# Air Pollution and Innovation

Does air pollution hamper innovation-led growth ?

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# Air pollution

- Fine particulate matter – $PM_{2.5}$
- For 80% caused by human activity
- Severe health effects – 6.5 mln. deaths annually (WHO)

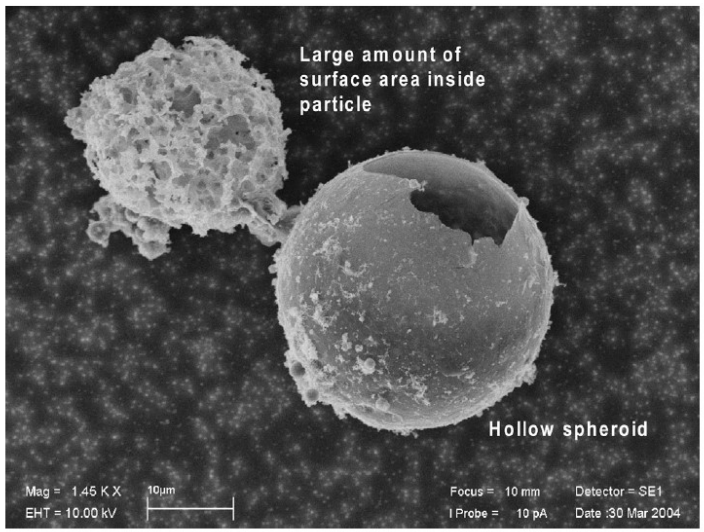



FIGURE 3.3 **Scanning electron micrograph of coarse particles emitted from an oil-fired power plant.** Diameters of the particles are greater than 20 µm optical diameter. Both particles are hollow, so their aerodynamic diameter is significantly smaller than if they were solid. *Source characterization study by Stevens R, Lynam M, Proffitt D, 2004. Photo courtesy of Willis R, U.S. Environmental Protection Agency.*

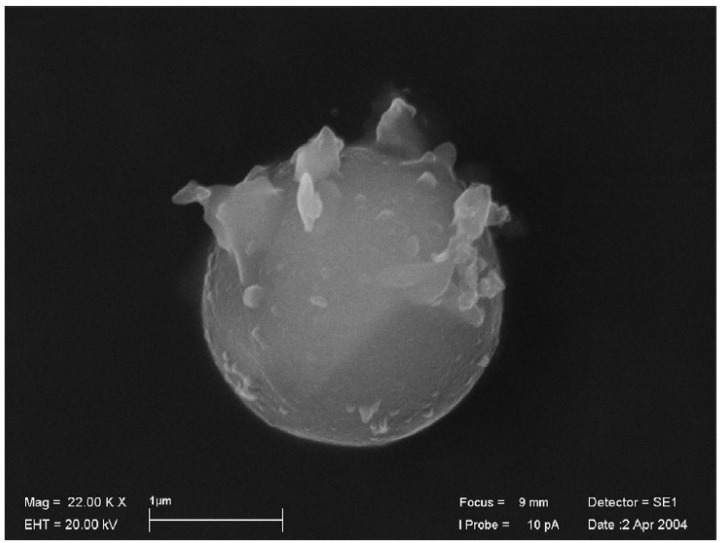



FIGURE 3.4 **Scanning electron micrograph of spherical aluminosilicate fly ash particle emitted from an oil-fired power plant.** Diameter of the particle is approximately 2.5 µm. *Photo courtesy of Willis R, U.S. Environmental Protection Agency.*

Source: Vallero (2014)

# Economic costs of air pollution

- Cost estimates important for regulation
- Common assessments:
  - Premature mortality: **0.092%** of GDP (Landrigan et al. 2018)
  - Accounting for absenteeism, health expenditures and agricultural yields: **0.3%** of GDP (OECD 2016)
- 'Hidden' productivity effects:
  - Labor supply (Hanna & Oliva 2015)
  - Productivity conditional on hours worked (Zivin & Neidell 2012, Chang et al. 2016, 2019)
- Aggregate economic output (Dechezleprêtre et al. 2019):
  - 10% less air pollution $\Rightarrow$ **0.8%** higher GDP

# Overview

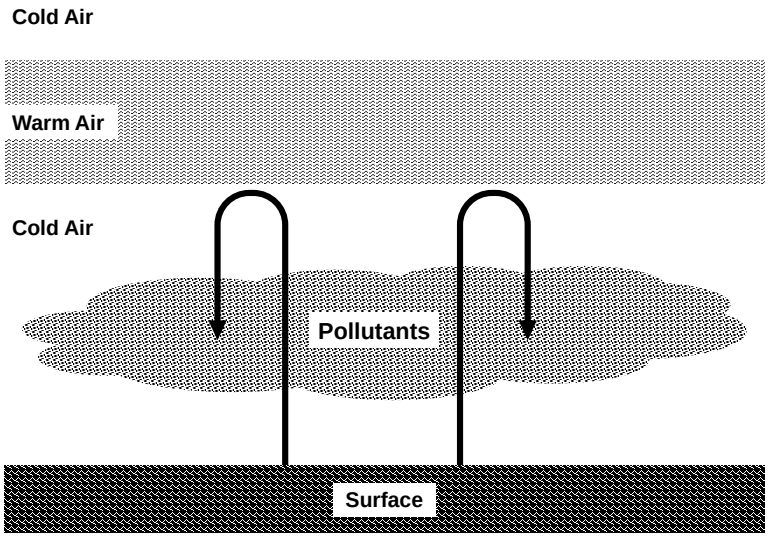
**What is the effect of air pollution on inventive output?**

- Study design
  - Panel of 1288 NUTS-3 regions in Europe 2001-2013
  - Patents as measure for inventive output
  - Exposure to $PM_{2.5}$ as measure of air pollution
  - Weather as source exogenous variation
- Findings
  - $0.17 \mu g/m^3$ *more* $PM_{2.5} \Rightarrow$ 1.7% *less* patents
  - Back-of-the-envelope: 10% of effect on GDP
  - Heterogeneity regions
- Interpretation
  - **Not** inventor mobility (zero-sum)
  - **Not** mortality or R&D expenditures (in prior assessments)

