

Interactive comment on “Representing ozone extremes in European megacities: the importance of resolution in a global chemistry climate model” by Z. S. Stock et al.

We would like to thank both reviewers for their comments. We provide a response to comments and details of any changes to the manuscript below.

Anonymous Referee # 1

General Comments

The paper addresses an interesting topic of the importance of model resolution on ozone on global, regional and local scales. This has been studied several times in the past, but the authors have chosen a very relevant angle of ozone extremes in megacities. The paper is well written and most of the conclusions seem sound. However, some clarifications are needed before the paper can be considered for publication. The conclusion that changes in boundary layer height due to model resolution are largely responsible for the observed differences between HR and CR is interesting, but requires some additional clarification. My concern is regarding the model setup, and more specifically, to what degree the impact of model resolution is a result of the free- running mode, which would make the meteorology in the two model configurations (HR and CR) deviate. Because of this, and because the model has only been applied at two different model resolutions, I am not convinced about the robustness of the model results.

- First of all we would like to clarify our position with regards to boundary layer height (BLH) and its impact on differences between HR and CR. We mention in the paper that emission resolution and chemical regime differences (and not BLH) are the major contributors to differences in HR and CR in the month of November (both at the regional and local scale). For July however, we would like to point out that ozone concentrations are generally higher and differences between HR and CR are much smaller compared to November (see e.g. Fig. 3 and Fig. 6). Therefore, although we identified BLH differences as potentially playing a role in the small ozone differences in July, this is only a small part of the story which helps us to explain the small differences between HR and CR in the summer months. In order to avoid confusion for the potential reader, we have decided to modify the abstract. We adjust page 27424 lines 23-26 to “We find the observed differences in model behaviour between CR and HR configurations to be largely caused by chemical differences during the winter and meteorological differences during the summer.”

We acknowledge the reviewer’s concerns about using only two model resolutions, and understand that, in order to show systematic convergence of the results, a series of intermediate model resolutions would be ideal. Previous studies have analysed in detail the effect of resolution on meteorology and climate and show that a resolution of $\sim 0.5^\circ$, similar to our HR simulations, is optimal, as it displays the largest improvements in meteorological fields and the least computational cost. (see for example Demory et al., Clim. Dyn. 2013. doi:10.1007/s00382-013-1924-4 and

references therein). Since we are interested in looking at the impact of resolution on ozone extremes in chemistry climate models we have focused on the two specific model resolutions for the following reason: CR is used in current state of the art chemistry climate models and HR is what (based on the above studies) we foresee being used for the same purpose in the near future. In this context, we believe our results are still useful, as they help understand the extent of the improvement in ozone representation when running the new generation of higher resolution chemistry climate models. A similar argument applies with regards to the use of free-running model integrations. As we are ultimately interested in addressing the ability of chemistry climate models to represent ozone and its extremes in a future climate, the use of 'nudging techniques' would not be appropriate (since this is not an option when performing future climate integrations). We discuss in more detail the impact of using a free-running versus nudged model configuration in our response to the specific comment (Page 27428, lines 13-15).

We also concede that the meteorology in the two model configurations is of importance for the results and therefore include supplementary plots and address the reviewers concerns in our response to the specific comment (Page 27428, lines 15-17). We thank the reviewer for requesting the supplementary information as it does help clarify the meteorology for the period and show that the differences between CR and HR over the months in question are small.

Specific comments

Page 27427, lines 20-22. Are the meteorology (UKCA) and chemistry (UM) modules fully coupled (i.e., do changes in chemistry feed back to the meteorology), and if so, do you expect that to have a significant impact on the results?

- In this study the model is run such that the meteorology does feedback to the chemistry but changes in chemistry do not feedback to the meteorology.

Page 27428, lines 13-15. Is free-running model configuration suitable for this type of model experiment? As one month is relatively long in terms of numerical weather prediction, I would expect that differences in meteorology could arise not only from differences in model resolution (and associated changes due to model time step and parameterization parameters as have been mentioned), but also from the fact that small initial deviations may lead to substantially different meteorology in the long run. In an extreme case you may get, near the end of the simulation month, a stable high pressure system over Europe in one resolution and low pressure activity in the other. If this is the case, it would not make sense to compare the effect of model resolution on ozone chemistry on local and regional scales, and comparison to observations would not be meaningful. Can you comment on how different the meteorology (e.g., location and magnitude of pressure fields) over Europe is between the two model configurations near the end of the simulation period? If they are substantially different, which I may expect, one way to avoid this problem is to re-run the two model configurations in nudged mode, as long as the nudging is not so strong that the impact of model resolution on meteorology will become too small. Another option is to re-initialize the two model

configurations from the same initial (nudged) field several times during each one-month simulation.

- Our assumption in this study, widely used in the analysis of climate data, is that whilst the two models will have different meteorological development in the course of the month, therefore making day-to-day comparison between the models and with observation meaningless, they should nevertheless produce a similar monthly 'climatology'. Results for a specific day are strongly dependent on the day's meteorological conditions, however, over the whole month the two models will sample many different meteorological conditions all consistent with the month in question. By focusing on the monthly mean data, differences in winds and circulation developing as part of the chaotic behaviour of the atmosphere are greatly reduced and differences between CR and HR are more likely arising from model configuration and resolution. We therefore believe that the free-running model configuration is suitable as long as the analysis focuses on the model behaviour over the whole month rather than for specific days. Furthermore, nudging would artificially remove some of the pitfalls of the coarse resolution and although helpful in some contexts it would not be suitable for this study.

