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Transboundary air pollution by sulphur, nitrogen, ozone and particulate matter in 2021

Greece

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Contents

1 Introduction

This report is one in a series of country-specific notes, complementary to the EMEP Status Report 1/2023. It presents an overview of transboundary pollution of sulphur, nitrogen, ozone and particulate matter for Greece in 2021.

All model runs for 2021, as well as the trend runs, have been performed with the EMEP MSC-W model version rv5.0, using ECMWF-IFS meteorology. The transboundary contributions presented here are based on source-receptor calculations with the EMEP MSC-W model for 2021, using meteorological and emission data for the year 2021.

As a basis for their correct interpretation, this section briefly explains what types of results are shown in this report and how they have been calculated.

1.1 The chapters of this report

Emissions *(Chapter 2)* : The emissions for 1990–2021 have been derived from the 2023 official data submissions to UNECE CLRTAP as of 1 June 2023. The spatial (gridded) distribution of the emissions has been provided by the EMEP Centre on Emission Inventories and Projections (CEIP).

The gridded emission data used in the model calculations are available on WebDab at: https://www.ceip.at/webdab-emission-database/emissions-as-used-in-emep-models

For the years 2005–2021, emissions of condensable organics from residential combustion have been included based on the EMEPwRef2_v2.1C dataset from TNO (Netherlands Organisation for Applied Scientific Research). For more details please consult Appendix *Trend simulation done in 2023* in the EMEP Status Report 1/2023.

Time series *(Chapter 3)* : Time series in depositions and air concentrations are presented for the period of 1990–2021. For all years, the meteorology of the respective year is used. Thus, interannual variability in the model results is due to changes in both emissions and meteorology. It should also be noted that the emission data and model version are updated regularly (see respective chapters on emissions and model updates in the EMEP Status Report 1/2023), which may lead to differences between results reported here and in earlier reports.

Transboundary fluxes *(Chapter 4)* : Data are presented in the form of maps and pie charts. The data are generated by source-receptor calculations, where emissions for each emitter of one or more precursors are reduced by 15%. The results have been scaled up to represent the entire emission from an emitter.

Transboundary concentrations *(Chapters 5 and 6)* : Data are presented in the form of maps and bar charts. Ozone and particulate matter are subject to significant non-linearities in chemistry. Therefore we calculate the effect of 15% reductions in emissions only.

The horizontal maps show the reduction in concentrations when emissions are reduced by 15% in Greece. By convention, reductions in concentrations are represented by positive values in the maps. Thus, any negative values mean that concentrations increase as a result of an emission reduction (due to non-linearities in chemistry).

The bar charts identify the six most important emitter countries in terms of their effects on concentrations in Greece that would result from a 15% reduction in emissions. In the bar charts, the sum of the *absolute values* of these effects corresponds to 100%. The percentage values (vertical scale in the bar charts) thus give an indication of the relative importance of the various emitter countries that influence concentrations in Greece (positive or negative, large or small contributions). Again, reductions are represented by positive values. Hence, a negative bar in the chart means that a *reduction* in emissions from an emitter country would lead to an *increase* in concentration in Greece. In some countries this can occur because of strong non-linearities in chemistry.

In addition, for $PM_{2.5}$ and PM_{10} we show the total concentrations along with the percentage contribution from natural sources (sea salt and natural dust) to the total concentrations.

In the figures for ozone, we do not show contributions from areas that are outside the EMEP domain. Until 2019 these had been included as BIC (Boundary and Initial Conditions) and were calculated by reducing NOx and NMVOC at the model boundary. However, the most important contributor to ozone from areas outside the EMEP domain is ozone itself, transported hemispherically across the model boundary. Including the BIC contribution that is due to NOx and NMVOC only would be misleading. In principle, the BIC contribution due to hemispherically transported ozone could be included, but we choose here to focus on the contribution from countries within the EMEP domain.

Comparison with observations from the EMEP network *(Chapter 7)* : The map of monitoring stations shows stations of Greece in the EMEP measurement network with measurements in 2021 submitted to EMEP. The frequency analysis plots compare daily observation results with the model results. The measurement data are available from CCC:
https://ebas.nilu.no

The table provides annual statistics of the comparison of model results with observations for each measured component. Comparison is done only for stations with a sufficiently consistent set of data available in monthly or higher time resolution.

Risks from ozone and PM *(Chapter 8)* : Particularly relevant for health impact, model results for SOMO35 (an ozone indicator) and particulate matter concentrations are shown. However, the results correspond to regional background levels and are not representative of local point measurements where these values can be much higher (e.g. in cities).

1.2 Web interface for comparison with observations

A more detailed evaluation against measurements from both the EMEP network and the European Environment Agency's (EEA) Air Quality e-Reporting Database can be found at the AeroVal web interface that has been developed recently:
https://aeroval.met.no/evaluation.php?project=emep&exp_name=2023-reporting

On that page the user can select the set of measurement data, the station or country of interest, and view a large number of statistical parameters (bias, correlation, root mean square error, etc.).

The web interface displays co-located observational and model datasets and contains:

- daily and monthly time series for each station, averaged per country, or the whole area covered by the model and the measurement network;
- statistics and scatter plots calculated for each station and country;
- an overall evaluation of the results using statistics calculated for each country or the whole area covered by the model and the measurement network (so-called Heatmaps and Taylor Diagrams).

Evaluation is made for O_3, $PM_{2.5}$, PM_{10}, SO_2, SO_4, NO_2, and several other nitrogen-containing species. The different types of visualization (bar charts, line charts, tables, etc.) are available both for viewing and for download.

1.3 Country codes

Many tables and graphs in this report make use of codes to denote countries and regions in the EMEP area. Table 1 provides an overview of these codes and lists the countries and regions included in the source-receptor calculations for 2021.

Code	Country/Region/Source	Code	Country/Region/Source
AL	Albania	IS	Iceland
AM	Armenia	IT	Italy
AST	Asian areas	KG	Kyrgyzstan
AT	Austria	KZ	Kazakhstan
ATL	N.-E. Atlantic Ocean	LI	Liechtenstein
AZ	Azerbaijan	LT	Lithuania
BA	Bosnia and Herzegovina	LU	Luxembourg
BAS	Baltic Sea	LV	Latvia
BE	Belgium	MC	Monaco
BG	Bulgaria	MD	Moldova
BIC	Boundary/Initial Conditions	ME	Montenegro
BLS	Black Sea	MED	Mediterranean Sea
BY	Belarus	MK	North Macedonia
CH	Switzerland	MT	Malta
CY	Cyprus	NL	Netherlands
CZ	Czechia	NO	Norway
DE	Germany	NOA	North Africa
DK	Denmark	NOS	North Sea
DMS	Dimethyl sulfate (marine)	PL	Poland
EE	Estonia	PT	Portugal
ES	Spain	RO	Romania
EU	European Union (EU27)	RS	Serbia
EXC	EMEP land areas	RU	Russian Federation
FI	Finland	SE	Sweden
FR	France	SI	Slovenia
GB	United Kingdom	SK	Slovakia
GE	Georgia	TJ	Tajikistan
GL	Greenland	TM	Turkmenistan
GR	Greece	TR	Türkiye
HR	Croatia	UA	Ukraine
HU	Hungary	UZ	Uzbekistan
IE	Ireland	VOL	Volcanic emissions

Table 1: Country/region codes used throughout this report.

1.4 Definitions, statistics used

The following definitions and acronyms are used throughout this note:

SOA - secondary organic aerosol, defined as the aerosol mass arising from the oxidation products of gas-phase organic species.

SIA - secondary inorganic aerosols, defined as the sum of sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+). In the EMEP MSC-W model SIA is calculated as the sum:

$$\mathrm{SIA} = SO_4^{2-} + NO_3^-(\text{fine}) + NO_3^-(\text{coarse}) + NH_4^+.$$

SS - sea salt.

MinDust - mineral dust.

PPM - primary particulate matter, originating directly from anthropogenic emissions. One usually distinguishes between fine primary particulate matter, $PPM_{2.5}$, with aerosol diameters below 2.5 µm and coarse primary particulate matter, PPM_{coarse} with aerosol diameters between 2.5 µm and 10 µm.

