

Supplementary material to the manuscript entitled

Assessing CO₂ fluxes over Greece using CTDAS-WRF – A sensitivity analysis

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Table S1. Physics options used for the WRF simulations

Physics	Scheme name	Option
Microphysics	Morrison double-moment (Morrison et al., 2009)	10
Longwave radiation	RRTMG scheme (Iacono et al., 2008)	4
Cumulus parameterization	Grell 3D (Grell, 1993; Grell & Dévényi, 2002)	5
Shortwave radiation	RRTMG scheme (Iacono et al., 2008)	4
Surface layer	Eta similarity (Janjić, 1994)	2
Land surface physics	Noah Land Surface Model (Chen & Dudhia, 2001)	2
Planetary boundary layer	Mellor-Yamada-Janjić (Janjić, 1994)	2
Urban surface physics	Urban canopy model (Kusaka & Kimura, 2004)	1

S2. Derivation of the correlation length from region geometry

In the state vector used here, the prefectures can be considered as regions within which prior emission scaling factors are fully correlated, with zero correlation between regions (a Heaviside correlation function). A characteristic correlation length can be derived from the region geometry, representing each region (i) by the radius of a circle of equivalent area, $r_i = (A_i/\pi)^{1/2}$, where the area A_i was derived from the number of region pixels multiplied by the pixel area of the 12 km grid (approximately 144 km² per pixel). The per-region radii were aggregated into a single correlation length L_{corr} using an area-weighted mean, $L_{corr} = \sum (A_i \times r_i) / \sum A_i$, so that small, spatially fragmented island regions, whose equivalent radius was least meaningful, contribute little weight. This yields an area-weighted correlation length of $L_{corr} \approx 62\text{km}$ (the per-region radii and the mean, median and area-weighted estimates are listed in Table S2).

Table S2. Region geometry and derived correlation length.

Equivalent-circle radius of each state-vector region. Regions classified as island group are spatially fragmented archipelagos, for which a single equivalent radius is not a meaningful descriptor, note that large compact islands such as Crete are not in this category and are retained. The summary below reports the correlation length for all 13 regions and for the subset excluding the island groups.

Region	N pixels	Area (km ²)	Radius (km)	Classification
1.Thessaly	101	14401	67.7	included

Region	N pixels	Area (km ²)	Radius (km)	Classification
2.Continental Greece	105	14972	69	included
3. Ionian islands	15	2139	26.1	island group
4. Western Greece	80	11407	60.3	included
5. Peloponnese	107	15257	69.7	included
6. Attica	24	3422	33	included
7. North Aegean	29	4135	36.3	island group
8. South Aegean	35	4991	39.9	island group
9. Crete	58	8270	51.3	included
10. East Macedonia and Thrace	102	14544	68	included
11. Central Macedonia	134	19107	78	included
12. West Macedonia	68	9696	55.6	included
13. Epirus	62	8840	53	included

Summary correlation length and implied localization length.

The area-weighted radius is taken as the correlation length L_{corr} . Excluding the island groups changes L_{corr} only modestly (62.4 vs 64.9 km), confirming that the result is robust to how these regions are treated. The implied localization length applies the $\times 3$ rule of Peters et al. (2005), with the Heaviside-to-Gaussian shape factor $2/\pi^{1/2} \approx 1.13$; the 163–220 km range spans the mean, median and area-weighted radii, both region selections, and the plain and shape-adjusted conventions.

Radius statistic	All 13 regions	Excluding island groups
Mean radius (km)	54.4	60.6
Median radius (km)	55.6	64
Area-weighted radius, L_{corr} (km)	62.4	64.9
Implied localization length, $\times 3$ rule (km)	163–220 (range across all variants)	

Table S3. Model evaluation for the simulations varying by the assimilation window (January 2019)

Site	Simulation	RMSE (ppm)	Mean Bias (ppm)	R ²
Thissio	2 weeks	9.96	-2.33	0.71
	3 weeks	10.85	-3.54	0.67
Finokalia	2 weeks	1.15	0.53	0.76
	3 weeks	1.16	0.55	0.76
Helmos	2 weeks	1.08	0.06	0.48

3

3 weeks

1.08

0.06

0.48

Table S4. Model evaluation for the simulations varying by the prior emission uncertainty (January 2019)

