Response to Reviewers on “Projections of mid-century summer air-quality for North America: effects of changes in climate and precursor emission”, by J. Kelly, P. A. Makar, and D. A. Plummer
Draft 2, May 15, 2012

Reviewer 1:

The manuscript presents a comprehensive analysis of decadal regional air quality simulations over North America… The authors are thorough in placing their work in the context of earlier studies.

We thank the reviewer for the kind words on the paper, which was the result of a four year effort by the three authors.

I have two minor suggestions for the authors to consider when revising the paper:

1) While well-written and comprehensive, the 10 page introduction section feels too long. Shortening this section would improve the readability of the manuscript.

This was a common theme amongst all three reviewers, and the editor. Reading over the manuscript again after a sufficiently long period, we agree – the introduction is almost of sufficient length to be a review paper on the subject matter. We’ve greatly reduced the introduction in the current version to half the length of the original. We’ve also taken the liberty of making reference to the ACPD version of the paper in the revised introduction, for those readers who may wish to read this review of the state of the science in its entirety.

2) The authors should provide more justification for their choice to use the A2 scenario for greenhouse gas emission in the global and regional climate simulations but to use the RPC6 scenario rather than the A2 scenario for scaling the ozone and PM2.5 precursor emissions for the regional air quality simulations. In addition to providing this justification, it would also be useful to include a table comparing the greenhouse gas and precursor emissions between these two scenarios both globally and over North America

This arrangement in part was driven by the available driving global climatology available for dynamical downscaling by the regional climate model employed here at the time the project was underway (GCM simulations with RCP6 were unavailable for driving the RCM). However, we feel that this choice is unlikely to seriously deter from our conclusions.

The RCP scenarios have the significant advantage of being based on detailed, process-based projections, unlike the earlier A2 and A1B scenarios. This level of process detail makes the RCP scenarios particularly suitable for processing by the SMOKE emissions processing system. That is, the thousands of emissions

profiles and tens of thousands of emitting activities contained within the SMOKE databases allow for a good matching by process with the scaling factors set out by Fujino *et al* (2006) and Hijoka *et al* (2008) in their construction of RCP 6. The RCP emissions data thus lend themselves to a precise interpretation using the available current emissions data for North America.

The current generation of precursor projections contained in the RCPs are also more in line with the prevailing view that emissions control technology will continue to evolve and lead to a divergence between activity levels and precursor emissions. All of the RCP scenarios developed for AR5 show significant declines in ozone precursor emissions over the 21st century, though some developing countries show continued increases over the near-term. In addition, all future scenarios investigated by the recent Royal Society report on ozone projections (Ground level ozone in the 21st century: future trends, impacts and policy implications, Report 15/08, 2008) showed large decreases in precursor emissions over the course of the 21st century. These newer future projections are also more in line with emissions trends over the recent past for developed countries in North America and Europe.

The prevailing current view of future emission decreases is at odds with the earlier projections of precursor emissions found in the SRES scenarios. A large majority of the original SRES scenarios contained significant increases in ozone precursor emissions, even for developed countries, as the use of emissions control technology was very crudely included, if at all. The divergence in the projections of precursor emissions can be seen in the table of emissions projections given below and included in the article. While the use of the A2 scenario to project physical climate and RCP6 to project emissions is a mismatch in terms of the era of emissions projection, the end result is that the future emissions reflect the current prevailing view that precursor emissions, particularly in developed countries, will decrease in the future.

We also note that the range of future climate projections produced for the 4th Assessment Report do not diverge greatly at mid-century, despite the large differences in climate forcing between these scenarios by that year (cf. Figure 5 from IPCC 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA reproduced below). Global radiative forcing and mean temperatures from multi-model ensembles show relatively little spread in their predictions by 2050 for the different scenarios, with the largest changes occurring *after* this time. The climate system is thus relatively insensitive to the changes in GHG emissions until post-2050. However, the RCP 6 ozone and aerosol precursor emissions in 2020 are based on more detailed projections than either A1B or A2 (see Table 2 for a comparison, and recall that 2020 is our base year

for applying IPCC-based emissions factors), and are thus more suitable for AQ emissions scaling.

