Are decadal anthropogenic emission reductions in Europe consistent with surface ozone observations?

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1. Introduction

1. Understanding the history of tropospheric ozone (O\textsubscript{3}) during the last decades is quite a challenge. The global increase of O\textsubscript{3} precursor emissions has progressively raised the mean global O\textsubscript{3} level [Akimoto, 2003]. However, the increasing number of ground-based, airborne or radiosounding observations shows a far more heterogeneous picture, even in the sign, of O\textsubscript{3} level trends [Oltmans et al., 1998, Vingarzan, 2004, Saraf and Beig, 2004, Zbinden et al., 2006]. In Europe, even though high surface O\textsubscript{3} events are decreasing, the O\textsubscript{3} baseline appears to have increased by up to few ppb per year at several surface sites [Naja et al., 2003, Monks et al., 2003; Simmonds et al., 2005; Carslaw, 2005], with uncertainty on rates.

2. Observations and Simulations

2.1 The consistency between pollutant emission reductions in Europe during the 1990–2002 period and ozone observations is quantitatively verified by 13-year long simulations over the whole period using the regional chemistry-transport model and the EMEP emission inventory. A statistically significant decadal tendency of 0.65 ppb/year is found in the difference between simulated and observed summer 90th percentiles of ozone daily maxima when model emissions are kept constant from year to year. By contrast the use of yearly dependent emissions does not yield a statistically significant percentile difference tendency. The regional structure of the 90th percentile differences shows that emissions may have decreased with a higher rate than assumed in the U.K. and at a lower rate in central Europe. The observed 10th percentiles are also compatible with the assumed emission reductions in Europe during 1990–2002, but are of lesser agreement with simulations using a uniform trend in the baseline ozone.


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deduced

Skill measures of the simulations of daily O₃

maxima as a function of year, for the 3 simulations, CTRL, FIXE and TREN. (top) Evolution of the summertime daily

maxima means (in ppb) for simulations and observations. (middle) Evolution of the correlation averaged over summer

and all stations. (bottom) Evolution of the root mean square error (in ppb) averaged over summer and all stations.

are selected in such a way that data are continuous and homogeneous from 1990 to 2002. Since we are looking for

responses to regional emission reductions, only summertime (April to September) O₃ daily maxima are considered.

Regional simulations are carried out using the gas-

phase version of the regional CHIMERE CTM described by

Schmidt et al. [2001], with updates described by Vautard et al. [2005]. This model gives an accurate simulation of O₃
daily maxima in summer [e.g., Vautard et al., 2005]. It is

driven by hourly meteorological fields issued from the

MM5 meso-scale model [Dudhia, 1993], which simulates

meteorological variables on a grid with an approximate

resolution of 40 km, and which is nudged to (and forced at

the boundaries by) the 6-hourly ERA40 European Centre

for Medium Range Weather Forecast reanalyses.

The chemistry-transport model is forced at the bound-

aries by a climatology of O₃ and precursors issued from the

global-scale LMDz-INCA model [Hauglustaine et al., 2004, Folberth et al., 2005], using monthly averages of a

5 year simulation with varying meteorology and biomass

burning emissions from 1997 to 2001. CHIMERE uses

hourly primary emissions derived from the EMEP inventory

[Vestreng, 2003], which are available for the period under

study on a yearly basis, except during the 1991–1994

period where a linear interpolation between 1990 and

1995 emissions is performed. As EMEP emission annual

totals and their variation are given in 10 anthropogenic

activity sectors, decadal reactivity changes in emissions are

taken into account in a rough manner.

A five day spin-up is considered before the first

analysis day (1 April) for each of the 13 summertime

periods. First, a reference (CTRL) simulation is performed

using fixed (with year) boundary conditions and year to

year variations in emissions according to the EMEP inven-
tory. Second, in order to study the effect of assumed

emission changes during the considered period, a simulation

(FIXE) uses a fixed-year emission set, all other parameters

being equal. The year 2001 is arbitrarily selected for

reference. Finally, in order to evaluate the influence of

possible trends in boundary conditions, another simulation

(TREN) is carried out assuming a positive 0.4 ppb/year

O₃ trend added to the LMDz-INCA climatology, no addi-
tional ozone in 2001 being arbitrarily assumed. This value is

an upper limit of summer trends in baseline O₃ deduced

from observations at Mace Head by Simmonds et al. [2005]

and Carslaw et al. [2005] who found respectively +0.39 ±

0.25 and +0.25 ± 0.06 ppb/year. A 0.4 ppb/year trend

is arbitrarily applied at all model boundaries (side and top),

and regional emissions inside the domain vary with year as

in the CTRL experiment.

