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Using CALPUFF to evaluate the impacts of power plant emissions in Illinois: model sensitivity and implications

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Abstract

Air pollution emissions from older fossil-fueled power plants are often much greater than emissions from newer facilities, in part because older plants are exempt from modern emission standards required of new plants under the Clean Air Act. To quantify potential health benefits of emission reductions, there is a need to apply atmospheric dispersion models that can estimate the incremental contributions of power plants to ambient concentrations with reasonable accuracy over long distances. We apply the CALPUFF atmospheric dispersion model with meteorological data derived from NOAA's Rapid Update Cycle model to a set of nine power plants in Illinois to evaluate primary and secondary particulate matter impacts across a grid in the Midwest. In total, the population-weighted annual average concentration increments associated with current emissions are estimated to be $0.04\,\mu g\,m^{-3}$ of primary fine particulate matter ($PM_{2.5}$), $0.13\,\mu g\,m^{-3}$ of secondary sulfate particles, and $0.10\,\mu g\,m^{-3}$ of secondary nitrate particles (maximum impacts of 0.3, 0.2, and $0.2\,\mu g\,m^{-3}$, respectively). The aggregate impact estimates are moderately insensitive to parametric assumptions about chemical mechanism, wet/dry deposition, background ammonia concentrations, and size of the receptor region, with the largest uncertainties related to nitrate particles and long-range transport issues. Additional uncertainties may be associated with inherent limitations of CALPUFF, but it appears likely that the degree of uncertainty in atmospheric modeling will not dominate the total uncertainty associated with health impact or benefit estimation. Although the annual average concentration increments from a limited number of sources are relatively small, the large population affected by long-range transport and the number of power plant sources around the US imply potentially significant public health impacts using standard epidemiological assumptions. Our analysis demonstrates an approach that is applicable in any setting where source controls are being evaluated from a public health or benefit-cost perspective.

Keywords: Health effects; Particulate matter; Meteorological modeling; Power plants; Uncertainty analysis

1. Introduction

Under the Clean Air Act, older power plants have not been compelled to meet the same requirements as new facilities, based in part on the assumption that control costs would be excessive and older plants would soon be phased out (Ackerman et al., 1999). However, the unintended consequence of this "grandfathering" has been reduced capital turnover and an extended lifetime for older facilities (Maloney and Brady, 1988; Nelson et al., 1993). As a result, pre-1980 coal-fired power plants currently contribute about half of the electricity generation in the US and are responsible for 97% of power plant sulfur dioxide (SO_2) and 85% of power

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plant nitrogen oxide (NO_x) emissions (and 65% and 24% of national emissions of SO_2 and NO_x, respectively) (NRDC, 1998).

As of February 2001, four states (Massachusetts, Connecticut, New Hampshire, and Texas) had proposed regulations or legislation to require grandfathered power plants to emit levels of NO_x and SO_2 that are comparable to levels required of newer facilities. Other states are considering similar requirements and federal legislation to reduce emissions from older facilities is being discussed. Regulations for grandfathered facilities can take an array of forms, with varying degrees of emissions trading, site-specific reductions, and pollutant-specific controls. To evaluate the merits of these regulations and to develop control strategies that most cost-effectively improve the public health, there is a need to construct models to predict the air pollution and related health benefits of any proposed policies.

Multiple large-scale studies in recent years (e.g., ORNL, 1994; EC, 1995; Rowe et al., 1995) have linked atmospheric dispersion modeling with epidemiological assessment to evaluate source-specific health impacts or environmental externalities. While some have tried to reconcile the differences between these studies (Krupnick and Burtraw, 1996; Levy et al., 1999), substantial differences remained that were attributed in large part to atmospheric modeling assumptions (in part because epidemiological evidence could be more readily transported between studies). The above studies were based in part on the long-term Industrial Source Complex model (ISCLT) and used models ranging in sophistication for long-range transport. The use of simple models for long-range transport and the need to merge the findings of multiple models undoubtedly has contributed to the significant model-related uncertainties. Moreover, past studies have generally done little to evaluate the degree of uncertainty in atmospheric modeling associated with critical parametric assumptions. These limitations make it difficult to determine appropriate estimates of environmental externalities and to evaluate important research directions to most effectively improve these estimates.

To address these issues within the context of evaluating the benefits of emission reductions at grandfathered fossil-fueled power plants, we selected the CALPUFF Lagrangian puff model (Earth Tech, Concord, MA). The US EPA has recommended CALPUFF for long-range transport modeling (US EPA, 2000), related to its ability to handle complex three-dimensional windfields. CALPUFF also allows for the estimation of both primary and secondary particulate matter concentrations, an important component given the context of our analysis. Although other prominent regional-scale models exist (such as UAM, Models-3, or REMSAD), CALPUFF was selected due to the US regulatory approval and because it could be run easily for single sources under multiple parametric assumptions to evaluate model sensitivity.

In this paper, we focus on a subset of power plants in Illinois to evaluate general trends and determine the influence of key atmospheric modeling assumptions on health-based conclusions. We consider the concentration increments associated with current emissions of both particulate matter and particle precursors, since these pollutants are relevant for the evaluation of health benefits. We use health evidence from past studies to estimate the mortality impacts of the concentration increments and to evaluate whether the magnitude of impacts merits closer investigation. We evaluate the sensitivity of our findings to key parametric assumptions and boundary decisions, and we compare the magnitude of these uncertainties with the expected uncertainties in other phases of a more comprehensive analysis to determine the next important steps for model enhancement.

