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Ozone Pollution, Health and Well-Being

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Ozone Pollution, Health and Well-Being

Preliminary Draft - Please Do Not Cite or Circulate

Julia Rechlitz* Luis Sarmiento[†] Aleksandar Zaklan[‡]

February 6, 2019

This paper evaluates the effect of ozone pollution on individuals' subjective health satisfaction and well-being, allowing us to capture both direct and indirect effects of ozone pollution on adults. Specifically, we focus on differences between households with and without children. We combine geo-coded individual-level data from the German Socio-Economic Panel (SOEP) with data on ozone concentrations from measuring stations in Germany. We precisely assign pollution levels to individuals by exploiting information about the date of the SOEP interview. We find that ozone decreases the well-being of adults sharing households with children, while not causing losses in their own subjective health. The effects are stronger for a greater length of exposure. Our results suggest that damages from ozone in the general population may primarily stem from indirect effects through health effects for children.

JEL codes: Q53, Q51, C23,

Keywords: Local pollution, ozone, subjective well-being, subjective health, climate policy co-benefits

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1 Introduction

Understanding the link between local air pollution and human health and well-being is an important issue for economists. Considering the effects of ground-level ozone on humans is especially relevant, as it is an aggressive pollutant leading to increases in the morbidity and mortality of affected persons (Schwela, 2000). Short-term effects include decreases in lung capacity, inflammations of the respiratory tract, and a greater frequency of asthma attacks, while long-term exposure increases the risk of developing chronic lung disease, such as asthma (EPA, 2016), and potentially an increase in cancer risk (Rocks et al., 2017; Kim et al., 2018). The health effects of ozone are strongest among high-risk populations, such as children, the elderly, outdoor workers and individuals suffering from respiratory ailments such as asthma. While the health effects are reversible in the short term, especially for otherwise healthy individuals, continued exposure to high concentrations of ground-level ozone causes economic costs through greater expenditures on health services, losses in labor supply, e.g. through an increase in absenteeism, and decreases in labor productivity (e.g. Zivin and Neidell (2012)).

Ground-level ozone is a secondary pollutant formed through the reaction of nitrous oxides (NO_x) and volatile organic compounds (VOC), mainly emitted by motor vehicles and combustion plants, in combination with sunshine.¹ Ozone concentrations have remained stable and may even increase due to climate change through the associated rise in heat waves. Heat waves diminish wind flows that disperse ozone precursors, and increase the use of air conditioning and cooling devices that emit ozone precursors (Rosenzweig et al., 2004; Selin et al., 2009). Mitigating climate change by decreasing the combustion of fossil fuels, e.g. through a large-scale electrification of road transport or decommissioning of fossil-fuel power generation, may decrease ozone concentrations, as the concentrations of precursor pollutants will decline. Therefore, lower damages from ozone exposure represents a co-benefit of climate policy.

In this paper, we consider the effects of ground-level ozone pollution on the subjective health and well-being of on a panel of German individuals. Evaluating subjective health effects of ozone exposure is relevant in contexts of moderate ozone concentrations and generally healthy populations, as in Germany. In such settings, economic costs will be

¹In contrast to ground-level ozone, which is largely man-made, the majority of ozone in the earth's atmosphere occurs naturally in the stratosphere, between about 10 and 50km above the earth's surface. This ozone layer plays an important role in protecting life on earth from part of the sun's ultraviolet radiation.

realized in the short to medium term if individuals *feel* less healthy due to ozone exposure. In such cases they may be expected to use health services, decrease their labor supply and/or suffer losses in productivity, even if the impact on objective health is limited. Conversely, a moderate deterioration in objective health may not lead to economic cost in the short to medium term, if the individual generally *feels* well. Evaluating the effect of ozone on subjective well-being is also of interest, as it allows us to evaluate indirect effects of pollution: While pollution may not significantly affect a generally healthy adult directly, it may affect the individual indirectly through others sharing the same household, e.g. children affected by ozone. Such indirect effects may affect the subjective well-being of the individual. Such changes in well-being may also have economic consequences, such as absences from work to care for affected relatives or losses in productivity due to well-being effects, even if the person's own health is not directly affected by ozone concentrations.

We identify the effect of ozone on individuals by combining geo-coded data on ozone pollution from measuring stations across Germany with geo-coded individual level data on subjective health and subjective well-being from the German Socio-Economic Panel Study (SOEP), a representative survey of German individuals. Our sample period covers 2005 to 2015. We exploit information on the precise date of the SOEP interview and our daily pollution data to assign pollution exposure to each individual. We calculate the level of ozone pollution experienced by each individual by constructing weighted averages of ozone levels from nearby stations using inverse distance weighting techniques. In addition to calculating short-term exposure to ozone on the day of the interview we also construct longer-term averages for ozone exposure prior to the interview date. We thus exploit variation in pollution across space - ozone levels differ in Germany at any one time - and across time, as SOEP interviews take place at different times of the year. The richness of our dataset therefore enables us to control for a comprehensive set of potential confounders. SOEP data include a wealth of individual-level controls, allowing us to control for many relevant observables, such as income. Moreover, the panel structure of the data allows us to control for individual fixed effects. We add additional controls are the county level from Eurostat, and additional weather-related controls from monitoring stations of the German meteorological service.

There is substantial evidence that ozone decreases objective measures of human health, especially of children. Devlin et al. (1991) use an experimental design to test the reaction of healthy nonsmoking adults to ambient levels of ozone. They conclude that even at ambient

levels as low as 0.08 particles per million (ppm), there are negative impacts of exposure to ozone on the respiratory system. Koken et al. (2003) find that increases in ozone correlate with hospitalizations of elderly adults due to cardiovascular ailments. Gryparis et al. (2004) use data from 24 different European urban agglomerations and conclude that an increase by 10 milligrams per cubic meter (mg/m^3) in the levels of 1-hour maximum daily ozone raise total mortality rates by 0.31%. Using time-series methods Holgate et al. (2003) finds that an increase of 10 mg/m^3 in daily average-ozone raises mortality by 0.25%. Bell et al. (2005) compares the study in Holgate et al. (2003) to a meta-analysis of 39 different time-series studies on the effects of ozone exposure on mortality. Their results point towards an even higher coefficient (0.83%) than the one found by Holgate et al. (2003). Graff Zivin and Neidell (2012) analyze the consequences of ozone exposure on the productivity of Californian farm workers. They find significant decreases in farm output due to increases in ozone concentrations.