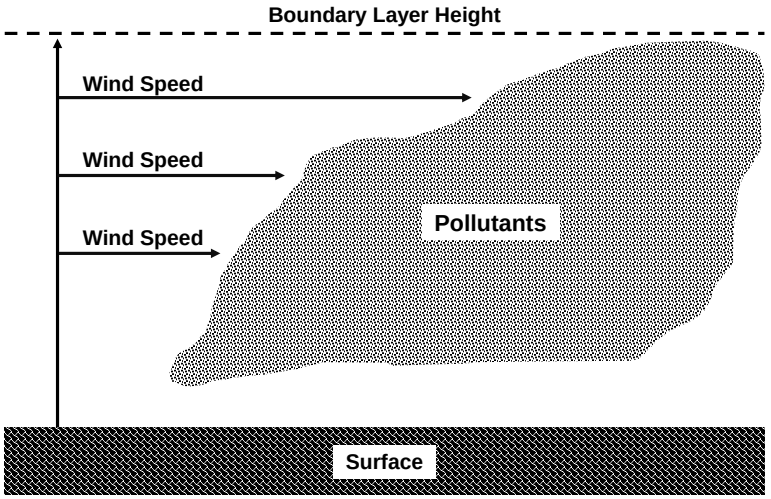
# Empirical strategy

- Measuring inventive output
  - Next year's number of patent filings in region
  - Lag between invention and patent application
- Exposure to air pollution
  - $PM_{2.5}$ concentration at high resolution
  - Weight for population density
- Exogenous variation in air pollution
  - Thermal inversions
  - Ventilation capability

# Instrumental variables




**(a)** Thermal Inversions




**(b)** Ventilation Coefficient

- **Relevance:** Positive correlation documented in atmospheric studies (Xu et al. 2017, Hou et al. 2018)
- **Exogeneity:** Determined by large-scale atmospheric dynamics
- **Exclusion Restriction:** Include a large set of weather controls

# IV regression

## First Stage

$$P_{it} = \alpha_1 TI_{it} + \alpha_2 VC_{it} + \alpha_3 Pop_{it} + \alpha_4 X_{it} + \omega_{ct} + \eta_i + \nu_{it}$$

- $P_{it}$: $PM_{2.5}$ concentration for NUTS-3 $i$ in year $t$
- $TI_{it}$: Share of days per year with thermal inversions
- $VC_{it}$: Avg. number of consecutive days with low ventilation coefficient

## Second Stage

$$Y_{it} = \beta_1 \widehat{P_{it}} + \alpha_2 Pop_{it} + \beta_3 X_{it} + \lambda_{ct} + \alpha_i + \varepsilon_{it}$$

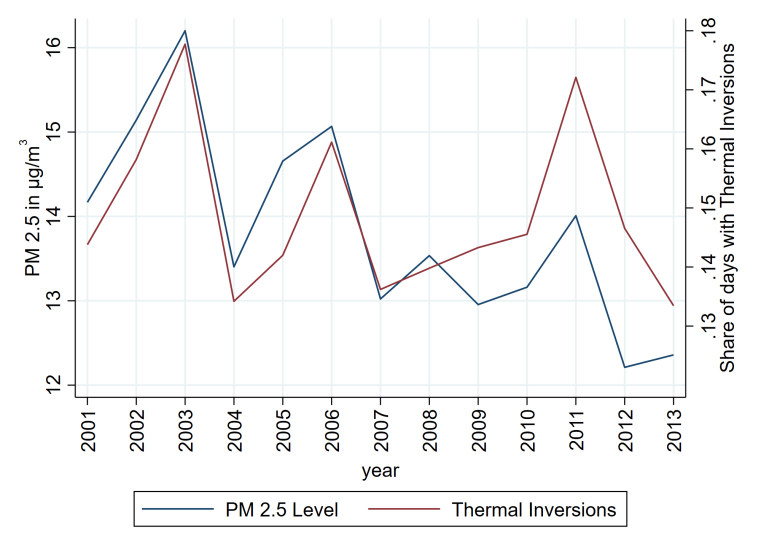
- $Y_{it}$: Number of patent filings for NUTS-3 $i$ in year $t+1$

# Data

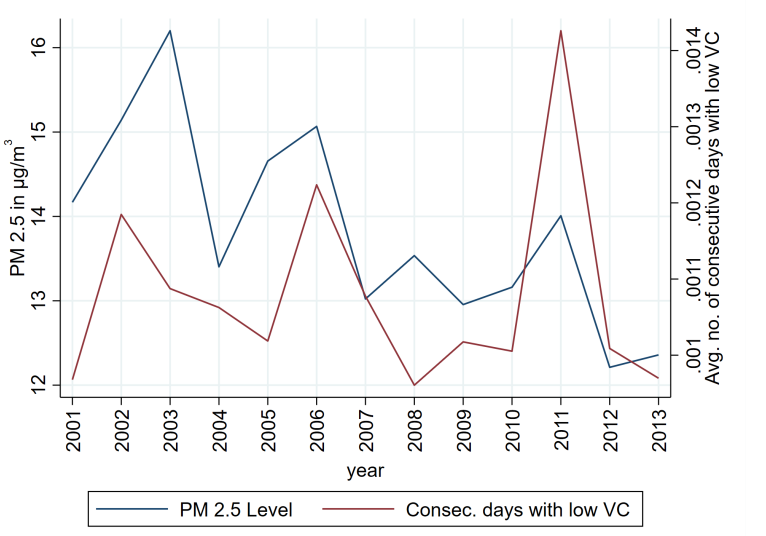
- Geocoded inventor addresses (de Rassenfosse et al. 2019) and PATSTAT
- $PM_{2.5}$ concentration (Van Donkelaar et al. 2019) and population data in Europe (Columbia University 2018)
- Atmospheric data from MERRA-2 (Gelaro et al. 2017)
- Atmospheric and climate data from ERA5 and ERA5-Land (Hersbach et al. 2020, Muñoz-Sabater 2019)
- Geographic indicators for NUTS-3 regions from Eurostat

