

Article

The Future Impact of Shipping Emissions on Air Quality in Europe under Climate Change

Michael Russo ^{1,*} , David Carvalho ² , Jukka-Pekka Jalkanen ³ and Alexandra Monteiro ¹ 

¹ Department of Environment and Planning, CESAM, University of Aveiro, 3810-193 Aveiro, Portugal

² Department of Physics, CESAM, University of Aveiro, 3810-193 Aveiro, Portugal

³ Finnish Meteorological Institute, FI-00101 Helsinki, Finland

* Correspondence: michaelarusso@ua.pt

Abstract: Ship engine combustion emits several atmospheric pollutants, such as PM, SO_x, and NO_x, which can have adverse health effects and are significant contributors to decreased air quality. Due to the distribution of maritime transport activity routes in the EU, a large portion of the population is exposed to shipping emissions throughout Europe. Therefore, in light of the European Commission long-term objective of “zero-waste, zero-emission” for maritime transport, the focus of this study was to quantify the impact of shipping emissions in the present, as well as the future, considering both emissions projection for the shipping sector and a climate change scenario. The WRF-CHIMERE modelling system was used to quantify the impact of shipping in Europe. To obtain the current and future contributions of maritime transport to the total pollutant concentrations, simulations were divided into two present (baseline and without shipping) and three future scenarios (shipping projection, climate change, and shipping projection and climate change). The results indicate that the current and future impacts of shipping emissions on pollutant concentrations are similar in some regions (NO₂ for Northern Europe and SO₂ for Southern Europe), which is due to the enforcement of emission control areas for those pollutants. However, efforts towards lowering emissions from the shipping sector are negated in the south of this domain due to the concentration changes caused by the climate change scenario. In light of these changes, the introduction of a NECA is proposed for the Mediterranean, which would help us to make great strides to reduce the impact of the shipping sector in the region and aid in counteracting the effects of climate change.

Keywords: shipping emissions; climate change; air quality



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1. Introduction

Air pollution is recognised as the highest environmental threat to human health, and a large part of the European population is still breathing air with pollution levels exceeding the EU standards and World Health Organization Air Quality Guidelines (WHO AQG) for the protection of health [1]. In many of these regions, there are exceedances above WHO Air Quality Guideline (AQG) limit values, which have been altered and are now even more strict, while the AQ directive is being revised and will define the new limit values, which are closer to the previous WHO AQG, mainly focusing on the most critical pollutants over Europe—nitrogen oxides (NO_x), particulate matter (PM) and ozone (O₃) [2]. This indicates that if no additional air quality plans and strategies are implemented, the number and areas with exceedances will greatly increase after the new directive’s implementation.

Emissions of air pollutants are derived from almost all economic and societal activities. Progress has been made in tackling air pollutants such as sulphur dioxide (SO₂), carbon monoxide (CO) and lead (Pb) [3]. On the other hand, the transportation sector, industry, households, and agricultural activities continue to emit large amounts of air pollutants.

Maritime transport is an important sector in Europe that enables trade and contact between all European countries, with almost 90% of the external freight trade being

seaborne [4]. Due to the growth of the shipping industry, it makes non-negligible contributions to the degradation of air pollution, making shipping activities an increasingly serious concern in coastal regions for the reasons of both environmental quality and human health [5–9]. Evidence for the importance of ship emissions has even been derived from satellite observations, such as GOME [10] and SCIAMACHY [11]. Studies have suggested that around 15% and 4–9% of all global anthropogenic emissions of NO_x and SO₂, respectively, are from ocean-going ships [12,13]. As most of the ship emissions arise within 400 km of coastlines [3], they primarily contribute to air pollution in coastal areas [9,14–18], emitting carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur dioxide (SO₂), carbon monoxide (CO), hydrocarbons and primary particulates, as well as secondary particulate precursors [19]. However, these emissions can be transported hundreds of kilometres downwind and impact a much broader region [14,16].

During the last two decades, great efforts have been made in Europe to reduce other types of emission sources (industrial, power generation, etc.), which, in parallel with the rise of the global shipping fleet, has increased the weight of shipping emissions relative to the total anthropogenic emissions [19,20]. Although it has high emission reduction potential through technological improvements, alternative fuels or ship modifications, shipping is one of the least regulated sources of anthropogenic emissions. Recently, international regulations have been enforced to lower global shipping emissions. The International Maritime Organization (IMO) tightened the global marine fuel sulphur content from 3.5% to 0.5% starting in 2020 and implemented different shipping emission control areas (ECA) in Europe and North America [21]. In addition, the decarbonization goals assigned for the 2030 and 2050 horizons will considerably change the shipping industry [20].

There are a large number of studies on the impacts of shipping emissions, with and without control measures, on air quality in different areas of the world and their importance for local communities near major ports and coastal areas [7,15,22–26]. The contribution of shipping in these studies varies depending on the type of pollutant and region. The highest contributions have been found for coastal regions, with 1–14% of ambient air of PM₁₀ level and 7–24% of NO₂ being attributable to shipping, with impacts up to 30 km inland [9]. Most of these studies usually project shipping emissions for future years based on proxies that are highly correlated with total ship activity (e.g., seaborne trade, port throughput, fuel usage, and engine power) using current meteorological scenarios but do not consider the future impacts of climate change. As a result, they do not account for future variations in the atmosphere, which will influence air pollutants dispersion, transport and chemical transformation and, consequently, the effectiveness of mitigation strategies. It is therefore important to understand the impacts of future shipping emissions in climate change scenarios, especially those on air quality in coastal and critical areas.

In this study, we assessed the impact of emissions from shipping over a European domain using a comprehensive air quality modelling system, WRF-CHIMERE. The RCP8.5 scenario was used in order to consider the worst case in terms of climate change conditions, and the STEAM shipping emissions inventory was selected, since it is the most accurate shipping emissions inventory currently available [27]. Model simulations for Europe were carried out, with and without shipping emissions, in both current and future climate conditions.

In the following sections, we describe the methodology applied and the air quality modelling setup used for this impact assessment study (Section 2). Then, the modelling results are presented and discussed in Section 3, and the discussion is provided in Section 4, with the summary and conclusions in Section 5.

