Characterization of the Air Quality Index in Southwestern Taiwan

Yen-Yi Lee¹, Yen-Kung Hsieh^{2*}, Guo-Ping Chang-Chien^{3,4*}, Weiwei Wang^{5*}

¹ Center for General Education, Cheng Shiu University, Kaohsiung 83347, Taiwan

² Ocean Affairs Council, Kaohsiung 80661, Taiwan

³ Super Micro Mass Research and Technology Center, Cheng Shiu University, Kaohsiung 83347, Taiwan

⁴ Department of Cosmetics and Fashion Styling, Cheng Shiu University, Kaohsiung 83347, Taiwan

⁵ School of Resources and Environmental Engineering, Hefei University of Technology, Hefei 246011, China

ABSTRACT

This study provides an investigation of atmospheric PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃ in the period from 2015–2017 in the southwestern and central part of Taiwan. In addition, the seasonal distribution of six AQI classes and corresponding primary pollutants were further analyzed. The daily AQIs were 15–194 in 2015, 17–213 in 2016, and 16–184 in 2017, respectively. During the three year period, in the studied area, the mean proportions of levels with Grade I, II, III, IV, V, and VI were 3%–31%, 30%–57%, 17%–46%, 0%–12%, 0%–1% and 0% in spring; were 38%–76%, 21%–57%, 0%–10%, 0%–2%, 0% and 0% in summer; were 2%–45%, 34%–77%, 13%–36%, 0%–18%, 0% and 0% in fall, and were 0%–12%, 38%–67%, 24%–41%, 1%–22%, 0% and 0% in winter. Generally, it was found that summer has the best air quality and that winter has the worst, where spring and fall are similar in terms of air quality. PM_{2.5} was the typical primary air pollutant when the AQI classes were 51–200, followed by O₃ in summer, spring and fall, and PM₁₀ in winter. As for class 201–300, the primary air pollutant was O₃ and the 300–500 class did not occur.

Keywords: AQI; PM_{2.5}; PM₁₀; SO₂; NO₂; CO; O₃.

INTRODUCTION

In recent years, air pollution has become a particularly serious issue in many cities in the world (Ran *et al.*, 2011; Li *et al.*, 2012; Tang *et al.*, 2012; Li *et al.*, 2014). Previous investigation demonstrated the close relationship between air pollutants and human health (Pope and Dochery, 2006; Cao *et al.*, 2012; Heal *et al.*, 2012; Pope and Dochery, 2013; Jin *et al.*, 2017). Air pollutants in the atmospheric environment, including ozone (O₃) and particle matter (PM), have had serious impacts on human health (Liu *et al.*, 2002), such as premature death (Schwartz *et al.*, 1996), respiratory-related hospital admissions and emergency room visits (Thurston *et al.*, 1992), acute respiratory symptoms with aggravated coughing and difficult or painful breathing, chronic bronchitis, aggravated asthma (Anderson *et al.*, 1992), lung function experienced as shortness of breath, and so on. It is important to inform the public about the current air quality and to take corresponding health protection measures.

Initially, a local Environment Pollution Administration (EPA) established the Pollutant Standards Index (PSI) system to estimate air quality in Taiwan. Base on the US EPA, this PSI system contains sub-indices for ozone (O₃), coarse particulate matter (PM₁₀), carbon monoxide (CO), sulfur dioxide (SO₂), and nitrogen dioxide (NO₂). These sub-PSI indices were associated with ambient pollutant concentrations scaled from 0 to 500, where an index value of 100 can be defined as normal, and an index value of 500 is associated with significant harm to human health (Liu *et al.*, 2002). A daily major pollutant is defining as a pollutant with the largest daily sub-index value. The PSI system was based on general increases in O₃ concentrations and decreases in PM₁₀ levels in a steadily increasing PSI system. It was replaced with the Air Quality Index (AQI), which can lead to a better understanding of the effects of O₃ and fine particulate matter (PM_{2.5}) on the general air quality.

In Taiwan, the air quality in several areas has worsened along with growth in population density and the rapid increases in the use of coal-fired power plants and motor vehicles. Since 1955, the control of air pollution began to gain attention, and Taipei began to implement controls on the burning of coal (Lee *et al.* 2018). Previous studies have demonstrated that the pollutant standards index (PSI) in Taiwan is often between 50 and 100, and some places even reach more than 100 (unhealthy air quality) (Bureau of Air

* Corresponding authors.

