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Air quality resolution for health impacts assessment: influence of regional characteristics

T. M. Thompson[1,*], **R. K. Saari**[1], **and N. E. Selin**[2]

[1]Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, 77 Massachusetts, Ave., Bldg E19-411, Cambridge, MA 02139, USA
[2]Engineering Systems Division and Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, USA
[*]now at: Cooperative Institute for Research in the Atmosphere, Colorado State University, 1375 Campus Delivery, Fort Collins, CO 80523, USA

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Correspondence to: T. M. Thompson (tammy.thompson@colostate.edu)

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Abstract

We evaluate how regional characteristics of weather, population, and background pollution might impact the selection of optimal model resolution when calculating the human health impacts of changes to air quality. Using an approach consistent with air quality policy evaluation, we use a regional chemical transport model (CAMx) and a health benefits mapping program (BenMAP) to calculate the human health impacts associated with changes in ozone and fine particulate matter resulting from an emissions reduction scenario. We evaluate this same scenario at 36, 12 and 4 km resolution for nine regions in the Eastern US representing varied characteristics. We find that the human health benefits associated with changes in ozone concentrations are sensitive to resolution, especially in urban areas where we estimate that benefits calculated using coarse resolution results are on average two times greater than benefits calculated using finer scale results. In three urban areas we analyzed, results calculated using 36 km resolution modeling fell outside the uncertainty range of results calculated using finer scale modeling. In rural areas the influence of resolution is less pronounced with only an 8 % increase in the estimated health impacts when using 36 km resolution over finer scales. In contrast, health benefits associated with changes in $PM_{2.5}$ concentrations were not sensitive to resolution and did not follow a pattern based on any regional characteristics evaluated. The largest difference between the health impacts estimated using 36 km modeling results and either 12 or 4 km results was at most ±10 % in any region. Several regions showed increases in estimated benefits as resolution increased (opposite the impact seen with ozone modeling) due to a higher contribution of primary PM in those regions, while some regions showed decreases in estimated benefits as resolution increased due to a higher contribution of secondary PM. Given that changes in $PM_{2.5}$ dominate the human health impacts we conclude that human health benefits associated with decreases in ozone plus $PM_{2.5}$, when calculated at 36 km resolution are indistinguishable from the benefits calculated using fine (12 km or finer) resolution modeling in the context of policy decisions.

ACPD
13, 14141–14161, 2013

1 Introduction

Air pollutants such as ground level ozone and fine particulate matter (particulate matter with a diameter $< 2.5\,\mu m$, $PM_{2.5}$) have been found to negatively impact human and ecosystem health. To mitigate health damages, regulatory authorities have established maximum allowable concentrations of these pollutants. Because of the complex physical and chemical processes influencing both the formation and atmospheric transport of ozone and $PM_{2.5}$, chemical transport models (CTMs) are used to inform regulatory strategies and to estimate health impacts of policies. CTMs aggregate processes spatially and temporally to evaluate the influence of chemistry, emissions and transport on concentrations. In atmospheric chemistry as well as a broad range of related scientific fields, the question of the selection of appropriate modeling scale is a challenge, and has become increasingly relevant as computational advances have enabled modeling at resolutions previously infeasible. Here, we apply a method elaborated previously (Thompson and Selin, 2012), with which it was shown that in policy-relevant applications such as air quality policy, the choice of model resolution requires considering the contributions of uncertainties associated with the policy, modeling and health impacts. We use this method to address the influence of varying meteorological patterns, current pollutant levels, and population densities, on determining the optimal resolution for regulatory air quality modeling of ozone and $PM_{2.5}$ in the Eastern United States.