Figure 1 shows the skill of the model in simulating

the daily and interannual variability of summertime daily O₃

maxima. The simulated summertime ozone averages faith-

fully follow the observed ones. Mean daily maxima corre-

lations lie around 0.8 and their root mean square (RMS)

errors range from 8 to 12 ppb. During the 13-year period

there is a general decrease of the RMS, probably due to

emission decrease, as photochemistry is more sensitive to

meteorological variability, and thus to meteorological errors

as precursor emissions are higher. The CTRL and TREN

simulations, both based on year-varying emissions, have a

comparable best skill. The FIXE simulation has a clear

negative bias in the early nineties, resulting in a larger RMS

ero, a first sign of a real impact of emission reductions on

O₃ daily maxima.

3. Time Evolution of the 10th and 90th Percentiles

As noticed by Roemer et al. [2003], the observed
downward trend of O₃ is better captured in high percentiles

of the distribution (Figure 2a). During the study period, the

90th percentile decreases by about 10 ppb. A trend of

similar amplitude is obtained in the simulations with yearly

changing emissions (CTRL), and no trend is found in the

FIXE simulation. CHIMERE systematically underestimates

the 90th percentile by at least 5 ppb. This discrepancy is not

surprising as high percentiles are generally reached in

reality in concentrated structures having sizes smaller than

the model grid size (50km), like city or power plant plumes.

The simulated 90th percentile difference evolutions

(Figure 2b) display a clear, statistically significant positive

tendency of 0.65 ppb/year (p < 0.01) for the FIXE simula-
tion, while the slight negative tendencies (respectively

−0.18 ppb/year and −0.07 ppb/year) for the CTRL and

TREN simulations are not statistically significant (p > 0.1).

The evolution of observed lower percentiles (bottom

curves of Figure 2) does not exhibit any trend, and is not
sensitive to emission changes. The 10% percentile differences do not show either a significant tendency (respectively 0.03 ppb/year and 0.10 ppb/year). However the trend imposed in O\textsubscript{3} boundary conditions leads to an equivalent tendency in differences of the 10% percentile (0.40 ppb/year, p < 0.001). The model overestimates the O\textsubscript{3} daily maxima 10% percentile by about 3 ppb, which could be due to model deficiencies on physical processes.

[15] From Figure 2 we conclude that the highest daytime O\textsubscript{3} values are sensitive to emissions and insensitive to increasing ozone at boundary conditions. Most likely, high O\textsubscript{3} concentrations are obtained in episodic stagnant weather conditions where transport time is larger than deposition time. During these episodes, the O\textsubscript{3} formation results from local or regional photo-chemical production. In cloudy and windy conditions the situation is reversed: O\textsubscript{3} molecules largely come from outside Europe, which explains why the 10th percentile sensitivity to boundary conditions rather than to regional emissions. However we cannot reject the possibility that model deficiencies make its low percentiles too sensitive to boundary conditions at inland stations, explaining the discrepancies for the trended simulation.

[16] Of the three simulations CTRL is the one that best fits the observed 10th and 90th percentiles. Assuming no major model errors, one concludes that, (i) a uniform baseline O\textsubscript{3} increase of 0.4 ppb year\textsuperscript{-1} at the whole domain boundaries is not consistent with observations, and (ii) the EMEP inventory emission changes, during the 13 year period, are consistent with the O\textsubscript{3} observations over North-Western Europe, on average. Further results shown in this paper only use the CTRL simulation.

