Original Article

The Impact of Relative Humidity and Atmospheric Pressure on Mortality in Guangzhou, China*

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Abstract

Objective Although many studies have examined the effects of ambient temperatures on mortality, little evidence is on health impacts of atmospheric pressure and relative humidity. This study aimed to assess the impacts of atmospheric pressure and relative humidity on mortality in Guangzhou, China.

Methods This study included 213,737 registered deaths during 2003-2011 in Guangzhou, China. A quasi-Poisson regression with a distributed lag non-linear model was used to assess the effects of atmospheric pressure/relative humidity.

Results We found significant effect of low atmospheric pressure/relative humidity on mortality. There was a 1.79% (95% confidence interval: 0.38%-3.22%) increase in non-accidental mortality and a 2.27% (0.07%-4.51%) increase in cardiovascular mortality comparing the 5th and 25th percentile of atmospheric pressure. A 3.97% (0.67%-7.39%) increase in cardiovascular mortality was also observed comparing the 5th and 25th percentile of relative humidity. Women were more vulnerable to decrease in atmospheric pressure and relative humidity than men. Age and education attainment were also potential effect modifiers. Furthermore, low atmospheric pressure and relative humidity increased temperature-related mortality.

Conclusion Both low atmospheric pressure and relative humidity are important risk factors of mortality. Our findings would be helpful to develop health risk assessment and climate policy interventions that would better protect vulnerable subgroups of the population.

Key words: Relative humidity; Atmospheric pressure; Temperature; Mortality

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INTRODUCTION

Global climate change is a significant and emerging threat to public health. In the last decade, there has been extensive evidence from various regions that the thermal stress is associated with a variety of adverse health outcomes, including mortality, hospitalizations, emergency visits, particularly from cardiovascular, and respiratory diseases[1-4]. Most previous studies focused on daily minimum, mean, and maximum temperatures, and diurnal temperature range. Studies on health effects of daily temperature on mortality have often controlled for the potential confounding effects of atmospheric pressure and relative humidity[1,4-6], while uncertainty remains whether daily atmospheric pressure and humidity themselves are independent risk factors of mortality. Experimental evidence indicates that humidity affects the transmission and survival of airborne viruses, bacteria, and fungi[7-9]. Recently, a US study revealed that humidity was negatively associated with influenza epidemics and influenza-related mortality[10-11]. Significant effects of humidity on mortality and hospital admissions for heart diseases were also observed in Brazil and Sicily[12-13], but not consistent with US studies[14-15]. The deleterious effects of extremely low or extremely high atmospheric pressure on human are recognized in special circumstances, such as while high-altitude mountaineering, flight, and diving, whereas the potential health effects of day-to-day variability in atmospheric pressure under normal conditions have not been well documented. A few studies seek to link atmospheric pressure and cardiovascular and respiratory diseases[16-19]. Less is known about the exposure-response function and the lagged effects of these two meteorological factors. Epidemiological evidence suggests that people with cardiovascular or respiratory diseases, the infant, the elderly, and those socially deprived are at particular risk of temperature-associated mortality[1,20]. Vulnerability to the effect of atmospheric pressure and relative humidity needs detailed investigation.

The combined effect of temperature and other meteorological parameters was examined using a complex index, such as apparent temperature[21-22], Humidex[23], and wind chill temperature index[24]. The effect size and exposure-response relationship of these indexes are different with that of temperature, indicating that there should be the joint effect. Distinguishing the effect of each factor among the composite index is necessary. Other meteorological factors could be investigated separately from temperature for better understanding the weather-health association.

The present study aims to assess the effects of atmospheric pressure and relative humidity on mortality after controlling for daily mean temperature, and to explore the joint effects with mean temperature.

