CityZen

megaCITY - Zoom for the Environment

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Impact of emission changes on air pollution

Introduction

Megacity emissions worldwide differ not only in total emission fluxes but also in emission ratios. The differences between megacities with relatively similar economical development and technological standards are generally less pronounced. Both total emission fluxes and emission ratios influence atmospheric composition and reactions, and hence air quality.

In this study, we investigate the effects of emission changes in four selected megacity areas on air pollution. These megacity areas comprise the BeNeLux (BNL) area (small), the greater Istanbul (IST) area and the Pearl River Delta (PRD) area as defined in the Cityzen project plus the Sao Paulo (SAP) megacity (Tab. 1). The study focuses on the year 2001, which is a year with relatively normal climatological conditions in these regions. Model simulations were carried out with the global chemistry climate model ECHAM5-MOZ at a horizontal resolution of T63, corresponding to around 1.875 degree, and a vertical resolution of 31 levels. The model simulation is done in a nudged mode with ERA Interim meteorological input data. Model simulation was started in July 2000 to allow for a spin-up of 6-months.

Megacity Area	Abbreviation	Megacity Boundaries [LON LAT]	Total Capita [mio.]	Total Area [km2]	Mean Population Density [cap km-2]
BeNeLux small	BNL	2.5 8 49.33 53.67	48.94	169,298	289
Istanbul big	IST	28 30.5 40 42	13.14	46,655	282
Pearl River Delta	PRD	112 115.5 21.5 24	53.65	99,763	538
Sao Paulo	SAP	-48.62 -44.62 -25.53 -21.53	31.25	181,385	172

Tab. 1: Megacity areas of investigated in this study. The total population in the megacity areas was calculated from the UN adjusted GPWv3 data of the year 2000 available from CIESIN/CIAT (2005).

The monthly gridded global emission inventory recently established for use in chemistry-climate simulations in connection to the IPCC-AR5 assessments (Lamarque et al. 2010) is used as emission input fluxes into the model. The inventory provides decadal mean monthly estimates of anthropogenic and biomass burning emissions gridded in a 0.5 degree resolution. While the biomass burning data have an intraannual variability, the monthly anthropogenic data are constant throughout a given year. To obtain emission data for the year 2001, the historic emission data for the decade 2000 were linearly interpolated in time with the corresponding RCP85 emission scenario data for 2005.

To study the effects of emission changes on air quality, four sensitivity simulations have been carried out in addition to the reference simulation described above. In the sensitivity simulations, only the urban emissions in the four megacities were modified at the original 0.5 degree resolution of the emission input data. The four modified megacity emission scenarios were calculated as follows:

- For each megacity area, the per capita emissions were calculated for each species and sector (see Tab. 2 to Tab. 4 using the total population information given in Tab. 1).

- The total urban per capita emissions calculated for a given megacity X was multiplied with the gridded population density (Fig. 1) in the three remaining megacity area of this study to obtain gridded total urban emissions for the emission scenario of megacity X (SCEN-MCX, with MCX=BNL, IST, PRD, SAP). The emissions in all other areas remained unchanged.

The gridded population density data (Fig. 1) and the gridded urban emission fluxes used in the reference simulation (for example CO emission fluxes, Fig. 2) highlight the pronounced spatial gradient between megacity area and the surroundings for PRD and SAP, while in BNL and IST the population and the urban emissions are spatially more evenly distributed.

Tab. 2 to Tab. 4 show that compared to all other megacity areas included in this study, total urban per capita CO and NMVOC (NMVOC-MOZ) emissions are highest in PRD while they are lowest in SAP. Total urban per capita NO emissions are highest in BNL and lowest in SAP. The relative contribution of the per capita emissions from the different urban sectors to the total urban per capita emissions differs distinctively between megacities. While in PRD and SAP, industrial activities make up the largest share to the total urban per capita emissions of CO and NO, it is the traffic sector in BNL and the domestic (and traffic (for NO)) sector in IST. For NMVOC, the domestic sector contributes by far the greatest part (76%) to total urban NMVOC emissions in PRD, while urban NMVOC emissions are more evenly distributed over all urban sectors in the other megacities. For instance, production and use, traffic and domestic activities contribute each 31, 26 and 18% to total urban NMVOC emissions in BNL.

The distinctly different sectoral NMVOC emission characteristics lead to very different NMVOC speciation profiles in the four megacity areas (Fig. 3). This is of particular relevance for tropospheric ozone formation since the individual NMVOC compounds have strongly differing photochemical ozone creation potential (POCP) (Wei et al. 2008). From urban NMVOC-MOZ species, ethene and propene have by far the highest POCP. Both contribute 70% to total urban NMVOC-MOZ emitted in PRD and only between 11 and 17% in the other three megacities. Not only the composition of the NMVOC mixture influences the ozone production but also the NMVOC/NOx ratio crucially. The NMVOC-MOZ/NO ratio calculated for the total urban emissions is 0.32 for BNL, 0.69 for IST, 0.78 for PRD and 1.00 for SAP.

The emission modifications aim at answering the question: how would air pollution in megacity X change if it had the same urban emissions per capita as megacity Y? It is, of course, unlikely that urban emissions patterns in the BenNeLux area will evolve into those of the Pearl River Delta area, where the technological and environmental standards of the vehicle fleet and other combustion facilities are still lower and where, at the same time, total energy consumption and related combustion by the general population (e.g. the number of vehicles per capita) is still distinctively lower. However, on the reverse, it can be expected that the emission per capita patterns in megacity areas of newly industrialised countries will, on the long term, evolve towards the pattern of the industrialised countries (e.g. BeNeLux area) with high standards of air pollution control technologies and measures.

