Understanding the process of setting air quality limit values and the associated compliance challenge—the ozone study

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The European Commission is proposing to revise air quality standards to align them more closely with the World Health Organization (WHO) guidelines. This article focuses on O_3, and assesses how current and projected compliance trends will change under the current EU AQLV, as well as under lower limit values and under different emission reduction scenarios. It also highlights the need to follow a two-step process including both risk assessment *and* risk management when considering further close alignment of the current EU AQLVs for O_3 with the WHO guidelines.

Introduction

The European Commission (EC) recently completed the fitness check of the EU Ambient Air Quality (AAQ) Directives (Directives 2008/50/EC[1] and 2004/107/EC[2]). The EC drew on the experience from all Member States and various other stakeholders, focusing on the period from 2008 to 2018 (i.e. the period in which both Directives were in force) and finalised the process by publishing its Staff Working Document in November 2019.[3] The EC has concluded that, overall, the AAQ Directives have been broadly fit for purpose; however, the existing air quality framework remains subject to further improvements that would help in achieving the overarching ambition to fully meet all air quality limit values (AQLVs) for all pollutants and throughout the European Union.

Specifically, the fitness check identified several lessons learnt that should be considered in any follow-up decisions made by the EC. Among others, these include the following:

a) The EU AQLVs have been instrumental in driving a downward trend in exceedances, and in exposure of the population to exceedances. However, the current AQLVs are not as ambitious as established scientific advice suggests for several pollutants; the World Health Organization (WHO) is currently reviewing its air quality guidelines, and the EC is closely following this process.

b) AQLVs have been more effective in facilitating downward trends than other types of air quality standards, such as target values.

These important considerations have been taken into account by the EC in its Communication of the European Green Deal and its plan to adopt, in 2021, a zero pollution action plan for air, water and soil.[4] The EC has announced that it will draw on the lessons learnt from the fitness check of the AAQ Directives, and will notably propose to revise air quality standards to align them more closely with the WHO's recommendations,1 [5, 6] which are lower than the limit values set in the AAQ Directives for the majority of regulated pollutants.

Ozone (O_3) is one of the 13 air pollutants for which AQLVs have been set under the current AAQ Directives. O_3 is a secondary pollutant which is not directly emitted into the atmosphere, but is formed (and removed) via complex chemical reactions that take place in the presence of sunlight and gas precursors (mainly nitrogen oxides (NO_x) and volatile organic compounds (VOCs)) emitted by both anthropogenic and biogenic sources. The EU AQLV for O_3 was set under Directive 2002/3/EC[7]—the 'Third Daughter Directive'—which is focused entirely on O_3. This introduced a 'target value' of 120 µg/m^3 for maximum daily 8-hour O_3 mean concentrations,2 not to be exceeded on more than 25 days per calendar year averaged over three years, that should be met as of 1 January 2010.

1 In the preface of the WHO *Air Quality Guidelines for Europe*, it states that '*It should be emphasised, however, that the guidelines are health-based or based on environmental effects, and are not standards* per se. *In setting legally binding standards, considerations such as prevailing exposure levels, technical feasibility, source control measures, abatement strategies, and social, economic and cultural conditions should be taken into account.*' As risk management is not considered in the WHO guidelines values, these are lower than the limits set in the AAQ Directives for the majority of regulated pollutants. https://www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf

2 The daily maximum 8-hour mean is the maximum of the valid 8-hour running means for that day. Calculation of all the 8-hour running means for a given day is a prerequisite.

In addition, a long-term objective was introduced for O_3 which refers to the same 'target value' of 120 µg/m^3 but without any allowance for exceedance days within a calendar year. The AQLVs set in this Directive reflected the risk assessment undertaken by the WHO in the late 1990s, and no changes were made when the Third Daughter Directive was replaced with Directive 2008/50/EC.

Since the establishment of the EU AQLV for O_3, significant further research has been undertaken on the health impacts of O_3. This was already partly reflected in the 2005 revision of the WHO's Air Quality Guidelines[5] in which the WHO reduced the O_3 guide value (i.e. the maximum daily 8-hour O_3 mean concentration) from 120 µg/m^3 to 100 µg/m^3. This represents a significant toughening of the guide value, which might be lowered further based on the outcome of the ongoing review of the WHO's air quality guidelines. It is therefore highly likely that, in the expected revision of the AAQ Directives, the current 'target values' for O_3 will be revised downwards and will be made binding (and get the same status as, for example, NO_2 and PM_{10}).

However, any decision for further close alignment of the current EU AQLVs for O_3 with the WHO air quality guidelines should not be made by only taking into account the environmental and human health risks presented by concentrations of air pollutants (risk assessment step). According to the WHO instructions, this should be a two-step process where the risk assessment step will be followed by an assessment of how these risks may be managed (risk management step). In practical terms, the risk management step should assess how emissions of pollutants and their precursors may be controlled, how emission limits are technically achievable, the associated cost, and the level of success in improving air quality.