Studies of the effect of ozone on children’s health also have produced substantial evidence regarding the damaging impact of ozone on respiratory health, lung capacity, long-term inadequacy of lung growth, increases in hospitalizations, mortality, and in the use of asthma medicine (Bates, 1995). Burnett et al. (2001) analyse the effects of ozone on the hospitalization rates of children less than two years old. They find that increasing daily concentrations of ozone to one-hour maximum values typically found in summertime (45 ppb) would increase daily hospitalizations due to respiratory disease by 35%. Heinrich et al. (2000) uses the natural experiment of German unification to analyze how the associated drop in air pollution affected the health of children between the ages of 5 to 14 years. He finds a substantial decrease in total suspended particles (TSP) and other pollutants that are precursors of ozone. The study connects drops in TSP to decreases in bronchitis, otitis, and frequent colds. Thurston et al. (1997) find significant correlations between lower lung capacity and high levels of atmospheric ozone when studying the effect in children between 7 and 13 years old attending an asthma camp. Galizia and Kinney (1999) find that exposure to high levels of ozone during childhood affect the lung capacity of university students several years later. Ostro et al. (2001) find that asthmatic children between the ages of 8 and 13 years increase medicine use during higher ozone episodes. Lee et al. (2002) find that, for South Korean children under the age of 15, the risk of asthma-related hospitalization increases by 7 to 13 percent when atmospheric ozone rises by 21 ppb. Friedman et al. (2001) uses the variation in environmental policies during the

Atlanta summer games to infer that the associated drops in peak daily ozone levels (81.3 to 58.6ppb) were responsible for 56 fewer asthma-related emergency room admissions. Using the same source of variation in ozone values, Tolbert et al. (2000) find that increasing the 8-hour maximum ozone level by 20 ppb increases pediatric emergency room visits due to asthma by 4%.

A related literature analyzes the effect of ozone on school absences. Gilliland et al. (2001) uses time series methods to infer that an increase of 20 ppm in ozone levels raises respiratory-health-related school absences by 84 %. They also conclude that the peak of absenteeism occurs five days after the high-ozone episode. Chen et al. (2018) find an adverse effect of ozone, particle matter, and a composite pollution index on the health of school children and their related school absenteeism. They estimate that an increase by 10 mg/m^3 in daily ozone concentrations increases school absences by 0.99%. Currie et al. (2009) uses difference-in-differences designs and data from the Texas school system to find that exposure to carbon monoxide also rises school absences, while not obtaining significant results for ozone.

Finally, concerning studies linking environmental pollution with subjective measurements of well-being, Rehdanz and Maddison (2008) uses the German Socio-Economic Panel Study to infer that when people claim to be affected by higher air pollution, its levels of life satisfaction diminish. Luechinger (2009) uses the life satisfaction approach on SOEP data aggregated at the county level to infer that a decrease in SO_2 yearly concentration of 17.67 mg/m^3 would be equivalent to the effect of reducing the local unemployment rate by one standard deviation (4.64%). Ferreira and Moro (2010) Uses the same method with Irish electoral districts to conclude that if the annual mean value of particle matter increases by 150% (50 mg/m^3) will reduce subjective wellbeing by 0.75 in a scale from 1 to 8. Cunado and De Gracia (2013) regress life satisfaction on the number of days per year exceeding 50 micrograms per cubic meter ($\mu\text{g/m}^3$). An increase of one day diminishes life satisfaction by 0.003 units. Additional literature is Ferreira et al. (2013) on a European level and Ambrey et al. (2014) in Queensland, Australia.

We contribute to the stream of the literature on health effects by evaluating whether moderate levels of ground-level ozone, as in Germany, make individuals *feel* less healthy. As we expect individuals to demand healthcare services if they feel less healthy due to ozone, we can assess whether currently moderate ozone levels may lead to health-related economic costs. Our additional focus on the broader measure of well-being also allows

us to estimate the likelihood of indirect sources of economic costs due to ozone exposure. Such effects may occur not due to impacts on the individual’s own health, but due to the effect of ozone on other members of their households, e.g. their children, which affects the adults’ well-being. Our paper also contributes to the stream of the literature on subjective measures of welfare by linking ozone pollution to subjective measures of health and well-being. To our knowledge, this is the first paper that evaluates the effect of ozone on both subjective health and well-being and in this way analyzes both more narrow and wider welfare effects of air pollution.

We estimate short-run and medium-run effects of ozone exposure on subjective health satisfaction and subjective well-being through a set of fixed-effects regressions, controlling for both time and individual fixed effects, individual-level covariates, county-level macro variables and weather-related data. We find statistically and economically significant negative effects of ozone on subjective well-being both in the short and medium term, with stronger effects in the medium term, after longer exposure to higher ozone levels. The negative impact of ozone on people’s well-being is concentrated among individuals living in households with children under 16 years of age. We do not find that the well-being of individuals living in children-less households is affected. This suggests that ozone pollution has a significant indirect effect on the welfare of adults, through its effect on their children. In contrast, we do not find that ozone exposure affects individuals’ subjective health satisfaction, neither in the full sample nor for individuals sharing households with children. Our results are robust to controlling for other pollutants. Our findings suggest that ozone concentrations in Germany are not high enough to significantly affect the subjective health of the general population. However, they do negatively affect the life satisfaction of adults sharing a household with children. This result is in line with the literature demonstrating stronger health effects of ground-level ozone pollution on children. Our findings suggest that in Germany ozone primarily affects parents’ welfare through the diminished health of children sharing the same household. This result suggests that in addition to direct health effects ozone also has important indirect effects. In advanced economies such as Germany such indirect effects may be relatively more important than direct health effects, at least for the population of generally healthy adults.

The remainder of the article is structured as follows: Section (2) presents our dataset and provides a descriptive analysis. Section (3) outlines our research design, while Section (4) presents the preliminary results. We summarize and conclude in Section (5).

2 Data and descriptives

2.1 Data

We obtain individual-level and associated household-level data from the German Socio-economic Panel Study (SOEP) over the period 2005 to 2015. The SOEP is a representative longitudinal panel study that started in West Germany in 1984. Between 2005 and 2015, SOEP surveyed 30,051 different households and 80,339 unique individuals. On average, individuals and households spent around five years as members of the panel.

Our outcome variables are responses to questions asking individuals to rate their life satisfaction and health, respectively, as follows: "How satisfied are you with your life, all things considered?" and "How satisfied are you with your health, all things considered?" Respondents are asked to provide an answer on an 11 point scale from 0 (completely dissatisfied) to 10 (completely satisfied) (Richter et al., 2013). In addition to our outcome variables, the SOEP also provides a large set of sociodemographic and economic information, such as marital status, age, and gender, income, employment status, and tax payments.

