Publizierbarer Endbericht

Gilt für Studien aus der Programmlinie Forschung

A) Projektdaten

Allgemeines zum Projekt	
Kurztitel:	ATtain-O3
Langtitel:	Evaluating the effects of climate warming and precursor emission changes on the attainment of the Austrian ozone standard
Zitiervorschlag:	Rieder H.E., Bednar-Friedl B., Moshammer H., Mayer M., Knittel N., Preinfalk E., Schmidt C., Kult-Herdin J., Karlicky J., Staehle C., Wolkinger B., Jury M., Truhetz H., Formayer H. (2023): Evaluating the effects of climate warming and precursor emission changes on the attainment of the Austrian ozone standard, Publizierbarer Endbericht im Rahmen von ACRP.
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Allgemeines zum Projekt	
	Regional Climate Research Group (Regional Climate)
Schlagwörter:	Ozon, Klimawandel, Luftgüte, Gesundheitsfolgen, ökonomische Auswirkungen
Projektgesamtkosten:	248 904 €
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Klimafonds-Nr:	KR18AC0K14686
Erstellt am:	12.02.2023

B) Projektübersicht

1 Kurzfassung

Im Rahmen des Projekts ATtain-O3 wurde die Veränderung in der Ozonbelastung bodennaher Luft für Österreich und damit verbundene Auswirkungen auf die menschliche Gesundheit und ausgewählte ökonomische Sektoren untersucht. Die Projektionen für die zukünftige Ozonveränderungen wurden mittels Chemie-Transportmodell (CTM) Simulationen quantifiziert, welche Veränderungen in Vorläufersubstanzen und Klima in der Breite der repräsentativen Konzentrationspfade (RCPs) berücksichtigten. Die CTM-Projektionen zeigen sehr unterschiedliche zukünftige Belastungsszenarien für bodennahes Ozon auf, angetrieben durch Unterschiede in Klimaänderung und Emissionsverhalten in den RCPs. Die Ergebnisse von ATtain-O3 geben Auskunft über die Wahrscheinlichkeit der zukünftigen Einhaltung bzw. Überschreitung des Zielwertes zum Schutz menschlicher Gesundheit unter den verschiedenen RCPs sowie die Effizienz von Emissionsminderungsmaßnahmen zur Verbesserung der Luftgüte. Des Weiteren zeigen die Szenarien sehr deutlich die negativen Folgen der fortschreitenden Erderhitzung (Klima- und Methan-Pönalen) unter einem Hochemissionsszenario (RCP8.5) auf. ATtain-O3 bietet auch eine Fülle von Informationen hinsichtlich der Auswirkungen zukünftiger Veränderung der Ozonbelastung auf die menschliche Gesundheit und landwirtschaftliche Erträge. Sektorale Vermeidungskosten für Vorläufersubstanzen sowie Ozonschäden wurden für den Beginn und die Mitte des 21. Jahrhunderts quantifiziert, sowie Kosten und Nutzen veränderter Ozonbelastung in einer volkswirtschaftlichen Analyse gegenübergestellt.

Die CTM-Simulationen zeigen eine deutliche Verringerung der Ozonbelastung unter RCP2.6 und RCP4.5, angetrieben durch die reduzierte Emission von Vorläufersubstanzen. Die Anzahl der durchschnittlichen jährlichen Überschreitungen des Zielwerts für den Gesundheitsschutz nimmt in diesen Szenarien um durchschnittlich 9 bzw. 7 Tage bis Mitte des 21. Jahrhunderts ab. Hauptverantwortlich für die verringerte Belastungssituation zeigen umfassende NOx Reduktionen. Diese Ergebnisse zeigen aber auch auf, dass rein nationale Bestrebungen zur Emissionsreduktion nicht ausreichen um die Ozon-Zielwerte umfassend und flächig einzuhalten. Grund hierfür ist, dass die lokale Belastungssituation neben den in situ Emissionen auch durch die globale Hintergrundbelastung und das photochemische Regime bestimmt wird. Im Gegensatz zu diesen beiden Szenarien zeigen die Ergebnisse für RCP8.5 eine deutlich erhöhte Belastungssituation sowie umfassende regionale Erschwernisse in der Zielwerterreichung. Es zeigt sich jedoch nicht nur eine generell erhöhte Belastungssituation, sondern auch eine Verlängerung und Verschiebung der saisonalen Ozonspitzen angetrieben durch die steigende Methankonzentration und Ozonhintergrundbelastung. Für die Mitte des 21. Jahrhunderts zeigen die Modellergebnisse eine Zunahme an Tagen mit Zielwertüberschreitung, im Gemeindemittel rund 5 Tage. Diese erhöhte Belastung tritt trotz verringerter NOx-

Emission auf, verursacht durch erhöhte Methankonzentration und durch die durch steigende Temperaturen erhöhte Effizienz ozonaufbauender chemischer Reaktionen. Zusammengefasst zeigen diese Ergebnisse die Bedeutung der gemeinsamen Anstrengung für Klimaschutz und Verbesserung der Luftgüte auf.

Höhere Ozonbelastungen beeinträchtigen die menschliche Gesundheit und führen zu vorzeitiger Sterblichkeit. Unter RCP8.5 werden die ozonbedingten Todesfälle im Vergleich zu heute bis 2030 um etwa 20% und bis 2050 um 40% ansteigen. Im Gegensatz dazu ist der Anstieg unter RCP4.5 bis 2030 weniger als halb so hoch wie unter RCP8.5 und geht danach aufgrund ambitionierter NO_x-Reduktion zurück. Die Bewertung der gesundheitlichen Auswirkungen hat jedoch auch gezeigt, dass demografische Veränderungen mindestens ebenso große Auswirkungen auf die Gesundheitsbelastung und Sterblichkeit haben.

Auch das Pflanzenwachstum wird durch bodennahes Ozon beeinträchtigt. Bei den landwirtschaftlichen Erträgen zeigen sich die stärksten ozonbedingten Ertragsminderungen bei Weizen, Sojabohnen und Kartoffeln, während z. B. Gerste und Zuckerrüben nicht negativ betroffen sind. Über alle Kulturen hinweg beläuft sich der Ertragsverlust im historischen Zeitraum für Österreich auf insgesamt 10%, reduziert sich in den 2030er Jahren (unabhängig vom RCP-Szenario) auf 5-7%, steigt aber unter RCP8.5 auf 10%, während er unter RCP4.5 in den 2050er Jahren auf 7% sinkt.

Hinsichtlich der gesamtwirtschaftlichen Auswirkungen übertreffen die Auswirkungen auf die Gesundheit jene auf die Landwirtschaft in ihrer Größenordnung. Im Jahr 2030 sind die Ertragsverluste in der Landwirtschaft in beiden Szenarien sehr ähnlich, aber im Jahr 2050 führen die geringeren Ertragsverluste unter RCP4.5 zu geringeren gesamtwirtschaftlichen Kosten und damit zu einem Wohlfahrtsgewinn. Die höheren Kosten für die Einhaltung der Vorschriften im RCP4.5-Szenario führen jedoch zu einem Netto-Wohlfahrtsverlust im Jahr 2030. Obwohl die Wirksamkeit von Maßnahmen zur Kontrolle von Ozonvorläufersubstanzen im Vergleich zur Minderung von Treibhausgasemissionen kürzer ist, zeigt sich eine zeitliche Diskrepanz in den Kosten- und Nutzenströmen einer strengeren Regulierung: diese zahlt sich nur auf lange Sicht (2050er Jahre) aus, nicht aber kurzfristig (2030er Jahre) aus.

In Ergänzung zu den Auswirkungen des Klimawandels in Österreich im Rahmen des COIN-Projekts stellen die makroökonomischen Folgen von ATtain-O3 einen neuen Aspekt dar: sowohl in der Landwirtschaft als auch im Gesundheitsbereich entstehen klimawandelbedingte Schäden durch bodennahes Ozon. In der Landwirtschaft überwiegen die negativen Folgen von Ozon gegenüber den möglichen positiven Effekten durch längere Vegetationsperioden. Die ozonbedingte vorzeitige Sterblichkeit ist eine wichtige Ergänzung zu den hitzebedingten Todesfällen. In der nahen Zukunft (2030er Jahre) übersteigen die ozonbedingten vorzeitigen Todesfälle sogar die hitzebedingten Todesfälle; in der fernen Zukunft (2050er Jahre) machen die ozonbedingten vorzeitigen Todesfälle immer noch ein Drittel der hitzebedingten Todesfälle aus.

2 Executive Summary

The ATtain-O3 project investigated changes in the ozone burden and associated health and economic impacts and costs for Austria out to the 2050s. To this end projections of future ozone burdens have been derided from chemistry-transport model (CTM) simulations based on a broad range of representative concentration pathways. These projections show diverse futures for surface ozone burdens dependent on precursor emission and climate scenario. Results of ATtain-O3 provide information on the likelihood of attainment of the national O_3 target values for a wide range of climate and emission scenarios and the effectiveness of reduction scenarios to improve ambient air quality and the project outlines the impact of climate and methane penalties on air quality under a high emission scenario (RCP8.5). Furthermore, ATtain-O3 provides information on changing health burdens, and impacts on agricultural yields for these diverse futures, and assesses sectoral costs associated with precursor emission reductions as well as ozone damage by early and mid-21st century. Finally, costs and benefits of reduced ozone burdens are compared from an economy-wide perspective.

In brevity our CTM results show substantial improvements in attainment under precursor emission reductions as prescribed under RCP2.6 and RCP4.5. The number of annual ozone target value exceedance days is reduced by about 9 days and 7 days by the 2050s. These air quality improvements are attributable to ambitious NOx reductions. While a welcomed improvement these results also indicate that full attainment of the target value cannot be reached by domestic emission reductions alone, given that ozone burdens are besides in situ emissions driven by global backgrounds and prevailing chemical regime (i.e. photochemical production). In contrast to these scenarios, we find under RCP8.5 continuously high ozone burdens and frequent non-attainment of the target value across Austrian municipalities. We do however, not only find an increased frequency of non-attainment but also an expansion and seasonal shift of the prime ozone season driven by increased backgrounds and elevated methane abundances. By mid-21st century we find a general increase in the number of non-attainment days, which yields in the municipal average additional 5 days with exceedance of the target value for health protection. This worsening occurs despite NOx reductions, and is driven largely by elevated global methane backgrounds, and in parts by increases in temperature elevating ozone production efficiency. Therefore, our results highlight the importance of combined efforts for climate protection and improved air quality.

Higher ozone burdens affect human health and lead to premature mortality. Under RCP8.5, ozone-related deaths have been estimated to increase by about 20% by 2030 and 40% by 2050 compared to today. In contrast, increases under RCP4.5 are less than half of those of RCP8.5 by 2030 and declining thereafter due to ambitious NOx controls. But the health impact assessment also demonstrated that demographic changes have at least as important impacts on health outcomes.

Also plant growth is impacted by ground-level ozone. For agricultural yields, we find strongest ozone-related reductions in crop yields for wheat, soybean and potatoes while e.g. barley and sugar beet are not negatively affected. Across crops, the yield loss in the historic period amounts to 10% for Austria in total, reduces to 5-7% in the 2030s (regardless of the RCP scenario), but increases to 10% under RCP8.5 while it reduces to 7% under RCP4.5 in the 2050s.

