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Influence of Air Quality Model Resolution on Uncertainty Associated with Health Impacts

Tammy M. Thompson and Noelle E. Selin

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For more information, please contact the Joint Program Office

Postal Address: Joint Program on the Science and Policy of Global Change
77 Massachusetts Avenue
MIT E19-411
Cambridge MA 02139-4307 (USA)

Location: 400 Main Street, Cambridge
Building E19, Room 411
Massachusetts Institute of Technology

Access: Phone: +1(617) 253-7492
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Influence of Air Quality Model Resolution on Uncertainty Associated with Health Impacts

Tammy M. Thompson[*†] and Noelle E. Selin[*]

Abstract

We evaluate the uncertainty associated with regional air quality modeling grid resolution when calculating the health benefits of proposed air quality regulations. Using a regional photochemical model (CAMx), we ran two modeling episodes (a 2006 basecase and a 2018 attainment demonstration, both for Houston, Texas) at 36, 12, 4 and 2 km resolution. The basecase model performance was evaluated for each resolution for both monitor-based and population-weighted calculations of daily maximum 8-hour averaged ozone. Results from each resolution were more similar to each other than they are to actual measured values. However, the model performance improved when population weighted ozone concentration was used as the metric versus the standard daily maximum ozone concentrations at monitor site locations. Then population-weighted ozone concentrations were used to calculate the estimated health impacts of modeled ozone reduction from the basecase to the attainment demonstration including the 95% confidence intervals associated with each impact from concentration-response functions. We found that estimated avoided mortalities were not significantly different using coarse resolution, although 36 km resolution may over predict some potential health impacts. Given the cost/benefit analyses requirements of the Clean Air Act, the uncertainty associated with human health impacts and therefore the results reported in this study, we conclude that population weighted ozone concentrations obtained using regional photochemical models at 36 km resolution are meaningful relative to values obtained using fine (12 km or finer) resolution modeling. This result opens up the possibility for uncertainty analyses on 36 km resolution air quality modeling results, which are on average 10 times more computationally efficient.

Contents

1. INTRODUCTION

Ground level ozone air pollution has been linked to adverse human health impacts (EPA 2010a) and is regulated in the United States by the Environmental Protection Agency (EPA) with the goal of protecting health. In implementing these regulations, states use results from air quality models to demonstrate compliance (called attainment demonstrations). While many

[*] MIT Joint Program for the Science and Policy of Global Change, Cambridge, MA.

[†] Corresponding Author, Email: TammyT@mit.edu

elements of ozone concentration and impacts are uncertain (including emissions, chemistry, and health impacts), model resolution requirements make uncertainty analyses in attainment demonstrations unfeasible. However, understanding the true projected benefits of ozone regulation, as the Clean Air Act also mandates, requires uncertainty analysis. Here, we compare the variation associated with simulated ozone at various model resolutions with uncertainty in estimated human health impacts, applying population-weighted concentrations. We use the results of this analysis to evaluate the potential for using coarser-scale model resolution for uncertainty analyses of prospective ozone regulations.

Air quality modeling is applied extensively in the U.S. to assess implementation of air quality standards. Many U.S. counties are in non-attainment of the 2008 EPA National Ambient Air Quality Standards (NAAQS) standard of 75 ppb. Many more will be designated non-attainment if the standard is decreased in 2011, as planned. Non-attainment means that the three year average of the fourth highest 8-hour average ozone concentration (called a "design value") at any monitor is greater than the standard. Where non-attainment occurs, states are charged with developing an attainment demonstration to show how they plan to meet the standard. Because the formation of ozone occurs in complex, non-linear chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs), attainment demonstrations require air quality modeling to help develop and evaluate pollution control strategies. At a minimum, EPA requires a resolution of 12 km by 12 km or smaller for attainment demonstrations using approved air quality models (with coarse resolution grid cells extending over all potentially contributing sources), but recommends that each case be evaluated independently to identify the potential model prediction improvements associated with finer scale resolution.

Extensive analyses in the atmospheric chemistry literature have evaluated the impact of model resolution on ozone production (Arunachalam *et al*., 2006; Cohen e*t al*., 2006; Jang *et al*., 1995; Tie *et al*., 2010; Valari & Menut, 2008). Eulerian photochemical air quality models instantly and homogeneously disperse low level emissions (including ozone precursors NOx and VOCs) throughout the grid cell. This spatial averaging impacts the chemistry by smoothing concentration gradients of precursors over large areas, which in some cases has shown to reduce modeled ozone titration effects and ozone formation hotspots. As a result, many studies have found that larger scale resolution (> 12 km grid cells) leads to an under-prediction of daily maximum 8 hour ozone averages, and an over-prediction of daily minimum 8 hour ozone averages (Jang *et al*., 1995; Arunachalam *et al*., 2006; Tie *et al*., 2010). Some studies indicate that 12 km resolution is often not fine enough to capture sharp ozone concentration gradients that can occur near large sources of precursors, like power plants or dense urban areas with a lot of traffic (Valeri & Menut, 2008; Kumar & Russell, 1995).

