Assessment of air quality and meteorological changes induced by future vegetation in Madrid

Supplementary Materials

Table S1. Dimensions and spatial resolution of WRF and CMAQ modelling domains

Domains	Geographic area	WRF X-Y Dimensions (km)	CMAQ X-Y Dimensions (km)	Horizontal resolution (km)
D1	Europe	248 x 220	187 x 176	27
D2	Iberian peninsula	159 x 129	131 x 99	9
D3	Spain central area	84 x 87	60 x 60	3
D4	Greater Madrid area	159 x 168	136 x 144	1

Table S2. Air quality parameter regulated by the Directive 2008/50/EC on ambient air quality and cleaner air for Europe

Average time	NO_2 ($\mu g\ m^{-3}$)	O_3 ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)
Annual mean	40	-	40	20
Daily mean	-	120 [2]	50 [3]	-
Hourly mean	200 [1]	-	-	-

[1] Not to be exceeded more than 18 times per calendar year
[2] Maximum daily eight-hour mean. Not to be exceeded more than 25 times per calendar year
[3] Not to be exceeded more than 35 times per calendar year

Table S3. Properties of relevant natural-land uses (WRF VEGPARM file)

Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SHDFAC	0.80	0.79	0.80	0.79	0.79	0.77	0.76	0.80	0.79	0.80	0.79	0.80	0.78	0.76	0.70	0.71
NROOT	3.00	4.00	3.00	4.00	3.00	3.00	4.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	3.00	3.00
RS	40.00	104.00	40.40	104.00	49.10	69.80	92.50	40.40	56.20	70.20	80.00	40.60	62.00	84.70	169.70	159.10
RGL	100.00	30.00	99.70	30.00	91.80	73.20	52.80	99.70	85.40	64.80	57.70	99.40	80.20	59.80	99.70	85.40
HS	36.25	53.00	36.32	53.00	37.80	41.31	45.17	36.32	39.01	44.17	45.25	36.45	40.06	43.89	39.23	41.33
SNUP	0.04	0.08	0.04	0.08	0.04	0.06	0.07	0.04	0.05	0.04	0.05	0.04	0.05	0.06	0.04	0.04
MAXALB	66.00	57.00	65.90	57.00	64.60	61.30	57.60	65.90	63.40	60.00	58.70	69.90	65.40	60.60	64.90	62.60
LAIMIN	1.56	2.29	1.57	2.29	1.85	2.50	3.22	1.57	2.07	2.01	2.42	0.55	1.51	2.53	0.62	1.31
LAIMAX	5.68	3.78	5.68	3.78	5.65	5.60	5.53	5.68	5.63	4.01	4.31	2.92	3.63	4.37	2.61	3.20
EMISSMIN	0.92	0.93	0.92	0.93	0.92	0.93	0.94	0.93	0.93	0.93	0.93	0.92	0.93	0.93	0.93	0.93
EMISSMAX	0.99	0.93	0.98	0.93	0.98	0.97	0.96	0.99	0.98	0.99	0.98	0.96	0.96	0.95	0.95	0.95
ALBEDOMIN	0.17	0.15	0.17	0.15	0.17	0.16	0.14	0.20	0.19	0.16	0.15	0.19	0.17	0.16	0.22	0.20
ALBEDOMAX	0.23	0.16	0.23	0.16	0.22	0.19	0.17	0.25	0.23	0.20	0.19	0.23	0.20	0.18	0.30	0.27
Z0MIN	0.05	0.50	0.05	0.50	0.10	0.22	0.35	0.02	0.12	0.20	0.26	0.10	0.21	0.33	0.01	0.11
Z0MAX	0.15	0.50	0.15	0.50	0.19	0.28	0.39	0.10	0.18	0.20	0.26	0.12	0.23	0.34	0.06	0.15