[17] So far we have considered trend statistics for all stations taken together. The tendencies of the biases in 90th percentiles, calculated for each station, exhibit an interesting regional pattern (Figure 3a). Over the UK a marked positive tendency of about 1 ppb/year is found in the simulation-minus-observation difference. Figures 3b–3c show that, over the UK stations, the model strongly underestimates

the percentile in the earlier part of the period (by about 5 – 15 ppb) while reasonable agreement is found in summer 2000 to 2002. Over Germany and central Europe, the agreement is rather found at the beginning of the period and a stronger underestimation is obtained at the end.

[18] Figures 3a–3c show that there are areas where the O\textsubscript{3} daily maxima behaviour is not consistent with the evolution of the EMEP emissions: the emission reduction would be larger than in the reported inventory for the UK and smaller over Germany and central Europe. Furthermore, the early nineties UK emissions would be underestimated in the inventory whereas central European emissions would be rather underestimated in late years.

[19] A similar analysis is carried out with nitrogen dioxide observations using daily averages instead of daily maxima (not shown) as given by Jonson et al. [2005]. For most of the NO\textsubscript{2} sites (located in Central Europe) a negative tendency is found in the model-minus-observation difference, indicating once more that the downward trend in reported EMEP emissions in central/northern Europe may be too large. Such regional differences are also consistent

Figure 2. (left) Time evolutions of the simulated and observed O\textsubscript{3} daily maxima 90th and 10th percentiles (considering all stations), in ppb. (right) Differences (simulation–observations) of the percentiles, with regression lines.

Figure 3. (a) 1990–2002 O\textsubscript{3} daily maxima 90th percentile bias (simulation minus observation) tendency at each station used in ug/m3/y. Stations where tendencies are significant at the p < =0.1 level are marked with a solid circle inside. (b) 90th percentile of O\textsubscript{3} daily maxima bias (simulation minus observation) averaged over the summers 1990 to1992 in ppb; (c) As Figure 3b but for an average over the summers 2000 to 2002. For this period many more EMEP sites have O\textsubscript{3} observations than for the early nineties.
with the results of Jonson et al. [2005] and the inverse modelling of emission study of Konovalov et al. [2005].

4. Discussion and Conclusions

[20] Using a tendency analysis of the simulated-minus-observed differences in daily O$_3$ maxima 90th percentiles we found that the decadal evolution of the emissions of the EMEP inventory is quantitatively consistent with the observations when all available European observations are taken together. This can be considered as a verification of the ensemble of reported national emission estimates made in the framework of the international Convention on Long-Range Transboundary Air Pollution (CLRTAP). However when considering individual stations we found that observed 90th percentiles have a larger decrease rate than simulated over the UK, while the reverse occurs over Germany and central Europe. This behaviour probably results from an underestimation of precursor emissions in the early nineties in the UK. By contrast over Germany and central Europe the downward emission trend is overestimated in our simulations, suggesting too low inventory emissions in the latest years.

[21] This regional contrast gives one confidence that there is no systematic deficiency of the model regarding the sensitivity to emissions. However the specific climate of the UK and its upwind geographical location call for further discussion of our results. This maritime climate makes the model there less sensitive to errors in surface physics than over continental Europe. Oversensitivity to emissions may thus be due to a lack of dispersion over land, such as too thin daytime boundary layers over land or too weak winds. Although we cannot reject this possibility, it is to be noticed that MM5 winds are nudged to the global ERA40 analyses, themselves strongly constrained by radiosoundings and surface observations. Percentile difference tendencies over Western maritime Europe could not either be biased by a possible upward trend in Atlantic lower-atmosphere O$_3$ concentrations as it would oppose the general O$_3$ decrease.

[22] On average, the emission reductions during the 1990–2002 time period led to an O$_3$ maxima decrease that are consistent with the observations made at several sites over Northwestern Europe, which is the main result of this article. The model underestimates the impact of emissions reductions over the UK and overestimates it over Germany and Central Europe, a hint that our above main result may not be valid on a country basis.

[23] Finally a side result of our study is that applying an artificial strong trend (0.4 ppb/year) all along European boundaries has no impact on strong episodic O$_3$ maxima, but leads to simulated low percentiles that are not consistent with observed ones.

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References