Regarding the economy-wide effects, we find that the effects on health dominate the effects on agriculture in magnitude. In 2030, agricultural yield losses are very similar across the two scenarios, but in 2050 lower yield losses in RCP4.5 result in lower economy-wide costs and lead therefore to a welfare gain in RCP4.5. However, the higher compliance costs in RCP4.5 in the next decade lead to a net welfare loss in 2030. While the effectiveness of ozone precursor control measures is shorter compared to the mitigation of greenhouse gas emissions, we still find a temporal mismatch in the flows of costs and benefits of stricter compliance: higher compliance only pays-off in the far term (2050s), but not in the short term (2030s).

Considering the most comprehensive assessment of climate change impacts that occur within Austria in the COIN project, macroeconomic consequences from ATtain-O3 represent a new aspect: in both agriculture and health, climate change-related damages associated with surface ozone. In agriculture, negative consequences of ozone outweigh the potential positive effects from longer growing seasons, which have been considered in COIN. Ozone-related premature mortality is a relevant complement to the heat-related deaths. In the near future (2030s), ozone-related premature fatalities even exceed heat-related fatalities; in the far future (2050s), ozone-related premature fatalities still constitute a third of heat-related fatalities, increasing climate-induced fatalities by around 30%.

3 Hintergrund und Zielsetzung

Climate and air quality are inextricably connected (e.g., von Schneidemesser et al., 2015) and the relationships between climate change, atmospheric chemistry and air pollution received increasing attention over the last decade. Particularly the potential for climate warming to exacerbate ozone (O_3) has led to widespread use of the term "climate penalty" (e.g., Wu et al., 2008) to highlight adverse impacts of climate change on air pollution.

To protect public health, national governments, the EU and the World Health Organization (WHO) define a suite of ambient air quality thresholds for O_3 and other criteria pollutants. Despite these legal frameworks and concentrated efforts in abating air pollution, many regions are yet experiencing regular violations of target values. Also in Austria the target value for O_3 is regularly exceeded, as are the limit values for NO_2, and PM10 (Umweltbundesamt, 2019).

ATtain-O3 aimed to support Austrian policymakers in their efforts to implement successful strategies to abate surface ozone pollution. Specifically the project has been designed to deliver policy relevant information for the development of management strategies and corrective action through: (i) tailored projections for ozone air quality up to 2050 under a wide range of emission and climate scenarios, (ii) emission scenarios that would attain the Austrian O_3 target values under various climate trajectories, (iii) cost-benefit analyses for attainment/violation of the Austrian O_3 target value under specific stakeholder determined emission scenarios.

The specific project objectives of ATtain-O3 have been to:

(i) Quantify changes in the frequency, duration, severity and seasonality of O_3 exceedances of the target values out to 2050 and the role of changes in anthropogenic emissions and climate warming.

(ii) Quantify the range of natural variability in O_3 predictions through decadal time slice simulations with two leading chemistry-transport models (CTMs) and transient multi-ensemble member chemistry-climate model (CCM) simulations.

(iii) Characterize the spatio-temporal properties of co-occurring climate and O_3 pollution extremes.

(iv) Quantify the achievability of attainment of the Austrian O_3 target values under RCPs and stakeholder developed emission trajectories.

(v) Quantify regional/local O_3 penalties emerging from precursor transport from neighboring regions with limited precursor emission reductions and/or high precursor production.

(vi) Quantify economic costs associated with potential non-attainment of the O_3 target values and degraded surface air quality as well as sectoral emission reductions in the transport and industry sectors and quantify economic benefits associated with reduced health costs and increased agricultural productivity stemming from reduced O_3 pollution for the scenarios considered.

(vii) Brief policymakers on opportunities to attain the Austrian O_3 target values and associated costs and benefits from the objectives above.

4 Projektinhalt und Ergebnis(se)

ATtain-O3 is an interdisciplinary project with seven connected work packages (WPs). Within WP1 a dedicated analysis of a multi-member ensemble of chemistry-climate model (CCM) simulations under various RCPs has been performed. WP2 focused on the stakeholder dialogue and the selection of a precursor emission scenario considered feasible by policy stakeholders. WP3 has been dedicated to the preparation of input data for a suite of high-resolution CTM simulations in WP4. Within WP4 a comprehensive set of ten-year time slice CTM simulations has been performed and analyzed and output metrics for the health and economic assessments (WPs 5 and 6) have been prepared. WP5 has been dedicated to the economic assessment of changes in the surface ozone burden, with focus on avoided impacts of ground-level O_3 pollution for public health and agriculture. WP6 focused on the assessment of the economy-wide consequences of reduced O_3 pollution. WP7 comprised all tasks related to project management, stakeholder involvement, dissemination and policy briefing. The project team has applied and combined a series of methods to assess the potential future changes in the Austrian ozone burden, and associated health and economic impacts and costs. Methods are described in greater detail in section 3. Below we summarize results and research highlights on WP basis.

WP1 Chemistry-climate model analysis

In WP1 we analyzed a set of multi-member simulations of the Geophysical Fluid Dynamics Laboratory chemistry-climate model CM3, which have been performed in contribution to the 5th IPCC assessment report as well as a series of targeted sensitivity simulations, which allowed to analyze the influence of changes in climate vs. changes in ozone precursor emissions. These analyses provided a first estimate for surface ozone changes in Austria out to the 2050s and informed CTM modelling activities in WP4. The set of transient CM3 RCP simulations show a pronounced decrease in the surface ozone burden under RCP4.5 while the peak ozone burden is projected to increase under the high emission scenario RCP8.5 (see Figure 1). Furthermore, under both RCPs a “climate penalty” emerges in absence of NOx emission reductions. The difference between simulations under RCP4.5 and RCP8.5 might appear surprising at first, given that nitrogen oxide (NOx) emissions decrease strongly under both scenarios. A key difference between these scenarios is however the strong increase of methane burdens under RCP8.5. The set of sensitivity simulations with methane concentrations held constant at year 2005 levels, but all other emissions evolve as prescribed under RCP8.5 helps unravelling the evolution of the surface ozone burden. Driven by increased methane backgrounds, a strong seasonal shift in the prime ozone season from summer (present day) to spring (mid-21st century) is identified (see Figure 2). Furthermore, sensitivity simulations assuming no change in ozone precursor emissions (NOx held constant at year 2005 levels) indicate the risk of emergence of a summertime “climate penalty” on ozone in contrast to the transient RCP8.5 simulation considering NOx abatement (see Figure 2).

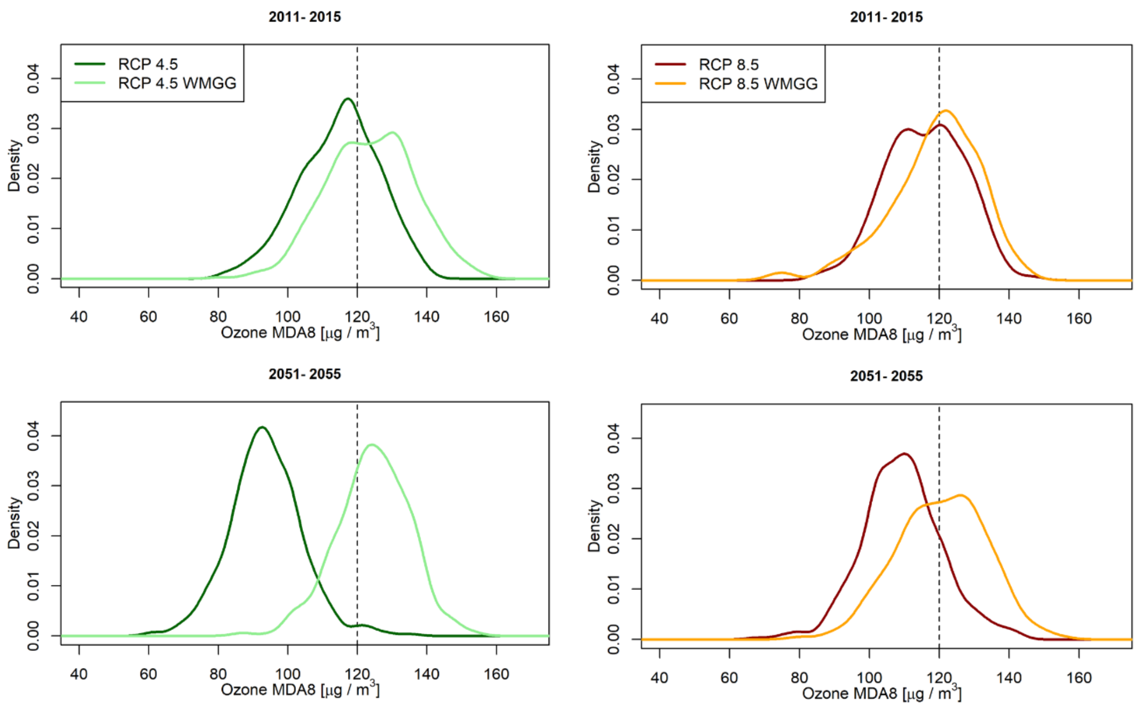

Figure 1: *Probability density function of summertime MDA8 O_3 under the RCP4.5 (left column) and RCP8.5 scenario (right column) along with corresponding RCP4.5 and RCP8.5 sensitivity scenarios with NOx emissions held constant at year 2005 levels (WMGG). Top panels for 2011-2015, bottom panels for 2051-2055.*

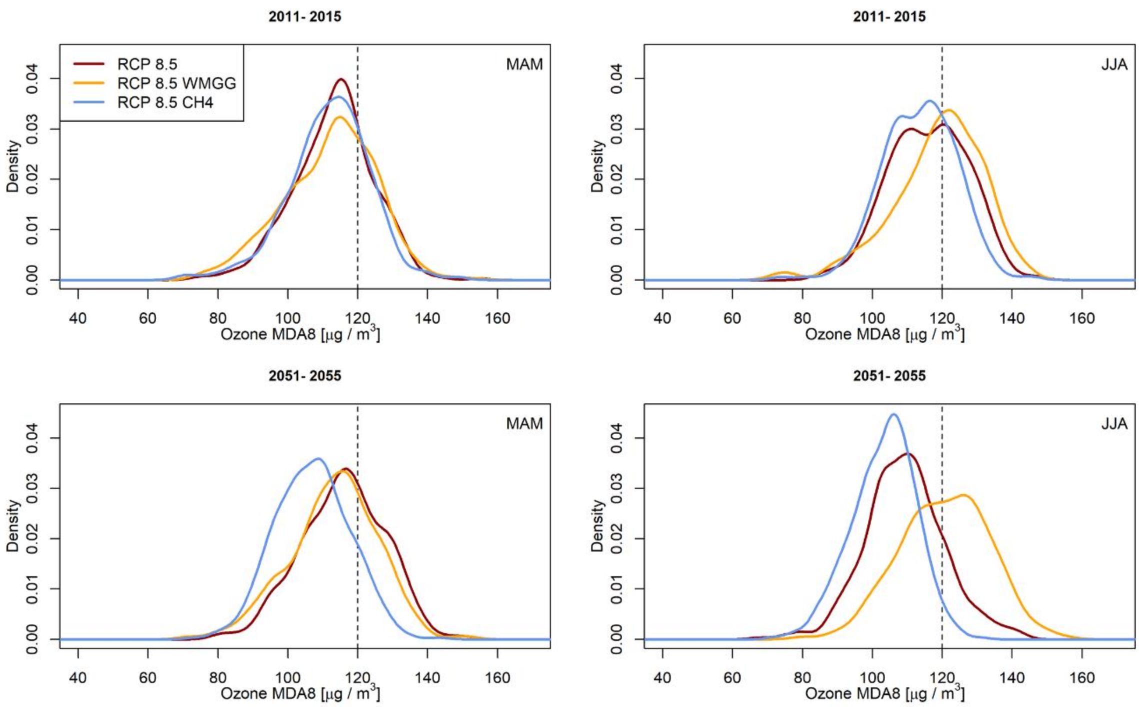

Figure 2: *Probability density function of MDA8 O_3 under the RCP8.5 scenario and sensitivity scenarios with NOx emission (WMGG) or methane (CH4) held constant at year 2005 levels. Panels show spring (left column) and summer (right column) in 2011-2015 (top row) and 2051-2055 (bottom row).*

