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Beyond point estimates in Air Quality Health Indices: A severity-informed analysis of pollutant risk weights

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INTRODUCTION

Air Quality Health Indices (AQHIs) represent an important advance in translating epidemiological evidence into actionable public health communication. A recent proposal by Adebayo-Ojo et al. [1] constructed a globally applicable AQHI using concentration-response functions (CRFs) derived from two systematic reviews and meta-analyses [2,3]. In its $PM_{2.5}$-based variant, the index assigns inverse weights (w_i) to$PM_{2.5}$, NO_2, SO_2 and O_3 based on their excess mortality risk (ER) at the 2021 WHO long-term Air Quality Guideline (AQG) values, yielding $\{PM_{2.5},NO_2,SO_2,O_3\}$ weights of $\{1.000,0.451,0.273,0.125\}$. The approach is transparent and evidence-based, yet it embeds an assumption that deserves critical scrutiny: that point estimates from meta-analyses can be treated as exact quantities in downstream computations. We argue that these risks conveying false precision in pollutant comparisons and illustrate -using the severity testing framework of Mayo and Spanos [4,5]- how the weight structure changes when uncertainty is formally accounted for.

The weighting mechanism and its statistical assumptions

The weight w_i for pollutant *i* with concentration c_i is defined as $ERPM_{2.5}/ER_i$, where $ER_i=100(e^{(\beta_i \cdot c_i)}-1)$ and β_i is the meta-analytic log-linear coefficient (per μg/m³) for pollutant *i* [1]. The WHO 2021 long-term AQG value for $PM_{2.5}$ is 5 μg/m³, substantially lower than for the gaseous pollutants (NO_2: 10 μg/m³; SO_2: 20 μg/m³; O_3: 60 μg/m³). Consequently, the ER at the $PM_{2.5}$ AQG is small relative to that of the other pollutants, which mechanically widens all weight ratios. Because each β_i coefficient carries a 95% confidence interval (CI), however, these ER values and their ratios are uncertain. The question is not merely whether the gaseous pollutants are riskier than $PM_{2.5}$ at their respective AQG concentrations (c_i), but by how much -and whether the point-estimate weight ratios faithfully represent the warranted magnitude of these differences.

The severity framework

Classical null hypothesis testing answers whether two estimates differ statistically, but not how large a difference is warranted by the evidence. The severity framework of Mayo and Spanos [4,5] addresses this directly. For a comparison $H_0{:}\delta\leq0$ versus $H_1{:}\delta>0$, where $\delta=ER_i\text{-}ERPM_{2.5}$, the severity of claiming $\delta>\gamma$ given observed statistic $T=\hat{\delta}/SE_\delta$, is $SEV(\delta>\gamma;x_0)=\Phi(T\text{-}\gamma/SE_\delta)$ where Φ is the standard normal CDF, and SE_δ is the standard error of δ. The minimum γ achievable at 90% severity is $\gamma_{90\%}=(T\text{-}1.28)\cdot SE_\delta$ A severity-informed weight $w_{i,SEV}=ERPM_{2.5}/(ERPM_{2.5}+\gamma_{90\%})$ rather than $ERPM_{2.5}/ER_i$, deliberately using the conservatively warranted minimum excess risk of the comparator pollutant rather than its point-estimate value. By design, this produces weights that are closer to unity, i.e., less differential than those derived from point estimates alone.

Numerical analysis

Standard errors were derived from published 95% CIs using $SE=(CI_{upper}\text{-}CI_{lower})/3.92$, where $3.92=2\cdot1.96$

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Table 1. Pairwise severity analysis of excess risk (ER%) at WHO 2021 AQG values relative to $PM_{2.5}$

Comparison	ERδ (%)	SEδ (%)	T statistic	SEV(δ > 0)	γ_{90}% (%)
NO_2 vs $PM_{2.5}$	0.396	0.0854	4.64	>99.9%	0.287
O_3 vs $PM_{2.5}$	2.289	0.2862	8.00	>99.9%	1.923
SO_2 vs $PM_{2.5}$†	0.863	0.1639	5.26	>99.9%	0.653

†SO_2 CI estimated from [3]; all other CIs from [2]. AQG = Air Quality Guideline; ER = excess risk; SE = standard error; T = test statistic; $\gamma_{90\%}$ = minimum discrepancy warranted at 90% severity; SEV = severity

is the full width of a 95% CI in SE units. From Orellano et al. [2], the $PM_{2.5}$ coefficient gives β=0.000648 per µg/m³ (SE=0.000107). The ER at the AQG value of 5 µg/m³ is 0.325% (SE=0.0535%). SE for the ER difference was obtained by the delta method as $SE_\delta = \sqrt{SE^2_{ER_i} + SE^2_{PM_{2.5}}}$. This formulation assumes statistical independence between the meta-analytic estimates of different pollutants, which is appropriate given they were predominantly derived from single-pollutant models in the underlying literature. Table 1 summarizes the pairwise severity analysis for each gaseous pollutant versus $PM_{2.5}$.