$PM_{2.5}$ - particulate matter with aerodynamic diameter up to 2.5 µm. In the EMEP MSC-W model $PM_{2.5}$ is calculated as

$$\begin{aligned} PM_{2.5} = {} & SO_4^{2-} + NO_3^-(\text{fine}) + NH_4^+ + SS_{2.5} + \text{MinDust(fine)} \\ & + \text{SOA(fine)} + PPM_{2.5} + 0.13\,NO_3^-(\text{coarse}) + \text{PM25water}. \end{aligned}$$

(PM25water = PM associated water).

PM_{coarse} - coarse particulate matter with aerodynamic diameter between 2.5 µm and 10 µm. In the EMEP MSC-W model PM_{coarse} is calculated as

$$PM_{coarse} = 0.87\,NO_3^-(\text{coarse}) + \text{SS(coarse)} + \text{MinDust(coarse)} + PPM_{coarse}.$$

PM_{10} - particulate matter with aerodynamic diameter up to 10 µm. In the EMEP MSC-W model PM_{10} is calculated as

$$PM_{10} = PM_{2.5} + PM_{coarse}.$$

SS_{10} - sea salt aerosol with diameter up to 10 µm.

$SS_{2.5}$ - sea salt aerosol with diameter up to 2.5 µm.

SOx - group of oxidized sulphur components (SO_2, SO_4^{2-}).

NOx - group of oxidized nitrogen components (NO, NO_2, NO_3^-, N_2O_5, HNO_3, etc.).

redN - group of reduced nitrogen components (NH_3 and NH_4^+).

O_3 - Yearly average of ozone surface concententrations.

max O_3 - daily maximum of ozone.

SOMO35 is the Sum of Ozone Means Over 35 ppb, an indicator for health impact assessment recommended by WHO. It is defined as the yearly sum of the daily maximum of 8-hour running average over 35 ppb. For each day the maximum of the running 8-hours average for O_3 is selected and the values over 35 ppb are summed over the whole year. If we let A_8^d denote the maximum 8-hourly average ozone on day d, during a year with N_y days (N_y = 365 or 366), then SOMO35 can be defined as:

$$\mathrm{SOMO35} = \sum_{d=1}^{d=N_y} \max\big(A_8^d - 35\,\mathrm{ppb}, 0.0\big)$$

where the `max` function evaluates $\max(A-B, 0)$ to $A-B$ for $A > B$, or zero if $A \leq B$, ensuring that only A_8^d values exceeding 35 ppb are included. The corresponding unit is ppb.days.

MDA8 - Maximum daily 8-hour mean ozone concentrations.

$\mathrm{MDA8_{AS}}$ - April to September average of MDA8. This corresponds to the peak season ozone level specified by WHO. The 2021 WHO AQG (Air Quality Guideline) gives a target level of 60 µg for $\mathrm{MDA8_{AS}}$ as well as interim targets of 100 µg and 70 µg.

AOT40 is the accumulated amount of ozone over the threshold value of 40 ppb, i.e.:

$$\mathrm{AOT40} = \int \max(O_3 - 40\,\mathrm{ppb}, 0.0)\, dt$$

where the `max` function ensures that only ozone values exceeding 40 ppb are included. The integral is taken over time, namely the relevant growing season for the vegetation concerned, and in some daytime period. The corresponding unit is ppb.hours (abbreviated to ppb.h). The usage and definitions of AOT40 have changed over the years though, and also differ between UNECE and the EU.

Although the EMEP model generates a number of AOT-related outputs, we will concentrate in this report only on two definitions:

MM-AOT40f - AOT40 calculated for forests using estimates of O_3 at forest-top (uc: upper-canopy). This AOT40 is that defined for forests by the UNECE Mapping Manual, but using a default growing season of April-September.

MM-AOT40c - AOT40 calculated for agricultural crops using estimates of O_3 at the top of the crop. This AOT40 is close to that defined for agricultural crops by the UNECE Mapping Manual, but using a default growing season of May-July, and a default crop-height of 1 m.

POD_Y - Phyto-toxic ozone dose, is the accumulated stomatal ozone flux over a threshold Y, i.e.:

$$\mathrm{POD}_Y = \int \max(F_{st} - Y, 0)\, dt$$

where stomatal flux F_{st}, and threshold, Y, are in nmol m^{-2} s^{-1}. This integral is evaluated over time, from the start of the growing season (SGS), to the end (EGS).

For the generic crop and forest species, the suffix gen can be applied, e.g. $\mathrm{POD}_{Y,gen}$ is used for forests. POD was introduced in 2009 as an easier and more descriptive term for the accumulated ozone flux.

2 Emissions

2.1 Emissions used in the EMEP MSC-W model calculations

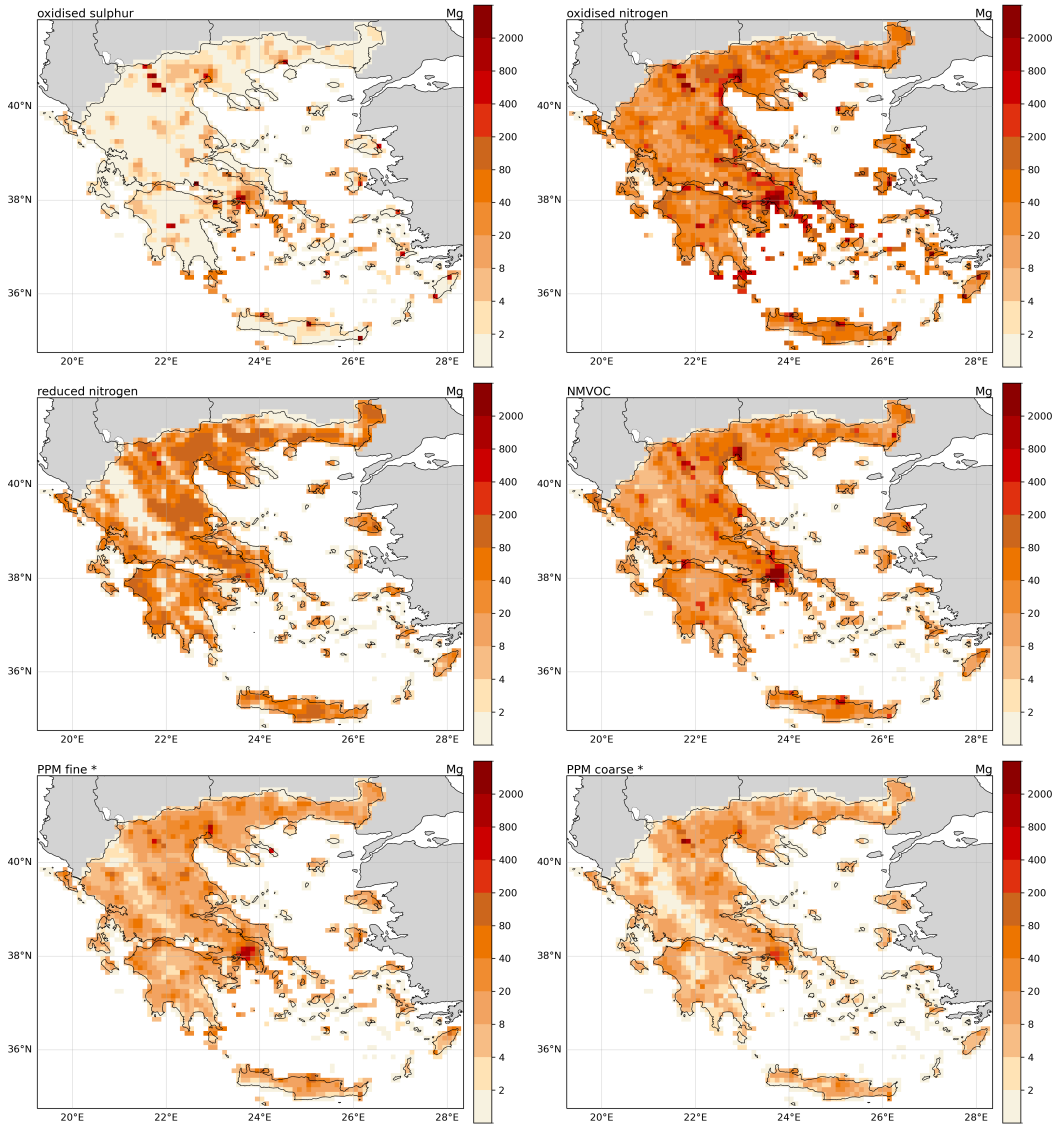

Figure 1: Spatial distribution of emissions from Greece in 2021.