2. Data and Methods

The WRF-CHIMERE modelling system was applied for this study. This system combines the capabilities of the Weather Research and Forecasting (WRF) model [28] that provides meteorological data for the CHIMERE air quality model that computes ambient pollutant concentrations [29–31]. The modelling system components are detailed in Figure 1. Hourly simulations were performed using a 10 × 10 km² horizontal resolution

for each simulated year over a European domain. The relevant model options were as follows: LMDz4_INCA boundary conditions for gaseous and particle species; a reduced MELCHIOR chemical mechanism with chemically active aerosols; and the second-order Van Leer vertical advection scheme. For a more accurate quantification of future changes due to climate change, WRF was run for a representative meteorological year for the baseline and the future scenario driven by the Max Planck Institute Earth System Model (MPI-ESM). Additionally, the model was run with two nested domains, spectral nudging, SST updates every six hours and the following physics options: WSM 6-class graupel scheme microphysics, RRTMG longwave and shortwave radiation, the Monin–Obukhov similarity surface-layer scheme, Noah Land Surface Model, YSU boundary-layer scheme and Grell–Devenyi ensemble cumulus option. Both CHIMERE and WRF were run with the default output options, providing the full range of pollutants and 3D meteorological variables, respectively.

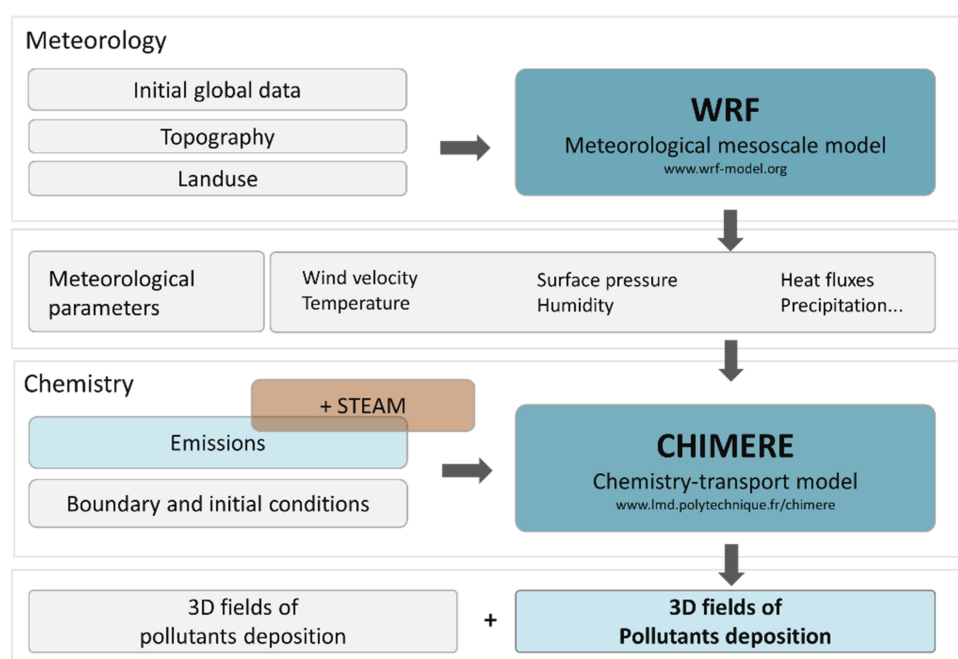


Figure 1. WRF-CHIMERE modelling system diagram.

Four scenarios were simulated, as well as a baseline (2015) for comparison. The future year was chosen according to the shipping emissions target, which is 2050. The “No Shipping” (NS) scenario has the emissions from the shipping sector completely removed from the input inventory. This is used to assess the current impact of shipping emissions and quantify their contribution to air quality by comparing this simulation with the baseline, which has no alterations. Next, the “Shipping Projection” (SP) scenario is a projection of the shipping emissions alone up to 2050. The projection considers multiple factors, such as: the addition of the SECA and NECA areas that are already in effect and will be added in the coming years, which will determine the expected fuel changes in the Baltic, North and Mediterranean seas; the expected increase in the global and European shipping fleet, which the IMO estimates will increase by at least 40% to 50%; the gradual increase in energy efficiency from existing and new vessels, known as the Energy Efficiency Design Index (EEDI) which is a technical measure that aims to promote more energy efficient equipment and engines in ship design; the overall goal of the sector to reduce total annual emissions from shipping to below 50% of their 2008 value by 2050. To isolate the effects of climate change on pollutant concentrations and compare them to SP scenario, “Climate Change” (CC) is a scenario that only differs from the baseline run by changing the meteorological input files from the baseline WRF data to the WRF simulation for 2050. Since the objective of this study is to assess the effectiveness of changing shipping emissions when compared

to the effects of climate change, the worst-case climate change scenario, RCP8.5, was chosen. Finally, “CC + Shipping Projection” (CCSP) considers both the CC scenario and the SP scenario, allowing for the assessment of the combined effect of climate change and emissions projections from the shipping sector. This scenario will provide valuable insight into the effectiveness of emission reduction strategies for shipping throughout Europe in a climate change context.

The emissions data used for baseline was the 2015 EMEP emissions inventory, which covers the entirety of Europe at a horizontal resolution of 0.1 by 0.1 degrees, with yearly accumulated values by activity sector for CO, NH₃, NMVOC, NO_x, SO_x, PM₁₀ and PM_{2.5}. For the shipping sector, which is the focus of this study, emission simulations for the baseline and 2050 projections were performed with the Ship Traffic Emission Assessment Model (STEAM). The STEAM model works in three main stages, the first is data assimilation where the AIS activity data from ships is processed, a ship database is built and the routes for the ships are generated. Second, the vessel state and characteristics are estimated from the onboard equipment, technical properties of the ship, engine characteristics, among other technical details. And third, the final emissions from each ship are calculated from their fuel consumption, engine load and emissions factors. For more detail on the STEAM model and examples please refer to [22,32–34]. Figure 2 shows the projected emissions reduction in 2050 of the main primary pollutants addressed in this study (NO_x, SO_x and PM_{2.5}).