SOEP also provides two key pieces of information, which are critical to the identification in this paper: First, SOEP provides the geo-coordinates of surveyed households' dwellings on a strictly confidential basis. We use these geo-codes to match individuals surveyed by SOEP to nearby pollution measuring stations. This allows for a clean spatial matching of pollution and individuals. Second, SOEP also contains information on the exact day of the interview. This allows for a precise temporal match of individuals and their ozone exposure at the time when they provide information on their well-being and health satisfaction, respectively.

Data on the daily concentration of ozone and other air pollutants come from the German Environmental Agency (*Umweltbundesamt*, henceforth UBA). UBA maintains an extensive network of monitoring stations, each station measuring different types of pollutants. In total, UBA has 696 stations measuring different air pollutants, of which 378 stations measure the concentration of ozone in the environment.² Figure (1) shows the spatial distribution of ozone monitoring stations across Germany. Stations tend to be concentrated in and around urban clusters such as Berlin in the northeast, Hamburg in the north, and the Ruhr area in the west.

²Because of malfunction and routine maintenance, stations measuring ozone have missing values around 10% of the time.

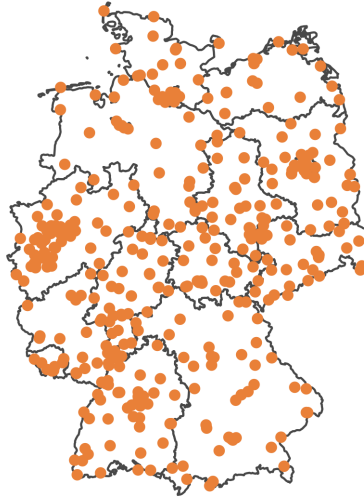


Figure 1: Ozone measuring stations in Germany.
Source: German Environmental Agency.

Weather controls are obtained from measuring stations of the German meteorological service (*Deutscher Wetterdienst, DWD*). Weather station data are also geo-coded and can be matched to the data from UBA measuring stations and SOEP. Finally, Eurostat provides county-level macroeconomic controls. The macroeconomic variables we use in this paper are unemployment rate, gross domestic product per capita, and population density.

2.2 Descriptive analysis

In this section we provide a descriptive analysis of our dataset. In Section (2.2.1) we present descriptives on our main outcome variables, life satisfaction and health satisfaction, both on their own and in relation to other important individual-level covariates. We focus on the role of children, the main risk-group of interest in our analysis of ozone exposure. Section (2.2.2) presents data on our main causal variable of interest, the concentration of ground-level ozone at the measuring-station level.

2.2.1 Individual-level data

Table (1) presents basic descriptive statistics for the full SOEP sample. We observe that the mean of both life satisfaction and health satisfaction is in the upper part of the distribution, with a value of 7.14 for life satisfaction and 6.7 for health satisfaction.

We also observe that there is greater variation in health satisfaction. It has a standard deviation of 2.22, compared to a standard deviation of 1.77 for life satisfaction. Further, the surveyed individuals had 1.1 children on average and were employed in 54% of the time periods. On average, they are in their late 30s and their available annual income was about 40 thousand euro.

Table 1: Full SOEP sample, main individual-level variables

Variable	Mean	Std. Dev.	Min	Max	Share Unavail-ables
Life Satisfaction	7.14	1.77	0.00	10.00	32.09
Health Satisfaction	6.70	2.22	0.00	10.00	32.49
Number of Children	1.10	1.27	0.00	11.00	0.00
Employment Status	0.54	0.50	0.00	1.00	23.88
Post Government Income	40.63	30.43	0.00	2,808.47	0.00
Age	37.67	22.76	0.00	105.00	0.54
Number of Observations: 377057					
Number of individuals: 80339					
Number of Households: 30051					

Note: Employment status is a binary variable indicating if the person is employed in each year or not. Post-government income is in thousand Euro. The total number of observations, individuals and households are with respect to the entire dataset. The share of unavailables indicates the share of missing observations for each variable.

Figure (2, left panel) shows the distribution of life satisfaction across the sample. The highest frequency of responses is between seven and nine. On average, individuals were mostly satisfied with their life during the sample period. Figure (2, right panel) plots the yearly mean of life satisfaction across the sample. The figure shows a steady growth in life satisfaction across the country.

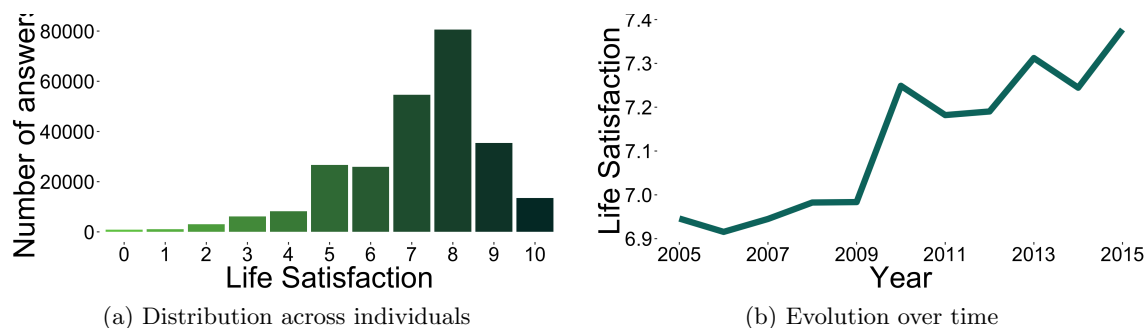


Figure 2: Life satisfaction of SOEP individuals

Figure (3, left panel) shows the relationship between life satisfaction and income and figure (3, right panel) its association with employment status. The difference in life sat-

isfaction between the lowest and highest income quintiles is of 1.3 units³. On average, employed persons have a life satisfaction 0.25 points higher than unemployed individuals.

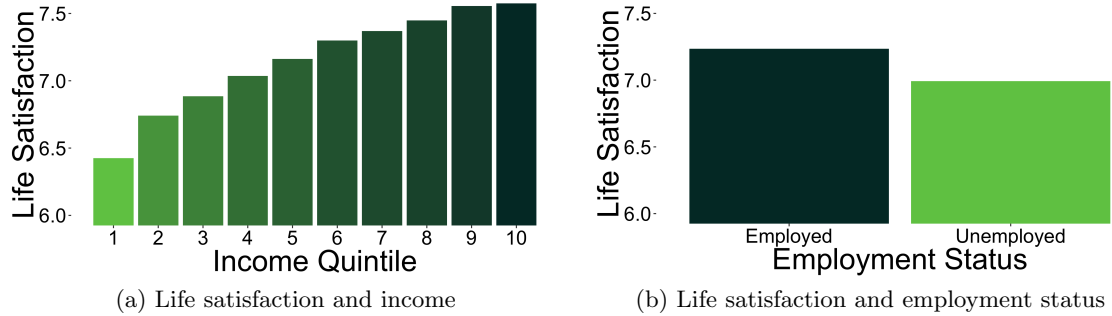


Figure 3: Life satisfaction, income and employment

Figure (4) shows the distribution of health satisfaction for the SOEP sample, across the point scale and over time. It has some similarities to the distribution of life satisfaction in that it is also right-skewed, with the majority of individuals declaring a health satisfaction above 5 (4, left panel). However, one difference does appear between both datasets, for health satisfaction, there is a concentration point at five. Figure (4, right panel) depicts the time series of health satisfaction across the study period. The figure shows a drop in the years around the 2008 global economic crisis, and an increase starting in 2010.