1 Dryland, Cropland and Pasture
2 Average urban tree in Madrid
3 Metropolitan forest
4 Dryland, Cropland and Pasture and (0 – 5%) Metropolitan forest
5 Dryland, Cropland and Pasture and (5 –20%) Metropolitan forest
6 Dryland, Cropland and Pasture and (20 – 50%) Metropolitan forest
7 Dryland, Cropland and Pasture and (50 –90%) Metropolitan forest
8 Irrigated Cropland and Pasture and (0 – 5%) Metropolitan forest
9 Irrigated Cropland and Pasture and (>5%) Metropolitan forest
10 Cropland/Woodland Mosaic and (0 – 5%) Metropolitan forest
11 Cropland/Woodland Mosaic (>5%) Metropolitan forest
12 Grassland (0 – 10%) Metropolitan forest
13 Grassland (20 – 40%) Metropolitan forest
14 Grassland (>40%) Metropolitan forest
15 Mixed Shrubland/Grassland (0 - 5%) Metropolitan forest
16 Mixed Shrubland/Grassland (> 5%) Metropolitan forest

Meteorological evaluation

To gain confidence in the results of the meteorological model, we performed a statistical assessment for the whole year 2015 using hourly observations of the main variables (temperature at 2 m height, relative humidity, wind speed and wind direction). In addition, we incorporated estimations of the planetary boundary layer height from a SODAR-RASS instrument operated by Madrid City Hall. In our analysis, we include all the meteorological stations from NOAA in our modelling domain, as well as observations from Madrid's meteorological network (Table S-met), totalizing more than 400000 observations.

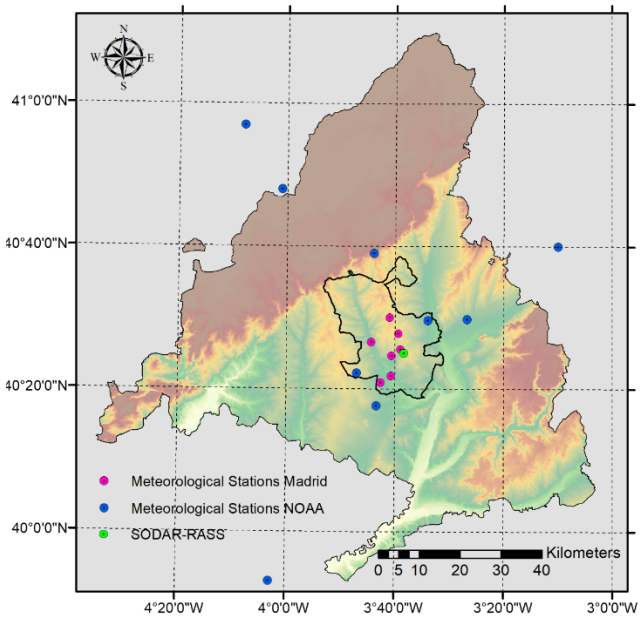

Figure S-met. Meteorological stations and SODAR RASS used in evaluation model.

The analysis is stratified for each network, since measurement procedures are not necessarily comparable. In addition, the stations integrated in Madrid's meteorological network are located in urban areas and observations may be affected by local influences, hindering comparability with those integrated in the World Meteorological Network, provided by NOAA. We present the corresponding summaries in Table S4 and Table S5.

We computed a series of common statistics for a comprehensive view of model performance:

FAC2 - fraction of predictions within a factor of two

MB – mean bias

MGE - mean gross error

NMB - normalized mean bias

NMGE - normalized mean gross error

RMSE - root mean squared error

r - Pearson correlation coefficient

IOA - index of agreement

N- number of complete pairs of data for that meteorological variable

Obs. Avg – mean observed value

Model Avg – mean predicted WRF value

Table S4. Statistical evaluation of the meteorological simulations (NOAA meteorological stations)

Statistic	T (2m)	RH	WS (10m)	WD (10m)
FAC2	0.95	0.99	0.62	0.72
MB	-0.2°C	-0.3%	-0.21 m s^{-1}	-7.81°
MGE	1.4°C	6.8%	1.6 m s^{-1}	69.25°
NMB	0.0	0.0	-0.07	-0.04
NMGE	0.1	0.1	0.5	0.4
RMSE	1.9°C	9.2%	2.19 m s^{-1}	113.5°
r	0.98	0.93	0.62	0.47
IOA	0.91	0.84	0.53	0.62
N	49914	49901	43536	43536
Obs. Avg	16.0°C	55.5%	3.1 m s^{-1}	181.3°
Model Avg	15.8°C	55.2%	2.9 m s^{-1}	173.5 °