Page 27428, lines 15-17. Due to the limited time period simulated, a brief description, and perhaps a plot or two (for instance in an Appendix or Supplementary) illustrating the meteorological conditions during the two months (July and November) is needed. Can you say something about how representative the chosen months are for summer and winter conditions? Do you expect the results to be substantially different if other time periods were chosen?

- In order to address differences in the meteorology between the two model runs we include a number of plots in supplementary material. Fig S1 and S2 show monthly mean sea level pressure (MSLP) for July and November respectively. Both CR and HR show good agreement with ERA interim data for 2005. The plots also show relatively small differences between HR and CR. Focusing onto the region of interest, Fig S3 and S4 show monthly mean 10m winds over Europe for July and November respectively. These highlight some small differences in the general circulation patterns over Northern Europe and the British Isles when comparing HR, CR and ERA data for 2005. The differences are more marked in November compared to July, but the general circulation pattern remains fairly similar. Fig. S3 and S4 additionally show 10m winds from 30 years of ERA Interim data for the summer (JJA) and winter (DJF) seasons. A similar comparison was performed for European surface temperature: this shows that July 2005 is slightly warmer compared to a climatological JJA season while Nov 2005 is significantly warmer than the climatological DJF season, particularly over Northern Europe. For the purpose of this study, July and November seem to have a similar MSLP and winds compared to the climatological mean summer and winter season. Despite the fact that temperature differences between November and the climatological winter season are significant (up to 5 degrees warmer over most of Europe), the direct effect of temperature on ozone chemistry is thought to be small. We note that on regional and local scales other resolution studies (e.g. Hodnebrog et al. 2011, Wild and Prather 2006, Yoshitomi et al. 2011) find similar model behaviour when studying resolution effects during other time periods. We therefore believe that, for the purpose of this study, November and July provide reasonable examples of two very different

chemical regimes, one driven by local emissions and the other driven by photochemistry.

Page 27429, line 21. This would be illustrated more clearly if two additional plots were included in Fig. 1, showing the absolute (or perhaps relative is better?) difference between HR and CR for each of July and November.

- We agree that plotting the differences between HR and CR on the global scale in Figure 1 could be interesting, although the regional focus of the paper makes us reluctant to do this. Figure 1 is intended to show the tropospheric ozone distribution is what we expect in both configurations and this would not be illustrated by a difference plot. Therefore we feel the discussion presented in section 3.1 is sufficient to make our point without the addition of extra plots.

Page 27429, lines 23-26. It would be interesting to know whether or not your results for global scale are in agreement with previous studies presenting similar experiments (e.g., Wild and Prather, 2006). Can you compare your results, in terms of impact of model resolution on global ozone burden, to previous findings, and if so, are your results broadly in agreement?

- It is difficult to directly compare our results to other studies due to differences in model setup and associated parameterisations. Wild and Prather 2006 run a chemical transport model at four different resolutions to consider changes to the global tropospheric ozone burden averaged over March and April 2001. They find a 3% difference in ozone burden between a T106 ($1.1^\circ \times 1.1^\circ$) and a T42 run ($2.8^\circ \times 2.8^\circ$). This fits with our conclusion that on a global scale the global ozone burden is broadly similar, however they find the lower ozone burden to be in the higher resolution run. Differences in convection parameterisations and in representing influx from the stratosphere are potential causes of the difference but it is hard to quantify such contributions with so many varying factors.

Page 27430, lines 8-13. Meteorological and chemical processes also occur on scales smaller than those investigated here. Do the authors expect that the scales considered here (~150 km to ~40 km) are the most important for ozone formation?

- We agree with the reviewer that smaller scales are important for meteorological and chemical processes. The scales chosen in this study were not chosen as the most important for ozone formation, but as a pragmatic approach to studying resolution in present day climate models. The CR is the standard resolution currently run in global chemistry climate models, with the HR representing the new resolution chemistry climate models aim to run at within a few years and certainly in the future.

Page 27434, line 22. Note that weekly and diurnal emission profiles are available for Europe through EMEP (see Simpson et al., 2012, ACP).

- We thank the reviewer for their suggestion and are aware of the availability of weekly and diurnal emission profiles. The model configurations in our study use a relatively simple representation of precursor emissions to be consistent with the

chemistry climate models currently run for longer timescales. We agree with the reviewer that introducing higher temporal resolution in emissions would make for interesting further study but feel this is beyond the scope of the paper.

Page 27439, line 9. The difference in boundary layer height between CR and HR is extremely large. Could this be a result of the model being run in free-running mode, and not only a result of the different model resolution? Would it be possible to run at additional resolution configurations, either coarser than CR or in between HR and CR (I suppose finer resolution than HR is not feasible for a global model), to see whether or not the model results converge when increasing the model resolution, and to get a feeling for how robust the results are?

- In our experience, the difference in boundary layer height between CR and HR is largely dependent on the tuning of the boundary layer parameterisation scheme (particularly in the values set for entrainment rates) and not so much dependent on free-running vs nudged model configurations. When we compare results from the nudged CR run (as described in Table 1) with our free running CR runs we find large improvement in MSLP and winds but very little change in BLH (of the order of 5-10%). On the other hand, we performed a test run using the HR parameterisation settings for CR and this was shown to increase BLH for CR in July by 50-70% in central Europe and the UK, bringing it in much closer agreement to the HR data. The improvement in BLH for November was much smaller (of the order of 10%).

Figure 1 caption. I would replace "Global mean tropospheric..." with "Global distribution of monthly mean tropospheric..."

- We accept the reviewer's suggestion and alter the caption for Figure 1 accordingly.