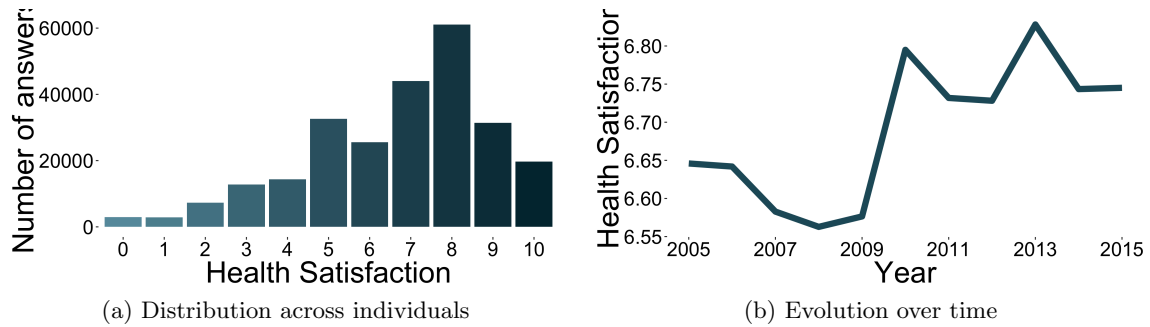


Figure 4: Health satisfaction of SOEP individuals

Similarly to Figure (3), Figure (5) plots the relationship between health satisfaction, income and employment. As can be seen in Figure (5, left panel), the relationship of income with health satisfaction is similar to that for life satisfaction. Health satisfaction differs between the first to the last quintiles by 1.25 units, a somewhat smaller difference less than for life satisfaction. In contrast, the relationship between health and employment status is stronger than in the case of life satisfaction, employed persons' health satisfaction

³The lowest income quintile is between 0 and 15,700 Euros, the highest between 69,000 and 2,810,000 Euros.

being 0.6 units higher than for unemployed individuals. This is substantially higher than the difference in life satisfaction by income status of 0.25 points.

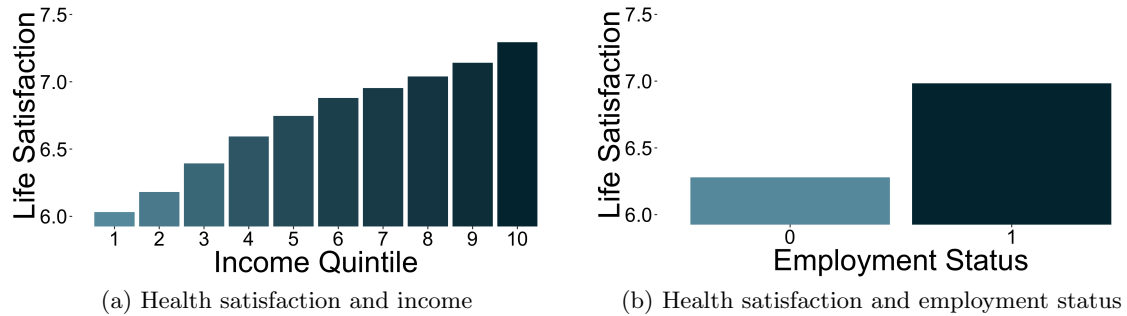


Figure 5: Health satisfaction, income and employment

We now turn our attention to the descriptive relationship between the number of children and life and health satisfaction, respectively. Figure 6 shows the shares of observations, depending of the number of children per individual. 46 percent of all surveyed persons have no children. Of those who do have offspring, the overwhelming majority has between 1 and 3 children.

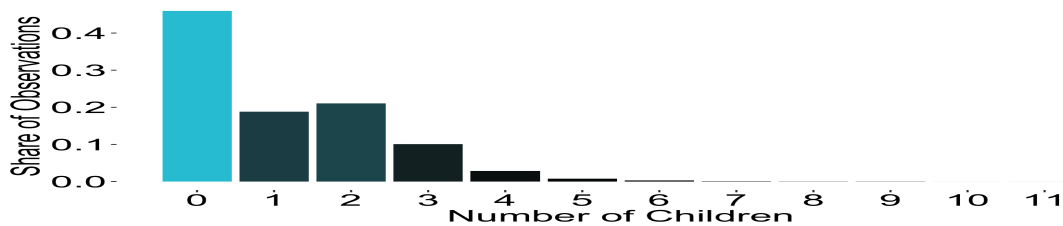


Figure 6: Share of Observations by Number of Children

We observe a positive relationship between life satisfaction and child status. Figure (7, left panel) shows that childrearing persons tend to answer that their overall satisfaction with life is higher than for childless individuals. They have a larger share of responses for the higher categories and lower rates for the low numbers. Figure (7, left panel) shows that average satisfaction with life increases with the number of children, except for a slightly lower life satisfaction for individuals with more than three children, compared to those with three.

Figure (8, left panel) shows that the responses on health satisfaction, with respect to child status, is similar to those regarding life satisfaction. Persons with children appear to be more satisfied with their health than childless individuals. However, while individuals with children report a higher health satisfaction than those without, health satisfaction

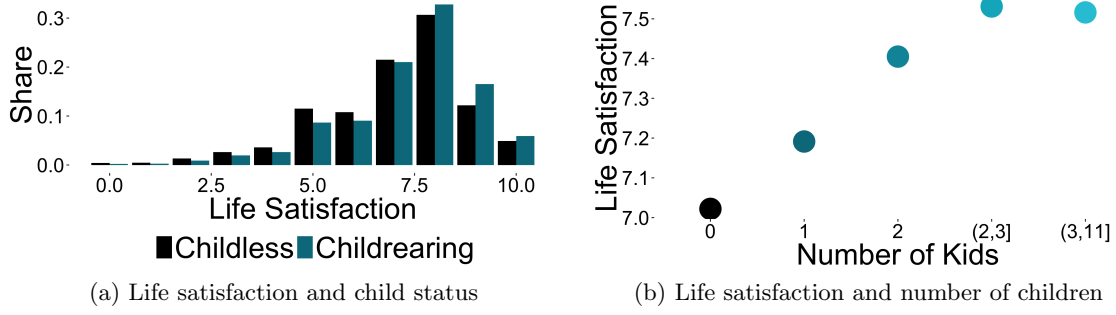


Figure 7: Life satisfaction and children

appears to plateau with an increasing number of children Figure (7, left panel).