3 Time series

Important: For correct interpretation of the results shown in this chapter please read the paragraphs on *Emissions* and *Time series* in Section 1.1.

	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
SO_x	512	522	558	585	233	102	81	90	86	80	49	47
NO_x	409	402	431	483	364	263	262	268	259	250	222	222
NH_3	91	80	77	75	71	64	64	64	63	63	64	63
NMVOC	321	307	313	338	219	169	160	155	149	149	141	146
CO	1239	1061	1006	864	612	533	477	490	467	460	422	424
$PM_{2.5}$	75	66	66	68	47	42	39	39	37	36	34	36
PM_{10}	162	130	127	123	89	68	67	65	59	58	56	57

Table 2: Emissions from Greece. Unit: Gg. (SO_x given as SO_2, and NO_x as NO_2).

	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
SO_x dep.	208	209	167	153	83	56	50	47	48	48	37	36
NO_x dep.	70	70	65	75	61	53	49	47	49	45	40	41
redN dep.	46	44	39	41	38	42	37	37	37	37	38	33

Table 3: Estimated deposition of Sulphur (S) and Nitrogen (N) in Greece. Unit: Gg(S) or Gg(N).

	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
mean ozone	43	42	42	42	40	41	40	41	40	41	40	40
max ozone	55	52	54	53	51	51	51	52	50	50	49	50
MM-AOT40f	55129	46708	49297	47807	42423	40250	38743	42641	39738	39888	36409	38055
SOMO35	6299	5478	5803	5703	5027	4999	4801	5237	4823	4866	4479	4534
$POD_{1.0,gen\text{-}DF}$	32	35	32	40	33	24	23	22	26	23	22	19
$PM_{2.5}$ anthrop.	16	12	13	11	10	8	8	7	8	8	7	8
PM_{10} anthrop.	20	16	18	15	14	11	12	10	11	11	10	13

Table 4: Estimated yearly mean values of air quality indicators averaged over Greece. Unit: daily mean ozone (ppb), daily max ozone (ppb), MM-AOT40f (ppb·h), SOMO35 (ppb·d), $POD_{1.0,gen\text{-}DF}$ (mmol/m2), $PM_{2.5}$ (µg/m^3) and PM_{10} (µg/m^3).

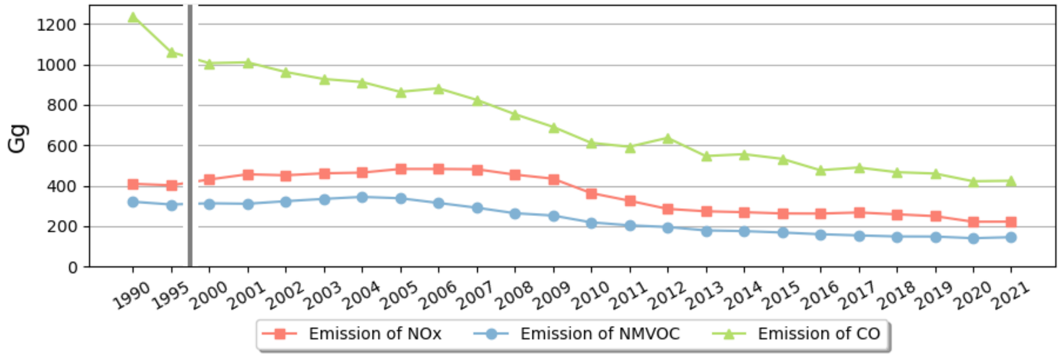

Figure 2: Annual emissions of photo-oxidant pollution precursors. Unit: Gg (note that NO_x is here given as NO_2).

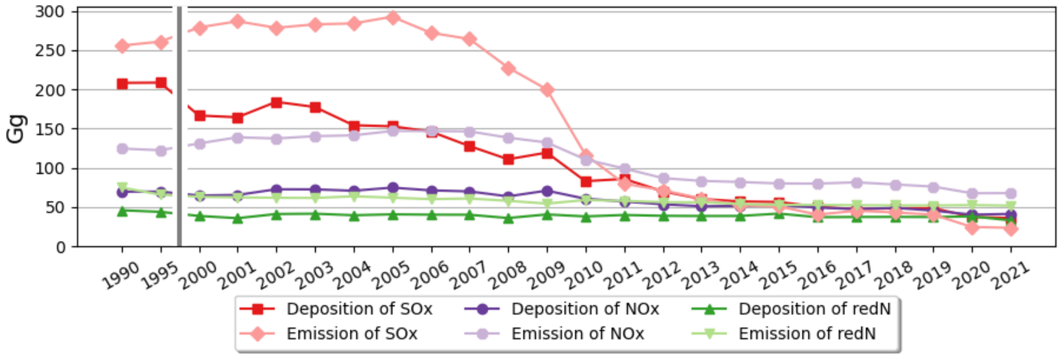

Figure 3: Annual emissions and depositions of oxidised sulphur, oxidised nitrogen and reduced nitrogen. Unit: Gg(S) or Gg(N).

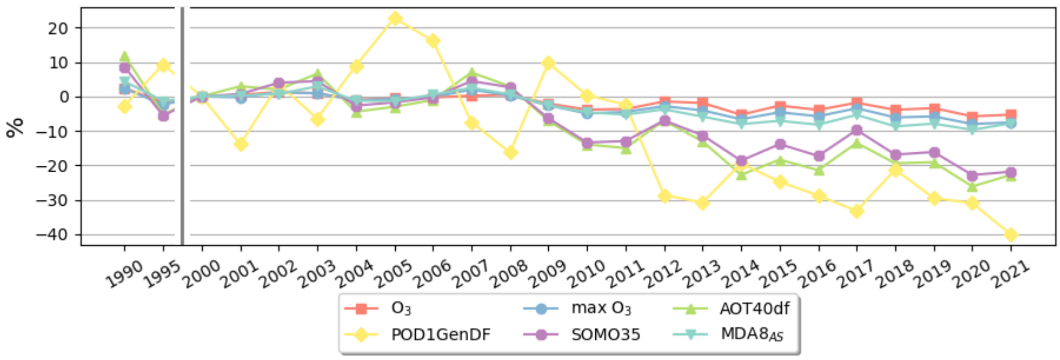

Figure 4: Changes in ozone related pollution relative to 2000. Unit: %. The large changes from year to year in some countries are mainly related to meteorological variability.

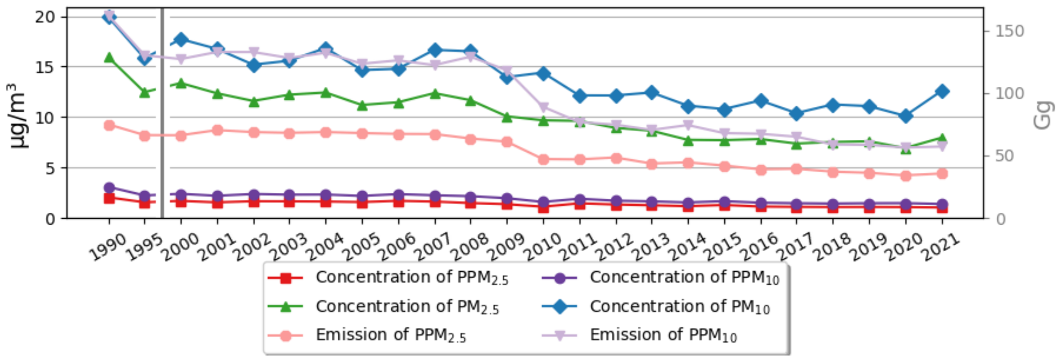

Figure 5: Mean concentrations and annual emissions of particulate matter (PM) and primary particulate matter (PPM). Units: µg/m^3 for concentrations (left vertical axis) and Gg for emissions (right vertical axis).