# Descriptive patterns

- $PM_{2.5}$ concentration falls on average by $0.17 \mu g/m^3$ every year




**(c)** $PM_{2.5}$ and Thermal Inversions



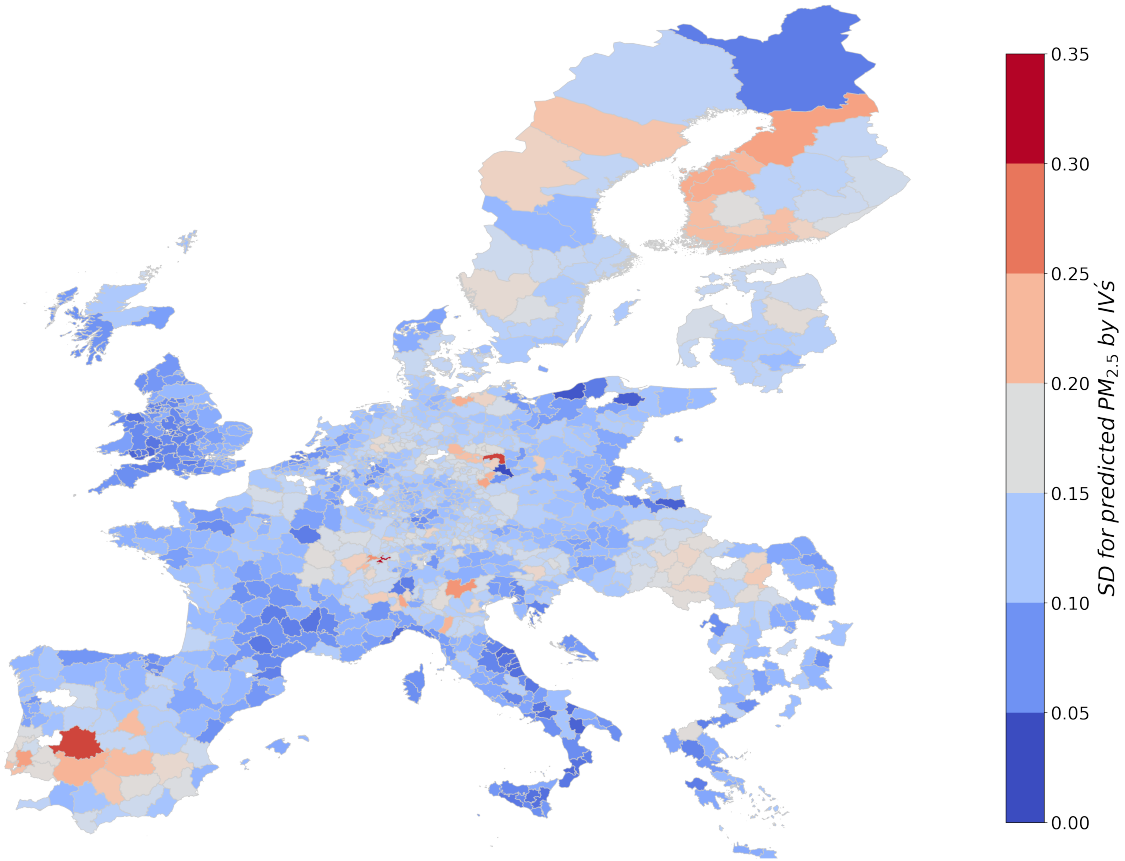

**(d)** $PM_{2.5}$ and Ventilation Capability

# Summary statistics

- 1288 NUTS-regions in 30 countries for the period 2001 - 2013
- Trim $PM_{2.5}$ at 1% at each side of the distribution
- Drop NUTS-3 regions equal or below 5th percentile of the distribution for total number of patent filings map

| | N | Mean | Std. Dev. | 10th | 50th | 90th |
|---|---|---|---|---|---|---|
| Nb. patent filings | 16744 | 108.56 | 222.63 | 3 | 41 | 257 |
| Population (*in thd*) | 14845 | 385.59 | 437.93 | 94.75 | 270.11 | 736.28 |
| Pop-weighted PM 2.5 | 16407 | 13.62 | 4.79 | 8.31 | 12.88 | 20.38 |
| Nb. thermal inversions | 16484 | 54.38 | 32.58 | 13 | 51 | 100 |
| Share thermal inversions | 16484 | 0.15 | 0.09 | 0.04 | 0.14 | 0.27 |
| Ventilation Coefficient ($m^2/s$) | 16328 | 1642.95 | 784.28 | 599 | 1613 | 2667 |
| Avg consecutive days with low VC | 16328 | 0.00 | 0.0003 | 0.0008 | 0.0010 | 0.0015 |
| Surface pressure ($Pa$) | 16328 | 97969.59 | 3468.87 | 93819 | 98969 | 101094 |
| Relative humidity (%) | 16484 | 0.74 | 0.06 | 0.64 | 0.75 | 0.81 |
| Temperature ($K$) | 16328 | 283.03 | 2.67 | 280 | 283 | 286 |
| Wind speed ($m/s$) | 16328 | 2.49 | 0.93 | 1.24 | 2.47 | 3.62 |
| Precipitation ($m$) | 16328 | 0.13 | 0.04 | 0.09 | 0.12 | 0.18 |
| $N$ | 16744 | | | | | |

# PM variation induced by the IVs




Predicted $PM_{2.5}$ concentration by NUTS-3

# Main result

- $1\mu g/m^3$ increase in $PM_{2.5} \Rightarrow$ 10% less patent filings
- Europe's average yearly reduction in air pollution has led to 1.7% more innovations per year

| | OLS | IV with TI | | IV with VC | | IV with TI & VC | |
|---|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Patents) | Log(Patents) | $PM2.5_{t-1}$ | Log(Patents) | $PM2.5_{t-1}$ | Log(Patents) | $PM2.5_{t-1}$ |
| $PM2.5_{t-1}$ | -0.0057 | -0.10** | | -0.10** | | -0.10*** | |
| | (0.0037) | (0.048) | | (0.050) | | (0.036) | |
| *Share Inversions*$_{t-1}$ | | | 3.70*** | | | | 3.65*** |
| | | | (0.52) | | | | (0.52) |
| *Share low VC*$_{t-1}$ | | | | | 261.3*** | | 256.8*** |
| | | | | | (39.4) | | (39.6) |
| NUTS-3 FE | YES | YES | | YES | | YES | |
| Country-Year FE | YES | YES | | YES | | YES | |
| Controls | YES | YES | | YES | | YES | |
| KP F-stat. | | 50.4 | | 43.9 | | 44.0 | |
| Hansen J stat. P-Val | | | | | | 0.96 | |
| N | 12864 | 12864 | 12864 | 12864 | 12864 | 12864 | 12864 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

