Putting a price tag on air pollution: the social healthcare costs of air pollution in France

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Overview of my research interests

Axis 1: Estimating the cost of pollution

- Putting a price tag on air pollution: the social healthcare costs of air pollution in France
- The Societal Cost of Air Pollution from Energy Production: A Study of the 1970s French Energy Transition with Marion Leroutier, Hélène Ollivier and Aurélien Saussay
- Health Outcomes of Residential Agricultural Pesticide Exposure (HORAPEST) with with Olivier Allais, Philippe Caillou and Michèle Sébag

Axis 2: Avoidance and adaptation behaviour to environmental conditions

- Air pollution and choice of place of residence with with Olivier Allais and Antoine Nebout
- Effect of drought on child nutrition: health systems as mitigating factor with Christoph Strupat

Air pollution is the greatest external threat to human health on the planet

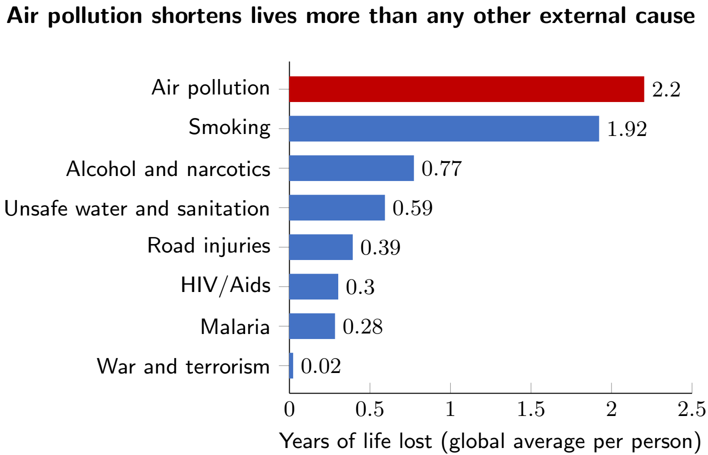

Figure: Years of life lost, global average per person in 2021. *Source: AQLI annual update, Lee and Greenstone*

Air pollution has well-documented adverse health effects, but costs are rarely quantified

Exposure to air pollution has well-documented adverse health effects

- Increased the risk for cardiovascular and respiratory disease, cancer, and generally all organs.
- 48,000 premature deaths in France per year vs. 73,000 for smoking and for 41,000 alcohol.

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Exposure to air pollution has well-documented adverse health effects

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- 48,000 premature deaths in France per year vs. 73,000 for smoking and for 41,000 alcohol.

Yet, there is an ongoing debate about the costs of air pollution

- It is often argued that air quality standards are set arbitrarily.
- Most studies are incomplete, assessing healthcare costs only partially.
- Information about costs matters for environmental policy.

About this study

First quasi-experimental study to *comprehensively quantify the healthcare costs* caused by acute exposure to moderate levels of air pollution in a *nationwide representative sample*.

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- Location fixed effect model to account for residential sorting.
- IV approach exploiting shocks to pollution from changes in altitude atmospheric conditions.

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Estimate effect heterogeneity

- By medical specialty: sanity test including placebo specialties
- By patient characteristics: age, chronic health status, enrollment in state subventioned insurance.
- By location characteristics: average income, unemployment rate, city size.

Related literature

The quasi-experimental literature on the health effects of air pollution

- Limited geographic area, events limited in time, specific part of the population, limited selection of health conditions or mortality.
  (Ex: Moretti et al., 2011; Anderson, 2015; Schlenker and Walker, 2015; Bauernschuster et al.,2017; Deryugina et al., 2019; Godzinski and Suarez Castillo, 2019; 2021)

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⇒ This study: representative sample, all types of health care and exact costs.

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⇒ This study: representative sample, all types of health care and exact costs.

⇒ This study: heterogeneity analyses by patient and location characteristics.

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Cost-benefit analyses

- Costs are evaluated indirectly through simulations using mortality/morbidity rates, concentration-response parameters.
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⇒ This study: allows to put into perspective by how much healthcare costs have been underestimated.

Preview of the results

Significant healthcare costs caused by exposure to moderate pollution levels

- €0.5 billion additional spending per year for a 1 $\mu g/m^3$ (7%) increase in NO2.
- Order(s) of magnitude larger than previous estimates.

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- Effects exist across all age groups.

⇒ Air pollution reduction policies have the potential to reduce health inequalities.

⇒ The young and the elderly are not the only groups vulnerable to air pollution.

Outline

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Air pollutants

Pollutants of greatest concern

- Nitrogen dioxide (NO_2)
- Ground-level ozone (O_3)
- Particulate matter (PM) 10 and 2.5

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Air pollutants

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- Nitrogen dioxide (NO2)
- Ground-level ozone (O3)
- Particulate matter (PM) 10 and 2.5

	NO2	O3	PM10	PM2.5
NO2	1			
O3	-0.556	1		
PM10	0.595	-0.252	1	
PM2.5	0.616	-0.377	0.907	1

More

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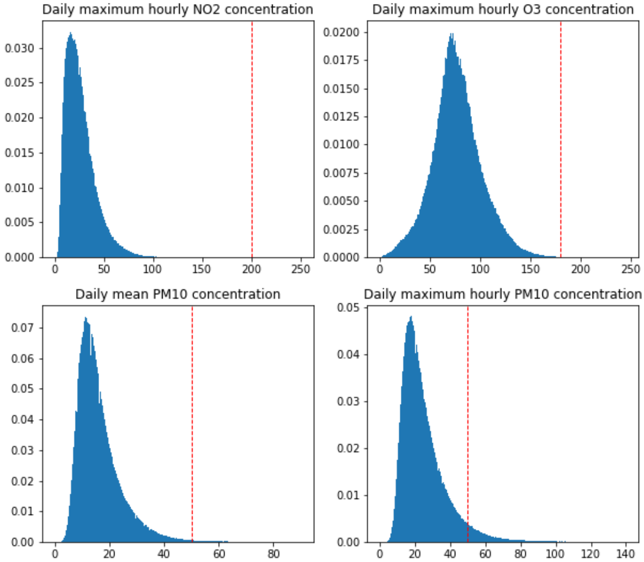
Air quality in France

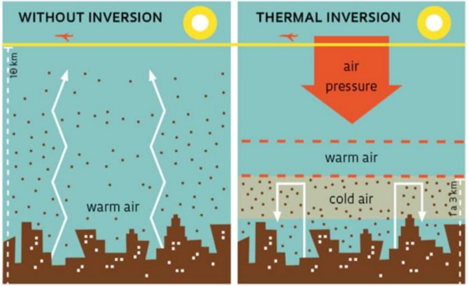


Distribution of postcode-day concentrations shows that **pollutant concentrations are mostly below current limit values**.