MATERIAL AND METHODS

Data

Our study included six central urban districts of Guangzhou where there are 7.7 million permanent residents. There were a total of 213,737 registered deaths from January 2003 to December 2011. The Guangzhou Center for Disease Control and Prevention provided individual death data including cause of death, date of birth, date of death, sex, and education attainment. Causes of death were classified by the Tenth Revision of the International Classification of Diseases (ICD-10). We examined non-accidental mortality (A00-R99), mortality due xto cardiovascular diseases (I00-I99) and respiratory diseases (J00-J99), and the subcategories: stroke (I60-I69), ischemic heart diseases (IHD, I20-I25), and chronic obstructive pulmonary diseases (COPD, J40-47). We also examined the effects in subgroups by gender (male and female), age (0-64, 65-74, and ≥75), and education attainment (no education, primary education, and secondary or higher education). Those with no education attainment represent the illiterate or semi-illiterate.

We obtained daily meteorological data for Guangzhou from China Meteorological Data Sharing Service System, including daily mean temperature, minimum, maximum temperature, atmospheric pressure, and relative humidity. These meteorological data were collected from Guangzhou Weather Station, located at 23.10°N latitude and 113.20°E longitude in the central urban area of Guangzhou. This station is the only national basic weather station in Guangzhou (Figure 1). We obtained air pollution data on daily concentration of particulate matter less than 10 μm in aerodynamic diameter (PM_{10}), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) from Guangzhou Bureau of Environmental Protection.

Statistical Methods

Spearman correlation analyses were performed to explore the association between environmental parameters. The effects of daily atmospheric pressure and relative humidity on mortality were examined using a quasi-Poisson regression model combined with a distributed lag non-linear model (DLNM). Based on the flexible definition of a bi-dimensional cross-basis, DLNM can simultaneously estimate the potential non-linear exposure-response relationship and delayed effects[25]. Since Gasparrini[26] developed the R package dlnm for implementing this model, it has been widely applied in recent studies of ambient temperatures and mortality. The model can be specified as follows:

Y_t~Poisson(μ_t)

$$Log\ (\mu_t)=\alpha+ns\ (time_t, 7\times9)+ns\ (PM_{10t}, 3)+ns\ (SO_{2t}, 3) +ns\ (NO_{2t}, 3)+\gamma DOW_t+vHoliday_t+\varphi \mathrm{Temp}_{t,l} +\beta_1 PRE_{t,l}+\beta_2 RH_{t,l} =\alpha+\varphi \mathrm{Temp}_{t,l}+\beta_1 RH_{t,l}+\beta_2 PRE_{t,l}+\mathrm{COVs} \quad (1)$$

Where Y_t is the observed daily death counts on day, t. *ns(…)* is a natural cubic spline, $time_t$ was days of calendar day on day t. We used a *ns* with 7 degrees of freedom (df) per year for $time_t$ to control for long-term trends and seasonality of daily mortality. DOW_t and $Holiday_t$ are categorical variables indicating day of the week and holiday, respectively. PM_{10t}, SO_{2t}, and NO_{2t} were daily mean concentration of PM_{10}, SO_2, and NO_2 on day t, and their potential confounding effect can be adequately controlled for using natural cubic splines with 3 df[5,27]. $Temp_{t,l}$ was a matrix obtained by applying the DLNM to mean temperature to control its confounding effect over the current day (lag 0) to lag l days. As in our previous studies of temperature effect on mortality[4-5], we used 5 df natural cubic spline for mean temperature and 4 df natural cubic spline for lag which was chosen based on minimizing Quasi-likelihood Akaike's Information Criterion (Q-AIC), and we specified a relatively long lag time of 20 d for temperature. $PRE_{t,l}$ and $RH_{t,l}$ were matrices of atmospheric pressure and relative humidity. Their effects were also modeled using a cross-basis of natural cubic spline functions. The maximum lag was set to 10 d for both atmospheric pressure and relative humidity. The choice of the dfs for atmospheric pressure, relative humidity and their lag was based on minimizing Q-AIC for the sum of quasi-Poisson values for all the models of cause-/gender-/age-/education-specific mortality[5,27]. Partial autocorrelation function was used to check whether the model residuals were independent over time. The final composition of the spline functions in primary analyses was 3 df for relative humidity and 3 df for its lag, and 4 df for atmospheric pressure and 4 df for its lag, respectively (Supplementary Table 1).