While previous studies have assessed the errors in predicted ozone versus monitor concentrations, it is unclear what the impact of resolution-based errors are on predicted benefits of regulation. Section 812 of the Clean Air Act (CAA) requires the EPA to conduct a cost/benefit analysis of the impact of that act (EPA, 2011). As part of the latest periodic assessment, EPA conducted an uncertainty analysis on the CAA and the latest standards by comparing estimated human health impacts of ozone and particulate matter concentrations in 2020 under the environmental regulation mandated by the CAA, versus likely concentrations of those two pollutants if the CAA were not implemented. While the uncertainty analysis addressed relative potential impacts of many uncertainties, probability distributions were included only for concentration response functions. With respect to atmospheric uncertainties, the EPA argued that errors in ozone benefits using a 12 km grid are likely minor, but primarily because the benefits are far outweighed by PM reductions; they did not quantitatively compare resolution. These types of analyses are not assessed during attainment demonstrations; previously, Wesson *et al*. (2010) noted this disconnect and argue that multi-pollutant strategies are more effective than traditional attainment strategies at reducing population risk. The National Research Council (NRC) has also criticized the lack of comprehensive uncertainty analyses in the evaluation of environmental policy options, calling for probabilistic multi-source uncertainty analyses (NRC, 2002).

A growing literature has used regional modeling to assess the potential impacts of global climate change and future emissions on ozone concentrations (Selin *et al.*, 2009; Chang *et al.*, 2010; Bell *et al*., 2007; West *et al.*, 2007; Tagaris *et al*., 2009; Knowlton *et al*. 2004). Bell *et al.* (2007) calculated a 0.11% to 0.27% increase (the 95% confidence interval) in percent change in mortality across 31 cities in the U.S. based on the difference between modeled maximum daily ozone concentrations in five summers each around 2050 and the 1990s. Similarly, Knowlton *et al*. (2004) projected a 4.5% increase on average in acute mortality in New York State in 2050 due to climate change. Tagaris *et al.* (2009) evaluated the uncertainty associated with meteorological conditions based on the range of temperature and humidity values modeled by several global change models, concluding that uncertainty due to meteorology was larger than uncertainty associated with human health impacts. All of these studies used resolution of 36 km or coarser from climate models. Given the stochastic nature of the climate system, ensemble analyses of future projected ozone changes, incorporating uncertainties, would be beneficial to produce probabilistic information for decision-making (NRC, 2002).

Here, we address the disconnect between methodologies for attainment demonstrations and for impacts analysis. We evaluate the impact on modeled potential ozone exposure and calculated human health response uncertainty resulting from the temporal and spatial smoothing seen in coarse grid domains (Jang *et al*., 1995; Arunachalam *et al*., 2006; Tie *et al*., 2010) due to the spatial smoothing of ozone precursors, which can eliminate NOx titration and hot spot formation. We focus on comparing the relative uncertainty associated with model resolution and resulting predicted ambient concentrations, with uncertainty associated with projected human health impacts. We use this comparison to identify a resolution appropriate for impacts analysis uncertainty, taking into account relative errors and computational limitations.

2. METHODS

2.1 Comprehensive Air Quality Model with Extensions (CAMx)

We use CAMx (www.camx.com), an EPA-approved regional air quality model (EPA, 2007). We use a well-documented air quality episode developed in part during the Texas Air Quality Study II (TexAQSII) (TCEQ, 2006; TCEQ, 2010b). The episode was created for the Houston/Galveston/Brazoria (HGB) non-attainment area and includes a 2006 basecase and a 2018 attainment demonstration scenario. Emissions inventories were speciated, and spatially and temporally processed using the Emissions Preprocessing System (EPS3). The 2006 basecase inventory represents actual 2006 emissions, while the 2018 emissions inventories were created to demonstrate HGB attainment with the 1997 ozone standard and includes proposed controls on ozone precursors (TCEQ, 2010a). Resolution of the original episode includes a coarse parent grid at 36 km, and three nested grids at 12 km, 4 km, and 2 km (**Figure 1**). Meteorological inputs are consistent in both scenarios and were developed using the fifth generation Penn State/NCAR mesoscale model MM5 (Grell *et al*., 1994) for August 13-September 15, 2006; for the 2 km domain, meteorological data is interpolated by CAMx from 4 km. A detailed description of the episode is provided by the Texas Commission on Environmental Quality TCEQ (2010a). Performance of the episode was evaluated previously (TCEQ, 2010a), and met EPA criteria (+-15% for bias and error as described below for 1 hour ozone concentrations with a 60 ppb threshold).