4 Transboundary fluxes

4.1 Deposition of oxidised sulphur

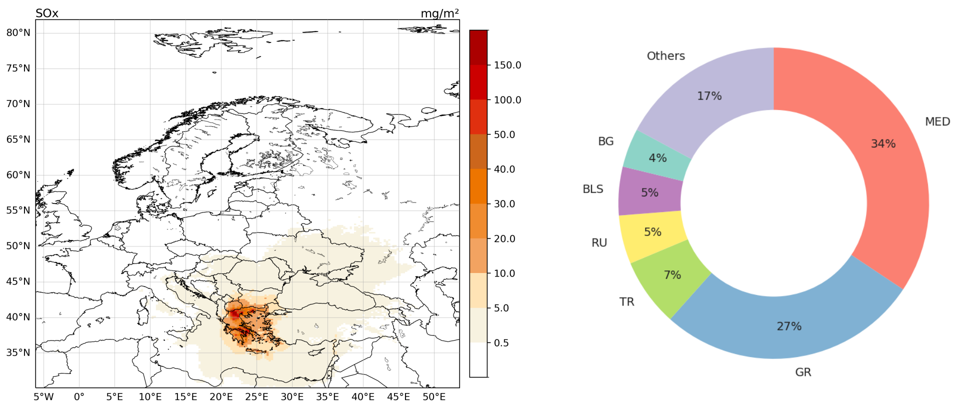

Figure 6: Contribution of emissions from Greece to deposition of oxidised sulphur in the EMEP domain. Unit: mg(S)/m^2. The pie chart shows the six main receptor areas where oxidised sulphur from Greece is deposited. Unit: %.

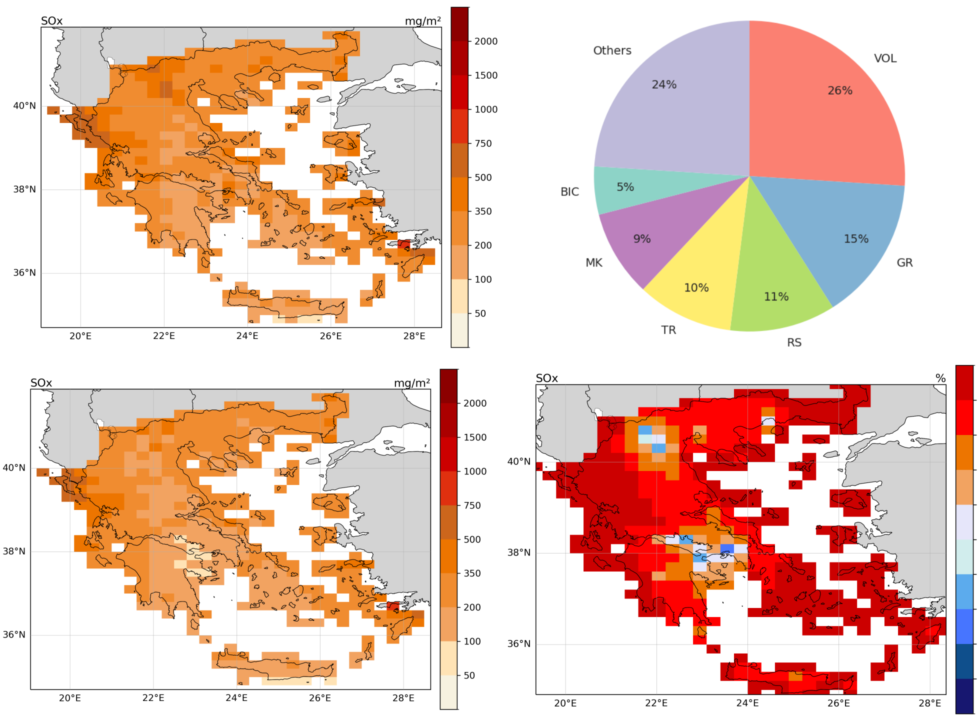

Figure 7: Top left: Deposition of oxidised sulphur in Greece. Unit: mg(S)/m^2. Top right: The six main contributors to oxidised sulphur deposition in Greece. Unit: (%). Bottom left: Oxidised sulphur deposition from transboundary sources. Unit: mg(S)/m^2. Bottom right: Fraction of transboundary contribution to total deposition. Unit: %.

4.2 Deposition of oxidised nitrogen

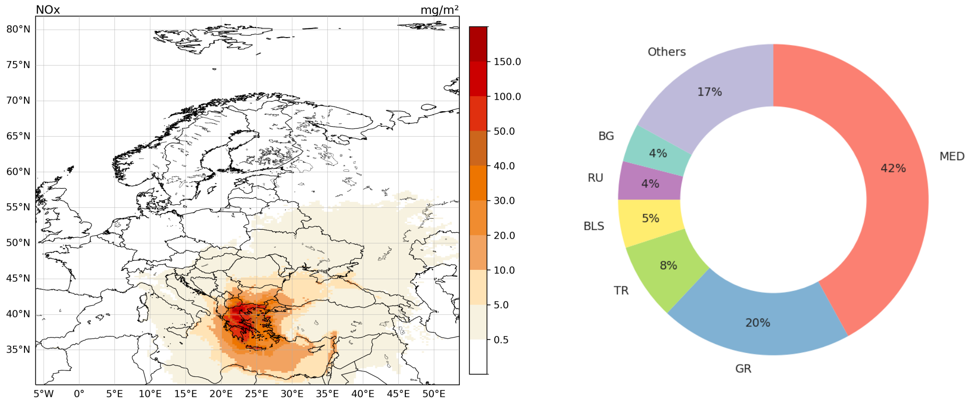

Figure 8: Contribution of emissions from Greece to deposition of oxidised nitrogen in the EMEP domain. Unit: mg(N)/m^2. The pie chart shows the six main receptor areas where oxidised nitrogen from Greece is deposited. Unit: %.

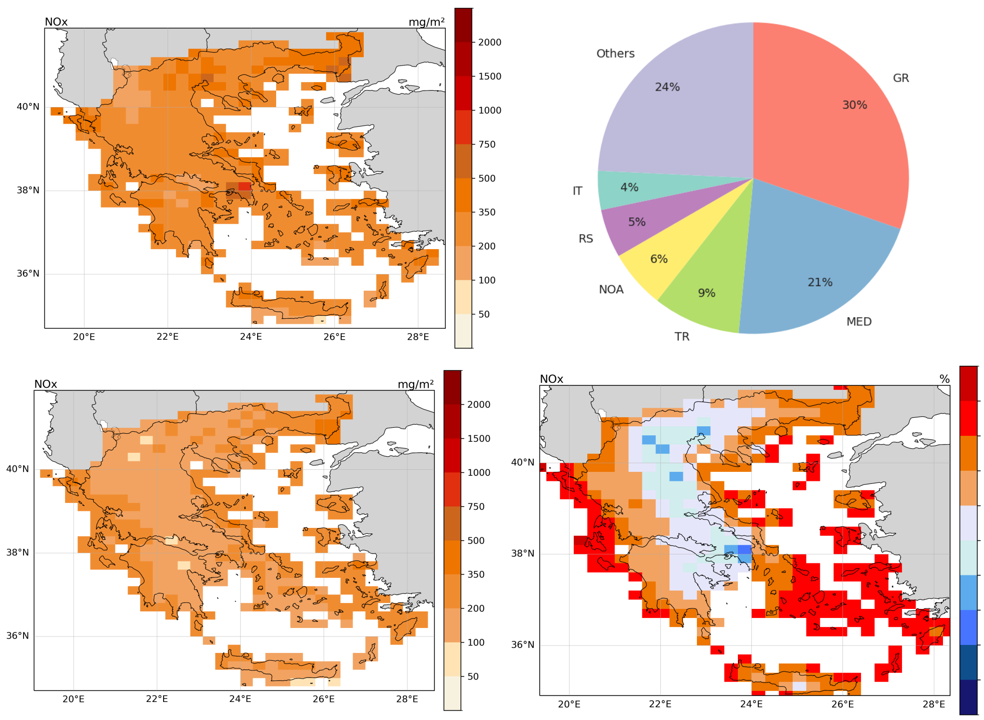

Figure 9: Top left: Deposition of oxidised nitrogen in Greece. Unit: mg(N)/m^2. Top right: The six main contributors to oxidised nitrogen deposition in Greece. Unit: %. Bottom left: Oxidised nitrogen deposition from transboundary sources. Unit: mg(N)/m^2. Bottom right: Fraction of transboundary contribution to total deposition. Unit: %.