Site	Simulation	RMSE (ppm)	Mean Bias (ppm)	R ²
Thissio	Prior	19.58	-14.0	0.59
	10%	11.22	-4.52	0.71
	25%	10.26	-2.87	0.72
	50%	9.96	-2.33	0.71
	100%	10.14	-1.70	0.69
Finokalia	Prior	1.20	0.43	0.70
	10%	1.16	0.58	0.76
	25%	1.15	0.56	0.76
	50%	1.15	0.53	0.76
	100%	1.20	0.62	0.76
Helmos	Prior	1.03	0.09	0.52
	10%	1.08	0.06	0.48
	25%	1.08	0.06	0.48
	50%	1.08	0.06	0.48
	100%	1.09	0.1	0.47

Table S5. Posterior emission scaling factors for the Attica, Western Greece and Crete prefectures during January 2019 for simulations performed with prior uncertainties of 10%, 25%, 50% and 100%. A scaling factor of 1.0 indicates no change from the prior, values above 1.0 indicate an upward correction and values below 1.0 indicate a downward correction of the prior emissions.

Station	Week	10%	25%	50%	100%
Attica (Thissio)	2019-01-01	2.482	2.684	2.781	2.757
	2019-01-08	2.364	2.567	2.592	2.599
	2019-01-15	1.491	1.81	1.981	2.04
	2019-01-22	1.631	1.429	1.176	1.078
	2019-01-29	1.431	1.725	2.009	2.124
West. Greece (Helmos)	2019-01-01	0.953	0.838	0.44	0.196
	2019-01-08	1.158	1.17	1.317	2.48
	2019-01-15	0.941	0.791	0.417	0.368
	2019-01-22	1.224	1.685	2.369	2.694
	2019-01-29	0.897	0.473	0.351	0.229
Crete (Finokalia)	2019-01-01	0.974	0.76	0.283	0.066
	2019-01-08	1.079	1.121	1.453	2.815
	2019-01-15	0.934	0.637	0.483	0.305
	2019-01-22	1.163	1.685	2.096	2.546
	2019-01-29	0.852	0.492	0.236	0.141

Table S6. Posterior uncertainty reduction (%) in anthropogenic CO₂ emissions for each of the 13 Greek prefectures for the whole year 2019, for the three localization lengths tested (180, 400 and 600 km).

Regions	180 km	400 km	600 km
Thessaly	3%	5.9%	6.6%
Continental Greece	14.2%	15.9%	16.1%
Ionian Islands	1.8%	9.2%	11.1%
Western Greece	10.2%	17.5%	18.7%
Peloponnese	15.6%	18.2%	19%
Attica	83.6%	86.9%	87.1%
North Aegean	1.4%	2.4%	3%
South Aegean	1.1%	2.6%	2.9%
Crete	5.6%	6.9%	7.3%
East Macedonia and Thrace	0.1%	0.9%	1.5%
Central Macedonia	0.4%	2.3%	3.4%
West Macedonia	0.9%	4.4%	5.9%
Epirus	0.7%	4%	4.9%
Domain Mean	10.7%	13.6%	14.4%

Table S7. Model evaluation for the simulations for the whole year 2019 varying by the localization length (Test 5, 6 and 7)

Site	Simulation	RMSE (ppm)	Mean Bias (ppm)	R ²
Thissio	Prior	14.51	-7.47	0.55
	180 km	8.67	-1.51	0.77
	400 km	8.60	-1.71	0.78
	600 km	8.53	-1.53	0.78
Finokalia	Prior	2.16	0.37	0.85
	180 km	2.07	0.29	0.86
	400 km	2.03	0.35	0.86
	600 km	1.91	0.30	0.87
Helmos	Prior	1.71	0.43	0.87
	180 km	1.67	0.41	0.87
	400 km	1.70	0.45	0.87
	600 km	1.67	0.47	0.88

Table S8. Monthly and annual total anthropogenic CO₂ emissions (Mt CO₂) over Greece for 2019 from the EDGAR inventory, the CAMS prior, and the three CAMS posterior simulations with localization lengths of 180, 400 and 600 km.