RCP 6 was thus chosen due its level of detail and similarities with the A1B GHG emissions, while the A2 climate scenario was chosen based on necessity and the knowledge that the GHG emission changes by the year 2050 have only a minimal effect on the resulting climate. We thus believe that our choice of A2 for climatology and RCP 6 for anthropogenic emissions is a reasonable compromise –definitely not perfect (as would be an RCP 6 climate and RCP 6 precursor emissions setup), but unlikely to significantly deter from our results.

This discussion and the two tables have been added to the Scenarios section of the revised manuscript, given below.

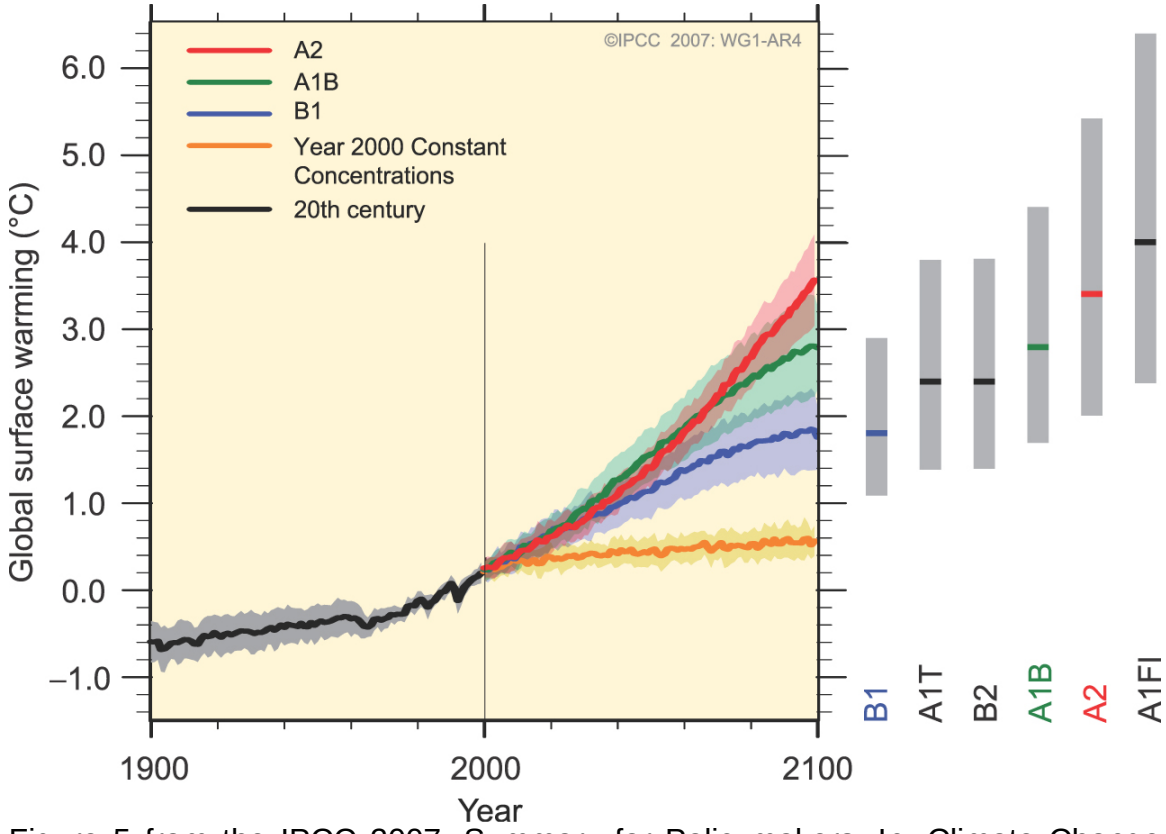

Figure 5 from the IPCC 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

The text added to the manuscript: "The use of current anthropogenic precursor emissions with an SRES A2 future climate (or RCP 6 future anthropogenic precursor emissions in conjunction with an SRES A2 future climate) raises the

