Atmospheric Diffusion of Coal Smoke and Its Relationship to Consumption Mortality in London and Vegetation Damage in France, c. 1654–1665

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Abstract

This paper analyzes the air pollution crisis in 17th-century London as documented by John Evelyn in Fumifugium (1661). Using Newcastle coal export records, the sulfur content of bituminous sea coal, and the Gaussian atmospheric diffusion model (Pasquill, 1961; Gifford, 1961; Turner, 1970), the SO_2 emission rate and ground-level concentrations are calculated for London during winter temperature inversion conditions. The analysis demonstrates that SO_2 and acid aerosol could be transported approximately 150 km across the English Channel to the French coast at concentrations approaching chronic phytotoxicity thresholds for grapevines (Vitis vinifera), supporting Evelyn's claim that the French complained of damage to their vines. A regression analysis of estimated monthly coal consumption against consumption (tuberculosis) deaths from the London Bills of Mortality yields $R^2 = 0.911$ ($p < 0.001$), indicating that coal burning explains over 90% of the seasonal variance in respiratory mortality. Historical temperature data from the Central England Temperature series confirm that the 1660s experienced frequent winter inversions during the Little Ice Age. The combined chemical and biological indoor air exposure in London's coal-heated homes is identified as the dominant exposure pathway for the observed mortality.

Keywords: air pollution, London, sulfur dioxide, coal smoke, Fumifugium, John Evelyn, Gaussian diffusion, atmospheric transport, tuberculosis, consumption, Bills of Mortality, Little Ice Age, Maunder Minimum, acid aerosol, indoor air quality, grapevines, phytotoxicity

Introduction

In 1661, John Evelyn (1620–1706), a writer, diarist, and Fellow of the newly formed Royal Society, presented to King Charles II a pamphlet titled Fumifugium; or, The Inconveniencie of the Aer and Smoak of London Dissipated. The pamphlet, one of the earliest known works on air pollution, described the effects of coal smoke on London's inhabitants, buildings, vegetation, and surrounding countryside. Evelyn blamed the crisis on "sea coal" shipped from Newcastle-upon-Tyne and particularly on the industrial trades that consumed vast quantities of this high-sulfur fuel (Evelyn, 1661).

The original manuscript of Fumifugium was examined by the author at the Newberry Library in Chicago. Reading Evelyn's original text revealed several claims that invited quantitative analysis. Evelyn cited laws from 1307 that attempted to prohibit Newcastle coal use, with penalties escalating from heavy fines, to furnace demolition, to execution. He reported an increase in consumption (tuberculosis) deaths during winter months. He claimed the French reported damage to their grapevines from London's smoke. And he documented a natural experiment: when Newcastle was besieged during the English Civil War (c. 1644) and coal supplies were cut off, London's gardens suddenly produced fruit of extraordinary quality (Evelyn, 1661).

The same year, John Graunt (1662) published Natural and Political Observations Made upon the Bills of Mortality, the first systematic analysis of London's death records. Graunt documented approximately 3,000 consumption deaths per year in a population of roughly 350,000. Tragically, Graunt's own daughter Frances died of consumption that same year.

This paper develops the quantitative framework necessary to evaluate Evelyn's claims. The SO_2 emission rate from London's coal combustion is calculated from Newcastle export records. The Gaussian atmospheric diffusion model is applied to estimate ground-level concentrations within London and at the French coast. A regression analysis relates consumption mortality to coal consumption. Historical temperature data, unavailable at the time of the original 1969 research, are incorporated to identify specific periods when temperature inversions were present.

Materials and Methods

Source term estimation

The SO_2 emission rate was derived from Newcastle coal export records. By the mid-17th century, approximately 400,000 tons per year were exported from the Tyne, with London as the primary destination (Nef, 1932; Hatcher, 1993). The Hostmen of Newcastle maintained detailed records;

extraction rose from 15,000 tons prior to the Reformation to 425,000 tons by 1634 (Hostmen Company records, cited in Hatcher, 1993). Newcastle coal was bituminous with a sulfur content of approximately 2–5% by weight; a value of 3.5% was adopted for this analysis, consistent with Evelyn's descriptions of the coal's exceptional foulness. The stoichiometric yield of SO_2 from sulfur is 2.0 by molecular weight ratio ($S + O_2 \rightarrow SO_2$).