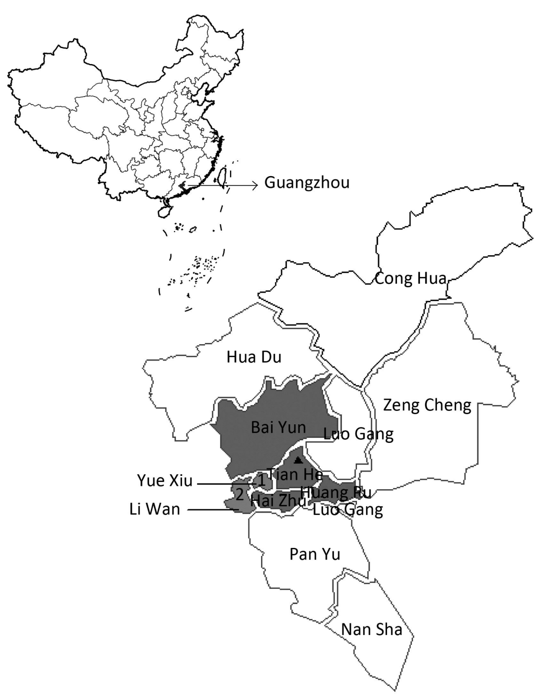

Figure 1. Map of districts in Guangzhou. The grey areas are the six central urban districts of Guangzhou under study. The triangle shows the location of Guangzhou Weather Station.

To examine the joint effects of atmospheric pressure/relative humidity and mean temperature on mortality, we used a natural cubic spline with 6 df for atmospheric pressure/relative humidity and mean temperature[5,28]. We plotted the 3D graphics to assess whether there was an interaction between atmospheric pressure/relative humidity and mean temperature on cause-specific mortality. Model (1) was modified by changing the single terms of $Pre_{t\text{-}l2}$, $RH_{t\text{-}l1}$, and $Temp_{t\text{-}l}$, into bivariate terms as follows:

$$Log(\mu_t)=\alpha+ns\ (\mathrm{Temp}_{t,l}, RH_{t,l}, 6)+\beta_1 PRE_{t,l}+\mathrm{COVs} =\alpha+ns\ (\mathrm{Temp}_{t,l}, PRE_{t,l}, 6)+\beta_2 RH_{t,l}+\mathrm{COVs} \quad (2)$$

Sensitivity analyses were conducted to check the robustness of our results. We used different maximum lag for mean temperature (21-30 d), df for time (8-10 df per year), PM_{10}, SO_2, and NO_2 (4-6 df).

All data manipulation and statistical analyses were performed using 'mgcv' and 'dlnm' packages of *R* software (The *R* Foundation for Statistical Computing, Version 2.15.2).

RESULTS

There was an average of 63 non-accidental deaths per day, with 24 (38.4%) and 12 (19.2%) from cardiovascular diseases and respiratory diseases, respectively (Table 1). Guangzhou has a subtropical climate with a mean temperature of 22.9 °C during the study period. The mean daily atmospheric pressure and relative humidity were 1008.2 hPa and 71.1%, respectively. Mean temperature was strongly reversely associated with atmospheric pressure (r_s=-0.840), but weakly related to relative humidity (r_s=0.092). There were also weak correlation between meteorological parameters and air pollution levels (Table 2).

The exposure-response curve revealed a monotonic but non-linear increase in mortality with decreasing relative humidity at lag 0, while the curve for atmospheric pressure seems to be v-shaped, with a clear increase in mortality risk at low atmospheric pressure and a slight rise at extremely high pressure (Figure 2). The effect of atmospheric pressure and relative humidity persisted for approximately 4 d (Figure 3). The exposure-response curve at lag 0-4 also showed a similar relationship (Supplementary Figure A).

