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Abstract:

Climate change will further increase not only the frequency but also the intensity of extreme weather events. As a result, weather conditions favouring pneumonia occurrence - suddenly warmer weather during cold seasons - can increase due to higher meteorological variability which is also linked with climate change. These meteorological trends are expected to lead to adverse effects on peoples' health (Sohn et al., 2019). Community-acquired pneumonia, in the following simply called pneumonia, is one of the most common causes of death worldwide (Aliberti et al., 2021). At the same time, clear linkages between this disease and both meteorological and air conditions are present (Wang et al., 2021). Consequently, it is crucial to understand the effect of these meteorological and air conditions on pneumonia cases more deeply but also more specifically how these effects interact and depend on the personal characteristics and medical backgrounds of patients.

It is well studied that especially extreme weather and air conditions, the latter including air quality and wind conditions, have an impact on the number of people hospitalized for pneumonia (Y. Liu et al., 2014; Onozuka et al., 2009). However, many studies analyse the effects of meteorological and air conditions separately with mortality data as an endpoint while predominantly covering the Asian continent and specifically larger cities (Basu & Samet, 2002; Chung et al., 2009; Ge et al., 2013). Therefore, data on other geographical regions and combinations of rural and metropolitan areas are required. Additionally, little is known about how personal characteristics (age, sex) and health background (smoking history, chronic lung diseases, heart insufficiency, overweight) affect the sensitivity of pneumonia cases regarding meteorological and air conditions.

We close this research gap by analysing a prospective multicenter cohort that was treated in an in- or outpatient setting for pneumonia in 22 German hospitals or outpatient clinics. The dataset contains personal and health information for more than 10,000 patients. We match this data with daily regional meteorological and air condition data while not only considering the conditions on the day of hospitalization but also up to four days before. Logistic regressions are used to examine the impact of meteorological and air conditions on pneumonia cases considering a short-term and long-term perspective as well as the modification effects of various personal characteristics on these relationships. This research is valuable since it aims to not only determine but also predict when certain groups of people are at increased risk of pneumonia. This can support health care providers during periods of weather conditions factoring pneumonia in better preparing resources such as staff and treatments but also in guiding prophylaxis such as limiting outdoor activities.

Keywords: pneumonia, climate change, meteorology, air conditions, Germany.

JEL Classifications: I10, Q53, Q54, R10

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Acronyms

AIC: Akaike Information Criterion

BMI: Body Mass Index

CO: Carbon monoxide

COPD: chronic obstructive pulmonary disease

CAMS: Copernicus Atmosphere Monitoring Service

DTR: Diurnal Temperature Range

DWD: German Weather Service (Deutscher Wetterdienst)

IQTIG: Institut für Qualitätssicherung und Transparenz im Gesundheitswesen

NO_2: Nitrogen dioxide

RH: Relative Humidity

RKI: Robert Koch Institut

SO_2: Sulfur dioxide

O_3: Ozone

PM: Particulate matter

PT: Pneumonia Temperature

SRTM: Shuttle Radar Topography Mission

WHO: World Health Organization

WMO: World Meteorological Organization

1. Introduction

Respiratory diseases, including pneumonia, have a high societal and economic importance not only worldwide but also in Germany (Plass et al., 2014; World Health Organization, 2007). In Germany in 2008, the treatment of patients with respiratory diseases led to treatments costs of 14.2 billion euros (Gillissen & Welte, 2014). The yearly number of community-acquired pneumonia cases in Germany is estimated to lie between 400,000 and 600,000 (RKI, 2017). About 30 to 50 % of these pneumonia cases end up being treated in hospitals (Höffken et al., 2009; Schnoor et al., 2007). The age-related mortality of pneumonia in Germany is 13% (Institut für Qualitätssicherung und Transparenz im Gesundheitswesen [IQTiG], 2016). At the same time, this number is likely even larger due to underestimations caused by the monocausal nature of mortality statistics.