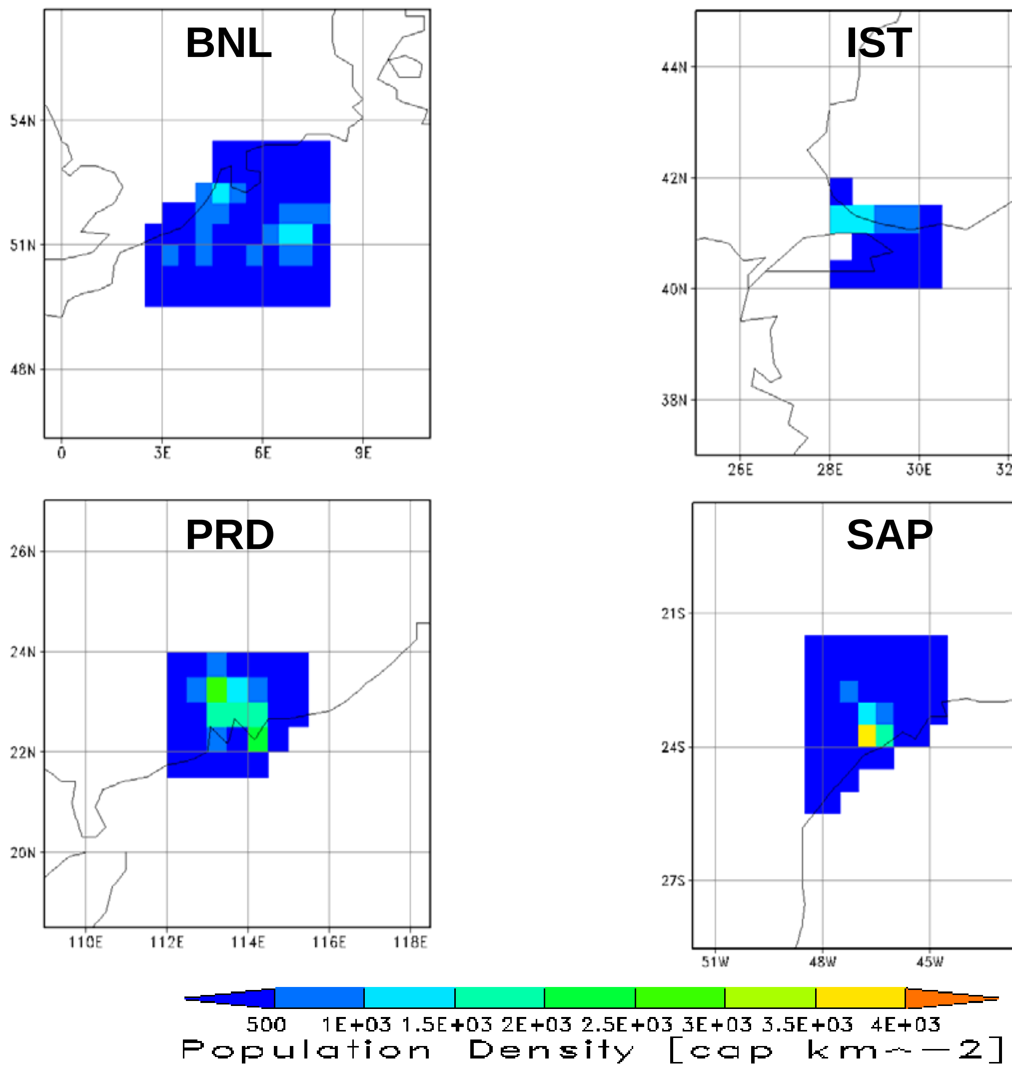

Fig. 1: Population density in the four megacity areas selected for this study based on UN-adjusted GPWv3 population data for the year 2000 (see also Tab. 1). The grid resolution is in 0.5 degree.

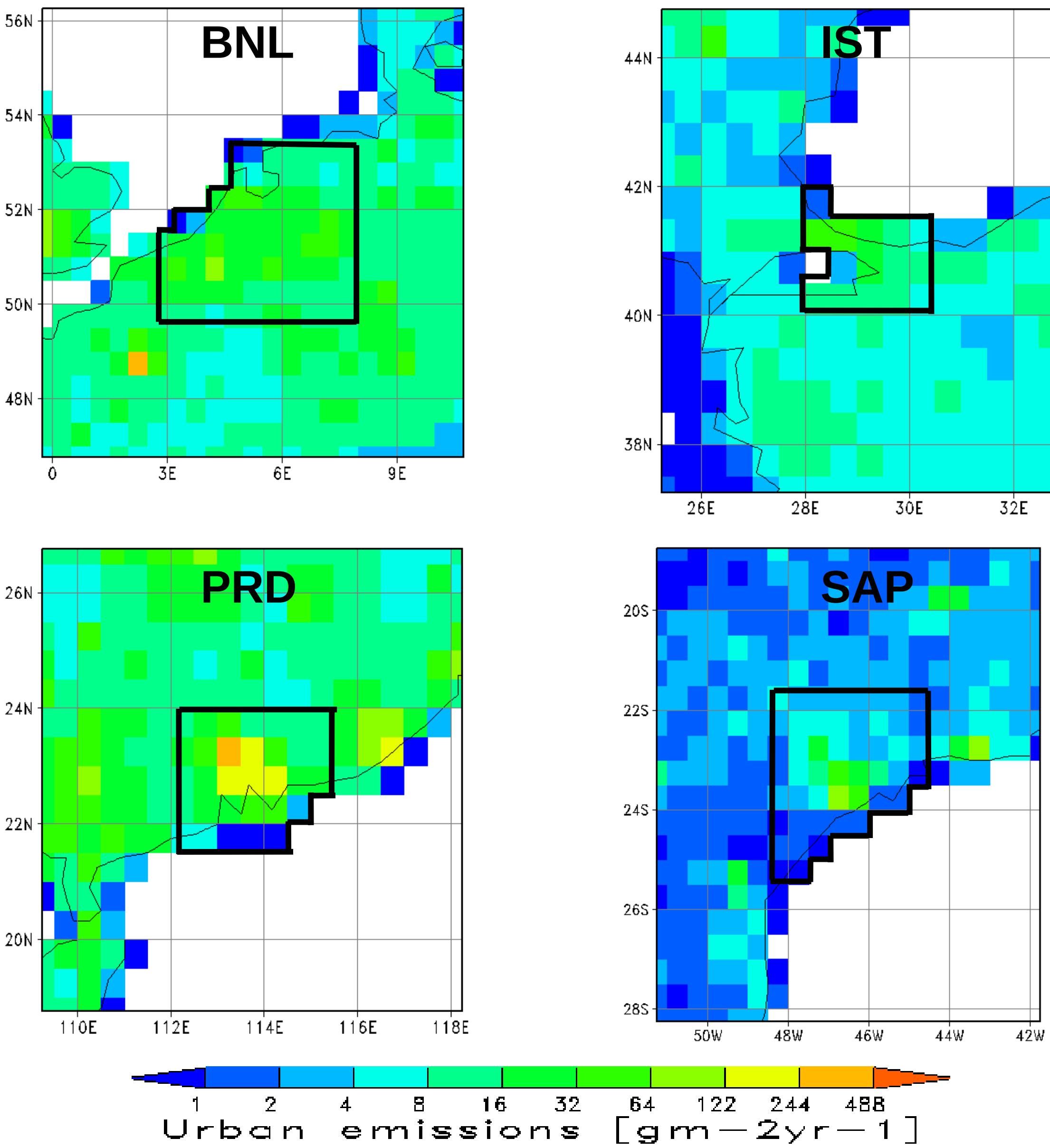

Fig. 2: Urban CO emission fluxes used in the reference simulation for the year 2001 in the four megacity areas selected for this study (contoured by black lines). To illustrate the spatial emission gradients towards their outskirts, the surrounding areas (around 300km) are shown as well. The grid resolution is 0.5 degree.

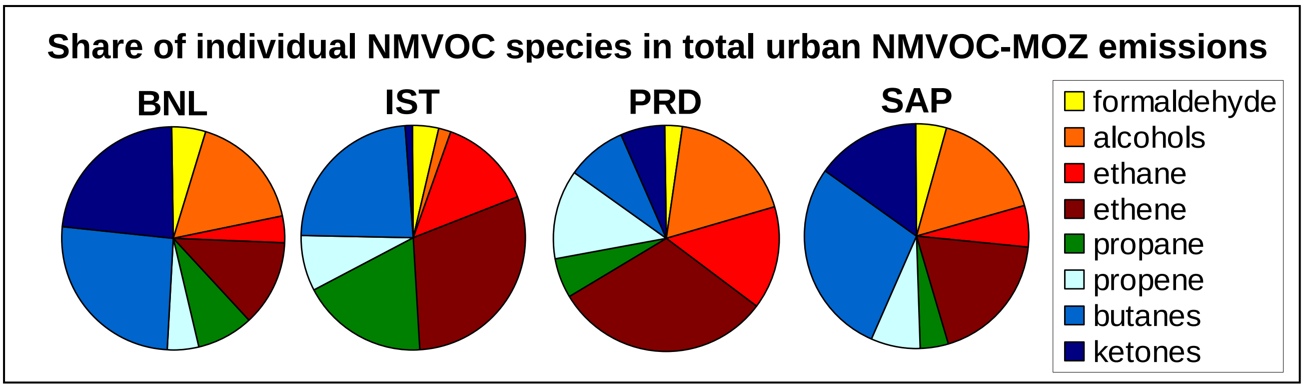

Fig. 3: Share of individual NMVOC species in total urban NMVOC-MOZ emissions in the year 2001 in the for megacity areas.