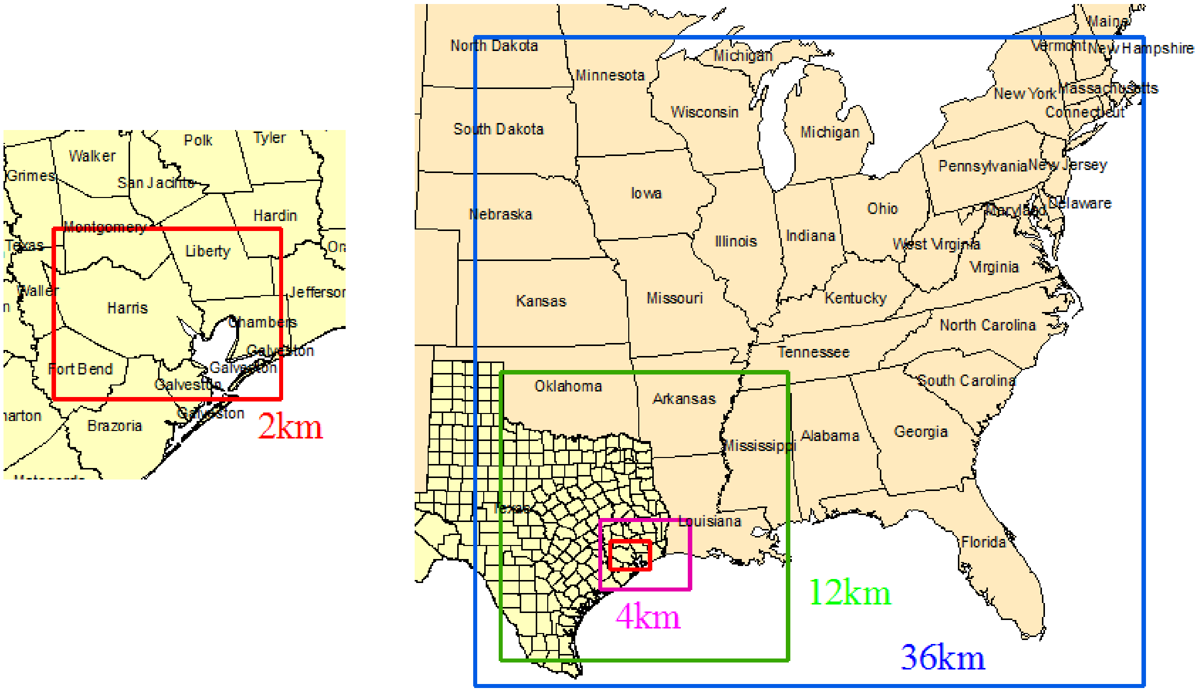

Figure 1. CAMx Modeling domain. For each resolution only the modeling results within the area covered by the 2 km domain (the HGB area), shown above, are used.

2.2 Variable Grid Performance Analysis

We focus here on the HGB area (Figure 1, red square). We conduct four simulations each for the two cases (2006 basecase and 2018 control case), with increasingly coarse resolution over the HGB area (2 km, 4 km, 12 km, and 36 km). We evaluate the performance of the 2006 basecase in reproducing daily maximum 8 hour averaged ozone concentrations at air quality monitors in the region. This metric is selected for evaluation because it determines attainment and it is necessary for input into concentration-response functions for impact analysis; this metric is not required by EPA performance evaluation. We use the statistical measures Mean Normalized Bias (MNB) and Mean Normalized Gross Error (MNGE) as shown in Equation 1 and Equation 2 respectively.

$$MNB = \frac{1}{N}\sum_{1}^{N}\left(\frac{(Model - Obs)}{Obs}\right) * 100\ \% \quad (1)$$

$$MNGE = \frac{1}{N}\sum_{1}^{N}\left(\frac{|Model - Obs|}{Obs}\right) * 100\ \% \quad (2)$$

2.3 Health Impacts

For our analysis of health impacts and potential benefits, we use maximum daily population weighted concentrations (M_{Pop}) as a surrogate for exposure for both model and measurement calculated using Equation 3.