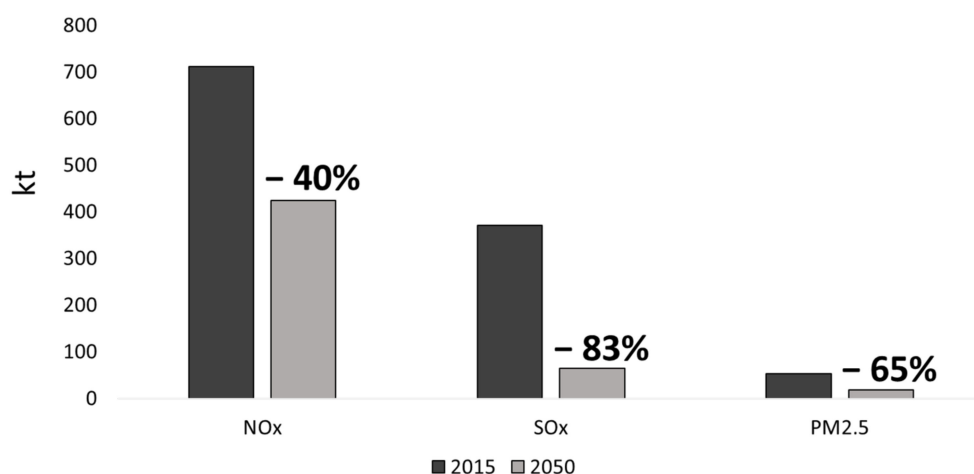


Figure 2. Projected 2050 STEAM emissions reduction of NO_x, SO_x and PM_{2.5}.

The STEAM emission data were then used to replace the shipping sector within the default EMEP inventory, creating two emission datasets, one with the improved shipping emissions for the baseline and another with the shipping emission projections for 2050. This air quality modelling system was validated and evaluated in the last decade for Europe and smaller domains [25,35–37], together with the STEAM emission model that is regarded as a reference for shipping emissions inventories [23,27]. This supports the notion that the WRF-CHIMERE system, combined with the high accuracy of the shipping emissions from the STEAM model, provides a robust framework with which to assess the impact of current and future shipping emissions on air quality.

To quantify the effect of each scenario, the median differences between each of them were calculated, as well as the 10th and 90th percentiles. In this case, the median instead of the average difference was selected as the most adequate approach to study the variations between the scenarios, because the dataset resulting from the calculated differences presented a skewed distribution. To aid in the discussion and to provide insight into the range of possible differences between the studied scenarios, the P10 and P90 plots were also added to the results.

To calculate the median, P10 and P90, the datasets were divided into two main periods: cold (October–March) and warm months (April–September). Then, the median hourly differences were computed between the baseline and each of the scenarios detailed above.

using the “xarray” Python package median and quantile functions. The same procedure was performed for the monthly median differences that are available in the Supplementary Materials. To calculate the exceedances of the air quality limit values, the yearly dataset was taken for the assessment, with either the number of days exceeding the limit value or an indication of whether or not the annual limit values were exceeded, presented according to the pollutant in the analysis (Table 1).

Table 1. Selected pollutants, limit values and averaging period for air quality exceedance analysis.

Pollutant	Concentration	Averaging Period
Fine particles (PM _{2.5})	25 $\mu\text{g}\cdot\text{m}^{-3}$	1 year
Nitrogen dioxide (NO ₂)	200 $\mu\text{g}\cdot\text{m}^{-3}$	1 h
Sulphur dioxide (SO ₂)	350 $\mu\text{g}\cdot\text{m}^{-3}$	1 h
Ozone	120 $\mu\text{g}\cdot\text{m}^{-3}$	Maximum daily 8 h mean

3. Results

For the quantification of the effect of shipping emissions on air quality in Europe, as well as a comparison between each of the studied scenarios, the differences between the baseline and each scenario were analysed. Shipping activity is typically higher during the late spring and summer months; therefore, the following analysis focuses on the warm month period of the simulations. Nonetheless, the monthly median differences are presented in the Supplementary Materials to provide some insight into intra-yearly variability.

3.1. Median, P10 and P90

Starting with the NS scenario, there are large contributions of NO₂ due to shipping activity throughout the study domain (Figure 3), mainly along larger shipping routes and larger ports in Northern Europe, as well as various locations in the Mediterranean. The median hourly differences in shipping routes and ports vary from $-3 \mu\text{g}\cdot\text{m}^{-3}$ to $-5 \mu\text{g}\cdot\text{m}^{-3}$, while the P10 differences show maximum reductions of over $-17 \mu\text{g}\cdot\text{m}^{-3}$ when shipping is absent. There are a few hotspots within the domain, particularly along major shipping routes, the ports of Rotterdam and Hamburg, Oresund and the Gibraltar Strait. The shipping projections in the SP scenario suggest that the future deltas in the concentrations of NO₂ from the projected shipping emissions are equivalent to the present contribution of shipping in the north of Europe (a median difference of over $-5 \mu\text{g}\cdot\text{m}^{-3}$ and a P10 of up to $-17 \mu\text{g}\cdot\text{m}^{-3}$). This is indicative of the long-term effects of the recent addition of a NECA in the North and Baltic Seas, which has been in full effect since 2021. The median differences in the Mediterranean suggest a smaller reduction in shipping below $-2 \mu\text{g}\cdot\text{m}^{-3}$ and up to a maximum of $-4 \mu\text{g}\cdot\text{m}^{-3}$, as seen for the P10 differences.

When examining the isolated difference due to climate change alone (scenario CC), there is a median increase in NO₂ concentrations in locations which were already hotspots for this pollutant, mainly large urban areas and regions that have high shipping activity, with an increase of $+3$ to $+4 \mu\text{g}\cdot\text{m}^{-3}$. For the P10 and P90 values, a larger range of differences are noted, particularly the road transport network throughout Europe, as well as a clear view of the shipping routes (largest variation registered for P90 with values of approximately $20 \mu\text{g}\cdot\text{m}^{-3}$). Finally, in the CCSP scenario, which combines the effects of climate change and shipping projections, the effects of climate change over the land areas still remain, but the estimated reduction in NO₂ concentrations from the shipping sector in the north of Europe can offset the expected increase from climate change, achieving a median reduction of 2 to $3 \mu\text{g}\cdot\text{m}^{-3}$. However, in the Mediterranean, the reduction in shipping emissions in the future scenario leads to a low reduction in NO₂ concentrations attributable to shipping, which is not sufficient to counteract the effect of climate change, leading to neglectable median differences in this region.