Atmospheric conditions and local pollutant concentrations

Atmospheric conditions

- Thermal inversions
  - Pollutants are trapped and cannot escape
- Planetary boundary layer
  - Pollutants have less space to diffuse
- Altitude wind
  - Wind leads to mixing of the atmospheric layers, diffusion of pollutants away from their sources



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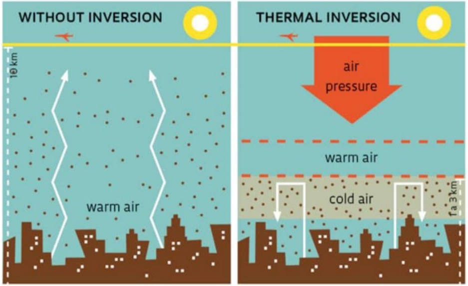

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Different effects by pollutant

- Usually opposite effects for NO2 and PM on the one hand and O3 on the other hand
  - Complex, often inverse relationship with NO2
  - Different behavior due to vertical mixing where O3 from the upper layers is brought to the ground

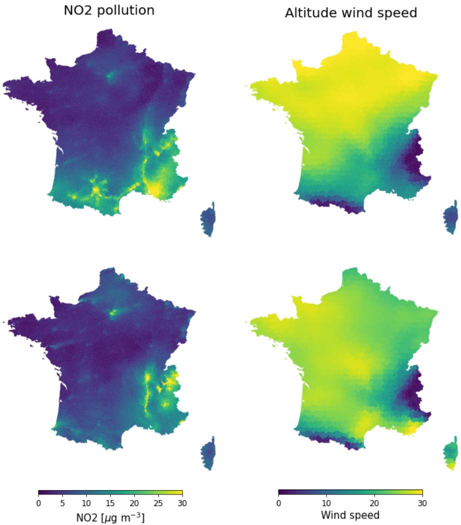
Example: Altitude (ca 1.5km) wind speed and ground level NO2 concentrations

- Wind carries NO2 (and PM) away from their sources, causing dispersion.

⇒ More wind, lower NO2 and PM.

- Wind carries O3 down from higher layers; NO2 interacts with O3.

⇒ More wind, higher O3.



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The data

Health care use and costs (2015-2018)

- *Système National des Données de Santé* (SNDS): administrative data on healthcare costs and reimbursements including 98.8% of the French population, all types of insurance.
- *Echantillon Généraliste de Bénéficiaires* (EGB): 1/97th random permanent representative sample.

Summary stats

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Pollution concentrations and meteorological conditions (reanalysis data)

- NO2, O3, PM 10, and PM 2.5 concentrations from by INERIS.
- Wind speed, wind direction, temperature and precipitation by pressure levels from ECMWF.

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- NO2, O3, PM 10, and PM 2.5 concentrations from by INERIS.
- Wind speed, wind direction, temperature and precipitation by pressure levels from ECMWF.

Other

- Postcode-level average household income, unemployment rate from INSEE.
- Data on holidays from `https://www.data.gouv.fr`

Summary stats

Outline

The method

Location and time fixed effects model

- Pollution exposure is not random.

⇒ Inclusion of location fixed effects to account for residential sorting.

$$H_{wpc} = \sum_{x} \beta_x P_{wpx} + \alpha_p + \alpha_{m/mdep} + \alpha_{y/my} + \gamma X_{wp} + \epsilon_{wpc},$$

H_{wpc} - healthcare use or cost in week day w, postcode area p, for medical specialty c
P_{wpx} - pollution concentrations of pollutant x
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P_{wpx} - pollution concentrations of pollutant x
α_p - postcode FE
$\alpha_{m/mdep}$ - month or month-by-department FE
$\alpha_{y/my}$ - year or month-by-year FE
X_{wp} - additional time-varying covariates (holidays and weather conditions)

Also include a lag to allow for some serial correlation/lagged effects.
Also estimate the model at daily frequency with additional inclusion of day-of-the-week FE.

Altitude atmospheric conditions as instruments for ground-level air pollution

Potential remaining endogeneity problem

- Air pollution levels and healthcare use correlate with economic activity.

Altitude atmospheric conditions are good instruments

An IV needs to

- be sufficiently correlated with the endogenous variable: Altitude atmospheric conditions are correlated with pollution levels.

Altitude atmospheric conditions as instruments for ground-level air pollution

Potential remaining endogeneity problem

- Air pollution levels and healthcare use correlate with economic activity.

$\Rightarrow$ Use altitude atmospheric conditions as instruments for air pollution levels.

Altitude atmospheric conditions are good instruments

An IV needs to

- be sufficiently correlated with the endogenous variable: Altitude atmospheric conditions are correlated with pollution levels.
- not have a direct effect on the outcome variable: conditional on ground-level atmospheric conditions and additional weather covariates, altitude atmospheric conditions should not affect health other than through its effect on pollution levels.

Wind speed as instrument for air pollution - first stage specification

First stage specification

$$P_{wpx} = \sum_{k} \beta_k IV_{wpk} + \alpha_p + \alpha_{mdep} + \alpha_{y/my} + \delta X_{wp} + \epsilon_{wpx}$$

IV_{wpk} is a **vector of atmospheric conditions** in week w and location p

- Thermal inversions
  - Sum of hours of inversions, sum of hours during night/day/different moments of the day
- Planetary boundary layer height
  - Height in m, height at different moments during the day
- Altitude wind speed
  - Average wind speed at different altitude levels

Outline

OLS and IV estimates of NO2, O3 and PM pollution on healthcare expenditure

	OLS		IV		IV lasso	
	Sum of weekly healthcare spending					
Weekly mean NO2	44.33***	43.23***	18.42***	17.23***	20.40***	20.18***
	(2.692)	(2.418)	(3.820)	(3.719)	(3.881)	(3.750)
Weekly mean O3	4.189***	4.912***	6.282***	3.275***	6.177***	3.296***
	(0.383)	(0.390)	(0.773)	(0.662)	(0.783)	(0.666)
Weekly mean PM10	-12.06***	-13.21***	12.37***	3.540	10.75***	1.519
	(0.981)	(0.993)	(2.815)	(2.843)	(2.839)	(2.842)
Lag weekly mean NO2		9.461***		-3.423		-6.877
		(2.106)		(4.062)		(4.134)
Lag weekly mean O3		-0.181		6.497***		7.033***
		(0.364)		(0.795)		(0.814)
Lag weekly mean PM10		-1.424		18.14***		23.10***
		(0.872)		(2.616)		(2.724)
Observations	1,209,572	1,186,311	1,209,572	1,186,311	1,209,572	1,186,311

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

First stage results | First stage Lasso results

Main results

Conservative estimate of €0.5 billion additional healthcare spending per year for a 1 $\mu g/m^3$ increase in NO2.