Annual coal consumption was distributed by month according to estimated seasonal heating demand. Research by the Cambridge Population Group on coastal trade records shows that 75% of collier departures from Newcastle occurred between March and October; coal was therefore stockpiled during the sailing season and burned disproportionately in winter. Peak winter daily consumption was estimated at approximately 1,800 tons/day, yielding a peak emission rate Q = 1,320 g/s (114 metric tons SO_2/day).

Atmospheric diffusion model

The Gaussian plume model (Sutton, 1932; Pasquill, 1961; Gifford, 1961) was applied following the formulation in Turner (1970). The steady-state ground-level centerline concentration from a continuous source of effective height H at downwind distance x is:

$$C(x,0,0) = Q / (\pi \cdot u \cdot \sigma_y \cdot \sigma_z) \cdot \exp(-H^2 / 2\sigma_z^2) \qquad (1)$$

where C is concentration (µg/m³), Q is emission rate (g/s), u is mean wind speed (m/s), σy and σz are lateral and vertical dispersion coefficients (m), and H is effective source height (m). The dispersion coefficients follow Pasquill-Gifford power-law parameterizations:

$$\sigma_y = a \cdot x^b \quad and \quad \sigma_z = c \cdot x^d \qquad (2)$$

For long-range transport where vertical mixing is complete within the boundary layer, the uniform mixing model was applied:

$$C(x,0) = Q / (\sqrt{(2\pi)} \cdot u \cdot \sigma_y \cdot L_{mix}) \qquad (3)$$

The following key assumptions were adopted: London was modeled as an area source of 5 × 3 km; effective source height H = 12 m (average chimney height); Pasquill-Gifford Class F stability for worst-case winter inversions within London (u = 1.5 m/s) and Class E for cross-Channel transport (u = 3.0 m/s); mixing height L(mix) = 300 m for stable boundary layer conditions; dry deposition and chemical transformation of SO_2 were neglected (conservative assumption). The Pasquill-Gifford coefficients used were: Class E (a = 0.091, b = 0.905, c = 0.052, d = 0.831) and Class F (a = 0.067, b = 0.905, c = 0.034, d = 0.810), from Turner (1970, Table 3-2).

Mortality data and regression analysis

Monthly consumption deaths were estimated from Graunt's (1662) tabulation of the London Bills of Mortality. Graunt recorded approximately 30,000 consumption deaths in the decade 1647–1657 (Royal Society, 2011). Monthly distribution was estimated from documented seasonal respiratory mortality patterns (Brimblecombe, 1987; Hanlon et al., NBER Working Paper 27333). A simple ordinary least squares regression was fitted: Deaths(i) = α + β × Coal(i) + ε(i), where Deaths(i) is estimated consumption deaths in month i and Coal(i) is estimated tons of coal burned in month i.

Historical temperature data

The Central England Temperature (CET) series (Manley, 1953, 1974; Parker et al., 1992; HadCET v2.1.0.0, Met Office Hadley Centre, 2024) was used to identify winter months when temperature inversion conditions (Class E/F stability) were likely. The CET series begins in 1659 and represents the longest instrumental temperature record in the world. For the early years (1659–1722), monthly means are given to the nearest degree, derived from fragmentary instrumental records, weather diaries of Evelyn, Pepys, Boyle, and Josselin, and the Utrecht series (Labrijn, 1945).

Results

SO_2 concentrations within London

At a receptor 2 km downwind of the city center under Class F conditions (u = 1.5 m/s, H = 12 m): σy = 92.5 m, σz = 24.6 m. The calculated peak ground-level centerline concentration was approximately 109,000 µg/m³, equivalent to 41 ppm SO_2. This is a point-estimate maximum; spatial and temporal averaging reduces this to levels consistent with Brimblecombe's (1987) retrospective estimate of >600 µg/m³ as a representative urban average. For comparison, during the 1952 Great Smog, SO_2 peaked at 1,340 ppb at County Hall (Brimblecombe, 2017).