1.1. Source characteristics

For this case study, we evaluated the aggregate impacts of nine grandfathered power plants in Illinois on a grid approximately 750 km × 750 km (Fig. 1). The nine facilities were selected as the major power plant sources in close proximity to or upwind of the Chicago area. We developed an emission scenario meant to reflect current emissions. Since the most recent publicly available emissions at the time of our analysis did not reflect recent emission controls at a subset of facilities, we estimated current practice from a combination of data sources. For SO_2 and NO_x, we combined reported emissions for the first two quarters of 2000 (EPA CEMS database) with 1998 heat rates to estimate expected annual emissions for 2000. For filterable $PM_{2.5}$, we first estimated PM_{10} rates by applying the emission rates per unit of heat input from 1997 (EPA AIRS database) to the 1998 heat rates. We then used the EPA's Particle Calculator Version 2.0.2 (US EPA, 2001) to estimate the $PM_{2.5}/PM_{10}$ ratio, given unit configuration and reported control technologies from EIA-767 forms. We also estimated condensable PM using the latest AP-42 emission factors and 1998 facility heat inputs, with coal sulfur content derived from COALdat (Resource Data International, Inc.) data for January–July 2000. Since Edwards is the only facility not using low-sulfur coal, the condensable rates are somewhat higher. For Will County, given a reported doubling of the electrostatic precipitator area on Unit 4 in recent years, we assume (given no measured emissions) that this resulted in a halving of particulate emissions from that unit. All emissions were assumed to be uniform across the year, a simplifying assumption due to data limitations. The nine power plants have slightly higher summer generation and emissions, but seasonality is generally mild for these

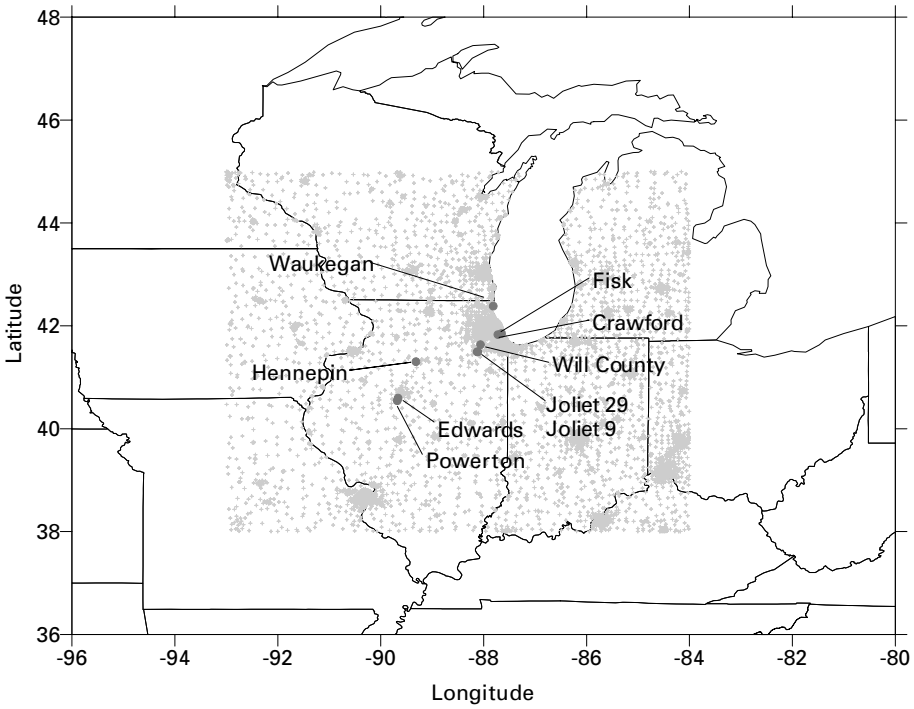

Fig. 1. Location of nine modeled power plants and scope of receptor region.

facilities and would not be expected to substantially influence the results.

All stack characteristics are listed in Table 1 and all emission rates are listed in Table 2. Within this report, we focus exclusively on the impacts associated with current emissions. Lower target rates achievable by Best Available Control Technology (BACT) could be readily defined, but this would require us to evaluate assumed unit-by-unit control strategies (which depend on emissions trading provisions and other cost-related issues). Modeling the behavior of individual power plants and companies under an array of possible regulations is beyond the scope of this report, although we approximate the magnitude of control benefits given on-site compliance.

1.2. Methodology

To develop meteorological data for CALPUFF, we combined NOAA prognostic model outputs with mesoscale data assimilation systems for a full year (26 January 1999–25 January 2000). Although computationally intensive for a long-term analysis, this approach is preferred to diagnostic windfield models because of the imposition of dynamic constraints to the system. We used NOAA's Rapid Update Cycle (RUC2) model to represent upper air features captured by the radiosonde network in addition to other data sources such as upper level winds determined from satellite imagery analysis, VHF radio sounders, and ACARS aircraft-reported wind and temperature data. One drawback in applying the RUC2 data directly to air quality studies is that it provides 40 km grid spacing, which is insufficient resolution to capture the relevant flow and thermal structures at ground level.

To introduce high-resolution terrain and surface observations, we use the ARPS Data Assimilation System (ADAS) as our primary mesoscale assimilation tool. The ADAS system starts with a first-guess field derived from NOAA model data and then reads in observational data (surface, upper air, satellite, and radar) and performs climatological, spatial, and temporal continuity checking for invalid data. The range of data sources is blended into a unified three-dimensional distribution for each target variable, using the Bratseth implementation of the optimal interpolation algorithm. Mass conservation and boundary conditions are applied to derive the vertical motion fields.