Table 3 shows the effects of low atmospheric pressure/relative humidity, estimated by the percentage change in mortality comparing the 5th and 25th percentile of distribution. We observed a significant cumulative effect of low relative humidity at lag 0-4 with an increase in mortality due to cardiovascular diseases (3.97%, 95% CI: 0.67%-7.39%) and IHD (6.47%, 95% CI: 0.78%-12.47%), while the estimated effects were non-significant for other mortality categories. There was also a significant effect of low atmospheric pressure with an increase of 1.79% (95% CI: 0.38%-3.22%) in non-accidental mortality, and the effects were particularly larger on mortality due to cardiovascular diseases. Mortality risk increased for all categories comparing the 99th percentile to the 95th percentile of atmospheric pressure, and this effect of extremely high atmospheric pressure was statistically significant on non-accidental mortality but not on other subcategories.

Table 1. Summary Statistics for Daily Weather Conditions, Air Pollutants, and Mortality in Guangzhou, China from 2003 to 2011

Variables	Min	Percentiles					Max	Mean	SD
		P_5	P_{25}	P_{50}	P_{75}	P_{95}			
Mean temperature (°C)	5.4	11.0	18.5	24.4	27.9	30.8	34.2	22.9	6.2
Atmospheric pressure (hPa)	988.7	997.6	1003.0	1007.9	1013.4	1019.5	1027.2	1008.2	6.9
Relative humidity (%)	20.0	46.0	64.0	72.0	81.0	90.0	99.0	71.1	13.0
PM_{10} (μg/m^3)	7.0	27.3	52.1	80.0	114.6	164.2	370.1	88.2	48.5
NO_2 (μg/m^3)	24.7	32.2	48.0	65.8	89.9	126.8	281.3	73.2	34.0
SO_2 (μg/m^3)	6.1	10.3	29.3	49.7	80.3	119.8	237.3	59.3	39.6
Non-accidental mortality	20	44	53	60	70	87	233	62.5	13.7
Cardiovascular mortality	6	14	19	23	28	37	102	24	7.3
Stroke	0	3	6	8	10	14	31	8	3.3
IHD	0	2	5	7	10	14	27	8	3.4
Respiratory mortality	2	6	9	11	14	20	46	12	4.4
COPD	0	2	4	6	8	12	27	6	3.1

Table 2. Spearman Correlation between Daily Meteorological and Air Pollution Variables in Guangzhou

Variables	Mean Temperature	Atmospheric Pressure	Relative Humidity	PM_{10}	SO_2	NO_2
Mean temperature	1	-0.840**	0.092**	-0.114**	0.152**	-0.235**
Atmospheric pressure	-	1	-0.389**	0.248**	-0.033	0.332**
Relative humidity	-	-	1	-0.161**	0.111**	-0.115**
PM_{10}	-	-	-	1	0.673**	0.864**
SO_2	-	-	-	-	1	0.655**

Note. **P<0.01.

We evaluated the effects on non-accidental mortality for subpopulations by sex, gender, and education attainment (Table 3). The effects of low atmospheric pressure were strong and significant for women, but less and non-significant for men. There was significant effect modification by age and education attainment, while the pattern of vulnerability by age was different for atmospheric pressure and relative humidity. The strongest effect of decreased relative humidity was observed for persons aged 75 years or older, while those aged 64-75 years were at highest risk for atmospheric pressure effect. The illiterate and semi-illiterate were more susceptible to decreased atmospheric pressure, while those with primary education were more susceptible to the effects of relative humidity, compared to those with secondary or higher education level (Table 3).

There were joint effects of atmospheric pressure/relative humidity and mean temperature on mortality at lag 0 (Figure 4) and lag 0-4 as well (Supplementary Figure B). Temperature-related mortality