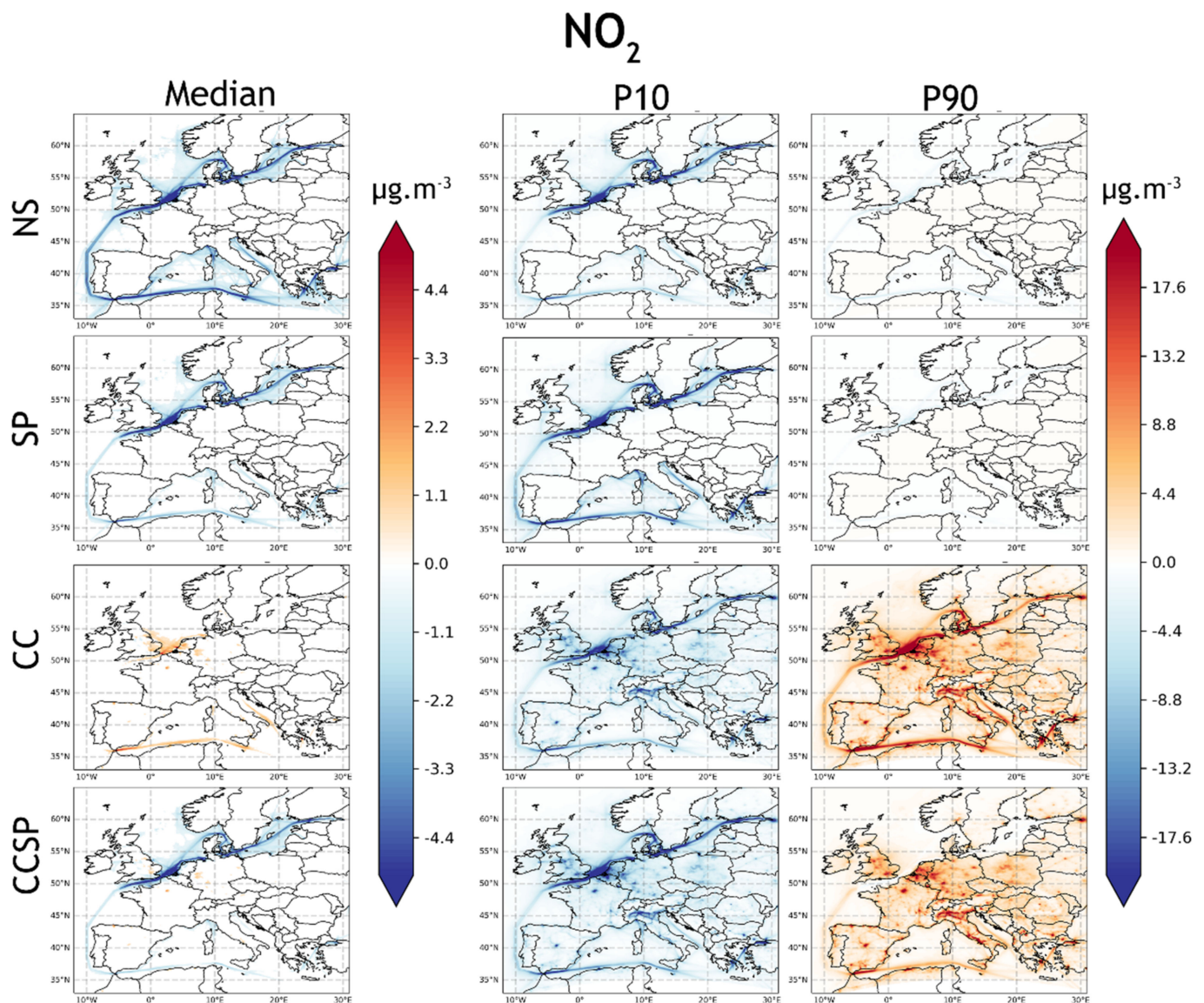


Figure 3. Median hourly difference for NO_2 (left), along with 10th (middle) and 90th (right) percentile differences during warm months for the four studied scenarios (NS—no shipping; SP—shipping projection; CC—only climate change; CCSP—climate change and shipping projection).

Figure 4 shows the current impacts of the NS scenario on ozone—a secondary and photochemical pollutant—where there is an increase in concentrations along the major shipping routes and ports, where the NO_2 concentrations were higher. With a decrease in ozone precursors, ozone depletion in those areas is lower, which leads to an increase in ozone concentrations. Without the presence of shipping emissions, the O_3 concentrations increase by approximately $+9 \mu\text{g}\cdot\text{m}^{-3}$ along shipping routes and port areas in the North and Baltic Seas and below $+2 \mu\text{g}\cdot\text{m}^{-3}$ in the Mediterranean. However, in areas where NO_2 concentrations were not as high, such as the areas adjacent to shipping routes in Southern Europe and the Atlantic, there is a decrease in ozone concentrations, suggestion that in these areas, ozone production is NO_x -limited, registering median decreases between -2 and $-6 \mu\text{g}\cdot\text{m}^{-3}$. This is similar to the changes that are shown for the SP scenario, where the value in the north of the domain is equivalent to NS due to the effects of the NECA, while in the south, the median difference falls below $+1 \mu\text{g}\cdot\text{m}^{-3}$. The P10 and P90 plots do show some higher differences between the baseline and SP scenario in the Mediterranean (-5 to $+10 \mu\text{g}\cdot\text{m}^{-3}$), but these are still relatively low when compared to the north. When only accounting for the changes related to climate change (CC scenario), there

is an overall decrease in ozone concentrations throughout the domain, with the exception of southeastern Europe. This is in agreement with the spatial distribution of the average changes for the RCP8.5 climate change scenario, which indicates, for example, an increase in solar radiation in the northwestern and southeastern parts of the domain, as well as Mediterranean locations such as Italy. When combining these changes with the projected shipping emissions in the CCSP scenario, the expected decrease in NO_2 concentrations in the north as compared to the SP scenario are higher than the effect of climate change, which translates to an increase in ozone concentrations of $\sim 4 \mu\text{g}\cdot\text{m}^{-3}$. In the case of the southern and Atlantic regions, the projected changes show a low impact on the total O_3 concentrations, with no significant changes from the CC scenario.