issue of inconsistency between the climate and air-quality emissions. To be very specific, the future scenarios employed here make use of A2 greenhouse gas emissions, and present-day (or RCP 6) emissions of *other* anthropogenic pollutants. Both future scenarios thus diverge from IPCC projections. However, the use of current anthropogenic precursor emissions in conjunction with future climate is the only logical means to determine the impact of climate change alone on air-quality for the A2 future climate. This approach has been used extensively in the literature in the past. By the same token, making use of RCP 6 smog precursor emissions and A2 future climate allow the combined effects of emission changes and climate change to be assessed. The RCP 6 smog precursor emissions were chosen due to their level of detail in comparison to the earlier SRES projections (making them ideally suited to detailed scaling of emissions with the SMOKE emissions processing system). We also chose to scale future emissions following RCP 6 because this projection reflects the current view that precursor emissions in developed countries will continue to decrease in the future. We note that all of the RCPs show continued decreases in precursor emissions for developed countries (OECD90) throughout the 21st century, despite large differences in GHG emissions. As can been seen below in Table 2, the use of the original SRES A2 projections to derive emission changes from 2020 to 2050 would have resulted in very different future emissions. The A2 climate scenario was chosen out of necessity (GCM and RCM runs being available for this scenario and not for A1B or RCP 6). However, global radiative forcing and mean temperatures from multi-model ensembles show relatively little spread in their predictions by 2050 for the different scenarios, with the largest changes occurring *after* this time.Our "RCP 6" scenario here should thus be taken as an indication of how RCP 6 *smog precursor* emissions would impact air-quality under an A2 climate, but not how RCP 6 *greenhouse gas* emissions would affect climate."

Table 2: Projected O3 and Aerosol precursor emissions for 2020 and 2050 for the OECD group of countries from IPCC emission scenarios. SRES data is taken from IPCC (2000) and RCP data is taken from RCP Database (2012).

Year		2000	A2		RCP6	
Emitted Species	Units	SRES-A2	2020	2050	2020	2050
SO_X total	Tg-S/yr	17	8.7	9.8	11	4.6
CO	Tg-CO/yr	161	175	141	153	99
NMVOCs	Tg/yr	36	44	42	33	25
NO_x	Tg-N/yr	12	16	16	9.0	4.5

References to be added

Intergovernmental Panel on Climate Change (IPCC) (2000), Special Report on Emissions Scenarios, edited by N. Nacenovic and R. Swart, 612 pp., Cambridge Univ. Press, New York.

RCP Database, http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=compare, accessed on May 18, 2012.

Reviewer 2:

This study examines the impacts of future climate change and emission change on air quality for North America. Extensive analysis and simulation have been carried out in this study. I think this manuscript could contribute to our understanding on the evolution of atmospheric composition but it could be further improved with some revisions.

We thank the reviewer for the suggestions; our responses to these are given below:

(1). Some sections, especially the introduction is unnecessarily long; some background information is not closely related to this study.
Please see our response to Reviewer 1, below: we agree, and have shortened the introduction considerably, and made reference to the ACPD version for those wishing a more detailed review.

(2). p3879, L12 - Is it true that the global model provides not only boundary condition but also initial conditions to the regional climate model?
In our case, the global model does in fact provide initial conditions as noted, but these correspond to the start of the initial RCM run in 1958; the initial conditions have long since disappeared by the time the RCM runs reach the start date of the simulations performed here (recall that the RCM had additional output fields added for our study, and we started from restart files from the original RCM run). The GCM continues to affect meteorological variables in the interior of the RCM through spectral nudgling (von Storch, H., H. Langenberg, and F. Feser, 2000: A spectral nudging technique for dynamical downscaling purposes. Mon. Wea. Rev., 128, 3664–3673). The given passage in the text appeared in the original Introduction, which has been greatly reduced in size in the revised version; the sentence was removed in the process of reducing the size of the Introduction.

(3). p3887-3890 - How the chemical boundary conditions for the regional air quality model is obtained/handled?

This is described on page 3891 of the original manuscript; the last paragraph of section 2.

(4). p3900, L21-23: the model results show decreased OH with higher biogenic HC emissions; however, some studies (e.g. Lelieveld et al. 2008) have shown that biogenic HC emissions don't actually decrease OH levels - please provide some explanation here, such as the chemical scheme used in the model.

Lelieveld, et al., Atmospheric oxidation capacity sustained by a tropical forest, Nature,452, 737–740, 2008.