Month	EDGAR (Mt CO ₂)	CAMS-Prior (Mt CO ₂)	CAMS-Posterior 180 km (Mt CO ₂)	CAMS-Posterior 400 km (Mt CO ₂)	CAMS-Posterior 600 km (Mt CO ₂)
2019-01	6.64	5.53	6.12	5.96	5.93
2019-02	5.74	4.29	5.51	4.65	5.30
2019-03	5.11	4.21	4.00	3.03	2.90
2019-04	4.81	3.93	3.76	3.33	2.75
2019-05	4.55	4.30	4.33	3.50	4.09
2019-06	4.66	4.54	4.93	5.61	5.99
2019-07	4.88	4.81	6.57	7.15	7.68
2019-08	4.82	4.59	5.95	5.48	5.49
2019-09	4.59	4.26	3.65	2.26	1.76
2019-10	4.85	4.43	3.74	2.38	2.14
2019-11	5.23	4.65	4.81	4.25	3.70
2019-12	5.62	5.48	7.93	7.44	7.86
Total	61.5	55.0	61.3 (±1.8)	55.0 (±1.8)	55.6 (±1.9)

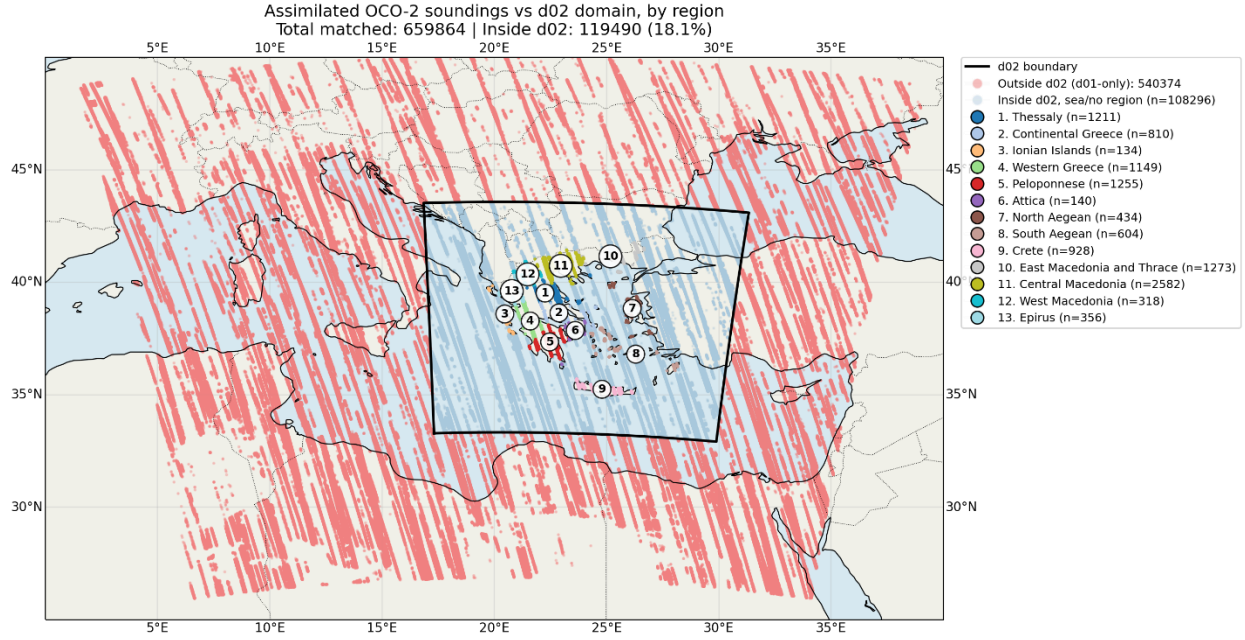


Figure S1. Spatial distribution of assimilated OCO-2 soundings (2019) relative to the d02 domain (black outline).