Table S5. Statistical evaluation of the meteorological simulations (Madrid meteorological network stations)

Statistic	T (2m)	RH	WS (10m)	WD (10m)	PBL Height
FAC2	0.87	0.98	0.42	0.67	0.41
MB	2.0°C	-0.3%	-0.12 m s^{-1}	3.18°	84.5 m
MGE	2.4°C	7.9%	0.79 m s^{-1}	75.77°	473.4 m
NMB	0.14	-0.01	-0.1	0.02	0.15
NMGE	0.17	0.15	0.66	0.49	0.8
RMSE	3.2°C	10.8%	1.02 m s^{-1}	114.1°	728.1 m
r	0.97	0.88	0.51	0.42	0.62
IOA	0.84	0.80	0.53	0.61	-0.01
N	51521	51521	51521	51521	8265
Obs. Avg	14.3°C	52.5%	1.2 m s^{-1}	154.9°	564.7 m
Model Avg	16.3°C	52.2%	1.1 m s^{-1}	158.1°	661.2 m

According to these results, we found the results reliable enough to support the analysis proposed, since departures from the observations are within reasonable limits for a mesoscale meteorological model. It can be seen, nonetheless, that WRF presents slightly better results for the NOAA dataset, reported from meteorological stations outside the Madrid urban area.