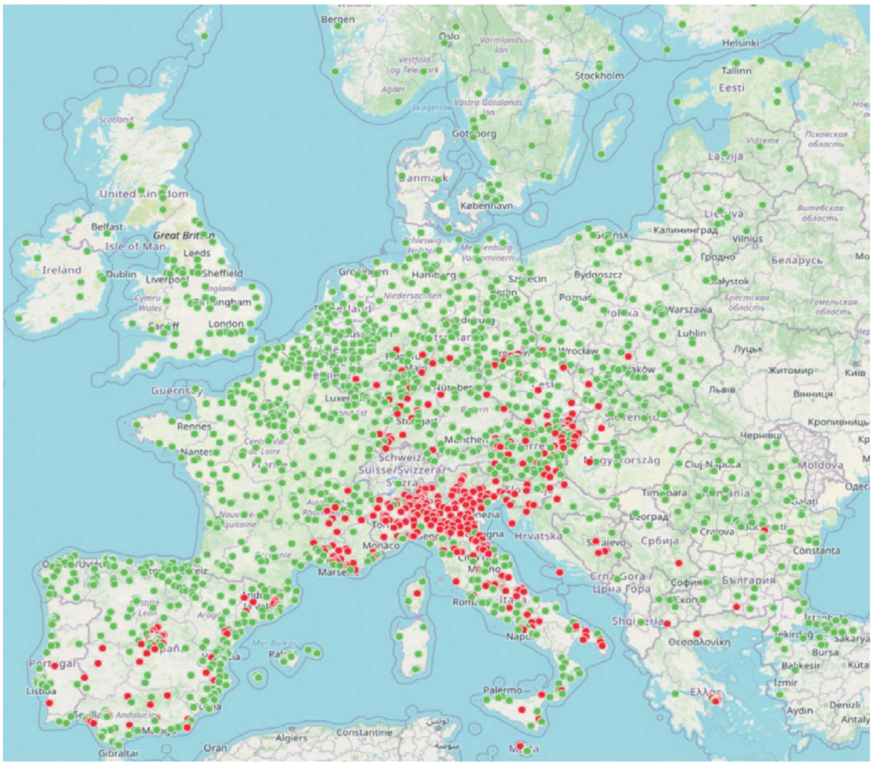
Building on the important insights derived from an earlier Concawe study[8] with respect to the significance of the risk management step as part of the AAQ Directive revision process, Concawe worked with Aeris Europe to carry out a study that analyses the current compliance trends for O_3 in Europe, and how these would change in response to a potential lowering of the AQLV to the current WHO guideline value of 100 µg/m^3. In addition, the analysis of these trends is extended into the future (up to 2030) to also assess the implications of changing the EU AQLV under the current EU legislative emissions projections and under several emissions scenarios. The analysis covers the EU, with a special focus on five Member States (France, Germany, Italy, Poland and Spain) and the UK.[3] For brevity, this article uses illustrative examples from the analysis to demonstrate the results of the study.

[3] The United Kingdom left the EU on 1 February 2020 but will apply EU law until the end of the transition period.

Current compliance trends for O_3

Based on available hourly measurement data from all European O_3 monitoring stations (~2,200 stations) taken from the European Environment Agency (EEA) Air Quality e-Reporting database,[9] the state of compliance in each Member State under the current AQLV of 120 µg/m^3 (with an exceedance allowance of 25 days) was analysed. The analysis covered both the latest year for which O_3 data were available (i.e. 2017) at the time when the study was undertaken, as well as historical years. Figure 1 shows the O_3 compliance picture in Europe in 2017 under the current AQLV.

Figure 1: Maximum daily 8-hour mean O_3 concentrations (µg/m^3) in Europe in 2017



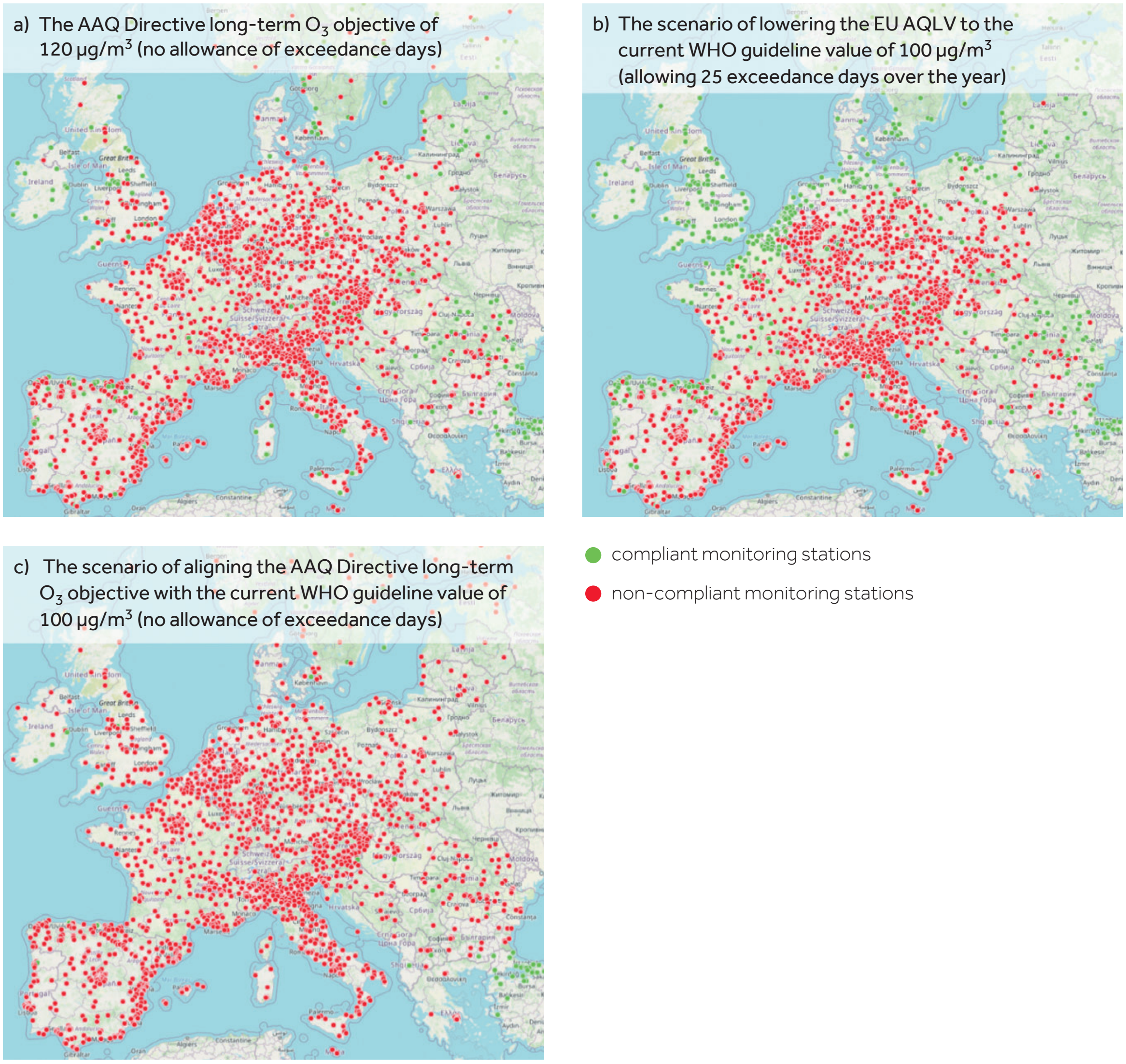
- monitoring stations that measure concentrations below the target value of 120 µg/m^3 (not to be exceeded on more than 25 days) (compliant stations)
- monitoring stations that measure concentrations above the target value (non-compliant stations)

In 2017, approximately 81% of all stations measuring O_3 in Europe were compliant with the current EU AQLV. However, on the national scale, full compliance in all monitoring stations within a country is only achieved in approximately 35% of European countries, with 17 Member States and 5 other reporting countries[4] registering concentrations above the O_3 target value for more than 25 days. O_3 compliance also shows a strong spatial variability, with most of the non-compliant stations being found in southern and eastern European countries; this indicates the important role that meteorology plays on O_3 formation, especially during peak O_3 episodes which are strongly linked and favoured by warm, stagnant conditions which occur in this part of Europe. Ozone concentrations also show a strong inter-annual variation, with compliance ranging between 75–90% over the past five years.