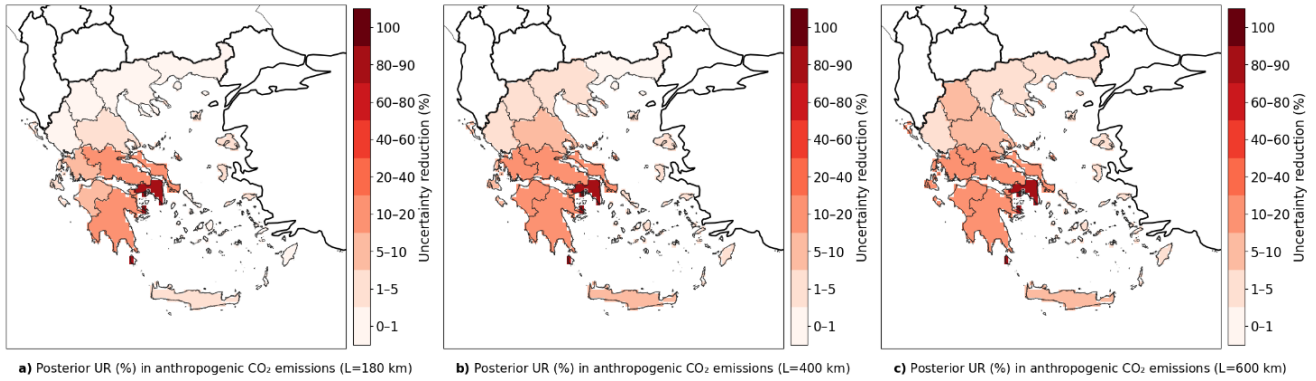


Figure S2. Posterior uncertainty reduction (%) in anthropogenic CO₂ emissions over Greece for localization lengths of a) 180 km, b) 400 km and c) 600 km.

