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Interactive Comment

Interactive comment on "Impact of climate change on photochemical air pollution in southern California" *by* D. E. Millstein and R. A. Harley

D. E. Millstein and R. A. Harley

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We thank the reviewers for their comments and suggestions on this manuscript. Below we provide responses to all comments, and indicate how the manuscript has been revised.

Response to Referee #2:

Comment 1: Provide information on meteorological model performance.

Reply: A comprehensive evaluation of the meteorological model outputs used in this study can be found in Appendix V to the 2007 Air Quality Management Plan for the Los Angeles area (see pages V-4-23 to V-4-29 of SCAQMD, 2007). A summary of the evaluation has been added to our revised manuscript, and we have also added a reference (SCAQMD, 2007) for readers interested in further details. To summarize, when compared to observations, the meteorological model predicted wind speeds/direction, temperature, and humidity well. Over the 14-19 July 2005 simulation period, small biases were found for wind speed (ranging from -0.03 to +0.23 m/s depending on the day). Observed temperatures were generally under-predicted, but the biases were not large. Most days showed less than 0.5°C negative bias compared to observations; the largest average underprediction (1.2°C) of observed temperatures was for July 19th. The largest bias of humidity was -5% also for July 19th.

Comment 2: Specify up front the temporal resolution of the climate modeling results used as input.

Reply: Temperature changes from Snyder et al. (2002) are monthly average values and are applied uniformly across all days and hours unless otherwise specified. This information has been added to the revised manuscript.

Comment 3: Indicate the averaging period associated with the quoted range of predicted temperature increases.

Reply: The averaging range for the predicted temperature increase was 5 years. This information was added to the manuscript, further details can be found in Snyder et al. (2002).

Comment 4: Explain process of making perturbations to air quality model more precisely.

Reply: Temperature changes from each of the larger 40x40 km grid cells in the regional climate model output from Snyder et al. (2002) were assigned to 64 of the smaller 5x5 km grid cells. Text was added to clarify this point as well as further describe the different methods for each perturbation.

Comment 5: Explain more precisely how anthropogenic emissions were changed in the future year emissions scenario. It would be helpful to include a summary table.

Reply: A new Table 2 showing current and future emissions by county for NOx, AVOC

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and BVOC has been added to the revised manuscript. In addition the discussion of the future emissions scenario has been expanded to describe the methods and assumptions in greater detail (see section 2).

Comment 6: Explain response of peak ozone to altered humidity. Why does it first increase then go negative as you move from Anaheim to Palm Springs?

Reply: The response of peak ozone to altered humidity is sensitive to whether an area is NOx limited or saturated. In NOx saturated areas increased processing of NOx serves to increase ozone levels and the opposite effect is seen in NOx limited regions. Discussion of this effect has been added to section 3.2.

Comment 7: Discuss how study results are limited by omission of other prospective changes in meteorology that may accompany the temperature and humidity changes.

Reply: Our assessment focuses on how the severity of air pollution problems in southern California could increase starting from baseline conditions where ozone levels were already high. Unlike other parts of the country where high-ozone events occur infrequently, most summer days in California are conducive to ozone formation. We acknowledge in the revised manuscript (see sections 1 and 4) that there could be other important effects of climate change on meteorology and air quality that we have not modeled, including a longer high-ozone season, changes in other meteorological variables such as flow patterns and planetary boundary layer height, changes to other pollutants such as particulate matter, and changes in the frequency and/or extent of forest fires.

Response to Referee #3:

Comment 1: Provide additional information on future emission scenario. Consider whether smaller changes in emissions would lead to different ozone response.

This has been done. See referee 2, comment 5 for further details.

Comment 2: The referee points out that future emissions will not be reduced in a step

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change. This raises questions as to what could happen under different future emissions scenarios.

Reply: To address this issue, a sensitivity analysis of the combined future emission and climate scenario was run to examine the response of ozone to percentage changes in NOx and VOC emissions. Additional text was added to the manuscript at the end of section 3.4 (Combined Effects) to describe the results and implications of this sensitivity analysis. The sensitivity analysis reveals that most of the urban areas are NOx saturated including Los Angeles, Pomona and Riverside. This indicates that smaller changes to emissions would have the same directional effects as the full future scenario, and that reducing emissions to a create a NOx limited region would require much stronger controls than discussed in this research. A new Supplemental Figure 3 was added showing these results. By defining geographic regions that are NOx saturated this sensitivity analysis provides additional insight into the response of ozone to adjustments/uncertainties in the future emissions scenario.

Specific Comments

Comment 3: Would irrigation also increase atmospheric humidity and impact ozone?

Reply: Yes, this is a good point. Some work has shown increases in relative humidity with irrigation in other regions of the U.S. (Mahmood et al., 2008), but the focus of research concerning California has been on irrigation effects on temperature changes. The manuscript has been edited to include mention of potential humidity effects as an important area for further study. Additionally, the discussion of a diurnal pattern in future temperature increases has been expanded to include recent work concerning sea-breeze effects by Lebassi et al. (2009).

Comment 4: is the future emission scenario business as usual for CO2 only? This is ambiguous as you have just stated that emission factors for other anthropogenic gases have been reduced by 80%.

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Reply: The future emissions scenario for 2050 addresses local emissions within California and includes reductions in emissions that are likely to occur due to ongoing efforts to control traditional air pollutants such as CO, NOx and VOC. Growth in population and pollution-causing activity is also factored in, with separate growth factors for each county within the study region. Note that the future scenario considered here does not reflect recent commitments to reduce greenhouse gas emissions back to 1990 levels by 2020 or to lower than 1990 levels by 2050. The term "business as usual" was removed to avoid confusion.