Apart from the societal and economic effects of pneumonia, climate change and its impact on health in general but pneumonia specifically has gained broad scientific attention over the last decades. It has been well studied that especially extreme weather and air conditions, the latter including air quality and wind factors, affect the number of people hospitalized for pneumonia (Y. Liu et al., 2014; Onozuka et al., 2009; Wang et al., 2021). Climate change is associated with not only more frequent and intense weather extremes but also a higher variability in weather conditions which can negatively affect peoples' health. Different studies evaluated the possible relationship between meteorological factors on pneumonia and other well-known respiratory diseases. Temperature was determined to be one of the factors that shows the greatest contribution to pneumonia mortality and morbidity (Braga et al., 2002; Kim et al., 2016; L. Liu et al., 2011). However, the pattern of the relationship of temperature with pneumonia (j-shaped, u-shaped or v-shaped) strongly depends on the study location and associated climate (Braga et al., 2002; Falagas et al., 2008; Nascimento-Carvalho et al., 2010) as well as the selected temperature factors. The most widely used temperature factors include the diurnal temperature range (DTR) defined as the difference between the minimum temperature and maximum temperature on a given day and pneumonia temperature (PT), defined as the current day's average temperature minus the previous day's average temperature. Relationships of both precipitation and relative humidity (RH) with pneumonia have predominantly been reported in countries with abundant rainfall (Chan et al., 2002; Mäkinen et al., 2009; Nascimento-Carvalho et al., 2010).

With regard to air quality, Nhung et al. (2017) performed a systematic review and meta-analysis of the short-term correlation between ambient air pollutants (sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter (PM) with diameter 10 (PM10) and 2.5 mm (PM2.5)) and hospitalization of children due to pneumonia. They found a positive correlation between daily levels of ambient air pollutants and hospitalization of children due to pneumonia. Furthermore, a long-term prospective, observational study in a Chinese hospital showed that meteorological and air pollution factors contributed more to severe pneumonia in children than did respiratory viruses (Wang et al., 2021).

As presented, many studies attempted to examine the relationship between meteorological and health conditions with pneumonia while placing a focus on specific weather or air conditions in relatively broad areas, predominantly Asia, with mainly mortality data as an endpoint (Basu

& Samet, 2002; Chung et al., 2009; Ge et al., 2013). However, health issues should not solely be based on outcomes such as mortality but also morbidity. Furthermore, only rarely did studies account for how the sensitivity of pneumonia cases to meteorological and air conditions differs when considering personal characteristics and medical background. For example the research by Basu and Samet (2002) indicates that people with pre-existing cardiovascular and respiratory diseases have an elevated risk of death associated with especially ambient heat exposure and that risk is also higher for specific population groups such as the elderly, infants, and persons of low socioeconomic status.

We address the previously mentioned shortcomings by not only including the personal characteristics of 10,000 patients treated in 22 German hospitals or outpatient clinics for pneumonia but also information on health background such as smoking history, chronic lung diseases, heart insufficiency, and overweight. We match this with high spatial and temporal resolution (daily), regional meteorological and air conditions data, only considering data in a one-hour catchment surrounding each hospital. The regional meteorological and air conditions include the following factors displayed in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Logistic regressions are used to then examine the modification effects of various personal characteristics on the impact of meteorological and air conditions on pneumonia cases. Furthermore, we want to disentangle how the sensitivity of pneumonia cases to meteorological and air conditions changes when considering the patients' personal and health backgrounds. We aim to quantify the relationship between both meteorological and air conditions with pneumonia cases to not only determine but predict when certain groups of people are at an increased risk of pneumonia. This would both support health care providers in better preparing resources such as staff and treatments and guiding prophylaxis such as limiting outdoor activities during periods of weather conditions which promote pneumonia.

We find that several weather and air conditions influence the risk of pneumonia not on their own but only in combination with other factors: e.g., low temperature in combination with low air pressure or high air pressure together with high air pollution lead to more pneumonia cases. Furthermore, we find several differences in the sensitivity of various population groups to the different weather and air conditions.

2. Methodology

2.1 Medical data description

The medical data contains information on 10.808 people admitted for pneumonia from 22 German hospitals or doctor´s practices between February 2003 and December 2017 including the exact day of hospitalisation (Figure 1).

