

***Interactive comment on* “Quantifying population exposure to airborne particulate matter during extreme events in California due to climate change” by A. Mahmud et al.**

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R2C1: In section 1.1 some of the descriptions should be improved for the readers who are not familiar with the models described by the authors. In particular a better description of the BC and IC (page 5885 lines 28–29, 5886 lines 1-2) should be available in the text and not simply refer to a previous publication of the authors. A short description and an explanation of the term "source oriented" photochemical model should be provided (page 5586). How the model describes aerosol chemical composition and size distribution?

Response: BC and IC will be elaborated in the method section on page 7 of the revised

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manuscript.

Seasonally variable initial conditions (ICs) and boundary conditions (BCs) of gas-phase and particle-phase species were specified for the air quality model calculations. A total of 25 model species including ozone, oxides of nitrogen (NO_x), peroxy acetyl nitrate (PAN), isoprene, elemental carbon (EC), nitrate, sulfate and ammonium ions were assigned initial and boundary concentrations for the current work. Seasonal variations in background concentrations were also taken into account for the boundary conditions. For example, the boundary condition for ozone along the Pacific coast was set to 35 ppb for fall and winter and 40 ppb for spring and summer seasons. A detailed summary of the ICs and BCs utilized in the current study can be found in Mahmud et al. (2010).

A description of the source-oriented modeling will be added on Page 8 line 161.

In the source-oriented model, pollutants emitted from different sources are tracked separately through all major aerosol processes including emissions, transport, deposition, gas-phase reactions, gas-particle conversion and coagulation. For the current study, secondary PM components (nitrate, sulfate, and ammonium) were tracked as a full external mixture while primary PM components were tracked using inert internal tracers. The inert tracer technique allows the model to efficiently preserve source information throughout the aerosol evolution processes, but it does not provide the capability to predict how source-oriented particles will influence local meteorology.

R2C2: In Section 1.2 PM_{2.5} annual average concentrations simulated by the model over California are presented without showing any comparison to measurements. An evaluation of the model in reproducing PM_{2.5} concentrations and/or some of its components (sulfate, organic carbon, ..) should be presented or cited and summarized if done in previous publications. It should be also shown if the simulation, which covers only the 40% of each year, is able to represent the observed seasonal and inter-annual variability. For example it is claimed at page 5889, line 20, but the authors did not show or cite any previous paper to demonstrate this.

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Response: The comparison of the model results to measurements in current climate was performed in a previous study (Mahmud et al., 2010). A brief discussion of these results and a reference to the previous study will be added to the result section on page 7 line 248.

The performance of the UCD/CIT model in predicting quality over climatically relevant time periods was evaluated comprehensively by Mahmud et al. (2010). Predicted annual average total and speciated mass concentrations of fine particulate matter (PM_{2.5}) were compared with measured concentrations at six representative sites in heavily populated air basins in California for the present-day (2000-06) period. The air quality model under-estimated annual average PM_{2.5} mass concentrations by ~4-39% due to over-predictions in downscaled wind speed. Measured annual average PM_{2.5} total mass concentrations were $\sim 20 \pm 2 \mu\text{g m}^{-3}$ in the SoCAB and SJV compared to predicted concentrations of $\sim 13-18 \mu\text{g m}^{-3}$. The model also under-predicted components of PM mass such as elemental carbon, organic carbon, nitrate and sulfate due to these same wind speed over predictions. The bias in downscaled wind speed is assumed to be constant between present and future climate periods.

R2C3: The effects of climate change on annual mean and extreme PM_{2.5} concentrations are discussed without a description of the changes in climate which may affect the chemical composition, accumulation, removal of aerosols in the atmosphere. The authors in Section 2 generally refer to increasing stagnation and increased annual averaged wind speeds. A description of the changes in the climate conditions should be better addressed, in particular in relation to the processes which are determining aerosol concentrations and secondary aerosol formation (for example, sulfate production from SO₂ oxidation).

Response: The changes in climate that lead to changes in PM_{2.5} concentrations will be discussed in the revised manuscript.

Minor comments: Page 5882, in the abstract, when the term 'extreme event' is used, it

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is not always clear if it is related to extreme pollution events or extreme meteorological conditions which determine high pollution events.

Response: The term extreme event is used to describe extreme air pollution events, which are almost always caused by some form of extreme meteorological event involving high stagnation.

Page 5883, line 10, Samet et al., 200; Correct reference year. Response: Referencing will be fixed.

