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The impact of meteorological conditions on Air Quality Index under different urbanization gradients: a case from Taipei

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Abstract

With the concentration of air pollutants increasing, air pollution has many hazards to the human body. Meteorology is the main factor affecting the diffusion of air pollutants. Studying the dynamic connection between them can provide references for the construction of urban air environment. In this research study, data from meteorological factors (temperature, humidity, wind speed, and rainfall) and air pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, O_3, and NO_2) were collected in 2018 from the areas of Zhongshan, Shilin, and Yangmingshan of Taipei City. The Granger causality test was used to analyze the intrinsic dynamic relationship between meteorological factors and Air Quality Index (AQI). The results showed that: (1) the overall level of AQI in Taipei was good, and the main pollutant that contributed to AQI was $PM_{2.5}$. (2) The range of AQI values in the three study areas were Zhongshan (downtown) > Shilin (suburbs) > Yangmingshan (outskirts). (3) In downtown Zhongshan, temperature and humidity were the Granger cause of AQI; in the suburbs of Shilin, humidity, and wind speed were the Granger cause of AQI; in the outskirts of Yangmingshan, humidity was the Granger cause of AQI. (4) The air pollution of Taipei was found to be mainly a process of self-accumulation and self-diffusion. The self-accumulation effect of AQI was more than 70%. Once the diffusion condition of air pollution deteriorated, it formed air pollution. (5) Wind speed was the main meteorological factor affecting AQI in downtown Zhongshan and the suburbs of Shilin, while the AQI in the outskirts of Yangmingshan was mainly affected by humidity. In the construction of urban air environment, the emission of air pollutants should be controlled and reduced, the construction of urban ventilation system should be strengthened, and the layout of urban space should be rationally planned to create a better urban air environment.

Keywords Air pollution · Granger causality test · Meteorology · Urban planning

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1 Introduction

Air quality indicates the quality of the atmospheric environment. With the development of urbanization, air quality has declined day by day, which has led to increasingly serious air pollution problems. As we all know, air pollution has become a worldwide issue, which has been recognized for causing wide-ranging effects on human health (Newby et al. 2015). Researches had shown that air pollution has become a leading risk factor for global disease burden (Brauer et al. 2016). Long-term exposure to air pollution could lead to acute and chronic effects on human health, leading to respiratory infections (Brauer et al. 2002; Dominici et al. 2006), bronchitis (Chiang et al. 2016; Ghosh et al. 2016), cardiovascular disease (Brook et al. 2010), and even lung cancer (Pope et al. 2002; Raaschou-Nielsen et al. 2013). Outdoor air pollution had led to 3.3 million premature deaths worldwide in 2010, especially in Asia (Lelieveld et al. 2015). From 2010 to 2015, all-age mortality increased over 10% because of air pollution in Asia (Lelieveld et al. 2018). $PM_{2.5}$ had become the fifth-ranking mortality risk factor, causing 4.2 million deaths and 103.1 million disabilities in 2015 (Cohen et al. 2017). Air pollution not only affects people's own health, but even affects the health of the next generation (Baccarelli 2009; Ward-Caviness 2019). Ishikawa et al. (2006) found that air pollution-induced genotoxic effects could cause genetic damage. From these studies, we can find that with the rapid development of social economy, the problem of air pollution has become more and more dangerous to our daily lives (Fu et al. 2018). The ability to control and reduce air pollution and effectively prevent the aggravation of air pollution has become a major issue worldwide.

There are many factors that affect air quality, for instance, socioeconomic activity (Ji et al. 2018; Jiang et al. 2018), land use (Wang et al. 2018; Zhu et al. 2019), meteorological (Gu et al. 2018; Wang et al. 2019) and so on. Meteorological conditions have been recognized as one of the key factors affecting air quality, which has great impact on the diffusion, transportation, and dilution of air pollutants (Zhang 2019). Meteorology displayed some influence for one or more of the air pollutants, which meant meteorology is an important driver for air quality (Pearce et al. 2011), such as temperature and humidity were found to have great impact on air pollutants (Ramsey et al. 2014). Squizzato and Masiol (2015) investigated the relationships between air pollutant sources and wind circulation patterns and found that air pollutant sources were strongly affected by local meteorological circulation. The relationship between meteorological conditions and air pollutants in developing countries has always attracted the attention of experts. In east Asia, (Tao et al. 2018) found that land use change can modulate regional meteorological conditions, which consequently will influence air quality. Hien et al. (2002) also found that the $PM_{2.5}$ and $PM_{2.5-10}$ concentrations could affect by the meteorological conditions in Hanoi, Vietnam. All these studies have well compensated for the research gap between air pollutants and meteorological and have important guiding significance for preventing air pollution in cities. However, there have been few studies on the relationship between meteorological factors and air pollutants along different urbanization gradients.

The intrinsic connection between meteorological factors and air pollutants is complex. In this study, we choose the Granger causality test to analyze the relationship between meteorological factors and Air Quality Index (AQI). The Granger causality test can test the causality between meteorological factors and air quality. It is also considered to be one of the main methods for analyzing causality in different disciplines and has been widely used in economics (Cowan et al. 2014; Shahbaz et al. 2013), management (Lev et al. 2009; Tang and Tan 2015), and environmental sciences (Jalil and Mahmud 2009; Meng and Han

2018). In addition, we further analyzed the dynamic relationships between meteorological factors and AQI by impulse response and variance decomposition. This method can clearly show the specific effects of different meteorological factors on AQI. As a world-recognized first-tier city, Taipei City has a high level of urbanization and clear urban structure (GaWC 2018). The analysis of the dynamic relationship between meteorological factors and AQI in different urbanization gradients in Taipei can provide reference for the study of air environment in other cities. Through this study, we aim to better explain the interaction between meteorological conditions and air pollution, as well as the impact of the level of urbanization on urban air pollution. In addition, this research can provide guidance for cities in different stages of urbanization in order to improve air conditions in urban environments. In this way, the main objectives of this study are as follows: (1) understand the effects of meteorological factors on air pollutants along different urbanization gradients and (2) determine which meteorological factors have the greatest impact on air pollutants in different urbanization gradients.