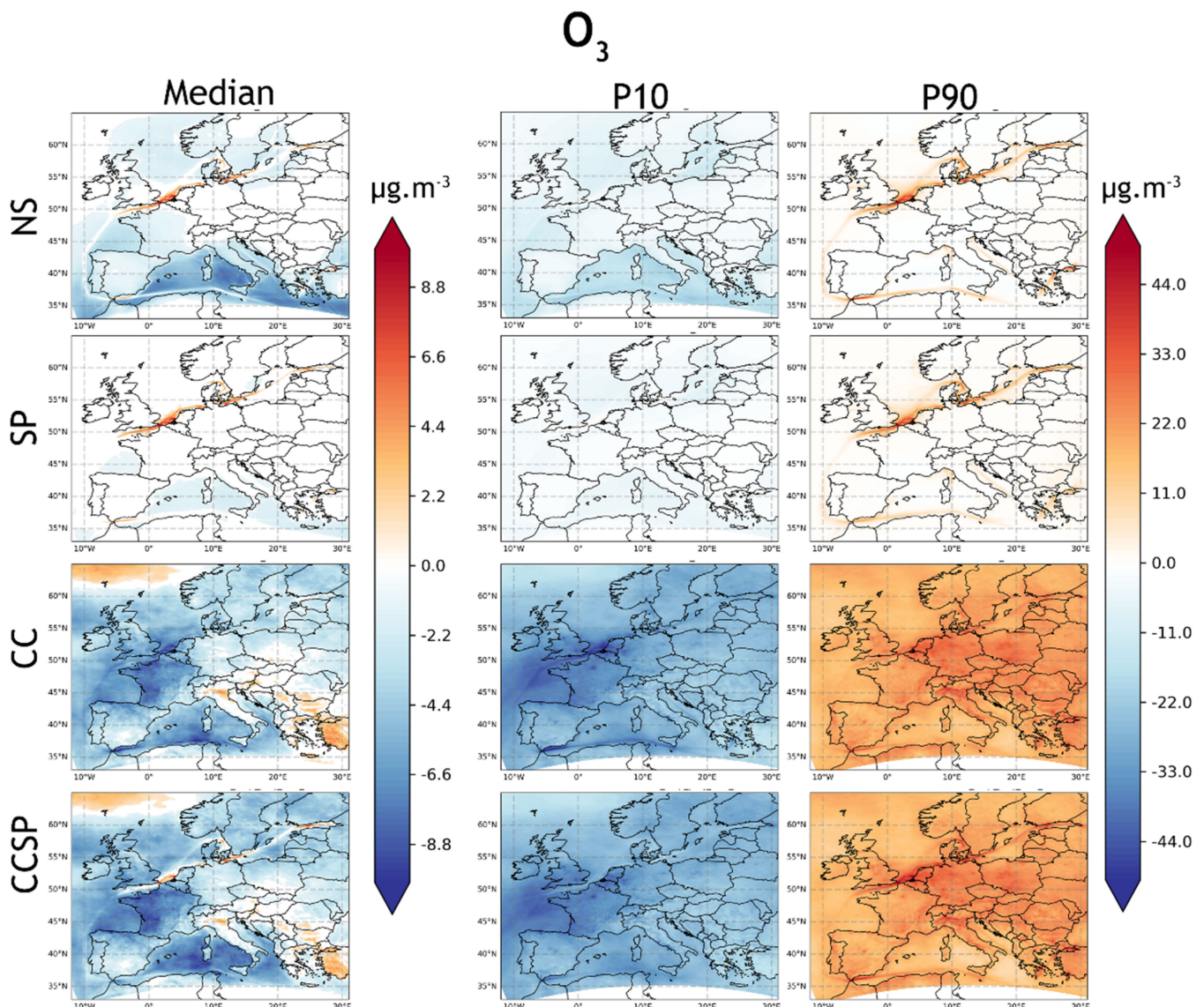


Figure 4. Median hourly difference for O_3 (left), along with 10th (middle) and 90th (right) percentile differences during warm months for the four studied scenarios (NS—no shipping; SP—shipping projection; CC—only climate change; CCSP—climate change and shipping projection).

The SO_2 median concentrations differences (Figure 5) for NS only show noticeable contributions of shipping activity in the Atlantic and Mediterranean, ranging from $-3 \mu\text{g}\cdot\text{m}^{-3}$ median differences to $-10 \mu\text{g}\cdot\text{m}^{-3}$ P10 differences. A SECA has been enforced in the North and Baltic Seas since 2005/2006; hence, removing shipping emissions from this area has little to no effect on the SO_2 concentrations for the region. Considering the SP scenario, there

is evidence showing that the implementation of the SECA in the Mediterranean (which should be in full effect in 2025) will replicate the effect of what has happened in Northern Europe, reducing the future contribution of the shipping sector by a value equivalent to the current contribution (3 to $4 \mu\text{g}\cdot\text{m}^{-3}$).