E-mail address: yk886963@gmail.com (Y.K. Hsieh);
guoping@csu.edu.tw (G.P. Chang-Chien);
1326642149@qq.com (W. Wang)

Quality Protection and Noise Control, 1991; Fang and Chen, 1996). These factors, including geographic conditions, emission sources, and meteorological factors are all important contributors to the air quality problem in Taiwan (Zhang *et al.*, 2009; Liu *et al.*, 2012; Liu and Wang, 2014; Zhang and Cao, 2015; Li *et al.*, 2017a; Shen *et al.*, 2017).

The object of this study was to examine air quality in the southwestern and central part of Taiwan through a discussion of the characteristics of atmospheric $PM_{2.5}$, PM_{10} , SO_2 , NO_2 , CO , and O_3 , after which the calculated Air Quality Index (AQI) was used as an important basis for judging the air quality. In addition, the seasonal variations in AQI are further discussed, as well as the corresponding primary pollutants. This research is intended to provide valuable information and better understanding of the air pollution characteristics in seven specific areas of Taiwan.

METHODS

The air quality of seven cities or townships in Taiwan, Puzih, Singang, and Chiayi in Chiayi City, and Douliou, Taisi, Lunbei, and Mailiao in Yunlin County, were analyzed in this study. From January 2015 to December 2017 in these districts, meteorological data, including $PM_{2.5}$, PM_{10} , SO_2 , NO_x , CO , and O_3 levels, were collected from local air quality stations.

Chiayi City is located in the southwestern part of Taiwan, which is crossed by the Tropic of Cancer and has a subtropical humid climate, with an annual average temperature of 22.0°C and an annual rainfall capacity of 1,500 mm. Yunlin County is a central area, located in the center of Taiwan. It has a south subtropical humid climate, where the annual average temperature is about 22.6°C, and the precipitation is approximately 1,697 mm.

Air Quality Index (AQI)

The sub-AQI of the six criteria pollutants was first calculated with the observation concentrations, as shown in Eq. (1) (She *et al.*, 2017; Shen *et al.*, 2017). The overall AQI represents the maximum of the sub-AQI of all pollutants, where when the AQI is higher than 50, the highest sub-AQI contributor is defined as the primary pollutant on that day, as shown in Eq. (2) (She *et al.*, 2017; Shen *et al.*, 2017):

$$IAQI_P = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C_P - C_{low}) + I_{low} \quad (1)$$

$$AQI = \max(I_1, I_2, \dots, I_n) \quad (2)$$

$IAQI_P$: the air quality sub index for air pollutant P .

C_P : the concentration of pollutant P .

C_{low} : the concentration breakpoint that is $\leq C_P$.

C_{high} : the concentration breakpoint that is $\geq C_P$.

I_{low} : the index breakpoint corresponding to C_{low} .

I_{high} : the index breakpoint corresponding to C_{high} .

The six criteria air pollutants have acute effects on human health. The daily AQIs were calculated using the

24-hour average concentrations of SO_2 , NO_2 , $PM_{2.5}$, PM_{10} , CO , and the daily average 8-hour maximum concentration of O_3 . Based on the United States Environmental Protection Agency (U.S. EPA) AQI, the ranges of the AQI values related to air quality can be classified into six classes: Grade I: 0–50 (Good, Green); Grade II: 51–100 (Moderate, Yellow); Grade III: 101–150 (Unhealthy for Sensitive Groups; Orange); Grade IV: 151–200 (Unhealthy; Red); Grade V: 201–300 (Very unhealthy; Purple), and Grade VI: 300–500 (Hazardous; Maroon) (Hu *et al.*, 2015; Lanzafame *et al.*, 2015; She *et al.*, 2017; Zhao *et al.*, 2018).

RESULTS AND DISCUSSION

$PM_{2.5}$ Concentration

$PM_{2.5}$ is suspended in the atmosphere for long periods and transports over long distances, which has a detrimental effect on both human health and air quality. During the period from 2015–2017, the atmospheric monthly $PM_{2.5}$ concentrations in Puzih City, Singang Township, and Chiayi County are presented in Figs. 1(a)-1, 1(b)-1, 1(c)-1, and those in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township are presented in Figs. 1(a)-2, 1(b)-2, 1(c)-2, respectively.