2 Materials and methods

2.1 Overview of Taipei City

Taipei City is located in the southeastern part of China and is characterized by its mid-subtropical climate. The geographical coordinates are 25°03′00″N, 121°31′00″E. The city has a total area of 271.8 km^2. Taipei is the capital city of Taiwan. In 2016, Taipei was ranked as the world's first-tier city by Globalization and World Cities (GaWC 2018). With a resident population of 2.68 million, it is the most densely populated city in Taiwan. In 2017, Taipei's GDP was 77.3 billion USD, and the per capita GDP was 28,114.2 USD (Group 2018). In this study, we selected three study areas: the downtown area of the Zhongshan District, the suburbs of the Shilin District, and the outskirts of the Yangmingshan area (Fig. 1).
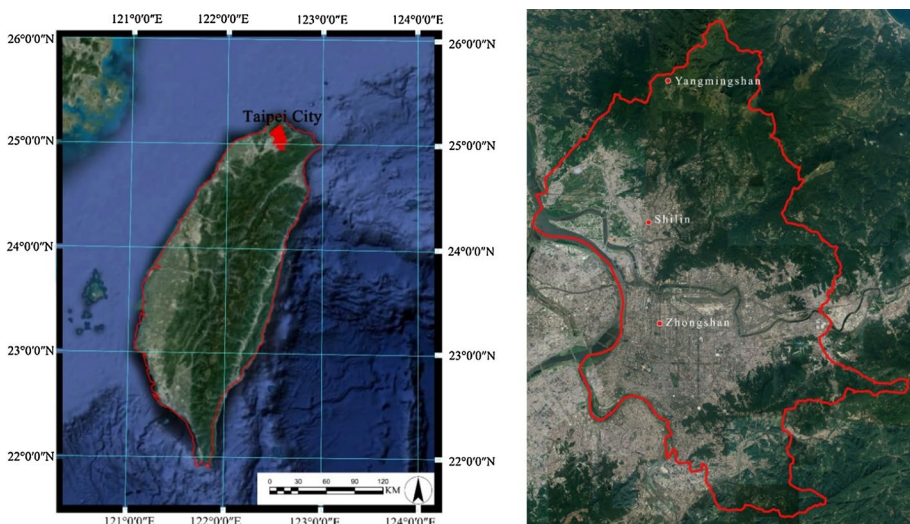
Fig. 1 Left: Location of Taipei in Taiwan; right: location of three study areas in Taipei

2.2 Data analysis

2.2.1 Data source

In this study, we collected the data of meteorological factors and air pollutants in Taipei, 2018, from the Environmental Protection Administration Executive Yuan R.O.C.T (Taiwan) (https://taqm.epa.gov.tw/taqm/tw/default.aspx). In this research, according to the relevant research of other experts, we finally selected six main air pollutant components in air environment, including $PM_{2.5}$, PM_{10}, SO_2, CO, O_3, and NO_2. And four significant meteorological factors that affect air quality, respectively, average temperature (AT), relative humidity (RH), average wind speed (WS), and rainfall (RF).

2.2.2 Research methods

1. Air Quality Index (AQI)

AQI simplifies the concentration of six air pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, O_3, and NO_2) monitored into a single conceptual index value. It grades air pollution levels and air quality conditions and is suitable for representing short-term air quality conditions and trends in cities. This research classifies the AQI of Taipei City according to US National Ambient Air Quality Standards (NAAQS) (Ohio 2018) and calculates the Taipei City AQI according to Eq. (1).

$$AQI = \frac{(I_{high} - I_{low})}{(C_{high} - C_{low})} (C - C_{low}) + I_{low} \tag{1}$$

where AQI is the Air Quality Index, I_{high} is the index breakpoint corresponding to C_{high}, I_{low} is the index breakpoint corresponding to C_{low}, C is the pollutant concentration, C_{high} is the concentration breakpoint that is $\geq C$, and C_{low} is the concentration breakpoint that is $\leq C$.

2. Statistical analysis

The VAR (Vector Auto Regression model) is a multi-equation model. It is often used to predict interconnected time series systems and to analyze the dynamic effects of random disturbances on variable systems. The calculation equation is Eq. (2) (GRANGER 1969).

Based on the results of VAR, we developed an analysis of the Granger causality test. The Granger causality test can be used to test whether all lag values of one variable affect the current values of one or more other variables. If the effect is significant, there is a Granger causality between this variable and one or more other variables; otherwise, there is no Granger causality. The operation method is shown in Eqs. (3, 4).

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + \cdots + A_p y_{t-p} + \varepsilon_t \tag{2}$$

$$y_t = \sum_{i=1}^{q} \alpha_i x_{t-i} + \sum_{j=1}^{q} \beta_j y_{t-j} + 1_t \tag{3}$$

$$x_t = \sum_{i=1}^{s} \lambda_i x_{t-i} + \sum_{j=1}^{s} \sigma_j y_{t-j} + _{2t} \tag{4}$$

Here, y_t is a k-dimensional endogenous variable, and x_t is a d-dimensional exogenous variable. $A_1 \ldots A_p$ and B are the matrix of coefficients to be estimated. ε_t is the perturbation vector, which can be correlated with each other simultaneously, but not with its own lag values and with the variable on the right of the equation.