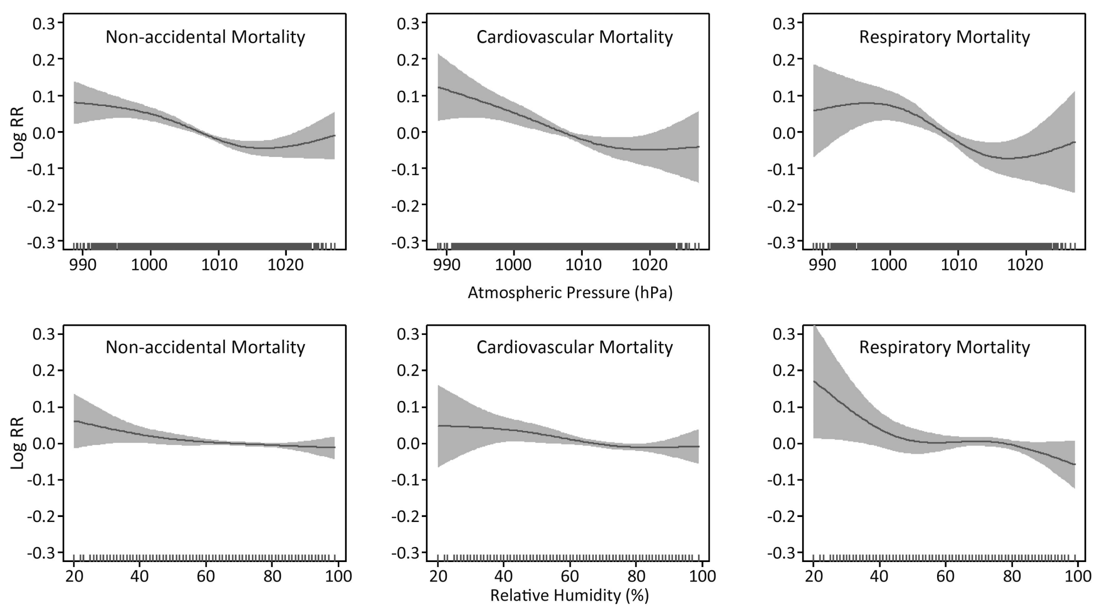

Figure 2. The dose-response curve of atmospheric pressure (hPa) and relative humidity (%) on mortality at lag 0.

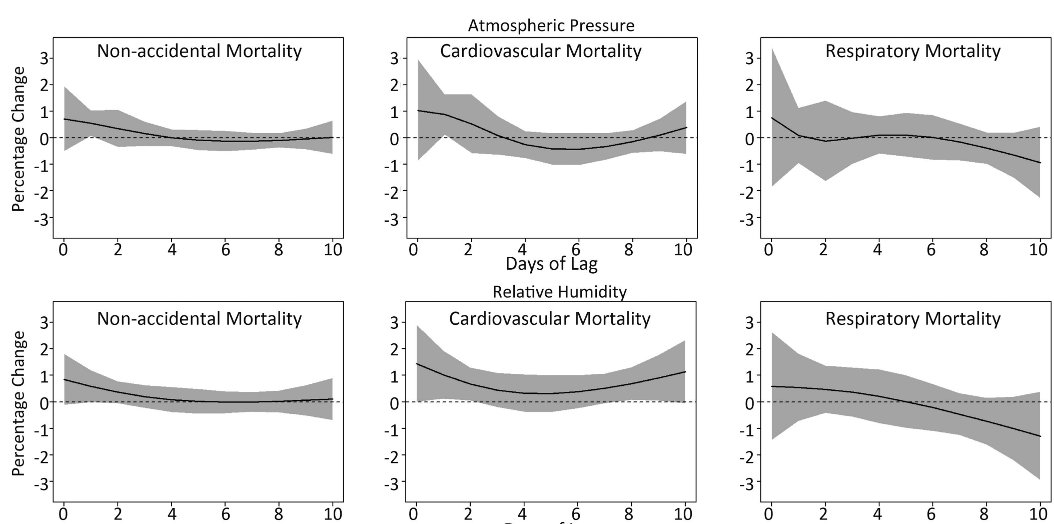

Figure 3. Percentage change in mortality comparing the 5th and the 25th percentile of atmospheric pressure/relative humidity along lags of 0-10 d.