$$M_{Pop} = \frac{\sum_g p_g \max \{c_g\}}{\sum_g p_g} \qquad (3)$$

where p_g is the population in grid cell g, and c_g is the maximum 8 hour ozone concentration in grid cell g. Population distribution is from U.S. Census data, mapped using Geographical Information System (GIS) software. For the base case, year 2007 is used, and for the 2018 policy case, projected 2015 population is applied. For population-weighted analysis for monitor data, only those grid cells with monitors located in them are used in the calculation. This metric represents a rough but best available and commonly-used estimate for the potential for human exposure. In reality, exposure depends not only on the ambient concentration of pollutants at any given time and location, but also on the daily patterns of people being exposed: when, where and how they travel to and from activities and their initial health (EPA, 2010b). The potential impacts on human health of changes in ozone concentrations are calculated by multiplying population-weighted concentrations by concentration response functions for acute mortality, respiratory hospital admissions (adults over 65 yrs), respiratory symptom days, minor restricted activity day, asthma attacks, and bronchodilator usage. We use the survey of Bickel and Friedrich (2005) to specify these functions and related 95% confidence intervals, assuming a linear relationship between daily maximum 8 hour ozone concentrations and impacts, and no minimum health impact threshold. For baseline mortality rate, we used the average rate for developed countries from Lopez *et al*. (2006)

3. COMPARISON OF MONITOR-BASED AND POPULATION-BASED PERFORMANCE EVALUATION

3.1 2006 Basecase: Monitor-based Analysis

We first evaluated the performance of the 2006 basecase episode on the daily maximum 8 hour ozone concentrations modeled for each of the air quality monitors located in the HGB domain for each of the four spatial resolution runs. **Figure 2a** shows the error (Equation 2) in comparing monitor values to simulated concentrations in the grid cell containing the monitor (at each resolution). Error increases from 25% to 74% as model resolution increases from 2 km to 36 km. **Figure 2b** compares the difference between the three coarser resolutions relative to the 2 km fine scale modeling result; the difference in predicted ozone between coarser and finer scale resolution ranges from 1%-15%. We conclude from this comparison that results from the different resolutions are more similar to each other than they are to actual measured values.