[4] Andorra, North Macedonia, Bosnia and Herzegovina, Serbia and Switzerland.

However, the vast majority of the monitoring stations in Europe are a long way from fulfilling the long-term O_3 objective of 120 µg/m^3 without any allowance for exceedance days set in the AAQ Directive. In 2017, only 17% of all stations in Europe were compliant with the long-term O_3 objective of zero exceedances of 120 µg/m^3 (maximum 8-hour daily average)—see Figure 2a. In addition, a significant downward change in the AQLV raises notable compliance problems. For example, a reduction in the EU AQLV to the current WHO guideline value of 100 µg/m^3, while keeping the 25 exceedance days threshold, results in a substantial EU-wide increase in O_3 non-compliance (67% in Europe)—see Figure 2b. The non-compliance issues could be even more significant when the long-term O_3 objective is aligned with the current WHO air quality guideline value, as only 6% of all O_3 monitoring stations in Europe were able to achieve this value in 2017 (Figure 2c).

Figure 2: O_3 compliance in Europe in 2017 under three different scenarios



a) The AAQ Directive long-term O_3 objective of 120 µg/m^3 (no allowance of exceedance days)

b) The scenario of lowering the EU AQLV to the current WHO guideline value of 100 µg/m^3 (allowing 25 exceedance days over the year)

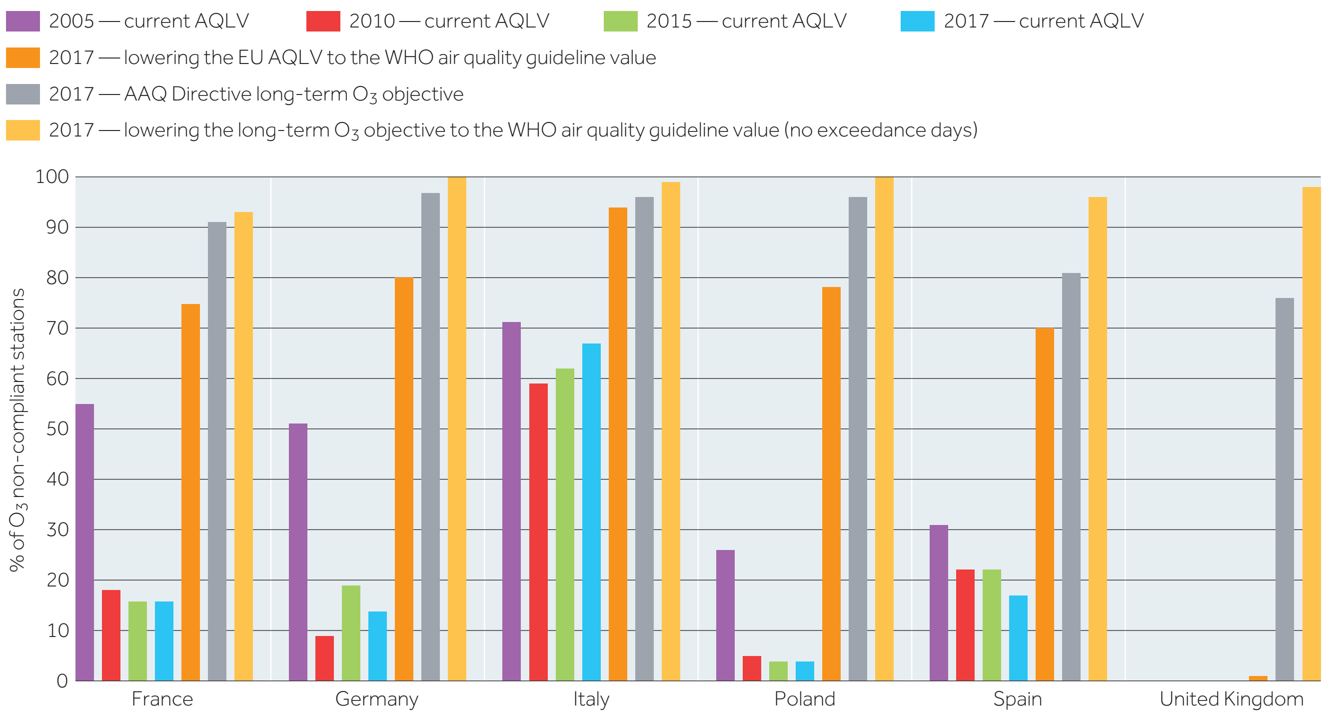
c) The scenario of aligning the AAQ Directive long-term O_3 objective with the current WHO guideline value of 100 µg/m^3 (no allowance of exceedance days)

compliant monitoring stations

non-compliant monitoring stations

Analysing the O_3 compliance trends at a national scale, in the six countries (i.e. five EU-27 Member States and the UK) used for a more detailed focus, the results show that over the years from 2005 to 2017, O_3 compliance has generally improved. However, full compliance with the current EU AQLV is currently achieved only in the UK, with non-compliance in 2017 ranging from 4–70% in the other five countries (Figure 3). A move to a limit value of 100 µg/m^3, or a move towards zero allowable exceedances at the current or lower AQLV, creates a significant non-compliance problem. These findings provide an important illustration of the need to include the risk management step in any AQLV setting revision process.

Figure 3: Percentage of O_3 non-compliant monitoring stations in six European countries (five EU-27 Member States and the UK) under the various scenarios



Another important finding that can be derived from the analysis is that O_3 compliance does not show a similar spatial pattern in all areas within a country. This can be more evident in the major urban areas where, in most cases, the analysis shows that O_3 concentrations could impose compliance issues in contradiction to the general compliance improvement at the national scale. This is mainly attributed to reductions in NO_x emissions in urban areas, mainly due to the implementation of measures to mitigate road transport emissions, which could eventually favour the formation of O_3.