The datasets developed by this system can be input into CALMET using its ability to ingest MM5 fields and interpolate them to the CALMET grid. For this study, a grid was developed to cover the domain of interest at a cell size of 15 km. The grid has 14 vertical levels, going up to about 5100 m AGL, with vertical grid spacing stretched from about 20 m near the ground to 600 m near the top of the domain. This allowed CALMET to

Table 1
Unit and stack parameters for nine power plants in Illinois

Plant	Unit	Nameplate capacity in Megawatts (1998)	Heat input in Million BTU (1998)	Stack height (m)	Stack inner diameter (m)	Exit temp (K)	Exit velocity (m/s)
Crawford	7	239.4	10,578,612	118	3.1	416	42.7
	8	358.2	15,991,284	115	3.6	422	43.9
Edwards	1	136.0	5,950,673	153	6.4	422	14.9
	2	280.5	13,735,495	153	6.4	422	14.9
	3	363.8	18,627,177	153	7.6	414	12.5
Fisk	19	374.1	18,901,367	136	4.3	444	35.1
Hennepin	1	75.0	3,345,169	84	4.4	415	27.1
	2	231.3	15,865,737	84	4.4	415	27.1
Joliet 29	71	660.0	13,507,203	168	5.3	417	36.6
	72	—	20,454,671	168	5.3	417	36.6
	81	660.0	9,641,086	168	5.3	417	36.6
	82	—	13,832,003	168	5.3	417	36.6
Joliet 9	5	360.4	15,430,328	137	4.3	422	39.3
Powerton	51	892.8	15,442,830	152	10.4	422	33.8
	52	—	14,714,863	152	10.4	422	33.8
	61	892.8	20,840,882	152	10.4	422	33.8
	62	—	19,943,596	152	10.4	422	33.8
Waukegan	17	121.0	5,360,512	101	3.5	450	21.0
	7	326.4	19,544,713	137	4.3	422	36.3
	8	355.3	23,596,412	137	4.1	422	37.2
Will County	1	187.5	5,464,305	106	4.0	445	29.6
	2	183.8	7,718,918	106	4.0	445	29.6
	3	299.2	17,601,858	137	4.5	422	36.9
	4	598.4	25,713,650	152	5.0	416	35.1

interpolate from a higher- to a lower-resolution grid (since CALMET uses eight vertical layers).

For each hour in the yearlong study, an ADAS analysis was performed using the RUC analysis for a first-guess field and combining it with the METAR surface observations. The assimilation of the surface data allows us to recapture high-resolution information lost to the 40 km grid and to recompute mass conservation in the presence of the higher-resolution 15 km terrain. In addition, METAR reports of fractional cloud coverage were analyzed to create a gridded cloud coverage field. Since the ADAS output incorporated the observations at the scale of the CALMET grid, we did not reintroduce the same data in the CALMET processing, but simply used CALMET to perform a terrain adjustment and to calculate the micrometeorological parameters used by CALPUFF.

The basic coordinate grid for CALMET consisted of 50 grid cells along the x-axis (east–west) and 52 grid cells along the y-axis (north–south), spaced 15 km apart, and the coordinate system was converted to a Lambert projection grid. The eight vertical layers incorporated into the CALMET processing had heights of 20, 50, 100, 500, 1500, 2500, 3500, and 4500 m. As mentioned above, the MM5 input data have 14 levels between the surface and about 5000 m, requiring a candidate choice of a subset of levels. To incorporate wet and dry deposition into the CALPUFF model, precipitation data were obtained from over 400 observing stations from the National Climatic Data Center (TD-3240 data). All CALMET program defaults were used to interpolate between these observing stations.

CALPUFF was run with separate model input files for each of the nine power plants. In general, we used the

Table 2
Estimated current emission rates of SO_2, NO_x, filterable $PM_{2.5}$, and condensable $PM_{2.5}$ from nine Illinois power plants (Annual average, g/s)

Plant	Unit	Estimated current emission rate			
		SO_2	NO_x	Filterable $PM_{2.5}$	Condensable $PM_{2.5}$
Crawford	7	98.0	45.6	1.8	1.5
	8	146.1	82.8	2.8	2.3
Edwards	1	388.5	40.2	0.3	12.8
	2	529.6	103.7	0.7	29.6
	3	569.4	117.9	0.9	40.1
Fisk	19	151.9	100.6	3.1	2.7
Hennepin	1	34.2	19.2	0.9	0.5
	2	162.4	91.3	4.9	2.3
Joliet 29	71	118.4	50.5	2.8	2.0
	72	179.3	76.5	4.2	3.0
	81	83.5	55.5	1.4	1.4
	82	119.8	79.6	2.0	2.0
Joliet 9	5	136.6	159.8	4.3	2.2
Powerton	51	121.9	168.8	2.9	2.2
	52	116.1	160.8	2.0	2.1
	61	164.5	227.8	3.9	3.0
	62	157.4	218.0	3.7	2.9
Waukegan	17	53.0	50.1	1.5	0.9
	7	202.8	64.7	4.6	3.4
	8	272.5	57.7	5.5	4.1
Will County	1	52.4	66.0	1.0	0.8
	2	70.4	95.5	1.4	1.1
	3	173.4	88.6	2.3	2.6
	4	256.7	74.0	1.7	1.9

CALPUFF default model assumptions for most parameters (corresponding to the values suggested by US EPA), with sensitivity runs for those parameters that were potentially influential. Our baseline model used the MESOPUFF II chemical transformation mechanism and the default wet and dry deposition model routines within CALPUFF with default chemical parameters and size distributions of particles. We used hourly ozone data taken from CASTNET stations in Perkinstown, WI (PRK1340), Alhambra, IL (ALH157), and Oxford, OH (OXF122), with the CALPUFF default value of 80 ppb used for dates when hourly data were not available at the time of our analysis (1–25 January 2000). Since background ammonia concentrations were not available, we used the CALPUFF default of 10 ppb with a sensitivity run using a concentration of 1 ppb. We did not incorporate building downwash into our CALPUFF model given a lack of available data, which likely has a minimal effect given tall stack heights.