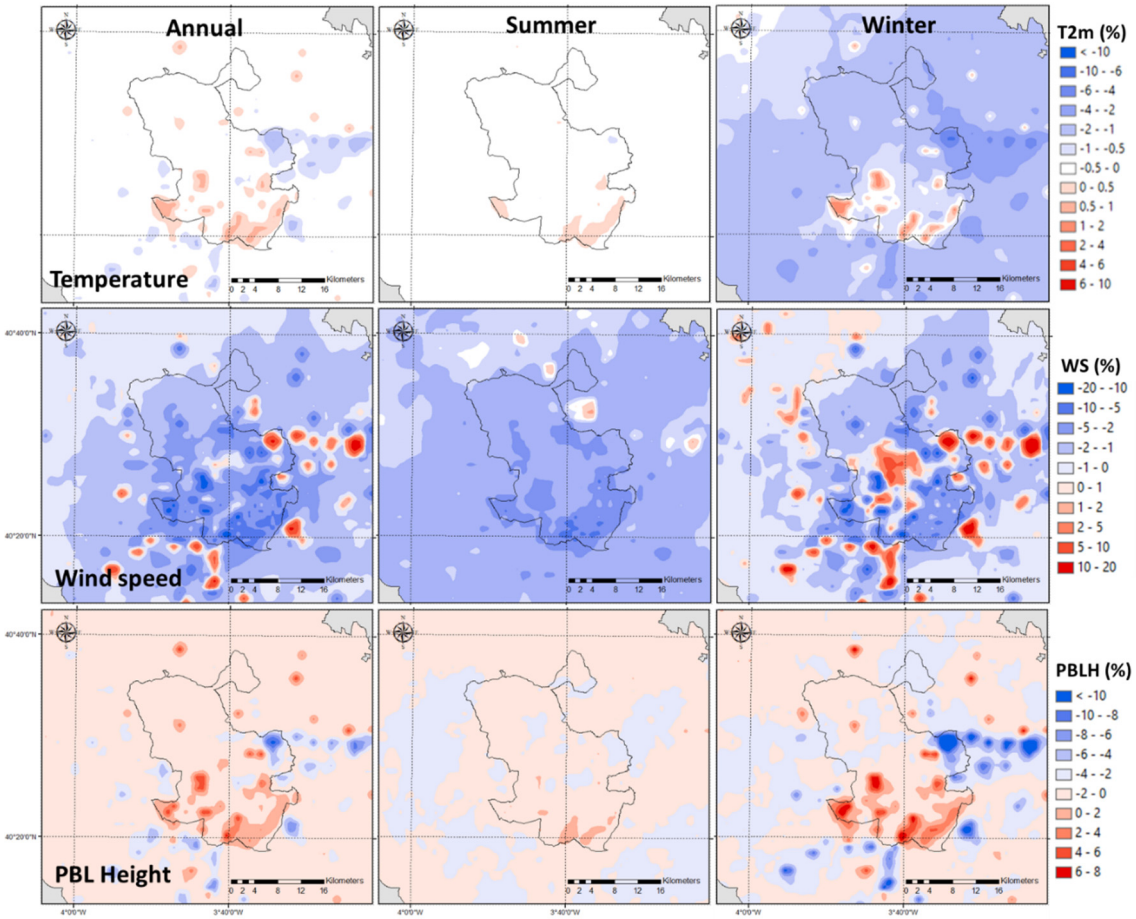

Figure S1. Annual mean temperature, wind speed (10m) and PBL height relative changes (100 x (Future – Baseline) / Baseline)

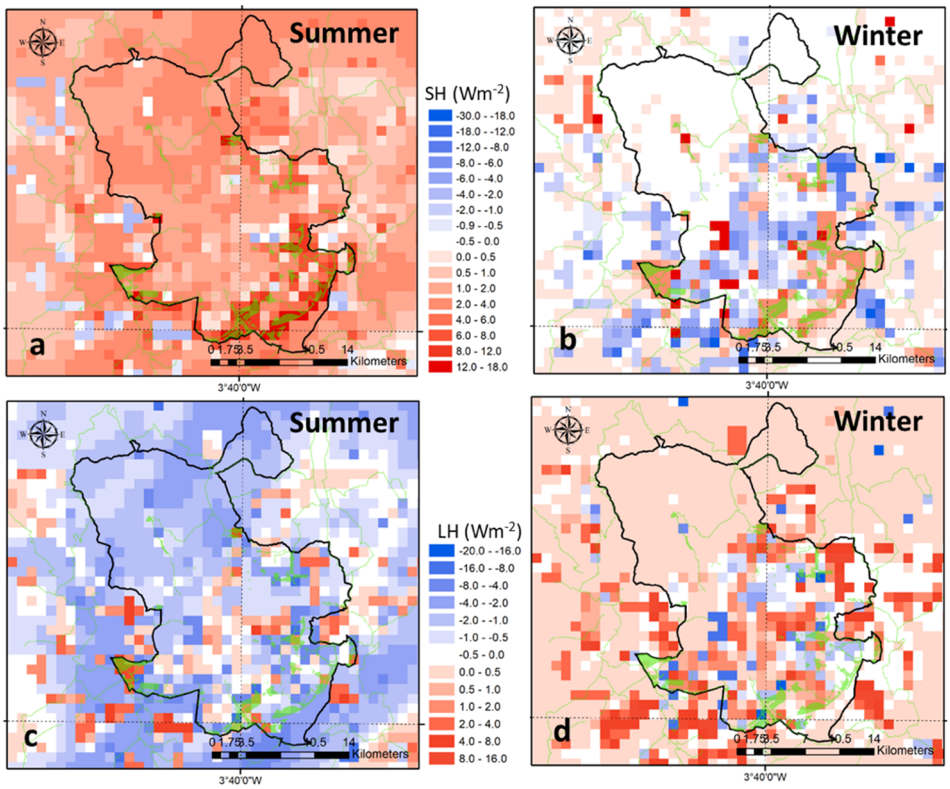

Figure S2. Seasonal mean variation (Future–Baseline) sensible heat flux (W m^{-2}) at the surface in summer (a) and winter (b). Seasonal mean variation (Future–Baseline) latent heat flux at the surface in summer (c) and winter (d).