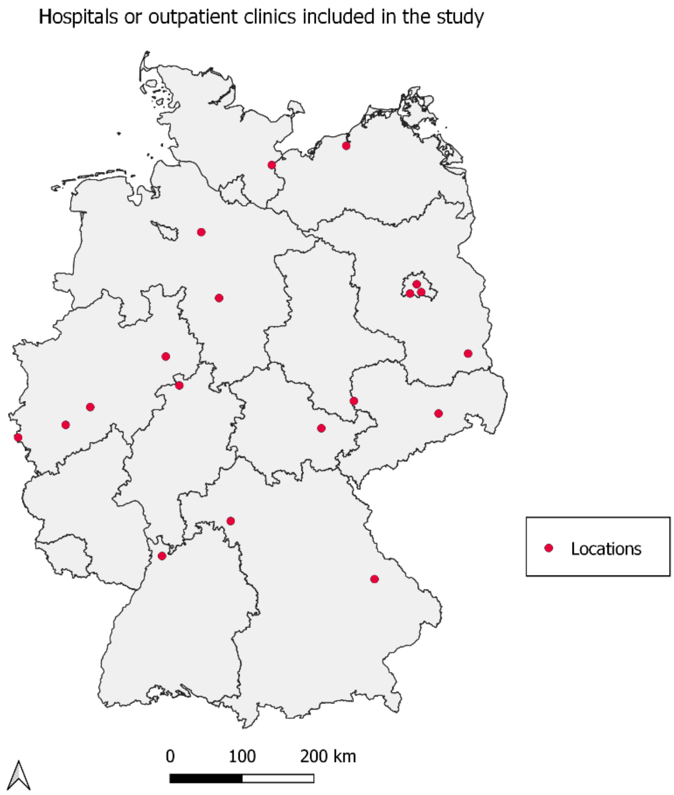

Figure 1: Hospitals or outpatient clinics included in the study.

2.2 Meteorological and air quality data description

The climate data used in this study comes from the operational official station monitoring networks of the German Weather Service (DWD). This data covers the period from 2000 until 2021 and includes all daily available meteorological station data (Behrendt et al., 2011; DWD Climate Data Center, 2021). Within the study period, a larger number of stations was converted to automatic data acquisition in 2009, which led to data outages in some cases. Quality controls include temporal and content consistency checks to correct for random and gross measurement errors, following the World Meteorological Organization (WMO) and DWD standards (Kaspar et al., 2013). The daily mean values of air pressure, relative humidity, temperature, minimum and maximum temperature, and the number of hours of sunshine considered in this study come from the previously described data source.

The Shuttle Radar Topography Mission (SRTM) terrain model, version 4, is used to account for diurnal climatological effects due to terrain. Data with an average resolution of 60x60 meters in Germany is resampled bilinearly to 500*500-meter cells (Jarvis et al., 2008; Reuter et al., 2007).

To obtain regionalized climate values for each municipality in Germany, it is necessary to spatially interpolate the daily climate data which is only available as point measurements. Numerous approaches exist to perform such interpolations, some of which differ considerably. Besides comparatively simple approaches like an inverse distance weighted method, spline-based methods and especially kriging methods have proven to be very useful techniques for interpolations. In situations with a changing and small number of point data (climate stations) that aim to be interpolated, ordinary kriging with external drift (KED) is the most efficient standard method and the most commonly used geostatistical approach for estimating climate variables (Benavides et al., 2007). Since the above-mentioned climate elements are known to be dependent on topography, KED is used considering terrain elevations as secondary data to estimate the climate variables of interest (Bianchi et al., 2016).

In the kriging-based approaches, the study area of Germany is divided into a finite number of cells (2.226.005) with a resolution of 500 m to determine climate parameter fields. A two-step procedure is then applied to compute daily climate maps using R software. In the first step, an autoadaptive optimization of the variogram data is determined from the co-variance models (Gräler et al., 2016; Pebesma, 2004; R Core Team, 2021). In the second step, the optimized covariance model is utilized for each daily climate variable in the universal kriging procedure. Kriging differs from simpler interpolation methods in that it is based on the spatial arrangement of the empirical observations rather than on the assumed model of spatial distribution. With at least moderate spatial autocorrelation, it is a useful method for preserving spatial variability. The universal kriging used in this study has a modified assumption of stationary in that the mean of the values at different locations can be deterministically different while only the variance remains constant across the field (Bivand et al., 2008). This second-order stationery is often an important assumption for environmental exposure such as climate values or pollution levels. To represent the external drift, the SRTM terrain heights are used and integrated into the Kriging procedure.

The data on total precipitation and wind speed comes from a different data set, namely from the COSMO-REA6 reanalysis, with a grid resolution of 6m x 6km for 2000 until August 2019 covering Europe (Bollmeyer et al., 2015). The extreme precipitation data is based on E-OBS observational data at the daily temporal scale and a spatial resolution of 0.02° x 0.02° (Copernicus Climate Change Service, 2020). The air pollutant data comes from Copernicus Atmosphere Monitoring Service (CAMS) global reanalysis (EAC4) with a spatial resolution of 0.75° x 0.75° (Inness et al., 2019).