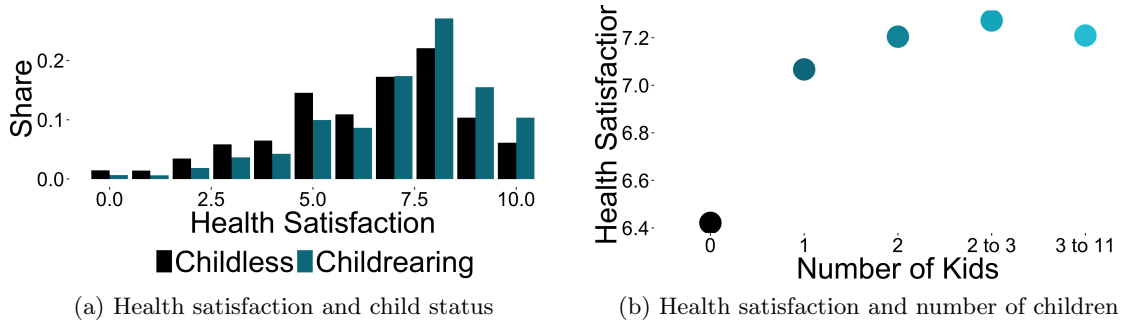


Figure 8: Health satisfaction and children

2.2.2 Ozone data

Our main explanatory variable of interest is ground-level ozone. Ozone is a secondary environmental pollutant created by the interaction of solar radiation with primary contaminants by human activity. Its existence in the atmosphere is mainly a consequence of emissions of nitrous oxides and volatile organic compounds from the burning of fossil fuels. In Germany, ozone has an average atmospheric concentration of $47.7 \mu\text{g}/\text{m}^3$, with a standard deviation of $24.45 \mu\text{g}/\text{m}^3$ and a maximum of $199.9 \mu\text{g}/\text{m}^3$. To put these figures into context, the European Union has mandated a maximum-8-hours limit for ozone of $120 \mu\text{g}/\text{m}^3$ (EU, 2008). As the concentrations of primary pollutants vary geographically, the atmospheric concentration of ozone also varies significantly across space. Ozone measurements are higher for background ($48.6 \mu\text{g}/\text{m}^3$) and lower in traffic stations ($35.8 \mu\text{g}/\text{m}^3$). While this may seem counterintuitive, it is important to note that there are two sides to the interaction of ozone with nitrous oxides and volatile organic compounds. On one hand, the interaction of solar radiation with

these contaminants is what forms atmospheric ozone. On the other hand, it also degrades it. There is no linear relationship between these primary contaminants and ozone, as nitrous oxides are also responsible for the degeneration of atmospheric ozone back into oxygen. In areas with high levels of nitric oxide, ozone degrades at faster rates. This phenomenon is usually referred to as the "ozone paradox." The ozone paradox also explains why the level in rural areas ($57.4 \mu\text{g}/\text{m}^3$) is lower than in suburban ($45.4 \mu\text{g}/\text{m}^3$) and urban ($42.1 \mu\text{g}/\text{m}^3$) districts.

Due to public policies to reduce air pollution, all primary air pollutants exhibit steady reductions in their environmental concentration. Figure (9) shows the evolution of average annual concentrations of ozone, particulate matter ($PM_{2.5}$) and sulfur dioxide (SO_2) across Germany. While average concentrations of $PM_{2.5}$ and SO_2 decrease over time, the average concentration of ozone shows remains roughly stable between 2005 and 2016 Figure (9, left panel).

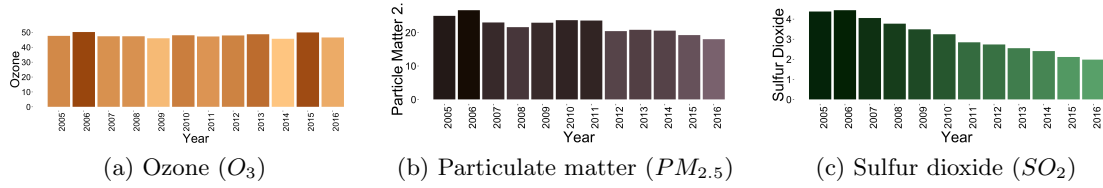


Figure 9: Average yearly air pollution in Germany, 2005-2016

However, while annual averages are stable, ozone concentrations vary significantly within each year and geographically. Figure (10, left panel) shows the monthly time trend of ozone in Germany. Given that ozone is triggered by the interaction of primary contaminants with solar radiation, the level of ozone is higher in the summer months. Figure (10, right panel) shows the spatial distribution of ozone across Germany, with data from measuring stations aggregated by state. We observe lower levels of ozone in traditionally industrial states such as Northrhine Westphalia, Hamburg, and Bremen, and higher levels in more rural areas, such as Schleswig-Holstein and Saxony Anhalt.

Regional concentrations vary significantly by season (Figure (11)). Figure (11, left panel) depicts the average concentration of atmospheric ozone per state in May and June, while Figure (11, right panel) shows concentrations in December and January. While concentrations are higher in the summer in all states, relative concentrations change by season. In the winter, the states with higher ozone concentrations are the more rural Eastern and Northern states, especially Saxony and Schleswig-Holstein. In summer, due to the influ-

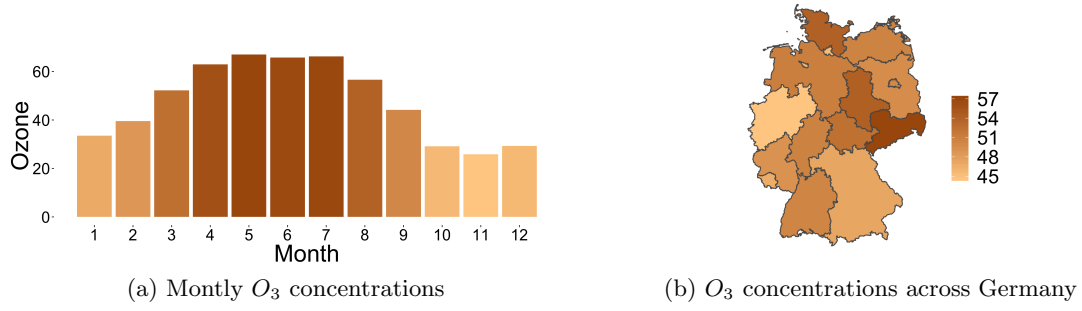


Figure 10: Ozone concentrations in Germany, by month and region

ence of solar radiation on ozone formation, the southern states of Baden Wuerttemberg, Hessen, and once again Saxony exhibit the relatively highest concentrations.