The CALPOST program was used to develop concentration files for all modeled compounds. In order to match the predicted concentrations with the demographic data needed for health impact calculations, our final receptor grid consisted of the geographic centroids of all US census tracts between 38°N and 44°N and between 84°W and 93°W (8237 discrete receptors). Ground elevations of all receptors were developed at the CALMET grid scale and were input into the CALPUFF model. The final output of the post-processor consisted of annual average concentrations for each pollutant (SO_2, NO_x, $PM_{2.5}$, SO_4, and NO_3). We report particle sulfate concentrations as ammonium sulfate and nitrate as ammonium nitrate using the molecular masses to convert, discussing underlying assumptions in the sulfate–nitrate–ammonia system within our sensitivity analysis.

2. Results

Since we adopt a health perspective in this analysis and most epidemiological evidence points toward particulate matter as a stronger causal agent for mortality and morbidity than gaseous SO_2 or NO_x, we focus exclusively on primary and secondary particulate matter concentrations in this report and do not address the primary gaseous pollutants or ozone. In addition, under the assumptions that important health effects have linear dose–response functions with no population thresholds above current ambient levels, the population-weighted annual average concentration increment will correspond directly with the health effects. The magnitude of this figure is strongly influenced by the size of the receptor region, and this estimate is not necessarily indicative of the magnitude of local effects. Nevertheless, we focus on this measure in our analysis, with some discussion of geographic patterns of impacts.

Fig. 2 depicts the patterns and magnitudes of primary $PM_{2.5}$, sulfate, and nitrate concentration increments. As anticipated, the concentration increments for secondary particles are more uniform than for primary particulate matter, with secondary particulate matter concentrations peaking further from the source and diminishing more slowly with distance from the source. In the aggregate, maximal impacts are centered around the two power plant clusters near Chicago and Peoria, related to both primary and secondary particulate matter concentration patterns.

In total, the nine modeled power plants contribute $0.3\,\mu g\,m^{-3}$ to the population-weighted annual average concentrations of $PM_{2.5}$ across our receptor region. Thirteen percent of this total can be attributed to the

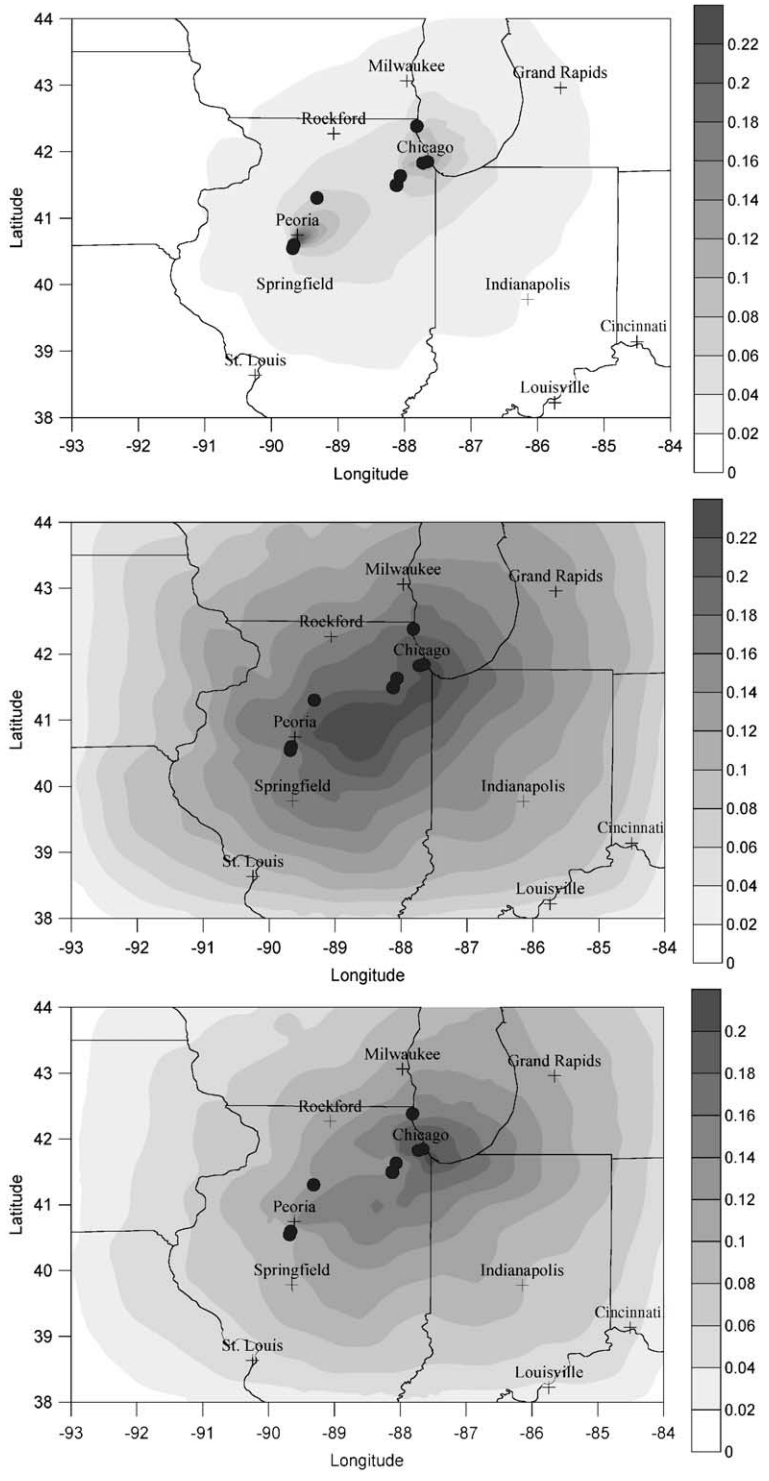

Fig. 2. Annual average primary $PM_{2.5}$, particulate sulfate, and particulate nitrate concentration increments ($\mu g\,m^{-3}$), using baseline CALPUFF dispersion model.

combination of filterable and condensable particulate matter, with 50% from sulfates and 37% from nitrates. The maximum concentration increment in any one location is $0.3\,\mu g\,m^{-3}$ of primary $PM_{2.5}$, $0.2\,\mu g\,m^{-3}$ of sulfates, and $0.2\,\mu g\,m^{-3}$ of nitrates (with the maxima occurring at different locations for each pollutant, but all in the Chicago–Peoria region). By way of comparison, annual average ambient $PM_{2.5}$ concentrations in Illinois in 1999 ranged between 14 and $22\,\mu g\,m^{-3}$, according to EPA AIRS data. Thus, these nine facilities contribute a relatively small fraction to ambient concentrations in any one setting (maximum total $PM_{2.5}$ concentration increment of $0.6\,\mu g\,m^{-3}$, near Chicago), although this represents only a small subset of nationwide pollution sources influencing the region.