Page 5883, line 16, "2.3 times higher than the NAAQS". Maybe would be good to insert the NAAQS limit here in parenthesis. Response: The NAAQS limit for 24-hr average PM_{2.5} will be provided in parenthesis.

Page 5883, line 20, maybe an error here 'trapping leading' Response: The sentence will be corrected in the revised manuscript.

Page 5884, lines 16-23, the authors claim here and also later on page 5889 that the present climate simulations (1000 days for 7 years) is able to capture the inter-annual variability. But they don't show if the PM inter-annual variability is well represented by the model. See also comment 2).

Response: The inter-annual variability for PM_{2.5} has previously been shown in Figure 5 by Mahmud et al. (2010) for present and future climate periods. The relative standard deviations (standard deviation divided by the mean) are 2%,3%, 6% and 9% for the present (2000–2006), and 5%, 6%, 8% and 7% for the future (2047–2053) periods at Riverside, central Los Angeles, Bakersfield, and Fresno, respectively. The value of 9% relative standard deviation for Fresno in current climate compares favorably to the measured value of 10.5% relative standard deviation for the San Joaquin Valley between the years 2000-07 (statistics calculated from monitoring data available at arb.ca.gov).

Page 5885, line 4, PCM data ... were dynamically downscaled ... Response: This will

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be changed in the updated manuscript.

Page 5885, line 6-7, the global simulation with PCM was driven by nudging the present climate meteorology or only SSTs were prescribed?

Response: The details of the PCM data down-scaling technique have been provided by Zhao et al. (2011a). WRF simulations of the free atmosphere (above the PBL) were nudged for wind (u,v,w), humidity, and temperature. Sea surface temperatures were also nudged. Other variables inside the PBL were not nudged.

Page 5885, line 12, is not very clear why the authors say "unbiased sample".

Response: The authors intend to say that any choice of days with a sampling pattern within 7-year period described in the text would have generated the same level of variance in the sample.

Page 5885, line 12, in the previous sentence they say 153 (17*9) days per year, which is a total of 1071 days, while here they say only 1008 days.

Response: The PCM-WRF downscaled output has always been saved at UTC time. Because of the 8 hour time difference between UTC and PST, an additional day in each episode was required to match a complete 24-hour data in the last day of the episode. This is why the meteorological downscaling was carried out for a total 1071 days in each period of 7-years, but the air quality model was run for a total of 1008 days for the same period of time.

Page 5885, line 16-17, the vertical resolution of the AQ model is rather coarse, only 10 levels from surface up to 5 km. In such setting, the authors should show how well the model is able to reproduce observed PM and/or gas (e.g SO₂ and other aerosol precursors) concentrations.

Response: The performance of the UCD-CIT model has been documented by Mahmud et al. (2010). The climate-air quality modeling system successfully predicted the spatial pattern of present climate PM_{2.5} concentrations in California but the abso-

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lute magnitude of the annual average PM_{2.5} concentrations were under-predicted by 4–39% in the major air basins. The majority of this under-prediction was caused by excess ventilation predicted by PCM-WRF that should be present to the same degree in the current and future time periods so that the net bias introduced into the comparison is minimized.

Page 5885, lines 18-25. When possible the authors should indicate a reference for the emission inventory and for the EMFAC and BEIGIS models.

Response: The references for EMFAC and BEIGIS models will be incorporated in the updated manuscript.

Page 5885, lines 26-27. I think that would be helpful to shortly describe here the IC and BC conditions, even if a previous work is cited. When simulating a period of 17 days, a spin-up period was performed?

Response: The discussion of ICs/BCs will be elaborated in the text. A total of 25 model species including ozone, oxides of nitrogen (NO_x), peroxy acetyl nitrate (PAN), isoprene, elemental carbon (EC), nitrate, sulfate and ammonium ions were assigned initial and boundary concentrations for the current work. Seasonal variations in background concentrations were also taken into account for the boundary conditions. For example, the boundary condition for ozone along the Pacific coast was set to 35 ppb for fall and winter and 40 ppb for spring and summer seasons.

Yes, the PCM-WRF downscaling involved a spin-up of 3-days for each period, where output from model spin-up was not saved during the project.

Page 5886, lines 3-13. The AQ model should be described with more details on the aerosol description: Chemical composition, size distribution, internally -externally mixtures? What does it mean exactly "source-oriented" model? I think this is important also to understand for example Table 1, where concentrations of some aerosol species are provided together with aerosols from specific emission sources.