- €17.23 per week per postcode for 6,048 postcodes in a sample of $1/97$ of the French population:

$\Rightarrow$ €17.23 $\cdot$ 97 $\cdot$ 52 $\cdot$ 6,048 $=$ €525,620,310 additional healthcare spending per year.

Up to €1.3 billion additional healthcare spending per year for a 1 $\mu g/m^3$ increase in all pollutants.

- €(17.23 + 3.28 + 6.5 + 18.14) per week per postcode for 6,048 postcodes in a sample of $1/97$ of the French population

$\Rightarrow$ $=$ €1,377,350,957

Does not include costs from mortality, lost productivity...

Results with only one pollutant

Effect of *only NO2* on sum of weekly healthcare spending						
	OLS		IV		IV lasso	
Weekly mean NO2	30.33***	27.37***	22.71***	15.87***	24.98***	16.09***
	(1.927)	(1.689)	(1.952)	(1.805)	(2.137)	(1.840)
Lag weekly mean NO2		8.699***		8.286***		9.055***
		(1.506)		(1.873)		(1.917)
Effect of *only O3* on sum of weekly healthcare spending						
	OLS		IV		IV lasso	
Weekly mean O3	0.362	1.025**	0.957	-0.618	1.106	-0.918
	(0.353)	(0.341)	(0.680)	(0.557)	(0.696)	(0.565)
Lag weekly mean O3		-0.963**		4.699***		5.009***
		(0.352)		(0.688)		(0.702)
Effect of *only PM10* on sum of weekly healthcare spending						
	OLS		IV		IV lasso	
Weekly mean PM10	4.053***	2.770***	16.87***	11.59***	16.14***	10.98***
	(0.570)	(0.597)	(1.375)	(1.335)	(1.364)	(1.317)
Lag weekly mean PM10		2.590***		8.493***		10.21***
		(0.562)		(1.242)		(1.269)
Observations	1209572	1186311	1209572	1186311	1209572	1186311

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Results by medical specialty - sanity check

Separate regressions for 15 different categories of medical specialties

- Potentially affected: family practice, otorhinolaryngology, ophthalmology, stomatology, dentistry, cardiology and vascular medicine, pulmonology, neurology, gynaecology, ambulance services.
- Placebo: gastro-hepatology, rhumatology, nephrology and plastic surgery.

Results by medical specialty - sanity check

	General med.	O.R.L.	Ophtalmo.	Stoma.	Chir. den.	Cardio-vasc.	Pneumology
Weekly mean NO2	7.773***	0.0110	0.992***	0.0497	0.426	0.339	0.0338
	(1.691)	(0.082)	(0.223)	(0.080)	(0.802)	(0.228)	(0.159)
Weekly mean O3	1.572***	0.0249	0.163***	-0.00662	0.342*	0.102*	0.0363
	(0.228)	(0.016)	(0.041)	(0.015)	(0.164)	(0.042)	(0.032)
Weekly mean PM10	0.0715	0.0811	-0.0659	-0.0501	2.118***	0.181	0.207
	(1.245)	(0.058)	(0.162)	(0.057)	(0.590)	(0.167)	(0.116)

	Neurology	Gyneco.	Ambulance	Gastro. hep.	Rhuma.	Nephrology	Chir. trauma	Chir. plas.
Weekly mean NO2	0.0969	0.0931	0.0381	-0.596	0.416*	0.0905	0.252	-0.0863
	(0.159)	(0.139)	(0.274)	(0.370)	(0.179)	(0.078)	(0.214)	(0.101)
Weekly mean O3	0.00444	0.0170	0.00854	0.0850	0.0333	0.0135	0.0606	0.0272
	(0.026)	(0.027)	(0.054)	(0.077)	(0.027)	(0.016)	(0.038)	(0.020)
Weekly mean PM10	0.0525	0.215*	0.611**	0.485	-0.124	-0.0282	0.0481	0.163*
	(0.116)	(0.104)	(0.209)	(0.311)	(0.145)	(0.055)	(0.151)	(0.075)
Observations	1209572	1209572	1209572	1209572	1209572	1209572	1209572	1209572
First-stage F-stat	2648.7	2648.7	2648.7	2648.7	2648.7	2648.7	2648.7	2648.7

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Results by medical specialty - sanity check continued

	General med.	O.R.L.	Ophtalmo.	Stoma.	Chir. den.	Cardio-vasc.	Pneumology
Weekly mean NO2	4.956***	0.0236	1.108***	0.0104	0.120	0.466*	0.0177
	(1.492)	(0.084)	(0.228)	(0.086)	(0.820)	(0.223)	(0.179)
Weekly mean O3	0.927***	0.00108	0.107*	-0.00156	-0.142	0.0401	0.0127
	(0.235)	(0.017)	(0.042)	(0.017)	(0.161)	(0.040)	(0.035)
Weekly mean PM10	-1.180	-0.0468	-0.336*	-0.0453	0.614	-0.0541	0.180
	(1.143)	(0.062)	(0.170)	(0.059)	(0.609)	(0.159)	(0.139)
Lag weekly mean NO2	2.513	0.0897	0.192	0.0268	0.244	-0.00495	-0.300
	(1.297)	(0.084)	(0.240)	(0.078)	(0.873)	(0.225)	(0.202)
Lag weekly mean O3	1.217***	0.0476**	0.206***	0.0102	1.119***	0.178***	0.0273
	(0.264)	(0.017)	(0.044)	(0.017)	(0.164)	(0.041)	(0.031)
Lag weekly mean PM10	3.329***	0.140**	0.318*	0.0258	2.151***	0.239	0.260*
	(0.835)	(0.052)	(0.149)	(0.053)	(0.557)	(0.142)	(0.126)
Observations	1186311	1186311	1186311	1186311	1186311	1186311	1186311
First-stage F-stat	2063.7	2063.7	2063.7	2063.7	2063.7	2063.7	2063.7

