural and an urban background station. In Riga, NO_2 is captured well at the urban background station with a NMB of -5%, but with -60% it is much too low at the traffic station. PM_{10} is much too low at all stations with NMB of -80% and -91%. Again, this high negative bias is probably due to an underestimation of local particle emissions and low PM_{10} concentrations in the regional background concentrations.

Table S2-I: Measurement stations with type of stations and measured pollutant for Rostock, Riga and Gdansk-Gdynia.

Station	Type	Pollutants
Gdansk-Gdynia		
Port	Urban background	NO_2, PM_{10}
Siedlce	Urban background	NO_2, PM_{10}
NovyPort	Urban background	NO_2, PM_{10}
Pogorze	Urban background	NO_2, PM_{10}, O_3
Szedolki	Urban background	NO_2, PM_{10}, O_3
Sopot	Urban background	NO_2, PM_{10}
Wrzescez	Urban background	NO_2, PM_{10}, O_3, $PM_{2.5}$
Redlowo	Urban background	NO_2, PM_{10}, O_3
Rostock		
Am Strande	Traffic	NO_2, PM_{10}
Hohlbeinplatz	Traffic	NO_2, PM_{10}, O_3
Stuthof	Rural	NO_2, PM_{10}, O_3
Warnemünde	Urban background	NO_2, PM_{10}, O_3, $PM_{2.5}$
Riga		
Brivibas	Traffic	NO_2, PM_{10}
Park	Urban background	NO_2
Kronvalda	Traffic	PM_{10}, $PM_{2.5}$

Table SII-2: Model performance statistics of CityChem for NO$_2$ based on hourly concentration at stations with sufficient data availability in 2012 in all Baltic Sea urban domains.

Station	$\bar{O}$ [μg/m^{-3}]	$\bar{M}$ [μg/m^{-3}]	STD$_O$ [μg/m^{-3}]	STD$_M$ [μg/m^{-3}]	NMB [%]	Corr [-]	RMSE [μg/m^{-3}]	IOA [-]	FAC2 [%]
Gdansk-Gdynia									
Port	23.62	19.09	18.76	15.44	-19.20	0.23	21.86	0.50	57
Siedlce	23.86	23.06	14.95	20.58	-0.88	0.30	21.57	0.53	70
NovyPort	17.65	16.06	12.97	17.67	-8.99	0.23	19.40	0.49	46
Pogorze	13.75	11.45	11.73	16.27	-16.76	0.24	17.82	0.45	59
Szedolki	15.46	11.50	11.90	14.04	-25.60	0.35	15.42	0.56	53
Sopot	14.92	14.45	11.09	13.17	-3.17	0.33	14.13	0.58	66
Wrzescez	20.12	21.01	14.51	20.61	4.36	0.28	21.64	0.49	66
Redlowo	17.11	12.71	14.26	10.53	-25.73	0.33	15.29	0.57	62
Rostock									
Am Strande	44,06	20.52	25.23	19.10	-53.43	0.32	35.38	0.53	35
Hohlbeinplatz	32.26	14.12	17.42	12.78	-56.42	0.37	25.12	0.53	32
Stuthof	11.59	8.76	8.50	22.30	-24.37	0.11	23.16	0.24	30
Warnemünde	14.89	10.14	12.03	15.79	-31.95	0.37	16.66	0.57	36
Riga									
Brivibas	38.36	15.23	26.59	11.37	-60.29	0.50	32.72	0.55	19
Park	34.18	32.50	20.75	17.26	-4.92	0.46	20.13	0.67	74

Table SII-3: Model performance statistics of CityChem for PM$_{10}$ based on daily averaged concentrations at all stations with sufficient data availability in 2012 in all Baltic Sea urban domains.

Station	$\bar{O}$ [µg/m^{-3}]	$\bar{M}$ [µg/m^{-3}]	STD$_O$ [µg/m^{-3}]	STD$_M$ [µg/m^{-3}]	NMB [%]	Corr [-]	RMSE [µg/m^{-3}]	IOA [-]	FAC2 [%]
Gdansk-Gdynia									
Port	28.69	12.17	16.91	7.49	-57.58	0.47	22.25	0.52	35
Siedlce	19.30	23.06	11.93	17.45	19.51	0.44	16.70	0.61	62
NovyPort	18.47	8.21	12.12	5.87	-55.57	0.27	15.77	0.49	33
Pogorze	17.21	8.56	10.24	6.86	-50.29	0.35	13.33	0.53	37
Szedolki	18.06	9.28	10.49	9.08	-48.60	0.11	15.79	0.44	34
Sopot	17.61	15.17	11.61	11.57	-13.83	0.48	12.05	0.68	47
Wrzescez	21.88	21.05	19.02	25.19	-3.81	0.25	27.76	0.46	56
Redlowo	17.91	11.39	13.17	15.74	-36.45	0.18	19.70	0.45	41
Rostock									
Am Strande	26.37	10.63	16.04	3.35	-59.69	0.14	22.40	0.40	40
Hohlbeinplatz	22.14	9.64	15.85	2.91	-56.45	0.02	20.34	0.38	45
Stuthof	16.11	10.46	14.43	4.77	-35.12	0.04	16.02	0.30	60
Warnemünde	16.03	10.95	11.22	2.51	-31.65	0.15	12.23	0.38	68
Riga									
Park	38.71	3.48	17.36	2.22	-91.02	0.39	38.96	0.37	1
Kronvalda	22.86	4.70	14.18	2.78	-79.46	0.34	22.64	0.43	11

Table SII-4: Model performance statistics of CityChem for O_3 based on 8h running mean concentrations at all stations with sufficient data availability in 2012 in all Baltic Sea urban domains.

Station	$\bar{O}$ [µg/m^{-3}]	$\bar{M}$ [µg/m^{-3}]	STD$_O$ [µg/m^{-3}]	STD$_M$ [µg/m^{-3}]	NMB [%]	Corr [-]	RMSE [µg/m^{-3}]	IOA [-]	FAC2 [%]
Gdansk-Gdynia									
Pogorze	48.40	35.19	21.21	19.75	-27.28	0.27	28.14	0.55	62
Szedolki	44.66	39.39	20.59	19.61	-11.80	0.20	25.92	0.52	64
Wrzescez	41.66	27.72	20.75	16.48	-33.45	0.31	26.16	0.56	53
Redlowo	47.34	34.24	21.35	21.19	-27.67	0.29	28.48	0.57	59
Rostock									
Hohlbeinplatz	35.80	36.05	18.81	19.23	0.72	0.46	19.68	0.68	65
Stuthof	48.31	45.03	21.92	19.80	-6.80	0.40	23.18	0.63	73
Warnemünde	53.17	46.14	24.53	22.31	-13.22	0.45	25.58	0.67	72

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