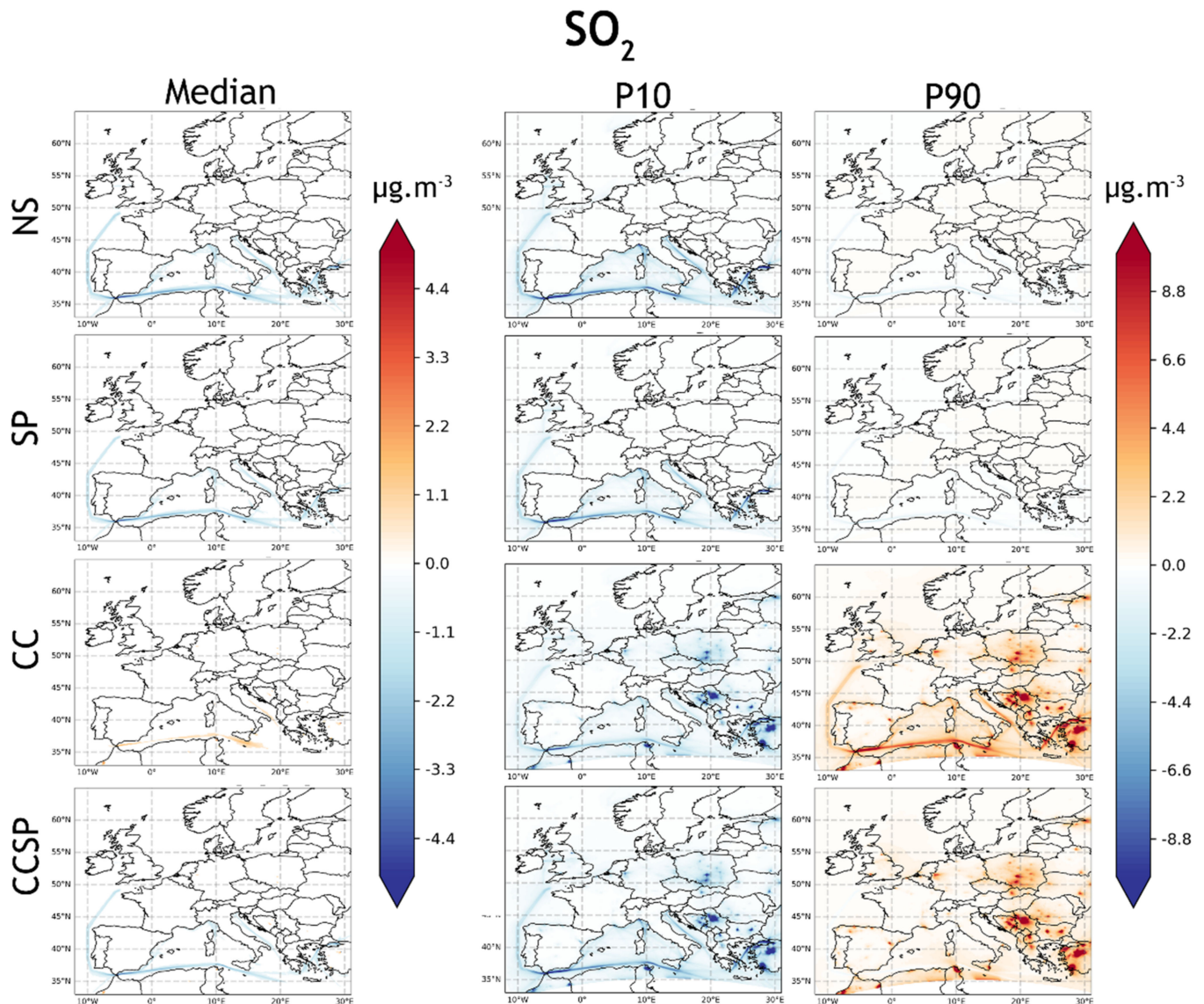


Figure 5. Median hourly difference for SO_2 (left), along with 10th (middle) and 90th (right) percentile differences during warm months for the four studied scenarios (NS—no shipping; SP—shipping projection; CC—only climate change; CCSP—climate change and shipping projection).

Sulphur is generally associated with either ship combustion, industrial activities or coal-fired energy production. These sources are evident for the CC scenario when analysing the median difference, where the variations in SO_2 concentrations are mainly along shipping routes (up to $10 \mu\text{g}\cdot\text{m}^{-3}$ for P90 differences) and in Eastern Europe, where coal power plants are still one of the main sources of electricity (over $10 \mu\text{g}\cdot\text{m}^{-3}$). Regarding the CCSP scenario, the addition of a SECA in the south of the domain will have a positive effect on the concentrations of SO_2 , with sufficient reductions in shipping emissions to counteract the effect of climate change, resulting in a median net decrease of $2 \mu\text{g}\cdot\text{m}^{-3}$ along the Mediterranean and Atlantic routes.

While the implementation of a SECA is mostly focused on the reduction in the sulphur content in fuels to achieve a reduction in sulphur oxide emissions, these measures also

reduce PM_{2.5} emissions by approximately 25%. This means that the overall spatial distribution and behaviour of the PM_{2.5} differences in each of the tested scenarios are very similar to those of SO₂ in the NS and SP scenarios (Figure 6). The median difference for NS shows a higher contribution of shipping to the PM_{2.5} concentrations in the Mediterranean and Atlantic regions than those in the north, with values of +1 to +2 $\mu\text{g}\cdot\text{m}^{-3}$ to below +1 $\mu\text{g}\cdot\text{m}^{-3}$, respectively. For the SP scenario, the median difference in the PM_{2.5} concentrations is low, being approximately $-1.5 \mu\text{g}\cdot\text{m}^{-3}$ ($-10 \mu\text{g}\cdot\text{m}^{-3}$ for P10), with the highest differences in the Mediterranean and the international shipping route from the coast of Portugal to the English Channel.