WP2 Stakeholder dialogue and development of future emission inventories – case studies for Styria and Lower Austria

During initial meetings held in project year 1, stakeholders raised the question regarding ***changes in surface ozone during recent decades and the underlying driver of changes in ozone abundance*** and number of exceedance days. To answer these question we performed an in-depth analysis of changes in ozone concentration and the number of exceedance days of the ozone target value for the 30-year observational time period spanning 1990-2019 (see Appendix, Figure A1a,b). Further the analyses showed among others a strong correlation between the number of ozone exceedance days and high summertime temperature and an overall decrease in the surface ozone burden following emission reductions in recent years (see Appendix, Figure A1c-e). The analysis of measurement series of important ozone precursors allowed also to investigate seasonal differences in the limiting chemical regime for ozone production (NOx vs. VOC limitation). To further investigate the chemical regime, we performed an analysis combining the Vienna MAX-DOAS formaldehyde (HCHO) observations with daily averages of NOx and MDA8 O_3 both measured at Vienna's city center (in-situ, site Stephansplatz). The O_3 isopleths confirm that O_3 chemistry is predominantly VOC limited except for daily average mixing ratio of HCHO larger than 3.5 ppb. HCHO concentrations follow the annual cycle of radiation revealing that secondary HCHO emissions dominate (see Appendix, Figure A2). The findings of this analysis are ***published in Mayer et al., 2022***.

Half-way through the first project year the COVID-19 pandemic emerged and hindered on site-stakeholder engagements. Nevertheless, the project team has been in steady contact with national air quality managers and during these discussions the stakeholders raised interest in ***an analysis of the effects of the 2020 springtime lockdown on Austrian air quality***. The ATtain-O3 team responded to this request and provided an in-depth analysis of changing air quality burdens as these provided also a natural testbed for potential effects of future precursor emissions. Our analysis shows decreasing pollutant concentrations, although in magnitude dependent on pollutant and regional subdomain (see Appendix, Fig. A4). Largest reductions are found for NO_x reaching up to −68% at traffic sites reflecting the substantial decrease in non-essential transport. Subdomain averages of mean diurnal O_3 variations show comparably weak changes in response to precursor emission changes. Here, changes relative to 2019 are found between −18 and +8%. In contrast, individual measurement sites reveal stronger variations. Particularly large changes (−66 to +51%) have been identified during night-time, which can be attributed to titration effects. Pronounced night-time changes in O_3 concentrations have been found across all sectors. As daytime concentrations show only minor variations (−25 to +11%) it is assumed that the sensitivity of ozone production to radiation outweighs changes in precursor NO_x during the COVID lockdown in spring 2020. The findings of this analysis are ***published in Staehle et al., 2022***.

In the second reporting period, 2 stakeholder workshops were conducted. In November 2021, the project team presented interim results from WPs 2-5 to stakeholders in the two case study regions, with a focus on the past and current ozone concentrations and their implications. The first presentation explained the occurrence of ozone exceedance days in Austria for the period 2007-2019 and how well CTMs were able to replicate real world observations. Afterwards, the health impact assessment (see WP5 for details) for ozone was explained and ozone-related mortality was estimated for Austria and compared to available estimates from the European Environmental Agency and the OECD. Similarly, the approach for estimating damages to agricultural yields due to elevated ozone concentrations was explained. Finally, the project team gave an overview on air quality regulations in place, available measures to reduce ozone precursor emissions in transport, industry and buildings, and the available cost estimates on planned, existing and potential measures according to available scenarios (WEM = with existing measures; WAM = with additional measures; MTFRP = maximum technologically feasible reduction potential) in the GAINS model. The second part of the workshop was devoted to selecting emission reduction scenarios that stakeholders considered feasible based on their expertise in the two provincial authorities. For that purpose, the project team discussed the following questions with the stakeholders: How relevant are the available scenarios and which additional scenarios should be assessed additionally? Which possibilities for action to reduce ozone exist in their respective domain? Where do they see the most effective levers for reducing ozone-precursor emissions? What barriers/opportunities do you expect for the future? One central outcome was that stakeholder agreed that there is not much difference between WEM and WAM scenarios for Austria, and that the MTFRP scenario is highly unrealistic as it would be extremely costly and is therefore of minor interest for decision-makers. Instead, they suggested to, on the one hand, compare a WEM or WAM scenario to a less stringent regulation scenario to assess potential benefits of already implemented and planned policies, and on the other hand, to look into a high emission scenario on a global scale but with national ambitious emission reduction targets implemented. These suggestions were followed in the subsequent analysis.

In the second stakeholder workshop in September 2022, final results of the project were presented to stakeholders. The first presentation summarized how ozone pollution is projected to change in Austria until 2050 for different climate and emission scenarios. The second and third presentation illustrated the impacts of ozone pollution on agricultural yields of Austria's main crops and ozone related mortality for the 2030s and 2050s. Finally, the macroeconomic consequences of agricultural yields losses and increased mortality were presented and emission reductions were assessed in a cost-benefit framework. In the final feedback round, stakeholders expressed that the results were extremely interesting and useful for their daily work. For instance, experts from the air quality administrations were particularly interested in the seasonal shifts of ozone concentrations, while agricultural experts stressed that the consequences of climate change on ozone concentrations and subsequently on agricultural yields was so far overlooked in their daily work with farmers. Based on the project results they will start to integrate this into their work on heat and drought effects of climate change. The project team concluded that targeted fact sheets will be prepared that can help in communicating this important new information to both groups of stakeholders and using dissemination channels of stakeholders.

WP3 Preparation of chemistry-transport model input fields

Tasks in WP3 have been performed in support of modelling activities in WP4. ECMWF boundary conditions have been downloaded for regional climate model simulations. WRF and RegCM time-slice simulations for a central European domain around Austria have been performed. The comparison of elemental meteorological fields for base case WRF and RegCM simulations showed satisfactory results, when compared to observations. Given the broad agreement between both regional climate models further analyses in WP4 focused on simulations driven by WRF as these runs allowed the analysis of coupled meteorological and chemical simulations (WRF-chem configuration) and uncoupled simulations (CAMx simulations driven with dynamical fields of WRF-chem), driven by identical meteorological fields. Historic chemical boundary conditions for both CTMs have been taken from the CAM-Chem model and emissions have been pre-processed using the FUME model. For future simulations boundary conditions have been prepared from CCM fields, namely SOCOLv4 by the BOKU team and meteorological boundaries have been taken from bias-corrected CESM model fields.

WP4 Chemistry-transport modelling and scenario analysis

WP4 focused on the preparation and analysis of decadal time slice simulations with the CTMs WRF-Chem and CAMx. These included a set of hindcast simulations for the historic base period (2007-2016) performed, as well as 10-year time slice simulations for the 2030s and 2050s following selected RCPs and sensitivity simulations. Comparison between CTM output and observations for the hindcast period showed overall good agreement in seasonal mean ozone, despite regional biases and biases in maximum daily 8-hour average ozone (MDA8 O_3) and 1-hour mean ozone values, required for impact analyses in WPs 5 and 6.

An ***in-depth analysis of the hindcast simulations*** showed also the importance of the comprehensive study and simulation design chosen by the ATtain-O3 consortium. In detail, we investigated the performance of the two CTMs with different chemical mechanisms in reproducing the ambient maximum daily 8-hour average ozone MDA8 O_3 burden over Central Europe by contrasting a base case setup with boundary conditions (BC) for meteorology from the ECMWF reanalysis and chemical BC from CAM-Chem as well as effects of alterations in these BC based on global model fields. Our results show that changes in meteorological BC strongly affect the correlation with observations but only marginally affect the model biases, while changes in chemical BC increases model biases while correlation patterns remain largely unchanged. While the first effect is caused by a discrepancy between real weather and model weather, the second effect is caused by elevated ozone abundances in the CCM which penetrate to the model domain through chemical BC. These findings reflect also in differences in the width of the MDA8 O_3 distribution as measure of intrinsic variability and highlight the importance of meteorology as driver of the temporal variability in MDA8 O_3 and the importance of chemical BC for setting the ozone background. Our findings illustrate that CTM choice can have in terms of model biases and variability similar (or even larger) effects as alterations of meteorological or chemical BC. Given these identified biases, ozone fields have been bias-corrected following well established approaches (Rieder et al., 2015, 2018) and mapped through spatial interpolation on municipal levels for further analysis which have been utilized for all analysis of changing ozone burdens and impact metrics described below and in WPs 5 and 6.

The set of CTM simulations considered ozone precursor and greenhouse gas emission trajectories as described in the RCPs. For ozone air quality particularly changes in NOx and CH_4 are of importance, which are illustrated in Figure 3.

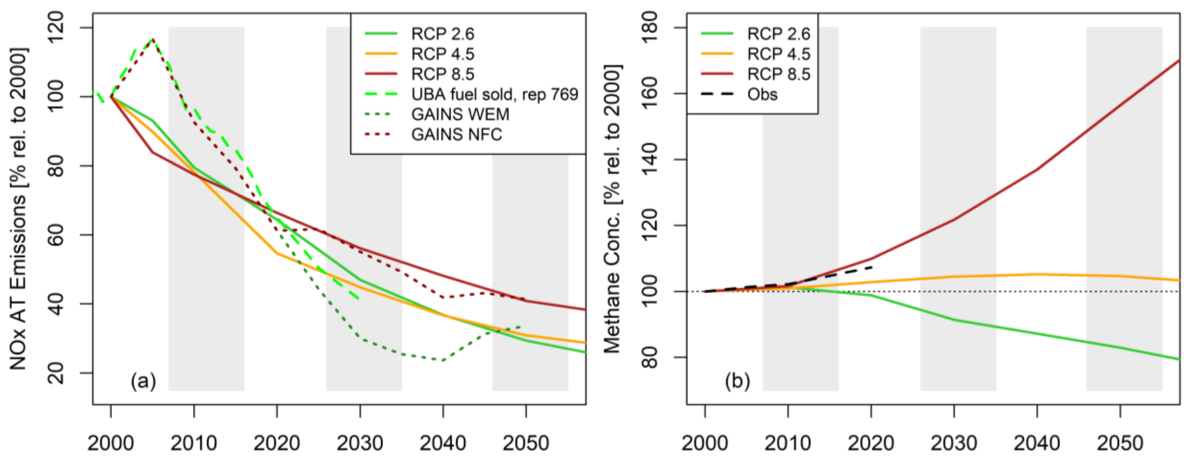

Figure 3: *Changes in Austrian NOx emissions (a) and global CH4 abundances (b) relative to year 2000 levels. For convenient reference decadal time slices (2007-2016, 2026-2035, 2046-2055) for CTM simulations are indicated by grey boxes. Scenario assumptions of the Environment Agency Austria (UBA) are given along with the RCPs* and NOx emission scenarios obtained by the GAINS model (WEM: with existing measures, NFC: no further control).

To ensure a robust agreement with the hindcast simulations all future scenario simulations have been driven with bias-corrected global climate model fields available from the CESM Model (Bruyere et al., 2015). For completeness we note that CESM output fields for the RCP2.6 scenario have not been available from NCAR due to the corruption of model output fields, thus we considered given the relatively small additional climate warming emerging till the 2030s a close alternate scenario considering ozone precursor emission changes following RCP2.6

and historic meteorological boundaries from the base period. This scenario was termed RCP2.6*.