The chemical scheme was described on page 3890, line 10, the ADOM-II mechanism of Stockwell and Lurmann, 1989. A reaction of between CH3C(O)O2 and HO2 is included, but the products are assumed to be methyl peroxide and formaldehyde; the OH yield noted in the recent lab studies referenced in Lelieveld et al is not included in our mechanism. The reference has been added to the paper in the discussion on Figure 10. In addition, we have modified the colour scale for Figure 10b to have equal positive and negative magnitudes at the endpoints of the range: Even without the extra OH source, its more accurate to say that he CC scenario also results in OH *increases* relative to the current time, in many locations, and particularly in North American cities. The statement in our original manuscript "Figure 10b shows that the CC values of OH decrease relative to the Current simulation over much of the domain, while increasing in the cities and over the prairie regions of Canada and the US," has been modified to "Figure 10b shows that the CC values of OH decrease relative to the Current simulation over much of the eastern part of the domain, while increasing in the cities and over the prairie regions of Canada and the US and parts of the Rockies in the US," and then the revised paragraph now ends with "Lelieveld et al (2008) also note that under low NOx conditions and in regions of high biogenic emissions (the Amazon), significant OH recycling from HO2 reactions with carbonyl radicals may take place. This process is missing from the mechanism used here. The magnitude of the OH decreases noted here should be considered upper limits. "

(5). p3901, L1-3: it looks the increases in O3 and PM is not the case for everywhere; some regions actually show decreases in O3 or PM with climate change (at least based on figures 7 & 8) - please clarify on this.

This is another case of the original colour scale chosen for the CC case (7b, 8b) being misleading, since the original scale had smaller magnitude minimum values than maximum values. The eye's expectation is that blue colours mean negative, and red mean positive, despite the numbers on the scale itself which show otherwise. In the revised figures, we've used colour contours which have equal magnitude minimum and maximum on the scale – this makes it easier to see that most of North America shows positive O_3 changes in Figure 7b (CC). The same is true of Figure 8b.*(6).*

(6) P3901, L5: how the "overall reactivity" is defined? Does that simply refer to the average atmospheric OH concentration?

Yes – the sentence has been modified to state "the average OH concentration of the atmosphere would decrease (the decreases shown here may be an upper limit; cf. Lelieveld *et al.,* 2008) " rather than "the overall reactivity of the atmosphere would decrease."

(7). p3902, L26-27: "health benefits associated with the associated reduction in smog precursors would be immediate" Does not read well; please considering rewriting this part.
The sentence has been changed to: "The timescale of impacts is worth considering in this regard: the effects of reductions of greenhouse gas emissions on climate change may require decades following enactment before a beneficial impact may be seen. However, if those greenhouse gas emissions reductions are accompanied by reductions in smog precursor emissions, significant health benefits would occur. The latter would take place essentially immediately.

(8). p3877, L27 "(5) decreased cloudiness" - is this a general/robust feature of climate change?
The start of this sentence has been changed from "Climate change impacts on air-quality include" to "Climate change impacts on air-quality noted in the literature include". The sentence is intended as an overview of what has appeared in the literature, but is not intended as a rating of robustness of any of the features.

(9). I'm not sure why the authors would choose different/inconsistent scenarios for future climate (A2) and emissions (RCP) - I would suggest using consistent scenarios if possible.

Please see our response to Reviewer 1's second question. Using consistent scenarios is of course preferable from the standpoint of evaluating, e.g. the net effect of the IPCC's RCP 6). However, by using incremental changes, we are able to separate out climate change versus emissions change effects. Also, most of the climate simulations to date indicate that the IPCC scenario climates do not significantly diverge until after 2050 – we feel that our next best choice of a mixed scenario should not alter our findings to a significant degree. We do however note that this is a limitation on our analysis.

Reviewer 3:
Overall, this is a very well written paper which should be published after considering the following comments:
1) Although biogenic emissions are allowed to change with the future climate, there is no discussion of how those emissions actually change between the current and future scenarios. The authors may want to consider including changes in BVOC emissions in Figure 2 or including an additional figure of a BVOC emissions map for the current decade and a delta from the future decade.

The biogenic emissions are calculated on-line in the AURAMS model, but unfortunately are not saved as one of AURAMS's standard outputs (i.e. regenerating emissions would mean rerunning the scenarios, which would be a significant task). Each of the future scenarios will have different biogenic VOC

concentrations, due to the change in anthropogenic emissions. In order to show the impact of climate change on the biogenic concentrations, we have included the mean isoprene concentration at the surface and the change in mean isoprene for the CE scenario, as additional panels in the revised Figure 2.