Ozone and many of the species that make up the total concentration of fine particulate matter ($PM_{2.5}$ reported in this study includes particulate sulfate, nitrate, ammonium, black carbon and organic aerosols) are formed in the atmosphere from chemical reactions between precursor species. Often, these chemical reactions are non-linear, involve species from different sources and can occur at locations removed from where the precursor species were emitted. Strong spatial concentration gradients of emissions, as often seen near large point sources, can influence chemical production, and thus modeling at too coarse a resolution can lead to errors due to spatial averaging of emissions. As a result, many studies have found that models at coarser scale res-

ACPD
13, 14141–14161, 2013

olution (> 12 km grid cells) under-predict maximum concentrations, and over-predict minima (Arunachalam et al., 2006; Jang et al., 1995; De Meij et al., 2007; Tie et al., 2010). For ozone, this smoothing has been shown to reduce modeled ozone titration effects and ozone formation hotspots. Similar to ozone, studies suggest that regional air quality modeling results for PM concentrations improve with increasing resolution (Fountoukis et al., 2013; De Meij et al., 2007). However, many studies find that even 4 km resolution is not fine enough to accurately represent the measured concentrations of PM (Mensink et al., 2008; Ott et al., 2008; Shreshtha et al., 2009).

There are also challenges with attempting to model at too fine a resolution, as uncertainty is introduced into air quality modeling at almost every step of the process. Mensink et al. (2008) found that while local and urban scale modeling (resolution < 4 km) provided more detailed data regarding PM exposure due to land use changes, these models were limited by their ability to fully account for the temporal patterns of secondary PM from sources outside of the region of study. Zhang et al. (2010) found that modeling future emissions changes at both 4 and 12 km led to the same estimated percentage decrease in ozone at monitor sites in North Carolina, but results for changes of total $PM_{2.5}$ differed between the two resolutions (sometimes considerably: at 6 of the 37 sites they evaluated, the results had opposite signs). A related study (Liu et al., 2010) suggests that the higher sensitivity to model resolution of $PM_{2.5}$ might be in large part to the challenges of meteorological modeling and geography. Queen and Zhang (2008) likewise found that increasing model resolution does not always improve the model's performance with respect to PM, suggesting that the highest sensitivity is to meteorological inputs, specifically rainfall. Fountoukis et al. (2013) found that finer resolution in both modeling and input emissions inventories improved the performance of CTMs for primary PM species (most notably BC) and in some cases for secondary species. However, they also suggested that uncertainty in emissions inputs might lead to larger discrepancies than model resolution between measured and modeled data.

In the United States, agencies require that air quality modeling for regulatory purposes be conducted at 12 km resolution or finer, and preferably at 4 km resolution (US

ACPD
13, 14141–14161, 2013

EPA, 2007). Because attainment of US air quality standards is based only on concentrations at specific air quality monitoring sites, air quality modeling for regulatory purposes primarily focuses on reducing the model estimated concentrations at those particular sites. In contrast, cost/benefit analysis of air quality policy, as required by Executive Order 12866 as it applies to the Clean Air Act (CAA), uses population weighted concentrations of pollutants to estimate benefits. A recent analysis conducted to estimate impacts of the CAA addressed in a relative sense the potential impacts of many uncertainties introduced in the air quality modeling process, however, probability distributions were included only for concentration response functions (US EPA, 2011a). Researchers have been called on to evaluate the many other sources of uncertainty in air quality modeling in order to aid in the policy decision making process (NRC, 2002). The complexity of regional air quality models and the computational and memory requirements, however, makes extensive uncertainty sampling approaches infeasible at 12 km resolution or finer at present.

While many studies as noted above have estimated the impact of model resolution on pollutant concentration, fewer have evaluated the impact of model resolution on the estimated changes to human health. These few studies indicate that human health benefits estimated using fine model resolution (< 36 km) do not provide more accurate results than human health benefits estimated using coarse model resolution (≥ 36 km) given the uncertainty associated with the human health response (Arunachalam et al., 2011; Thompson and Selin, 2012). These particular studies however are each limited in scope, the first to a single emission source (air travel) and only three regions (Atlanta, Chicago and Providence), the second to a single region (Houston). Thus, their general applicability to a broad range of meteorological conditions and background pollution/emissions levels across the US is limited.