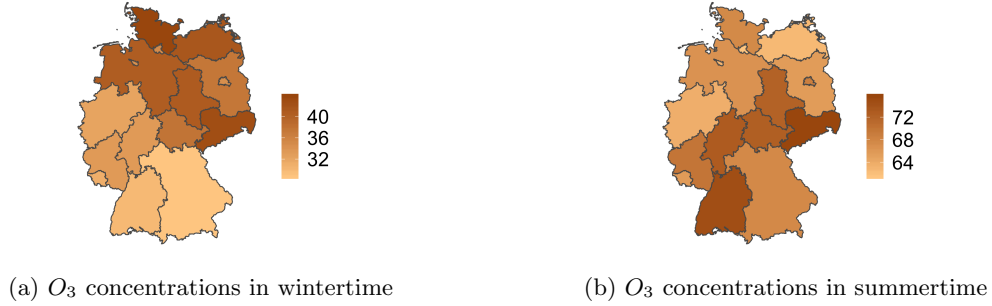


Figure 11: Seasonal ozone concentrations, by region

3 Research Design

3.1 Assigning ozone exposure to individuals

We assign ozone exposure to individuals using inverse distance weighting (IDW) between ozone monitoring stations and individuals' dwellings. Inverse distance weighting is a spatial interpolation technique that approximates the value of a point in space by weighting the values of comparable neighbors.

We assigns individual pollution measures to each person by providing additional weight to stations located near the person's dwelling. Equation (1) shows the representation of IDW interpolation.

$$V_{jt} = \left\{ \begin{array}{l} \frac{\sum_i^N \omega(dist_{ij}) * pol_{it}}{\sum_i^N \omega(dist_{ij})} \\ pol_{it} \rightarrow dist_{ij} = 0 \end{array} \right\} \Rightarrow \omega(dist_{ij}) = \frac{1}{distance(x_i, x_j)^p} \quad (1)$$

where pol_{it} refers to the value of pollution at station i at time t , and $dist_{ij}$ is the distance between pollution station i and household j .⁴ The power factor p modifies the heaviness of the weighting load; the higher p , the greater is the weight of closer stations.

Spatial data on is obtained through access to the exact coordinate location of both SOEP households and monitoring stations.

Once the distance between each station and dwelling is computed, we proceed to apply inverse distance weighting interpolation-techniques, according to 1, and infer individual household values.

3.2 Identification

We identify the effect of pollution on individuals by merging geo-coded data on ozone pollution from measuring stations across Germany with geo-coded individual level SOEP data. We exploit variation in pollution across space and time (Figures (10) and (11)), as SOEP interviews take place at different times of the year.

Our identification is also helped by the fact that there is a significant amount of variation in SOEP interview dates (Figure (12)). Roughly one half of the interviews were conducted during the period September – March, months with low ozone concentrations, while the other half was taken during the period April – August, when ozone levels are higher.

There is also a significant amount of variation in our two outcome variables (cf. Section 2.2). We further control for a host of individual-level, county-level and weather-related covariates. Moreover, the panel structure of the data allows us to control for individual fixed effects. Due to this rich set of covariates we are confident that our pollution mea-

⁴To focus on local ozone concentration, we cut off stations located further away than 10 kilometres. We use the great circle distance formula to calculate the distance between coordinate points. The formula computes the shortest possible distance between two points on the surface of a sphere (Shumaker and Sinnott, 1984):

$$D_{mn} = 2 \arcsin \sqrt{\sin^2\left(\frac{lat_m - lat_n}{2}\right) + \cos(lat_m) * \cos(lat_n) * \sin^2\left(\frac{lon_m - lon_n}{2}\right)},$$

where D_{mn} refers to the distance between points m and n .

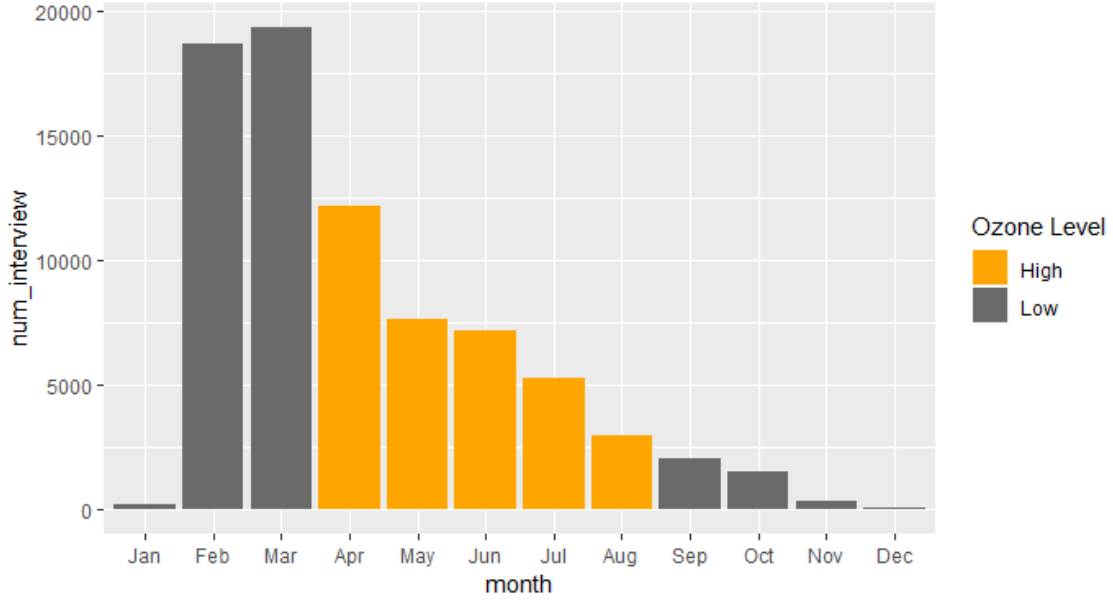


Figure 12: Number of SOEP interview dates by month.
Source: SOEP.

tures are exogenous, conditional on observables, and that our estimations allow for a causal interpretation.