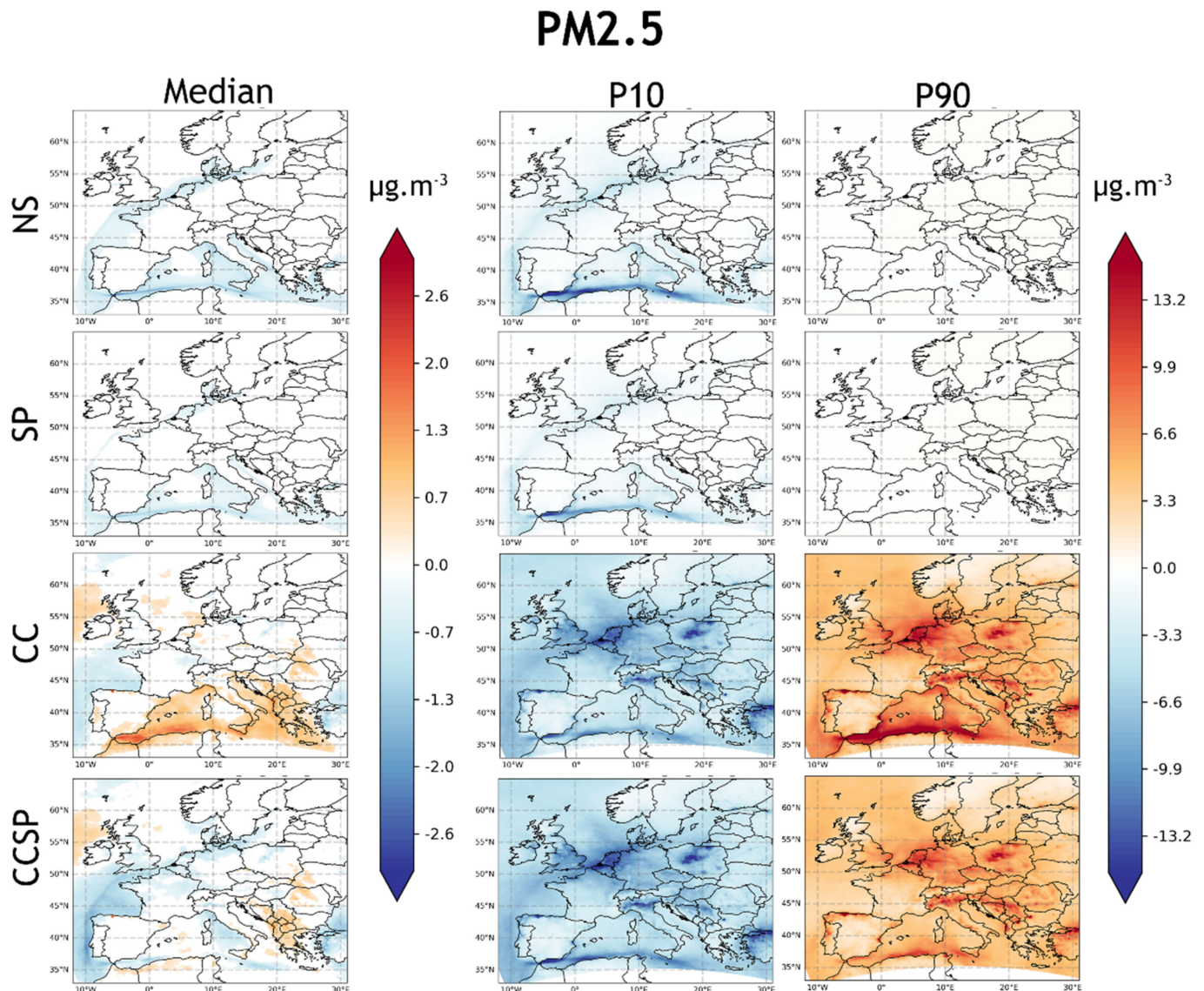


Figure 6. Median hourly difference for PM_{2.5} (left), along with 10th (middle) and 90th (right) percentile differences during warm months for the four studied scenarios (NS—no shipping; SP—shipping projection; CC—only climate change; CCSP—climate change and shipping projection).

In the CC scenario, there is an expected increase in PM_{2.5} in the Mediterranean of approximately +1 $\mu\text{g}\cdot\text{m}^{-3}$ for most of the Mediterranean and up to +3 $\mu\text{g}\cdot\text{m}^{-3}$ for the Strait of Gibraltar, while most of the rest of Europe shows a very small decrease or negligible differences. Nonetheless, the differences can range from $-14 \mu\text{g}\cdot\text{m}^{-3}$ for P10 to over +15 $\mu\text{g}\cdot\text{m}^{-3}$ in P90. The CCSP scenario shows that the effects of the SECA to be enforced in the south will cancel out the increase projected for PM_{2.5}, with a further decrease in PM_{2.5} concentrations in the Atlantic region, reaching median values of 2 to 3 $\mu\text{g}\cdot\text{m}^{-3}$. This suggests that the planned emissions

control areas will be helpful in reducing or controlling PM_{2.5} concentrations where there is high shipping activity.

3.2. Exceedances of the AQ EU Directive

To study the impact of each scenario in further detail, the exceedances of the EU AQ directive for the studied pollutant limit values were calculated and are presented in Figure 7. It is noteworthy that for PM_{2.5}, there was a low number of exceedances and no noticeable difference between the scenarios presented here; thus, it is not presented in the analysis in this section.

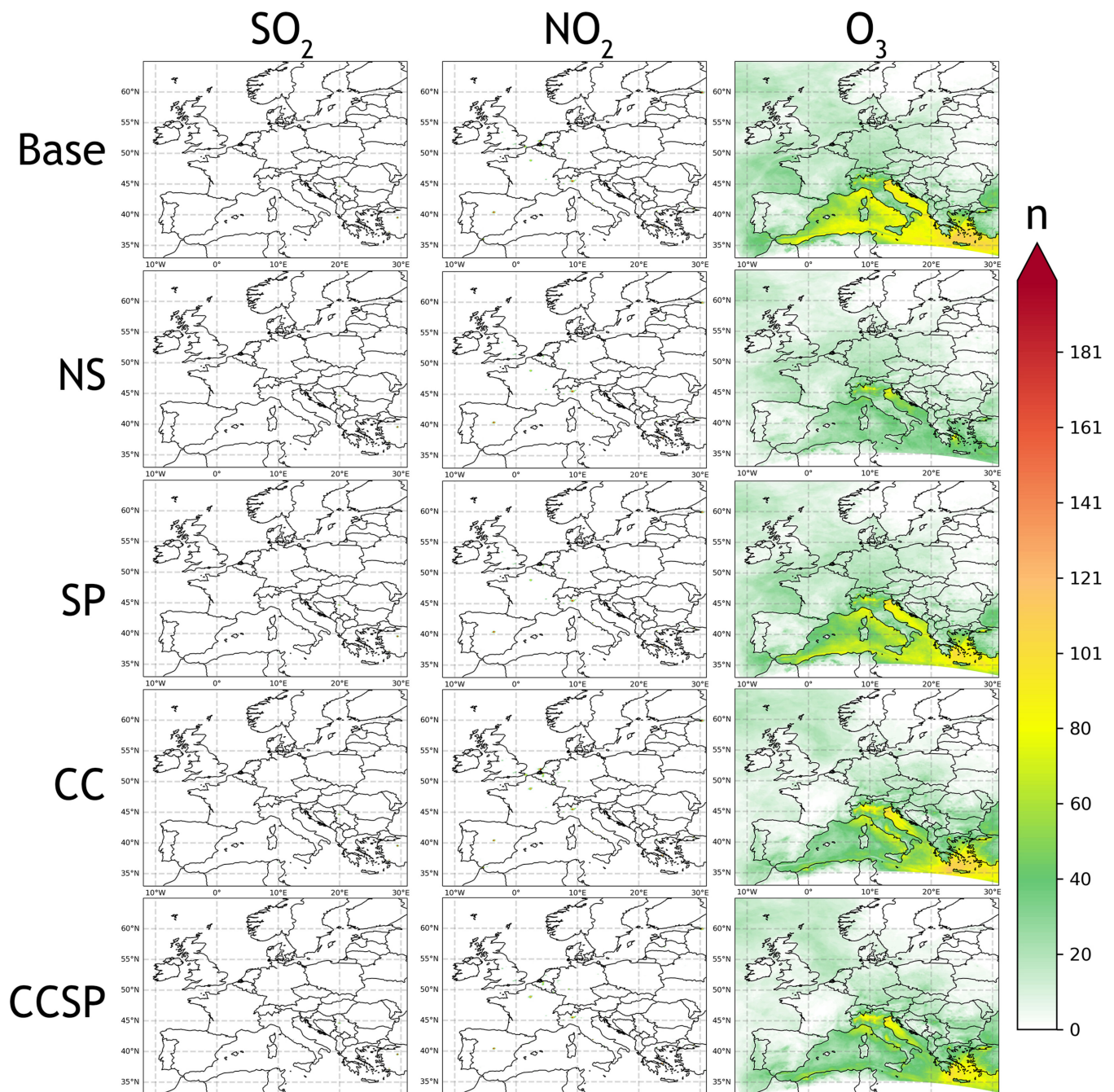


Figure 7. Number of exceedances of the EU air quality directive for SO₂ (n hours above the limit value), NO₂ (n hours above the limit value) and O₃ (n days with daily 8 h maximum above the limit value) for the baseline and each scenario (Base—baseline scenario; NS—no shipping; SP—shipping projection; CC—only climate change; CCSP—climate change and shipping projection).