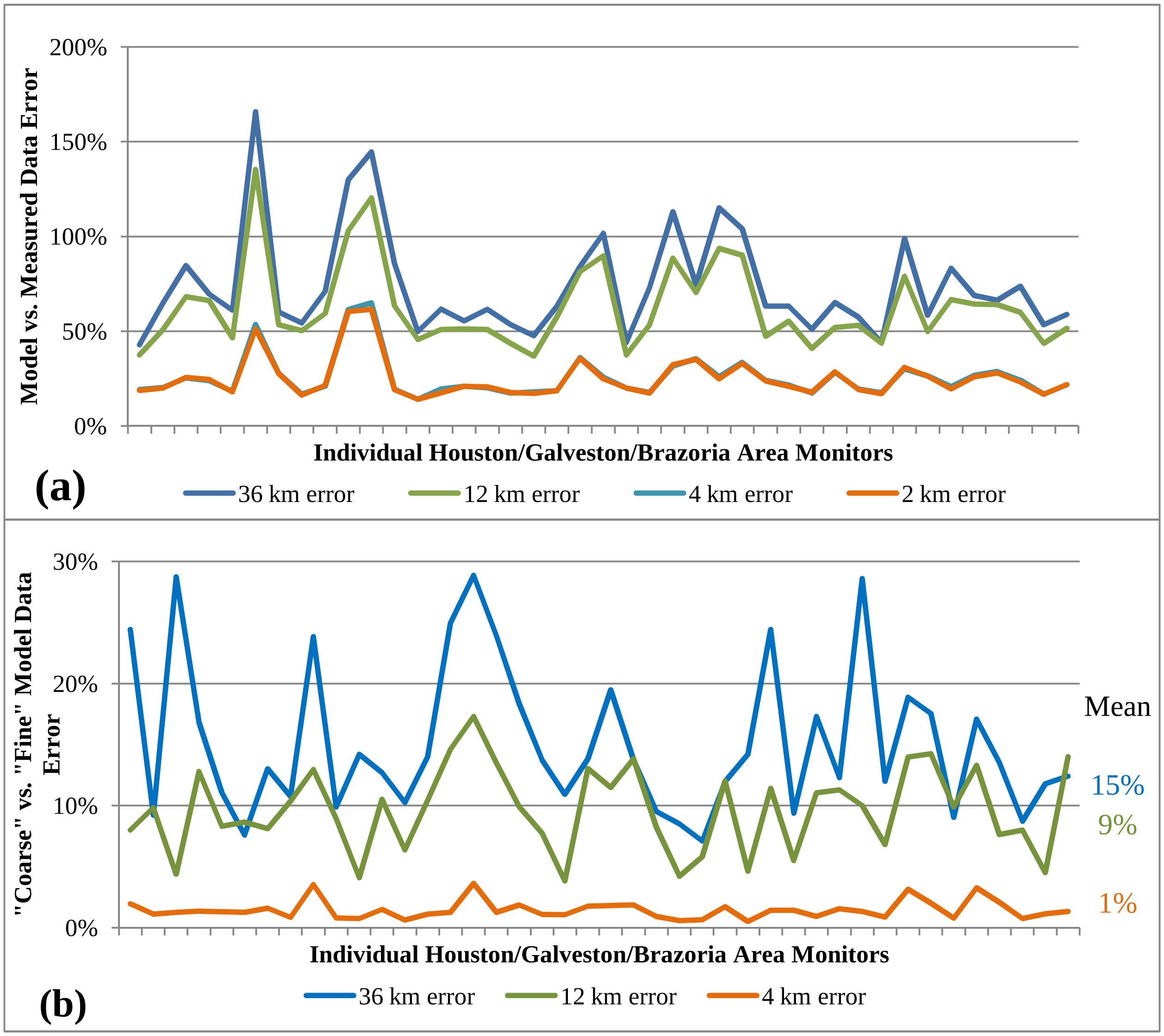

Figure 2. (a): Model Data vs. Measured Data: Model error comparing CAMx results for four grid resolution runs for the 2006 basecase to measured concentrations at all air quality monitor sites in the 2 km domain. Bias and error results are approximately the same due to a high bias of the model, so only error is shown in Figure 2a. **(b)**: "Coarse" Model Data vs. "Fine" Model Data: Model Error for modeled "coarse" resolution ozone concentrations compared with modeled 2k "fine" resolution ozone concentrations.

3.2 2006 Base Case: Population-weighted Analysis

To assess a metric more relevant to health impacts, we compared the ability of different model resolution to reproduce population-weighted concentration. **Figure 3** shows the impact of resolution on the population-weighted concentrations as modeled using the 2006 basecase. These results are compared to the measured concentrations at the monitors within the HGB domain. Higher-resolution modeling (4 or 2 km) exhibits no clear benefit in comparison with 12 km resolution when considering population-weighted concentrations. The 36 km simulation is biased high (by 3 ppb resolution relative to finer scale model results); however, on average across all monitor locations, modeled concentrations are 10 ppb higher than measured concentrations.

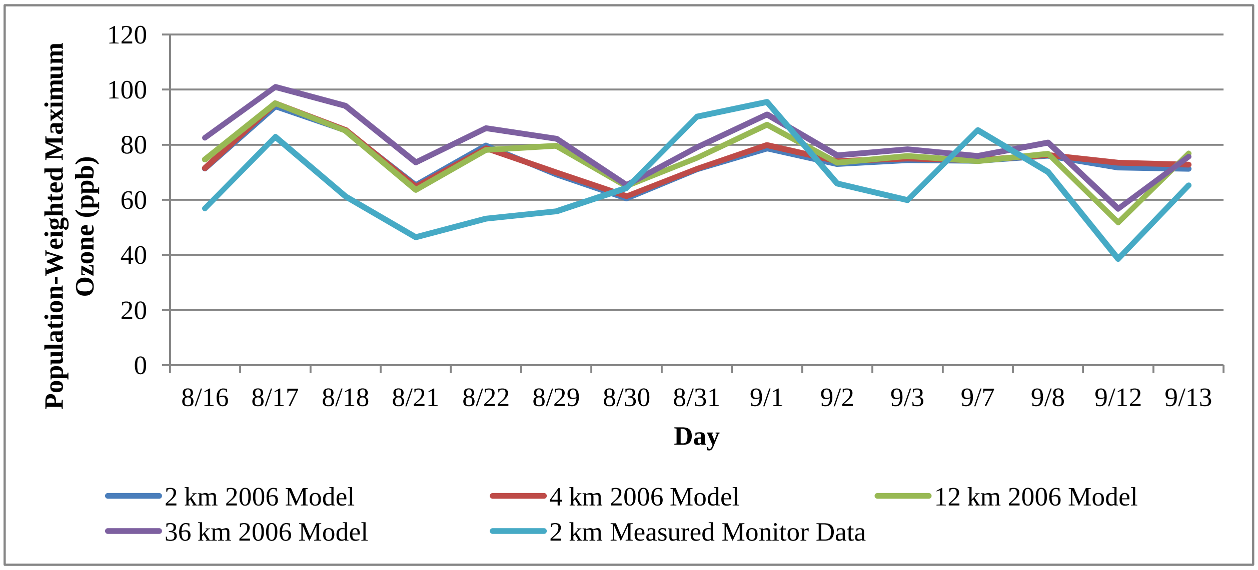

Figure 3. Population-weighted maximum ozone concentration for each resolution from the 2006 episode compared to the population-weighted maximum ozone concentration calculated from the measured values at the monitors using the 2 km resolution.