4.3 Deposition of reduced nitrogen

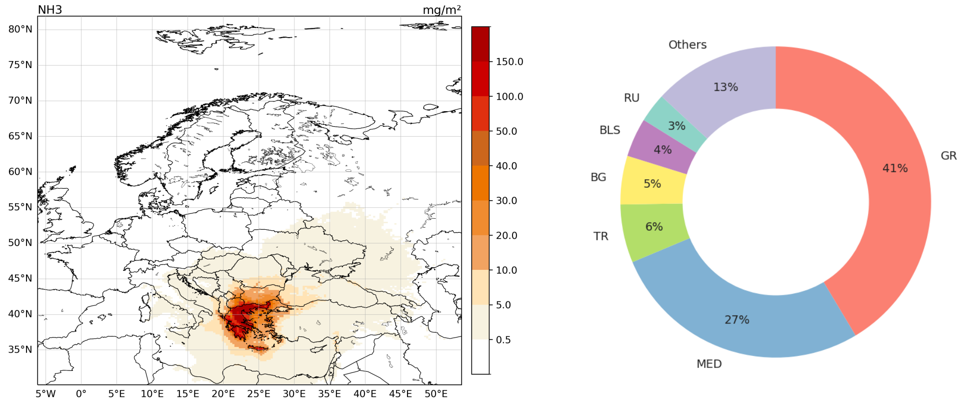

Figure 10: Contribution of emissions from Greece to deposition of reduced nitrogen in the EMEP domain. Unit: mg(N)/m^2. The pie chart shows the six main receptor areas where reduced nitrogen from Greece is deposited. Unit: %.

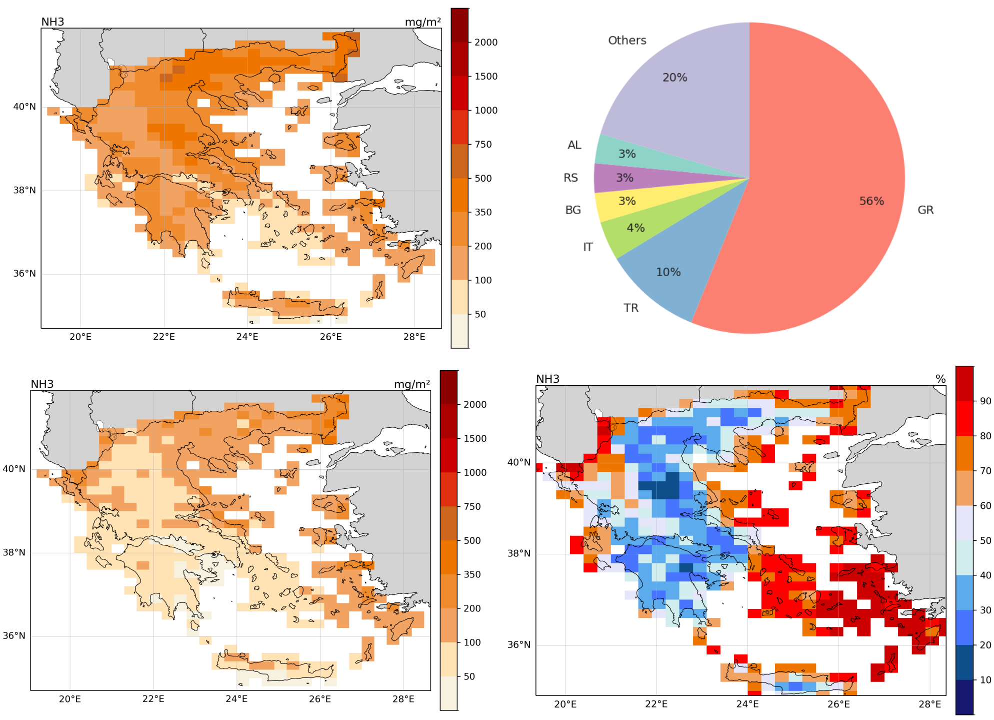

Figure 11: Top left: Deposition of reduced nitrogen in Greece. Unit: mg(N)/m^2. Top right: The six main contributors to deposition of reduced nitrogen in Greece. Unit: %. Bottom left: Deposition of reduced nitrogen from transboundary sources. Unit: mg(N)/m^2. Bottom right: Fraction of transboundary contribution to total deposition. Unit: %.

5 Transboundary concentrations of ozone

5.1 MM-AOT40f

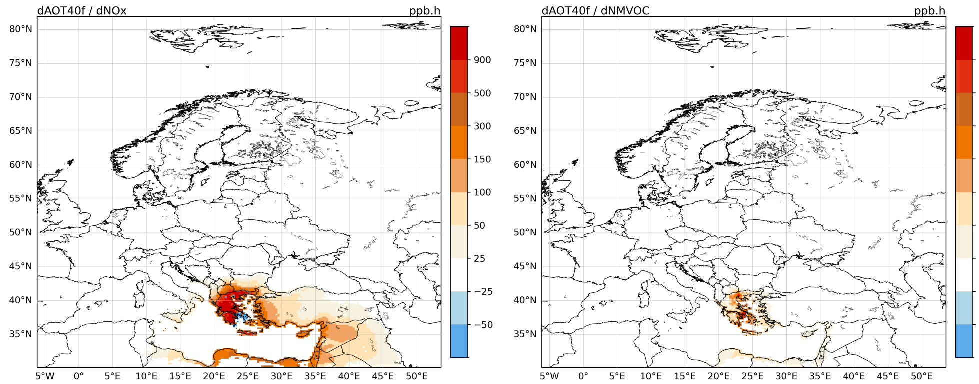

Figure 12: Reduction in MM-AOT40f that would result from a 15% reduction in emissions of NO_x (left) and NMVOC (right) from Greece. Unit: ppb·h.

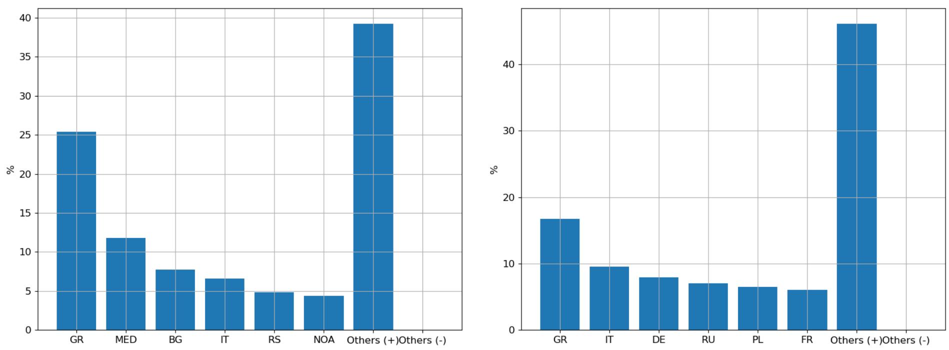

Figure 13: The six most important emitter countries or regions, with respect to their effects on MM-AOT40f in Greece that would result from reductions in NO_x emissions (left) and NMVOC emissions (right).

5.2 $POD_{1.0,gen\text{-}DF}$ – Ozone fluxes to deciduous forests

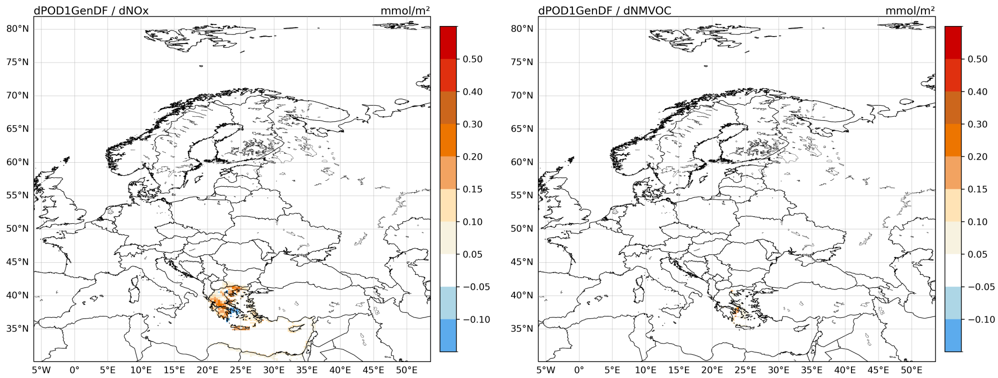

Figure 14: Reduction in $POD_{1.0,gen\text{-}DF}$ that would result from a 15% reduction in emissions of NO_x (left) and NMVOC (right) from Greece. Unit: mmol/m^2.