As a final step, current municipality geometries were homogenized to 2012 based on official EuroStat data (Europäische Kommission - Eurostat/GISCO, 2022) to then calculate descriptive statistics of climate variables for each of the municipalities. Proportional grid cells with appropriate precision weighting were also considered.

Table 1: Meteorological and Air Conditions included in the study.

Factor	Unit	Description
Sunshine duration	hours	Daily hours of sunshine
Air pressure	Pa	Average daily air pressure
Relative Humidity	K	Daily average relative humidity
Average, minimum, and maximum temperature	°C	Daily average, minimum, and maximum temperature

Diurnal temperature difference	°C	Daily difference between the minimum temperature and maximum temperature on a given day
Pneumonia temperature	°C	Current day's average temperature minus the previous day's average temperature
Total precipitation	kg/m^2	Daily total precipitation
Precipitation at fixed percentiles (95th, 99th percentile)	kg/m^2	Total precipitation when daily precipitation amounts exceed the 90th, 95th, or 99th percentiles in wet days (daily precipitation ≥ 1 mm) computed over the 30-year period (1989-2018).
Maximum wind speed	m/s	Daily 10 m maximum wind speed
Maximum total column* CO	kg kg-1	Daily maximum total column of CO
Total column* NO_2	kg kg-1	Daily maximum total column of NO_2
Total column* O_3	kg/m^2	Daily maximum total column of O_3
Total column* SO_2	kg kg-1	Daily maximum total column of SO_2
PM 10 concentrations	kg/m^3	Daily maximum of particulate matter < 10 µm (aerosol)
PM 2.5 concentrations	kg/m^3	Daily maximum of particulate matter < 2.5 µm (aerosol)
Black carbon aerosol optical depth**	dimensionless	Daily maximum aerosol optical depth at 550 nm for black carbon
Dust aerosol optical depth**	dimensionless	Daily maximum aerosol optical depth at 550 nm for dust aerosols
Total aerosol optical depth**	dimensionless	Daily maximum aerosol optical depth at 550 nm for total aerosols

* Total column refers to the total amount of the selected variable in a column of air extending from the surface of the Earth to the top of the atmosphere.

**The aerosol optical depth (AOD) measures the amount of light lost due to the presence of aerosols on a vertical path through the atmosphere.

2.3 Methodological approach

The statistical approach is designed to examine whether weather and air conditions potentially caused these people to be admitted on that day and why not any other day. Therefore, we generate for each person in the medical database three alternative dataset entries that represent all personal characteristics except the hospitalisation date. These can be interpreted as alternative days at which the person could have been admitted but has not been admitted. As a result, we obtain 43.232 cases, 10.808 real cases and 32.424 non-real cases. Next, we match the weather and air condition data to each of these cases. Logistic regressions are used to examine the determinants of the occurrence of the real cases in comparison to the non-real cases.

In this approach the calculation of the non-real cases is crucial. Therefore, two procedures are applied:

1) Total comparison: In this procedure, the days of admission for the non-real cases are drawn randomly from the whole period of observation from the respective hospital (the periods of observation are different for the considered hospitals or outpatient clinics). In this case, the results show which general weather situations and air conditions are more likely to appear together with pneumonia cases. The question asked in this analysis is: Under what weather and air situations does pneumonia occur more frequently? By this also the seasonal characteristics linked to pneumonia are identified.

2) Contemporary comparison: In this procedure, a day is randomly drawn from the period spanning from ten days before the real case to ten days after the real case. Hence, all non-real cases fall into the same part of the year, excluding seasonal effects from the analysis. The goal pursued with this procedure is to determine the factors which potentially caused pneumonia to occur exactly on this day and not a few days earlier or later. The question asked in this analysis is: What weather and air conditions trigger pneumonia?

The adequateness of the logistic regression is tested with the Hosmer-Lemeshow-Test, which identifies a slightly significant deviation from the assumed logistic distribution (p-value=.0438). The weather and air conditions are assigned to each real and non-real case based on the location of the hospital and the day of hospitalisation. In general, the hospitalised people do not live at the location of the hospital but probably in the surrounding area. Therefore, we calculate the weather and air conditions in all municipalities that are less than 60 minutes driving time away from the hospital to approximate the relevant conditions. A weighted average is built for each hospital. Each municipality is weighted according to its population (larger cities have a higher probability that the patient origins from this city) and according to its distance to the hospital, a distance decay function is used as described in Brenner and Pudelko (2019).