Comment 5: The discussion of future boundary conditions is confusing. Specifically, why was ozone increased 30% rather than 15%?

Reply: By design, the specification of future boundary conditions was consistent with previous work by Steiner et al., (2006). The increases in CO and methane were based on A1B scenario predictions of increases in global emissions of these pollutants between 2000 and 2050. Increases in ozone concentrations in Pacific Ocean inflow were specified to evaluate the concern of increased long-range transport of ozone and precursors due to rapid growth in Asia. Parrish et al., (2004; 2009), and Jaffe et al., (2003) describe large observed increases in ozone levels in Pacific Ocean inflow to the western United States. Section 2 of the revised manuscript has been edited to clarify this issue.

Comment 6: does SAPRC99 include the reaction of biogenic VOC with ozone?

Reply: Yes, the chemical mechanism used in this study does include reactions of ozone with biogenic VOC (see page 56 et seq of the SAPRC99 documentation by Carter, 2000). In our modeling results we saw few instances of lower ozone concentrations in response to the increased biogenic VOC emissions. Instead, the added VOC tended to increase ozone concentrations in most locations.

Comment 7: from Supplemental Figure 2, it looks like the response to increased water is actually negative in most of the domain.

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Reply: Yes, but most of the ozone decreases are in sparsely populated desert areas. In contrast, the areas where ozone increases in response to increased water vapor are often urban and densely populated. An expanded discussion of humidity effects has been included in the manuscript in section 3.2.

Comment 8: Are the increases in ozone in coastal areas due to changes in precursors (CH_4 and CO) or ozone in the inflow?

Reply: It is the higher inflow of ozone itself that leads, both directly and through photolysis and HOx radical production, to higher ozone levels along the coast. The changes to the inflow of CO and CH_4 are less important as they are less reactive than ozone.

Comment 9: Referring to Supplemental Figure 3; given that the model struggles to partition odd oxygen (Ox) appropriately at night, is it a robust result that ozone concentrations increase substantially? Reviewer is concerned that the increases in ozone may be due to lower NOx emissions and less ozone titration at night.

Reply: Of the five sites discussed in Supplemental Figure 3, Anaheim and to a lesser extent Pomona have ozone results that contain larger errors at night than day. Still, this figure provides valuable information over time scales not discussed elsewhere. It shows future ozone concentrations at Anaheim, Los Angeles, and Pomona are consistently higher, with the exception of weekend days, than in the base case scenario. Ozone concentrations at Palm Springs decrease in the future case, while future concentrations at Riverside increase and decrease relative to the base case depending on conditions at the time of comparison. The manuscript has been changed to describe the nighttime uncertainty.

Comment 10: Reviewer suggests changing the scale of Supplemental Figure 4 so changes are easier to see. Reviewer also asks why only temperature was changed for this comparison.

Reply: We decided maintain the 20 ppb scale to facilitate comparison with the previous

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Supplemental Figure 3 showing effects of constant temperature increases and other changes on ozone. Temperature was the only value changed for this comparison however; Supplemental Figure 5 shows effects of biogenic emission changes. Humidity changes were not examined and were assumed to be small as increasing humidity at night would not lead to greater photolysis of H2O.

Comment 11: If daytime temperature increases are being suppressed by increased irrigation, and presumably higher latent heat flux, wouldn't this be associated with an increase in relative and absolute humidity during the day? Should this also be included?

Reply: The study design used here is to consider each perturbation individually, then in concert with other related changes. We agree with the referee that there may be further interactions between temperature and humidity changes. For example, humidity changes resulting from changes in irrigation is an area of ongoing research. These issues are now mentioned in section 3.5 of the revised manuscript.

Technical Comments

The technical comments from Referee #3 have all been addressed in the revised manuscript.

Response to Referee #4:

Comment 1: It would be informative to have a broader discussion of how other potential climate drivers, such as frequency of stagnation events might impact air quality in southern California.

Reply: This has been done. See referee #2, comment 7, and reply.

Comment 2: It would be useful to evaluate ozone increases based on an 8-h timeframe that is more closely linked to adverse health effects and U.S. EPA air quality standards.

Reply: This has been done. A supplemental table has been added to show ozone

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changes over the 8-hour peak time of day. Changes in 8-hour ozone averages are similar to changes in the 1-hour peak values. Results of the 8-hour and comparison to 1-hour results have been added to the revised manuscript in Section 3.4.

Comment 3: the paper includes not only isoprene, but also methyl-butenol and terpenes for biogenic emissions. Most papers consider only isoprene, so this is an important strength of the work.

Reply: We agree.

Comment 4: Additional discussion of why the response of peak ozone to increased humidity is mostly positive would be valuable.

Reply: Additional discussion of humidity effects on ozone levels has been included. See referee #2, comment 6, and reply.

Comment 5: With respect to Table 2, why does the effect of inflow BC change at the various sites?

Reply: This result is expected. The various sites are located progressively further inland, so the relative importance of inflow BC versus local emissions from within the LA basin varies by site. In particular, the within-basin emissions become a more dominant contributor to ozone concentrations further downwind for which there are longer transport/reaction times and where ambient temperatures are higher.

Comment 6: Also with respect to Table 2, why do the combined effects not equal the sum of the individual effects?

Reply: This result is also to be expected. The combined effects of multiple perturbations acting together were calculated using the air quality model, not by summing the individual effects. Ozone formation is non-linear, such that individual perturbations may interact in ways that lead to offsetting or magnifying effects on ozone.

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