METHODS

Ambient Air Quality Data

We selected the pollutants and metrics for this analysis a priori on the basis of current hypotheses regarding potentially causal pollutants and components.[9,10] We also included pollutants in the a priori list that may be useful markers for sources or for groups of related pollutants (eg, carbon monoxide as a potential marker for primary traffic-related pollutants).

For the period 1 January 1993 through 31 August 2000, we obtained ambient air quality data for 24-hour average PM_{10} mass (PM with an average aerodynamic diameter less than 10 micrometers), 8-hour maximum ozone, and 1-hour maximum nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) from several existing monitoring networks, including the Air Quality System (AQS, formerly the Aerometric Information Retrieval System or AIRS), the Georgia Department of Natural Resources, and Metro Atlanta Index. (See map, with the electronic version of this article.) Ozone levels were not monitored during the winter months when ozone levels in Atlanta are low; the remaining pollutants were measured year-round. The AQS air quality data have been described elsewhere.[8]

For the final 25 months of the study period (1 August 1998 through 31 August 2000), an extensive suite of pollutants, including PM size fractions and components, was measured at the ARIES monitoring station. We selected the following pollutants and metrics for this analysis a priori: oxygenated hydrocarbons (OHC), $PM_{2.5}$ mass (PM with an average aerodynamic diameter less than 2.5 micrometers), coarse PM (PM with an average aerodynamic diameter between 2.5 and 10 micrometers), ultrafine PM count (PM with an average aerodynamic diameter between 10 and 100 nanometers [nm]), and the $PM_{2.5}$ components sulfate, acidity, elemental carbon (EC), organic carbon (OC), and an index of water-soluble transition metals. The metrics for PM size fractions and components and for OHC were 24-hour averages, 8-hour maximum for ozone, and 1-hour maximum for NO_2, SO_2, and CO. The measurement methods for the ARIES monitoring station have previously been described.[8,11]

Average temperature and dew point temperature (average of the daily minimum and maximum), as well as additional meteorological data measured at Hartsfield-Atlanta International Airport, were obtained from the National Climatic Data Center network. Speciated pollen counts were obtained from the Atlanta Allergy Clinic.

Emergency Department Data

Of the 41 hospitals in the 20-county Atlanta metropolitan statistical area, 37 agreed to participate and 31 provided usable computerized billing records for at least part of the study period. (The map available with the electronic version of this article shows hospital locations.)

Computerized billing records for all emergency department visits between 1 January 1993 and 31 August 2000 were collected, including primary International Classification of Diseases 9th Revision (ICD-9) diagnostic code, secondary ICD-9 diagnosis codes, age, date of birth, sex, race, and residential zip code. Residents of the Atlanta metropolitan statistical area, determined by residential zip code at the time of the visit, were included in the analyses. Repeat visits within a single day were counted as a single visit.

Respiratory case groups of interest were defined using the primary ICD-9 diagnostic codes (all 2-digit extensions were used unless otherwise specified): asthma (493, 786.09), COPD (491, 492, 496), URI (460–466, 477), pneumonia (480–486), and an all-respiratory-disease group that combines the above 4 groups. We assessed the adequacy of the modeling approach using visits for finger wounds (883.0), an outcome group that has comparable temporal variations to the respiratory outcomes of interest and is expected to be unrelated to air pollution.

Analytic Methods

All analyses were performed using SAS statistical software, version 8.2 (SAS Institute, Inc., Cary, NC) unless otherwise indicated. We defined a priori single-pollutant models to control for long-term temporal trends and meteorological conditions. For the a priori analyses we used Poisson generalized estimating equations,[12] with a stationary 4-dependent correlation structure to account for possible autocorrelation in the outcome data (URI, asthma, all respiratory disease) and Poisson generalized linear models[13] for outcomes with minimal autocorrelation (pneumonia, COPD). Risk ratios and 95% confidence intervals were calculated for an increase of approximately a standard deviation of pollutant levels. The basic model had the following form:

$$\begin{aligned} \log(E(Y)) = \alpha &+ \beta\, pollutant + \textstyle\sum_k \lambda_k\, DOW_k \\ &+ \textstyle\sum_m \xi_m season_m + \sum_n \nu_n\, hospital_n \\ &+ \textstyle\sum_p \zeta_p\, holiday_p + g(\gamma_1,\ldots,\gamma_N;\, time) \\ &+ g(\delta_1,\ldots,\delta_N;\, temp) + g(\eta_1,\ldots,\eta_N;\, dew\ point), \end{aligned}$$

where Y indicated the count of emergency department visits for a given day for the outcome of interest. The a priori models contained a 3-day moving average of pollution levels lagged 0, 1, and 2 days relative to the visits (levels on the same day as the visit, 1 day previous, and 2 days previous, respectively) (*pollutant*). Long-term temporal trends were accounted for using cubic splines with monthly knots [$g(\gamma_1,\ldots,\gamma_N;\, time)$]. Because ozone data were not available from November through March, ozone models used separate time splines for each year. Additional season indicator variables (the 21st day of March, June, September, and December) were added to further control for seasonal trends (*season*). Cubic splines also were used to control for daily average temperature [$g(\delta_1,\ldots,\delta_N;$ *temp)*] and dew point [$g(\eta_1,\ldots,\eta_N;$ *dew point*)] with knots at the 25th and 75th percentiles (moving average of lags 0, 1, and 2). Indicator variables for day of week (*DOW*), federal holidays (*holiday*), and hospital entry and exit (*hospital*) also were included in the a priori model (as the hospitals provided data for varying amounts of time). The cubic splines, *g(x)*, were defined as follows:

$$g(\gamma_1,\gamma_2,\ldots\gamma_N;x) = \gamma_1 x + \gamma_2 x^2 + \gamma_3 x^3 + \sum_{j=4}^{N}\gamma_j w_j(x),$$

where $w_j(x) = (x-\tau_j)^3$ if $x \geq \tau_j$, and $w_j(x) = 0$ otherwise. The cubic splines were defined so that the first and second derivatives were continuous. We evaluated multipollutant models using the same covariates as the single-pollutant models.

We performed several secondary analyses. To assess the lag structure between pollutant levels and emergency department visits, we initially examined separate models for each lag from 0 to 7 days before the visit (up to 2 weeks prior to the visit for asthma). To estimate the overall effect of a unit increase in pollution during the previous 2 weeks, and to investigate whether associations persisted longer than 3 days, we ran unconstrained distributed lag models, including pollution levels from 0 to 13 days before the visit, with additional cubic terms for lags 3–13 for temperature and dew point (in addition to the cubic splines for lags 0–2). For the distributed lag models we presented results only for the pollutants available for the entire study period as the models became unstable for the pollutants available only 25 months.

We examined age-specific case groups (ages 0–1 year, 2–18, 19 years and older, and 65 years and older) as well as season-specific models for warm (April 15 to October 14) and cool (October 15 to April 14) periods. Daily pollen counts (grass, oak, and ragweed) and daily counts of influenza emergency department visits were assessed as confounders. We also assessed general additive models using S-Plus 2000 software (Insightful Corporation, Seattle, WA) with nonparametric LOESS smoothers and nonparametric smoothing splines (10^{-14} convergence criterion).[14,15]

In addition to examining the alternate outcome group believed unrelated to air pollution (finger wounds), we performed other analyses to evaluate the adequacy of the modeling approach. We explored negative lags for pollution (pollution levels on days after the visit) as exposure variables, controlling for positive lags, to evaluate the possibility that the modeling choices induced positive associations. We altered the placement (day of the month) and number of knots (degrees of freedom) in the cubic splines for time.

RESULTS

Descriptive statistics for the air quality variables are presented in Table 1; Spearman rank correlation statistics between the daily measures were previously published.[8] (Appendix Table 1, available with the electronic version of this article, presents the correlation statistics.) The extent of correlation among the pollutants followed expected patterns. Ultrafine PM count levels were negatively correlated with several pollutants, including ozone, PM, and PM components (sulfate, acidity, and metals). CO, NO_2, $PM_{2.5}$ organic carbon, and $PM_{2.5}$ elemental carbon were moderately correlated (r = 0.55–0.68). PM_{10} and $PM_{2.5}$ mass were moderately correlated with the $PM_{2.5}$ components (r = 0.56–0.77). Acidity and sulfate were highly correlated with each other (r = 0.85) and moderately correlated with ozone (r = 0.64 and 0.63, respectively) and temperature (r = 0.84 and r = 0.64, respectively). The diurnal patterns of CO and NO_2 indicate that mobile source emissions contributed substantially to these pollutant levels. SO_2 levels peaked in both summer and winter, corresponding to peak energy demands. SO_2 levels exhibited marked temporal and spatial variability, with occasional mid-afternoon peaks resulting from power plant plume fumigation events. Compared with other U.S. cities, ozone and $PM_{2.5}$ are relatively high (with sulfate and organic carbon comprising relatively high proportions of $PM_{2.5}$ mass), and acidity is relatively low.[16]

The 31 hospitals providing usable data for these analyses receive 80% of the annual emergency department visits in the Atlanta area, and contributed information on 4,407,535 total emergency department visits. Respiratory problems accounted for 11% of all emergency department visits. For the entire study period, average daily outcome counts of the subgroups ranged from 7 for COPD to 103 for URI, and the combined respiratory disease group had an average daily count of 172 (Table 2). For the final 25 months of the study, the 31 hospitals contributed 1,888,973 visits.

Results from the a priori single-pollutant models examining 3-day moving averages (lags 0, 1, and 2) of pollutant levels are shown in Table 3. PM_{10}, ozone, NO_2, and CO were individually associated with 1–3% increases of URI visits per standard deviation increase of pollutant; similar results were observed for the combined respiratory disease group (60% of all respiratory visits were for URI). Weak and less stable associations were observed for URI in relation to SO_2, $PM_{2.5}$, and organic carbon. A 20 pbb increase of NO_2 and a 1 ppm increase in CO were associated with 3.5% and 2.9% increases of COPD visits, respectively. Additional estimates for COPD were elevated, but COPD was the smallest outcome group and therefore had the widest confidence intervals. A 2.8%