We address the challenge of selecting appropriate model resolution for air quality benefits evaluation by applying a methodology that compares quantitative benefits estimation given model simulations conducted at varying resolutions (Thompson and Selin, 2012). Using an air quality policy episode for the entire Eastern US, we con-

ACPD
13, 14141–14161, 2013

duct nested simulations of 36, 12 and 4 km in nine regions of the US, evaluating the influence of urban versus rural land use, emissions mix, current pollution levels and differing meteorological patterns on (1) the ability of coarse scale modeling to simulate changes in population-weighted concentrations of ozone and PM similarly to finer scale modeling, and (2) the errors contributed by model resolution changes relative to benefits evaluations. Section 2 presents the detailed modeling methods we use, including the air quality model (in Sect. 2.1) and the health benefit model (in Sect. 2.2). Section 3 presents the human health benefit results, first for ozone (Sect. 3.1) then $PM_{2.5}$ (Sect. 3.2) and finally comparison of multiple concentration response function results for a single illustrative region (Sect. 3.3). We discuss our results in Sect. 4 and compare the policy-relevant insights gained by modeling at these different resolutions in Sect. 5. We discuss implications of these findings to current regulatory procedures, human health benefit estimations, and the potential for model uncertainty analyses.

2 Methods

We follow regulatory procedures to first conduct air quality modeling using two emissions scenarios, and then evaluate the human health impacts due to the differences between these emissions scenarios at nine US locations representing a variety of regional characteristics. Repeating this analysis using three different model resolutions, we evaluate the impact of model resolution on the resulting estimation of human health benefits across the selected locations.

2.1 Comprehensive Air Quality Model with extensions (CAMx)

We use CAMx (www.camx.com), a US EPA-approved regional air quality model (US EPA, 2007). We use a well documented year-long air quality episode developed and fully evaluated by the US EPA to evaluate the impact of the proposed Cross-State Air Pollution Rule (US EPA, 2011b). Emissions inventories include a 2005 base case and

ACPD
13, 14141–14161, 2013

a 2014 control case and were speciated and spatially and temporally processed using the SMOKE preprocessing system (CMAS, 2010). The 2005 base case inventory represents calculated year 2005 emissions, while the 2014 emissions inventories were first forecast from 2005 to 2014 by incorporating population and economic growth, technological advancements and all air quality regulations in place by 2010. 2014 forecast emissions were then reduced by applying proposed controls on electricity generating units in the mid- and Eastern US (US EPA, 2011c). On average, NO_x emissions decrease by 35 % from 2005 base case to control case, SO_2 emissions decrease by 56 %, CO emissions decrease by 19 % and VOC emissions decrease by 26 % from the 2005 base year to the 2014 policy case. In contrast to methods in a traditional regulatory impact assessment, we compare the 2005 base case to the 2014 policy case rather than the 2014 projected base case, because the resulting ozone reductions from CSAPR are quite modest (~ 0.2 %) and we prefer to explore a larger range to examine the non-linearities associated with ozone formation.

We explore three model resolutions including a coarse parent grid at 36 km that covers the entire continental US, a nested 12 km grid covering the Eastern US, and nine nested 4 km grids (Fig. 1) that are each 108 km by 144 km in size and are situated over areas of interest. The areas chosen for this analysis were: Atlanta, Boston, Washington DC, Detroit, Houston, New York State, New York City, Western Pennsylvania, and Virginia. These sub-domains are selected to represent a variety of meteorological conditions, population and industrial density, local emissions, and existing pollution concentration levels. Figure 1 outlines the characteristics specific to each location. The results reported for each of the three resolutions come from these 9 sub-domains only. Meteorological inputs are consistent in both the 2005 base case and the 2014 policy case and were developed using the fifth generation Penn State/NCAR mesoscale model MM5 (Grell et al., 1994) for every day of 2005; for the 4 km domain, meteorological data is interpolated by CAMx from 12 km.

The particular episode used for this study is evaluated because it represents recent federal efforts to improve US air quality via NO_x and SO_2 reductions under CSAPR

ACPD
13, 14141–14161, 2013

and is therefore well-known within the regional modeling and health impacts communities. Additionally, the episode performance has been evaluated extensively (US EPA, 2011b). A detailed description of the episode and policy including model evaluation is provided by the US EPA (2011b). Emissions totals are consistent across all resolutions.