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Response: The description of the air quality model will be elaborated in the updated manuscript. In the source-oriented model, pollutants emitted from different sources are tracked separately through all major aerosol processes including emissions, transport, deposition, gas-phase reactions, gas-particle conversion and coagulation. For the current study, secondary PM components (nitrate, sulfate, and ammonium) were tracked explicitly as separate variables in the model calculation while primary PM components were tracked using inert internal tracers. The inert tracer technique allows the model to efficiently preserve source information throughout the aerosol evolution processes, but it does not provide the capability to predict how source-oriented particles will influence local meteorology.

Page 5886, line 23, is the population homogeneously distributed within the single basins, or is it distributed according to the main urban areas?

Response: The 2000 census population data were extracted in a 8-km resolution gridded domain to match the air quality modeling domain encompassing all of California in the current study. The air basin boundary was generated from ARB data. The population was not homogeneously distributed in an air basin rather the population under each air basin was taken into consideration for the population-weighted concentrations of PM.

Page 5887, line 6-7, a statistical test (e.g t-test) was applied to determine if the two (future and present climate conditions) pm2.5 distributions have significant different averages?

Response: Yes, statistical t-test was performed to determine the significance of differences between the two means from the present-day and future.

Page 5887, line 13, I would remove '... x in the range of ...' Response: This will be removed in the manuscript.

Page 5888, lines 1-6. I think that in this session a comparison with measurements

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could be described to know how well the model can simulate PM concentrations (total pm2.5 or single chemical species, like sulfate or organic carbon).

Response: The performance of the air quality model for individual PM2.5 components was discussed by Mahmud et al. (2010). A summary discussion on the performance of the air quality model in the climate-air quality simulations will be added right after the discussion of the results presented in Table 1. Predicted annual average total and speciated mass concentrations of fine particulate matter (PM2.5) were compared with measured concentrations at six representative sites in heavily populated air basins in California for the present-day (2000-06) period. The air quality model under-estimated annual average PM2.5 mass concentrations by ~4-39% due to over-predictions in downscaled wind speed. Measured annual average PM2.5 total mass concentrations were $\sim 20 \pm 2 \mu\text{g m}^{-3}$ in the SoCAB and SJV compared to predicted concentrations of $\sim 13\text{-}18 \mu\text{g m}^{-3}$. The model also under-predicted components of PM mass such as elemental carbon, organic carbon, nitrate and sulfate due to these same wind speed over predictions. The bias in downscaled windspeed is assumed to be constant between present and future climate periods.

Page 5888, lines 12-13, "90% confidence interval for the mean difference". It is not very clear how the average differences and the CI are calculated. In the discussion (page 5892 line 12) it is suggested that statistical tests were performed to verify if the differences were significant, but in the methods and here it is not clearly mentioned what kind of test is done (t-test?). Also to help the visualization of Figures 2, S1 and S2, the statistically significant differences could be highlighted with a different color or in bold.

Response: For each period of present-day (2000-06) and future (2047-53) simulations, annual average PM2.5 total mass concentration was first calculated along with associated variance/standard deviation for that specific period. The % difference between the future and present-day annual average PM2.5 was calculated as: $\Delta_{(F-P)} (\%) = ((\mu_{F \pm \sigma_F}) - (\mu_{P \pm \sigma_P})) / ((\mu_{P \pm \sigma_P})) \times 100$

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$$CI(90\%) = \pm ABS(\Delta_{(F-P)}) \times \sigma_{(F-P)} \times 1.8$$

Page 5889, lines 20-21, the authors claim that the inter-annual variability (of the meteorological fields/ chemical fields?) is captured but they do not show or cite previous papers to support this. See also previous comments.

Response: See response to previous comment regarding the ability of the model to capture interannual variability. Mahmud et al. (2010) showed that the annual average PM_{2.5} concentrations are likely to vary over a longer period of time. This reference will be added in the revised manuscript.

Page 5890, line 10. Fig.S3, the tails are not easy to see due to the scale of y-axis. The authors could consider showing only the tails in the same or another figure.

Response: The figures will be updated to show the tails of the distribution clearly in the supplemental information section (Fig. S3).

Page 5890, line 14, some references would be needed here on extreme concentrations and public health relationships.

Response: Several references on extreme events/concentrations of PM will be added in the updated version of the manuscript.

Page 5890, line 17, Fig.3, I would use the same scale for panels a and b, to highlight the differences between future and present-day simulations.

Response: The panels a and b in Fig. 3 will be modified to consider the same scale for future and present –day result PM_{2.5} concentrations during extreme pollution events.