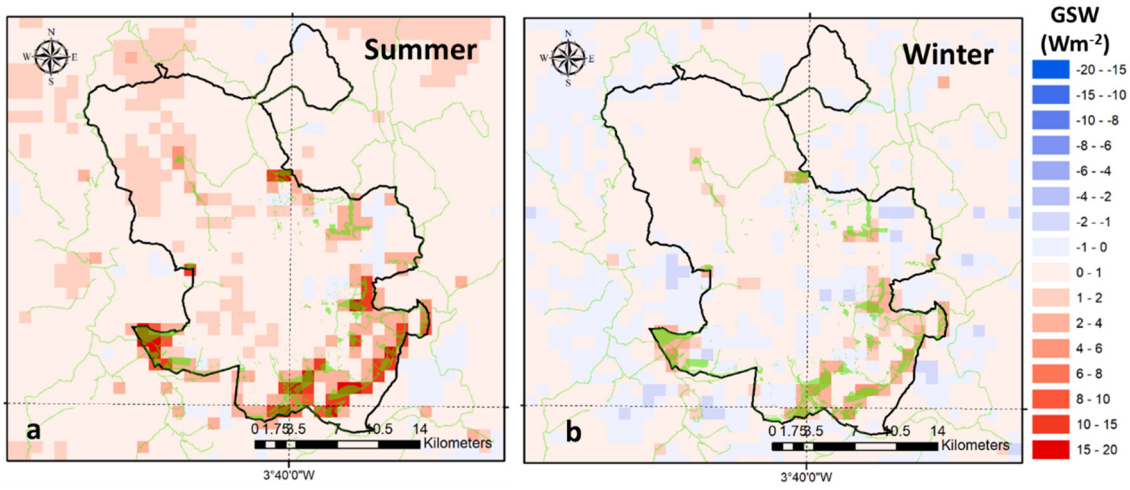

Figure S3. Seasonal mean variation (Future–Baseline) of solar radiation absorbed at ground in winter (a) and summer (b)