2.2 Health impacts

For our analysis of health impacts and potential benefits, we use the US EPA's Benefits Mapping and Analysis Program (BenMAP) (Abt, 2010). Our health impact assessment methods (including BenMAP) closely follow those used by the US EPA for the Regulatory Impact Analysis (RIA) conducted to evaluate federal policy (US EPA, 2011d). Our inputs to BenMAP include modeled pollutant concentrations (daily maximum 8 h averaged ozone, and 24 h averaged total $PM_{2.5}$), model domain grid definitions and projected 2014 census block population data (GeoLytics Inc., 2010) that is spatially allocated to 4 km grid cells using GIS software. For each of the 9 locations and 3 model resolutions, daily pollutant concentrations, model grid cell domain definitions and projected US population data are combined within BenMAP to estimate average population weighted pollutant concentrations (concentrations are averaged for May through September in the case of ozone, and annually in the case of $PM_{2.5}$). BenMAP then averages the values from each domain and reports the change in seasonally averaged population weighted concentrations of ozone and $PM_{2.5}$ between the 2005 base case and the 2014 control case for each resolution and sub-domain. The population-weighted concentration change serves as a best estimate of human exposure to air pollution and as such is then applied to concentration response functions and baseline health incidence rates (e.g., the baseline all-cause mortality rate) to estimate a change in human health endpoints, including morbidity and mortality, due to reduced pollution exposure. The modeled changes in population-weighted ozone and $PM_{2.5}$ concentrations between the 2005 base case and the 2014 control case are reported and discussed in the Supplement.

ACPD
13, 14141–14161, 2013

We use a 2015 baseline mortality rate that is based on 2004–2006 county-level individual mortality data, as reported to the US CDC (CDC, 2006) and projected using national-level census mortality rate projections (Abt, 2010). Where inconsistencies in population totals occurred due to rounding errors in grids in BenMAP (parent population data is based on census boundaries), we scaled the estimated mortality to the reported 4 km population so that population matched exactly.

The concentration-response functions applied in this study are those peer-reviewed epidemiological studies in BenMAP version 4.0 that estimate increased mortality risk (the particular studies used are listed along the x-axis in Fig. 3a for ozone and Fig. 3b for $PM_{2.5}$). All concentration response functions are modeled as a log-linear relationship between daily maximum 8 h ozone (or 24 h averaged $PM_{2.5}$) concentrations and increased mortalities, with no minimum health impact threshold (US EPA, 2011e).

The uncertainties inherent in estimating mortalities from these functions are represented in this study in two ways. First, each epidemiological study has an associated 95 % CI, which represents the statistical confidence of that study, given its methodology, population and sample period. Second, the differences in study designs themselves can give rise to non-overlapping confidence intervals when studies are compared. Users of BenMAP in regulatory assessments sometimes attempt to mitigate the latter source of uncertainty by appealing to expert elicitation (Abt, 2010) or using statistical techniques to pool estimates from multiple studies (e.g., the CSAPR RIA (US EPA, 2011d). Here, we do not pool the health estimates, instead we present all estimates for side-by-side comparison.

Mortality valuation determined using the Value of a Statistical Life (VSL) typically dominates the monetized benefits associated with health improvements come from mortality reduction (US EPA, 2011a); thus, we present mortalities exclusively.

ACPD
13, 14141–14161, 2013

3 Uncertainty analysis of health impacts at varying model resolution

Using BenMAP as described in Sect. 2.2, we calculate the estimated change in human mortality between the 2014 control case and the 2005 base case emissions inventories for each of the nine regions of interest, and each of the three modeling resolutions. The point value of the estimated change in mortality is presented with a 95 % confidence interval that represents the uncertainty associated with the concentration response functions only. Model uncertainty is not estimated.