For policy purposes and to assist in model validation and future applications, we are also interested in quantifying the fraction of total health impacts occurring within given radii of the facilities. We can define "total exposure" as the sum across all receptors of the product of the ambient concentration increment and the population at the affected receptor. In Fig. 3, we provide the fraction of the total exposure occurring within given radii of a source, by pollutant and power plant (including all power plants combined). This figure indicates that the distribution of total exposure depends on population patterns, with sources located closer to Chicago having greater amounts of total exposure closer to the source. In total, approximately 40% of primary $PM_{2.5}$ total exposure is located within 50 km of the power plants, with values ranging from 3% to over 80% across plants. Another 30% of combined total exposure occurs between 50 and 200 km, with the remainder beyond 200 km. In contrast, for secondary sulfates, approximately 20% of combined total exposure is located within 50 km of the power plants (range: 1–45%), with half beyond 200 km. The importance of longer-range impacts is similar for secondary nitrates, which has 25% of combined total exposure within 50 km (range: 1–50%) and over 40% beyond 200 km. It should be noted that the absolute magnitude of these percentages would differ if the geographic scope of the analysis were changed, but the relative comparisons between different radii would not change.

To give a sense of the potential public health impacts of these modeled concentration increments, we apply a concentration-response function for premature mortality derived elsewhere (Krewski et al., 2000). Although this is quite uncertain and has numerous issues associated with its implementation (e.g., weight of evidence for causality, possibility of population thresholds, differential effects by particle type or subpopulation, magnitude of life lost), this discussion is beyond the scope of this paper. The range of uncertainties associated with alternative health effect models and studies is discussed in Levy and Spengler (2001). We present this calculation as a simple illustration of the approximate magnitude of health impacts using standard epidemiological assumptions. The central estimate of a 0.5% increase in premature mortality risk per $\mu g\,m^{-3}$ increase of annual mean $PM_{2.5}$ concentrations is derived from a model that reanalyzed data from the American Cancer Society cohort study of adults age 30 and older (Pope et al., 1995). We apply this risk to a national average mortality rate of 0.014 deaths/person/year for people age 30 and older (Murphy, 2000). Doing this, we estimate approximately 320 premature deaths per year among the population in our region (33 million, of which 18 million are age 30 or older) due to current emissions from nine Illinois power plants.

2.1. Sensitivity analysis

With the above findings as our baseline, we consider some of the primary elements of parametric uncertainty within our CALPUFF application. This includes uncertainties that can be quantified (e.g., the incorporation of wet and dry deposition, the choice of chemical conversion mechanism, background pollution concentrations, and the size of the receptor region) and those that can be discussed qualitatively (uncertainties in the meteorological data). In this section, we do not address emission factor uncertainties (including possible seasonality of emissions or issues related to $PM_{2.5}/PM_{10}$ conversion), health effect estimate uncertainties, or model uncertainties associated with CALPUFF itself.

For deposition, we would expect substantial uncertainty in the plume depletion terms that produce wet and dry deposition losses. Past researchers have found that uncertainties of at least an order of magnitude exist for dry deposition of small particles (Seinfeld and Pandis, 1998) and that dry deposition velocity and scavenging coefficients range by two to three orders of magnitude across studies (McMahon and Denison, 1979). Wet deposition would be expected to be just as uncertain, especially related to the uncertainties involved with setting scavenging coefficients. Thus, even ignoring the fact that a deposition-based impact model should include indirect exposure pathways and environmental degradation associated with acid precipitation, our baseline model using CALPUFF-default deposition parameters could underestimate total impacts if deposition is overstated. Despite the numerous uncertainties regarding deposition terms, the results of the analysis change little when deposition is removed entirely from the model (Table 3). Inclusion of wet and dry deposition has the greatest impact on sulfate concentrations, with total impacts about two-thirds as high with deposition as without. Clearly, the impact of deposition on concentration changes will strongly depend on distance from the source, with a non-deposition model finding