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Results by medical specialty - sanity check continued

	Neurology	Gyneco.	Ambulance	Gastro. hep.	Rhuma.	Nephrology	Chir. trauma	Chir. plas.
Weekly mean NO2	0.101	0.102	-0.342	-0.513	0.485*	0.0517	-0.107	-0.0235
	(0.180)	(0.147)	(0.275)	(0.345)	(0.192)	(0.082)	(0.218)	(0.108)
Weekly mean O3	-0.0252	0.00422	0.0122	0.0480	0.0161	0.0130	0.0276	0.0306
	(0.031)	(0.029)	(0.056)	(0.084)	(0.033)	(0.017)	(0.040)	(0.021)
Weekly mean PM10	-0.0357	0.170	0.916***	0.370	-0.231	-0.0335	0.172	0.129
	(0.134)	(0.111)	(0.227)	(0.278)	(0.167)	(0.060)	(0.159)	(0.080)
Lag weekly mean No2	0.150	0.0581	-0.829**	-0.285	0.0129	0.0115	0.327	-0.111
	(0.162)	(0.160)	(0.291)	(0.410)	(0.171)	(0.091)	(0.222)	(0.106)
Lag weekly mean O3	0.0672*	0.0644*	0.251***	0.0281	0.0417	0.0138	0.0756	-0.0109
	(0.030)	(0.031)	(0.056)	(0.074)	(0.032)	(0.017)	(0.041)	(0.022)
Lag weekly mean PM10	0.0281	0.0318	0.784***	0.206	0.134	0.0418	-0.0926	0.0409
	(0.091)	(0.094)	(0.185)	(0.286)	(0.114)	(0.056)	(0.139)	(0.068)
Observations	1186311	1186311	1186311	1186311	1186311	1186311	1186311	1186311
First-stage F-stat	2063.7	2063.7	2063.7	2063.7	2063.7	2063.7	2063.7	2063.7

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OLS results

Outline

Results by individual characteristics - age

	Ages 0-20	Ages 21-40	Ages 41-60	Ages 61-80	Ages over 80
Weekly mean NO2	2.974**	2.844**	7.062***	2.559	1.508
	(0.962)	(1.057)	(1.867)	(1.651)	(1.173)
Weekly mean O3	0.876***	0.650**	2.177***	2.722***	0.557*
	(0.176)	(0.198)	(0.403)	(0.359)	(0.219)
Weekly mean PM10	1.313	0.431	4.705***	-1.002	1.506
	(0.696)	(0.817)	(1.371)	(1.191)	(0.819)
Observations	1209572	1209572	1209572	1209572	1209572
First-stage F-stat	2648.7	2648.7	2648.7	2648.7	2648.7

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Results by location characteristics

Panel A: *Heterogeneity by average postcode income quartile*

	Per capita spent - 1st quartile	Per capita spent - 2nd quartile	Per capita spent - 3rd quartile	Per capita spent - 4th quartile
Weekly mean NO2	0.123	-0.0431	0.0179	0.127**
	(0.101)	(0.093)	(0.068)	(0.045)
Weekly mean O3	0.0328	0.0505**	0.0292*	0.0712***
	(0.018)	(0.016)	(0.012)	(0.012)
Weekly mean PM10	0.0463	0.212**	0.173***	0.0959**
	(0.071)	(0.068)	(0.049)	(0.034)
Observations	306592	301080	299416	296660
First-stage F-stat	985.5	987.1	860.9	671.4

Panel B: *Heterogeneity by postcode unemployment rate quartile*

	Per capita spent - 1st quartile	Per capita spent - 2nd quartile	Per capita spent - 3rd quartile	Per capita spent - 4th quartile
Weekly mean NO2	0.104	0.0703	0.0860	0.0558
	(0.054)	(0.080)	(0.058)	(0.073)
Weekly mean O3	0.0591***	0.0432***	0.0293*	0.0196
	(0.012)	(0.013)	(0.012)	(0.018)
Weekly mean PM10	0.116**	0.121*	0.0610	0.0456
	(0.041)	(0.051)	(0.044)	(0.050)
Observations	232180	193388	176852	176748
First-stage F-stat	628.9	578.9	453.4	420.5

Results by location characteristics continued

Panel C: *Heterogeneity by postcode average NO2 quartile*				
	Per capita spent - 1st quartile	Per capita spent - 2nd quartile	Per capita spent - 3rd quartile	Per capita spent - 4th quartile
Weekly mean NO2	0.0384	0.121	0.109	0.0729*
	(0.149)	(0.091)	(0.065)	(0.032)
Weekly mean O3	0.0223	0.0484**	0.0502***	0.0480***
	(0.032)	(0.015)	(0.013)	(0.012)
Weekly mean PM10	0.142	0.107	0.0878	0.0876***
	(0.108)	(0.062)	(0.046)	(0.024)
Observations	293384	305708	308256	302224
First-stage F-stat	2388.1	1757.7	1521.1	985.2
Panel D: *Heterogeneity by postcode population size quartile*				
	Per capita spent - 1st quartile	Per capita spent - 2nd quartile	Per capita spent - 3rd quartile	Per capita spent - 4th quartile
Weekly mean NO2	0.0851	0.0688	0.0372	0.0893**
	(0.141)	(0.081)	(0.049)	(0.033)
Weekly mean O3	0.0616	0.0548***	0.0346***	0.0268***
	(0.034)	(0.015)	(0.009)	(0.006)
Weekly mean PM10	0.140	0.178**	0.115**	0.0577*
	(0.101)	(0.059)	(0.036)	(0.025)
Observations	299052	302484	304408	303628
First-stage F-stat	734.5	875.4	849.3	706.1

Outline

Effects on mortality

	OLS		IV		IV lasso	
			Sum of deaths in a week			
Weekly mean NO2	0.0000202 (0.000)	0.0000400 (0.000)	-0.0000132 (0.000)	-0.000114 (0.000)	0.0000157 (0.000)	-0.000111 (0.000)
Weekly mean O3	0.0000185 (0.000)	0.0000157 (0.000)	0.0000330 (0.000)	0.0000340 (0.000)	0.0000356 (0.000)	0.0000373 (0.000)
Weekly mean PM10	0.000131*** (0.000)	0.000116** (0.000)	0.000106 (0.000)	0.000259* (0.000)	0.0000977 (0.000)	0.000264* (0.000)
Lag weekly mean NO2		-0.0000476 (0.000)		0.00000354 (0.000)		-0.0000262 (0.000)
Lag weekly mean O3		-0.0000106 (0.000)		0.00000594 (0.000)		0.00000467 (0.000)
Lag weekly mean PM10		0.00000994 (0.000)		-0.000106 (0.000)		-0.0000835 (0.000)
Observations	1209572	1186311	1209572	1186311	1209572	1186311

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis.
All models include weather dummies, month, year and postcode fixed effects.