Table 3. The Cumulative Effects of Atmospheric Pressure/relative Humidity on Mortality Categories over Lag 0-4 d

Variables	Effect Estimates (95% confidence interval)		
	Low relative humidity[a]	Low atmospheric pressure[a]	Extremely high atmospheric pressure[b]
Cause of death			
Non-accidental	2.11 (-0.08, 4.35)	1.79 (0.38, 3.22)	2.93 (0.05, 5.88)
Cardiovascular	3.97 (0.67, 7.39)	2.27 (0.07, 4.51)	3.19 (-1.06, 7.62)
IHD	6.47 (0.78, 12.47)	2.85 (-0.83, 6.67)	1.77 (-5.17, 9.22)
Stroke	2.52 (-2.85, 8.18)	1.31 (-2.31, 5.06)	3.56 (-3.48, 11.11)
Respiratory	2.19 (-2.38, 6.98)	0.80 (-2.15, 3.85)	3.98 (-1.99, 10.33)
COPD	3.35 (-2.80, 9.89)	2.60 (-1.52, 6.88)	3.42 (-4.50, 11.99)
Sex			
Male	1.39 (-1.33, 4.19)	0.79 (-0.95, 2.57)	3.35 (-0.26, 7.09)
Female	2.99 (-0.16, 6.24)	3.04 (1.00, 5.13)	2.37 (-1.68, 6.59)
Age (years)			
0-64	-0.80 (-4.82, 3.39)	1.92 (-0.65, 4.57)	1.91 (-3.47, 7.60)
65-74	0.90 (-3.32, 5.31)	3.59 (0.83, 6.43)	2.84 (-2.78, 8.77)
75+	3.73 (0.86, 6.68)	0.92 (-0.92, 2.80)	3.43 (-0.28, 7.26)
Education attainment			
No	2.52 (-2.24, 7.51)	2.88 (-0.30, 6.17)	5.03 (-1.18, 11.63)
Primary	3.63 (0.43, 6.92)	1.60 (-0.46, 3.71)	3.20 (-0.97, 7.54)
Secondary or higher	1.18 (-2.17, 4.65)	1.25 (-0.87, 3.41)	0.31 (-4.02, 4.83)

***Note*.** [a]Effect is presented as percent change in mortality comparing the 5th and 25th percentile value of exposure; [b]Effect is presented as percent change in mortality comparing the 99th and 95th percentile value of exposure.