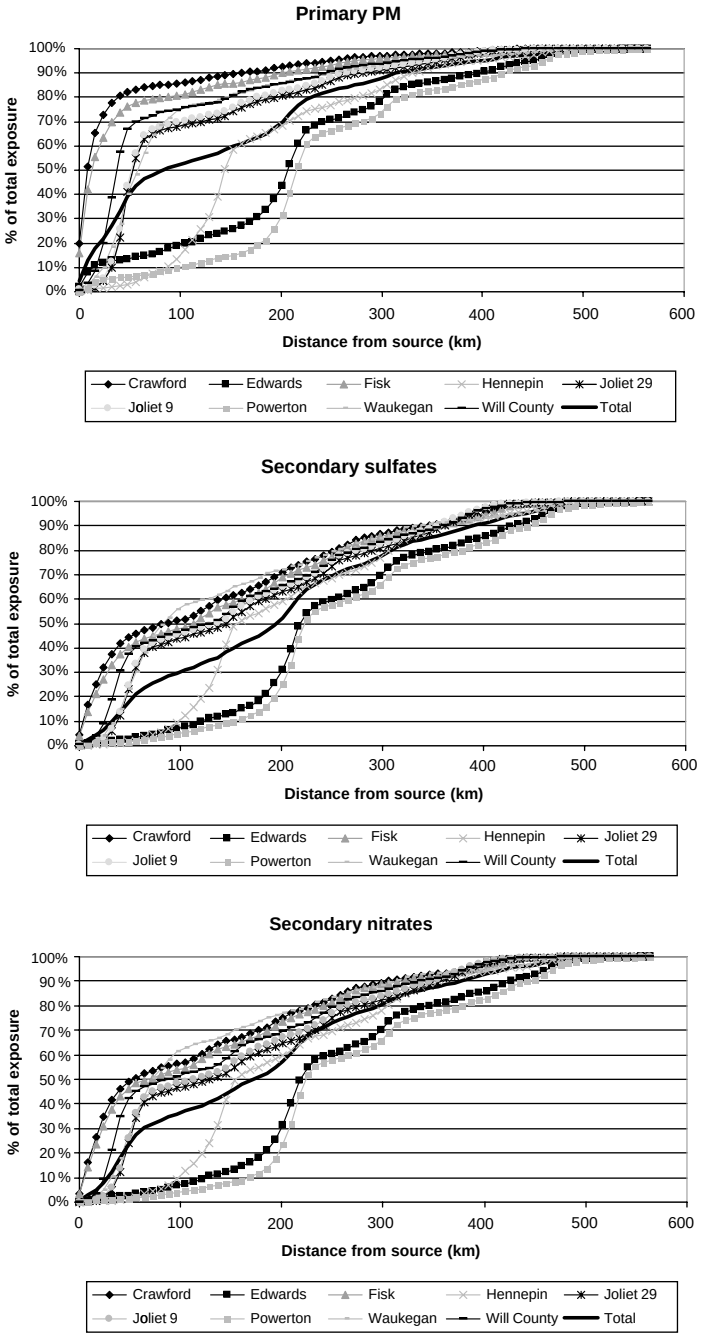

Fig. 3. Cumulative distribution of total exposure (concentration multiplied by exposed population), by power plant and pollutant.

more substantial long-range impacts than a model incorporating deposition. However, even this comparison is relatively insignificant, with 19% of the total exposure occurring within 50 km in the deposition-based model, compared with 17% in the non-deposition model. The possibility that deposition effects could be greater than implied by CALPUFF default parameters is not addressed in our quantitative analysis, but is certainly a plausible scenario that would reduce total impacts accordingly.

Another area of sensitivity in our CALPUFF model is related to the chemical mechanism used. The MESO-

Table 3
Summary of CALPUFF sensitivity analysis findings (ratio of population-weighted annual average concentration increments with model perturbation to baseline population-weighted annual average concentration increments)

Parametric change	Primary $PM_{2.5}$	Secondary sulfates	Secondary nitrates	Total exposure
1. Exclude wet/dry deposition	1.16	1.43	1.25	1.33
2. Use RIVAD/ARM3 chemical mechanism	1	0.95	1.70	1.23
3. Use 1 ppb background ammonia	1	1	0.70	0.89
4. Assume estimates beyond 200 km upwardly biased	0.85	0.76	0.79	0.78
5. Assume estimates beyond receptor grid based on fitted exponential regression models	1.24	2.14	1.70	1.85
Aggregate lower bound: 3,4	0.85	0.76	0.55	0.69
Aggregate upper bound: 1,2,5	1.43	2.90	3.60	3.03

PUFF II model selected in our model is preferred by the US EPA and is generally appropriate in most applications, but RIVAD/ARM3 has been stated to be appropriate in rural settings (which describes a portion of our receptor region) (Scire et al., 1999). Using RIVAD/ARM3 rather than MESOPUFF II has a minimal effect on primary particulate matter or secondary sulfates, but increases nitrate impacts by 70% and therefore increases total impacts by 23% (Table 3).

For background pollution, we used the CALPUFF default concentration of 10 ppb for ammonia, which may be an overestimate (particularly for urban and forested areas). Because of the preferential reaction between ammonia and sulfates, a lower ammonia concentration would tend to decrease particle nitrate concentrations prior to affecting particle sulfate concentrations. Reducing background ammonia to 1 ppb in our case study only affected secondary nitrate, lowering nitrate impacts by 30% (Table 3). Actual background ozone concentrations were used for most dates in our analysis, reducing the uncertainty associated with that parameter, but residual uncertainty could be associated with the use of default levels in January 2000 (when concentrations were far lower than 80 ppb). Although we do not quantify this term, since this background rate was used on $<7\%$ of dates, it is unlikely to have a significant effect on annual average impacts.

The final quantifiable element is the size of the receptor region, which consisted of points within approximately 400–500 km of the power plants. It is unclear whether this choice might result in an overestimate of impacts (if the model is upwardly biased at longer range) or an underestimate of impacts (if a significant fraction of total exposure occurs beyond 500 km). On the first point, tracer dispersion experiments have shown that CALPUFF is reasonably unbiased between 50 and 200 km but may tend to overestimate concentrations for greater transport distances by as much as a factor of 2, given the lack of accounting for nocturnal wind shear effects on enhanced dispersion (US EPA, 1999b). Assuming that all measurements within 200 km are unbiased but all measurements beyond 200 km are overestimated by a factor of 2 would reduce total impacts by 22% (Table 3). If we assume for the sake of argument that a similar magnitude of overestimation bias exists as well within 50 km (a range not evaluated in tracer dispersion experiments), total impacts would be reduced by 33%.