Megacity area	Species	Unit	IPCC AR5 emission sector								Urban sectors	All sectors
			ene	ind	tra	dom	slv	wst	agr	awb		
BNL	CO	Gg yr-1	65	900	1,340	770	0.4	33	0.0	13	**3,107**	**3,120**
		kg cap-1 yr-1	*1.3*	*18.4*	*27.4*	*15.7*	*0.01*	*0.67*	*0.00*	*0.26*	***63.5***	***63.7***
IST	CO	Gg yr-1	3	11	197	304	0.0	0.0	0.0	17	**516**	**532**
		kg cap-1 yr-1	*0.21*	*0.87*	*15.0*	*23.2*	*0.00*	*0.00*	*0.00*	*1.26*	***39.2***	***40.5***
PRD	CO	Gg yr-1	55	2,182	416	1,997	29	0	0	59	**4,678**	**4,737**
		kg cap-1 yr-1	*1.0*	*40.7*	*7.7*	*37.2*	*0.54*	*0.00*	*0.00*	*1.10*	***87.2***	***88.3***
SAP	CO	Gg yr-1	78	459	259	246	0.0	18	0.0	14	**1,060**	**1,074**
		kg cap-1 yr-1	*2.5*	*14.7*	*8.3*	*7.9*	*0.0*	*0.6*	*0.0*	*0.4*	***33.9***	***34.4***
GLOB	CO	Gg yr-1	19,589	99,232	210,655	249,344	686	4,252	13	19,524	**583,759**	**603,296**
		kg cap-1 yr-1	*3.2*	*16.4*	*34.8*	*41.2*	*0.11*	*0.70*	*0.00*	*3.22*	***96.4***	***99.6***

Tab. 2: Annual emissions of carbon monoxide (CO) of the four megacity areas (BNL, IST, PRD, SAP) and globally (GLOB) in the year 2001, differentiated by sectors. Regional totals (in Gg CO per year) and per capita emissions (in kg CO per capita and year) are shown. The individual sector definition is as follows: ene= energy production and distribution, ind= industry (combustion and non-combustion), tra= land transport, dom= residential and commercial, slv= solvents production and application, wst= waste treatment and disposal, agr= agriculture, awb= agricultural waste burning on fields. The two last columns provide totals for all sectors and all sectors categorised as urban (ene, id, tra, dom, slv,wst), respectively.

Megacity area	Species	Unit	IPCC AR5 emission sector								Urban sectors	All sectors
			ene	ind	tra	dom	slv	wst	agr	awb		
BNL	NO	Gg yr-1	133	104	337	98	0.0	0.9	23	0.4	**673**	**696**
		kg cap-1 yr-1	*2.7*	*2.1*	*6.9*	*2.0*	*0.00*	*0.02*	*0.46*	*0.01*	***13.7***	***14.2***
IST	NO	Gg yr-1	19	18	23	22	0.0	0.0	0.8	0.2	**81**	**82**
		kg cap-1 yr-1	*1.4*	*1.4*	*1.7*	*1.7*	*0.00*	*0.00*	*0.06*	*0.02*	***6.2***	***6.3***
PRD	NO	Gg yr-1	93	151	96	48	0.0	0.0	2.0	0.2	**388**	**390**
		kg cap-1 yr-1	*1.7*	*2.8*	*1.8*	*0.89*	*0.00*	*0.00*	*0.04*	*0.00*	***7.2***	***7.3***
SAP	NO	Gg yr-1	9	58	40	9	0.0	0.3	1.6	0.4	**117**	**119**
		kg cap-1 yr-1	*0.3*	*1.9*	*1.3*	*0.29*	*0.00*	*0.01*	*0.05*	*0.01*	***3.7***	***3.8***
GLOB	NO	Gg yr-1	15,599	10,452	22,842	5,962	0.0	189	1,405	405	**55,044**	**56,854**
		kg cap-1 yr-1	*2.6*	*1.7*	*3.8*	*1.0*	*0.00*	*0.03*	*0.23*	*0.07*	***9.1***	***9.4***

Tab. 3: Annual emissions of oxide of nitrogen (NO) of the four megacity areas (BNL, IST, PRD, SAP) and globally (GLOB) in the year 2001, differentiated by sectors. Regional totals (in Gg NO per year) and per capita emissions (in kg NO per capita and year) are shown. Please refer to Tab. 2 for the sector definition.

Megacity area	Species	Unit	IPCC AR5 emission sector								Urban sectors	All sectors
			ene	ind	tra	dom	slv	wst	agr	awb		
BNL	NMVOC-	Gg yr-1	30	22	57	38	68	1.2	0.0	0.6	**218**	**218**
	MOZ	*kg cap-1 yr-1*	*0.62*	*0.46*	*1.16*	*0.78*	*1.40*	*0.03*	*0.00*	*0.01*	***4.4***	***4.5***
IST	NMVOC-	Gg yr-1	0.2	12	19	25	0.0	0.0	0.0	0.0	**56**	**56**
	MOZ	*kg cap-1 yr-1*	*0.02*	*0.92*	*1.42*	*1.93*	*0.00*	*0.00*	*0.00*	*0.00*	***4.3***	***4.3***
PRD	NMVOC-	Gg yr-1	6	9	30	230	25	2	0.0	5	**301**	**306**
	MOZ	*kg cap-1 yr-1*	*0.11*	*0.16*	*0.55*	*4.28*	*0.47*	*0.03*	*0.00*	*0.09*	***5.6***	***5.7***
SAP	NMVOC-	Gg yr-1	40	10	34	12	18	2	0.0	1	**117**	**117**
	MOZ	*kg cap-1 yr-1*	*1.27*	*0.32*	*1.10*	*0.38*	*0.59*	*0.06*	*0.00*	*0.02*	***3.7***	***3.8***
GLOB	NMVOC-	Gg yr-1	9,191	1,862	7,771	15,288	3,449	339	2	1,158	**37,900**	**39,059**
	MOZ	*kg cap-1 yr-1*	*1.52*	*0.31*	*1.28*	*2.52*	*0.57*	*0.06*	*0.00*	*0.19*	***6.3***	***6.4***

Tab. 4: Annual emissions of lumped non-methane hydrocarbons (NMVOC-MOZ) of the four megacity areas (BNL, IST, PRD, SAP) and globally (GLOB) in the year 2001, differentiated by sectors. NMVOC-MOZ is the sum of all NMVOC species which are included in ECHAM5-MOZ chemistry scheme the NMVOCS and for which gridded anthropogenic emissions are available. These comprise ketones, ethane, ethane, propene, propane, formaldehyde, alcohols and butanes. Regional totals (in Gg NMVOC-MOZ per year) and per capita emissions (in kg NMVOC-MOZ per capita and year) are shown. Please refer to Tab. 2 for the sector definition.

In Tab. 5 and Fig. 4, total urban emission used in the megacity scenario simulations are summarised. Compared to the emissions used in the reference simulation, changing per capita urban emissions in BNL into those of IST or SAP will lead to reduction in total megacity emissions of CO and NO by between 40 to 80% and of between 5 to 20% for NMVOC. When the per capita emissions for PRD are applied, only NO decreases (by 50%) while CO and NMVOC increase by between 20 and 40%.

Megacity area	Species	Unit	SCEN-REF	SCEN-BNL	SCEN-IST	SCEN-PRD	SCEN-SAP
BNL	CO	Gg yr-1	3,107	*3,099*	1,916	4,256	1,656
	NO		673	*671*	302	353	182
	NMVOC-MOZ		218	*217*	209	274	182
IST	CO	Gg yr-1	516	832	*514*	1,142	445
	NO		81	180	*81*	95	49
	NMVOC-MOZ		56	58	*56*	74	49
PRD	CO	Gg yr-1	4,678	3,397	2,100	*4,666*	1,815
	NO		388	735	331	*387*	200
	NMVOC-MOZ		301	238	229	*300*	200
SAP	CO	Gg yr-1	1,060	1,978	1,223	2,717	*1,057*
	NO		117	428	193	225	*116*
	NMVOC-MOZ		117	139	134	175	*116*

Tab. 5: Annual total urban emissions of CO, NO and NMVOC-MOZ of the four megacity areas (BNL, IST, PRD, SAP in the year 2001 in the reference scenario (SEN-REF) and the four sensitivity scenarios (SCEN-BNL, SCEN-IST, SCEN-PRD and SCEN-SAP). The values of SCEN-REF refer to the urban totals given in Tab. 2-Tab. 4). For a given megacity (MC) area X, there are small differences in the emission totals between the scenarios of megacity X (SCEN-MCX) and the corresponding reference value (SCEN-REF) due to rounding error.

