The role of statistics in assessing the public health threat of air pollution

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Background

Since its foundation in 1970, the United States Environmental Protection Agency (USEPA) has had as one of its prime functions the enforcement of air pollution standards to protect the public health. Currently there are six "criteria pollutants" for air pollution: PM_{10} (defined as particulate matter of aerodynamic diameter 10 μg or less), ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and lead. In recent years, most of the public health concern has been focussed on PM_{10} and, increasingly, on fine particles (so-called $PM_{2.5}$), which are believed to penetrate deeper into the lungs and therefore to have a more specific human health impact, especially on cardiovascular disease.

In 1997, the USEPA proposed a new particulate matter standard based on $PM_{2.5}$, to take effect alongside the earlier standard for PM_{10}:

- the three-year average of the 98th percentile of $PM_{2.5}$ should not exceed 50 $\mu g/m^3$,
- the arithmetic mean (over all monitors within a given region) of the three-year average of daily $PM_{2.5}$ levels should not exceed 15 $\mu g/m^3$.

Following a series of court challenges, this standard is not currently being implemented. However, at the time of writing, the USEPA is producing a new Criteria Document (required by the Clean Air Act to document the scientific case) and it is widely expected that this will lead to a new $PM_{2.5}$ standard by 2005.

Although there is no question that elevated levels of particulate matter are, in general, bad for human health, there are many open questions concerning the precise quantification and interpretation of the effect. In this paper, we review the overall evidence, followed by specific examples to illustrate some of the controversies. The final section of the paper concerns the assessment of the current levels of $PM_{2.5}$, a critical issue in assessing the impact of any proposed changes in the standards.

For an earlier review of statistical issues in the setting of air pollution standards, see Cox (2000).

Overview of major health effects studies

The health effects studies are broadly of two types,

1. *Time series studies*, in which a measure of daily health impact (typically, total mortality in the elderly population or hospital admissions for asthma, etc.) is regressed against a number of covariates, including long-term trends, meteorological effects and air pollution. Such studies typically show significant correlations between PM_{10} or $PM_{2.5}$ and the health indicator of interest.
2. *Prospective studies*, in which a cohort is followed for a long period of time to determine long-term effect of air pollution together with unrelated health impacts such as smoking.

The time series studies have been extended to monitor PM_{10} effects for the largest 90 cities in the US as part of the NMMAPS study (Samet *et al.* 2000a, 2000b). During 2002, the discovery of a "software glitch" in the use of certain defaults in S-PLUS Generalized Additive Models software led to a reassessment of the entire research. The software problems have now been solved but the effect is to reduce by about one half the estimates of the pollution-mortality coefficient, with some rise in standard errors (Dominici *et al.* 2003a).

There are other interpretational issues connected with the time series studies including the possibility of nonlinear effects and thresholds (discussed further below) and the so-called "harvesting effect" which postulates that the mortality might be confined to a small group of already very sick patients (Dominici *et al.* 2003b).

Concerning the prospective studies, there have been three widely cited studies relevant to the current debate, those of Dockery *et al.* (1993), Pope *et al.* (1995) and Abbey *et al.* (1999). The first two were extensively re-analyzed by Krewski *et al.* (2000). These studies do measure long-term effects and also have considered explicitly the effect of $PM_{2.5}$ as opposed to PM_{10} or other pollutants. Nevertheless, there remain numerous statistical questions for the interpretation of these studies, some of which were noted in the reviewers' discussion of Krewski *et al.* (2000) and will be elaborated further in the verbal presentation.

An example: Time series analysis of data from Phoenix, Arizona

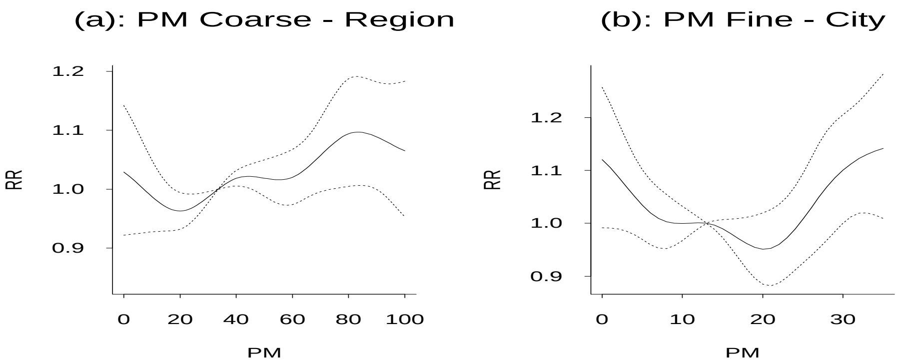

Fig. 1: Relative risks for PM_{10} and $PM_{2.5}$ in Phoenix, with confidence bands, relative to the overall mean PM_{10} or $PM_{2.5}$.

An example of some of the interpretational difficulties is given by Smith *et al.* (2000). This study included a comparison of $PM_{2.5}$ and coarse particle ($PM_{10}-PM_{2.5}$) effects on elderly mortality in Phoenix. Among the conclusions were

1. A comparison of linear effects showed that the $PM_{2.5}$ effect was not significant, but the coarse particles effect was, contrary to current beliefs about the relative effects of fine and coarse particles.

2. However, when the comparison was extended to include nonlinear effects, a $PM_{2.5}$ effect appeared above 20 $\mu g/\mathrm{m}^3$, higher than the proposed standard for long-term $PM_{2.5}$. See Fig. 1.