We include 20 weather and air condition variables in the analysis (Table 1). However, several conditions are highly correlated with each other and describe similar aspects. These are the three variables for temperature (average, minimum, and maximum), three variables for precipitation (total, >95%, and >99%) and eight variables associated with air pollution (CO, NO_2, O_3, SO_2, PM<10µm, PM<2.5µm, black carbon aerosol, and total aerosol). Including them together leads to multicolinearity problems. Hence, for each aspect only one variable is included, the one leading to the highest fit (lowest AIC).

Besides including the variables (and their variants) directly as independent variables, we also test the following additional versions:

- We study whether the change of variables from one day to the next has an impact (in the case average temperature this is called the Pneumonia temperature).

- For each independent variable, a quadric term is also considered. The aim here is to examine non-linear dependencies with a specific focus on u-shaped and inverted u-shaped effects.
- Furthermore, interaction terms are included in the analyses. Each pair of variables is considered to check whether the co-occurrence of conditions is specifically triggering pneumonia.

Four variants of time delays are examined: using the values on the day of hospitalisation, one, two and three days before hospitalisation. The variant is chosen according to the AIC (Akaike Information Criterion). The aforementioned approach results in 240 potential independent variables. A stepwise in- and exclusion of the variables is used, adding one variable after the other and eliminating insignificant (significance level: .05) variables. During the approach the models are checked for multicollinearity and in case of potential multicollinearity (VIF values above 10) those variables are excluded that lead to the lowest loss in model fitting (lowest AIC values).

3. Results

In the following subsections the results of the regression analysis of all cases (section 3.1) and the influence of personal characteristics on the sensitivity of pneumonia (section 3.2) are presented and discussed.

3.1 Analysis of all cases

The first interesting result concerns the time delay for the weather and air conditions: In the case of a comparison to non-real cases drawn randomly from the whole period (total comparison) using the conditions from two days before hospitalisation leads to the best fit. In the case of a comparison to non-real cases drawn from nearby days within 10 days before and after (contemporary comparison) the best fit results from using the conditions from the day of hospitalisation. Above we argue that the contemporary comparison focuses on triggering conditions, which seem to be present at the day of hospitalisation. The total comparison rather focuses on more long-lasting weather and air conditions, so that more days matter, reflected by a time distance of two days. The latter is in line with findings in the literature, which also follow rather a total comparison concept and find various lags, depending on the study design, considered meteorological factors as well as climate of the study area. For example, in Sohn et al. a 7-day lag was best to describe the risk of getting pneumonia and in Basu and Samet (2002) a lag of 0–3 days.

A further difference between the analysis types is the finding that three of the five significant determinants are changes in the variables in the contemporary comparison, while this is the case only for two out of 16 significant variables in the total comparison (Table 2). Thus, strong changes in the weather and air conditions trigger pneumonia cases: a decrease in sunshine hours, an increase in the diurnal temperature (difference between minimum and maximum temperature), and an increase in air pollution (NO_2 is most significant but the other air pollution variables lead to similar results). These findings align with the work by Murdoch and Jennings (2009) who found statistically significant correlations between pneumonia cases and decreasing sunshine hours and wind speed, and with increasing air pollution levels and humidity. Many other studies have also determined that increases in diurnal temperature correlate with increasing pneumonia cases (Lim et al., 2012; Xu et al., 2013). The fourth significant trigger (contemporary comparison) is an interaction term that also represents weather changes: Long sunshine duration and high precipitation (>95%-percentile) occurring together in a day also lead to more pneumonia cases. Other studies have also found correlations between high precipitation and pneumonia cases especially during warmer temperatures (Chan et al., 1999). The fifth variable found significant in the contemporary analysis is interaction term between high precipitation (>95%) and dust aerosols, probably because intensive rain reduces the effects of air pollution (Kwak et al., 2017).

Table 2: Regression results for the two created databases (p-values in brackets).