In Tab. 5 and Fig. 4, total urban emission used in the megacity scenario simulations are summarised. Compared to the emissions used in the reference simulation, changing per capita urban emissions in BNL into those of IST or SAP will lead to reduction in total megacity emissions of CO and NO by between 40 to 80% and of between 5 to 20% for NMVOC. When the per capita emissions for PRD are applied, only NO decreases (by 50%) while CO and NMVOC increase by between 20 and 40%. Changing the per capita urban emissions in IST and SAP, respectively, with those of the other megacities will lead to increases of total megacity emissions of CO, NO and NMVOC, except for SCEN-SAP in IST, where all three pollutants decrease slightly. Exchanging the per capita emission in PRD leads to a reduction of all three pollutants in SCEN-IST and SCEN-SAP. In SCEN-BNL, CO and NMVOC decrease in PRD while NO strongly increases.

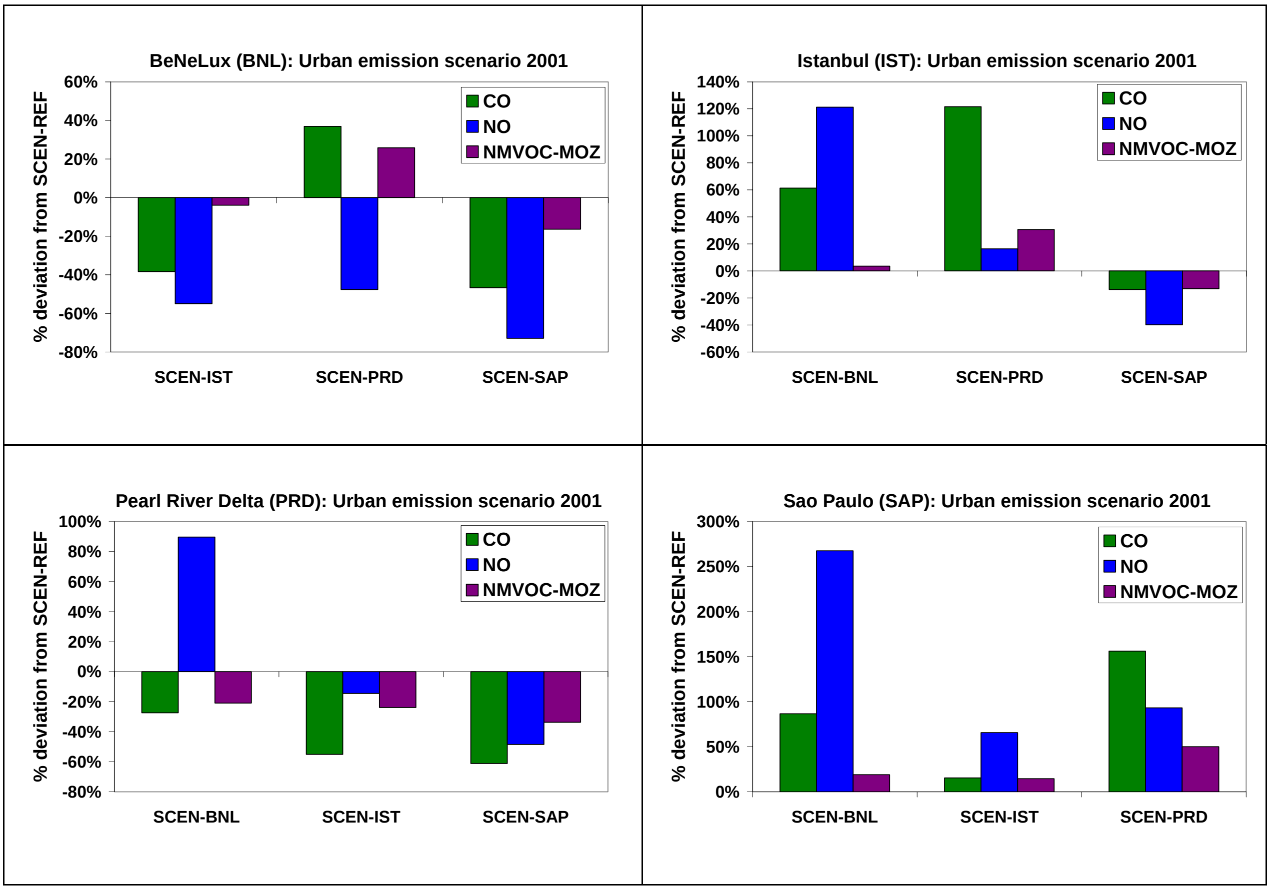

Fig. 4: Differences in annual total urban emissions between the emission scenarios and the reference value in the four megacity areas (see also Tab. 5).

Model evaluation: Reference simulation year 2001

Modelled surface concentrations of selected air pollutants were compared with station measurements to verify if the model produces realistic results.

The comparison of concentrations of carbon monoxide (CO) measured at selected background sites with corresponding model results (Fig. 5) shows that ECHAM5-MOZ reproduces fairly well the observed seasonal cycle. However, ECHAM5-MOZ almost constantly underpredicts observed concentrations by between 5 to 40 ppb in respect to the monthly averages.