Impulse response function describes the impact of an endogenous variable in VAR on other endogenous variables. Variance decomposition is the decomposition of changes in endogenous variables into the component impact of VAR. Therefore, variance decomposition gives information on the relative importance of each random disturbance that affects variables in VAR.

3 Results

3.1 AQI and meteorological conditions

As shown in Fig. 2, Yangmingshan had the lowest air pollutant concentration, except for O_3, in the three meteorology study stations. The air pollutant concentration generally showed that downtown (Zhongshan) > suburbs (Shilin) > outskirts (Yangmingshan). Along different urbanization gradients, the air pollutant concentration in Taipei was generally higher in spring and winter and lower in summer and autumn.

According to Eq. (1), we calculated the AQI of different urbanization gradients. We found that the $PM_{2.5}$ and PM_{10} were the main air pollutants that contributed to the AQI in Taipei. As shown in Fig. 3, the AQI value showed that $AQI_{ZS} > AQI_{SL} > AQI_{YM}$. Overall, our data showed that Taipei City had great air quality during 2018. In terms of categorizing AQI, the outskirts of Yangmingshan (AQI = 47.394) achieved a good level, while the suburbs of Shilin (AQI = 56.140) and downtown Zhongshan (AQI = 56.560) achieved the moderate level. In addition, the percentage of days with good level was 36.99% in Zhongshan, 38.90% in Shilin, and 61.37% in Yangmingshan. Figure 2 showed that the AQI in summer and autumn was significantly lower than spring and winter.

The meteorological conditions of different urbanization gradient were different from each other. As we can see from Fig. 4, the outskirts of Yangmingshan had the lowest temperature (17.384 °C), and highest relative humidity (92.743%), wind speed (2.577 m/s), and rainfall (0.525 mm). The meteorological conditions of Zhongshan and Shilin had similar variations in temperature, relative humidity, and rainfall. For the meteorological conditions of wind speed, we found that Shilin (1.825 m/s) was higher than Zhongshan (1.522 m/s). From our data, we can see a significant difference in meteorological conditions between the outskirts and downtown, while the difference between the suburbs and downtown is not significant. In addition, we can also see that the three different urbanization gradients show significant seasonal differences in meteorological conditions during 2018.
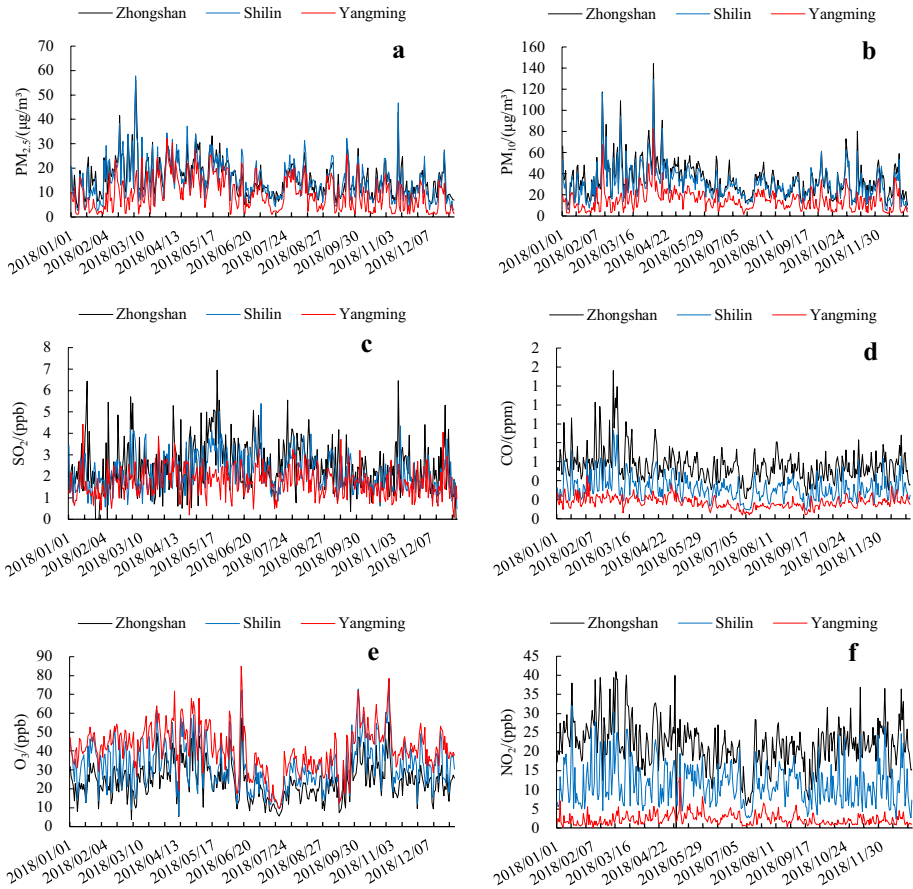
Fig. 2 Concentration of air pollutants ($PM_{2.5}$; PM_{10}; SO_2; CO; O_3; NO_2) in the three studied areas
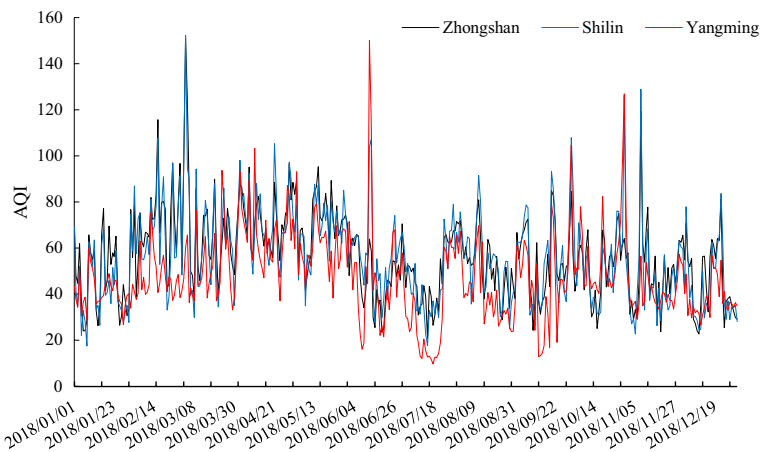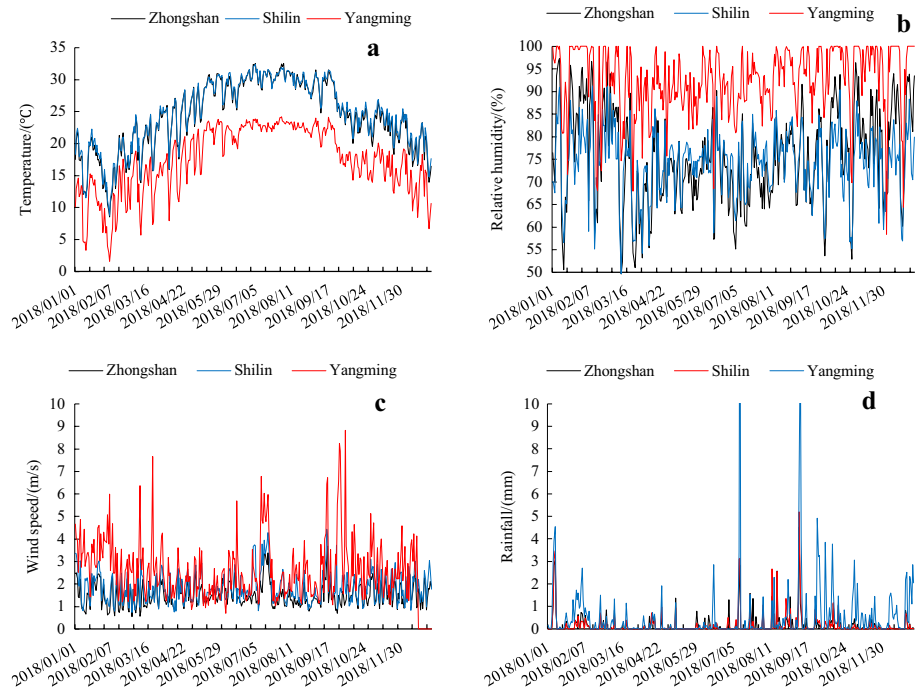