The 2006 basecase episode over-estimates the population weighted ozone concentrations on most days (Figure 3). This bias is consistent with the monitor-based results presented in Section 3.1 above. Additionally, the model is not able to consistently capture the daily variability of the measured results. However, the results are improved over the standard performance evaluation statistics for 12 km and 36 km resolution as presented in Figure 2. The mean normalized error of the population weighted daily maximum 8 hour ozone concentrations modeled using the 2006 basecase (and only cells containing monitors) compared to population weighted measured concentrations at air quality monitors average across the episode is 26%, 27%, 24% and 32% for 2 km, 4 km, 12 km, and 36 km resolution respectively.

3.3 2006 Basecase vs 2018 Control Case: Population-weighted Comparison

We compared population-weighted ozone changes between the 2006 basecase with the 2018 control case, to identify the variation in concentration between different resolutions for benefits analysis. **Figure 4** shows the maximum population-weighted concentration (Equation 3) calculated for each day of both the 2006 and 2018 episodes, using the fine resolution (2 km) modeling runs. Also shown are the population-weighted concentrations using measured monitor data and the HGB domain.

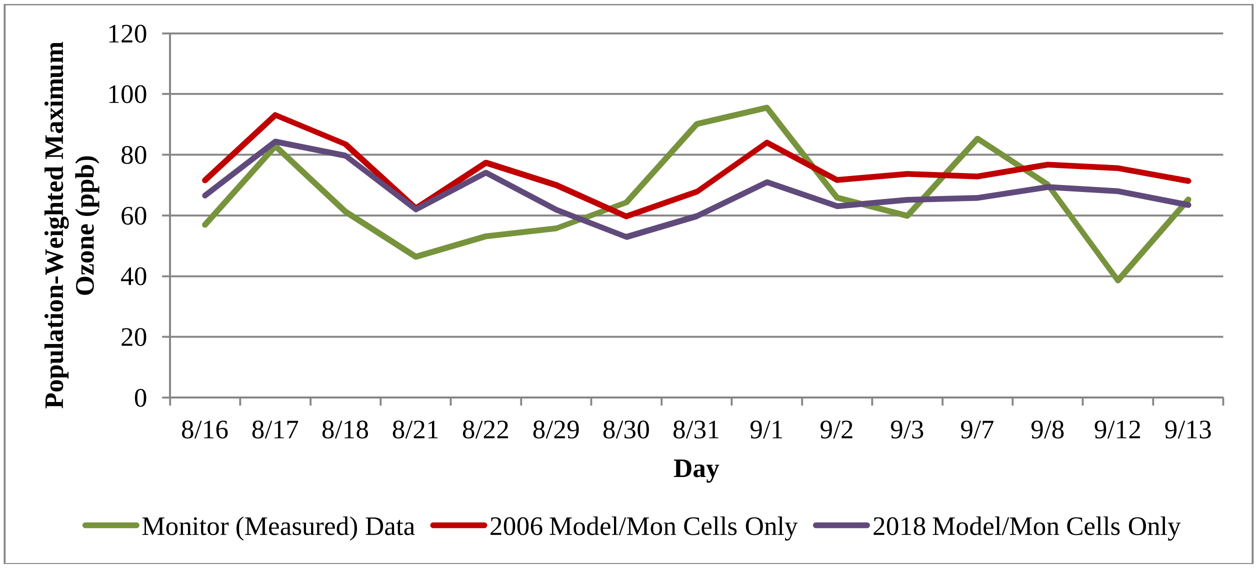

Figure 4. Population weighted daily maximum 8 hour averaged ozone concentrations using fine scale 2 km population and concentration data from monitors, and modeled values from each of the runs.