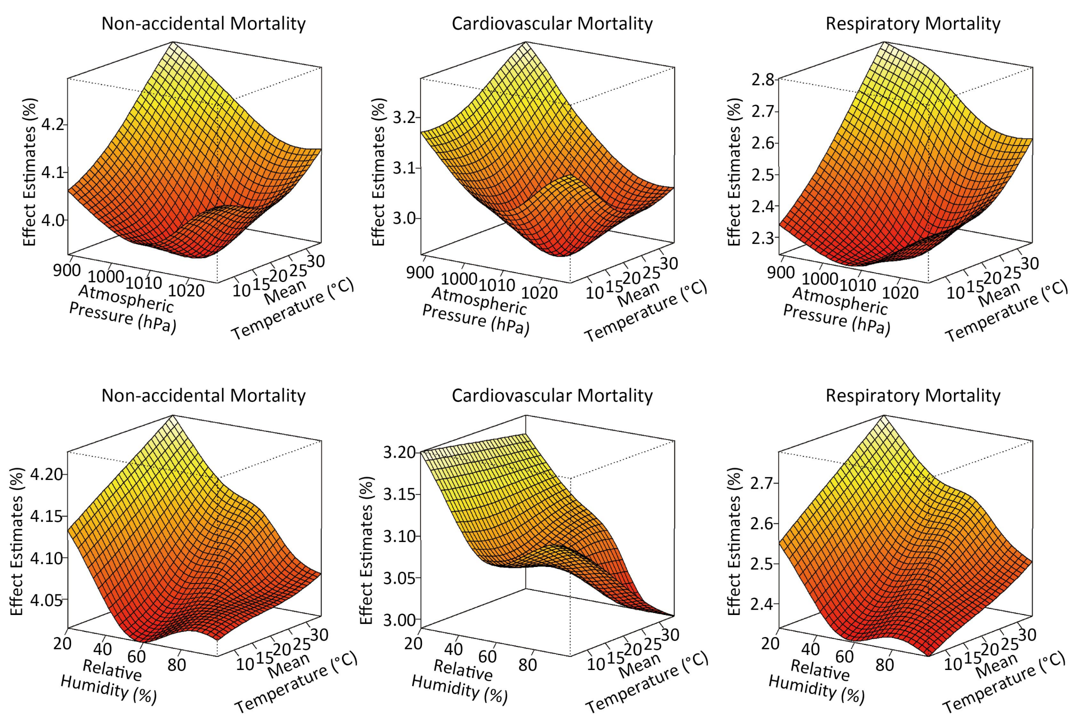

Figure 4. Bivariate response surfaces of atmospheric pressure/relative humidity and mean temperature for cause-specific mortality at lag 0.

generally decreased with an increase in relative humidity, but a slight increase in cold-related cardiovascular mortality was observed when relative humidity above 60%, suggesting a higher risk of cold-related cardiovascular mortality on humid days. We observed a threshold of atmospheric pressure (proximately 1014 hPa) for the interaction between atmospheric pressure and temperature. The effect of mean temperature on mortality increased above or below this threshold.

Sensitivity analyses were performed to check whether the results were robust to the specification of parameters in the model. We found that the effect estimates were stable when using 4-6 df for PM_{10}, SO_2, and NO_2, and the estimates were not changed substantially when using 8-10 df per year for time or changing the maximum lag for mean temperature to 21-30 d (Supplementary Figure C1-C3).

DISCUSSION

In the present study, we found significant effect of low atmospheric pressure/relative humidity on mortality, particularly for women, people aged 75 years and older, and those with low education attainment. Furthermore, low atmospheric pressure and relative humidity increased temperature-related mortality. Our findings highlight the need to strengthen the awareness of potential dangers of low atmospheric and humidity and enhance coping capacities to mitigate weather-related mortality. It is recommended that daily atmospheric pressure and relative humidity are broadcasted as standard weather parameters for presenting full weather forecast information to the public.

Little work has been done to examine the health impact of relative humidity. Overall, previous studies only focused on cardiovascular diseases, and their results were inconsistent. Two large surveys in 12 US cities did not show any significant association of daily humidity with mortality or with hospital admissions for heart diseases[14-15]. However, decreased humidity was found to be a risk factor for myocardial infarction and angina in other studies[12,13,29]. Recently, Barreca and Shimshack[11] also revealed a negative association between humidity and influenza mortality. Our results showed a monotonic and lagged effect of relative humidity on non-accidental mortality particularly on cardiovascular mortality, with a rise in mortality associated with a decrease in humidity.

Animal experimental models have shown that lowering barometric pressure aggravates pain-related and depression-related behaviors[30-31]. Epidemiological evidence suggests that decreased atmospheric pressure induces spontaneous delivery[32], occurrence of acute myocardial infarction[17], pulmonary embolism[18-19], violence, and mental health disorders[33]. Danel et al.[16] reported a v-shaped association between atmospheric pressure and coronary diseases, with a minimum mortality risk at 1016 hPa. Consistently, in the present study, we found a significant effect of low atmospheric pressure on mortality, and an increase in mortality observed at relatively extremely high atmospheric pressure (above 1020 hPa).

The latest WHO report on climate change showed much evidence for gender difference in health effects of ambient temperature and extreme climate events in previous studies[34]. The patterns of vulnerability by gender were dependent on behavioral and socio-economical differentials between men and women in terms of exposure to risk and adaptive capacities. There remains a lack of research on gender differences in vulnerability to atmospheric pressure and relative humidity. Staskiewicz et al.[19] found that the occurrence of pulmonary embolism was related to low atmospheric pressure and humidity in male patients, but no significant association was found for females. In the present study, we found females were more vulnerable to low atmospheric pressure and humidity. We also found that deaths among the elderly and those with no education were more strongly associated with low atmospheric pressure and humidity, in agree with the previous findings for temperature effect modification[4,35].