Ozone formation is mainly driven by emissions of NO_x and VOCs through complex photochemical reactions, and in areas where NO_x concentrations are significantly high (i.e. in urban areas and cities) O_3 formation is dominated by NO_x. In such areas, a reduction in NO_x emissions will have a counter-effect on O_3 formation, causing O_3 levels to increase.[10,11] In Madrid, for example, O_3 non-compliance remains an important issue from 2010 onwards, in contrast with earlier years (2005) when full compliance with the current EU AQLV was achieved (Figure 4).

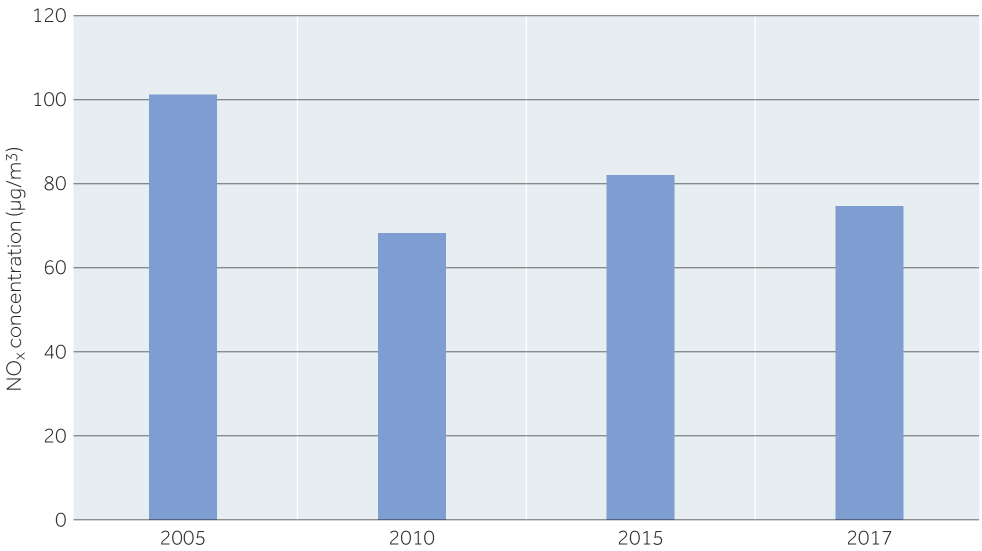
Figure 4: O_3 compliance in Madrid from 2005 to 2017

monitoring stations that measure maximum daily 8-hour mean concentrations below the target value of 120 µg/m^3 (not to be exceeded on more than 25 days) (compliant stations)

monitoring stations that measure concentrations above the target value (non-compliant stations)

In 2010, around 30% of the monitoring stations measuring O_3 in Madrid were not able to achieve compliance with the current EU AQLV, while in 2017 the proportion of O_3 non-compliant stations increased to 50%. On the other hand, NO_x concentrations in Madrid showed a downward trend, with concentrations in 2017 being 26% lower compared to 2005 (on average over Madrid) (Figure 5). It should be noted that 2015 and 2017 were two of the warmest years in Europe,[12,13] which could favour O_3 episodes. This fact, in combination with the effect of NO_x on O_3 formation, could explain the increased number of O_3 non-compliant stations in 2015 and 2017 compared to 2010.

Figure 5: Annual mean NO_x concentrations in Madrid, 2005–2017



Long-term O_3 compliance assessment

Modelling approach

To predict how O_3 concentrations will project into the future (i.e. 2030), as well as to assess the practicability of achieving compliance with current and lower ambient air quality limit values, a modelling approach was taken using the AQUIReS+ model.[14] The model uses a gridded emission inventory and source-receptor relationships[15] that relate a change in emission to a change in concentration. These data are derived from regional chemical transport models (EMEP,[16] CHIMERE [17]) used in air quality studies. The model takes into account the local environment, traffic and topographical characteristics of each monitoring station. Model predictions are compared with data from the EEA Air Quality e-Reporting database[9] to ensure that the model performs well and accurately reflects concentrations of pollutants over historic years.

Ozone concentrations at the monitoring stations were predicted under different emissions scenarios. The following section provides an overview of the scenarios examined, and the modelling results are presented in the section that follows thereafter.

Emissions scenarios

a) Current legislation baseline

The starting point of the modelling part of the study are the emissions under a current legislation (CLE) scenario. This is an official EU projection of how emissions (based on multiple sector contributions) will evolve over time. The CLE scenario takes account of economic growth and the progressive impact of European legislation currently in force. Projections are made in five-year steps (2015–2020–2025–2030). The geographic distribution of emissions is accounted for at a fine scale, and national emissions for the EU Member States (EU-27 + UK) are calculated by spatial aggregation.

The CLE scenario is described in the Thematic Strategy on Air Pollution (TSAP) Report #16, published by IIASA.[18,19,20] The focus of that report is on $PM_{2.5}$, NO_x, SO_2, NH_3 and NMVOCs (non-methane volatile organic compounds). For simplicity, the many source emissions are aggregated into 10 different sectors according to the SNAP (Selected Nomenclature for sources of Air Pollution) method.

b) Maximum Technically Feasible Reductions (MTFR) scenario

A second scenario used in policy planning is the Maximum Technically Feasible Reductions (MTFR) scenario. This is historically named and refers to the case where emissions from stationary sources are reduced by using all available technical measures. It gives a reference point for both 'minimum emissions' and 'maximum costs' for these sources. It is important to note that not all sources are included, and non-technical measures can also be used to reduce emissions. The implementation of non-technical measures would require specific political will, and their feasibility is not considered. Foreseen plant closures, such as the phasing out of some older fossil-fuelled power stations, are accounted for in the CLE scenario.

In addition to the MTFR scenario, and since O_3 formation strongly depends on NO_x and NMVOC emissions, two additional MTFR-based emissions scenarios were considered explicitly for the purposes of this study:

i) NO_x-MTFR: implementation of all available technical NO_x abatement measures only; and
ii) VOC-MTFR: implementation of all available technical NMVOC abatement measures only.