3.1 Impact of resolution on benefits associated with ozone

Figure 2a shows the calculated decrease in mortalities due to changes in ozone between the 2005 base case and the 2014 control case (2005–2014), based on modeled population-weighted concentration data within each area, from the three different modeling resolutions applied to the mortality results developed by Bell et al. (2004). For each endpoint (for both ozone and $PM_{2.5}$), the mean value is marked by the red (36 km), green (12 km) and purple (4 km) slashes and the 95 % confidence interval is shown by the error bars. For ozone, in every sub-region studied regardless of population density, location, and current attainment status, the largest benefit due to the policy is estimated using the coarsest scale modeling (36 km). In three of the nine regions (Houston, Detroit and New York City), the 36 km point estimate for change in mortality falls outside of the 95 % confidence interval for the two finer scale results. In Atlanta and Washington DC, the point estimate for the 36 km mortality results falls near the top end of the 95 % confidence interval of the results calculated using the two finer scales.

3.2 Impact of resolution on benefits associated with $PM_{2.5}$

Figure 2b shows the estimated decreases in human mortality resulting from reductions in $PM_{2.5}$ between the 2005 base case scenario and the 2014 control scenario cal-

ACPD
13, 14141–14161, 2013

culated using the concentration response function developed by Laden et al. (2006). Unlike ozone, $PM_{2.5}$ mortality results do not appear to be as sensitive to model resolution when uncertainties are considered. This is due in part to the mix of primary and secondary species that make up $PM_{2.5}$. $PM_{2.5}$ mortality decreases are on the order of 100 times greater than ozone mortality decreases.

3.3 Impact of concentration response function on estimated human health benefits

Figure 3a and b below shows the estimated avoided mortality calculated at each resolution, in the region surrounding Atlanta for all peer-reviewed concentration response functions (crfs) available within BenMAP version 4.0 for (a) Ozone and (b) $PM_{2.5}$. Atlanta results are presented here as an illustration, however results from all regions are presented in the SI and discussed below. As shown in Fig. 3a, three of the eight ozone crfs show 36 km mean mortality estimates that fall outside of the 95 % uncertainty range of the two finer resolution estimates. The avoided mortality due to the change in ozone concentration estimated using 36 km results is 40 % larger than 4 km results on average for each of the crfs. However, when comparing crfs, the average difference between the largest and smallest mean values of different ozone crfs calculated using results from the same resolution is 300 %. In contrast, the estimated avoided mortality due to changes in PM concentrations in Atlanta differs by only 7 % between resolutions for each crf and the mean estimates differ by 150 % between crfs when keeping resolution constant. Estimated human mortality is thus more sensitive to the selection of concentration response function than it is to the selection of air quality modeling resolution for both ozone and $PM_{2.5}$.

ACPD
13, 14141–14161, 2013

4 Discussion

Estimated changes in mortality due to ozone concentration changes are sensitive not only to resolution but also regional characteristics. Changes in mortality due to total $PM_{2.5}$ concentration changes are insensitive to resolution or regional characteristics.

The results shown in Fig. 2a suggest that 36 km resolution modeling has the potential to over-estimate ozone benefits in populated urban areas. For all nine regions evaluated, human health impacts due to changes in ozone calculated using 36 km resolution modeling were larger than impacts calculated using finer scale modeling. On average, in urban areas, the human health response calculated at 36 km resolution was 200 % larger than the response calculated at 12 km resolution, while the difference was only 8 % greater in rural areas. Even excluding Houston and New York City and the extreme differences between resolution results in those two regions, the remaining urban areas showed response to emissions changes that was 50 % larger in 36 km resolution. In contrast, the impact of resolution did not seem as important when considering an area's current ozone attainment status or proximity to the coast.