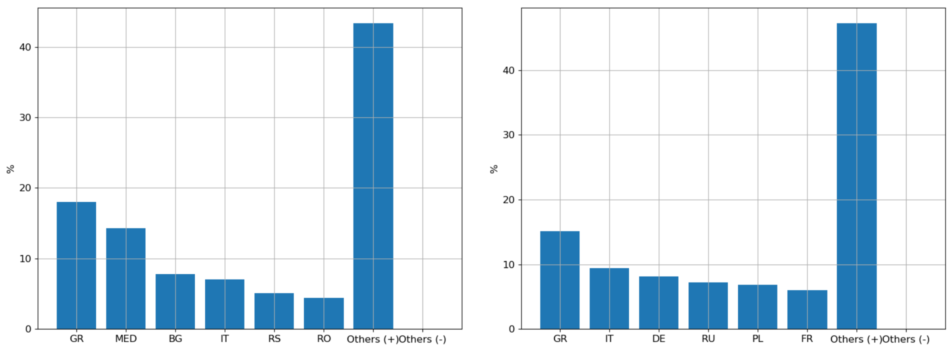

Figure 15: The six most important emitter countries or regions, with respect to their effects on $POD_{1.0,gen\text{-}DF}$ in Greece that would result from reductions in emissions of NO_x (left) and NMVOC (right).

5.3 SOMO35 – Risk of ozone damages to human health

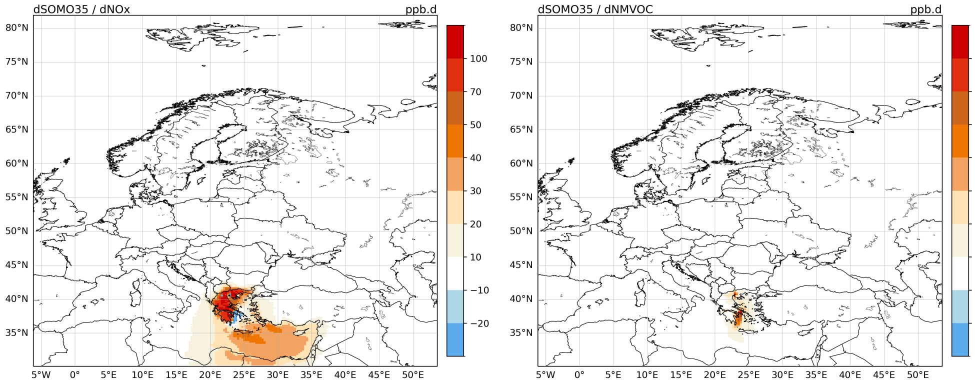

Figure 16: Reduction in SOMO35 that would result from a 15% reduction in emissions of NO_x (left) and NMVOC (right) from Greece. Unit: ppb·day.

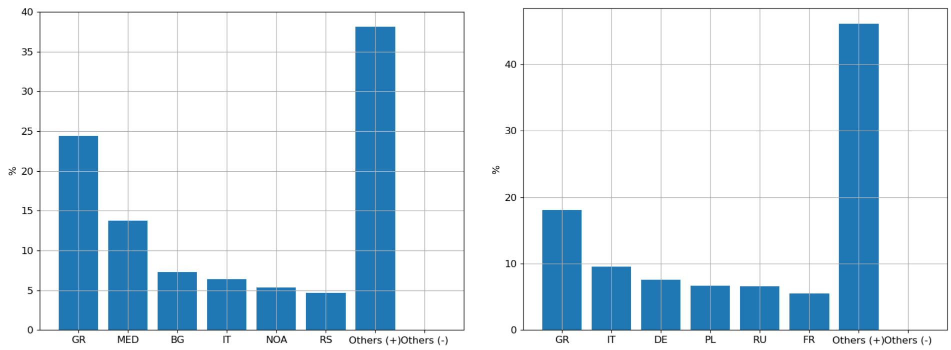

Figure 17: The six most important emitter countries or regions, with respect to their effects on SOMO35 in Greece that would result from reductions in emissions of NO_x (left) and NMVOC (right).

5.4 $MDA8_{AS}$– Risk of ozone damages to human health

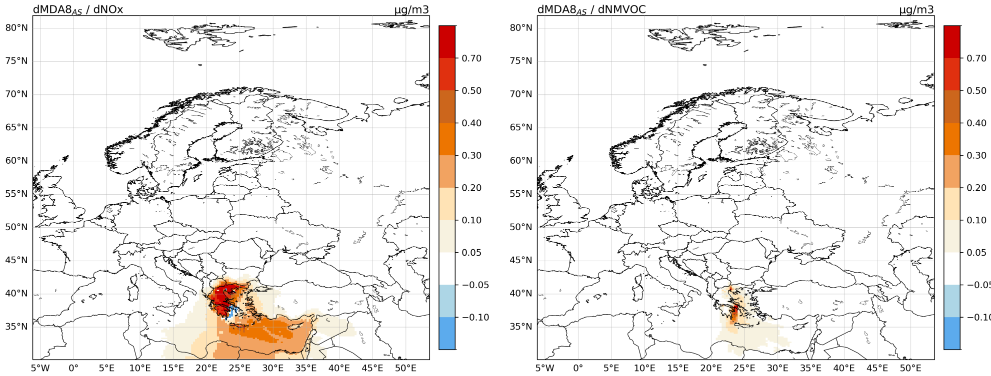

Figure 18: Reduction in $MDA8_{AS}$ that would result from a 15% reduction in emissions of NO_x (left) and NMVOC (right) from Greece. Unit: µ/m^3.

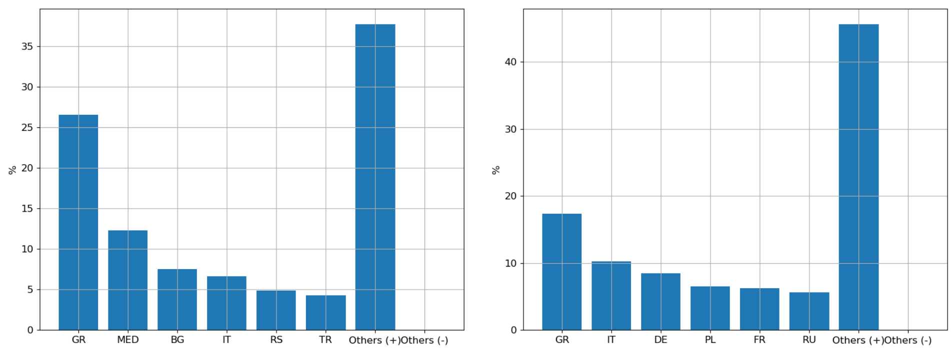

Figure 19: The six most important emitter countries or regions, with respect to their effects on $MDA8_{AS}$ in Greece that would result from reductions in emissions of NO_x (left) and NMVOC (right).

6 Transboundary concentrations of particulate matter

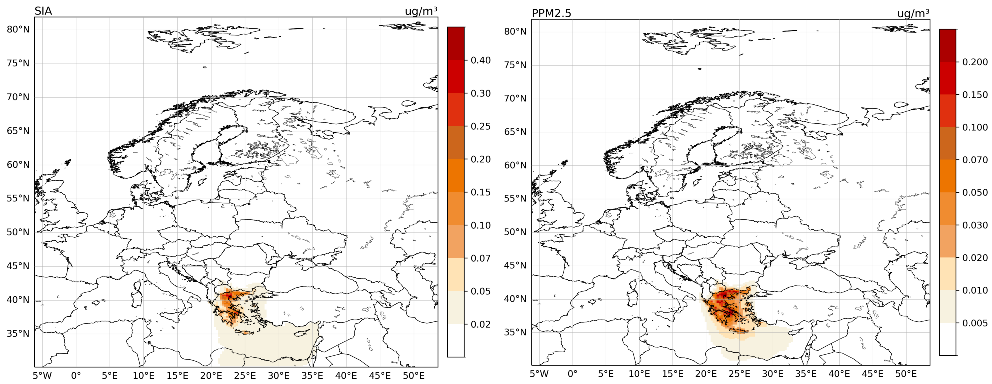

Figure 20: Reduction in concentrations of SIA (left) and $PPM_{2.5}$ (right) that would result from a 15% reduction in emissions from Greece. Unit: µg/m^3. Note the difference in colorbars.