Under both of these scenarios, the emissions of the remaining pollutants were assumed to remain below the levels projected under the CLE scenario.

c) Removal of NMVOC emissions

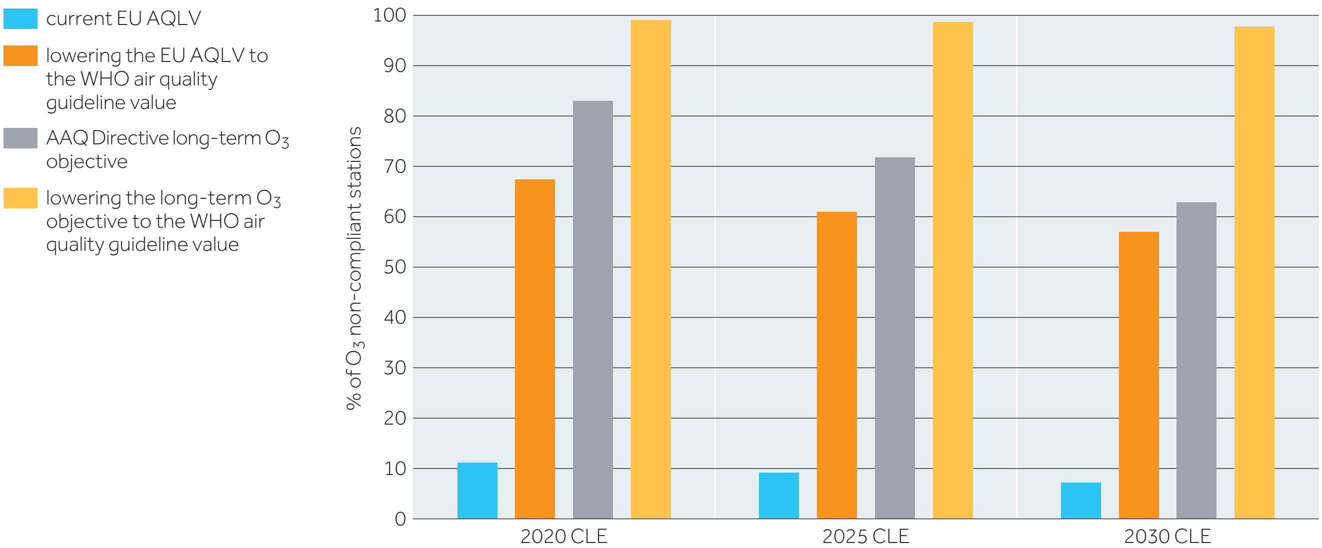
As the reduction of NMVOC emissions limits the formation of O_3, and can partially offset any increase in O_3 concentrations due to NO_x emissions reductions, especially in urban areas, an additional scenario was considered which assumes the removal of all NMVOC emissions from human activities. This scenario, however, is extreme and should be considered only as a sensitivity test.

Results

Figure 6 shows how O_3 compliance at a European level is projected into the future, from 2020 onwards until 2030, under the current CLE scenario, and how this changes depending on the AQLV that is set.

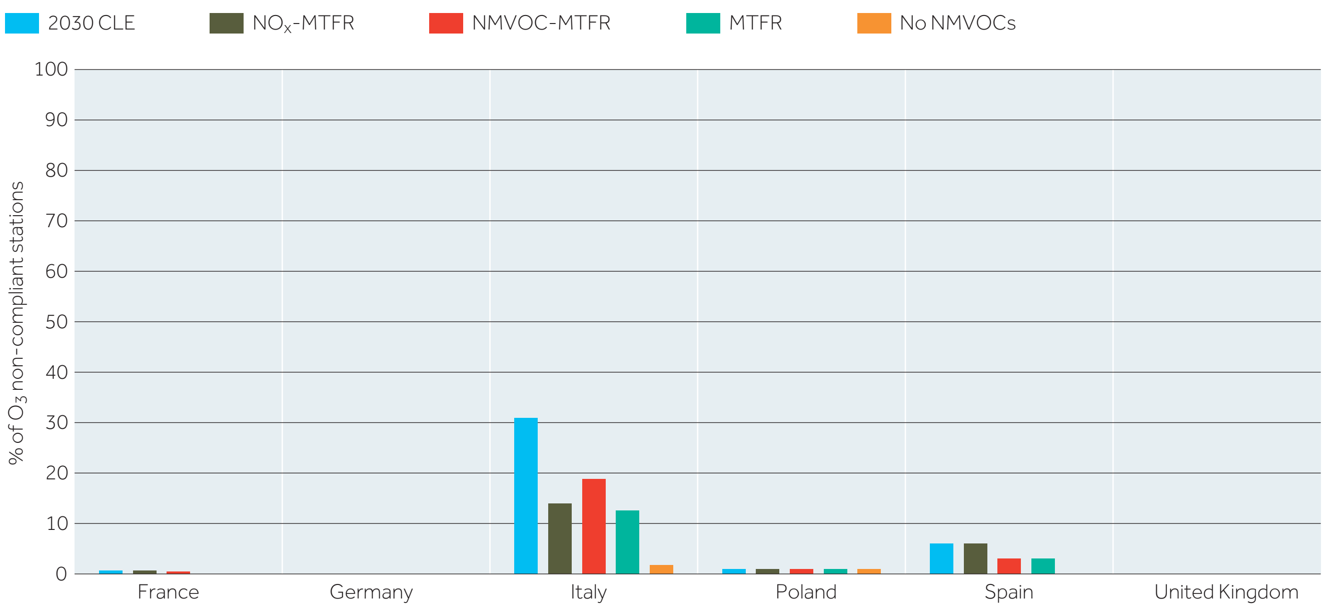
Under the CLE scenario, a slight O_3 compliance improvement with the current EU AQLV is predicted in Europe over the period. However, even in 2030, full compliance with the current EU AQLV is not predicted to be achieved as a remaining 7% of monitoring stations are found to record exceedances. Reducing the current AQLV clearly has important implications for making compliance more challenging in Europe, even in 2030. A lowering, for example, of the limit value to the current WHO level (100 µg/m^3), or a move towards zero exceedance days, is predicted to result in substantial EU-wide compliance issues with more than half of the O_3 monitoring stations measuring concentrations above the limits in all cases examined; this could increase by up to 97% in Europe if the EU AAQ Directive long-term O_3 objective is aligned with the current WHO air quality guideline value for O_3 (100 µg/m^3 and no exceedance days).