We start the discussion of changing ozone burdens with a focus on the set of RCP4.5 simulations. Overall ambitious NOx reductions yield a marked reduction in mean ambient ozone levels across Austria already in the near-term (2026-2035), which further progresses with time. Reductions are most pronounced during summertime in the eastern parts of Austria, which manifests the effectiveness of NOx controls during the time of the year without VOC limitations (Figure 4). Also, during other seasons, we find reductions in the peak ozone burden but less pronounced given that ozone production is generally limited by the availability of biogenic VOCs outside of the growing seasons and unfavorable ambient meteorology (cooler temperatures and reduced solar radiation to effectively drive atmospheric chemistry). The overall decrease in the regional ozone burden following ambitious NOx controls emerges even clearer focusing on the MDA O_3 burden. Here we find under RCP4.5 almost nationwide substantial reductions in the decadal mean frequency of non-attainment days of up to -20 exceedance days on the municipal level (see Figure 5). On a regional basis the largest improvements in attainment are found in the north and north-eastern states of Austria, central Styria and the southern parts of Carinthia. These results document that ambitious ozone precursor emission controls outweigh a climate penalty on ozone (elevated temperature). We note that also under RCP4.5 interannual variability in the ozone burden remains high, predominantly driven by meteorological variability, with higher ozone burdens emerging in warmer years.

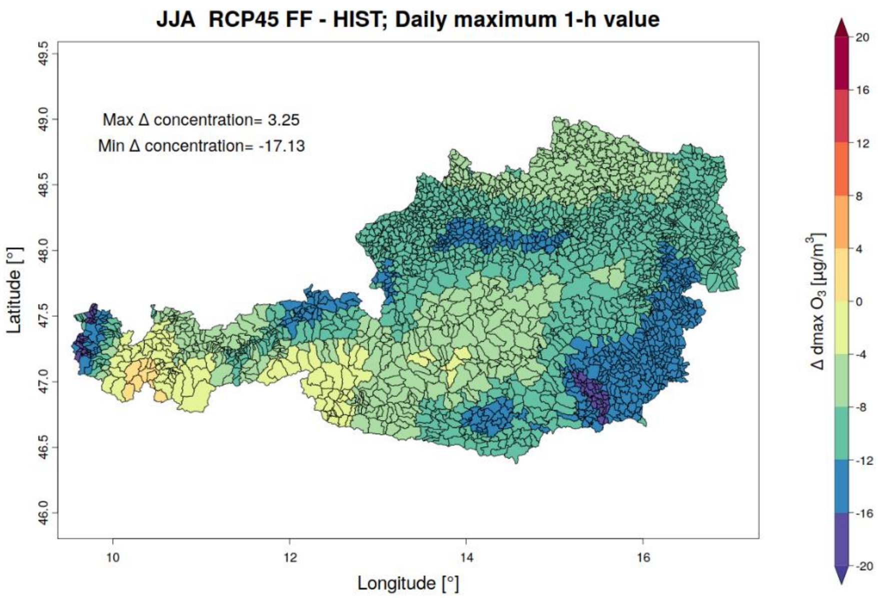

Figure 4: *Changes in decadal mean summertime (JJA) 1-hour maximum O_3 at the municipal level under RCP4.5, calculated as difference between 2046-2055 and 2007-2016 from WRF-Chem simulations.*

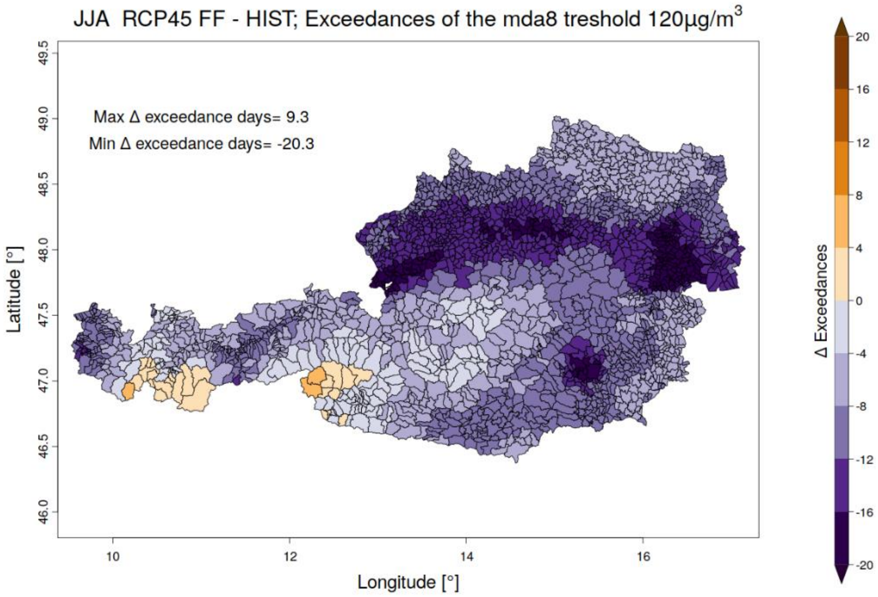

Figure 5: *Changes in the decadal mean summertime (JJA) frequency of exceedances of the MDA O_3 target value at the municipal level under RCP4.5, calculated as difference between 2046-2055 and 2007-2016 from WRF-Chem simulations.*

Next, we turn to the RCP2.6* sensitivity experiment which entails even more stringent NOx controls and does not suffer, by construction, from a climate penalty (meteorology corresponds to 2007-2016). This scenario shows for 2026-2035 nationwide substantial reductions in the frequency of non-attainment days highlighting the joint benefits of emission reductions for climate protection and air quality control. Nevertheless, we note that these reductions by 2026-2035 are less pronounced than for RCP4.5 by mid-21st century highlighting the importance of continuous NOx controls for ozone abatement. Finally, we turn to ozone changes under the high emission scenario RCP8.5. Under this scenario two interesting features emerge by mid-21st century. On the one hand side we find a reduction in the summertime ozone burden compared to the recent past despite a climate penalty on ozone production. While this might appear surprising at first, it can be explained by rigorous NOx emission controls (see Fig. 3). The residual climate penalty is though nicely visible contrasting results of RCP8.5 with those of RCP4.5 (see Figure 6). Second, we find a pronounced shift in the prime ozone season from summer towards spring, a feature emerging already in CCM analysis in WP1 (see Figures 1 and 2). This seasonal shift is indicative for an overall change in the chemical ozone production regime which is, due to elevated methane abundances, no longer VOC limited during spring, manifesting in a pronounced increase in the number of nonattainment days (Figure 7).

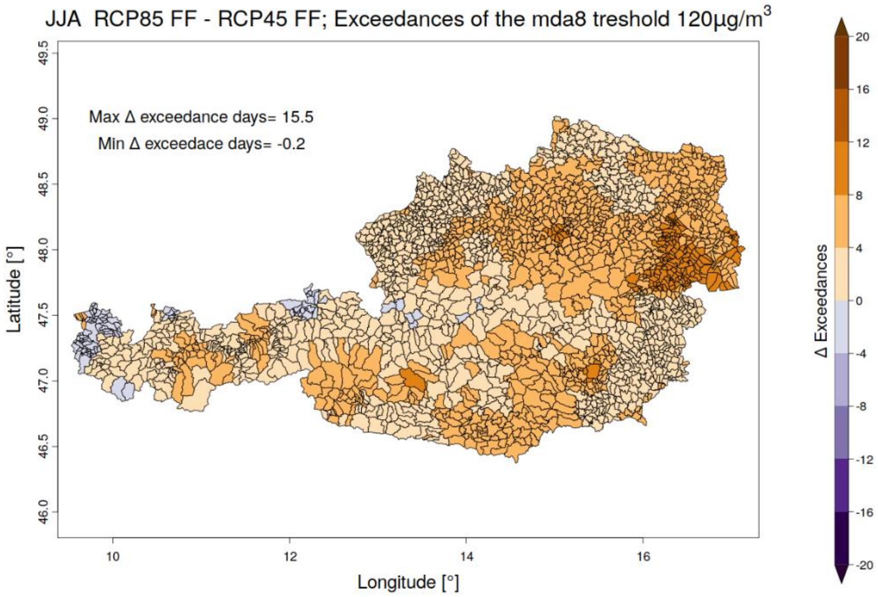

Figure 6: *Difference in the decadal mean summertime frequency of exceedances of the MDA* O_3 *target value at the municipal level between RCP4.5 and RCP8.5 by 2046-2055 from WRF-Chem simulations.*

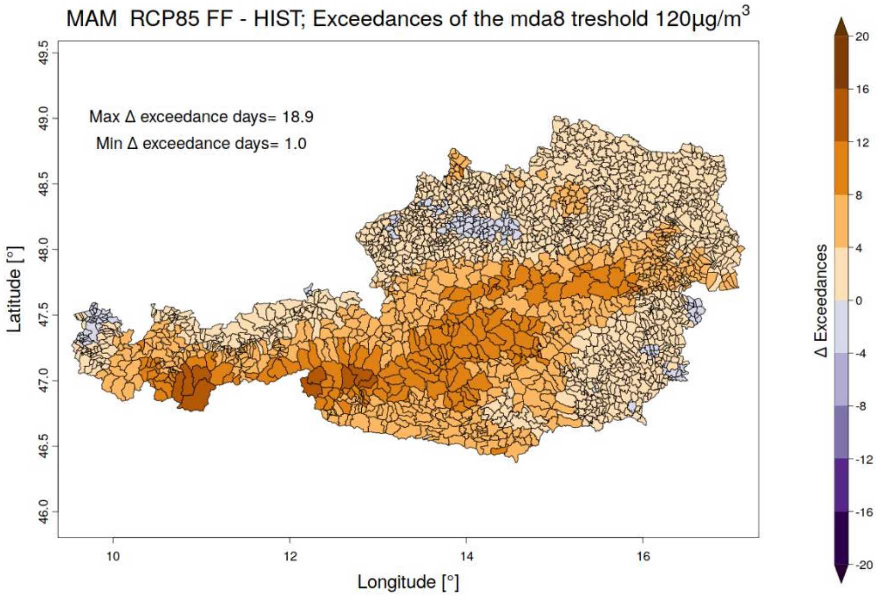

Figure 7: *Changes in the decadal mean springtime (MAM) frequency of exceedances of the MDA* O_3 *target value at the municipal level under RCP8.5, calculated as difference between 2046-2055 and 2007-2016 from WRF-Chem simulations.*

WP5 Direct costs of inaction and benefits of reduced ozone burdens

Health Impacts

Tropospheric ozone is a cytotoxic oxidizing substance and a secondary pollutant affecting human health through direct oxidising damage. At the same time, ozone serves as a marker of a broader range of secondary pollutants (including secondary particles) that have even more detrimental health effects. While short-term mortality effects are well established, chronic effects and effects on morbidity are less well documented. Also, due to privacy issues, reporting of diagnosis-specific hospital data is insufficient to enable a connection between the patient's diagnosis and district of residence. The **health impact assessment** (HIA) conducted in this WP analyses therefore primarily the **impact of short-term (daily) elevated atmospheric ozone levels on fatalities in Austria**.