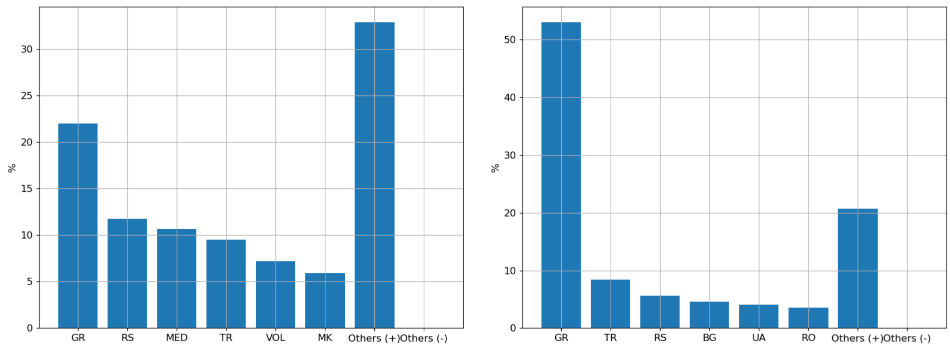

Figure 21: The six most important emitter countries or regions, with respect to their effects on SIA (left) and $PPM_{2.5}$ (right) in Greece that would result from reductions in emissions.

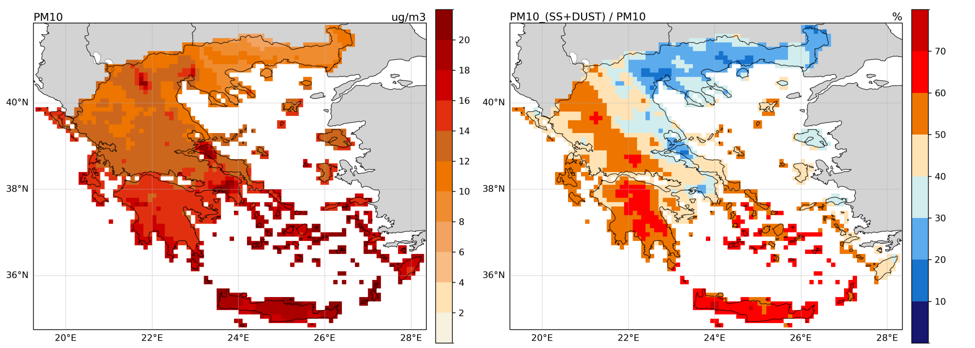

Figure 22: Left: PM_{10} concentration, and right: fraction of natural contributions of PM_{10} (sea salt and natural dust) to total PM_{10} concentration in Greece. Units: µg/m^3 (left), % (right).

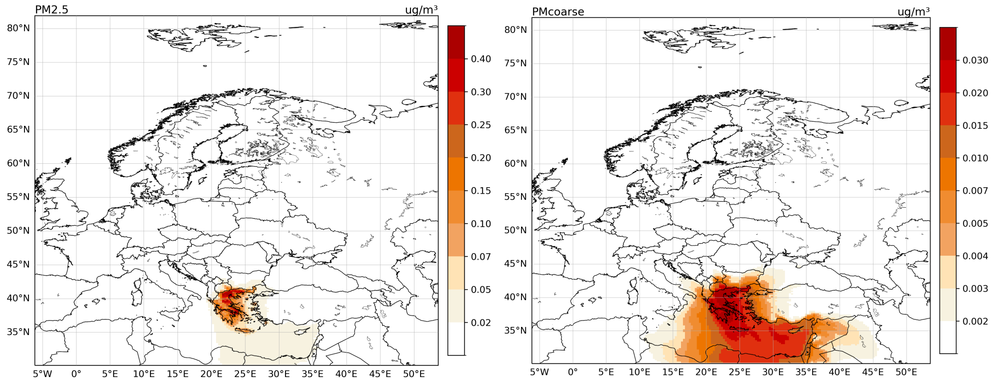

Figure 23: Left: Reduction in concentrations of $PM_{2.5}$ (left) and PM_{coarse} (right) that would result from a 15% reduction of emissions from Greece. Unit: µg/m^3. Note the difference in colorbars.

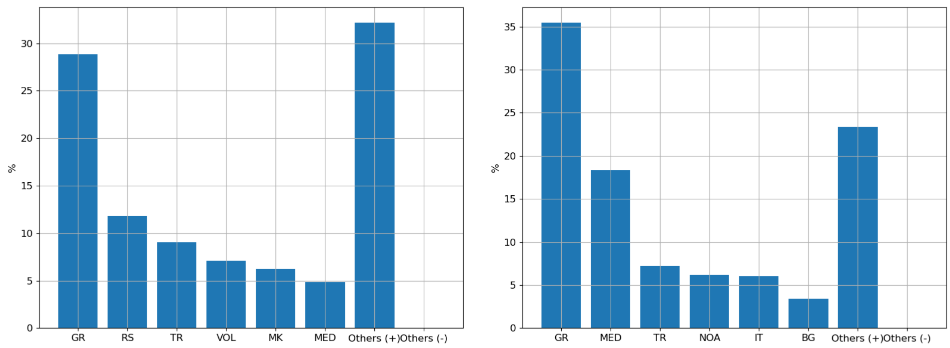

Figure 24: The six most important emitter countries or regions, with respect to their effects on $PM_{2.5}$ (left) and PM_{coarse} (right) in Greece that would result from reduction in emissions.

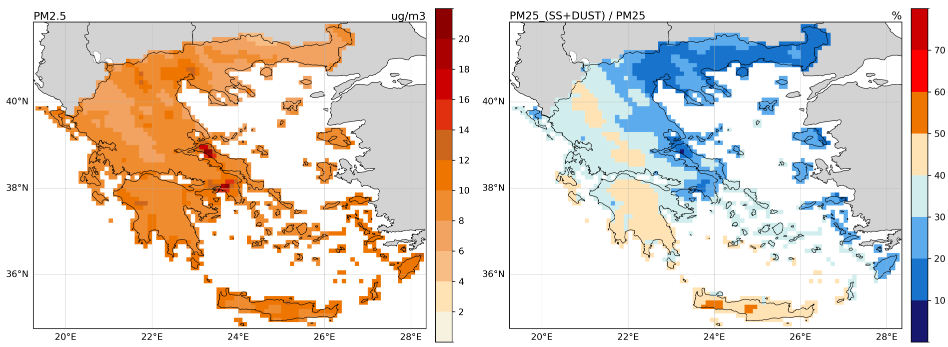

Figure 25: Left: $PM_{2.5}$ concentration, and right: fraction of natural contributions of $PM_{2.5}$ (sea salt and natural dust) to total $PM_{2.5}$ concentration in Greece. Units: µg/m^3 (left), % (right).

7 Comparison with observations

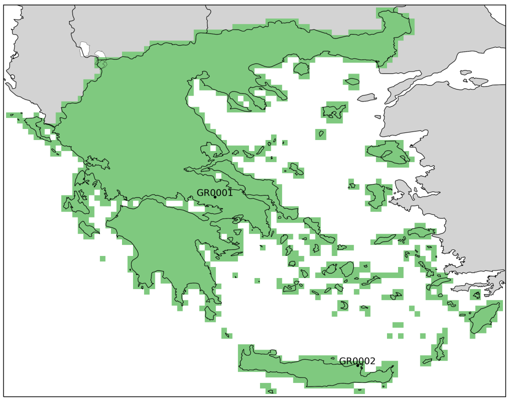

Figure 26: Location of stations in Greece.