Unlike the ozone results where coarse model resolution (36 km) lead to the largest concentration and thus estimated impact in mortality, $PM_{2.5}$ concentration does not show a trend with respect to model resolution. $PM_{2.5}$ is made up of both primary and secondary species. Since all emissions are assumed to be homogeneously dispersed to model grid cells immediately, if the same primary PM emissions source is modeled within a 4 km grid cell and a 36 km grid cell, the concentration within the 4 km grid cell will be 81 times greater the instant after the emission assuming no other sources are present in either grid cell. Therefore it follows that primary $PM_{2.5}$ species commonly show increasing modeled concentrations as model resolution increases. In contrast, particulate sulfate, the major secondary $PM_{2.5}$ species with more than one precursor, behaves more like ozone in that it is common to see maximum chemistry occurring (and therefore higher concentrations) when many sources are well mixed, as we would see in coarse scale modeling. The result is that total $PM_{2.5}$ (the combined concentrations

ACPD
13, 14141–14161, 2013

of primary and secondary $PM_{2.5}$ species each with different responses to resolution) is less sensitive to model resolution on average when compared to ozone in a policy context. As epidemiological data improve, and studies are able to provide concentration response functions specific to individual PM species, model resolution will become a more important consideration when evaluating the human health impacts of policy impacting PM.

The results shown here are presented in the context of policy and regulation. Human health impacts estimated using multiple resolutions, but with a single concentration response function are not independent and therefore statistical differences between them cannot be tested. In the context of policy, however, where decisions will be made based on the results estimated using a single model resolution, the findings here are important in demonstrating the trade-offs when modeling at a coarser resolution, and in demonstrating the input characteristics where these trade-offs are most important.

Population-weighted concentrations represent a rough but commonly used estimate of the potential for human exposure. Exposure depends not only on the ambient concentration of pollutants at any given time and location, but also on the exposure patterns, intake fractions, risk factors and sensitivity of the exposed population (US EPA, 2010). As exposure mapping procedures improve, the question of appropriate model resolution will need to be revisited.

5 Conclusions and implications for benefits analysis and policy

To evaluate the uncertainty associated with air quality modeling resolution for calculating health benefits of proposed policies, we ran one modeling episode with two emissions inventories (a 2005 base case and a 2014 control scenario) at 36, 12, and 4 km resolutions.

We compared the difference in the population weighted ozone concentrations between resolutions and between the 2005 base case and the 2014 control scenario. The coarse scale resolution (36 km) showed the largest decrease in pollution exposure

ACPD
13, 14141–14161, 2013

from the base case to the control scenario case. The impact of resolution on estimated changes in $PM_{2.5}$ was smaller, likely due to competing effects on estimates of primary and secondary species.

We used BenMAP to calculate acute mortality including eight peer-reviewed concentration response functions for ozone, and three for $PM_{2.5}$. The mean value calculated by the coarse resolution model fell within the range of uncertainty as calculated by both the 12 km and the 4 km resolution for all $PM_{2.5}$ health impacts. Since total impacts (ozone plus $PM_{2.5}$) are dominated by $PM_{2.5}$, the same claim can be made for total impacts. However, when looking at just the impacts of changes in ozone on human health, it appears that resolution does matter. For all eight crfs in Houston, New York City and Detroit, the 36 km mean results fell outside the uncertainty range estimated using 12 km and 4 km results. In Atlanta and Washington DC, three and five of the crfs respectively provided 36 km mean results that fell outside of the finer resolution 95 % uncertainty range. Therefore, we conclude that, with respect to ozone modeling in cities, the 36 km results have the potential to overestimate the benefits to human health when compared to the results obtained using fine scale modeling.

Given the uncertainty associated with human health impacts and the results reported in Figs. 2 and 3, we conclude that human health benefits associated with decreases in ozone plus $PM_{2.5}$, when calculated at 36 km resolution are indistinguishable from the benefits calculated using fine (12 km or finer) resolution modeling in the context of policy decisions. However, as human health responses becomes better known and the span of the uncertainty range decreases, more accurate air quality modeling results will be needed, potentially requiring the use of finer scale modeling.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/13/14141/2013/acpd-13-14141-2013-supplement.pdf.