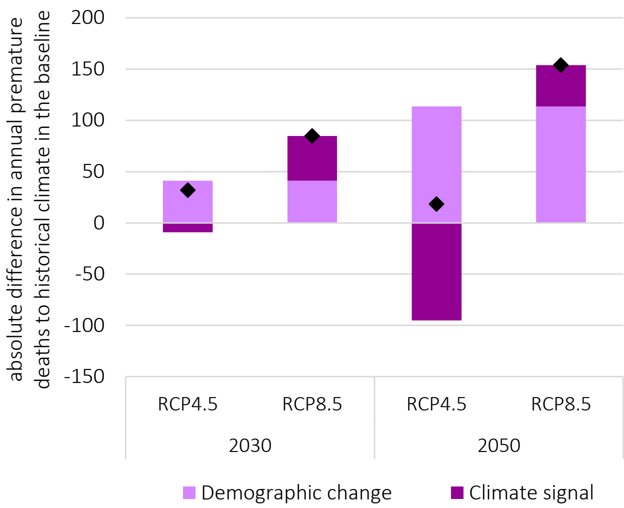

***Figure 8**: Absolute changes in premature fatalities disentangled by emission scenario (high-RCP8.5, medium-RCP4.5) and demographic development compared to estimated fatalities in the baseline.*

The estimated premature mortality from surface ozone in Austria for current emission levels and demography amounts to 367 annual deaths (Table 1). A number that increases until 2030 by 9% and 23% in a medium and high emission scenario, respectively. Until 2050, annual deaths rise significantly in the high emission scenario, with an estimated increase of 42%, leading to 521 annual premature deaths attributable to tropospheric ozone.

The disentanglement of absolute changes in premature mortality caused by tropospheric ozone in the near (2030) and far (2050) future shows that demographic change is a major driver, attributing to future exposition and vulnerability. Figure 8 depicts the absolute change in premature mortality in the near and far future compared to mortality under current emissions and demography (baseline). Overall, demographic change accounts for almost three quarters of additional deaths attributable to ground level ozone in 2050 in the high emission scenario, highlighting the significant role that demographic dynamics play for future exposure and vulnerability to air pollution. Monetized effects of mortality and morbidity are displayed in Table 1. We find that monetized welfare losses range from €2.2bn. in the baseline scenario to up to €4.8bn in the high emission scenario in 2050***. Results of the HIA have been summarized in Moshammer et al. 202x, to submitted for peer-review.***

Table 1 Total cases and monetized effect of ozone related mortality and morbidity across scenarios.

Year	Baseline scenario	2030		2050	
Emission scenario		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Ozone related mortality	367	399	451	385	521
Monetized mortality & morbidity (in Mio. EUR 2014)	2 157 [1 078-30235]	2 739 [1 370-4 109]	3 102 [1 550-4 652]	3 524 [1 762-5 286]	4 764 [2 382-7 147]

Impacts on agricultural yields

Surface ozone is a dynamic, short-lived air pollutant that negatively affects plant productivity. Focusing on Austria, we considered the most important crop types in terms of both yield and cultivation area. These include wheat, maize, barley, soybean, sugar beet and potato. We calculated district- and crop-specific yield changes due to ozone for the present period as well as for different future scenarios (RCP4.5 and RCP8.5) and future periods (2030s and 2050s). These changes were then aggregated to the Austrian scale.

The results show strong differences across agricultural crop types. The sensitivity of the specific crop to ozone exposure captured by the ERF is certainly the main driver of the results. However, other factors are relevant too. For example, the combination of high ozone concentrations with large cultivation area leads to greater changes in relative yields, whereas high ozone concentrations in regions with small or even without cultivation areas are irrelevant for agricultural output. Figure 9 shows the district-weighted sum of crop-specific yield changes for Austria expressed as a deviation from 1 (=100%). Strongest reductions in yield are projected for wheat, soybean and potatoes. In contrast, virtually no effect is projected for barley and even increases for sugar beet. A comparison across scenarios shows that there is no large difference in yield changes in the near future as well as for the lower emission scenario (RCP4.5) in the far future. All three scenarios also project lower impacts than in the current period due to improved air quality. However, impacts on yield changes in the high emission (RCP8.5) scenario in the 2050s are again significantly larger and offset any prior improvements. Thus, when considering the adverse effect of ozone on plant production, climate mitigation is required to achieve lower yield reductions. This should be seen in the context of other potentially relevant climate change impacts like heat and drought, which affect agricultural production and are typically increasing with higher warming scenarios.

For the macroeconomic impact assessment in WP6, we calculate a weighted sum over all crop types according to their relevance. The results reflect the patterns described above: overall crop loss in the historic period amounts to 10% and reduces to 5-7% in the near future with both scenarios and in the far future also with RCP4.5. However, in the far future with RCP8.5 crop loss amounts again to 10%.

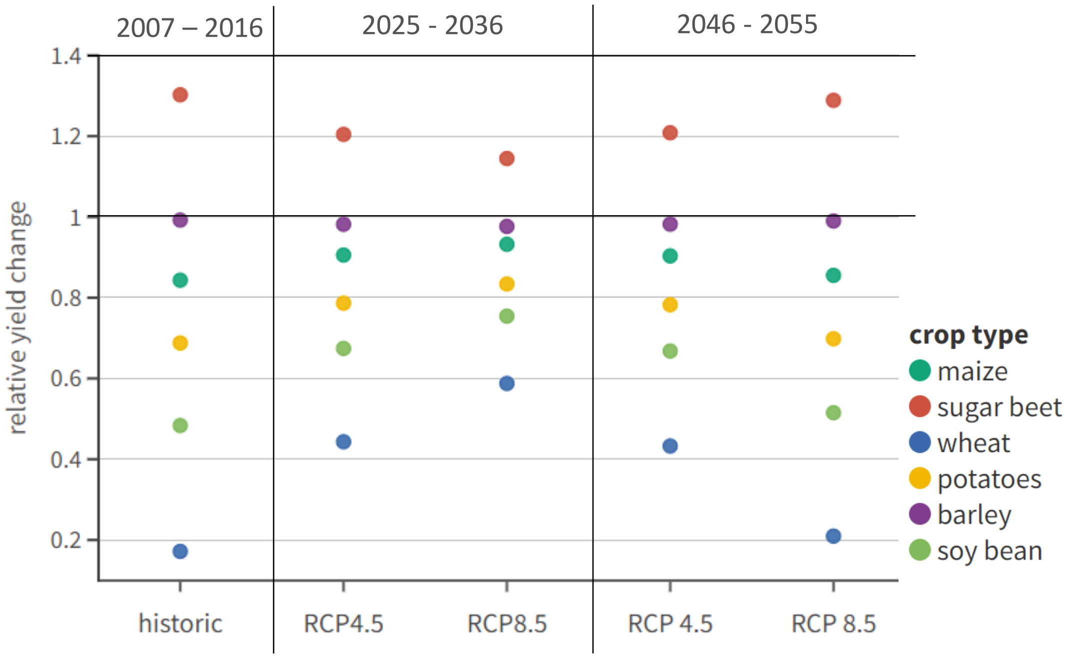

Figure 9: *Relative yield changes for considered crop types. District-weighted sum for Austria and historic data (Ø2007-2016) and for the medium (RCP 4.5) and the high emission scenario (RCP 8.5) for 2030 (Ø2026-2035) and 2050 (Ø2046-2055).*

Non-market impacts

In addition to the impacts on agricultural yields and food security (Mills et al. 2013, Emberson 2020), accounted for in this study via sectoral impacts on productivity, there is a **broad range of non-market impacts of ozone pollution** on ecosystems, ecosystem services and biodiversity. There is broad scientific consensus on the complex interactions of ozone and ecological processes, such as plant photosynthesis or nutrient cycling and the consequential impact on regulating services such as carbon sequestration, pollination and the water cycle (Mills et al. 2013, Agathokleous 2020, Fuhrer et al. 2016). Also, ozone related changes in the visual appearance and quality of the natural environment may impact the tourism industry (Mills et al. 2013). Yet, there is so far insufficient evidence to allow for economic quantification of these non-market impacts.

Another important impact dimension which we do not account for in this project is the immediate effect of ozone on labor productivity. The impact of elevated ozone levels on the productivity of exposed workers through the reduction of lung capacity and adverse cardiovascular effects has been widely adressed (Zivin & Neidell 2012, Klingen and Ommeren 2020, Cakmak et al. 2011 Neidell 2017), as well as their economy-wide implications (Lanzi et al. 2018, Greenstone et al. 2012, Vrontisi et al. 2016) In their EU-wide study, Vrontisi et al. (2016) find that the higher human capital productivity from avoided workdays lost in high mitigation scenarios fully offsets the costs of implementing abatement technologies.

Moreover, the adoption of more stringent mitigation policies can generate positive economic impacts in the sectors supplying the relevant abatement technologies. Due to insufficient knowledge on the supplying industries and their location in the context of this study, we do not consider this additional demand. In their EU-wide study, Vrontisi et al. (2016) explicitly account for the demand for abatement technologies, suggesting increases in sectoral activity of the technology suppliers, offsetting their negative spillover effects from abatement costs in other industries.

WP6 Macroeconomic assessment of benefits of reduced ozone burdens and costs of emission reduction requirements

WP6 was dedicated to the macroeconomic assessment of costs and benefits of different ozone levels in Austria. For the benefits of reduced ozone burdens, we considered lower agricultural yield losses as well as lower societal costs of ozone related mortality, as translated by the Value of Statistical Life. For the costs, we included sector-specific compliance costs, as shown across scenarios in Figure 8. We see an increase in compliance costs, both in the NFC (no further control) and the WEM (with existing measures) scenario until 2030, relative to the baseline costs. After 2030, costs decrease, such that by 2050, total compliance costs are below the total baseline costs in the NFC and WEM scenario. Compliance costs in the WEM scenario are higher compared to the NFC scenario, as many of the low-cost options, so-called “low hanging fruits”, have already been harvested.

In virtue of abiding with the concept of least-cost emission control pathways, compliance costs are not distributed evenly across sectors. Due to relatively high mitigation potential at relatively low cost (high cost effectiveness), absolute emission control costs are highest in the automotive industry with a share of around 80%, both in the NFC and WEM scenario in 2030. In 2050, when mitigation potentials in the automotive industry are increasingly exhausted, the power sector gains in importance in emission abatement, with a share of 35% and 41% of overall compliance costs in 2050. Moreover, significant abatement effort is required in the chemical, metal and print industry and to a lesser extent also in other industry and service sectors (see Figure 10).