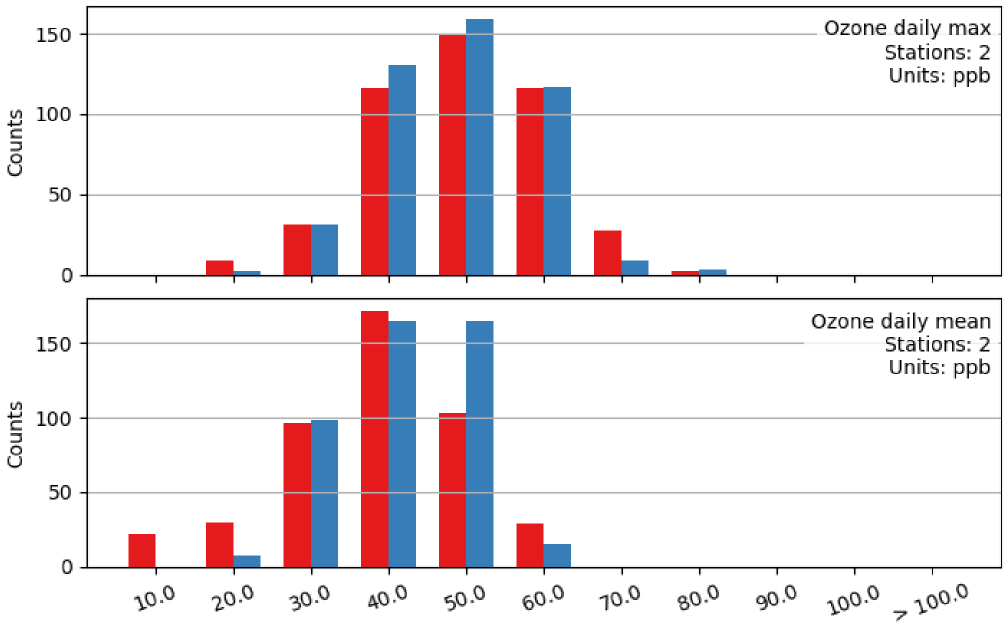

Figure 27: Frequency analysis of ozone in Greece at the stations that reported O_3 for 2021 (Observations, Model).

A sufficiently consistent set of daily wet deposition observations in GR for 2021 is not available for this analysis.

Figure 28: Frequency analysis of depositions in precipitation in Greece (Observations, Model).

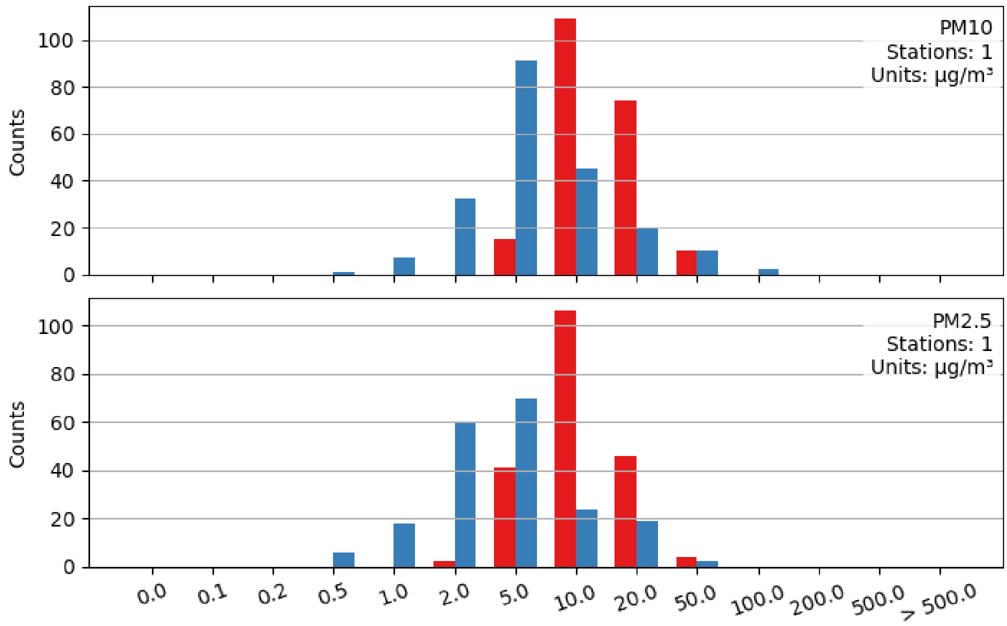

Figure 29: Frequency analysis of air concentrations in Greece (Observations, Model).

Component	No.	Bias%	Correlation	RMSE
SO2 in Air	0			
Sulfate in Air	0			
NO2 in Air	0			
NO3- in Air	0			
NH3+NH4+ in Air	0			
PM10	0			
PM2.5	0			
Ozone daily max	0			
Ozone daily mean	0			
SO4 wet dep.	0			
Nitrate wet dep.	0			
Reduced nitrogen wet dep.	0			
Precipitation	0			

Table 5: Annual statistics of comparison of model results with observations in Greece for stations with a sufficiently consistent set of data available in monthly or higher time-resolution. Standard deviations provide variability ranges between stations.

8 Risk of damage from ozone and particulate matter in Greece

8.1 Ecosystem-specific AOT40 values

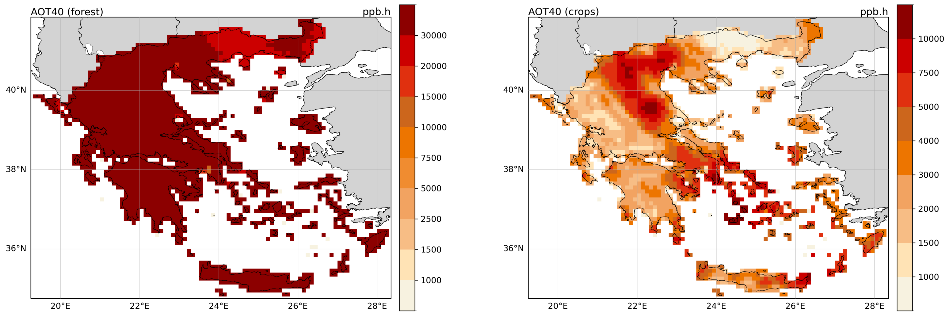

Figure 30: MM-AOT40f and MM-AOT40c in Greece in 2021. *MM-AOT40f: growing season April-September, critical level for forest damage = 5000 ppb·h; MM-AOT40c: growing season May-July, critical level for agricultural crops = 3000 ppb·h.)*

8.2 Ecosystem-specific ozone fluxes

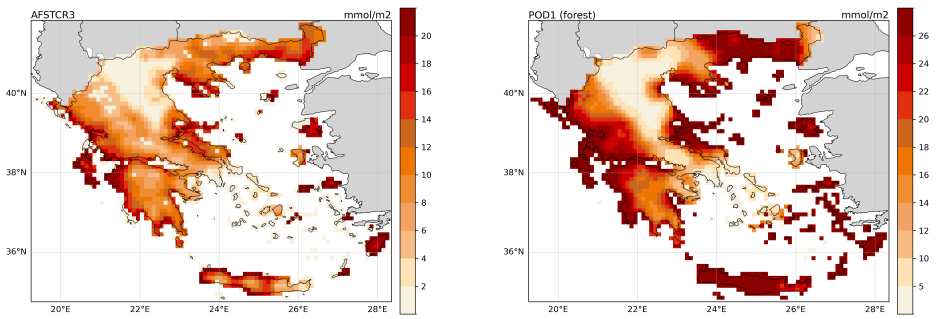

Figure 31: $POD_{3.0,gen-CR}$ and $POD_{1.0,gen-DF}$ in Greece in 2021. Unit: mmol/m^2.

8.3 Health impacts from ozone and particulate matter

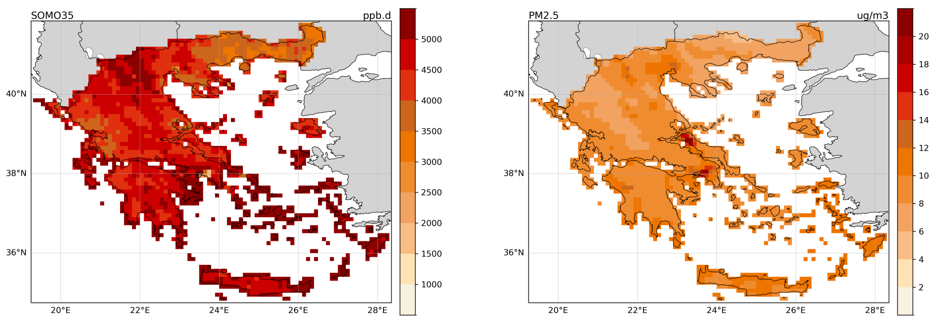

Figure 32: Left: Regional scale SOMO35, and right: $PM_{2.5}$in Greece in 2021. SOMO35 is given in ppb·h, while $PM_{2.5}$ concentrations are given in µg/m^3.