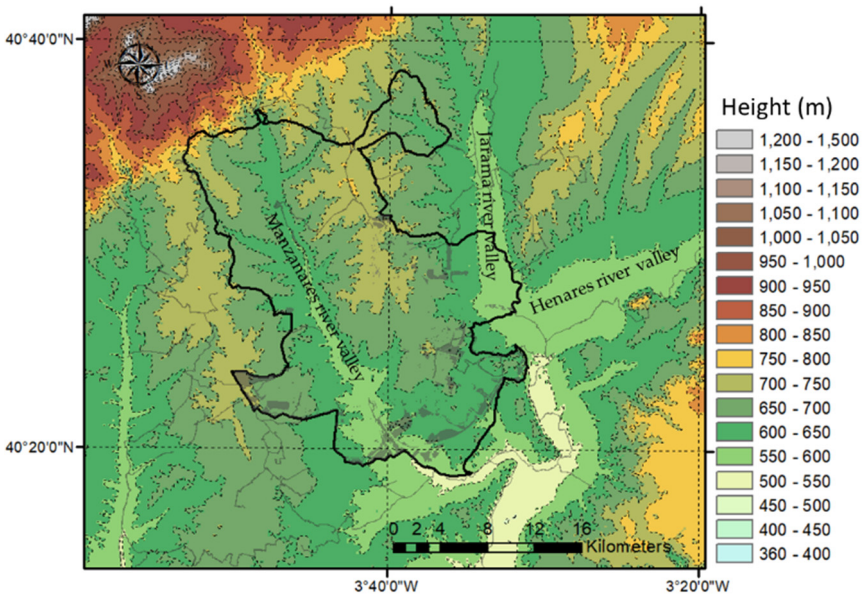

Figure S4. Detailed topographic map of the study area

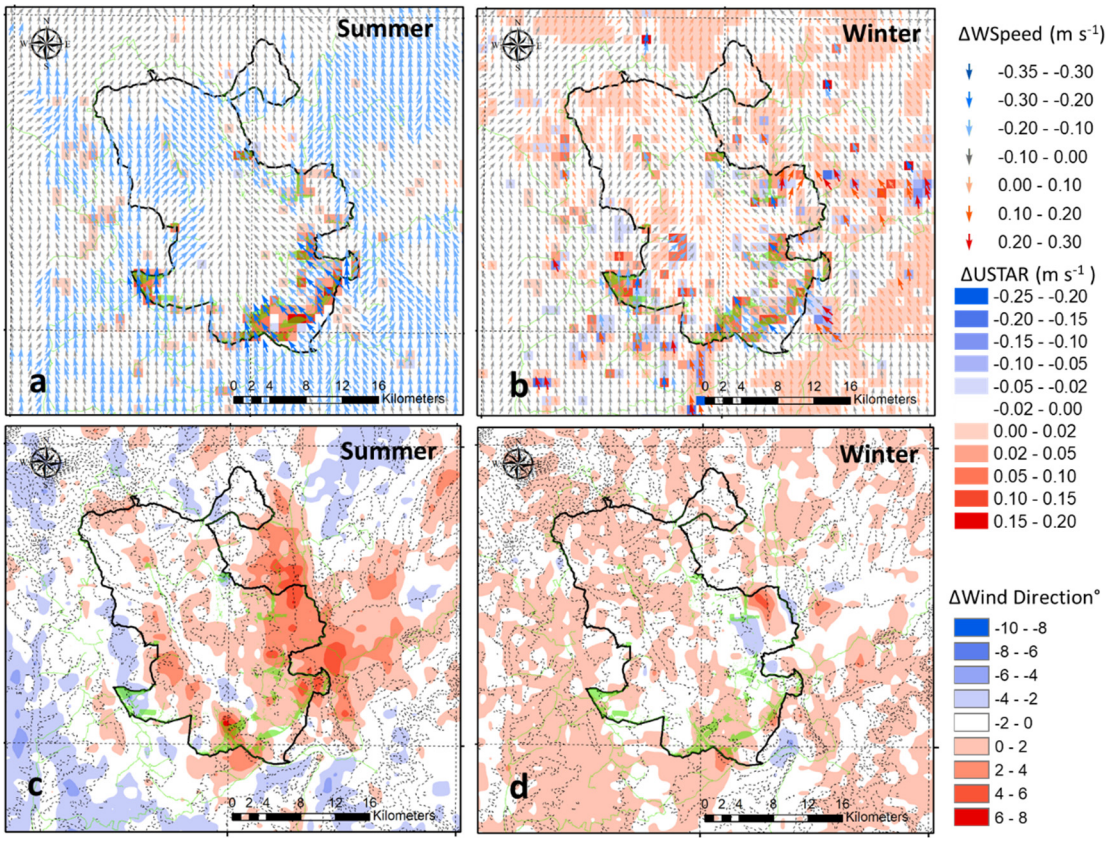

Figure S5. Seasonal mean variation (Future–Baseline) of friction velocity (ΔUSTAR) and wind speed in summer (a) and winter (b). Seasonal mean variation (Future–Baseline) wind direction in summer (c) and winter (d).