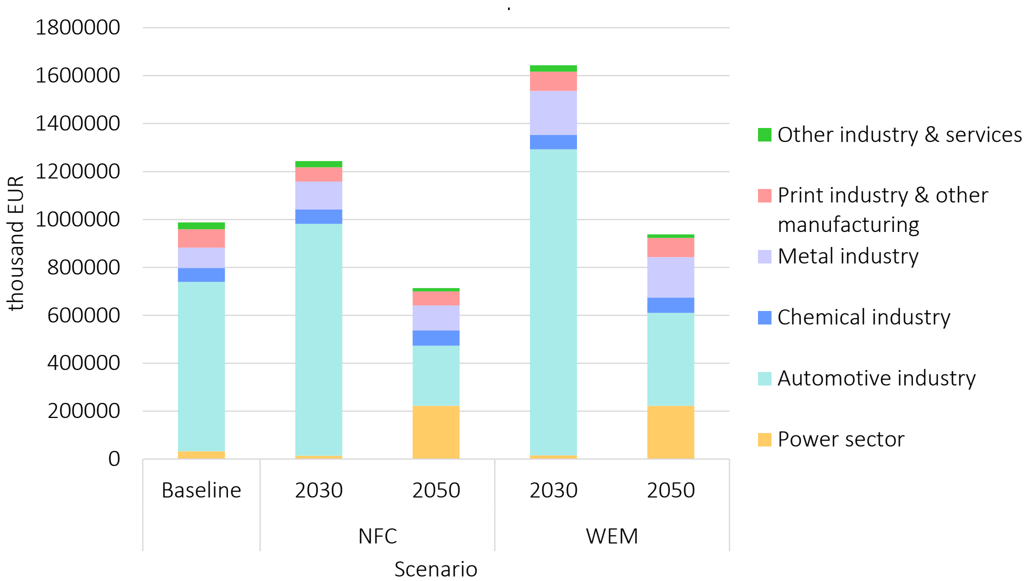

***Figure 10**: Annual compliance cost by sector in the baseline, in 2030 and 2050 for the no further control (NFC) and with existing measures (WEM) scenarios.*

To allow for a comparison of different regulatory and climate scenarios, we combined compliance costs for industry with the associated agricultural losses; i.e. the NFC (WEM) scenario results in emissions in accordance with the RCP8.5 (RCP4.5) scenario and thus agricultural losses with these higher (lower) emission. We performed a macroeconomic assessment of these two components. To represent overall societal welfare and to better compare the economy-wide benefits of a stricter regulation to the economy-wide compliance costs under different regulatory and climate scenarios, we included the welfare costs of mortality as calculated in WP5. Again, mortality in accordance with the RCP8.5 (RCP4.5) emission scenario was combined with the NFC (WEM) scenario, which implies lower (higher) compliance costs. In Figure 11 we show the difference between RCP8.5 and RCP4.5, where values above zero indicate welfare gains from stronger regulation scenarios and values below zero indicate welfare losses from stronger regulation scenarios.

The macroeconomic results reflect the direct impacts described in WP5. In 2030, agricultural yield losses are very similar across the two scenarios, but in 2050 lower yield losses in RCP4.5 as compared to RCP8.5 result in lower economy-wide costs and lead therefore to welfare gains. However, the higher compliance costs in RCP4.5 which is particularly pronounced in 2030 lead to a higher welfare losses in 2030. While the comparison of compliance costs and agricultural benefits would not yet provide the right incentives to follow a stricter regulation scenario, it is important to also consider economy-wide benefits of reduced ozone exposure for health.

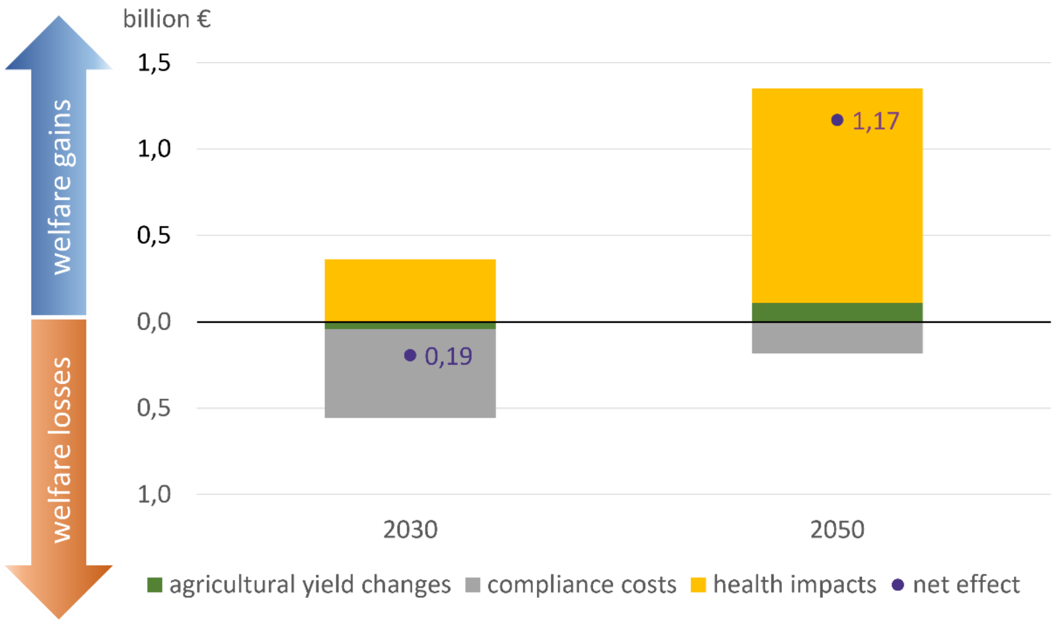

Figure 11: *Welfare losses and gains in 2030 and 2050 of RCP4.5 compared to RCP8.5 decomposed for effects through agricultural yield changes, compliance costs and health impacts, and denoting the net effect.*

Comparing the two scenarios with respect to avoided premature deaths expressed in monetary terms, Figure 11 shows strong welfare gains from stricter regulations. While in 2030 the gains do net yet exceed economy-wide costs and thus result in annual net welfare losses of € 0.19 bn, the net effect is clearly positive in 2050 with annual welfare gains of € 1.17 bn. We want to emphasize that welfare gains in 2050 depend on the pathway towards 2050 and hence require the higher costs for more stringent mitigation in 2030. Moreover, several adverse effects of ozone have not been assessed quantitatively as discussed in WP5.

To test the robustness of the results, we performed several sensitivity analyses. For example, agricultural crop loss estimates were based on the ozone indicator AOT40 accumulated over a 3-month period, which according to the literature represents the relevant growing season and builds the basis for the establishment of the ERFs (Mills et al., 2007). Considering agriculture in Austria, growing seasons can vary substantially across crops. We therefore also calculated crop losses based on actual crop-specific growing seasons in Austria. Effects tended to be larger, but there were no substantial qualitative differences. Regarding the health impacts, we used results from different cut-off concentrations (20 instead of 70 $\mu g/m^3$) and applied different VSL estimates. Again, welfare gains from following a stricter regulation scenario tend to be larger, but qualitative findings remain unchanged.

We presented and discussed the results at the stakeholder workshops. A key concern of participants was the significance of the produced results in Austrian policy-making. As has been established in earlier project parts, ozone emissions heavily depend on background emissions. While Austria can advocate for stricter emission regulations at the EU level, laws can only be enforced within Austria. The question therefore arose whether unilateral action in Austria would yield benefits, while neighboring countries do not comply to stricter emission standards. Benefits would clearly support decision-making such that unilateral action pays off. The project team has reacted to this request and calculated a third scenario, where Austrian emissions comply with the RCP 2.6 pathway, while global emissions are on a RCP 8.5 pathway. The results show that unilateral action indeed pays off in terms of an economy-wide benefit cost comparison of agricultural yield losses, compliance costs and health impacts. While the difference is small, the results support proactive ozone emission reduction actions. ***Above described and additional results are incorporated in the planned publication Preinfalk et al. (in preparation).***

WP7 Project management, stakeholder involvement, dissemination strategy and policy briefing

WP7 comprised all management and dissemination tasks of the project. Key outcomes of stakeholder engagement have been already described in WP2. The consortium has been interacting with the international advisory board and several joint publications have been emerging through fruitful discussions with these colleagues throughout ATtain-O3. An overview about publications and presentations and other dissemination activities is given in Section 8.

For references in Section 4 see Annex A.

5 Schlussfolgerungen und Empfehlungen

The project results highlight diverse futures for Austrian ozone air quality and associated health and economic impacts. Major project findings are summarized below as are potential directions for further research.

Results of the CCM analysis (WP1) indicated a breath of different futures for Austrian surface ozone air quality, dependent on the considered climate and emission scenario. These potential futures have been further investigated in high resolution CTM simulations (WP4) following RCP2.6, RCP4.5 and RCP8.5. The CTM simulations showed pronounced reductions in the surface ozone burden (mean, high quantiles, number of non-attainment days) in low and medium emission scenarios (RCP2.6, RCP4.5) while an increased ozone burden and a seasonal shift in the prime ozone season have been identified under a "business as usual scenario" (RCP8.5), driven by a so-called chemical penalty through increases in global methane background concentrations. Sensitivity experiments aided the identification of potential impacts of ambitious Austrian ozone precursor controls (emissions following RCP2.6, climate following RCP8.5) in the absence of a concentrated global effort (emissions and climate following RCP8.5). The air quality analyses have been completed by studies focusing on the historic changes in the Austrian ozone burden and the impacts of the COVID lockdowns emerging during the project duration, triggered through the stakeholder dialogue in WP2.

The CTM data has been further utilized in comprehensive health and economic impact assessments (WP5 and WP6). The health impact assessment (WP5) highlighted on the one hand the overlaying influence of demographic changes on the other substantial differences in scenario dependent health outcomes. Ozone-related deaths have been estimated to increase by about 20% by 2030 and 40% by 2050 under RCP8.5. In contrast, increases under RCP4.5 are less than half of those of RCP8.5 by 2030 and declining thereafter due to ambitious NOx controls. For agricultural yields, we find strongest ozone-related reductions in crop yields for wheat, soybean and potatoes while e.g. barley and sugar beet are not negatively affected. Across crops, the yield loss in the historic period amounts to 10%, reduces to 5-7% in the 2030s (regardless of the RCP scenario), but increases to 10% under RCP8.5 while it reduces to 7% under RCP4.5 in the 2050s.

The macroeconomic results (WP6) reflect the direct impacts on human health and agriculture, but the effects on health dominate the effects on agriculture in magnitude. In 2030, agricultural yield losses are very similar across the two scenarios, but in 2050 lower yield losses in RCP4.5 result in lower economy-wide costs and lead therefore to a welfare gain in RCP4.5. However, the higher compliance costs in RCP4.5 in the next decade leads to a net welfare loss in 2030. While the effectiveness of ozone precursor control measures is shorter compared to the mitigation of greenhouse gas emissions, we still find a temporal mismatch in the flows of costs and benefits of stricter compliance: higher compliance only pays-off in the far term (2050s), but not in the short term (2030s). A key element of the project has been the dissemination of project findings and policy support (WP7) via workshops and scientific publications.

Below we summarize further findings of the air quality, health impact and economic assessments.

Air Quality Assessment:

1. Interannual variability in surface ozone burdens remains high in all scenarios considered, driven by substantial interannual variability in meteorological conditions.
2. Regional differences in ozone air quality remain pronounced driven by local chemical regimes and precursor emissions. However, benefits of emission reductions and impacts of a climate penalty (high emission scenario) emerge more uniformly highlighting on the one hand nationwide benefits of ambitious precursor emission controls, on the other a climate penalty on ozone air quality under global inaction.
3. Summertime peak ozone burdens decline in low and medium emission scenarios, particularly after 2030. In contrast under RCP8.5 summertime ozone burdens remain high and a seasonal shift of the prime ozone season towards spring manifests driven by global backgrounds and elevated and accelerated VOC emission driven by temperature increase.
4. In absence of ambitious national precursor emission reductions and global climate action the ozone target value will not be attained in many regions across Austria.
5. Under ambitious emission controls ozone air quality is substantially improving, however non-attainment will still occur under unfavourable meteorological conditions as observed in the past.
6. Decadal time slice simulations with comprehensive CTMs provide important data for health and economic impact assessments and allow to assess health and economic effects on a national and municipal basis.

Health Impact Assessment:

1. The HIA highlights the significant role of demographic dynamics for future exposure and vulnerability to air pollution.
2. Ozone-attributed monetized welfare losses range from €2.2bn in the baseline scenario to up to €4.8bn in the high emission scenario in 2050.
3. Ozone-related deaths are estimated to increase by about 20% by 2030. In contrast increases under RCP4.5 are less than half of those obtained for

RCP8.5 and projected to slightly decline till mid-21st century due to further NOx controls.