Effects on sick leave payments

	OLS		IV		IV lasso	
	Sum of sick leave pay in a week					
Weekly mean NO2	0.00402 (0.002)	0.0109*** (0.002)	0.00896 (0.006)	0.0129* (0.006)	0.00877 (0.006)	0.0142* (0.006)
Weekly mean O3	0.00238*** (0.001)	0.00309*** (0.001)	0.00221* (0.001)	0.00179 (0.001)	0.00213 (0.001)	0.00177 (0.001)
Weekly mean PM10	-0.00355** (0.001)	-0.00578*** (0.001)	-0.00324 (0.004)	-0.00307 (0.004)	-0.00303 (0.004)	-0.00402 (0.004)
Lag weekly mean NO2		-0.00446* (0.002)		-0.0166** (0.006)		-0.0184** (0.006)
Lag weekly mean O3		0.000474 (0.001)		0.00244* (0.001)		0.00262* (0.001)
Lag weekly mean PM10		0.00236 (0.001)		0.0121** (0.004)		0.0141*** (0.004)
Observations	1209572	1186311	1209572	1186311	1209572	1186311

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis.
All models include weather dummies, month, year and postcode fixed effects.

Analysis at the level of the employment zone

Effects robust to conducting the analysis at a more aggregate level

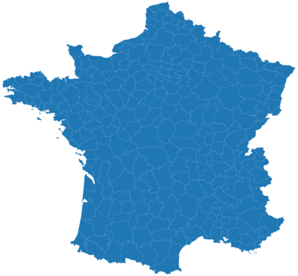
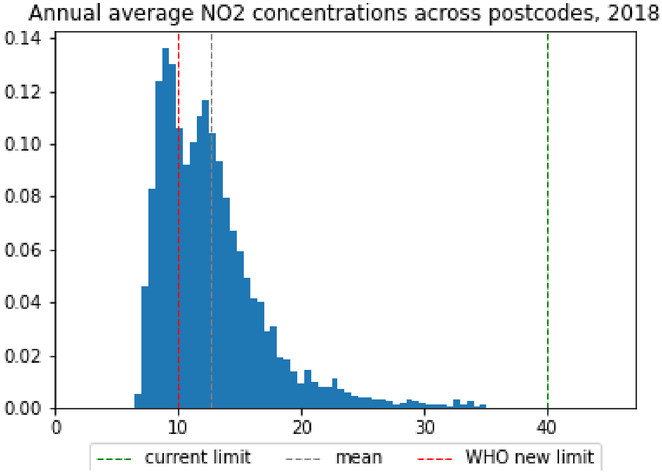


Figure: Division of France into 306 employment zones.

	Sum of healthcare spending a week		
	OLS	IV	IV lasso
Weekly mean NO2	793.7***	520.9*	646.6*
	(191.567)	(240.411)	(279.980)
Weekly mean O3	71.61***	45.08	48.47
	(8.365)	(39.424)	(37.935)
Weekly mean PM10	-250.6**	-115.9	-149.3
	(75.636)	(206.098)	(207.499)
Observations	59696	59696	59696

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

Policy recommendation: Revision of limit values?



WHO updated guidelines for NO2
from $40\mu g/m^3$ to $10\mu g/m^3$.
Average concentration in 2018 was 12.7.
⇒ Compliance saves €1.35 billion per year.

Robustness to different fixed effect structures and weather controls

Robust to alternative specifications with different time FE structures and weather controls

- Robust to using simpler time FEs: month and year FE rather than month-by-department and month-by-year FE.
- Robust to excluding the vector of temperature and precipitation bins.
- Importance of including day-of-the-week FE: Exclusion leads to 3 times larger estimates.

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Robust to alternative first stage specifications

- Qualitatively similar results using different instruments.

Outline

Discussion about the effect size

The estimate of the healthcare costs is large...

- Additional healthcare costs of €0.5 billion per year for a 1 $\mu g/m^3$ (7%) increase in NO2.
- Large compared to previous studies: £98.5 (€117.25) million additional NHS spending per year for a 1 $\mu g/m^3$ increase in PM2.5 *and* NO2. (Pimpin et al., 2018)
- Large compared to costs of pollution reduction: Compliance with the NEC Directive costs €9.9 billion per year (Amann et al., 2017) but could save more than €5.2 billion of healthcare spending.

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...while still remaining conservative

- Assumption that the effects scale linearly but effects from chronic exposure are likely larger.
- No information on avoiding behaviours which could lead to underestimation.

Conclusion

Sizeable healthcare costs caused by acute exposure to moderate levels of air pollution

- Sizeable effects on healthcare costs caused by levels of air pollution at or below WHO standards.

⇒ The healthcare costs caused by air pollution have been significantly underestimated.

Conclusion

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Heterogeneity of effects reveals who is most vulnerable

- Chronically sick and populations living in big cities are most affected.
- Effects across all age categories.

⇒ Air pollution reduction can reduce health inequalities.

⇒ Populations thought to be less vulnerable are still affected.