# Additional results

## Regional variation

- Effect larger in regions with above-median pollution ⏩ Results
- Similar effect for regions with medium vs. high levels of urbanization ⏩ Results

## Inventor Migration

- Geocoded data on disambiguated inventors (Morrison et al. 2017)
- Track mobility by changing addresses across patents (Zacchia 2018)
- Economically and statistically insignificant effect on inventor mobility ⏩ Results

# Mechanisms I

**Are these effects captured in prior assessments?**

- Mortality
- R&D spending

**Mortality** ⏩ Results

- Total mortality statistics per NUTS-3 region (Eurostat)
- Conservative estimate because inventors probably *less* likely to pass away (socioeconomic factors)
- Economically and statistically insignificant effect on total mortality

# Mechanisms II

## R&D spending ⇒ Science

Results

- Science funding should react less to air pollution
- Geocoded data on PubMed author affiliations (Torvik 2015)
- $1\mu g/m^3$ increase in $PM_{2.5}$ ⇒ 9% less journal articles

## R&D spending ⇒ Invention quality

Results

- Less R&D expenditures ⇒ Less low quality inventions ⇒ Higher observed quality
- Weight patent counts by forward citation counts
- Quality does not increase significantly

# Robustness checks

- Poisson fixed effects regression Results
- Accounting for spatial and serial correlation Results
- Altering threshold for the definition of a low Ventilation Coefficient Results
- Including all NUTS-3 regions for main results Results
- Altering the sample period up to the interval 2001 - 2008 Results
- Excluding weather covariates Results
- None of the weather controls are significantly correlated with # of patent filings Results

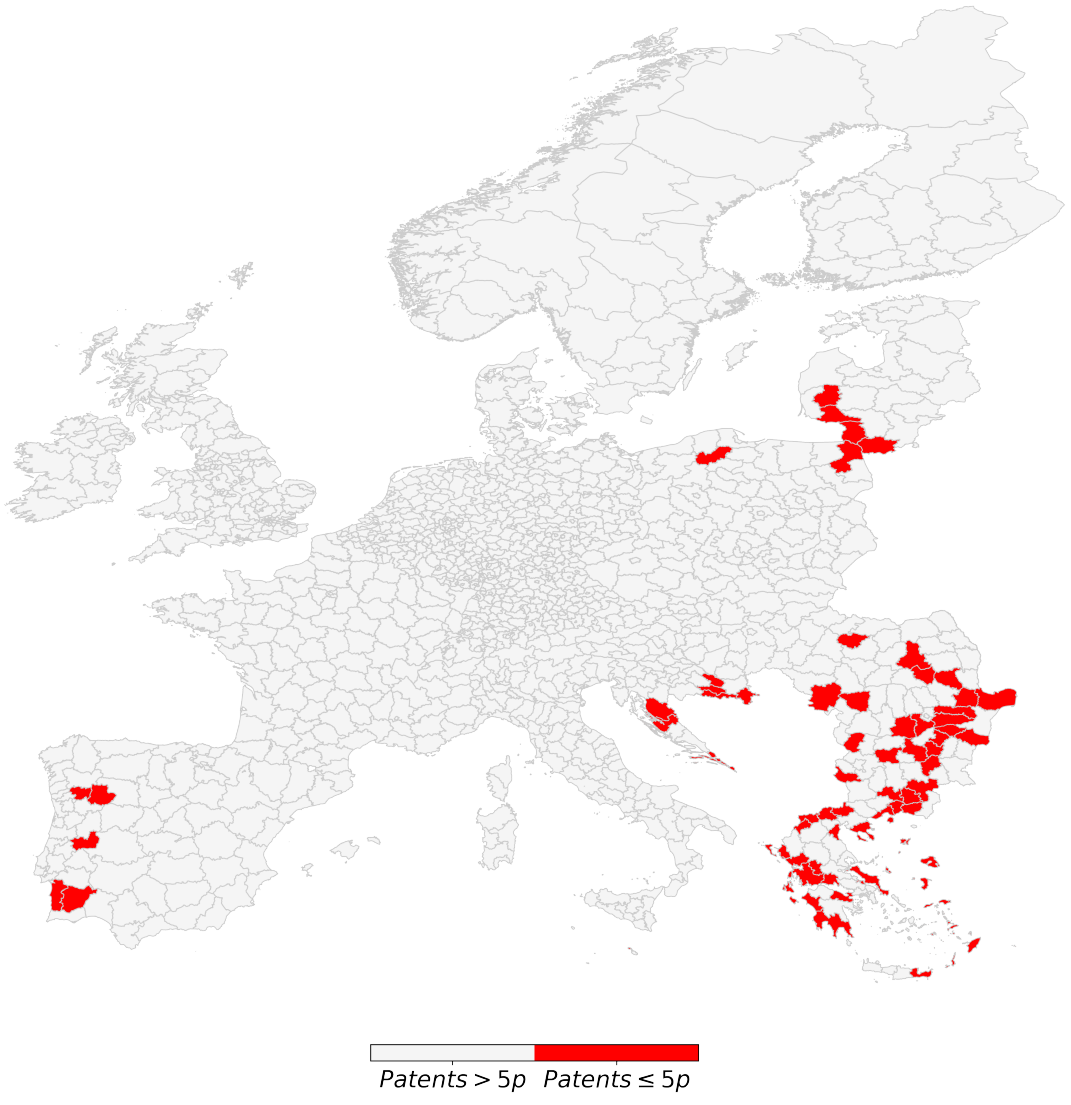
# Conclusion

- Negative effect of air pollution on innovation
  - Driven by more polluted regions
  - In regions with medium to high levels of urbanization
  - No evidence that migration drives the effect
- Cost not accounted for in previous assessments
  - Mortality and R&D spending unlikely to drive effect
- Back-of-the-envelope:
  - Use estimates of private and social value of innovation (Gambardella et al. 2008, Bloom et al. 2013, Zacchia 2018)
  - 21.3 bln. euros annually
  - Previous assessment using GDP understated with at least 10%