Fig. 3 AQI conditions data of three stations in Taipei

Fig. 4 Temperature, relative humidity, wind speed and precipitation data, per month, in three meteorological stations in Taipei, during the studied period

3.2 Dynamic effect between AQI and meteorological conditions

3.2.1 Granger causality test

The results of the Granger causality test showed the relationship between AQI and three meteorological conditions under different urbanization gradient. The results are listed in Table 1. At the 0.05 significance level, the null hypothesis showed that temperature (X_1) and relative humidity (X_2) do not Granger cause AQI (Y_{ZS}), and the result was rejected in Zhongshan. The null hypothesis showed that relative humidity (X_2) and wind speed (X_3) do not Granger cause AQI (Y_{SL}), with the result being rejected in Shilin. The null hypothesis showed that relative humidity (X_1) do not Granger cause AQI (Y_{YM}), and relative humidity (X_2) do not Granger cause AQI (Y_{YM}), and the result was rejected in Yangmingshan. Other null hypothesizes are all accepted in different urbanization gradient.

3.2.2 Impulse response function

The results of Figs. 5, 6 and 7 were obtained through impulse response analysis. In Zhongshan, with the increase of temperature (X_1), AQI will have a positive impact. The positive effect was greatest when temperature reached the second period, and then gradually declined. When temperature reached the eighth period, the effect became a negative one. Humidity has a negative effect on AQI in Zhongshan. In the second period, the negative