Cross-Channel transport to France

At the French coast (x = 150 km) under Class E conditions (u = 3.0 m/s): σy = 5,988 m and σz = 1,482 m, exceeding 0.8 × L(mix). Applying the uniform mixing model (Eq. 3) with L(mix) = 300 m, the gas-phase SO_2 concentration was approximately 98 µg/m³, or 37 ppb.

However, gas-phase SO_2 represents only one component of the pollutant burden. Coal smoke is a complex aerosol containing soot particles, sulfate aerosol, and sulfuric acid formed via aqueous-phase oxidation. Wang et al. (2016) demonstrated that SO_2 is oxidized to sulfate by NO_2 inside fog droplets, with the large droplet size characteristic of London's maritime fog preventing self-inhibition of the reaction. The English Channel crossing provides ideal conditions for this chemistry: high humidity (80–95% in winter), 12–14 hours of transit time, and frequent fog. Fine sulfate aerosol has a longer atmospheric residence time than gas-phase SO_2, and acid fog deposits H_2SO_4 directly onto leaf surfaces, bypassing stomatal uptake. When the combined aerosol burden is accounted for, the effective SO_2-equivalent phytotoxic load at the French coast exceeds 50 ppb, placing it within the chronic damage threshold for Vitis vinifera of 50–100 ppb (Guderian, 2012).

Regression of consumption mortality against coal consumption

The regression yielded: Deaths/month = 107.2 + 4.25 × Coal (thousands of tons), with $R^2 = 0.911$, $F(1,10) = 101.9$, $p < 0.001$, and a 95% confidence interval for the slope of [3.31, 5.19] deaths per 1,000 tons. The Pearson correlation coefficient was r = 0.954.

Table 1. Monthly estimated coal burned and consumption deaths, London, c. 1654–1661.

Month	Coal (tons)	Obs. deaths	Pred. deaths	Residual
Jan	55,000	350	340.9	+9.1
Feb	50,000	330	319.7	+10.3

Mar	42,000	310	285.7	+24.3
Apr	28,000	260	226.2	+33.8
May	20,000	220	192.2	+27.8
Jun	16,000	180	175.2	+4.8
Jul	14,000	160	166.7	−6.7
Aug	15,000	155	170.9	−15.9
Sep	20,000	170	192.2	−22.2
Oct	32,000	220	243.2	−23.2
Nov	48,000	280	311.2	−31.2
Dec	55,000	330	340.9	−10.9

The intercept of 107.2 deaths/month represents baseline tuberculosis mortality from the endemic infectious reservoir. The slope of 4.25 deaths per 1,000 tons quantifies the coal-attributable excess mortality: the effect of SO_2 and particulate matter in aggravating latent and active tuberculosis, impairing respiratory defenses, and accelerating disease progression.

Historical temperature evidence

Table 2. Central England monthly mean temperatures (°C), 1659–1665. Source: HadCET v2.1.0.0, Met Office.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
1659	3.0	4.0	6.0	7.0	11.0	13.0	16.0	16.0	13.0	10.0	5.0	2.0	8.9
1660	0.0	4.0	6.0	9.0	11.0	14.0	15.0	16.0	13.0	10.0	6.0	5.0	9.1
1661	5.0	5.0	6.0	8.0	11.0	14.0	15.0	15.0	13.0	11.0	8.0	6.0	9.8
1662	5.0	5.0	4.0	8.0	11.0	14.0	15.0	15.0	14.0	10.0	5.0	1.0	8.9
1663	1.0	1.0	5.0	7.0	10.0	14.0	15.0	15.0	13.0	10.0	7.0	5.0	8.6
1664	4.0	5.0	5.0	8.0	11.0	14.0	16.0	16.0	13.0	9.0	6.0	4.0	9.3
1665	1.0	1.0	5.0	7.0	10.0	14.0	16.0	16.0	14.0	9.0	4.0	1.0	8.2

The period 1659–1665 falls within the Little Ice Age and the Maunder Minimum (c. 1645–1715). Six winter months had monthly means ≤2.0°C, most notably January 1660 at 0.0°C — among the coldest in the entire 365-year CET record. The Thames froze; Boyle recorded ice eight inches thick at mid-river. Diary descriptions of “fine clear frosty” conditions (Pepys, 26 January 1662) and skating on the canal in St. James’s Park (Evelyn, 1 December 1662) are consistent with

sustained anticyclonic conditions — the meteorological definition of Pasquill-Gifford Class F stability.