**Evidence for another hidden cost of air pollution**

# Thank you!

# Dropped NUTS-3 regions

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# High- vs. low-pollution regions

| | Low PM 2.5 below Median | | High PM 2.5 above Median | |
|---|---|---|---|---|
| Dep. Variable: | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 |
| *PM*2.5 | -0.049 | | -0.15** | |
| | (0.049) | | (0.067) | |
| *Share Inversions* | | 3.17*** | | 3.89*** |
| | | (0.52) | | (0.94) |
| *Share low VC* | | 225.7*** | | 210.0*** |
| | | (44.9) | | (63.4) |
| Mean # Patents | 89.19 | | 130.81 | |
| Mean PM 2.5 | 10.49 | | 17.05 | |
| NUTS-3 FE | YES | | YES | |
| Country-Year FE | YES | | YES | |
| KP F-stat. | 32.1 | | 14.0 | |
| Hansen J stat. P-Val | 0.59 | | 0.94 | |
| N | 6605 | 6605 | 6307 | 6307 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

- Non-linear relationship between air pollution and innovation

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# Urban vs. rural regions

| | Predominantly Urban | | Intermediate | | Predominantly Rural | |
|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 |
| *PM*2.5 | -0.092** | | -0.17*** | | -0.0033 | |
| | (0.043) | | (0.062) | | (0.094) | |
| *Share Inversions* | | 5.43*** | | 2.66*** | | 3.91*** |
| | | (1.08) | | (0.80) | | (0.76) |
| *Share low VC* | | 303.7*** | | 238.2*** | | 148.7** |
| | | (83.3) | | (57.4) | | (67.9) |
| Mean # Patents | 208.26 | | 96.59 | | 40.84 | |
| Mean PM 2.5 | 14.14 | | 14.15 | | 13.06 | |
| NUTS-3 FE | YES | | YES | | YES | |
| Year FE | YES | | YES | | YES | |
| KP F-stat. | 18.9 | | 13.7 | | 16.2 | |
| Hansen J stat. P-Val | 0.60 | | 0.56 | | 0.25 | |
| N | 3370 | 3370 | 5746 | 5746 | 3704 | 3704 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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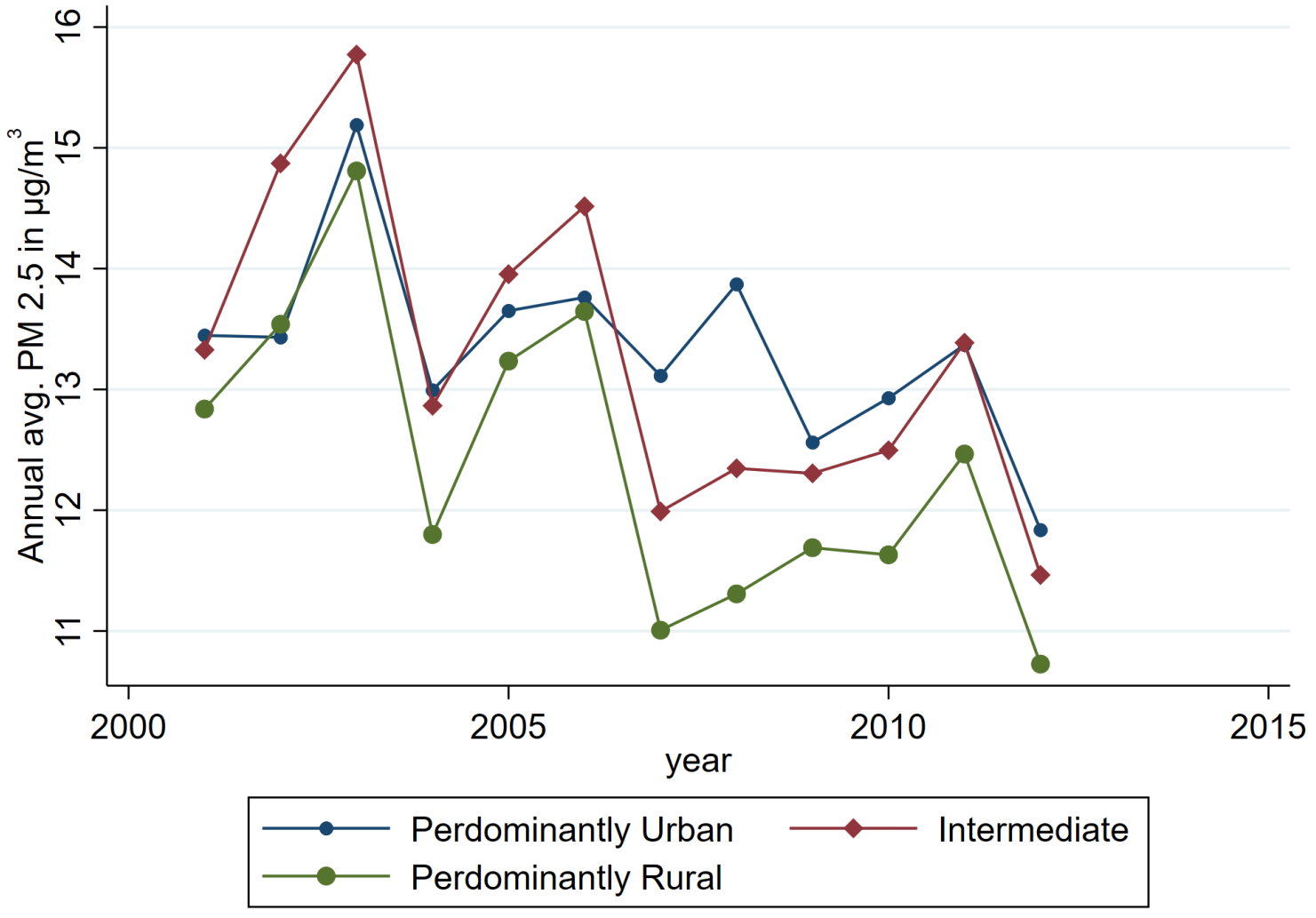
⏩ PM levels