Table 1 Granger causality/block exogeneity wald tests

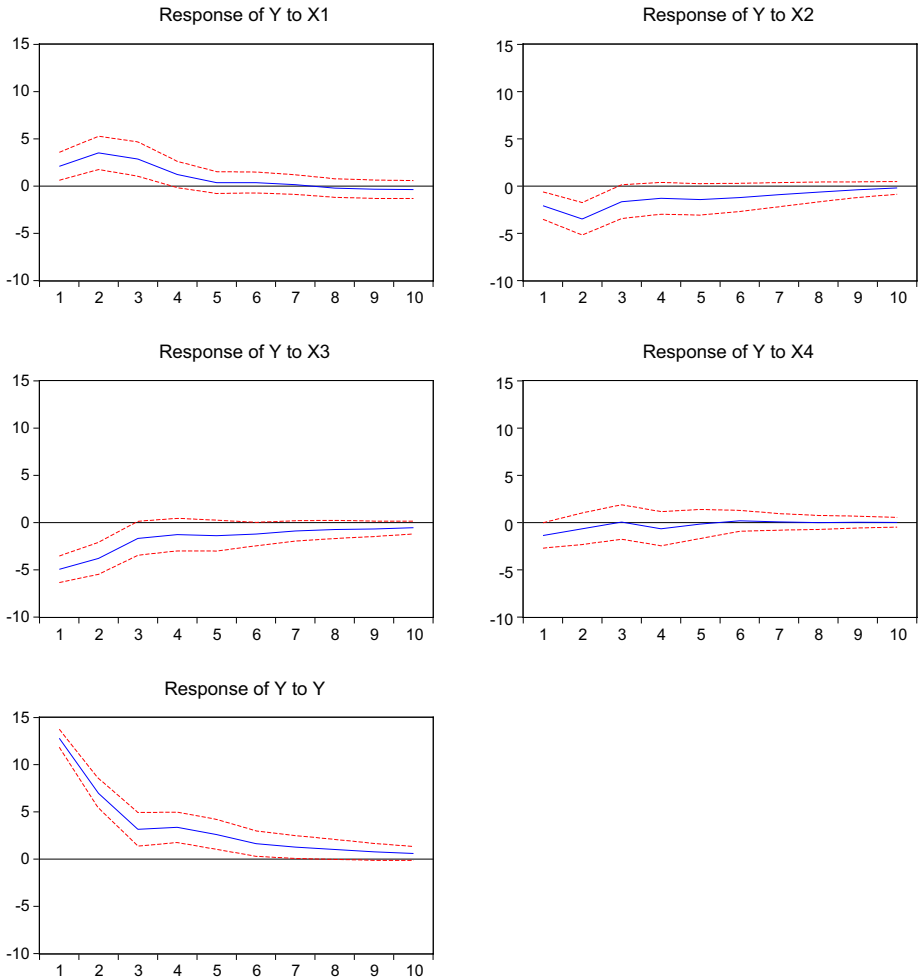|	Null hypothesis	Chi-sq	Prob.	Result
Zhongshan	Temperature (X_1) does not Granger cause AQI (Y_{ZS})	9.649	0.022	Reject
	Relative humidity (X_2) does not Granger cause AQI (Y_{ZS})	10.138	0.017	Reject
	Wind speed (X_3) does not Granger cause AQI (Y_{ZS})	1.887	0.596	Accept
	Rainfall (X_4) does not Granger cause AQI (Y_{ZS})	1.045	0.790	Accept
Shilin	Temperature (X_1) does not Granger cause AQI (Y_{SL})	3.134	0.209	Accept
	Relative humidity (X_2) does not Granger cause AQI (Y_{SL})	12.017	0.003	Reject
	Wind speed (X_3) does not Granger cause AQI (Y_{SL})	18.138	0.000	Reject
	Rainfall (X_4) does not Granger cause AQI (Y_{SL})	1.280	0.527	Accept
Yangmingshan	Temperature (X_1) does not Granger cause AQI (Y_{YM})	5.255	0.154	Accept
	Relative humidity (X_2) does not Granger cause AQI (Y_{YM})	13.498	0.004	Reject
	Wind speed (X_3) does not Granger cause AQI (Y_{YM})	4.630	0.201	Accept
	Rainfall (X_4) does not Granger cause AQI (Y_{YM})	1.316	0.725	Accept

The significance level is 5%

effect of humidity (X_2) was the most significant and then gradually decreased. Compared to the three other types of meteorological factors, wind speed (X_3) had the highest impact on AQI, with it showing a negative effect. In the first period, this effect was the strongest. After the third period, the negative effect on AQI began to be stabilize. Rainfall (X_4) had a low effect on AQI, and its performance characteristics were complex—mainly in the negative effect on AQI in the first period. AQI had the strongest effect on itself, reaching its maximum in the first period, then declining rapidly, and tending to be stable after the third period. The meteorological conditions on AQI of the suburbs of Shilin was similar to that of downtown Zhongshan, but in general, the influence of meteorological conditions on AQI was slightly lower. AQI had a higher effect on itself when compared to downtown Zhongshan. In Yangmingshan, the effect of temperature (X_1) on AQI showed a negative effect. The effect was relatively small and stable throughout the year, reaching its highest level in the third period. The effect of humidity (X_2) on AQI was similar to that of Zhongshan and Shilin, but the effect of Yangmingshan was stronger. The effect of wind speed (X_3) on AQI was complex. It showed a negative effect in the first period; then, the negative effect decreased rapidly and turned to a positive effect in the third period. Then, the effect of wind speed on AQI was almost zero. Rainfall (X_4) had a negative effect on AQI in Yangmingshan, which was relatively stable and reached its maximum in the third period. AQI had the strongest effect on itself, which was similar to Zhongshan and Shilin.

3.2.3 Variance decomposition

In this study, variance decomposition of 12 periods were performed according to the needs of the study. The results are shown in Tables 2, 3 and 4. From the results, we can see that whether it is downtown, suburbs or outskirts, the AQI level was mainly affected by itself which means the level of AQI is most affected by the emission of air pollutants. In the first period, the value of variance decomposition was 82.378% in Zhongshan, 91.322% in Shilin and 89.978% in Yangmingshan. Up until the fifth period, AQI levels were basically stable, with 71.174% in Zhongshan, 76.853% in Shilin and 78.650% in Yangmingshan. The influence of meteorological factors on AQI was the lowest in outskirts, followed by suburbs, and the