All three gaseous pollutants yield *T* statistics substantially above the 90% severity threshold (*T*>4.6 in all cases), confirming that they are genuinely riskier than $PM_{2.5}$ at their respective AQG concentrations. The O_3 comparison is the most striking (*T*=8.00), reflecting that its AQG concentration (60 µg/m³) is twelve times that of $PM_{2.5}$ (5 µg/m³), amplifying the absolute ER difference. The conservatively warranted minimum excess risks ($\gamma_{90\%}$) are 0.287 percentage points (pp) for NO_2, 0.653 pp for SO_2 and 1.923 pp for O_3.

Alternative severity-based weights

Severity-based weights are derived as $w_{i,SEV}=ERPM_{2.5}/(ERPM_{2.5}+\gamma_{90\%})$ Table 2 contrasts original and severity-based weights for all four pollutants.

The severity-based weights are consistently higher than the original point-estimate weights for all three gaseous pollutants. This is a structurally important result: it means that the original AQHI systematically overestimates the weight differentials between $PM_{2.5}$ and the gaseous pollutants. The downweighting of NO_2, SO_2 and O_3 is more aggressive in the original index than the available evidence statistically justifies. Practically, using the point-estimate weight of 0.124 for O_3 means that a day with very high ozone will contribute far less to the composite AQHI than a severity analysis supports (warranted weight: 0.144). The same logic applies to NO_2 (0.450 vs. warranted 0.531) and SO_2 (0.273 vs. 0.332).

The contrast with a PM_{10}-based AQHI is instructive. Using PM_{10} as reference (AQG = 15 µg/m³), the ER at the AQG is larger (0.617%), narrowing the gap with NO_2(0.721%) to the point that the NO_2–PM_{10} ER difference cannot be established at 90% severity at all (*T*=1.18). The $PM_{2.5}$ case is different precisely because its AQG value is so stringent that $PM_{2.5}$ER at the AQG is small, making all gaseous comparisons statistically robust. Nevertheless, even here the point-estimate approach overstates the warranted differentials.

DISCUSSION AND CONCLUSION

This commentary does not challenge the epidemiological rigor of the underlying meta-analyses [2,3], nor the value of multipollutant AQHIs as public health tools. Rather, it demonstrates that the $PM_{2.5}$-based AQHI weights derived from point estimates are more extreme, i.e., further from unity, than the evidence warrants. The severity framework [4,5] provides the formal apparatus to quantify this overstatement. Unlike standard confidence intervals, which bound the plausible range of a single parameter, severity analysis yields a post-data evidential statement about the magnitude of a difference: it identifies the minimum discrepancy that can be claimed with a specified degree of probing. This is precisely the quantity needed to construct defensible weight ratios.

Table 2. Original (point-estimate) versus severity-based weights (W) in the $PM_{2.5}$-based AQHI

Pollutant	Point-estimate weight	Severity-based weight (90%)	Basis for severity weight
$PM_{2.5}$	1.000	1.000	Reference
NO_2	0.450	0.531	$\gamma_{90\%}$=0.287%; ERc^{DD} = 0.611%
SO_2†	0.273	0.332	$\gamma_{90\%}$=0.653%; ERc^{DD} = 0.977%
O_3	0.124	0.144	$\gamma_{90\%}$=1.923%; ERc^{DD} = 2.247%

† SO_2 CI estimated from [3]. AQHI = Air Quality Health Index; ERc^{DD} = severity-warranted minimum excess risk at AQG concentration

A practically relevant consequence concerns Cape Town, where contributed little to the composite AQHI on most days because its weight (0.124) meant that even moderate ozone elevations were heavily discounted. The severity-based weight (0.144) partially corrects this. More broadly, the systematic nature of the bias -all gaseous pollutant weights being underestimated relative to what the data warrant- suggests that composite AQHI values in the $PM_{2.5}$-based variant may currently be lower than they should be on days when gaseous pollutants are elevated. By treating highly uncertain point estimates as exact, the original AQHI structure implicitly penalizes gaseous pollutants. A severity-based approach protects public health communication from this false precision by ensuring that the relative weighting of pollutants does not exceed what the data can strictly warrant.

We recommend that future AQHI construction incorporates: (i) formal uncertainty propagation (delta method or bootstrap) to derive CIs for weight ratios; (ii) sensitivity analyses presenting composite AQHI distributions under lower- and upper-bound weight scenarios; and (iii) the severity-based weighting rule proposed here as a minimum evidential standard. The methodology is applied at the construction stage and need not affect the public-facing traffic-light communication scheme.

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