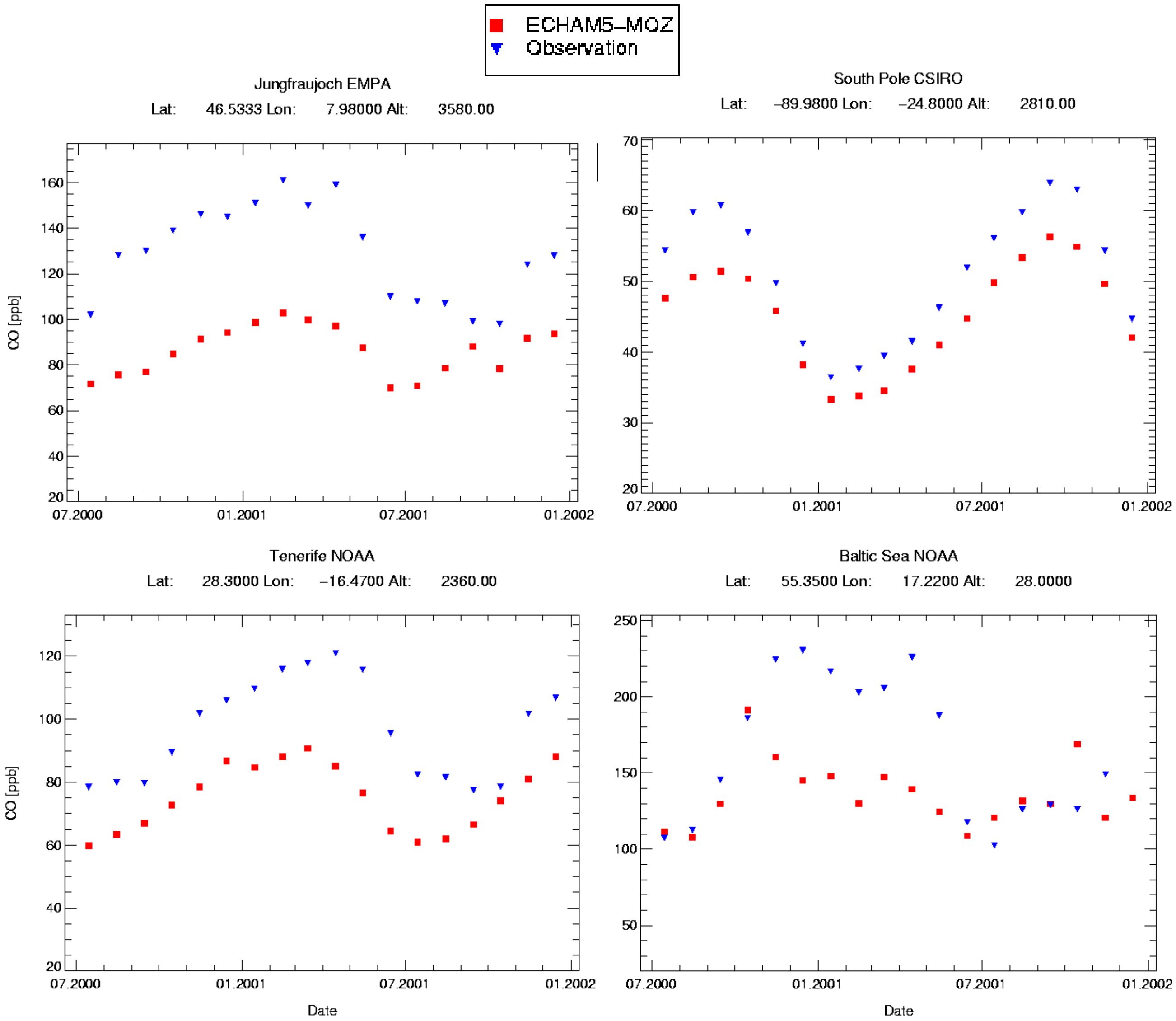

Fig. 5: Evaluation of simulated monthly mean concentrations of carbon monoxide with measurements from selected global atmospheric background stations.

Fig. 6 displays the comparison of simulated surface ozone concentrations with measurements from selected global atmospheric background stations. The figure shows that Annual mean ozone concentrations generally well captured. Seasonal cycle well captured for some stations (Spitsbergen, Zingst), partly captured at others (Mace Head, Ryori, Tsukuba, South Pole) and not well captured at the rest. Model reproduces daytime-nighttime differences very well.

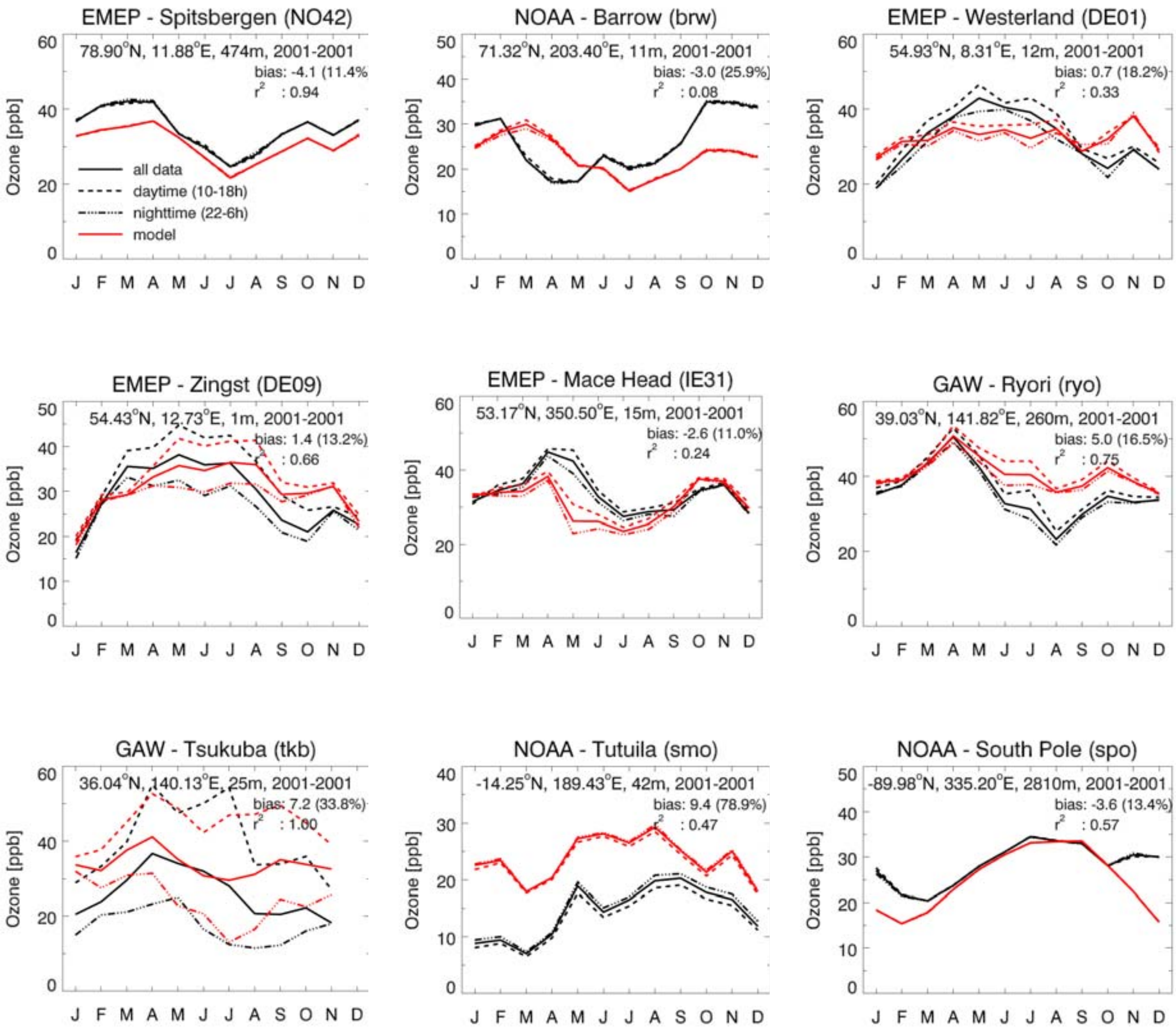

Fig. 6: Evaluation of simulated surface ozone concentrations for selected global atmospheric background stations. The comparisons are based on 3-hourly model output and hourly station data and take into account potential differences between daytime and nighttime conditions. The first bias value is the average monthly bias in ppb, the second value (in parantheses) is the average monthly absolute deviation in percent.

Modelled effects of modified urban emissions on air quality in 2001

The air quality effects of modified urban per capita emissions are illustrated in to Fig. 7 and Fig. 11 for annual mean surface concentrations of CO, O_3, NO_2, NO and PAN.

Annual mean ambient CO concentrations in the western BNL regions are predicted to decrease by 20 to 60 ppb when per capita emissions change into those of SCEN-IST and SCEN-SAP. Applying PRD per capita urban emissions leads to 20 to 80 ppb increases in annual mean CO levels in a horizontal band from 50 to 52N within the BNL domain. Differences of more than ± 20 ppb CO when compared to the reference simulation are observed in the northern regions of the IST megacity domain in the scenarios SCEN-BNL and SCEN-PRD, where annual mean CO concentrations increase by between 20 to 60 ppb. For all emission scenarios, annual mean CO levels are reduced by more than 40 ppb in the entire PRD megacity domain. Reductions in ambient CO concentrations relative to the reference simulation are also apparent in the outskirts west of the PRD megacity domain in the scenario SCEN-SAP. This reflects that strong reduction of CO emissions within a megacity may lead to a remarkably reduced outflow of CO to the adjacent regions. In SCEN-SAP, total megacity CO emissions are reduced by more than 60% in PRD compared to the reference emission inventory (see Fig. 4). In SAP, annual mean CO levels increase by more than 140 ppb in the SCEN-PRD scenario and by around 90 ppb in the SCEN-BNL emission scenarios, while changes are within ± 20 ppb CO in the SCEN-IST scenario.