Response of Y to X1

Response of Y to X2

Response of Y to X3

Response of Y to X4

Response of Y to Y

Fig. 5 Response to Cholesky one standard deviation (Downtown: Zhongshan)

most significant was downtown Zhongshan. In addition, we also concluded that wind speed was the main meteorological factor affecting AQI in the downtown and suburbs, while in the outskirts of Yangmingshan AQI was mainly affected by humidity. In downtown Zhongshan, the influence of wind speed on AQI accounted for 13.562% in the second period and then reached a relatively stable level. In the suburbs, the influence of wind speed on AQI accounted for 15.016% in the fifth period and then reached a relatively stable level. In the outskirts, the effect of humidity on AQI accounted for 17.151% in the third period and then reached a relatively stable level.
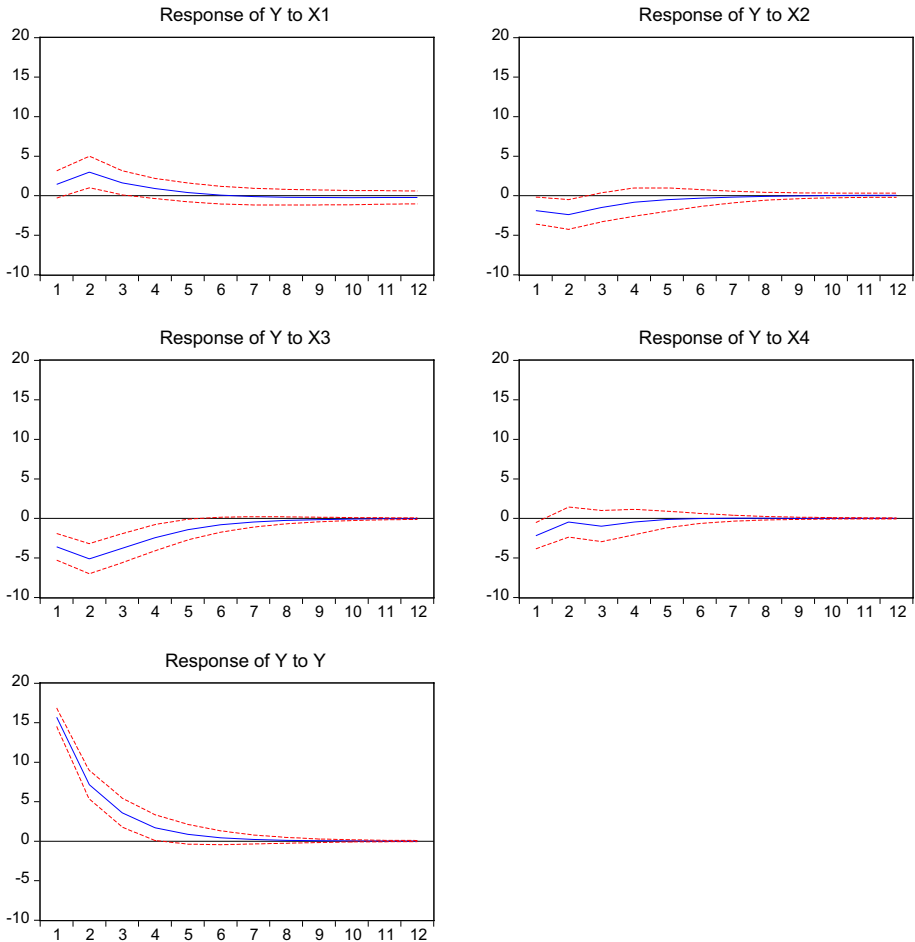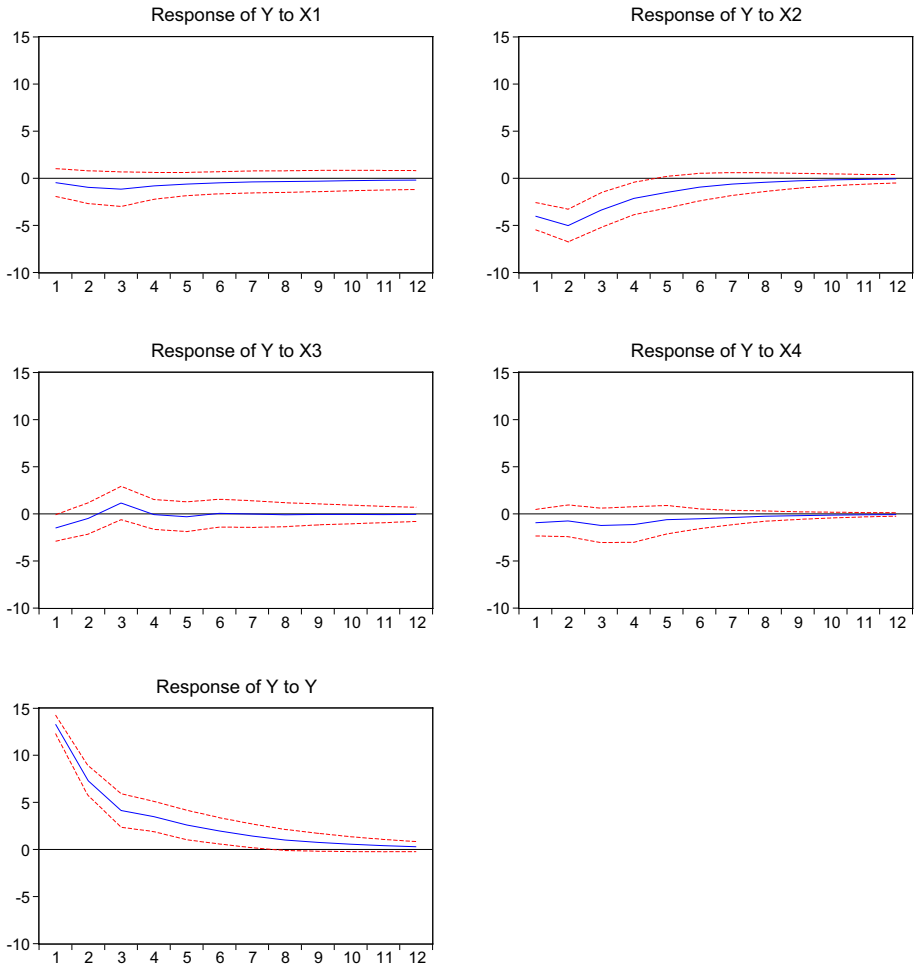
Fig. 6 Response to Cholesky one standard deviation (Suburbs: Shilin)