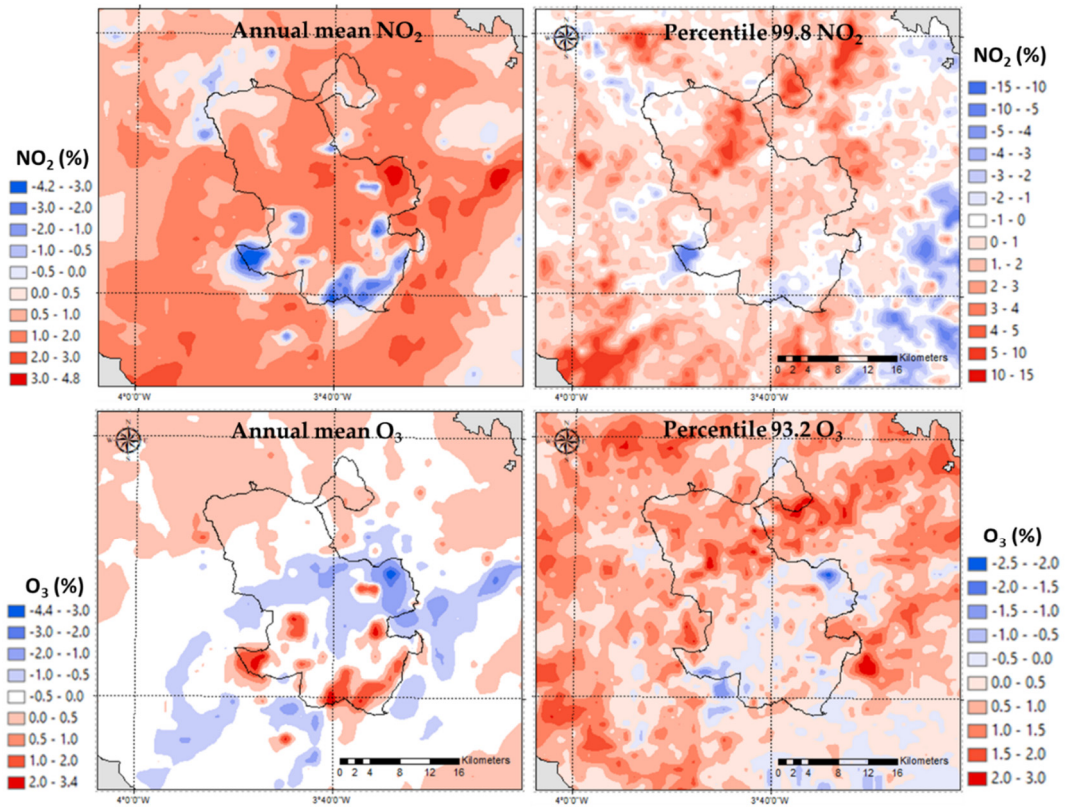

Figure S6. NO_2 and O_3 relative changes (100 x (Future–Baseline) / Baseline)

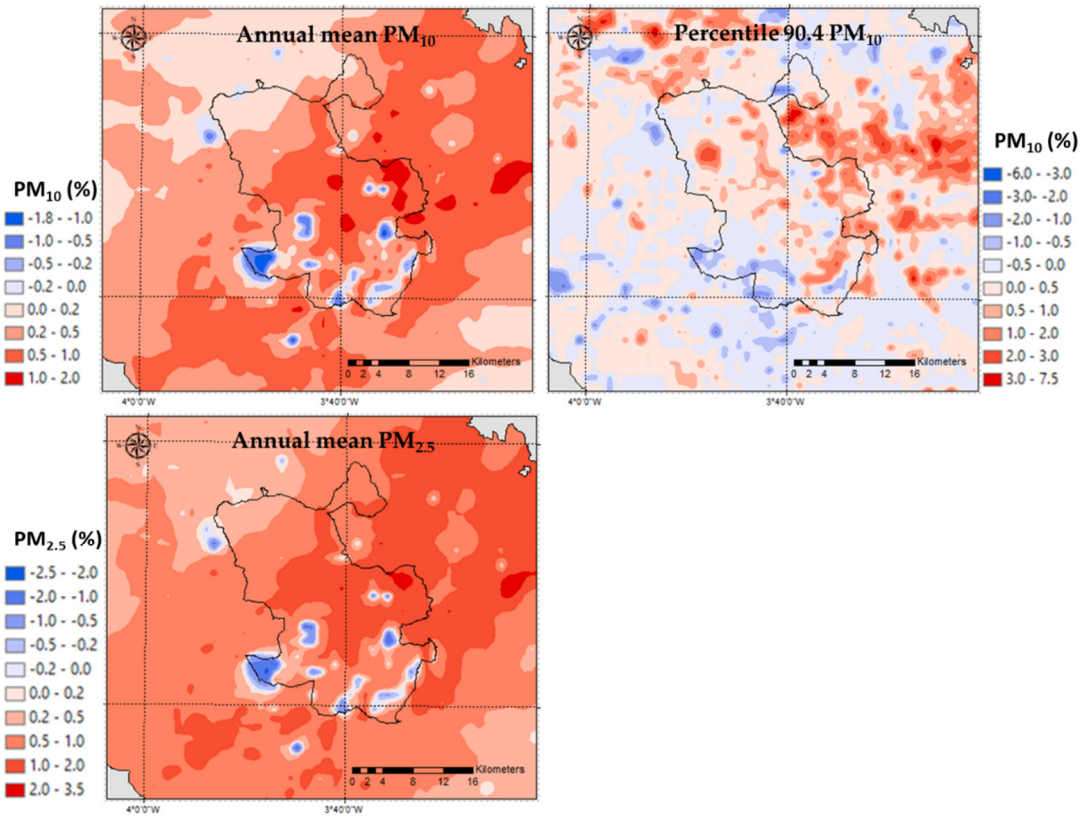

Figure S7. PM_{10} and $PM_{2.5}$ relative changes (100 x (Future–Baseline) / Baseline