Figure 5 shows the change in population weighted 8 hour ozone concentrations from base case 2006 model data to control case 2018 model data. Based on these results, the control scenarios as proposed by the TCEQ in the 2018 episode clearly impact the modeled ozone concentrations, with an average 10 ppb decrease in both population weighted concentrations and maximum daily 8 hour ozone concentration from 2006 basecase results. The calculated ozone decrease differs depending on what model resolution is used: the average decrease is 8 ppb for both the 2 km and 4 km model resolutions, 10 ppb for the 12 km model resolution, and 12 ppb for the 36 km resolution. For comparison, the average change in the fourth highest daily maximum 8 hour ozone at all monitor locations only is 8 ppb, 7 ppb, 7 ppb and 6 ppb respectively.

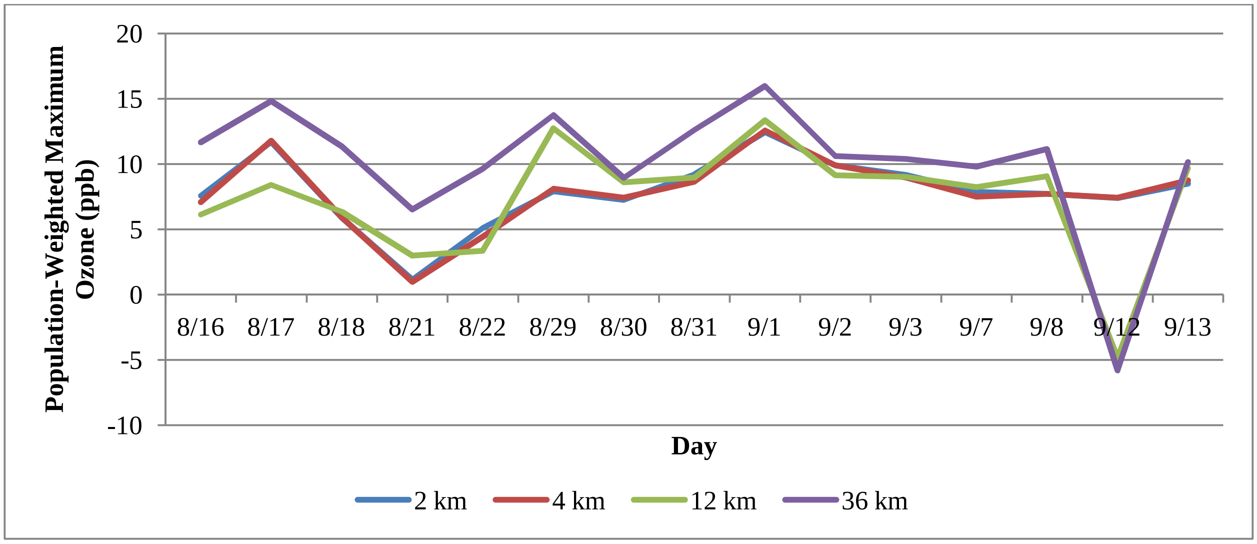

Figure 5. Impact of 2018 control strategy (2018 Control case – 2006 Base case) on daily maximum 8 hour ozone population weighted ozone concentration by resolution.

4. UNCERTAINTY ANALYSIS OF HEALTH IMPACTS AT VARYING MODEL RESOLUTION

We use the change in population weighted daily maximum 8 hour ozone shown above in Figure 5, averaged across all days of the episode, to calculate the expected health benefits from the Houston attainment demonstration. We use these values to compare the estimated benefits that would be calculated based on concentrations predicted at the four resolutions, and concentration-response functions and 95% confidence intervals as described above.

Table 1 shows the calculated change in mortalities and morbidities between 2006-2018, based on concentration information from the four different modeling resolutions. Also shown are the total number of cases in 2006 calculated using data from air quality monitors. The mean (5) and 95% confidence interval (2-7) for the change in mortalities is identical up to 12 km. For 36 km resolution, the mean is 7 and 95% confidence interval 2-9. Basecase (2006) mortality is calculated to be between 15 and 58 deaths per ozone month (May-September) due to acute exposure, with a mean at 44.

For avoided respiratory hospital admissions (adults >65 years of age) and avoided bronchodilator usage, health benefits estimated using the 36 km resolution ozone modeling results fully contain the 95% confidence interval calculated using finer scale modeling results. However, for changes in respiratory symptom days, minor restricted activity days and asthma attacks, the 36 km 95% confidence interval does not fully contain the confidence intervals for the finer scale resolution results. For these endpoints, an analysis done at 36 km resolution could potentially over-estimate the benefits due to modeled ozone reductions. However, the EPA has found that most of the monetary benefits associated with health improvements comes from reduction in mortalities due to the high value of a statistical life (EPA, 2011).