Figure 6: Predicted percentage of O_3 non-compliant monitoring stations in Europe under the CLE scenario



At a national scale, the projected future O_3 compliance trends are consistent with the predicted results across Europe. Analysing, for example, the projected O_3 concentrations in the six countries used for a more detailed focus in this study (i.e. five EU-27 Member States and the UK), the results show that under current legislation, Germany and the UK are predicted to achieve full compliance with the current EU AQLV for O_3 in 2030, and in France and Poland only a limited number of monitoring stations will remain non-compliant (Figure 7). The adoption of all available MTFR measures could eventually lead to full compliance in France and Poland. On the other hand, southern European countries (Italy, Spain) are predicted to have significant compliance problems with O_3 in 2030 under the current legislation. In Italy, for example, around 30% of the O_3 monitoring network is predicted to be non-compliant with the current EU AQLV in 2030 (Figure 7). The application of MTFR measures will reduce O_3 concentrations in both countries, although neither country will achieve full compliance. In Italy in particular, to arrive close to full compliance (~98% of its monitoring network), an extreme scenario of removing all NMVOC emissions from anthropogenic sources would be needed.

Figure 7: Predicted percentage of O_3 non-compliant monitoring stations in six European countries, with the current EU AQLV (120 µg/m^3 not to be exceeded on more than 25 days) in 2030 under the different scenarios examined

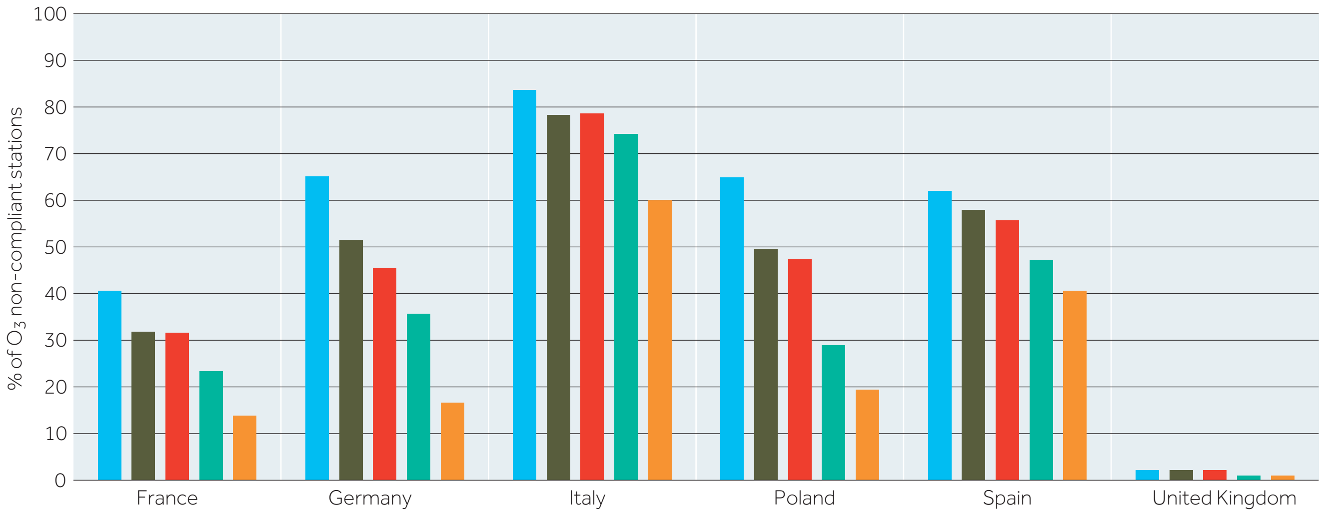


Any downward change of the current EU AQLV, either towards a reduction in the number of allowable exceedance days in order to achieve the EU AAQ Directive long-term O_3 objective, or a reduction in the current threshold of 120 µg/m^3 to align with the WHO air quality guideline value, will pose essential non-compliance problems in 2030 even with maximum abatement measures in place (Figure 8).

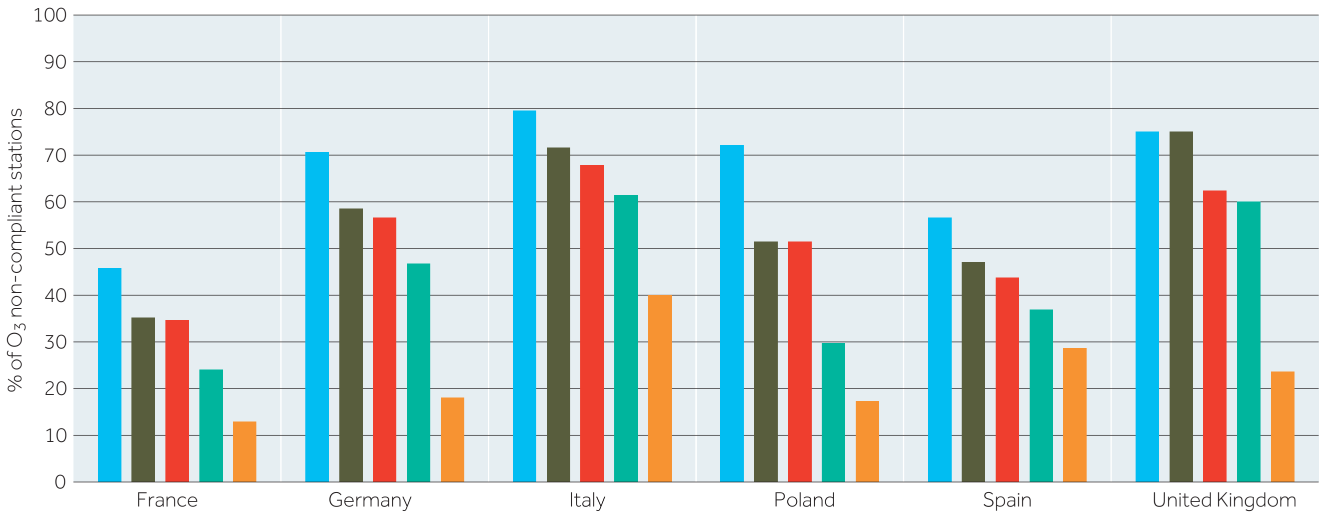
Figure 8: Predicted percentage of O_3 non-compliant monitoring stations in six European countries in 2030 under the different scenarios examined