Variable	**Contemporary comparison**	**Total comparison**
Sunshine duration		.0339*** (.0000)
Sunshine - Change	-.00828** (.0074)	
Interaction: Sunshine * Prec. (>95%)	.0314* (.0128)	
Air pressure		-.00713*** (.0000)
Air pressure - Squared		.000165*** (.0001)
Relative humidity		.00426* (.0204)
Relative humidity - Squared		-.000721*** (.0000)
Interaction: Humidity * Diurnal temp.		-.000280*** (.0000)
Diurnal temp. - Change	$6.342*10^{-13}$* (.0342)	
Minimum temp. - Change		.0184*** (.0002)
Minimum temp. - Squared		-.000889*** (.0000)
Interaction: Min. temp. * Air pressure		-.0000338*** (.0000)
Interaction: Min. temp. * SO_2		.00281*** (.0000)
Interaction: Air pressure * SO_2		.000110*** (.0000)
High precipitation (>99%) - Squared		-.6104** (.0012)
Interaction: Prec. (95%) * Dust aerosols	-.00000198** (.0061)	
Dust aerosols - Squared		$9.304*10^{-13}$* (.0216)
Interaction: Dust aerosols * SO_2		-.000000164** (.0001)
Maximum SO_2 - Change		-.00521*** (.0000)

Maximum NO_2 - Change	.00368** (.0074)	
Maximum SO_2 - Squared		-.00279*** (.0000)

The total comparison provides a long list of significant variables. While looking at these factors we must keep in mind that they characterise more long-lasting weather and air situations as well as seasons in which more pneumonia cases occur. We find that pneumonia is more frequent in periods with a lot of sunshine, very low air pressure (due to quadratic term), and very high relative humidity. The latter effect is increased in case of small temperature difference within a day (diurnal temperature). As previously mentioned Murdoch and Jennings (2009) also found that decreases in sunshine are consistently associated with higher pneumonia cases. Furthermore, Onozuka et al. (2009) supports the result that increased relative humidity correlates with increasing numbers of pneumonia cases since the survival of the pneumonia virus in aerosols was found to be best at extremes of relative humidity.

Interestingly we do not find a direct linear effect of temperature. The negative quadratic effect implies that pneumonia is more likely for average minimum temperatures. Furthermore, an increase in the minimum temperature comes together with more pneumonia cases. In contrast to this, a regression with only including (minimum) temperature leads to the clear result that pneumonia is more likely in colder times which is in accordance with findings by both Mäkinen et al. (2009) and Eccles and Wilkinson (2015). A proposed mechanism to explain why cold temperatures cause respiratory symptoms is that long-term exposure to cold air temperatures induces inflammatory reactions in the lower respiratory tract (Larsson et al., 1993). Nonetheless, even if short-term exposure to cold air may elevate the number of inflammatory cells, there is a lack of evidence to conclude that solely an increase in number is sufficient to trigger pathological reactions (Larsson et al., 1998).

However, the complete regression (Table 2) shows that temperature rather influences pneumonia together with other factors. First, it increases the effect of low air pressure. If this comes together with low minimum temperatures pneumonia is especially likely. This finding is consistent with the study by Mäkinen et al. (2009). Second, high temperature, as well as high air pressures, lead together with high air pollution (represented by SO_2) to more pneumonia cases. Chiu et al. (2009) also examined that high temperatures (>23°C) and elevated levels of SO_2 are correlated with increasing numbers of pneumonia cases.

No clear results are found for precipitation: the quadratic dependence is difficult to interpret because the variable takes average values only if some of the surrounding area of a hospital has very high rainfall (above 99%-percentile) but not all of the surrounding area. This would make pneumonia more likely and might indicate that punctual heavy rainfall is a weather condition which promotes pneumonia. As previously mentioned, some studies find correlations between heavy precipitation and pneumonia especially on warm days (Chan et al., 1999).

Surprisingly, we find rather negative effects of air pollution on pneumonia likelihood. Especially if dust aerosols and air pollution (represented by SO_2) are both low, pneumonia cases are more frequent. However, this must be seen in the context of the other findings: Air pollution together with high temperature or with high air pressures leads to more pneumonia cases. This outweighs the effects found for the pure air condition variables, which is confirmed by a significant correlation between air pollution and pneumonia in our data. It is given that in many locations, patterns of air pollution are driven by the weather, and at the same time air pollutant concentrations may be associated with temperature. The relations among air pollutant levels, temperature, and predominantly mortality have been investigated in several studies; however, leading to conflicting results: while the literature review by Nhung et al. (2017) concludes that the ambient air pollution, especially O3, NO_2, CO, PM10, PM25 and SO_2, organized in decreasing impact, was related to both pneumonia cases and severity, others see air pollutants rather as "confounders and/or effect modifiers" (i.e., a synergistic effect) of the temperature-mortality association (Katsouyanni et al., 1997), while such an effect is not found by others (Samet et al., 1998). Nevertheless, most studies show that air pollution does not influence pneumonia cases on its own but becomes relevant in connection with other conditions, in our study in connection with high air pressure or high temperatures. This nonetheless shows that additional studies are needed to further examine the effect of the relationship between air pollutants and temperature on pneumonia mortality but more specifically on morbidity.