Correlations between NO2 and O3

Complex relationship between NO2 and O3

- For high VOC/NOx ratios (low NOx), the regime is NOx-limited (typically countryside): more NOx will result in more O3
- For low VOC/NOx ratios (high NOx), the regime is NOx-saturated or VOC-limited (typically urban areas): more NOx reduces O3. (Kroll et al., 2020; Brancher, 2021)
- **Reduction in NO2 will translate to reduction in O3 in the longer term** after transition from NOx-saturated to NOx-limited regime. (Lee et al., 2021)

Back to Background

Summary statistics (1)

Table: *Summary statistics - pooled postcode-day observations, entire sample*

Variable	Mean	Std. Dev.	Min.	Max.	N
Health care spending					
Total spent	513.76	1415.4	0	351206.91	8835995
Family GP	172.56	508.53	0	71455.65	8836033
Cardiology and vascular medicine	7.25	50.75	0	37072.16	8836120
Otorhinolaryngology	2.75	23.37	0	10190	8836122
Pneumology	3.24	50.18	0	15664.6	8836126
Ophtalmology	11.73	64.19	0	6871.2	8836120
Neurology	2.8	46.1	0	10373.22	8836127
Trauma surgery	5.13	55.31	0	14687.84	8836114
Ambulance services	10.9	84.32	0	9434.66	8836112
Gynecology	6.15	41.46	0	6838.82	8836121
Gastroenterology and hepatology	4.61	111.49	0	26010.53	8836126
Rheumatology	4.07	48.72	0	11414.56	8836127
Stomatology	0.83	23.83	0	23800	8836126
Dental surgery	39.44	233.53	0	33874.4	8836111
Nephrology	1.63	24.86	0	11234.26	8836127
Plastic surgery	0.74	27.69	0	6321.91	8836128

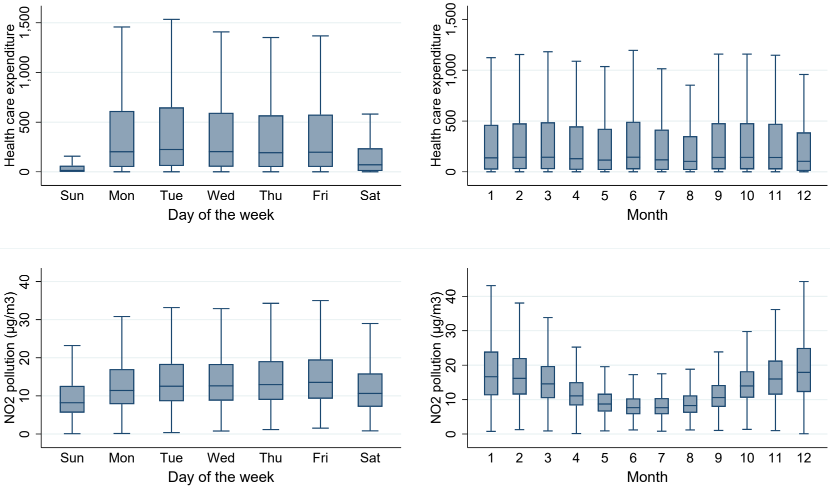
Back to data

Summary statistics (2)

Variable	Mean	Std. Dev.	Min.	Max.	N
Pollution measures					
NO2 emission (daily mean, $\mu g/m^3$)	13.8	8.44	0.09	138.44	8761974
PM 10 emission (daily mean, $\mu g/m^3$)	16.61	8.47	1.12	123.7	8761974
PM 2.5 emission (daily mean, $\mu g/m^3$)	10.58	7.44	0.32	104.97	8755985
O3 emission (daily mean, $\mu g/m^3$)	55.64	20.32	0	155.64	8761974
Meteorological conditions					
Temperature (daily mean, $^\circ$C)	12.5	6.73	-19.4	34.6	8836128
Precipitation (daily sum, mm)	2.01	4.60	0	150.6	8836128
Wind speed (daily mean at 10m, m/s)	3.11	1.7	0	29.6	8836128
Strike measures					
Strike at postcode area level = 1	0	0.02	0	1	8836128
Strike at department level = 1	0.04	0.19	0	1	8836128
Strike at national level = 1	0.25	0.44	0	1	8836128
Strike at any geographical level = 1	0.29	0.45	0	1	8836128
Postcode characteristics					
Income	22096.28	4050.53	7910	52670	8790837
Unemployment rate	2.88	0.73	1	7.5	5744652

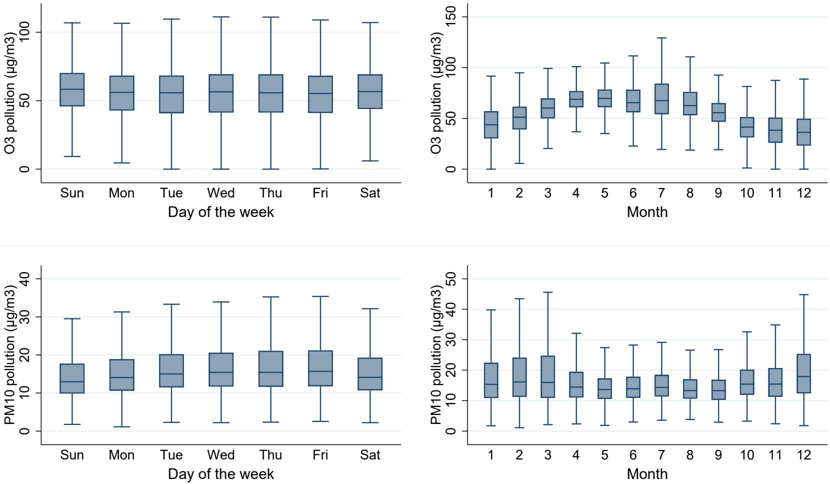
Back to data

Cyclicalities by weekday and month



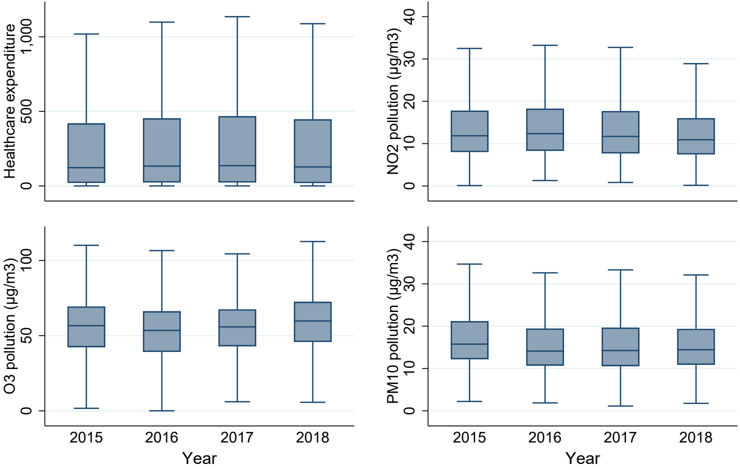
Back to data Back to method Back to main results

Cyclicalities by day-of-week and month-of-year



Back to data
Back to method
Back to main results

Evolution of healthcare spending and average pollution concentrations over the years