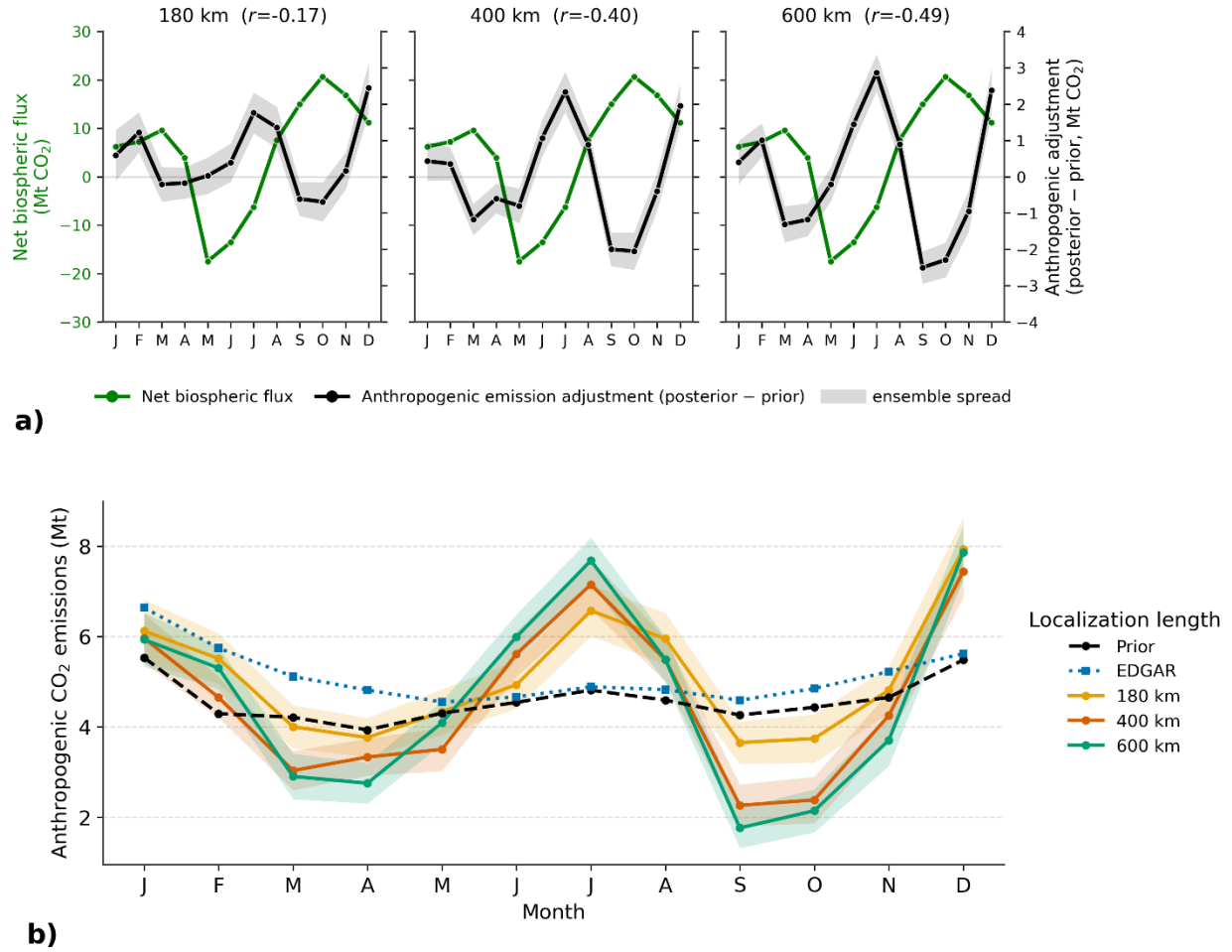


Figure S3. Monthly net biospheric CO₂ flux over Greece (green, left axis) and the optimized anthropogenic emission adjustment (posterior – prior; black, right axis) for the three localization lengths tested: (a) from left to right 180 km, 400 km, and 600 km, (b) Monthly variation of the optimized anthropogenic emissions for the three different localization lengths with the corresponding ensemble spread, the prior CAMS and the EDGAR emissions used in this study.

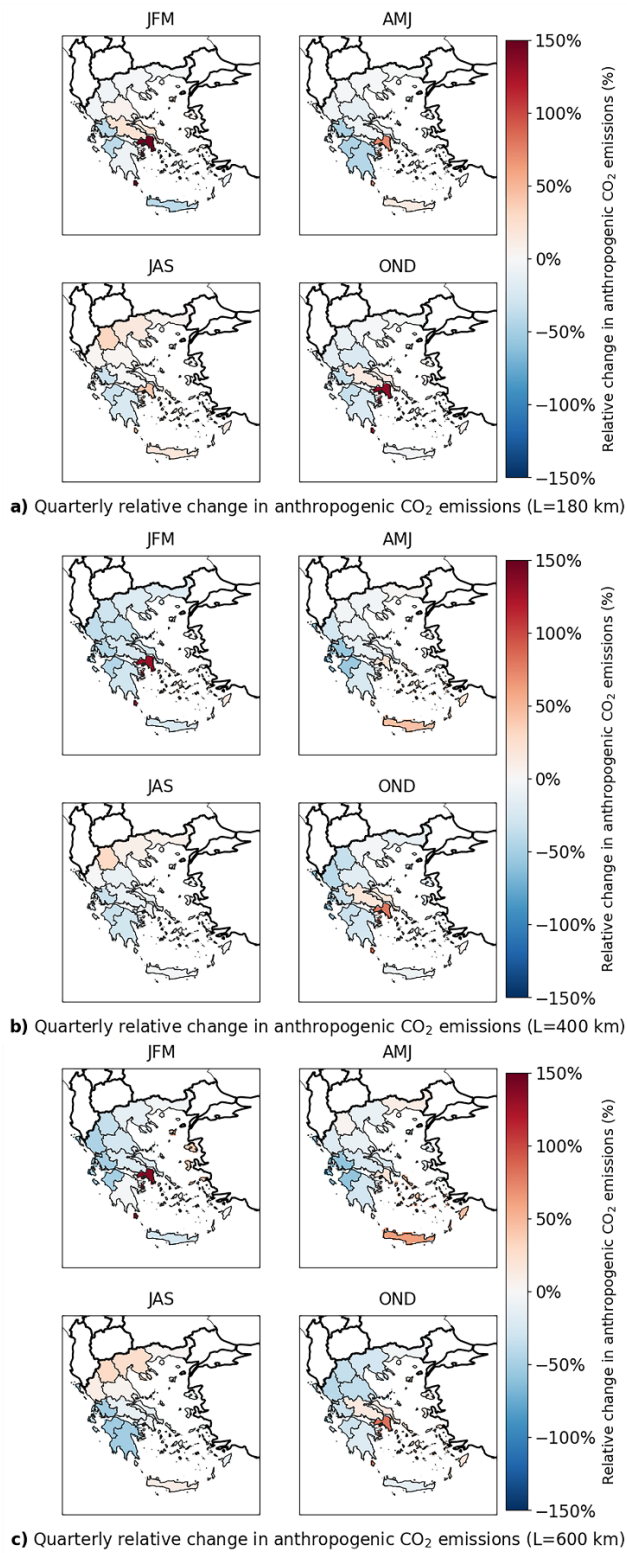


Figure S4. Quarterly relative change in anthropogenic CO₂ emissions for simulations performed with different localization lengths a) 180 km, b) 400 km and c) 600 km.

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