Page 5891, lines 10-13. If I well understood, the EVT was applied to extend the dataset of extreme values, which were used to calculate the 10 year return value with the GPD analysis. Maybe a more detailed description of this point (EVT) is needed, as it is also never mentioned before.

Response: Extreme value theory (EVT) has been replaced with extreme value analy-

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sis (EVA) in the text. A short discussion on the topic is also included in the updated manuscript. PM concentrations averaged over 24-hr periods were analyzed using the open source statistical software R version 2.10.0 with the University Cooperation for Atmospheric Research (UCAR) extremes toolkit version 1.62. Data from the present-day (2000-06) and future (2047-53) were analyzed separately, and the climate change impact was quantified by taking the difference between them. The 10-year return level and its associate parameters were calculated based on the Generalized Pareto Distribution (GPD) probability model first introduced by Pickands, 1975. In this method, the extreme values greater than some threshold are typically assumed to have the density function shown in the methods section of the manuscript. There has been a great interest in applying the GPD model to analyze extreme events in environmental datasets (see for example, Brabson et al., 2000; Pisarenko and Sornette, 2003; Li et al., 2005; Jagger et al., 2006; Coles and Tawn, 1991; Coles, 2001). The threshold value for each variable of interest in both the present-day and future datasets was chosen based on the distribution of all data points, which was approximately equivalent to the 3rd quantile value of the ranked dataset. The 90% confidence intervals (CI) of 10-year return levels were also calculated in this study.

Page 5891, lines 19-21. The authors should explain with more details why they observe a decrease in sulfate and increase in ammonium nitrate.

Response: The 10-year return levels for PM_{2.5} EC (+23%) and NO₃⁻ (+58%) averaged over the statewide population were predicted to increase in the future while statewide 10-year return levels for PM_{2.5} SO₄²⁻ (-46%) were predicted to decrease. These trends reflect increased stagnation during future pollution events which traps pollutants close to their emissions source and provides greater time for the formation of secondary products. NO_x is emitted in close proximity to population centers by combustion sources such as motor vehicles, leading to increased population exposure to NO_x reaction products such as NO₃⁻ when stagnation increases. SO_x is emitted from industrial facilities and from goods movement sources such as ships, leading

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to decreased population exposure to SO_x reaction productions such as SO₄²⁻ when stagnation increases.

Page 5891, lines 21-24. The increased stagnation is indicated as a cause of higher PM_{2.5} values, but this is not supported by further discussion. The selected extreme pollution events, are really in correspondence of stagnation period, and how this periods are identified in the simulations? Are the extreme events all characterized by similar meteorological conditions? See also the general comment 2).

Response: Extreme events were identified as those periods with the highest population-weighted PM_{2.5} concentrations. These events are all characterized by stagnant meteorological conditions associated with a high pressure system stalling over California leading to elevated temperature inversions and calm surface winds.

Page 5892, lines 8-15, it is not clearly described in the previous sections if a statistical test (t-test?) was applied to determine if averages of the 2 distributions are different.

Response: Yes, a t-test was performed on the two annual averages from the present-day and future particulate matter concentrations.

Page 5892, lines 23-25, increased wind-speed is indicated as the main reason for EC and OC reduction in annual averages of PM_{2.5}. Wind speed changes are not shown in the previous section, and why increased wind speed should reduce only EC/OC from primary sources and not the other PM species?

Response: The climate impact on meteorological parameter including wind speed has been discussed in Zhao et al. (2011). Analyses showed that the normalized number of stagnation days (NNSD) integrating all stagnation events, during which most of the air pollution episodes occur, in California's San Joaquin Valley (SJV) will increase and the intensity of stagnation will be stronger in the future for the two main air pollution seasons (i.e., summer and winter). Increases in surface wind and planetary boundary layer height (PBLH) were observed for the coastal part of Los Angeles County (LAC)

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during summer, suggesting stronger ventilation in this region. The effects of these changes on primary PM components such as EC and OC are not necessarily the same as changes to secondary components such as nitrate and ammonium ion because the location of maximum primary PM is different than the location of maximum secondary PM.

Supporting information: lines 48-54, the numbers in the text do not correspond to Figure S5 (neither S3). I would also suggest improving quality of Figure S1, S2, S4 and S5, the numbers of each column are overlapping with the vertical bars.

Response: The figures will be updated with better quality in the Supplementary information section.

Interactive comment on Atmos. Chem. Phys. Discuss., 12, 5881, 2012.

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