Annual mean ambient O_3 concentrations in the entire BNL megacity domain are elevated by 3 to more than 7 ppb in all megacity emission scenarios. Most pronounced is the increase in the scenario SCEN-SAP, followed by SCEN-PRD and SCEN-IST. Increases in annual mean O_3 levels are also observed several hundred kilometres beyond the BNL megacity domain demonstrating that emission changes within the megacity area has also effects on larger areas due to the modified outflow of pollutants. Although the meteorological conditions are identical in all scenarios, the spatial gradients of the outflow patterns differ, hinting to non-linearities in the ozone production and destruction during atmospheric transport when emission ratios of ozone precursors differ. Modelled ozone levels increase from SCEN-SAP, over SCEN-PRD to SCEN-IST, i.e. which is most likely linked to the increasing NMVOC-MOZ/NO emission ratios used in these scenarios. In the IST megacity area, ozone levels increase by 2 to 5 ppb in the SCEN-PRD scenario, while they decrease by around the same range in the SCEN-BNL scenario. For the PRD megacity areas, increases in the annual mean ozone levels above 3 ppb only occur in the scenario SCEN-SAP while SCEN-BNL leads to by more than 4 ppb decreased annual mean ozone levels in the PRD megacity area. For the SAP megacity area, all scenarios lead to a reduction of annual mean ozone levels by more than 4 ppb in the north-western section of the domain while slight increases (up to 3ppb) are predicted for some southern regions.

Conclusions and outlook

Megacity areas exhibit large differences in their per capita sectoral emission production leading to very particular emission patterns for each megacity. In this work, we investigated the air quality effects of modifying the per capita urban emissions in selected megacity areas and observed strong effects upon photochemical smog production. Further work will aim at clarifying in detail the involved chemical mechanism in the modelled ozone production and depletion (relation to PAN, NO and NO_2 levels , see Fig. 9 to Fig. 11) and the critical NMVOC/NOx ratio for each megacity emission pattern.

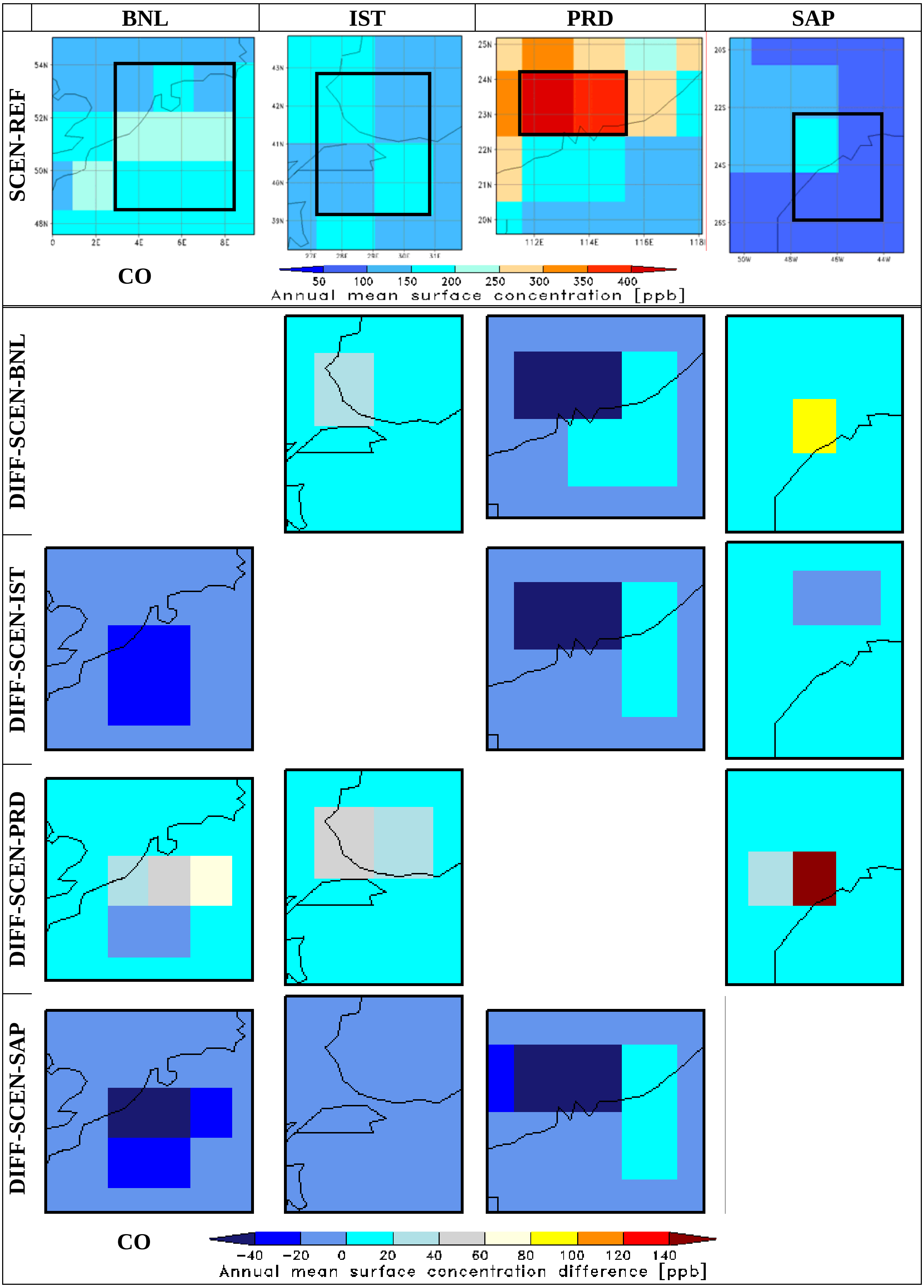

Fig. 7: Modelled annual mean carbon monoxide (CO) surface concentrations in the reference simulation (SCEN-REF) and the difference of between the results from the modified megacity emission scenarios (SCEN-MCX) and SCEN-REF (DIFF-SECN-MCX=SCEN-MCX - SEN-REF). The columns show the results for the four extended megacity areas selected for this study. The grid resolution is T63 (around 1.875 degree).