For both SO₂ and NO₂, the hourly limit value is quite high, and because of this, the most problematic areas with exceedances are extreme cases of pollution, such as Eastern European countries that still use coal for energy production and the largest cities/port areas where there is a very high density of road and maritime traffic. The baseline shows exceedances over 190 h and ranging from 80 to over 200 h for SO₂ and NO₂, respectively. For O₃, there are exceedances throughout the entire domain, but most notably in Southern Europe, which is to be expected, since this region has historically had the highest solar radiation and O₃ concentrations. The ozone exceedances for the baseline are below 20 for most of the domain, with higher values in areas adjacent to shipping lanes and the Po Valley, registering exceedances between 40 and 120 days in the Mediterranean and between 20 and 100 days in Italy.

Analysing the different scenarios, there is a pattern similar to the above median concentration differences. NO₂ exceedances are still present in the major cities in all scenarios, but for the shipping hotspots in Northern Europe, there is a decrease of 60 to 200 h and even to zero over the water and close to the coastline. Even with the expected increase in NO₂ exceedances due to climate change in the CC scenario, the combined effect in the CCSP shows that the introduction of the NECA area in the north will result in a positive contribution to compliance with the air quality directive. There is no difference for SO₂ in most of the scenarios, except for a slight increase in SO₂ exceedances due to the effects of climate change, increasing the number of hours to approximately 200. Finally, the NS scenario shows that many of the ozone exceedances in the Mediterranean are attributable to shipping activity, with a decrease of around 40 days when the sector is removed. Examining the other scenarios, there is an expected decrease for both the SP and CC scenarios, which, when combined, show an overall decrease in exceedances of approximately 10 to 20 days in most of the Mediterranean.

4. Discussion

The quantified contribution of the shipping sector in the current and future climate change conditions provides valuable insight into the strategies that have been outlined for the sector. The additions of the SECA in the Mediterranean and the NECA in Northern Europe both provide necessary reductions in SO₂ and NO₂ concentrations in those regions. Although the most noticeable effect between the two is a reduction in NO₂ exceedances in the north, a reduction in the overall concentrations of sulphur dioxide and PM_{2.5} is expected to occur in critical areas, such as the Strait of Gibraltar.

The results achieved here are in agreement with previous work conducted in other shipping-focused studies using similar methods. Nevertheless, most of the studies have focused on the northern and Baltic regions due to the increased efforts to control shipping emissions and consequent air quality issues in that area [25,38–41]. The Mediterranean region has been highlighted as a hotspot in terms of shipping pollution, and this study—together with a few others [42–44]—will support the development of strategies focusing on this specific area. Overall, for the present results in both regions, the contribution of shipping to the ambient pollutant concentrations are within ranges comparable to those achieved in previous works, with higher impacts on coastal communities and major port areas and non-negligible contributions up to 50 km inland. However, in terms of the future scenarios, one of the main focuses of the present study, there are some studies exploring the effects of shipping emissions due to future fuel changes and limitations on a global scale, with results for the European region [8,14], but no studies specifically focused on the effect of climate change forcing together with the shipping projections. This study adds to the current body of knowledge by introducing new data into the analysis, considering the isolated and combined effects of climate change on the future of the shipping sector. As we have seen in the different scenarios studied in this work, there are areas where some emission control strategies are either still not sufficient to counteract the effects of climate change or have little to no effect in reaching an overall reduction in concentrations where there is an expected increase due to CC, especially in the Mediterranean.

5. Summary and Conclusions

A numerical modelling approach based on the WRF-CHIMERE modelling system was used to evaluate the impact of shipping on regional air quality for the present and future (climate change) scenarios. This study focused on Europe due to the large number of ports and high shipping activity around this region, considering the most critical pollutants for the area (NO_2 , SO_2 , O_3 and $\text{PM}_{2.5}$). A high-resolution inventory for shipping emissions was used for the present and future projection of shipping emissions (STEAM). Regarding the present conditions, the modelling results show the critical areas affected by shipping emissions, namely, the Mediterranean, North and Baltic Seas, with a strong focus on shipping routes and port areas. The largest differences in terms of spatial distribution were found to be those related to O_3 due to its formation from precursors and significant transport and dispersion.

For the future scenario, two aspects are most evident. First, there were non-negligible reductions for all pollutant differences and for all scenarios along shipping routes, and even though maritime traffic will increase, the SP and CCSP scenarios show an overall decrease in concentrations in the future. Second, the contribution of climate change to variations in regional air quality over inland locations is comparable and at times higher than that caused due to a decrease in shipping emissions. These results are particularly important for understanding and quantifying the future impacts of both shipping emissions and climate change on regional air quality, since a combination of both is the only way to study and access the effectiveness of future strategies.

In terms of emission control areas and future policy implications, the results provide valuable insight into the benefits of the enforcement of the Mediterranean SECA. Additionally, the expected changes in the SP and CCSP scenarios regarding the NECA development in the North and Baltic Seas suggests that the Mediterranean would also greatly benefit from the implementation of a similar NECA. This finding is reinforced by the estimated changes in concentrations in the region when compared to Northern Europe, as well as the expected effect in reducing the overall exceedances for NO_2 in these areas. Similar to the effect of a SECA, NECA and other global caps on emissions for the shipping sector, the additive effect of emission control policies in sensitive regions is a mainline strategy for reducing the impact of shipping and aid in achieving the long-term targets for the sector.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos14071126/s1>, Figure S1: Median hourly difference for NO_2 , for each month of the year (top—Jan, bottom—Dec) for the four studied scenarios (NS—No Shipping; SP—Shipping projection; CCO—Only climate change; CCSP—Climate change and shipping projection); Figure S2: Median hourly difference for O_3 , for each month of the year (top—Jan, bottom—Dec) for the four studied scenarios (NS—No Shipping; SP—Shipping projection; CCO—Only climate change; CCSP—Climate change and shipping projection); Figure S3: Median hourly difference for SO_2 , for each month of the year (top—Jan, bottom—Dec) for the four studied scenarios (NS—No Shipping; SP—Shipping projection; CCO—Only climate change; CCSP—Climate change and shipping projection); Figure S4: Median hourly difference for $\text{PM}_{2.5}$, for each month of the year (top—Jan, bottom—Dec) for the four studied scenarios (NS—No Shipping; SP—Shipping projection; CCO—Only climate change; CCSP—Climate change and shipping projection).

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