In contrast, long-range transport (especially for secondary pollutants) might be expected to influence populations more than 500 km from the source. We cannot directly quantify this effect given the lack of modeling outside of our receptor region, but we approximate the magnitude of longer-range impacts by fitting regressions to predict concentration increments as an exponential function of distance (by pollutant and power plant). Although these regression equations are simple and do not capture some of the atmospheric complexities (e.g., time to formation for secondary particles), the predictive power of the regression equations is high (R^2 between 0.48 and 0.90, with 20 of 27 equations having R^2 above 0.8). Assuming uniform population density for simplicity and assuming that these regression equations apply to indefinitely long distances, we estimate that our limited receptor region may have underestimated primary particulate matter impacts slightly and secondary sulfate and nitrate impacts by approximately a factor of 2 (Table 3).

With these quantified factors, we can combine the terms to determine the magnitude of aggregate

uncertainty associated with these assumptions. This is a simplistic calculation that does not attempt to place probabilistic weights on scenarios according to their plausibility and does not deal with interactions between terms (e.g., the importance of longer-range modeling would depend on the inclusion/exclusion of deposition). Rather, we intend to shed some light on the relative magnitude of uncertainty by pollutant for a limited number of parametric perturbations. As indicated in Table 3, these five factors indicate that, assuming any of the sensitive calculations to be potentially valid, our aggregate impact estimate may be overstated by approximately a factor of 1.4 or underestimated by a factor of 3. Primary $PM_{2.5}$ impacts are relatively more stable than secondary sulfate impacts, which are relatively more stable than secondary nitrate impacts. This ordering and the magnitude of the uncertainties are clearly functions of the parameters chosen in this brief parametric sensitivity analysis (e.g., ammonia concentrations, chemical mechanism), but they are indicative of the magnitude of quantifiable uncertainty within our CALPUFF analysis. Additional aspects of model interpretation and broad questions of model uncertainty are addressed in Section 3.

One dimension of unquantifiable uncertainty that merits discussion is the methodology used to derive meteorological data for CALPUFF. In general, the NOAA RUC2 data used to generate CALMET input files have been well validated and handle the development of the Planetary Boundary Layer (PBL) thermal structure in a more sophisticated fashion than often used for CALMET. However, uncertainties could arise through our choice of vertical levels within CALMET, since eight levels must represent the 14 levels in MM5 input data. Since our CALMET vertical levels include multiple heights close to the surface, there could potentially be missing data for near-surface layers. On the other hand, multiple MM5 data points are likely smoothed in the deeper layers (e.g., 500–1500 m), which could conceivably lead to an underestimation of plume spreading and consequent overestimation of long-range concentrations. In addition, the use of a single year of meteorological data (based on processing limitations) would contribute to uncertainty for generalized findings. While these factors cannot be directly quantified, they must be acknowledged in the overall assessment of uncertainty.

3. Discussion

Our analysis of the impacts of current emissions from nine Illinois power plants demonstrates that the findings are somewhat sensitive to key parametric decisions, with the magnitude of the sensitivity depending on the pollutant. Primary particulate matter impacts were relatively more certain, given that most of the impacts likely occurred within our receptor region and were insensitive to chemical conversion issues. Uncertainties in the $PM_{2.5}$ emission factors would likely add to the uncertainties, given some variation in assumed $PM_{2.5}/PM_{10}$ emission ratios across power plants. Sulfate impacts were somewhat more uncertain, with the most substantial quantified underestimate potentially related to the limited transport region evaluated. Secondary nitrate impacts were most uncertain, with selected parametric perturbations generally increasing total nitrate exposure. However, it is important to realize that the combination of assumptions yielding larger values (no deposition, RIVAD/ARM3 chemical mechanism) may not represent best modeling practice. In addition, given the complexities of the atmospheric chemistry related to particle nitrate formation, it is quite possible that the CALPUFF model has overstated nitrate impacts. Particulate nitrate will only form given sufficient ammonia to neutralize all available sulfate, with highly non-linear behavior that can potentially cause particulate nitrate formation to increase when SO_2 emissions decrease (West et al., 1999).

Given these estimated rankings and magnitudes of uncertainty, the critical question is whether they render CALPUFF or comparable models inapplicable from a public policy perspective. In addressing this question, it is important to keep in mind that the context of our modeling exercise is to quantify public health benefits of emission controls for ultimate use in benefit-cost analysis. Thus, assuming that decisions are made from a benefit-cost perspective without considering the distribution of benefits, we are only concerned about the ability of the dispersion model to estimate population-weighted annual average concentration increments (since this is directly proportional to health impacts assuming a linear concentration-response function that is not dose-rate dependent). We are also incorporating dispersion model evidence into a decision framework with uncertain health effects per unit concentration, uncertain monetary valuation of health outcomes, and uncertain estimates of control costs. Therefore, while dispersion model uncertainties of the magnitudes described in Table 3 might be considered substantial in many atmospheric modeling contexts, this uncertainty may be a relatively small contributor to overall benefit-cost uncertainty. For example, the difference in concentration-response functions between time-series mortality studies and cohort mortality studies is as much as an order of magnitude, with similar uncertainty regarding the proper monetary value to assign to an air pollution-induced premature death (US EPA, 1999a). Furthermore, the overarching question is whether the dispersion modeling uncertainty is of a sufficient magnitude to alter policy decisions based on CALPUFF analyses; if control strategies would not differ based on

reasonable changes in dispersion modeling methodology or findings, the uncertainty is unimportant from a decision-making perspective.

Of course, there are additional elements beyond aggregate benefits and aggregate costs that would concern decision makers. Even if a multi-pollutant approach were adopted, decision makers would like to know which pollutants might have more cost-effective controls, an assessment that could be affected by differential uncertainties or biases in dispersion modeling. Most decision makers would be concerned with the distribution of concentrations, and given geographical differences in disease prevalence and susceptible subpopulations, the distribution could have an influence on total health benefits. Any notion that CALPUFF (or other dispersion models) might be biased near the source or at long range would affect the populations who contribute most to total benefits.