One potential concern is self-selection through moving behavior. Some individuals may move to areas where pollution is less significant. To avoid this issue from contaminating our results we exclude individuals that moved from dwellings during the sample period. By excluding movers we estimate a lower bound of the effect of ozone, as people that reallocate due to ozone exposure may be expected to react to ozone pollution more strongly than those who remain in their prior location.

3.3 Empirical model

In the first specification, we infer the relation between pollution exposure and our outcomes through fixed-effects regressions, controlling for time and individual fixed effects. We estimate the following equations:

$$y_{it} = \alpha + \rho \text{Ozone}_{it} + \mathbf{X}'_{it}\boldsymbol{\alpha} + \mathbf{Y}'_{ct}\boldsymbol{\beta} + \gamma_t + \lambda_i + \epsilon_{it}, \quad (2)$$

$$z_{it} = \alpha + \rho \text{Ozone}_{it} + \mathbf{X}'_{it}\boldsymbol{\alpha} + \mathbf{Y}'_{ct}\boldsymbol{\beta} + \gamma_t + \lambda_i + \epsilon_{it}, \quad (3)$$

y_{it} and z_{it} are subjective well-being and subjective health satisfaction, respectively, for each individual i , captured at each interview date. We estimate Equations (2) and (3) for different lengths of exposure to ozone. ρ represents the coefficient on pre-interview ozone exposure of different lengths. We estimate short-term effects by using the ozone exposure on the day of the interview as the main explanatory variable and capture longer-term effects by taking averages of ozone concentrations close to the individual’s dwelling during the year prior to the interview date.⁵ \mathbf{X}'_{it} is a matrix of time-varying individual level controls and \mathbf{Y}'_{ct} contains county-level controls, including weather-related controls. γ_t contains year fixed effects. Finally, λ_i are individual fixed effects and ϵ_{it} is the idiosyncratic error term clustered at the individual level.

4 Results

In this section we present our preliminary results. Section (4.1) contains our findings for the effect of ozone on life satisfaction, while Section (4.2) contains our results for health satisfaction. For each outcome, results are first presented for the full sample, and then for two subsamples: One subsample contains individuals living in a household with children under the age of 16, while the other contains persons living in households without children. We first show results on short-term effects of ozone exposure at the daily level, i.e. responses to ozone exposure on the day of the interview. We then show consider medium-term effects for average ozone exposure over the 365 days prior to the interview.⁶

⁵We are currently also estimating effects for the week, month and quarter prior to the interview date.

⁶We also calculate average ozone values for one week, one month and one quarter prior to the interview. These results will be available in time for the conference.

Table 2: Daily ozone concentrations and life satisfaction, full sample

<i>Dependent variable: Life satisfaction</i>				
	(1)	(2)	(3)	(4)
Ozone	−0.0019*** (0.0006)	−0.0018*** (0.0006)	−0.0020*** (0.0007)	−0.0020*** (0.0007)
Disp. income		0.000002*** (0.000001)	0.000002*** (0.000001)	0.000002*** (0.000001)
Children		0.0739** (0.0356)	0.0742** (0.0356)	0.0718** (0.0356)
Age		−0.0109** (0.0052)	−0.0110** (0.0052)	−0.0282*** (0.0071)
Married		0.0619 (0.0505)	0.0623 (0.0505)	0.0629 (0.0505)
Unemployed		−0.4008*** (0.0500)	−0.4009*** (0.0500)	−0.3980*** (0.0499)
Sunshine			0.0018 (0.0024)	0.0017 (0.0024)
GDP				−0.000001 (0.000002)
Pop. density				0.00004 (0.00004)
Unemployment				−0.0452*** (0.0115)
No. observations	77,680	77,680	77,680	77,680

Standard errors in parentheses, clustered at the household level.

*p<0.1; **p<0.05; ***p<0.01

Table 3: Yearly ozone concentrations and life satisfaction, full sample

	<i>Dependent variable: Life satisfaction</i>			
	(1)	(2)	(3)	(4)
Ozone	−0.0023* (0.0012)	−0.0021* (0.0012)	−0.0022* (0.0012)	−0.0023* (0.0012)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
No. observations	77,680	77,680	77,680	77,680

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

4.1 Life satisfaction

In Table (2) are our benchmark results on short-term effects of ozone pollution on life satisfaction. We observe a statistically strongly significant effect of stable magnitude across all specifications. The effect is also economically significant: An increase in ozone pollution by one standard deviation is predicted to decrease life satisfaction by 0.05 points in the short term. This corresponds to about 12.5% of the estimated negative impact of changing employment status on life satisfaction. The other covariates are related to life satisfaction in an intuitive way: Life satisfaction increases with income and the number of children, and decreases with age and moving from employment to unemployment. Life satisfaction is also lower in counties with higher unemployment rates.

We find that the effect of ozone on life satisfaction persists beyond the short term (Table (3)). We estimate a similar effect on life satisfaction even when taking the average ozone concentration during the 365 days prior to the interview, although statistically less significant.⁷

⁷For compactness we only present the full regression output for daily ozone exposure and the full sample. Full results tables are available upon request.

The effect is stronger once we estimate the same set of regressions for the subsample of individuals with children under the age of 16 living in their household. The short-run effect of ozone on life satisfaction is stonger than in the full sample, while also strongly statistically significant (Table (4)).

Table 4: Daily ozone concentrations and life satisfaction, individuals with children under age of 16

<i>Dependent variable: Life satisfaction</i>				
	(1)	(2)	(3)	(4)
Ozone	−0.0038*** (0.0011)	−0.0038*** (0.0011)	−0.0036*** (0.0011)	−0.0035*** (0.0011)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
Obs.	29,875	29,875	29,875	29,875

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

In contrast, we find no effect for the subsample of individuals without children living in their household (Table (5)). This suggests that the effect of ozone on the well-being of adults works - at least partially - indirectly: adults' well-being is diminished due to the negative impact ozone has on children, a well-known high-risk group with respect to ozone.

Table 5: Daily ozone concentrations and life satisfaction, individuals without children

<i>Dependent variable: Life satisfaction</i>				
	(1)	(2)	(3)	(4)
Ozone	−0.0008 (0.0008)	−0.0007 (0.0008)	−0.0010 (0.0009)	−0.0011 (0.0009)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
No. observations	29,875	29,875	29,875	29,875

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

The pattern repeats for ozone exposure in the medium term, using yearly instead of daily average ozone concentrations. We estimate that ozone decreases the life satisfaction of individuals living in households with children under the age of 16 (Table (6)), while individuals in households without children do not show a significant effect (Table (7)). As in the full sample, persistently higher exposure to ozone is estimated to have stronger effects on well-being. We estimate that the effect is stronger by about one third in the medium term than in the short term.