# PM level in urban vs. rural regions

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# Inventors' relocation and air pollution

| | OLS | IV | | OLS | IV | |
|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Emigr. Inv.) | Log(Emigr. Inv.) | $PM2.5_{t-1}$ | Log(Emigr. Inv. Patents) | Log(Emigr. Inv. Patents) | $PM2.5_{t-1}$ |
| $PM2.5_{t-1}$ | -0.011*** | 0.031 | | -0.017** | 0.027 | |
| | (0.0039) | (0.046) | | (0.0069) | (0.084) | |
| *Share Inversions*$_{t-1}$ | | | 3.78*** | | | 3.78*** |
| | | | (0.50) | | | (0.50) |
| *Share low VC*$_{t-1}$ | | | 227.2*** | | | 227.2*** |
| | | | (40.3) | | | (40.3) |
| NUTS-3 FE | YES | YES | | YES | YES | |
| Country-Year FE | YES | YES | | YES | YES | |
| Controls | YES | YES | | YES | YES | |
| KP F-stat. | | 42.5 | | | 42.5 | |
| Hansen J stat. P-Val | | 0.25 | | | 0.27 | |
| N | 13671 | 13671 | 13671 | 13671 | 13671 | 13671 |

| | OLS | IV | | OLS | IV | |
|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Immigr. Inv.) | Log(Immigr. Inv.) | $PM2.5_{t-1}$ | Log(Immigr. Inv. Patents) | Log(Immigr. Inv. Patents) | $PM2.5_{t-1}$ |
| $PM2.5_{t-1}$ | -0.0059 | -0.010 | | -0.0055 | -0.056 | |
| | (0.0039) | (0.043) | | (0.0068) | (0.079) | |
| *Share Inversions*$_{t-1}$ | | | 3.78*** | | | 3.78*** |
| | | | (0.50) | | | (0.50) |
| *Share low VC*$_{t-1}$ | | | 227.2*** | | | 227.2*** |
| | | | (40.3) | | | (40.3) |
| NUTS-3 FE | YES | YES | | YES | YES | |
| Country-Year FE | YES | YES | | YES | YES | |
| Controls | YES | YES | | YES | YES | |
| KP F-stat. | | 42.5 | | | 42.5 | |
| Hansen J stat. P-Val | | 0.56 | | | 0.85 | |
| N | 13671 | 13671 | 13671 | 13671 | 13671 | 13671 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Science

| | OLS | IV | |
|---|---|---|---|
| Dep. Variable: | Log(PubMed) | Log(PubMed) | PM2.5 |
| *PM*2.5 | -0.0023 | -0.086** | |
| | (0.0041) | (0.042) | |
| *Share Inversions* | | | 3.78*** |
| | | | (0.50) |
| *Share low VC* | | | 227.2*** |
| | | | (40.3) |
| NUTS-3 FE | YES | YES | |
| Country-Year FE | YES | YES | |
| Controls | YES | YES | |
| KP F-stat. | | 42.5 | |
| Hansen J stat. P-Val | | 0.26 | |
| N | 13671 | 13671 | 13671 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Invention quality

| | 5-year fw. cites | | Fw. cites normalized | |
|---|---|---|---|---|
| Dep. Variable: | Log(Cites) | $PM2.5_{t-1}$ | Log(Cites) | $PM2.5_{t-1}$ |
| $PM2.5_{t-1}$ | -0.12* | | -0.13*** | |
| | (0.062) | | (0.042) | |
| *Share Inversions*$_{t-1}$ | | 3.65*** | | 3.65*** |
| | | (0.52) | | (0.52) |
| *Share low VC*$_{t-1}$ | | 256.8*** | | 256.8*** |
| | | (39.6) | | (39.6) |
| NUTS-3 FE | YES | | YES | |
| Country-Year FE | YES | | YES | |
| Controls | YES | | YES | |
| KP F-stat. | 44.0 | | 44.0 | |
| Hansen J stat. P-Val | 0.73 | | 0.89 | |
| N | 12864 | 12864 | 12864 | 12864 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Total deaths and air pollution

| | OLS | IV | | OLS | IV | |
|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Deaths) | Log(Deaths) | PM2.5 | Death Rate | Death Rate | PM2.5 |
| *PM*2.5 | -0.0011*** | 0.0027 | | -0.0012*** | 0.0028 | |
| | (0.00036) | (0.0038) | | (0.00038) | (0.0040) | |
| *Share Inversions* | | | 3.43*** | | | 3.43*** |
| | | | (0.50) | | | (0.50) |
| *Share low VC* | | | 241.0*** | | | 241.0*** |
| | | | (40.7) | | | (40.7) |
| NUTS-3 FE | YES | YES | | YES | YES | |
| Country-Year FE | YES | YES | | YES | YES | |
| Controls | YES | YES | | YES | YES | |
| KP F-stat. | | 38.6 | | | 38.6 | |
| Hansen J stat. P-Val | | 0.24 | | | 0.30 | |
| N | 13230 | 13230 | 13230 | 13230 | 13230 | 13230 |

Death rate does not include population as control. Standard errors are reported in parentheses and clustered at the NUTS-3 level.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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# Count model

- Poisson fixed effects regression with control function approach to account for endogenous $PM_{2.5}$ (Lin & Wooldridge 2019)

| | Poisson | Poisson CF |
|---|---|---|
| Dep. Variable: | Nb. Patents | Nb. Patents |
| $PM2.5$ | -0.0077** | -0.071*** |
| | (0.0036) | (0.027) |
| $\hat{v}$ | | 0.064** |
| | | (0.027) |
| NUTS-3 FE | YES | YES |
| Country-Year FE | YES | YES |
| Log likelihood | -56582.7 | |
| Pseudo R2 | 0.96 | |
| Replications | | 500 |
| Clusters | 1196 | 1365 |
| N | 13599 | 16380 |