ACPD
13, 14141–14161, 2013

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ACPD
13, 14141–14161, 2013

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ACPD
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ACPD
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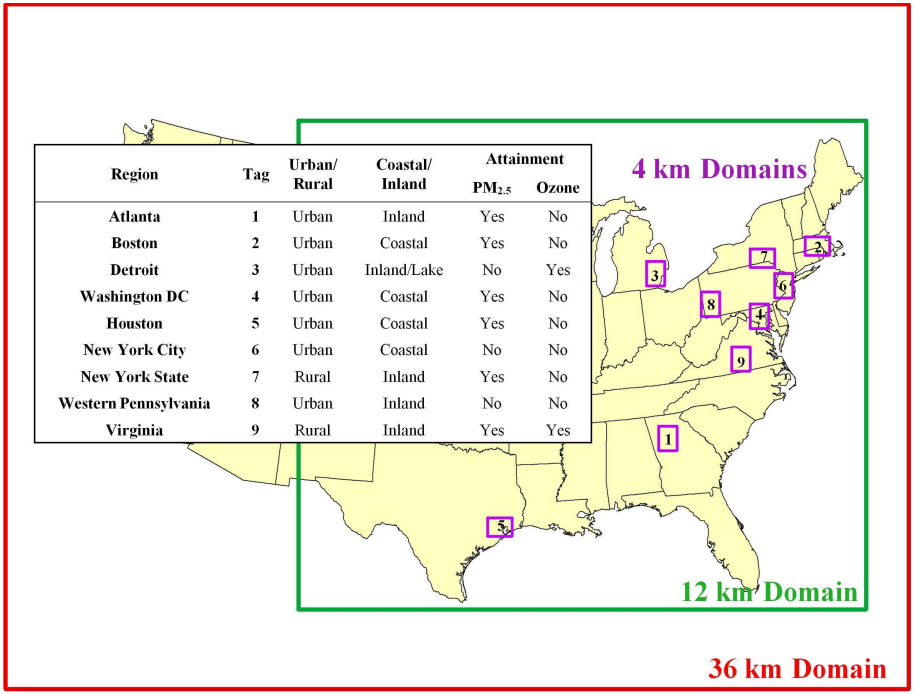

Region	Tag	Urban/ Rural	Coastal/ Inland	Attainment $PM_{2.5}$	Attainment Ozone
Atlanta	1	Urban	Inland	Yes	No
Boston	2	Urban	Coastal	Yes	No
Detroit	3	Urban	Inland/Lake	No	Yes
Washington DC	4	Urban	Coastal	Yes	No
Houston	5	Urban	Coastal	Yes	No
New York City	6	Urban	Coastal	No	No
New York State	7	Rural	Inland	Yes	No
Western Pennsylvania	8	Urban	Inland	No	No
Virginia	9	Rural	Inland	Yes	Yes

Fig. 1. Modeling domain. The extent of the 36 km domain is shown in red, the 12 km domain is shown in green, and nine 4 km domains are shown in purple. The results reported for each of the three resolutions apply to the nine 4 km sub-domains shown here.