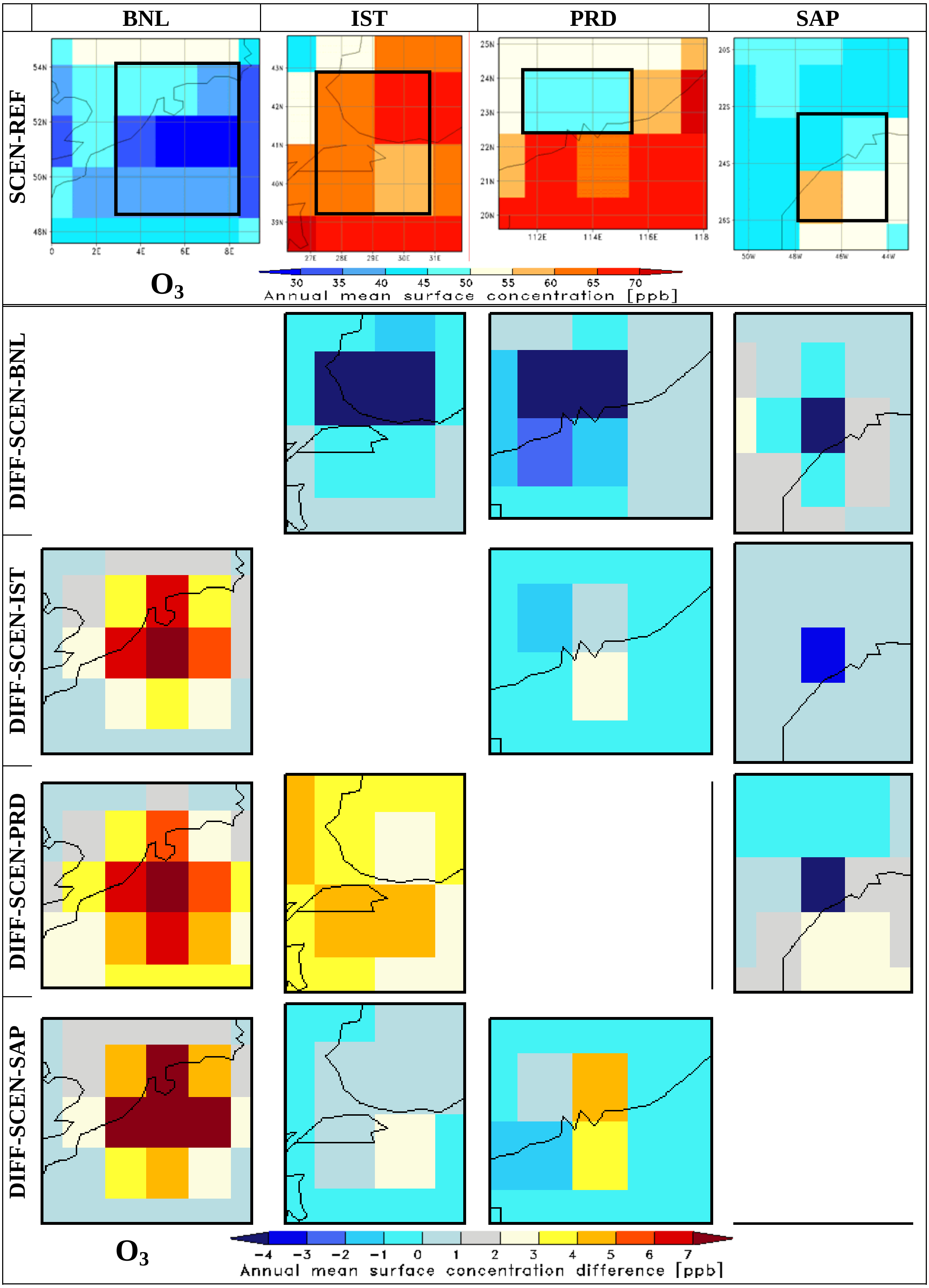

Fig. 8: Modelled annual mean ozone surface concentrations in the reference simulation (SCEN-REF) and the difference of between the results from the modified megacity emission scenarios (SCEN-MCX) and SCEN-REF (DIFF-SECN-MCX=SCEN-MCX - SEN-REF). The columns show the results for the four extended megacity areas selected for this study. The grid resolution is T63 (around 1.875 degree).

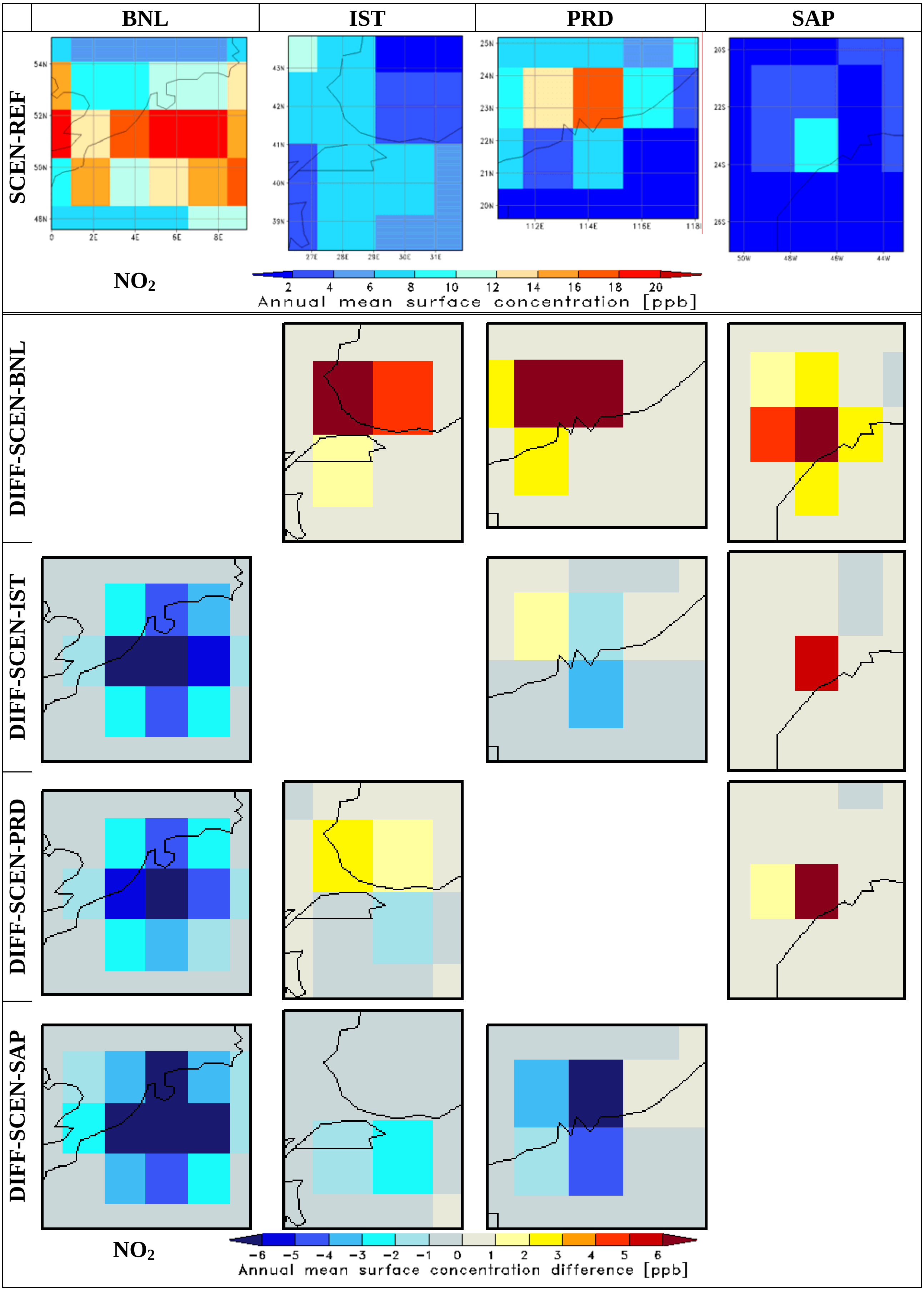

Fig. 9: Modelled annual mean nitrogen dioxide (NO_2) surface concentrations in the reference simulation (SCEN-REF) and the difference of between the results from the modified megacity emission scenarios (SCEN-MCX) and SCEN-REF (DIFF-SECN-MCX=SCEN-MCX - SEN-REF). The columns show the results for the four extended megacity areas selected for this study. The grid resolution is T63 (around 1.875 degree).