2030 CLE | NO_x-MTFR | NMVOC-MTFR | MTFR | No NMVOCs

a) The current EU AQLV lowered to the WHO air quality guideline value of 100 µg/m^3 (not to be exceeded on more than 25 days)



b) The current EU AQLV being aligned with the AAQ Directive long-term O_3 objective of 120 µg/m^3 (no allowance of exceedance days)



Under the current legislation, by lowering, for example, the concentration threshold to the current WHO guideline value of 100 µg/m^3 (with 25 allowable exceedance days), the proportion of monitoring stations that are non-compliant exceeds 40% in five of the Member States examined (in the UK, the number of non-compliant O_3 monitoring stations is only around 2%). The application of all available technical measures to reduce emissions of O_3 precursors (i.e.the NO_x-only and NMVOC-only MTFR scenarios) as well as the application of all available MTFR measures is predicted to significantly reduce O_3 concentrations in all Member States, thereby improving compliance. However, even with MTFR measures, full compliance with the 100 µg/m^3 threshold (even if the 25 allowable exceedance days are maintained) will be far from technically achievable (Figure 8a). Similar results are also predicted when the AAQ Directive long-term O_3 objective of 120 µg/m^3 (without the exceedance days allowance) is considered as the EU AQLV, with the UK experiencing a significant increase in non-compliance[5] (Figure 8b). These are important findings, as they reflect the need for the inclusion of a risk management process in setting AQLVs, bearing in mind that technical achievability may prevent several countries from meeting a new EU AQLV even if cost and social considerations are not barriers.

It should be noted that since O_3 formation depends strongly on the meteorological conditions, the predicted results are subject to some uncertainty. This arises from the fact that the modelling simulations do not take into account any changes in meteorology, as their only focus is to assess how O_3 concentrations will change in the future due to changes in emissions. However, the projected future trends in O_3 compliance, even though they are subject to some uncertainty due to meteorology, are still dominated by the changes in emissions.[21,22] The compliance picture is not, therefore, expected to change significantly due to meteorology. Another point of uncertainty may also arise from the fact that the analyses focus on how the already-agreed measures, as well as measures beyond the current legislation, to reduce emissions of O_3 precursors from anthropogenic sources would affect O_3 concentrations in the future. However, VOC emissions from biogenic sources also play a significant role in O_3 formation. Several studies have indicated that, despite biogenic VOC emissions being a subject of high uncertainty, the increased temperature in a future climate will result in higher biogenic VOC emissions that will enhance O_3 formation.[23,24,25,26] This might, therefore, offset the potential effectiveness of measures to reduce anthropogenic emissions of O_3 in future efforts to achieve compliance.

[5] This indicates that O_3 compliance in the UK is mainly subject to exceedances above the number of allowance days that is currently set, rather than absolute concentrations above the limits.

Conclusions

The zero pollution action plan for air, water and soil that the EC will adopt in 2021 as part of the European Green Deal includes, among others, a proposal for revising the current air quality standards and aligning them more closely with the WHO recommendations. The WHO's guidelines for the majority of regulated pollutants are lower than the limit values set in the current AAQ Directives.

An earlier Concawe study highlighted the importance of following a two-step process of firstly assessing the environmental and human health risks presented by concentrations of air pollutants (risk assessment step) and secondly, assessing how these risks may be managed (risk management step) when binding AQLVs are set. The current study builds on the earlier study, and focuses on O_3, for which the current EU AQLV reflects a risk assessment undertaken by the WHO in the late 1990s without further changes; a revision of the AQLV is therefore highly possible.

The study analyses the current O_3 compliance trends in Europe and how these would change in a potential lowering of the AQLV. In addition, the study uses modelling to analyse how these trends are extended into the future (up to 2030) under several potential emission reduction scenarios. The analysis covers the EU, with a special focus on six European countries (France, Germany, Italy, Poland, Spain and the UK). The results of these analyses are summarised below:

- Full compliance with the EU AQLV (120 µg/m^3, not to be exceeded on more than 25 days) is currently achieved (based on the 2017 EEA data) in nine Member States, with non-compliance issues mostly found in southern and eastern European countries.
- The vast majority of the European countries are currently not able to meet the AAQ Directive long-term O_3 objective of 120 µg/m^3 without any allowance for exceedances. In addition, they are unlikely to be able to achieve compliance if the EU AQLV is lowered to the current WHO guideline value of 100 µg/m^3 (either keeping the 25 exceedance days threshold or not).
- The current emissions legislation, as described under the CLE scenario, will be effective in reducing O_3 concentrations from 2025 onwards and improving compliance. However, full compliance with the existing EU AQLVs will not necessarily be achieved in all EU countries. The country variation in terms of O_3 compliance remains significant in the future, with countries in southern Europe still experiencing significant non-compliance issues (e.g. 30% of monitoring stations in Italy are non-compliant in 2030 under the CLE scenario).
- Reductions beyond the already-legislated emission reduction measures, and towards MTFR, will further improve O_3 compliance with the current EU AQLV. However, full compliance still remains unachievable in some countries (e.g. Italy, Spain), despite the significant economic investment that will be required for implementing all MTFR measures.
- A move to a threshold of 100 µg/m^3 (the current WHO air quality guideline value) or a move toward the AAQ Directive's long-term objective for O_3 (i.e. zero allowable exceedances at the current threshold) will essentially create an EU-wide compliance challenge for O_3. Under such a revision of the current EU AQLV, O_3 compliance will be far from technically achievable, regardless of the measures applied to control emissions.

The above findings provide an important illustration that moving to a binding EU AQLV which will be closely aligned to the WHO air quality guideline value (with potentially less or even zero allowable exceedance days) is highly likely to be infeasible in large parts of Europe. It is therefore essential that all consequences of changing the AQLVs embedded in the AQ Directive are considered from the perspective of implementation by including a risk management step in the AQLV revision process.

It should also be noted that the analyses focus on how already-agreed measures, as well as measures beyond the current legislation, to reduce emissions from anthropogenic sources would affect O_3 concentrations in the future. However, VOC emissions from biogenic sources also play a significant role in O_3 formation. Even though they are subject to a high degree of uncertainty, biogenic VOC emissions are predicted to increase in the future and enhance O_3 formation, therefore offsetting the effectiveness of anthropogenic emission reduction measures.