Back to data
Back to method
Back to main results

First stage

	Weekly mean NO2	Weekly mean O3	Weekly mean PM10
Thermal inversion (nb. h per week)	0.176***	0.0126	0.347***
	(0.009)	(0.021)	(0.012)
TI 0-4 h (nb. h per week)	0.0953***	0.0124**	0.189***
	(0.002)	(0.004)	(0.004)
TI 4-8 h (nb. h per week)	-0.0416***	0.119***	-0.0567***
	(0.002)	(0.005)	(0.004)
TI 8-12 h (nb. h per week)	-0.0759***	-0.425***	-0.0397***
	(0.005)	(0.010)	(0.006)
TI 12-16 h (nb. h per week)	0.201***	-0.663***	0.319***
	(0.007)	(0.019)	(0.009)
TI 16-20 h (nb. h per week)	0.0764***	-0.282***	0.155***
	(0.006)	(0.014)	(0.008)
TI 20-24 h (nb. h per week)	0.0630***	0.163***	0.0142***
	(0.002)	(0.006)	(0.004)
TI strength 0-4 h (diff degree C)	1.445***	-0.225**	0.0965*
	(0.034)	(0.072)	(0.047)
TI strength 4-8 h (diff degree C)	-0.842***	-1.500***	0.641***
	(0.032)	(0.066)	(0.036)
TI strength 8-12 h (diff degree C)	-1.222***	1.657***	-1.571***
	(0.045)	(0.104)	(0.043)
TI strength 12-16 h (diff degree C)	1.905***	-6.413***	3.612***
	(0.050)	(0.133)	(0.069)
TI strength 16-20 h (diff degree C)	-0.138*	-1.503***	-0.776***
	(0.061)	(0.153)	(0.080)
TI strength 20-24 h (diff degree C)	0.765***	0.455***	1.084***
	(0.034)	(0.073)	(0.046)

Back to main results

First stage continued

	Weekly mean NO2	Weekly mean O3	Weekly mean PM10
PBLH 0-4 h (m)	0.0000389	0.0114***	-0.00636***
	(0.000)	(0.000)	(0.000)
PBLH 4-8 h (m)	-0.00327***	-0.00595***	0.00115***
	(0.000)	(0.000)	(0.000)
PBLH 8-12 h (m)	-0.00284***	0.00266***	-0.00370***
	(0.000)	(0.000)	(0.000)
PBLH 12-16 h (m)	0.00108***	0.0192***	-0.000876***
	(0.000)	(0.000)	(0.000)
PBLH 16-20 h (m)	-0.00254***	-0.00219***	0.000179**
	(0.000)	(0.000)	(0.000)
PBLH 20-24 h (m)	-0.00420***	0.00310***	0.00263***
	(0.000)	(0.000)	(0.000)
Wind speed at 350 hPa (m/s)	0.0608***	-0.638***	-0.212***
	(0.005)	(0.013)	(0.008)
Wind speed at 400 hPa (m/s)	-0.254***	0.997***	-0.0726***
	(0.012)	(0.031)	(0.019)
Wind speed at 450 hPa (m/s)	0.182***	-1.117***	0.217***
	(0.016)	(0.041)	(0.027)
Wind speed at 500 hPa (m/s)	0.0279	1.713***	0.0238
	(0.018)	(0.055)	(0.027)

Back to main results

First stage continued

	Weekly mean NO2	Weekly mean O3	Weekly mean PM10
Wind speed at 550 hPa (m/s)	0.122***	-1.852***	0.150***
	(0.019)	(0.061)	(0.032)
Wind speed at 600 hPa (m/s)	-0.00984	1.520***	0.0843*
	(0.023)	(0.061)	(0.039)
Wind speed at 650 hPa (m/s)	-0.738***	-0.526***	-1.193***
	(0.025)	(0.068)	(0.045)
Wind speed at 700 hPa (m/s)	0.774***	0.168*	1.244***
	(0.025)	(0.071)	(0.045)
Wind speed at 750 hPa (m/s)	-0.166***	-1.422***	-0.651***
	(0.028)	(0.076)	(0.050)
Wind speed at 800 hPa (m/s)	-0.965***	2.390***	-0.0596
	(0.054)	(0.149)	(0.114)
Wind speed at 825 hPa (m/s)	1.285***	-3.477***	0.288*
	(0.063)	(0.180)	(0.142)
Wind speed at 850 hPa (m/s)	-0.309***	2.437***	-0.0563
	(0.028)	(0.079)	(0.064)
Constant	13.79***	65.18***	18.48***
	(0.127)	(0.305)	(0.169)
Observations	1209572	1209572	1209572

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

Back to main results

First stage lasso selected instruments

	Weekly mean NO2	Weekly mean O3	Weekly mean PM10
Thermal inversion (nb. h per week)	0.294***		0.339***
	(0.009)		(0.012)
TI 0-4 h (nb. h per week)	0.0809***	0.00256	0.186***
	(0.002)	(0.004)	(0.003)
TI 4-8 h (nb. h per week)	0.00956***	0.160***	-0.0548***
	(0.002)	(0.005)	(0.003)
TI 8-12 h (nb. h per week)	-0.0309***	-0.607***	-0.0488***
	(0.005)	(0.010)	(0.006)
TI 12-16 h (nb. h per week)		-0.658***	0.278***
		(0.020)	(0.009)
TI 16-20 h (nb. h per week)		-0.190***	0.208***
		(0.014)	(0.006)
TI 20-24 h (nb. h per week)	0.0227***	0.157***	
	(0.002)	(0.005)	
TI strength 0-4 h (diff degree C)	1.019***	-0.419***	
	(0.021)	(0.068)	
TI strength 4-8 h (diff degree C)		-0.894***	0.767***
		(0.058)	(0.026)
TI strength 8-12 h (diff degree C)	-1.078***		-1.756***
	(0.048)		(0.043)
TI strength 12-16 h (diff degree C)	0.882***	-6.229***	3.266***
	(0.026)	(0.114)	(0.060)
TI strength 20-24 h (diff degree C)			0.793***
			(0.021)