However, one primary limitation of our analysis is that we have focused on parametric uncertainty within CALPUFF but have not seriously addressed the appropriateness of CALPUFF itself for this analysis. Major concerns have been raised about the limitations in the sulfate and nitrate chemistry (Garrison et al., 1999), issues related to puff splitting effects and subsequent overestimation of long-range concentrations (Paine and Heinold, 2000), and near-field plume dispersion (US EPA, 1998). CALPUFF uses a relatively simple framework for secondary particulate estimation, and some of the complexities in the sulfate–nitrate–ammonia system (Seinfeld and Pandis, 1998; West et al., 1999) may not be appropriately modeled in CALPUFF. In particular, CALUFF does not adequately address in-cloud conversion processes, resulting in underestimation of aqueous phase sulfate formation (US EPA, 1999b). Since aqueous phase chemistry is often the dominant source of sulfate formation, this omission could lead to a systematic underestimate of sulfate impacts. In a context where secondary particulate matter contributes a majority of the concentrations and impacts, further investigation is needed to evaluate whether CALPUFF can provide unbiased estimates on a population-weighted annual average basis.

An additional limitation is related to the difficulty of validating the model outputs. For our analysis, population-weighted annual average concentration increments were on the order of $0.3\,\mu g\,m^{-3}$. Although impacts were as high as $0.6\,\mu g\,m^{-3}$ close to the facilities and daily concentration variability at specific monitors might imply a larger effect on selected days, the magnitude is within the range of normal variation and monitoring instrument uncertainty. Validation of model outputs must instead rely on comparison with other modeling studies with a similar framework. As an example, a recent analysis calculated the intake fractions (effectively, the population-weighted average concentration increments multiplied by the exposed population and the population-average breathing rate and divided by the emission rate) for 40 power plants across the US (Evans et al., 2001). The mean estimates were 2×10^{-6} for primary PM (range: 3×10^{-7}–6×10^{-6}), 2×10^{-7} for secondary sulfates (range: 8×10^{-8}–3×10^{-7}), and 3×10^{-8} for secondary nitrates (range: 1×10^{-8}–8×10^{-8}). This study divided CALPUFF nitrate outputs by four to account for seasonality in particulate nitrate formation; removing this term results in a mean of 1×10^{-7} and a range of 4×10^{-8}–3×10^{-7}. Our nine plant-specific estimates correspond to total intake fractions of 1×10^{-6} for primary PM (range: 6×10^{-7}–4×10^{-6}), 2×10^{-7} for secondary sulfates (range: 1×10^{-7}–3×10^{-7}), and 3×10^{-7} for secondary nitrates (range: 2×10^{-7}–5×10^{-7}). Despite substantial differences in modeling approaches and geographic regions evaluated, this comparison demonstrates that our estimates are plausible when compared with a similar study, with perhaps greater uncertainties associated with nitrates than sulfates or primary particulate matter.

In spite of these limitations, we can draw some conclusions from our modeling exercise. The dispersion modeling demonstrates that the concentration impacts of emissions from a small number of power plants are relatively small on an annual average basis. However, long-range transport of pollutants (especially secondary sulfate and nitrate particles) implies that a large number of people are exposed to these small concentration increments, with public health impacts that are potentially significant. Unit-by-unit compliance with BACT within our study would decrease SO_2 and NO_x emissions by approximately a factor of 3, with a corresponding reduction in estimated health impacts (approximately 200 fewer deaths/year). A recent national-level study using REMSAD and a source-receptor matrix estimated that emission reductions from the US power sector achievable through the application of BACT would lead to approximately 20,000 fewer premature deaths/year (Abt Associates et al., 2000). It is worth noting that the nationwide emission reductions are two orders of magnitude greater than the reductions estimated for our nine Illinois power plants, providing further validation of the approximate magnitude of our estimates. If the magnitudes of these estimates are correct, applying models that can provide insight regarding pollutant-specific benefits as well as the geographic distribution of benefits would have valuable public policy applications.

In addition, secondary particulate matter appears to contribute a large portion of concentration/health impacts from emissions at grandfathered coal plants (assuming equal particle toxicity), related to both the high current emission rates of SO_2 and NO_x and long-range transport of secondary pollutants. This information can be used to help focus resources on the most

important pollutants. Finally, our analysis demonstrated that there is a gradient in concentration (and potentially health) impacts associated with emissions, which can have implications for the structure of control programs and the magnitude of benefits obtained by local communities.

Future analyses should focus on application of other regional dispersion models to validate our findings and other CALPUFF-based public health estimates. Using the findings of other dispersion models and more comprehensive evaluation of within-CALPUFF uncertainty, dispersion modeling uncertainty can be compared with health effects uncertainty and monetary valuation uncertainty (generated through literature evaluations and expert judgment) to determine the influential terms in benefit estimation models. Given a robust dispersion modeling construct, analyses of the states or regions which might provide the most cost-effective emission controls from a public health perspective can be useful in the structuring of public policy.

4. Conclusions

We have used the CALPUFF dispersion model to estimate the primary and secondary particulate matter impacts associated with current emissions from a set of nine older fossil-fueled power plants in Illinois. In total, these nine power plants provide $PM_{2.5}$ concentration increments of $0.3\,\mu g\,m^{-3}$ on a population-weighted annual average basis (maximum increment of $0.6\,\mu g\,m^{-3}$ close to the facilities), with a majority of impacts related to secondary particulate formation. Parametric sensitivity analyses demonstrate that these estimates are relatively robust and that dispersion modeling uncertainties may not be most influential in health benefit estimation, although further investigation is needed to determine the magnitude of uncertainty associated with CALPUFF itself. The magnitude of the public health impacts associated with these concentration increments is potentially significant and illustrates that accurate long-range dispersion modeling can provide meaningful and policy-relevant information for the regulatory community.

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