Table 1. Change in human health impacts due to the control scenarios proposed as part of the 2018 Houston Attainment Demonstration. The top row shows baseline human health impacts due to ozone measured at monitors in 2006.

Mean with 95% Confidence Interval	Change in Mortality (# of deaths in area)	Respiratory Hospital Admissions Adults >65 yrs	Respiratory Symptom Day	Minor Restricted Activity Day	Asthma Attack	Bronchodilator usage
Values Calculated Using Population Weighted Concentrations as Measured by Air Quality Monitors in 2006						
06 Monitor Data	44 (15,58)	207 (-83,497)	546442 (94385,1043208)	190427 (72859,314618)	71037 (5464,137438)	1208796 (-430530,2649416)
Change (Decrease) in Metrics between the 2006 Modeled Basecase and the 2018 Modeled Control Case						
Model 2k	5 (2,7)	25 (-10,60)	65466 (11308,124980)	22814 (8729,37692)	8511 (655,16466)	144818 (-51579,317409)
Model 4k	5 (2,7)	24 (-10,59)	64601 (11158,123330)	22513 (8613,37195)	8398 (646,16248)	142906 (-50898,313218)
Model 12k	5 (2,7)	23 (-9,56)	61302 (10589,117031)	21363 (8174,35295)	7969 (613,15418)	135607 (-48299,297222)
Model 36k	7 (2,9)	32 (-13,76)	83552 (14432,159508)	29117 (11140,48106)	10862 (836,21015)	184827 (-65829,405101)

5. ERROR ANALYSIS AND APPLICABILITY TO OTHER REGIONS

As a first test of whether our results may be applicable to other regions, we use the CAMx Process Analysis (PA) tool to calculate individual contributions from each physical and chemical process within the model, to the final concentration of ozone. This allows us to better understand the cause of the resolution-dependent differences in our study. We used PA and the python based Process Analysis (pyPA) post-processing tool, developed by Henderson *et al.* (2011) to analyze results for September 12th because that day had the largest difference between the 2006 basecase and the 2018 control case (Figure 5). Our results indicate that the resolution difference is due to chemistry: ozone production due to chemistry in the fine resolution model is twice that of the coarse resolution model during the hours of 10AM to 12PM (12 ppb per hour vs. 6 ppb per hour). As chemistry processes are consistent across different regions, this suggests that our analysis may be valid beyond the Houston area; however, further studies could address other regions as episodes are developed.

6. CONCLUSIONS AND IMPLICATIONS FOR REGULATORY APPROACH

To evaluate the uncertainty associated with air quality modeling resolution for calculating health benefits of proposed regulations, we ran two modeling episodes (a basecase and an attainment demonstration, both for Houston, Texas) at 36, 12, 4 and 2 km resolution. We evaluated basecase model performance for each resolution for both monitor-based and population-weighted calculations of 8-hour maximum ozone. We then used population-weighted ozone concentrations to calculate the estimated health impacts of ozone reduction from the basecase to the attainment demonstration including the 95% confidence intervals associated with each impact from concentration-response functions. We found that estimated avoided mortalities were not significantly different using coarse resolution, although 3 km resolution may over predict some potential health impacts.

We evaluated the performance of the 2006 basecase with respect to monitor-based and population-weighted 8-hour maximum ozone. Results from each resolution were more similar to each other than they are to actual measured values. However, the model performance improved when population weighted ozone concentration was used as the metric versus the standard daily maximum ozone concentrations.

We compared the difference in the population weighted ozone concentrations between resolutions and between the 2006 base case and the 2018 control case. The coarse scale resolution (36 km) showed the largest decrease from basecase to attainment demonstration case. The average change in daily maximum 8 hour ozone population weighted concentrations are 10 ppb, 7 ppb, 8 ppb and 8 ppb for 36 km, 12 km, 4 km, and 2 km resolution respectively.

We used the population-weighted ozone concentration difference to calculate acute mortality, respiratory hospital admissions (adults over 65 yrs), respiratory symptom days, minor restricted activity day, asthma attacks, and bronchodilator usage. The confidence interval of the mortality predicted by the coarse scale resolution completely contains the confidence interval of the mortality predicted by the fine scale results.

Given the cost/benefit analyses requirements of the Clean Air Act, the uncertainty associated with human health impacts and therefore the results reported in Table 1, we conclude that population weighted ozone concentrations obtained using regional photochemical models at 36 km resolution are meaningful relative to values obtained using fine (12 km or finer) resolution modeling. This result opens up the possibility for uncertainty analyses on 36 km resolution air quality modeling results, which are on average 10 times more computationally efficient.

Acknowledgements

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