3. A comparison of seasonal effects suggested that the coarse particles effect was seasonal, but (again contrary to conventional wisdom) the effect appeared to be concentrated in the season for which the particles could be attributed to natural rather than anthropogenic causes.

These results may just be isolated departures from the overall trend, but they demonstrate the need to take nothing for granted.

Analysis of current $PM_{2.5}$ levels

At the time the new $PM_{2.5}$ standard was proposed, there was no national network of $PM_{2.5}$ monitors, so nobody really knew what the practical effect of the standard would be. Since 1999, an extensive network of around 800 monitors has existed, but there have been few detailed statistical studies of the data. The present analysis (Smith *et al.* 2003) is one such study. This study was limited to weekly data collected during 1999 on 74 monitors in the states of North Carolina, South Carolina and Georgia.

After taking square roots to stabilize the variances, a model was fitted of form

$$y_{xt} = w_t + \psi_x + \theta_x + \eta_{xt} \tag{1}$$

in which y_{xt} is the square root of $PM_{2.5}$ in location x in week t, w_t is a week effect, ψ_x is the spatial mean at location x (in practice, estimated through a thin-plate spline representation), θ_x is a land-use effect corresponding to the land-use as site x, and η_{xt} is a random error.

Spatial-temporal analysis of the η_{xt} terms suggested the values are independent in time but correlated in space, with a variogram of form

$$\begin{aligned} \gamma(h) &= E\left\{(\eta_{xt} - \eta_{x't})^2\right\} \\ &= \begin{cases} 0 & \text{if } h = 0, \\ \theta_0 + \theta_1 h^\lambda & \text{if } h > 0, \end{cases} \end{aligned} \tag{2}$$

where $h = |x - x'|,\ \theta_0 > 0,\ \theta_1 > 0,\ 0 \le \lambda < 2$.

The model defined by (1) and (2) was fitted to the data, and used to construct an interpolated surface and its standard errors, both for a single week of high $PM_{2.5}$ and for the overall average of $PM_{2.5}$ (Fig. 2).

Overall, the study confirms that the majority of the region under study currently violates the annual mean $PM_{2.5}$ standard. Other studies have suggested that this is true for the whole country, not just for the three states analyzed here.

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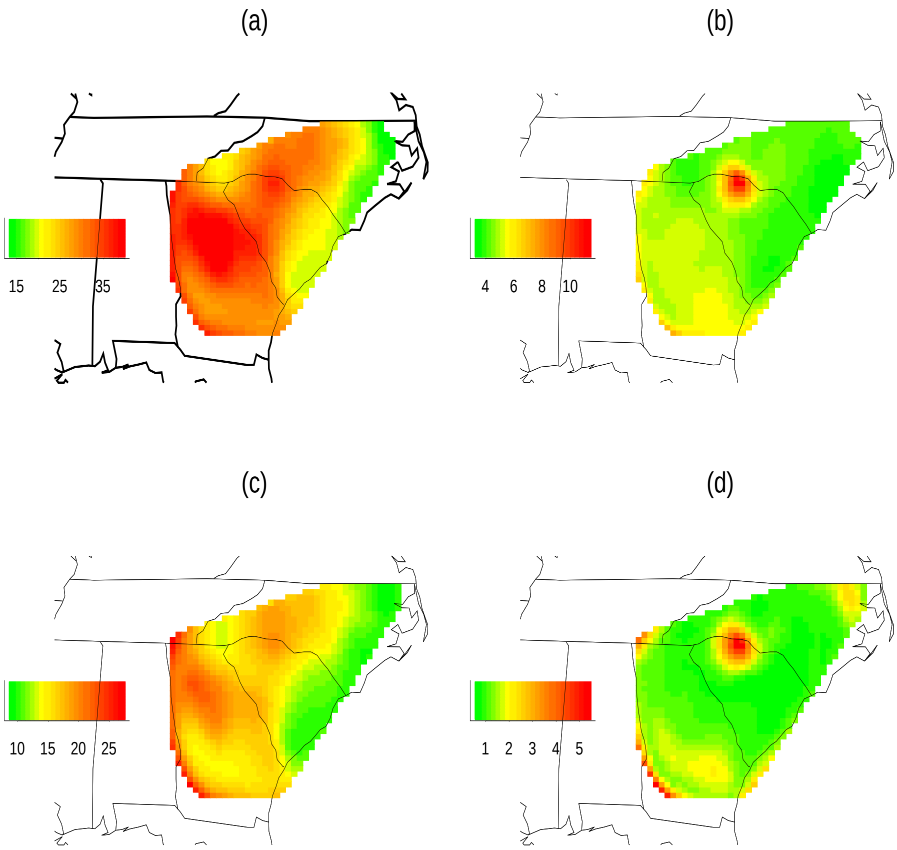

Fig. 2. (a) Map of estimated $PM_{2.5}$ surface in residential locations for week 33 of data. (b) RMS prediction errors for map in (a). (c) Map of estimated $PM_{2.5}$ surface in residential locations averaged over all weeks of data. (d) RMS prediction errors for map in (c).

We review current work on air pollution standards in the USA, focussing on (a) health effects research, (b) spatio-temporal analysis of current air pollution levels, in order to assess the likely impact and benefits of proposed tightened air pollution standards. The paper highlights a number of areas in which statistical analysis is relevant to assessing the case for tightened standards.