Table 6: Yearly ozone concentrations and life satisfaction, individuals with children under age of 16

	<i>Dependent variable: Life satisfaction</i>			
	(1)	(2)	(3)	(4)
Ozone	−0.0054** (0.0021)	−0.0053** (0.0021)	−0.0047** (0.0022)	−0.0046** (0.0022)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
Obs.	29,875	29,875	29,875	29,875

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

Table 7: Yearly ozone concentrations and life satisfaction, individuals without children

<i>Dependent variable: Life satisfaction</i>				
	(1)	(2)	(3)	(4)
Ozone	−0.0004 (0.0016)	−0.0001 (0.0016)	−0.0004 (0.0016)	−0.0008 (0.0016)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
No. observations	29,875	29,875	29,875	29,875

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

4.2 Health satisfaction

Table (8) contains our benchmark results for the short-run impact of ozone levels on the day of the SOEP interview on health satisfaction for the full sample. We find no statistically significant effect of ozone on subjective health satisfaction. Moreover, the point estimates for the effect of ozone on health satisfaction are an order of magnitude smaller than for life satisfaction. The results for medium-term exposure to ozone, during the year prior to the SOEP interview, are of similar magnitude and also insignificant (Table (9)).⁸

⁸As for the life satisfaction regressions, for compactness we only show the full regression output for daily ozone exposure and the full sample. Full results tables are available upon request.

Table 8: Daily ozone concentrations and health satisfaction, full sample

	<i>Dependent variable: Health satisfaction</i>			
	(1)	(2)	(3)	(4)
Ozone	−0.0005 (0.0007)	−0.0005 (0.0007)	−0.0006 (0.0008)	−0.0006 (0.0008)
Disposable income		0.000001 (0.000001)	0.000001 (0.000001)	0.000001 (0.000001)
Children		0.0670 (0.0411)	0.0672 (0.0411)	0.0662 (0.0411)
Age		−0.0685*** (0.0062)	−0.0686*** (0.0062)	−0.0700*** (0.0083)
Married		0.0063 (0.0504)	0.0065 (0.0504)	0.0058 (0.0504)
Unemployed		−0.1182** (0.0540)	−0.1183** (0.0540)	−0.1186** (0.0540)
Sunshine			0.0012 (0.0028)	0.0012 (0.0028)
GDP				0.000002 (0.000002)
Pop. density				−0.00003 (0.0001)
Unemployment				−0.0007 (0.0133)
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
No. observations	77,680	77,680	77,680	77,680

Note: Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

Table 9: Yearly ozone concentrations and health satisfaction, full sample

<i>Dependent variable: Health satisfaction</i>				
	(1)	(2)	(3)	(4)
Ozone	−0.0007 (0.0014)	−0.0007 (0.0014)	−0.0008 (0.0014)	−0.0006 (0.0014)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
No. observations	77,680	77,680	77,680	77,680

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

As for life satisfaction, we again split the sample into individuals who live in households with children under the age of 16 and persons without children in their households. We then run our regressions for both subsamples. We find that ozone exposure has no effect on health satisfaction for either type of individual, those with children (Table (10)) and those without (Table (11)). The same pattern holds for yearly ozone exposure. In neither case do we find a significant effect of ozone on health satisfaction.⁹

⁹For brevity we do not include the results tables for yearly ozone exposure. They are available upon request.

Table 10: Daily ozone concentrations and health satisfaction, individuals with children under age of 16

<i>Dependent variable: Health satisfaction</i>				
	(1)	(2)	(3)	(4)
Ozone	−0.0012 (0.0012)	−0.0013 (0.0012)	−0.0007 (0.0013)	−0.0007 (0.0013)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
Obs.	29,875	29,875	29,875	29,875

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

Table 11: Daily ozone concentrations and health satisfaction, individuals without children

	<i>Dependent variable: Health satisfaction</i>			
	(1)	(2)	(3)	(4)
Ozone	−0.0035 (0.0024)	−0.0035 (0.0024)	−0.0030 (0.0024)	−0.0027 (0.0024)
Micro controls	No	Yes	Yes	Yes
Weather controls	No	No	Yes	Yes
Macro controls	No	No	No	Yes
Individual FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
No. observations	29,875	29,875	29,875	29,875

Note: Micro controls are: disposable income (post-tax and post-transfer), number of children, age, marriage status, employment status; Weather control is sunshine duration; macro controls are GDP, population density and unemployment rate, all at the county level. All regressions control for individual and year fixed effects. Standard errors in parentheses, clustered at the household level. *p<0.1; **p<0.05; ***p<0.01

5 Summary and conclusion

In this paper, we consider the effects of ground-level ozone pollution on the subjective health and well-being of German individuals. Evaluating subjective health effects of ozone exposure is especially relevant in contexts with moderate levels of ozone, as in Germany, where economic costs will be realized in the short to medium term only if individuals subjectively rate their health less highly due to ozone exposure. Evaluating the effect of ozone on subjective well-being allows for an analysis of indirect effects of ozone pollution, through effects on high-risk members of the same household, such as children. Indirect effects may also lead to economic losses, e.g. due to absences from work to care for affected relatives.

We identify the effect of pollution on individuals by combining geo-coded data on ozone pollution from measuring stations across Germany with geo-coded individual level data on subjective health and subjective well-being from the German Socio-Economic Panel Study (SOEP), a representative survey of German individuals, during the period 2005 to 2015. We assign pollution exposure to each individual by exploiting information on the date of the SOEP interview. We calculate the level of ozone pollution experienced by each individual by constructing weighted averages of ozone levels from nearby stations using inverse distance weighting techniques. In addition to calculating short-term exposure to ozone on the day of the interview we also construct medium-term average ozone concentrations.

We estimate short-run and medium-run effects of ozone exposure on subjective health satisfaction and subjective well-being through a set of fixed-effects regressions, controlling for both time and individual fixed effects, individual-level covariates, county-level macro variables and weather-related data. We find statistically and economically significant negative effects of ozone on subjective well-being. The negative impact is concentrated among individuals living in households with children under 16 years of age. We do not find that the well-being of individuals living in children-less households is affected. This suggests that ozone pollution has a significant indirect effect on the welfare of adults, through its effect on children. In contrast, we do not find that ozone exposure affects individuals' subjective health satisfaction. Our findings suggest that ozone concentrations in Germany during the sample period are not high enough to significantly affect the subjective health of the general population. However, they do negatively affect the life satisfaction of adults sharing a household with children.

This result suggests that in addition to direct health effects of ozone and other local pollutants, as previously shown by the literature, also has important indirect welfare effects. In economies such as Germany such indirect effects may be relatively more significant than direct health effects, at least for the population of generally healthy adults.

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