Agricultural Impact Assessment:

1. Ozone pollution affects Austrian agricultural production already today, with strongest negative impacts on wheat, soybean and potatoes. Moreover, regional vulnerabilities can vary substantially.
2. Across crops, the yield loss in the historic period amounts to 10%, reduces to 5-7% in the 2030s (regardless of the RCP scenario), but increases to 10% under RCP8.5 while it reduces to 7% under RCP4.5 in the 2050s.
3. Clean air policies improve the situation, but only additional efforts to reduce greenhouse gases result in consistent improvements. Climate mitigation is therefore as important as ozone mitigation measures for agricultural productivity.

Economic Impact Assessment:

1. While ozone precursor emission reduction efforts imply costs for several industrial sectors, economy-wide benefits offset these costs and lead to welfare gains, at least by mid-century.
2. Ozone abatement costs exceed benefits in the medium-term (2030s), however, in the long-run (2050s) costs are clearly offset by economy-wide benefits. It is also important to consider that climate variability implies stronger or weaker effects in individual years.
3. Considering the most comprehensive assessment of climate change impacts that occur within Austria in the COIN project (Steininger et al. 2015), macroeconomic consequences from ATtain-O3 represent a new aspect: in both agriculture and health, climate change-related damages associated with ground-level ozone were not considered in the COIN project. In agriculture, negative consequences of ozone outweigh the potential positive effects from longer growing seasons, which have been considered in COIN. Ozone-related premature mortality is a relevant complement to the heat-related deaths, that have already been considered in COIN. In the lower emissions scenario (RCP4.5) and the near future (2030s), lower temperatures imply a greater importance of ozone-related premature mortality, while stronger temperature increases have significantly more severe effects of heat-related mortality in the far future (2050s). Nevertheless, ozone-related fatalities constitute a third of heat-related fatalities, increasing climate-induced fatalities by around 30%.

From these findings the ATtain-O3 consortium has developed a list of potential future research priorities and development actives detailed below.

Potential follow-up research and development activities:

- to investigate the effects of changes in biogenic VOC emissions on ozone burdens through changes in forest cover and tree composition under climate change;
- to investigate the connections between PM burdens and climate extremes as major urban/suburban health hazards;
- to investigate the joint health burden emerging from changes in air quality (O3, NOx, PM) and climate (heat, humidity, cold) and the associated risks and costs;
- to investigate the effect of climate-friendly transitions in the transport sector on air quality across urban, suburban and rural domains;
- to investigate the interaction effects between heat, drought, and ozone on agricultural yields in Austria;
- to investigate the effects of changing ozone burdens on ecosystems, ecosystem services and biodiversity in Austria;
- to investigate the costs of hospital admissions related to ozone (but also other hazards such as heat or PM) in market cost studies;
- to investigate the changing demand in abatement technologies across sectors and explore techniques beyond end-of-pipe technologies;
- to investigate the effect of changing ozone burdens on labour productivity;
- to investigate impacts of changing ozone burdens on larger spatial scale across Europe;
- to update cost of inaction assessments to account for connections between climate and air quality, e.g. on agricultural yields and mortality;
- to update coordinated modelling protocols to consider chemistry-climate connections on regional scale.

C) Projektdetails

6 Methodik

The project team has applied and combined a series of methods to assess the change in the Austrian ozone burden, associated health and economic impacts and the costs of action and inaction. In brevity these include, the analysis of transient CCM ensemble simulations, the production and analysis, bias-correction and re-analysis of decadal time slice CTM simulations (including sensitivity simulations), and the preparation of model output statistics and metrics for health and agriculture assessments, and performance of these assessments. The individual methods are described in greater detail in the subsequent paragraphs.

Chemistry-Climate and Chemistry-Transport Model Analyses
An initial series of analyses focused on a set of chemistry-climate model simulations performed in support of IPCC AR5. These transient simulations, and a series of targeted sensitivity simulations have been performed with the GFDL chemistry-climate model CM3 following the representative concentration pathways RCP4.5 and RCP8.5. The CCM analysis was providing an initial estimate for changes in surface ozone burdens under these two RCPs, while sensitivity simulations allowed to provide initial estimates for air quality penalties emerging from changes in climate or composition in isolation and combination.

Given that these CCM simulations have been only available on a course spatial grid the consortium performed a series of **targeted model simulations with high-resolution CTMs** (9x9 km grid) to provide robust estimates of future changes in ozone air quality and to inform health and economic impact assessments. Two CTMs (WRF-chem and CAMx) have been deployed to perform a series of decadal time slice simulations (2007-16, 2026-35, 2046-55) for the European domain and RCP2.6, 4.5 and 8.5. ECMWF reanalyses (or bias corrected CESM model fields) as meteorological boundary conditions have been downloaded for regional climate model simulations with WRF and RegCM to drive CTMs (WRF-Chem coupled, CAMx offline). Historic chemical boundary conditions have been taken from the CAM-Chem model and emissions have been pre-processed using the FUME model. Austrian road NOx emissions have been regionally increased by about a factor of two following disagreement between observed NOx burdens and modelled fields based on emission inventory input fields. Also, for ozone burdens CTM outputs showed biases compared to observations thus ozone fields have been bias-corrected following established techniques (quantile-mapping). For future CTM simulations chemical boundary conditions have been prepared from CCM fields (SOCOLv4) and meteorological boundaries have been taken from bias-corrected CESM fields (available from NCAR). Given that the RCP2.6 CESM outputs have been corrupted during output, the consortium used an alternative scenario termed

RCP2.6* comprising 2007-16 meteorological conditions and chemical boundaries and emissions for 2025-36 (reflecting ambitious precursor emission changes in a contemporary climate).

All CTM simulations have been performed on a 9x9 km grid and municipal burdens derived by spatial interpolation and aggregation over the study domain. Changes in ozone burdens have been assessed (on grid level and municipal basis) for a wide variety of metrics spanning from annual and seasonal averages to daily or hourly maximum values. **Selected ozone metrics** (daily 1-hour maximum, maximum daily 8-hour average, AOT40) have been prepared **on municipal basis for the health impact and economic assessments**.

Health Impact Assessment

Based on the concentration-response relationships derived from earlier epidemiological studies (Gryparis et al. 2004), we estimated the number of cases attributable to ozone exposure. Thereby, we considered different emission and climate scenarios, inducing long-term changes in ozone concentrations. In addition to climatic changes, also the demography and size of the population is dynamic over time and taken into account in the Health Impact Assessment. Therefore, in a first step, both the current and the various future ozone concentrations (2030 and 2050) were applied to the current population. This demonstrated the **effect of the changing ozone levels**. Next, future ozone concentrations were linked to future population estimates. This uncovered the effect of demographic change alone as well as the **combined effect of population change and the change in ozone concentrations**.

For the historical period, daily death counts per district were available per age group, sex, and main cause of death from Statistik Austria (data obtained for previous studies, see: Moshammer et al. 2020, Poteser et al. 2020). For future mortality data, the demographic forecast of Statistik Austria (2019) were used, estimating annual deaths (all causes combined) per district for every five years from 2020 until 2075.

Following the methodology developed by the HRAPIE project (WHO 2017), short term effects of daily ozone concentrations on total mortality can be calculated. For long-term effects of annual ozone concentrations, only estimates for respiratory deaths are proposed, based on an American study (Jerret et al., 2009) that only made use of summer ozone data, which limits the applicability of this approach. Due to this limitation, we assessed only short term effects, applying effect estimates based on the study by Gryparis et al. (2004) for daily 1-hour maximum ozone concentrations – a relative risk of 1.0024 per 10 µg/m³ increase. We calculated the effects of ozone compared to a base concentration of 70 µg/m³ (as suggested by HRAPIE). Calculations were performed using the spreadsheets provided by the APHEKOM project (APHEKOM 2013), which has set the standards for Health Impact Asessment in Europe (Perez et al. 2013). Because the uncertainty reported by these sheets as confidence intervals only reflect the uncertainty of the effect estimate reported by Gryparis et al. (2004), and not the additional uncertainties because of the modelling of exposure and demographic development, it was decided not to present these uncertainties but only report point estimates.

Agricultural Impact Assessment
Regarding agriculture, biophysical impacts on crop yields in response to O_3 during the growing season was used, differentiating for the ozone sensitivity of crop type. There are several studies investigating and attempting to quantify the effect of surface ozone on the production of different crops on a global level. A challenge involves the construction of an ozone indicator that best correlates with the effect of ozone on plant growth. In Europe, the AOT40 indicator has emerged as an established measure to calculate changes in plant production based on ozone influences (EEA, 2009). The AOT40 indicator measures hourly mean ozone concentration above the threshold of 40 ppb during daytime hours of the crop's growing season and its unit is parts per billion hours (ppb h). To relate the chosen ozone indicator to crop yield changes, a so-called exposure-response function (ERF) is required. Mills et al. (2007) evaluated plant response data from over 700 published articles and conference proceedings and established ozone ERFs for a wide range of European agricultural and horticultural crops. In ATtain-O3, we rely on the **crop-specific ERFs functions** proposed by Mills et al. (2007).

We considered the most important crop types in terms of both yield and cultivation area in Austria. These include wheat, maize, barley, soybean, sugar beet and potato. To obtain relative yield changes for Austria, we first identified the cultivation area for each crop type per district and combine these with a yield factor, which is available for each federal state from the AMA database. This results in district- and crop-specific yields for the present period. In a second step, we matched AOT40 values and crop-specific yield data at the district level and applied the ERFs by Mills et al. (2007) for each considered crop and for all considered scenarios and periods.

Economic Impact Assessment
For the economy-wide assessment of more stringent ozone regulation, we applied a computable general equilibrium (CGE) model, that is based on Mayer et al. (2021) and depicts Austria as a small open economy, where international trade is merely represented as import and export flows between Austria and the rest of the world. The economic structure is based on an input-output table of 72 NACE-classified economic sectors and a social accounting matrix (SAM) for Austria of the year 2014 provided by Statistics Austria. In a first step, we refined the model to allow for a more detailed representation of economic sectors within Austria, which enabled a sophisticated implementation of agricultural yield losses and sectoral

differentiated compliances costs. For that purpose, we disaggregated the agricultural sector into livestock and crop production. In a next step, we implemented agricultural yield losses as decreased agricultural output according to calculated yield changes in WP5.

We then used results from the GAINS model to **estimate emission control costs for the ozone precursors** nitrogen oxides (NOx) and volatile organic compounds (VOCs) alongside future emission control scenarios in the context of Austria. Drawing on activity projections for the economy, as well as the energy and agricultural sector, the integrated assessment model GAINS brings together anthropogenic drivers for pollution and emission control potentials and technology characteristics with associated costs on a country level (Amann et al., 2011). In contrast to behavioral changes or structural measures, the emissions reductions considered in this study do not modify the driving forces of emissions or change the structural compositions of the energy or agricultural system and are so-called end-of-pipe measures (Vrontisi et al., 2016). Based on bottom-up information on emission reductions and associated costs by the means of sectoral marginal abatement cost functions, GAINS allocates emission control measures across sectors in a least cost manner (Amann et al., 2011; Vrontisi et al., 2016).

Finally, to set premature mortality into context with policy costs and agricultural yield losses, we employed the value of statistical life (VSL), as a standard method to measure the economic cost of mortality. It constitutes the monetary value of a marginal reduction in the risk of mortality (Markandya et al., 2018). Thus, the VSL is not the value of a person's life, but rather an aggregation of the willingness to pay for small reduction in an individual's risk of premature death (OECD, 2012, 2016). Based on a comprehensive review a quality-screened sample of studies, the OECD estimates a VSL estimate for the EU corresponding to USD 3.6 million (2005-USD) (OECD, 2012). The VSL estimates were then multiplied with the number of premature deaths obtained in the Health Impact Assessment for each scenario, to yield an approximation of premature mortality in monetary terms. We captured uncertainty by accounting for an upper and lower bound in the VSL estimate, as proposed by the OECD (2012).