The consistency of our results with previous studies in terms of vulnerable subpopulation and mortality categories, and the persistence of the effect after adequately controlling for confounding effect of temperature and air pollution strongly argued for specific effects of relative humidity and atmospheric pressure on mortality, although the underlying biologic mechanisms responsible for this effect remain unclear. Sato et al.[36] found that barometric pressure was inversely associated with blood pressure and heart rate in rat models, but another experimental study did not observed association between blood pressure variability and barometric pressure[37]. Tauboll et al.[38] found cerebral hypoxia and hypocapnia induced by lowering barometric pressure in human volunteers in the artificial situation of a low pressure chamber. In the normal situation, two panel studies[39-40] also reported that decreases in atmospheric pressure and humidity were associated with declines in blood oxygenation and increases in pulse rate. This evidence indicates that low atmospheric pressure and humidity may induce hypoxia, increasing cerebrovascular and cardiovascular disease risk. Cold and dry air leads to excessive dehydration of nasal passages and the upper respiratory tract, leading to an increased chance of microbial and viral infection such as influenza[10,41]. Therefore, the effect of low humidity may be particularly dramatic in winter.

Although there are numerous studies assessing health effects of temperatures, this is the first study to examine the joint effects of relative humidity/atmospheric pressure and mean temperature. We found an increase in temperature-related mortality risk associated with low atmospheric pressure and relative humidity. It suggests that the assessment and the prediction of the impact of climate change need to take the joint effect of meteorological factors into account.

An increase in average ambient temperature has been consistently observed worldwide. In contrast, the long-term trend of changes in relative humidity and air pressure shows spatial heterogeneity. A decreasing trend in relative humidity during winter and spring was observed over the past fifty years in Canada[42], while little change has occurred in the US[43] or in most Chinese regions except for Xinjiang and central China[44]. Average air pressure has dropped for the years 1948-1998 at sea-level over the Arctic, Antarctic, and North Pacific, but has a rising trend in the subtropical North Atlantic Ocean, Southern Europe, and North Africa[45]. Atmospheric pressure controls the circulation patterns of air masses, therefore changes in atmospheric pressure can alter temperature, rainfall, and winds, leading to great health impact of climate change. Investigating the trend and health effects of relative humidity and atmospheric pressure may be able to complement analysis of climate change impact.

There are some limitations associated with this study. In the present study, we controlled for mean temperature and PM_{10}, NO_2, and SO_2, which have been regarded as main confounders in time-series studies of mortality, but some residual confounding may be present due to other uncontrolled atmospheric variables. Especially, atmospheric pressure is closely associated with weather and can often be used to predict the weather; therefore we cannot ignore the possibility that the air pressure-mortality relationship may be biased by other weather parameters related to air pressure. Further studies are needed to determine whether or not causality exists. This study was conducted in one single city. The inconsistency of previous results and individual susceptibility suggest potential heterogeneity by regions and populations. Multi-city studies using unified methodology are needed for better understanding the characteristics of health effects of humidity and atmospheric pressure. Also, the biological mechanism underlying the observed effects needs to be further studied, as a possible basis for epidemiological studies seeking to ascertain causal effect relationship.

CONCLUSION

The present study revealed a substantial adverse effect of low atmospheric pressure and low relative humidity on mortality after controlling for mean temperatures, and it is evident on the interaction between atmospheric pressure/relative humidity and mean temperature. These two factors should be taken into account for assessing health impacts of climate and weather, and for controlling their confounding effects in studies of air pollution, and mortality. We identified that women, the elderly, and people with low education level were particularly susceptible. This finding would contribute to developing health risk assessment and climate policy interventions that would better protect vulnerable subgroups of the population.

SUPPLEMENTARY MATERIALS

All the supplementary materials (Supplementary Table 1, Supplementary Figure A, Supplementary Figure B, Supplementary Figure C1, Supplementary Figure C2, Supplementary Figure C3) can be found in the websit of *www. Besjournal.com*

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