3.2 Influence of personal characteristics

To study whether the impact of weather and air conditions on pneumonia depends on personal characteristics, we add to the previously identified best models (with the determined lags and variable choices) addition interaction terms between all independent variables and various personal characteristics. Again, a stepwise approach is used, and insignificant interaction terms are excluded. For the contemporary comparison, the results are listed in Table 3.

While the impact of sunshine duration change (and interaction with precipitation) and air pollution change is not influenced by personal characteristics (regression results remain quite stable), other effects are strongly influenced. The results show that effects of increases in diurnal temperature is only given for people with a high body mass index (BMI>25). In addition, people with a high BMI are hospitalised for pneumonia more often if the amount of dust aerosols in the air is high or low.

Dust aerosols are found to have an impact mainly on people who smoke. This group of people is especially affected by a combination of high humidity and high levels of dust. This effect is counterbalanced by precipitation.

People with a tumor are more likely affected by pneumonia if relative humidity decreases from one day to the other. The same holds for people with diabetes who also benefit more from the counterbalancing effect of precipitation on air pollution. An interesting fact is that change in sunshine hours disappears by including the interaction term with diabetes. This implies that decreases in sunshine from one day to the next triggers pneumonia mainly for diabetes patients and not (significantly) for other people. We also tested various other personal characteristics (such as chronic pulmonary diseases and cardiac insufficiency) without significant results for the contemporary comparison.

Table 3: Regression results for contemporary comparison including interaction terms with personal characteristics (p-values in brackets).

	Personal characteristic			
Variable	**Smoking**	**BMI>25**	**Tumor**	**Diabetes**
Sunshine - Change	-.00758* (.0386)	-.00747* (.0416)	-.00952** (.0095)	Not significant
Interaction: Sun * Prec. (>95%)	.0307* (.0160)	.0306* (.0152)	.0308* (.0143)	.0319* (.0126)
Diurnal temp. - Change	not significant	not significant	not significant	not significant
Interaction: Prec. (95%) * Dust	not significant	-.00000188** (.0068)	-.00000153* (.0275)	-.00000143* (.0378)
NO_2 - Change	.00363** (.0083)	.00375** (.0065)	.00396** (.0040)	.00402** (.0036)
Personal characteristics interaction terms:				
Interaction: Humidity * Dust	$1.11*10^{-8}$* (.0146)			
Interaction: Prec. * Dust	-.00000405* (.0240)			
Diurnal temp. - Change		.0157* (.0470)		
Dust aerosols - Squared		$9.172*10^{-13}$* (.0359)		
Humidity - Change			-.0293*** (.0000)	-.0120*** (.0017)
Sunshine - Change				-.0241* (.0247)
Interaction: Prec. (95%) * NO_2				-.0120* (.0305)

Furthermore, we determined that personal characteristics matter more in the total comparison (Table 4) compared to the contemporary comparison. While we did not find any dependence on wind speed in the analyses above it seems to matter for people who smoke since they are more likely to get admitted for pneumonia if wind speed increases from one day to the next. Low wind speeds are also connected to a higher likelihood of pneumonia infections for tumor patients. Furthermore, tumor patients show an additional connection of pneumonia with higher minimum temperatures, increases in sunshine hours and high air pollution together with high diurnal temperatures.

Table 4: Regression results for total comparison including interaction terms with personal characteristics (p-values in brackets).