ACPD
13, 14141–14161, 2013

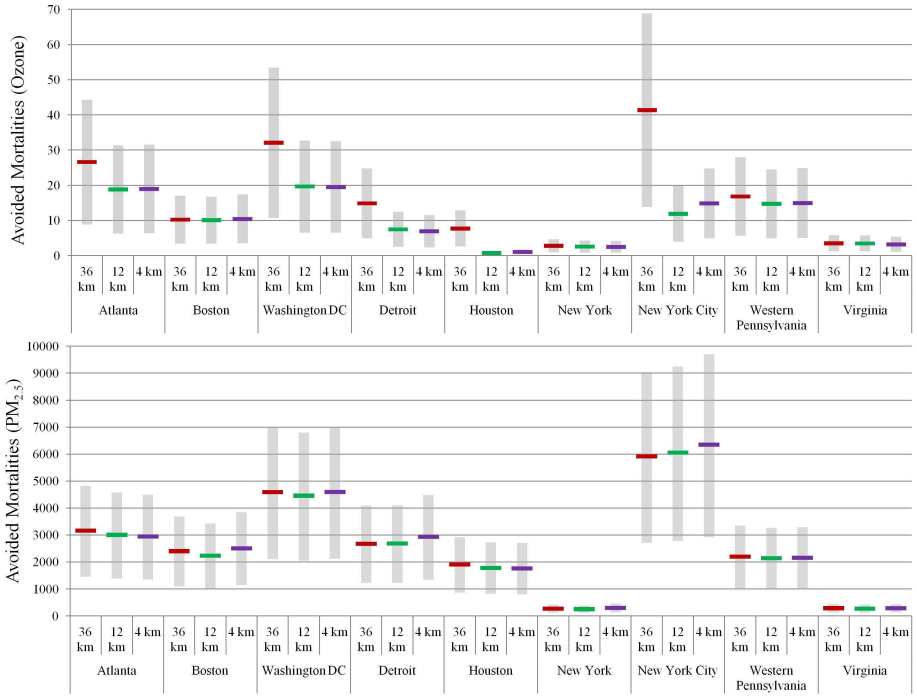

Fig. 2. (a) Mortalities avoided due to changes in ozone concentrations between the 2005 base case and the 2014 control case for each model resolution (red = 36 km, green = 12 km, blue = 4 km), calculated using the concentration response function developed by Bell et al. (2004). **(b)** Mortalities avoided due to changes in $PM_{2.5}$ concentrations between the 2005 base case and the 2014 control case for each model resolution (red = 36 km, green = 12 km, blue = 4 km), calculated using the concentration response function developed by Laden et al. (2006).

ACPD
13, 14141–14161, 2013

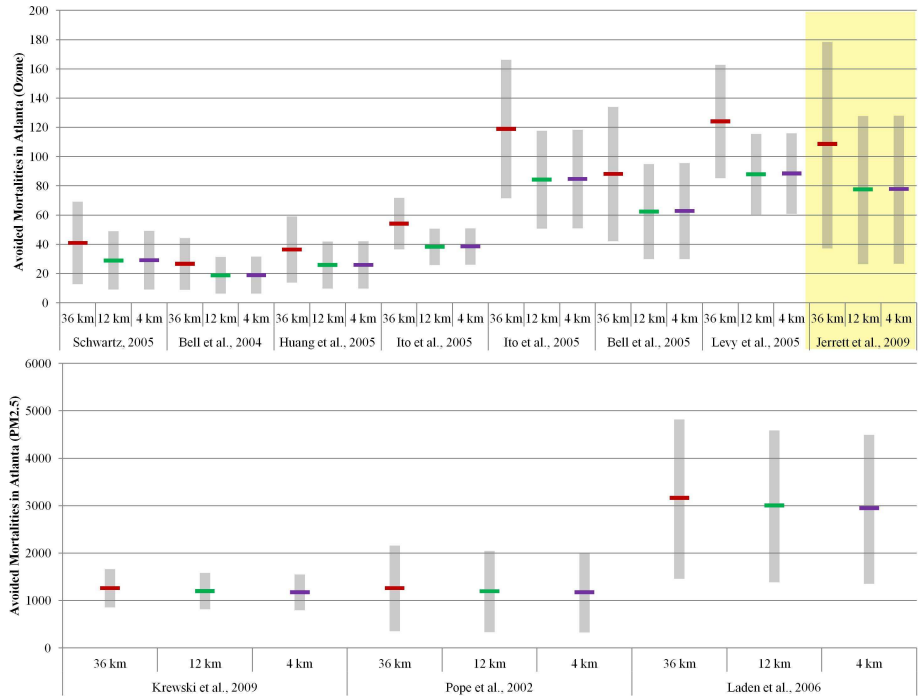

Fig. 3. (a) Mortalities avoided due to changes in ozone concentrations between the 2005 base case and the 2014 control case for each model resolution (red = 36 km, green = 12 km, blue = 4 km), calculated using eight different concentration response functions. The right most crf result, highlighted in yellow represents estimates for long-term effects of ozone exposure. All other ozone crf results represent short-term effects. **(b)** Mortalities avoided due to changes in $PM_{2.5}$ concentrations between the 2005 base case and the 2014 control case for each model resolution (red = 36 km, green = 12 km, blue = 4 km), calculated using three different concentration response functions (crfs). All $PM_{2.5}$ crf functions represent estimates for long-term effects of $PM_{2.5}$ exposure.

ACPD
13, 14141–14161, 2013