4 Discussion

4.1 Dynamic variation of AQI

The air quality in the outskirts was better than that of the suburbs and downtown, and there were with no significant difference between the suburbs and downtown. This result was consistent with the study of Fang et al. (2015), which found that urbanization level had shown a negative role in air quality because of population, urbanization rate, and secondary industry in urban areas. With advancements in the process of urbanization, the urbanization of suburbs and downtown are getting closer and closer, which had also became the main reason for the smaller difference of AQI between the two (Yu and Ng 2007). AQI had shown a significant seasonal variation characteristic during 2018, with the maximum in the winter and the minimum in the summer, which may be related to meteorological conditions in Taipei. This result was consistent with the Zhang et al. (2015)'s research, where his results confirmed meteorological conditions in air pollution play a crucial part with

Fig. 7 Response to Cholesky one standard deviation (Outskirts: Yangmingshan)

differ variations in different seasons. In addition, another important reason was that there are many traditional Chinese festivals in the spring, especially the Chinese Spring Festival. Huang et al. (2012)'s research on air quality during Chinese Spring Festival confirmed this theory. Fireworks and firecrackers were set off due to the influence of traditional activities, and air pollution emission sources vary and fluctuate greatly before, during and after the festival, which results in the increase of air pollution (Tsai et al. 2012; Wang et al. 2007; Yao et al. 2019).

4.2 Granger causality to AQI along different urbanization gradients

From the results of the Granger causality test, we found that AQI was affected by different meteorological factors under different urbanization gradients. Humidity was the only common Granger causality meteorological factor among the different urbanization gradients.

Table 2 Variance decomposition of meteorological variables (Downtown: Zhongshan)

Period	SE	X_1	X_2	X_3	X_4	Y_{ZS}
1	1.718	2.184	2.173	12.315	0.950	82.378
2	2.439	5.794	5.734	13.562	0.814	74.096
3	2.754	7.969	6.188	13.438	0.753	71.652
4	3.024	8.017	6.395	13.263	0.846	71.478
5	3.296	7.796	6.789	13.413	0.827	71.174
6	3.530	7.702	7.105	13.626	0.822	70.745
7	3.729	7.635	7.281	13.726	0.816	70.543
8	3.908	7.604	7.355	13.801	0.811	70.428
9	4.067	7.609	7.372	13.879	0.808	70.331
10	4.208	7.631	7.366	13.933	0.806	70.264
11	4.334	7.673	7.354	13.961	0.806	70.206
12	4.447	7.731	7.344	13.975	0.806	70.144

Cholesky ordering: X_1 = temperature; X_2 = relative humidity; X_3 = wind speed; X_4 = rainfall; Y_{ZS} = AQI (Zhongshan)

Table 3 Variance decomposition of meteorological variables (Suburbs: Shilin)

Period	SE	X_1	X_2	X_3	X_4	Y_{SL}
1	1.762	0.755	1.327	4.816	1.780	91.322
2	2.455	3.032	2.563	10.814	1.387	82.205
3	2.919	3.445	2.908	13.516	1.518	78.613
4	3.268	3.557	3.000	14.637	1.533	77.274
5	3.548	3.569	3.036	15.016	1.526	76.853
6	3.780	3.562	3.053	15.138	1.522	76.724
7	3.976	3.563	3.059	15.178	1.521	76.680
8	4.144	3.572	3.059	15.189	1.521	76.659
9	4.289	3.584	3.059	15.192	1.521	76.645
10	4.416	3.598	3.059	15.191	1.520	76.632
11	4.527	3.610	3.059	15.190	1.520	76.621
12	4.625	3.622	3.059	15.188	1.520	76.611

Cholesky ordering: X_1 = temperature; X_2 = relative humidity; X_3 = wind speed; X_4 = rainfall; Y_{SL} = AQI (Shilin)

This phenomenon was mainly related to the meteorological condition characteristics of humidity. This was consistent with Zhang et al. (2019) and Hien et al. (2002)'s research, where they mentioned that the relative humidity showed large control of the variations of $PM_{2.5}$, and higher humidity can effectively absorb and precipitate particulate matter, thereby effectively reducing air pollution. In downtown, there was no Granger causality between wind speed and AQI. The main reason may be related to the urban density and configurations of Taipei city. As a study by Ramponi et al. (2015) described that wind speed was strongly affected by the urban morphology. Yuan and Ng (2012) also mentioned planners can efficiently improve the urban ventilation by improving building porosity, which validated our hypothesis. Poor ventilation makes the dilution of $PM_{2.5}$ by wind speed difficult to achieve in downtown. The ventilation construction of downtown needs to be improved. The ventilation in suburbs was better than downtown because of the lower

Table 4 Variance decomposition of meteorological variables (Outskirts: Yangmingshan)