Back to main results

First stage lasso selected instruments continued

	Weekly mean NO2	Weekly mean O3	Weekly mean PM10
PBLH 0-4 h (m)		0.0120***	-0.00535***
		(0.000)	(0.000)
PBLH 4-8 h (m)	-0.00369***	-0.00626***	
	(0.000)	(0.000)	
PBLH 8-12 h (m)	-0.00196***	0.00249***	-0.00317***
	(0.000)	(0.000)	(0.000)
PBLH 12-16 h (m)		0.0182***	-0.000915***
		(0.000)	(0.000)
PBLH 16-20 h (m)	-0.00156***		
	(0.000)		
PBLH 20-24 h (m)	-0.00433***	0.00168***	0.00265***
	(0.000)	(0.000)	(0.000)
Wind speed at 350 hPa (m/s)	-0.0156***	-0.257***	-0.117***
	(0.001)	(0.003)	(0.002)
Wind speed at 500 hPa (m/s)		0.391***	
		(0.006)	
Wind speed at 650 hPa (m/s)	-0.126***		-0.143***
	(0.002)		(0.003)
Wind speed at 750 hPa (m/s)		-0.863***	
		(0.015)	
Wind speed at 850 hPa (m/s)	0.144***	0.879***	
	(0.006)	(0.021)	
Observations	1209572	1209572	1209572

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

Back to main results

OLS results by medical specialty

	General med.	O.R.L.	Ophtalmo.	Stoma.	Chir. den.	Cardio-vasc.	Pneumology	
Weekly mean NO2	10.15***	0.365***	1.194***	0.121***	5.159***	0.849***	0.0499	
	(0.660)	(0.038)	(0.110)	(0.033)	(0.410)	(0.102)	(0.071)	
Weekly mean O3	0.752***	0.0351***	0.108***	-0.00289	0.233**	0.0422*	0.0268	
	(0.121)	(0.008)	(0.021)	(0.007)	(0.073)	(0.019)	(0.016)	
Weekly mean PM10	-2.954***	-0.0879***	-0.200***	-0.0477*	-0.943***	-0.162**	0.0478	
	(0.315)	(0.018)	(0.048)	(0.019)	(0.176)	(0.050)	(0.039)	
	Neurology	Gyneco.	Ambulance	Gastro. hep.	Rhuma.	Nephrology	Chir. trauma	Chir. plas.
Weekly mean NO2	0.204**	0.558***	0.978***	0.403**	0.399***	0.0341	0.700***	0.180***
	(0.063)	(0.074)	(0.132)	(0.152)	(0.058)	(0.046)	(0.090)	(0.050)
Weekly mean O3	0.00658	0.0169	0.122***	0.0981	0.0229	0.0217**	0.0847***	0.0137
	(0.013)	(0.014)	(0.026)	(0.056)	(0.014)	(0.008)	(0.020)	(0.009)
Weekly mean PM10	-0.0583*	-0.0999**	-0.460***	-0.0744	-0.0863**	-0.0461*	-0.151**	-0.0156
	(0.029)	(0.034)	(0.066)	(0.082)	(0.032)	(0.023)	(0.047)	(0.023)
Observations	1209572	1209572	1209572	1209572	1209572	1209572	1209572	1209572

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

Back to IV results by medical specialty

OLS results by medical specialty

	General med.	O.R.L.	Ophtalmo.	Stoma.	Chir. den.	Cardio-vasc.	Pneumology
Weekly mean NO2	8.967***	0.334***	1.196***	0.0833*	4.239***	0.751***	0.0740
	(0.610)	(0.040)	(0.109)	(0.038)	(0.410)	(0.104)	(0.072)
Weekly mean O3	0.989***	0.0372***	0.117***	-0.00192	0.119	0.0407*	0.0295
	(0.121)	(0.008)	(0.021)	(0.008)	(0.077)	(0.020)	(0.017)
Weekly mean PM10	-2.800***	-0.0847***	-0.181***	-0.0451*	-0.771***	-0.133*	0.0476
	(0.351)	(0.018)	(0.049)	(0.020)	(0.188)	(0.052)	(0.038)
Lag weekly mean NO2	2.518***	0.139**	0.341**	0.105*	2.907***	0.297**	-0.126
	(0.584)	(0.044)	(0.113)	(0.043)	(0.418)	(0.100)	(0.074)
Lag weekly mean O3	-0.554***	0.00467	0.0376	0.000322	0.368***	0.0377*	-0.0217
	(0.133)	(0.008)	(0.024)	(0.009)	(0.083)	(0.019)	(0.019)
Lag weekly mean PM10	-0.675*	-0.0447*	-0.224***	-0.0311	-1.102***	-0.127**	0.0143
	(0.302)	(0.020)	(0.049)	(0.020)	(0.179)	(0.044)	(0.034)
Observations	1186311	1186311	1186311	1186311	1186311	1186311	1186311

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

Back to IV results by medical specialty

OLS results by medical specialty - sanity check continued

	Neurology	Gyneco.	Ambulance	Gastro. hep.	Rhuma.	Nephrology	Chir. trauma	Chir. plas.
Weekly mean NO2	0.270***	0.492***	1.031***	0.399*	0.356***	0.0416	0.643***	0.177***
	(0.073)	(0.071)	(0.134)	(0.158)	(0.062)	(0.044)	(0.092)	(0.053)
Weekly mean O3	0.00434	0.0200	0.188***	0.101	0.0262	0.0278**	0.0785***	0.0209*
	(0.015)	(0.015)	(0.027)	(0.064)	(0.016)	(0.008)	(0.021)	(0.010)
Weekly mean PM10	-0.0820*	-0.0701*	-0.483***	-0.0886	-0.0803*	-0.0380	-0.123*	-0.0166
	(0.034)	(0.035)	(0.068)	(0.089)	(0.034)	(0.023)	(0.048)	(0.024)
Lag weekly mean NO2	-0.157*	0.302***	0.0387	0.198	0.143*	-0.0227	0.222*	0.0632
	(0.062)	(0.091)	(0.111)	(0.148)	(0.066)	(0.044)	(0.091)	(0.048)
Lag weekly mean O3	-0.00281	0.00346	-0.00559	0.00507	-0.00419	-0.00500	0.0340	-0.0165
	(0.017)	(0.015)	(0.029)	(0.038)	(0.016)	(0.009)	(0.020)	(0.010)
Lag weekly mean PM10	0.0719*	-0.167***	-0.00932	-0.0241	-0.0465	-0.0159	-0.0629	-0.0476*
	(0.034)	(0.039)	(0.059)	(0.085)	(0.042)	(0.021)	(0.046)	(0.023)
Observations	1186311	1186311	1186311	1186311	1186311	1186311	1186311	1186311

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$. Robust standard errors clustered at the postcode level in parenthesis. All models include weather dummies, month, year and postcode fixed effects.

Back to IV results by medical specialty