The model interface for the economic impact assessment is depicted in Figure 12. Finally, non-market impacts were described qualitatively, as summarized above in section 3.

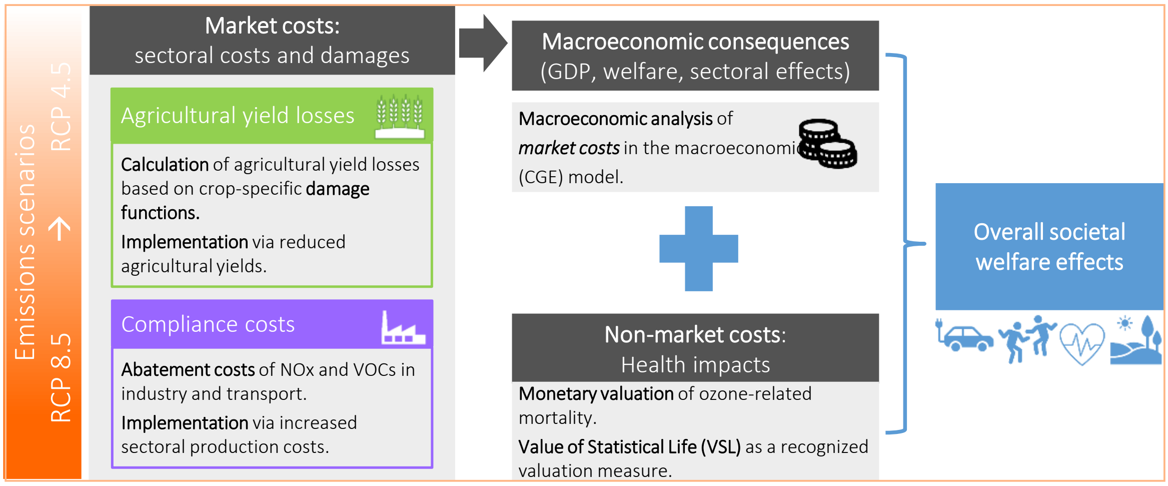

Figure 12: *Conceptual overview of the economic assessment.*

Stakeholder Dialogue

Throughout the project, public authorities (clean air administration, climate action administration), health professionals, agricultural stakeholders and researchers were engaged to contribute to the development of emission inventories and of feasible emission reduction scenarios, and to comment and review results of the project. This stakeholder engagement was facilitated by two workshops: in the first workshop, possible developments of ozone concentrations under different climate and emission scenarios were presented and possible mitigation scenarios (current legislation; future legislation; maximum technically feasible reduction; stakeholder informed scenario) were discussed and developed. The second workshop was devoted to the societal and economic benefits of tighter regulation for human health and agricultural yields. Moreover, the associated compliance costs of stricter ozone precursor measures in industry and transport were assessed. Finally, costs and benefits of regulation were compared from an economy-wide perspective. In addition, a communication format was elaborated with the stakeholders to ensure that the results as well as its limitations are clearly understood by the relevant audience. See section 4 above, WP2 description, for further details.

For references in Section 6 see Annex A.

7 Arbeits- und Zeitplan

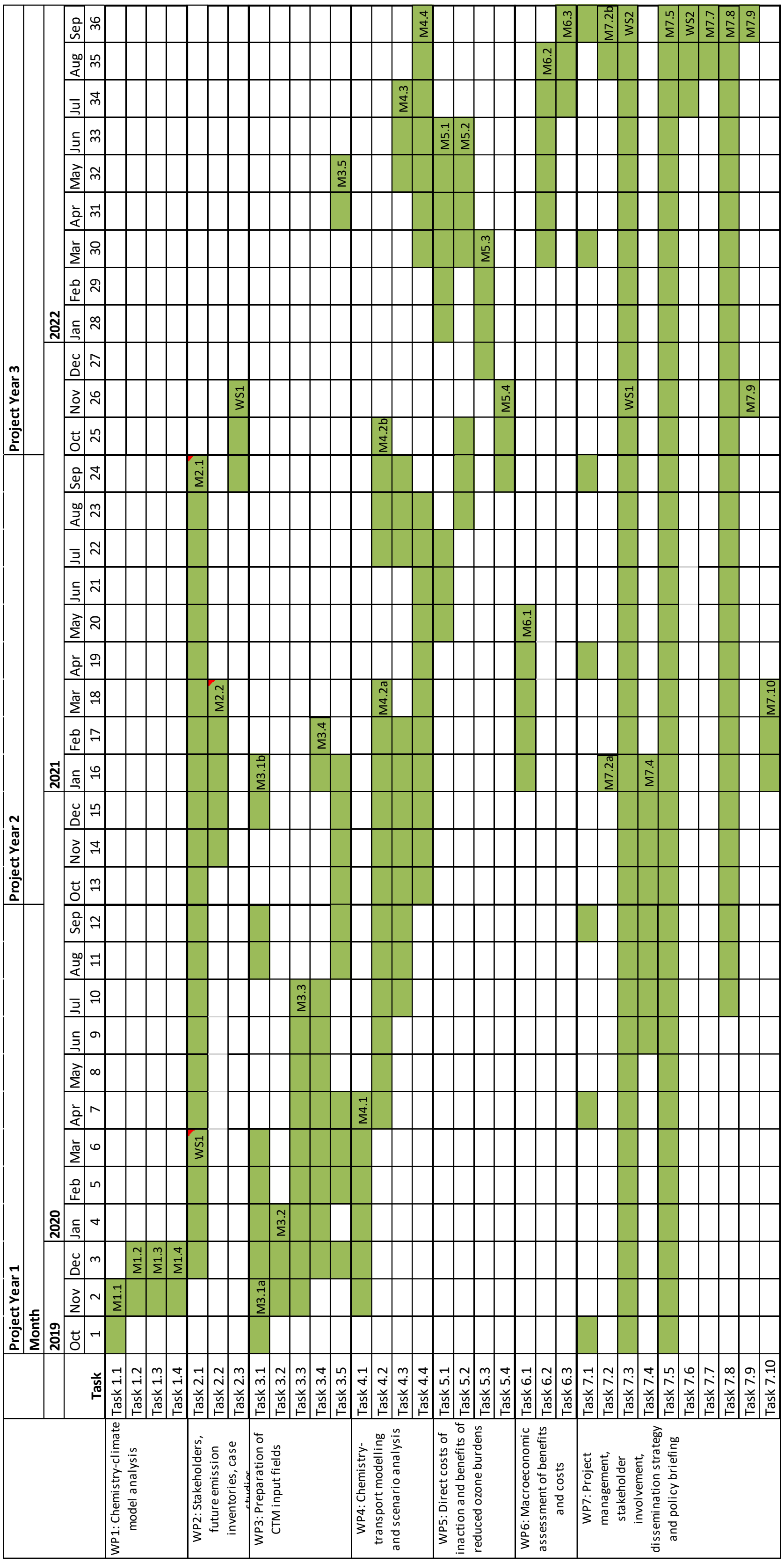

Chart 1: *Gantt Chart for ATtain-O3.*

8 Publikationen und Disseminierungsaktivitäten

Published Papers: (until 01/2023)

von Schneidemesser Erika, Driscoll Charles, Rieder Harald E. and Schiferl Luke D. (2020): How will air quality effects on human health, crops and ecosystems change in the future? Phil. Trans. R. Soc. A.37820190330, http://doi.org/10.1098/rsta.2019.0330

Mayer M., Schreier S.F., Spangl W., Staehle C., Trimmel H., & Rieder H.E. (2022): An analysis of 30 years of surface ozone concentrations in Austria: temporal evolution, changes in precursor emissions and chemical regimes, temperature dependence, and lessons for the future. Environmental Science, 2, 601 – 615, https://doi.org/10.1039/D2EA00004K

Staehle C., Mayer M., Kirchsteiger B., Klaus V., Kult-Herdin J., Schmidt C., Schreier S., Karlicky J., Trimmel H., Kasper-Giebl A., Scherrlin-Pirscher B., and Rieder H.E. (2022): Quantifying changes in ambient NOx, O3 and PM10 concentrations in Austria during the COVID-19 related lockdown in spring 2020. Air Qual Atmos Health 15, 1993–2007, https://doi.org/10.1007/s11869-022-01232-w

Conference contributions:

Rieder et al.: ATtain-O3 - Evaluating the effects of climate warming and precursor emission changes on the attainment of the Austrian ozone standard, Austrian Climate Day ACRP Sessions, September 2020 (online meeting)

Staehle et al.: Changes in European surface ozone air quality over the 21st century, EGU 2020 (online meeting)

Mayer et al.: Changes in the temperature sensitivity of surface ozone production: a case-study based on long-term observations in Austria, EGU 2020 (online meeting)

Mayer et al.: Surface Ozone Concentrations in Austria from 1990 – 2019: Evolution and Lessons for the Future, Quadrennial Ozone Symposium 2021 (online meeting)

Preinfalk et al.: Incentives for unilateral abatement action – an economy-wide assessment of ozone-related costs in Austria, submitted to the European Association of Environmental and Resource Economists conference (EAERE), Limassol, Cyprus, June 2023

Preinfalk et al.: Incentives for unilateral abatement action – an economy-wide assessment of ozone-related costs in Austria, submitted to the International Conference on Economic Modeling and Data Science (EcoMod), Prague, Czech Republic, July 2023

Schmidt et al.: Evaluating the effects of climate warming and precursor emission changes on surface ozone air quality over coming decades: a case study for Austria, submitted to EGU General Assembly 2023, Vienna, Austria, April 2023

Presentations at other scientific and stakeholder events:

Mayer et al. (2020): Influence of the COVID-19 related shutdown on air quality in Austria, ÖAW BLAG, September 2020

Rieder et al. (2020): Surface ozone and climate, ÖAW KKL, June 2020 (virtual event)

Rieder et al. (2020): Influence of the COVID-19 related shutdown on air quality in Austria – some initial results, ÖAW BLAG, May 2020 (virtual event)

Rieder et al. (2019): Current and future challenges in attaining air quality targets: the roles of precursor emissions, ambient meteorology, and climate warming, University of Innsbruck, ACCIN, December 2019

Rieder et al. (2019): Evolution of air quality in Styria, past development and future directions, ÖAW BLAG, Vienna, November 2019

Additional stakeholder meetings:

Participation at meetings of the Austrian state working group on air quality (Bundesländer-Arbeitskreis (BLAG), der ÖAW-KKL) in November 2019 (Vienna), May 2020 (virtual event) and September 2020 (Carinthia)

Stakeholder meeting with Styrian stakeholders (Umweltamt, Abt. 15 Amt der Steirischen Landesregierung), January 2020

Media: (only contributions with links active 31.01.2023 listed)

https://oe1.orf.at/programm/20200409/594871/Freie-Sicht-und-klare-Luft

https://open.spotify.com/episode/3Iq7u6dvIGsuDkjgGqzLQB

https://www.youtube.com/watch?v=ugxtOkzrI3U

https://www.wis-potsdam.de/de/institut-transformative-nachhaltigkeitsforschung-iass/planet-braucht-ehrgeizigere-emissionsgesetze

Diese Projektbeschreibung wurde von der Fördernehmerin/dem Fördernehmer erstellt. Für die Richtigkeit, Vollständigkeit und Aktualität der Inhalte sowie die barrierefreie Gestaltung der Projektbeschreibung, übernimmt der Klima- und Energiefonds keine Haftung.

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