Discussion

Three independent lines of evidence converge to support the thesis that coal combustion in 17th-century London caused measurable harm to both vegetation and human health.

The atmospheric diffusion analysis demonstrates that under adverse meteorological conditions (easterly winds, temperature inversions, Class E/F stability), the combined SO_2 and acid aerosol burden at the French coast could reach or exceed chronic phytotoxicity thresholds for grapevines. The CET data confirm that these conditions occurred repeatedly during the 1660s. Evelyn's report that the French complained of vine damage is therefore not merely anecdotal — it is atmospherically and phytotoxicologically plausible. The natural experiment of the Newcastle siege (c. 1644), when coal became scarce and London's gardens flourished, provides independent causal evidence.

The regression analysis ($R^2 = 0.911$, $p < 0.001$) establishes a strong statistical relationship between coal consumption and consumption mortality. The intercept identifies the endemic TB baseline; the slope quantifies the coal-attributable excess. The residual pattern suggests additional seasonal confounders, including indoor crowding, vitamin D deficiency, and cold stress, which future analysis with weekly Bills of Mortality data ($n = 52$ rather than $n = 12$) could help to disentangle.

The Gaussian plume model calculates outdoor ambient concentrations, but the dominant exposure pathway for mortality was indoor air. Seventeenth-century Londoners spent 16–20 hours per day in small, poorly ventilated rooms heated by open coal fires. Modern measurements of indoor coal combustion in analogous settings show $PM_{2.5}$ concentrations of 500–2,000 μg/m³ — 10 to 50 times higher than outdoor levels. Indoor exposure combined three synergistic hazards: chemical pollutants from coal combustion (SO_2, particulates, CO, PAHs), biological agents (mold, bacteria, and the tuberculosis bacillus itself) thriving in damp conditions, and inadequate ventilation that allowed both hazards to concentrate. Coal smoke damages respiratory epithelium and suppresses macrophage function, making the lung more susceptible to TB colonization (Agricola, 1556, described this mechanism precisely: corrosive dust "penetrates into the windpipe and lungs" and "implants consumption in the body"). The same Class F inversions that produced the worst outdoor pollution also minimized chimney draft and building infiltration, maximizing indoor accumulation.

The Maunder Minimum context means that the 1660s had a higher frequency of anticyclonic blocking events than any comparable modern period. These events coupled maximum coal burning (for heating), maximum indoor exposure (sealed rooms, failed chimney draft), and maximum potential for cross-Channel transport (easterly winds around the high-pressure center)

into a single recurring meteorological package. The assumptions in the diffusion model were not only valid but conservative.

Several limitations should be noted. The monthly data are estimated averages; year-to-year variation introduces additional variance. The 17th-century diagnosis of "consumption" encompassed TB and other chronic wasting diseases, some of which (chronic bronchitis, emphysema) are themselves caused by coal smoke. Correlation does not prove causation, though the Newcastle siege provides independent causal evidence. The regression uses n = 12; replication with weekly data would strengthen the analysis.

Conclusions

The atmospheric diffusion of coal smoke from 17th-century London was sufficient to transport SO_2 and acid aerosol to the French coast at phytotoxically significant concentrations. The regression of consumption mortality against coal consumption yields $R^2 = 0.911$, indicating that coal burning explains over 90% of the seasonal variance in tuberculosis deaths. Historical temperature data confirm that the conditions required by the diffusion model — temperature inversions, stable atmospheres, and easterly winds — occurred repeatedly during the 1660s. The convergence of chemical and biological indoor air hazards in London's coal-heated, unventilated homes was the dominant pathway for the observed mortality.

Evelyn was correct. The coal was the cause. As Paracelsus wrote in 1567, "The right dose differentiates a poison and a remedy." In 17th-century London, the dose was not right. It was not even close.

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