References

1. European Commission (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050
2. European Commission (2004). Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1575558618688&uri=CELEX:32004L0107
3. European Commission (2019). *Fitness Check of the Ambient Air Quality Directives*. Staff Working Document, SWD(2019) 42. https://ec.europa.eu/environment/air/quality/aqd_fitness_check_en.htm
4. European Commission (2019): *Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal.* COM/2019/640. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN
5. World Health Organization (2006). *Air Quality Guidelines. Global Update 2005. Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*. https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/pre2009/air-quality-guidelines.-global-update-2005.-particulate-matter,-ozone,-nitrogen-dioxide-and-sulfur-dioxide
6. European Commission (2013). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Clean Air Programme for Europe*. COM (2013) 918 final, Brussels, 18 December 2013. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0918:FIN:EN:PDF
7. European Commission (2002). Directive 2002/3/EC of the European Parliament and of the Council of 12 February 2002 relating to ozone in ambient air. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32002L0003
8. Concawe (2020). 'Understanding the process of setting air quality limit values and the associated compliance challenge.' *Concawe Review*, Vol. 29, No. 1, pp. 12–28. https://www.concawe.eu/wp-content/uploads/Air-quality-Review-29-1.pdf
9. European Environment Agency (2018). 'Air Quality e-Reporting' (website). https://www.eea.europa.eu/data-and-maps/data/aqereporting-8

10. Thunis, P., Rouil, L., Cuveliera, C., Stern, R., Kerschbaumer, A., Bessagnet, B., Schaap, M., Builtjes, P., Tarrason, L., Douros, J., Moussiopoulos, N., Pirovano, G. and Bedogni, M. (2007). 'Analysis of model responses to emission-reduction scenarios within the City-Delta project.' In *Atmospheric Environment*, Vol. 41, Issue 1, pp. 208–220. https://www.sciencedirect.com/science/article/abs/pii/S1352231006009101

11. Megaritis, A. G., Fountoukis, C., Charalampidis, P. E., Pilinis, C. and Pandis, S. N. (2013). 'Response of fine particulate matter concentrations to changes of emissions and temperature in Europe.' In *Atmospheric Chemistry and Physics*, Vol. 13, Issue 6, pp. 3423-3443. https://doi.org/10.5194/acp-13-3423-2013

12. European Environment Agency (2017). *Air quality in Europe — 2017 report*. EEA Report No 13/2017. https://www.eea.europa.eu/publications/air-quality-in-europe-2017

13. European Environment Agency (2019). *Air quality in Europe — 2019 report*. EEA Report No 12/2019. https://www.eea.europa.eu/publications/air-quality-in-europe-2019

14. Concawe (2016). *Urban Air Quality Study*. Sections 5.2–5.4 (description of AQUIReS+). Concawe Report No. 11/16. https://www.concawe.eu/wp-content/uploads/2017/01/rpt_16-11.pdf

15. Norwegian Meteorological Institute (2004). *Transboundary Acidification, Eutrophication and Ground Level Ozone in Europe*. EMEP Report 1/2004. https://emep.int/publ/reports/2004/Status_report_int_del1.pdf

16. Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á. and Wind, P. (2012). 'The EMEP MSC-W chemical transport model – technical description.' In *Atmospheric Chemistry and Physics*, Vol. 12, Issue 16, pp. 7825–7865. https://doi.org/10.5194/acp-12-7825-2012

17. École Polytechnique (2017). *Documentation of the chemistry-transport model CHIMERE*. LMD (CNRS), INERIS and LISA (CNRS). http://www.lmd.polytechnique.fr/chimere/docs/CHIMEREdoc2017.pdf

18. IIASA (2015). *Adjusted historic emission data, projections, and optimized emission reduction targets for 2030 – A comparison with COM data 2013. Part A: Results for EU-28*. TSAP Report #16A. https://ec.europa.eu/environment/air/pdf/review/TSAP_16a.pdf

19. IIASA (2015). *Adjusted historic emission data, projections, and optimized emission reduction targets for 2030 – A comparison with COM data 2013. Part B: Results for Member States.* TSAP Report #16B. https://ec.europa.eu/environment/air/pdf/review/TSAP_16b.pdf

20. European Commission (2017). *TSAP 16 Underlying Assumptions: Implementing Article 14(3) of NEC Directive 2016/2284 Requesting the European Commission to publish the TSAP 16 Underlying Assumptions used for determining the National Emission Reduction Potentials*. Produced by DG Environment, unit C.3 – Air, 8 February 2017. https://ec.europa.eu/environment/air/pdf/TSAP_16_underlying_assumptions.pdf

21. European Environment Agency (2018). *Air quality in Europe — 2018 report*. EEA Report No 12/2018. https://www.eea.europa.eu/publications/air-quality-in-europe-2018

22. European Topic Centre on Air Pollution and Climate Change Mitigation (2017). *Long-term air quality trends in Europe. Contribution of meteorological variability, natural factors and emissions*. Technical Paper 2016/7. https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etcacm_tp_2016_7_aqtrendseurope

23. Forkel, R. and Knoche, R. (2006). 'Regional climate change and its impact on photooxidant concentrations in southern Germany: Simulations with a coupled regional chemistry-climate model.' In *Journal of Geophysical Research (Atmospheres)*, Vol. 111, Issue D12. https://doi.org/10.1029/2005JD006748

24. Meleux, F., Solmon, F. and Giorgi, F. (2007). 'Increase in summer European ozone amounts due to climate change.' In *Atmospheric Environment*, Vol. 41, Issue 35, pp. 7577–7587. https://doi.org/10.1016/j.atmosenv.2007.05.048

25. Churkina, G., Kuik, F., Bonn, B., Lauer, A., Grote, R., Tomiak, K. and Butler, T. M. (2017). 'Effect of VOC Emissions from Vegetation on Air Quality in Berlin during a Heatwave.' In *Environmental Science & Technology*, Vol. 15, Issue 11, pp. 6120-6130. https://doi.org/10.1021/acs.est.6b06514

26. Jiang, J., Aksoyoglu, S., Ciarelli, G., Oikonomakis, E., El-Haddad, I., Canonaco, F., O'Dowd, C., Ovadnevaite, J., Minguillón, M. C., Baltensperger, U. and Prévôt, A. S. H. (2019). 'Effects of two different biogenic emission models on modelled ozone and aerosol concentrations in Europe.' In *Atmospheric Chemistry and Physics*, Vol. 19, Issue 6, pp. 3747-3768. https://doi.org/10.5194/acp-19-3747-2019