Period	SE	X_1	X_2	X_3	X_4	Y_{YM}
1	14.016	0.110	8.290	1.162	0.460	89.978
2	16.634	0.417	15.022	0.913	0.530	83.118
3	17.591	0.815	17.151	1.240	0.969	79.826
4	18.117	0.972	17.581	1.171	1.311	78.966
5	18.388	1.060	17.735	1.167	1.389	78.650
6	18.531	1.114	17.725	1.150	1.450	78.562
7	18.605	1.151	17.698	1.141	1.484	78.526
8	18.643	1.184	17.680	1.139	1.496	78.500
9	18.664	1.208	17.663	1.138	1.504	78.486
10	18.675	1.225	17.650	1.138	1.509	78.477
11	18.682	1.239	17.642	1.140	1.511	78.468
12	18.686	1.250	17.637	1.141	1.513	78.461

Cholesky ordering: X_1 = temperature; X_2 = relative humidity; X_3 = wind speed; X_4 = rainfall; Y_{YM} = AQI (Yangmingshan)

urban density, which can effectively guarantee the dilution and diffusion of wind speed of $PM_{2.5}$ in this area. Therefore, there is Granger causality between wind speed and AQI. In the outskirts, the relative humidity was the only meteorological condition that displayed Granger causality with AQI. There was abundant vegetation cover in Yangmingshan area. Deshmukh et al. (2019) emphasized the importance of planting denser vegetation and maintaining the integrity and structure of vegetation barriers to reduce pollution. Denser vegetation also weakens the dilution of pollutants by wind speed. However, the dense vegetation made the humidity in this area higher, and the particulate matter further precipitated, which improved the air quality in this area.

4.3 Meteorological conditions effect to AQI along different urbanization gradients

Under different urbanization gradients, the influence of meteorological factors on AQI also have similarities and differences. AQI in all regions showed the strongest effect on themselves. After reaching the maximum value in the first period, AQI decreased rapidly and tended to stabilize after the third period. The main reason was that Taipei's air pollutants are a self-aggregation process. If the diffusion conditions are poor, serious air pollution will occur in the third period. The impulse response effect of downtown and suburbs meteorological factors on AQI was similar, mainly due to the difference of meteorological conditions characteristics between them being small. Besides, the urban structure of the two were also similar, which lead to similar impulse response function of meteorological conditions. The impulse response function effect of the outskirts of Yangmingshan was quite different from that in the downtown and suburbs. Through our study, we can roughly judge that the main reason was that the urbanization level of the outskirts of Yangmingshan was lower than Zhongshan and Shilin, which had great ecological environment and higher humidity. As mentioned in the topic 4.2, AQI was well controlled by the effect of ecological environment and humidity, which led to the lower influence of temperature, wind speed, and rainfall on AQI.

In downtown Zhongshan, because of the high level of urbanization, its air self-purification ability was lower than suburbs and outskirts, which had a greater impact on

meteorological factors and other environmental factors. As Fang et al. (2015) and Xia et al. (2014) revealed, higher urbanization will lead to higher AQI. Zhongshan had showed a dependence on temperature, humidity, and wind speed to purify air. In the suburbs, as we mentioned in the topic 4.2, the lower urban density had effectively guaranteed the dilution and diffusion of wind speed to $PM_{2.5}$. In the outskirts, humidity was the main meteorological factor, and this was mainly related to three reasons: (1) related to the environment, where the denser vegetation had weakened the ability of wind speed to transmit and dilute air pollutants; (2) denser vegetation can adequately absorb more air pollutants; and (3) higher humidity can fully precipitate PMs, which can effectively reduce AQI. This is consistent with the results of Douglas et al. (2019), where his research demonstrated that forests can reduce the air pollution on a city-wide scale.

4.4 Urban air environment construction proposal

Our results showed that air pollutants in Taipei are mainly self-aggregation and self-diffusion processes, while meteorological factors can dilute and transport air pollutants. This meant that in order to create a better urban air environment, we must: First, pay attention to reducing the emission of air pollutants and reducing the sources of air pollutants—for example, to control the emission of industrial gases, there needs to be establishment of a green transportation system (Cheng et al. 2007; Topcu et al. 2003); second, suitable greening tree species must be planted in city as far as possible. As we mentioned in the topics 4.1 and 4.2, vegetation can not only absorb air pollutants to improve air quality, but also directly or indirectly improve air quality by adjusting regional meteorological conditions. The role of urban vegetation in reducing air pollution has been supported by many experts (Bottalico et al. 2016; Janhäll 2015); and third, compared with the downtown and suburbs, wind speed had a more significant effect on reducing AQI in the suburbs. The urban ventilation with lower density in the suburbs will be better than that in downtown with higher density (Yuan and Ng 2012). Therefore, in the construction of emerging cities in the future, it is necessary to rationally plan the spatial layout of the city to form a good urban ventilation system which will improve air quality.

5 Conclusion

Air pollution is an environmental problem that has plagued human beings for a long time. Air pollution has not only become an obstacle to social development, but also seriously endangers human health. The relationship between AQI and meteorological factors under different urban gradients was comprehensively analyzed. From our results, suggestions for air environment construction under different urban gradients in Taipei were put forward, which can help provide references for cities at different stages of development. However, there are still many factors that affect the urban air environment, such as the level of science and technology, the economic structure of urban industry, and topography. In further research, we should comprehensively analyze the impact of these factors on urban air quality and conduct in-depth discussions to better serve the construction of urban sustainable development and make the city's ecological environment better. Especially, research on air pollution in developing countries in Asia needs more attention. Since most developing countries are still dominated by heavy industry development, they have caused serious damage to the ecological environment and air environment. This not only affects the

ecological security of its own country, but also has serious consequences for global climate change. In short, no matter which stage of urbanization a city or country is, to solve the problem of air environment, we must start by reducing the emission of air pollutants from the source. And we need to provide a good meteorological conditions environment for the dilution and degradation of air pollutants through reasonable urban planning and make the ecological environment of cities become better and better.

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