2) On p. 3894, lines 1-5, the authors indicate that the effects of changing CO2 concentrations on BVOC emissions are not considered. Given that increasing atmospheric CO2 concentrations have the potential to offset any increase in BVOC emissions due to increasing temperatures, the authors should include a brief discussion of how their results may change if BVOC emissions were suppressed by rising CO2 concentrations.
We have included the following into the text: "It should be noted that with increased CO_2 concentrations, the size of the opening of plant stomata required for CO_2 uptake may be smaller than under current environments. This may potentially reduce biogenic emissions fluxes under future climate conditions below those described here."

3) Given the importance of the meteorological input for this analysis, it is important to provide some documentation of the performance of the meteorological simulations. Even something as simple as a comparison of modeled to observed temperature distributions would give the reader some confidence that the meteorological fields accurately represent observed patterns.
This work has been carried out in a previous paper by one of us (Plummer). The revised manuscript's section on Model Predictions: Meteorological Changes, now starts with the following sentence: "The reader is referred to Plummer et al. (2006) for an in-depth analysis and evaluation of the RCM's meteorological predictions."

4) On p. 3899, lines 12-15, the authors mention that changes in wildfire emissions are not considered. Some mention of wildfire emissions should also be made in Section 3 (Scenarios) when the emissions inventory is discussed. The manuscript would also benefit from a brief discussion of how the results may change as a result of changes in wildfire emissions.

The effect of wildfires has been noted in the Scenarios section as requested, with the following addition: "Wildfire emissions have not been included in either current emissions or future projections. Wildfires may have a very substantial impact on air-quality over large regions. The magnitude of changes in wildfire emissions due to climate change is complex, due to uncertainties within the emissions algorithms themselves, as well as in projecting forest cover and fire-inducing conditions in the future. Nevertheless, the absence of wildfire emissions is a potential confounding factor on the results presented here."

5) The figures with multiple panels would be more readable if each panel were labeled: (a), (b), (c), etc

We'll do this if permitted by the type-setters of ACP. One of us (Makar) has had the experience in the past where the letters as described were submitted for publication, and these were later removed at the request of the journal's typesetters.

6) On p. 3899, line 1, the authors comment that a reduction in ice cover (and the subsequent increase in sea salt emissions) is partially responsible for the increase in PM2.5 over Hudson's Bay. Beyond ice cover, what other land use/land cover categories were allowed to change between the current and future decades?

None. The change in sea-ice cover is a response to the change in climate, derived from the global coupled ocean-atmosphere model since sea-ice is a prognostic variable., Beyond that, fixed land use/land cover fields are assumed for other fields such as vegetation in both the RCM and CTM.

7) Given that this work produced such a long and extensive set of model simulations, it would be interesting to see a discussion and analysis of the inter-annual variability of the results (but this is probably better left to a follow up paper).
Thanks for the suggestion. One thing that we have done is compare the statistics for current conditions against observations for different averaging times. We found that convergence in the statistics only started to converge by the 8th year: interannual variability requires 10 year simulations to reduce these short-term variations.

8) The paper clearly isolates individual effects such as climate change and future emissions and dedicates quite a bit of time explaining the general effects on PM2.5 and O3 concentrations (e.g. changes in atmospheric reactivity), however, the paper does not make the connection between those general effects and the regional changes presented. For example, the author notes, but does not explain why the Air Quality Index improves in Houston, Phoenix, Dallas etc (page 3902, Line 3).

The text has been modified to explain the Air-Quality Health Index results, with Los Angeles as an example:" The cause of the impacts varies from city to city. For example, Los Angeles experiences increases in O_3 in the future scenarios, but the decreases in NO_x and $PM_{2.5}$ in that location are sufficient to result in net AQHI decreases. This illustrates the importance of using a multi-pollutant health indicator such as the AQHI in order to determine the overall impact of emissions changes on mortality.."

9) Page 3893. Line 6. The current RCP 6 total emissions are compared.... to what? evidently to the Current Decade but this is not clearly explained.

The sentence was intended to indicate a comparison between current and RCP 6 emissions, and has been modified to make this more clear.

10) In general, the introduction could be shortened.

Done. Shortened to ½ the original size, see response to Reviewer 1.