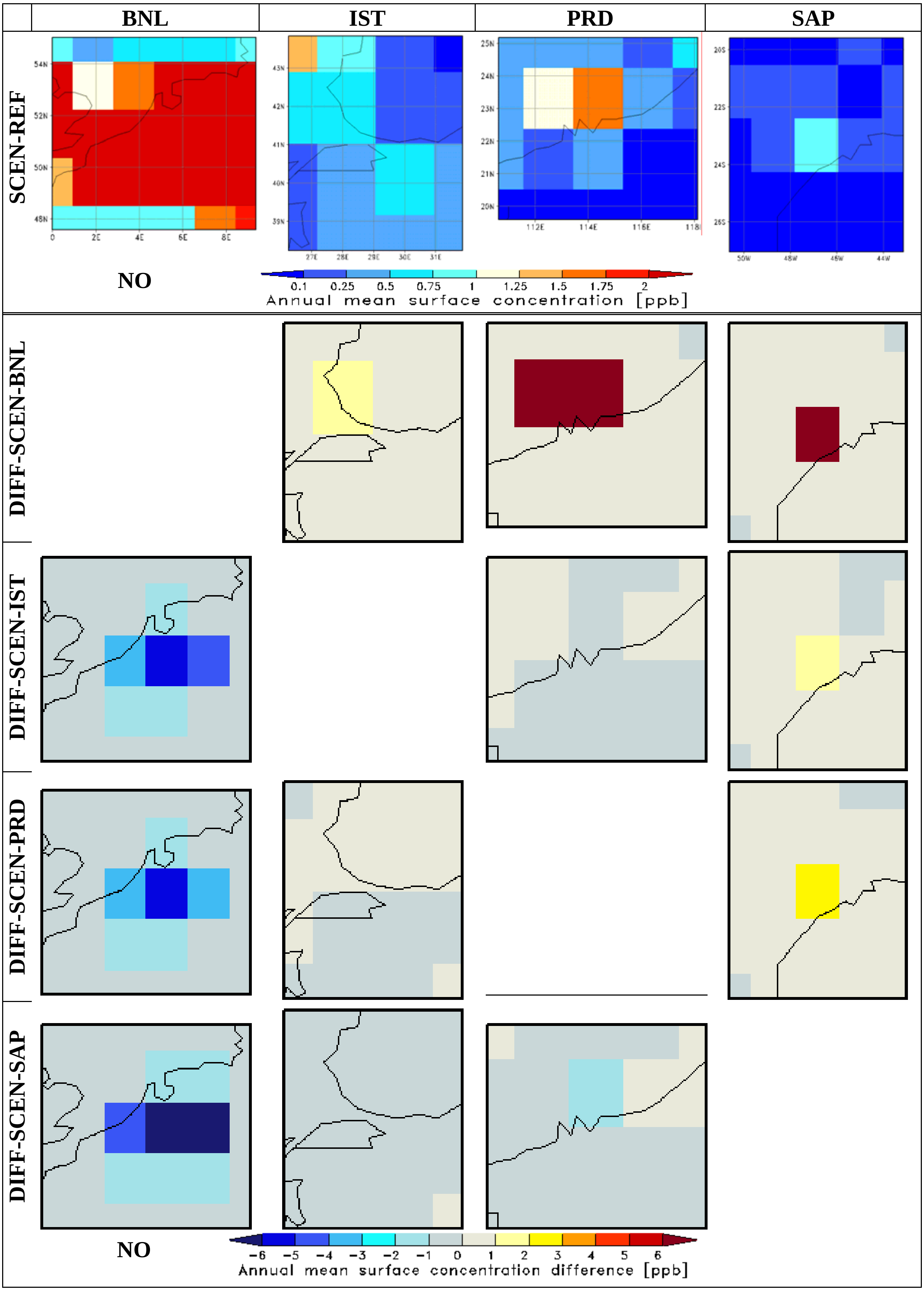

Fig. 10: Modelled annual mean nitrogen oxide (NO) surface concentrations in the reference simulation (SCEN-REF) and the difference of between the results from the modified megacity emission scenarios (SCEN-MCX) and SCEN-REF (DIFF-SECN-MCX=SCEN-MCX - SEN-REF). The columns show the results for the four extended megacity areas selected for this study. The grid resolution is T63 (around 1.875 degree).

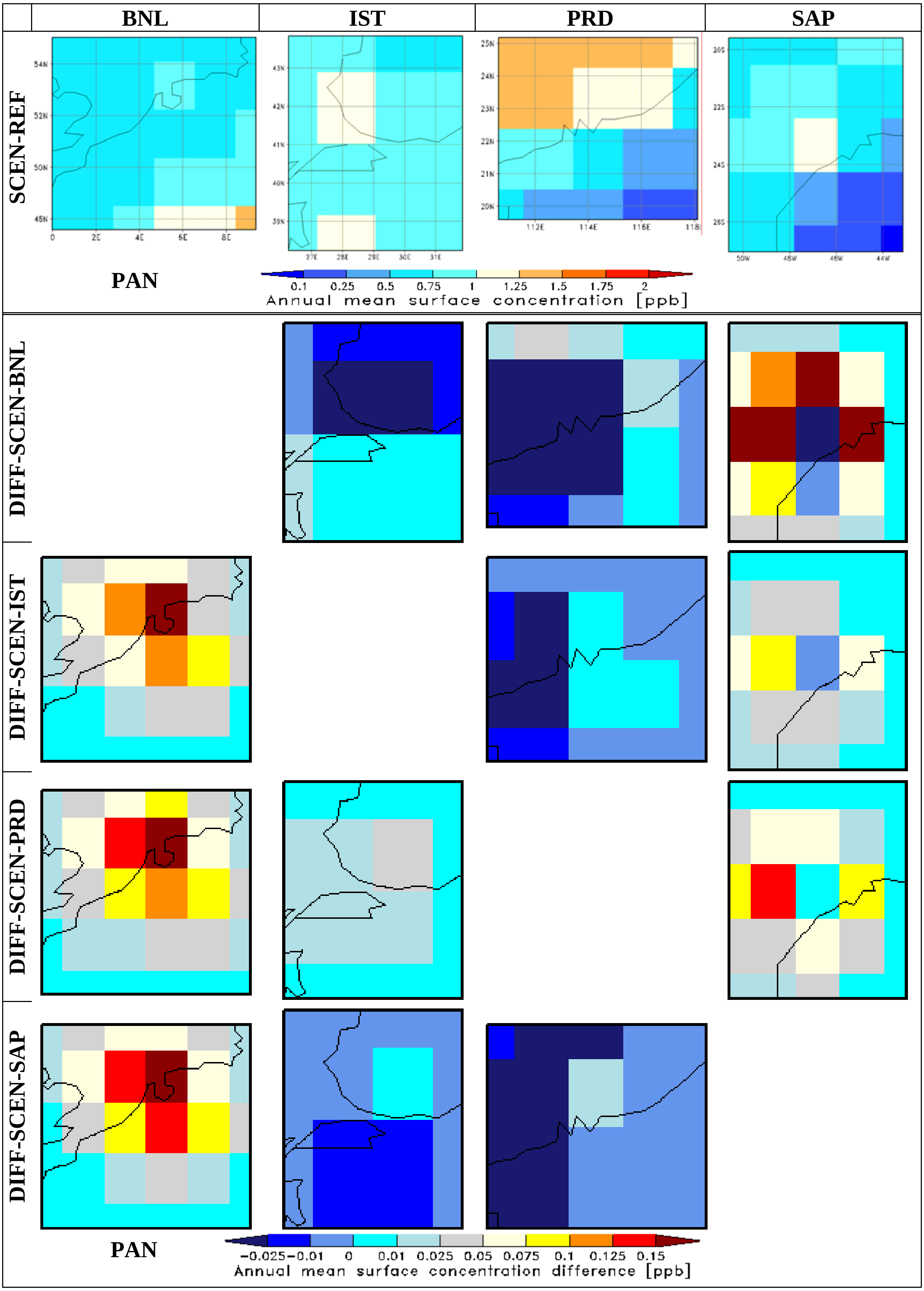

Fig. 11: Modelled annual mean peroxyacyl nitrates (PAN) surface concentrations in the reference simulation (SCEN-REF) and the difference of between the results from the modified megacity emission scenarios (SCEN-MCX) and SCEN-REF (DIFF-SECN-MCX=SCEN-MCX - SEN-REF). The columns show the results for the four extended megacity areas selected for this study. The grid resolution is T63 (around 1.875 degree).

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