SE are bootstrapped

* p<0.1, ** p<0.05, and *** p<0.01

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# Conley SE

- Adjust SE in line with Conley (1999, 2010) to account for spatial and serial correlation
- Assumption 1 (2) assumes a spatial correlation range of 500 (1000) kilometers and a serial correlation range of 5 (10) years

| | *Clustered SE* | *SE – Assumption* 1 | *SE – Assumption* 2 |
|---|---|---|---|
| Dep. Variable: | Log(Patents) | Log(Patents) | Log(Patents) |
| *PM*2.5 | -0.087** | -0.087** | -0.087** |
| | (0.036) | (0.044) | (0.042) |
| NUTS-3 FE | YES | YES | YES |
| Country-Year FE | YES | YES | YES |
| Controls | YES | YES | YES |
| N | 13671 | 13671 | 13671 |

SE are bootstrapped

* p<0.1, ** p<0.05, and *** p<0.01

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# Different thresholds for a low VC

| | *Low VC* $\leq p10$ | | *Low VC* $\leq p15$ | | *Low VC* $\leq p20$ | | *Low VC* $\leq p25$ | |
|---|---|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 |
| *PM*2.5 | -0.10** | | -0.088** | | -0.10*** | | -0.054* | |
| | (0.047) | | (0.043) | | (0.036) | | (0.028) | |
| *Share Inversions* | | 3.70*** | | 3.67*** | | 3.66*** | | 3.70*** |
| | | (0.52) | | (0.51) | | (0.51) | | (0.51) |
| *Share p*10 $\geq$ *VC* | | 90.6 | | | | | | |
| | | (82.0) | | | | | | |
| *Share p*15 $\geq$ *VC* | | | | 181.1*** | | | | |
| | | | | (53.4) | | | | |
| *Share p*20 $\geq$ *VC* | | | | | | 255.6*** | | |
| | | | | | | (39.5) | | |
| *Share p*25 $\geq$ *VC* | | | | | | | | 279.7*** |
| | | | | | | | | (31.5) |
| NUTS-3 FE | YES | | YES | | YES | | YES | |
| Country-Year FE | YES | | YES | | YES | | YES | |
| Controls | YES | | YES | | YES | | YES | |
| KP F-stat. | 26.5 | | 31.5 | | 44.9 | | 63.3 | |
| Hansen J stat. P-Val | 0.15 | | 0.81 | | 0.78 | | 0.27 | |
| N | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Different thresholds for dropping NUTS-3 regions

| | No trimming | | Trim NUTS-3 at 5% | | Trim NUTS-3 at 10% | | Trim NUTS-3 at 15% | |
|---|---|---|---|---|---|---|---|---|
| Dep. Variable: | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 |
| *PM*2.5 | -0.087** | | -0.099*** | | -0.14*** | | -0.14*** | |
| | (0.036) | | (0.036) | | (0.037) | | (0.036) | |
| *Share Inversions* | | 3.78*** | | 3.65*** | | 3.27*** | | 3.24*** |
| | | (0.50) | | (0.51) | | (0.50) | | (0.52) |
| *Share low VC* | | 227.2*** | | 253.7*** | | 258.6*** | | 259.5*** |
| | | (40.3) | | (39.5) | | (40.6) | | (41.8) |
| NUTS-3 FE | YES | | YES | | YES | | YES | |
| Country-Year FE | YES | | YES | | YES | | YES | |
| Controls | YES | | YES | | YES | | YES | |
| KP F-stat. | 42.5 | | 44.9 | | 39.0 | | 37.1 | |
| Hansen J stat. P-Val | 0.50 | | 0.82 | | 0.70 | | 0.96 | |
| N | 13671 | 13671 | 12984 | 12984 | 12267 | 12267 | 11699 | 11699 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Different sample periods

| Dep. Variable: | Log(Patents) | Log(Patents) | Log(Patents) | Log(Patents) | Log(Patents) |
|---|---|---|---|---|---|
| *PM*2.5 | -0.10*** | -0.097*** | -0.16*** | -0.16*** | -0.14*** |
| | (0.036) | (0.034) | (0.055) | (0.047) | (0.046) |
| Period | 2001-2012 | 2001-2011 | 2001-2010 | 2001-2009 | 2001-2008 |
| NUTS-3 FE | YES | YES | YES | YES | YES |
| Country-Year FE | YES | YES | YES | YES | YES |
| KP F-stat. | 44.9 | 46.5 | 18.3 | 23.0 | 24.9 |
| Hansen J stat. P-Val | 0.78 | 0.65 | 0.21 | 0.79 | 0.51 |
| N | 12924 | 11778 | 10659 | 9565 | 8475 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Main results with individual weather controls