	Personal characteristic						
Variable	**Smoking**	**Tumor**	**BMI>25**	**Chronic pulmonary disease**	**Age>64**	**Sex (female)**	**Cardiac insufficiency**

Variables as above (Table 2)	Results similar to above (Table 2)						
Minimum temp. - Squared					Not significant		
Personal characteristics interaction terms							
Wind speed - Change	$5.71*10^{-11}$* (.0284)						
Humidity							-.00221** (.0045)
SO_2			-.0177** (.0026)	.0242*** (.0010)			
Diurnal temp.			.00825* (.0115)				.0180** (.0031)
Air pressure - Change			.00803* (.0127)				
Interaction: Sunshine * Prec. (>99%)			-.188*** (.0008)			-.0754* (.0434)	
Interaction: Prec. (>99%) * Diurnal temp.			.109*** (.0002)				
Minimum temp. - Squared					-.000866* (.0209)		
Minimum temp.		.0159* (.0126)			.0133** (.0026)		
Wind speed		$-1.35*10^{-8}$*** (.0005)					
Sunshine - Change		.0196* (.0303)					
Interaction: SO_2 * Diurnal temp.		.00323** (.0056)					

Interaction: Air pressure * Humidity				-.00000145** (.0049)			
Dust aerosols - Change						.00000104* (.0139)	
Dust aerosols - Squared						$-1.42*10^{-12}$* (.0247)	

We also find clear differences between people with a high BMI compared to those with a low BMI: People with a high BMI are more likely to be hospitalised for pneumonia at times with high diurnal temperature, which is strengthened by high precipitation and increases in air pressure. At the same time, they seem to be less vulnerable to air pollution and the combination of heavy rainfall and sunshine within one day.

Especially interesting are people with chronic pulmonary diseases. However, we do not find any differences in the contemporary comparison and only two differences in the total comparison. Pneumonia appears more frequently among these people in times of high air pollution and of low air pressure in combination with low humidity.

Additionally, while the triggering conditions (contemporary comparison) are not found to differ between the young and the elderly, we find that the relationship between pneumonia and minimum temperature in the total comparison is due to the older people (above 64 in age) in the sample, while the younger people show no such dependence. Older people show a strong relationship between being hospitalised with pneumonia and very low minimum temperature. This finding is similar to the results of other studies which however predominantly detected a u-shape pattern, indicating that not only minimum but also maximum temperatures are causing higher numbers of pneumonia cases in the elderly subgroup (Green et al., 2010; Y. Liu et al., 2014).

A comparison between female and male people only results in slightly significant (above 1% level) differences, indicating a lower reaction on the level of dust aerosols but higher reaction on changes of dust aerosols by females. Furthermore, pneumonia is more likely among females compared to males at times of low sunshine combined with low precipitation.

Moreover, we find a relationship between pneumonia and cardiac insufficiency. People with cardiac insufficiency are more likely to be hospitalised for pneumonia compared to other people at times with high diurnal temperature and low humidity. No differences are found between people with and without diabetes.

4. Conclusion

While many studies examine the relationship between weather and air condition and pneumonia cases or deaths, our study includes two perspectives, a long-term and a short-term analysis while at the same time accounting for various personal and health background characteristics. The first aspect allows to distinguish between general conditions that are associated with higher frequencies of pneumonia cases whereas the second aspect rather focuses on triggering conditions that explain why pneumonia occurred at exactly this day and not a few days earlier or later. Triggering conditions are found to be especially strong during changes in the weather and air conditions, namely decreases in sunshine hours and increases in diurnal temperature and air pollution as well as days with changes between sunshine and heavy rainfalls. Climate change will make weather change more frequent and more extreme, so that we can expect a higher concentration of hospitalisation cases on a few days in the future.

The long-term analysis of the weather and air conditions co-occurring with higher frequencies of pneumonia confirms many of the findings in the literature. More specifically, we examine that temperature and air pollution seem not to influence pneumonia on their own but only in combination with each other or low air pressure. This implies that future research should avoid studying the impacts of weather and air conditions on pneumonia separately but in combination. Additionally, more research should be conducted on specific weather constellations.

The inclusion of various personal characteristics has shown that some findings do not hold for all people but are relevant only for certain subpopulations with specific personal or health background characteristics. For example, changes in the diurnal temperature seem to trigger pneumonia only among people with a high BMI, decreases in sunshine hours seem to impact predominantly people with diabetes, and low temperatures significantly co-occur with pneumonia solely for the elderly. Many further relationships between personal characteristics and the relevance of certain weather and air conditions are found in this paper. Based on our findings, not only both resources and treatments at hospitals or doctor´s practices during pneumonia triggering weather conditions can be better prepared but also detailed and personal guiding prophylaxis can be advised to reduce the risks of the most vulnerable subgroups to pneumonia.

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