| Dep. Variable: | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 | Log(Patents) | *PM*2.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *PM*2.5 | -0.075** | | -0.084** | | -0.079** | | -0.084** | | -0.076** | | -0.086*** | | -0.10*** | |
| | (0.030) | | (0.035) | | (0.031) | | (0.036) | | (0.031) | | (0.030) | | (0.036) | |
| *Share Inversions* | | 4.05*** | | 4.03*** | | 4.16*** | | 3.56*** | | 3.97*** | | 4.06*** | | 3.66*** |
| | | (0.49) | | (0.49) | | (0.51) | | (0.50) | | (0.49) | | (0.49) | | (0.51) |
| *Share low VC* | | 300.6*** | | 224.0*** | | 295.4*** | | 256.0*** | | 301.4*** | | 326.5*** | | 255.6*** |
| | | (39.2) | | (38.1) | | (39.1) | | (38.8) | | (39.2) | | (41.3) | | (39.5) |
| *Log*(*Pop*) | 0.32 | 0.74 | 0.34 | 0.83 | 0.32 | 0.75 | 0.33 | 0.75 | 0.33 | 0.77 | 0.33 | 0.72 | 0.36 | 0.88 |
| | (0.26) | (0.79) | (0.26) | (0.79) | (0.26) | (0.79) | (0.26) | (0.78) | (0.26) | (0.79) | (0.26) | (0.79) | (0.26) | (0.78) |
| *Surface Pressure* | | | 0.0014 | 0.020*** | | | | | | | | | 0.0022 | 0.024*** |
| | | | (0.0011) | (0.0033) | | | | | | | | | (0.0014) | (0.0041) |
| *Surface Pressure*$^2$ | | | -5.0e-09 | -0.000000077*** | | | | | | | | | -8.9e-09 | -0.000000092*** |
| | | | (4.9e-09) | (0.000000017) | | | | | | | | | (6.8e-09) | (0.000000021) |
| *Relative humidity* | | | | | 1.53 | 22.4** | | | | | | | -0.57 | 2.49 |
| | | | | | (3.51) | (9.19) | | | | | | | (3.49) | (9.57) |
| *Relative humidity*$^2$ | | | | | -0.89 | -17.8*** | | | | | | | 0.46 | -5.30 |
| | | | | | (2.48) | (6.58) | | | | | | | (2.46) | (6.78) |
| *Temperature* | | | | | | | 0.56 | 5.30 | | | | | -0.39 | -5.06 |
| | | | | | | | (1.06) | (3.60) | | | | | (1.37) | (4.50) |
| *Temperature*$^2$ | | | | | | | -0.0010 | -0.010 | | | | | 0.00063 | 0.0081 |
| | | | | | | | (0.0019) | (0.0064) | | | | | (0.0024) | (0.0080) |
| *Precipitation* | | | | | | | | | 1.27 | -236.2 | | | -0.86 | -159.6 |
| | | | | | | | | | (69.0) | (201.4) | | | (75.5) | (217.9) |
| *Precipitation*$^2$ | | | | | | | | | 13426.1 | 165018.1*** | | | 20722.2 | 208616.1*** |
| | | | | | | | | | (19623.1) | (50695.6) | | | (21520.4) | (51402.7) |
| *Wind speed* | | | | | | | | | | | -0.0095 | 0.15 | 0.035 | 0.71* |
| | | | | | | | | | | | (0.13) | (0.38) | (0.13) | (0.43) |
| *Wind speed*$^2$ | | | | | | | | | | | -0.014 | 0.035 | -0.012 | 0.070 |
| | | | | | | | | | | | (0.019) | (0.053) | (0.020) | (0.065) |
| NUTS-3 FE | YES | | YES | | YES | | YES | | YES | | YES | | YES | |
| Country-Year FE | YES | | YES | | YES | | YES | | YES | | YES | | YES | |
| KP F-stat. | 60.9 | | 49.5 | | 57.8 | | 45.3 | | 59.9 | | 62.5 | | 44.9 | |
| Hansen J stat. P-Val | 0.84 | | 0.91 | | 0.77 | | 0.88 | | 0.81 | | 0.86 | | 0.78 | |
| N | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 | 12924 |

SE clustered at NUTS-3
* p<0.1, ** p<0.05, and *** p<0.01

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# Patent filings and weather controls

| Dep. Variable: | Log(Patents) | Log(Patents) | Log(Patents) | Log(Patents) | Log(Patents) | Log(Patents) |
|---|---|---|---|---|---|---|
| *Log(Pop)* | 0.15 | 0.29 | 0.16 | 0.16 | 0.16 | 0.25 |
| | (0.27) | (0.25) | (0.27) | (0.27) | (0.27) | (0.26) |
| *Surface Pressure* | -0.00020 | | | | | -0.000044 |
| | (0.00080) | | | | | (0.00100) |
| *Surface Pressure*$^2$ | 4.0e-10 | | | | | -5.9e-10 |
| | (4.0e-09) | | | | | (5.2e-09) |
| *Relative humidity* | | 0.27 | | | | 0.031 |
| | | (3.20) | | | | (3.31) |
| *Relative humidity*$^2$ | | 0.027 | | | | 0.23 |
| | | (2.26) | | | | (2.34) |
| *Temperature* | | | 0.018 | | | -0.19 |
| | | | (0.91) | | | (1.13) |
| *Temperature*$^2$ | | | 0.0000082 | | | 0.00040 |
| | | | (0.0016) | | | (0.0020) |
| *Precipitation* | | | | 35.3 | | 50.1 |
| | | | | (63.8) | | (70.2) |
| *Precipitation*$^2$ | | | | -2336.3 | | -6023.3 |
| | | | | (17437.3) | | (18345.3) |
| *Wind speed* | | | | | -0.0022 | -0.035 |
| | | | | | (0.10) | (0.11) |
| *Wind speed*$^2$ | | | | | -0.014 | -0.015 |
| | | | | | (0.014) | (0.014) |
| NUTS-3 FE | YES | YES | YES | YES | YES | YES |
| Country-Year FE | YES | YES | YES | YES | YES | YES |
| F-stat. | 0.42 | 0.68 | 0.64 | 0.49 | 1.45 | 1.15 |
| R-sq | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 |
| N | 13270 | 13399 | 13270 | 13270 | 13270 | 13152 |

SE clustered at NUTS-3

* p<0.1, ** p<0.05, and *** p<0.01

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# Air pollution policy in Europe

**1999**

- 1st Daughter Directive AQ limit for $SO_2$, $NO_2$, $NO_X$, PM and lead (1999/30/EC)

**2000**

- 2nd Daughter Directive relating to $CO$ and benzene (2000/69/EC)

**2001**

- Directive on the limitation of emissions of certain pollutants into the air from large combustion plants (2001/80/EC)

**2002**

- 3rd Daughter Directive relating to $O_3$ in ambient air (2002/3/EC)

**2004**

- 4th Daughter Directive relating to $As$, $Ni$, $PAH$ in Ambient air (2004/107/EC)

**2008**

- Directive of the European parliament and of the Council on ambient air quality and cleaner air for Europe (2008/50/EC)

**2010**

- Industrial Emissions Directive constraining emissions locally, at the point where these leave the installation (2010/75/EU)

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