Among the seven cities and townships under consideration, the highest annual mean $PM_{2.5}$ concentration occurred in Lunbei Township ($31.1 \mu\text{g m}^{-3}$), which was in the range of $15.8\text{--}47.1 \mu\text{g m}^{-3}$, and the lowest level was found in Puzih City ($24.0 \mu\text{g m}^{-3}$), with a range of $10.0\text{--}39.1 \mu\text{g m}^{-3}$ in 2015. In 2016, the highest annual concentration of $PM_{2.5}$ occurred in Lunbei Township ($29.3 \mu\text{g m}^{-3}$), with a range of $15.5\text{--}41.8 \mu\text{g m}^{-3}$, and the lowest level was found in Taisi Township ($24.7 \mu\text{g m}^{-3}$) and was $11.1\text{--}35.9 \mu\text{g m}^{-3}$. In 2017, the highest annual average $PM_{2.5}$ concentration was found in Mailiao Township ($27.9 \mu\text{g m}^{-3}$), which ranged from $14.8\text{--}39.9 \mu\text{g m}^{-3}$, and the lowest values occurred in Puzih City ($21.9 \mu\text{g m}^{-3}$), with a range of $10.0\text{--}32.0 \mu\text{g m}^{-3}$. Overall, the three-year mean $PM_{2.5}$ concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 24.1 , 24.9 , 27.2 , 27.5 , 25.0 , 29.2 and $25.7 \mu\text{g m}^{-3}$, respectively. It was found that the highest levels occurred in Lunbei Township and the lowest in Puzih City. These investigated districts were all above the WHO air quality regulated standard ($10 \mu\text{g m}^{-3}$). Furthermore, with the exception of Douliou City, they exhibited annual declines in $PM_{2.5}$ concentration (29.1 , 26.7 and $26.6 \mu\text{g m}^{-3}$ in 2015, 2016, and 2017, respectively). The fluctuations did not have obvious downward trends in the other six cities and townships. $PM_{2.5}$ is the primary air pollutant in these districts; thus more efforts to reduce the $PM_{2.5}$ concentration would be meaningful.

As for seasonal variations, during 2015, the mean concentrations of $PM_{2.5}$ ranged between 23.0 (Puzih City) and $29.4 \mu\text{g m}^{-3}$ (Lunbei Township) in spring, were between 8.8 (Mailiao Township) and $17.5 \mu\text{g m}^{-3}$ (Lunbei Township) in summer, ranged from 25.2 (Mailiao Township) to $35.9 \mu\text{g m}^{-3}$ (Lunbei Township) in fall, and were between 33.7 (Taisi Township) and $42.0 \mu\text{g m}^{-3}$ (Douliou City) in

Fig. 1(a)-1. Monthly average atmospheric PM_{2.5} concentrations in Puzih City, Singang Township, and Chiayi County in 2015.

Fig. 1(a)-2. Monthly average atmospheric PM_{2.5} concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2015.

Fig. 1(b)-1. Monthly average atmospheric PM_{2.5} concentrations in Puzih City, Singang Township, and Chiayi County in 2016.

Fig. 1(b)-2. Monthly average atmospheric PM_{2.5} concentrations in Douliou City, Taisi Township, Lunbei Township and Mailiao Township in 2016.

Fig. 1(c)-1. Monthly average atmospheric PM_{2.5} concentrations in Puzih City, Singang Township, and Chiayi County in 2017.

Fig. 1(c)-2. Monthly average atmospheric PM_{2.5} concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2017.

winter. In 2016, the mean concentrations of PM_{2.5} ranged between 30.1 (Taisi Township) and 34.6 $\mu\text{g m}^{-3}$ (Lunbei Township) in spring, were between 14.1 (Chiayi County)

and 19.3 $\mu\text{g m}^{-3}$ (Lunbei Township) in summer, ranged from 24.3 (Mailiao Township) to 29.7 $\mu\text{g m}^{-3}$ (Lunbei Township) in fall, and were between 29.0 (Taisi Township)

and $37.3 \mu\text{g m}^{-3}$ (Chiayi County) in winter. In 2017, the mean concentrations of $\text{PM}_{2.5}$ ranged between $26.5 \mu\text{g m}^{-3}$ (Puzih City) and $34.5 \mu\text{g m}^{-3}$ (Mailiao Township) in spring, were between $12.4 \mu\text{g m}^{-3}$ (Puzih City) and $17.4 \mu\text{g m}^{-3}$ (Mailiao Township) in summer, ranged from $20.6 \mu\text{g m}^{-3}$ (Puzih City) to $26.8 \mu\text{g m}^{-3}$ (Mailiao Township) in fall, and were between $28.1 \mu\text{g m}^{-3}$ (Puzih City) and $38.1 \mu\text{g m}^{-3}$ (Chiayi County) in winter. The above study indicated that the $\text{PM}_{2.5}$ concentrations in the seven counties and townships generally occurred in the following order: winter > spring > fall > summer. This result is similar to that obtained locally by Lee (2018), who studied atmospheric $\text{PM}_{2.5}$ concentrations in 22 cities and counties in Taiwan and pointed out that the mean $\text{PM}_{2.5}$ concentrations were 23.2, 12.1, 19.1, and $25.0 \mu\text{g m}^{-3}$ in spring, summer, fall and winter, respectively. This may have been caused by the various air temperatures in different seasons, where temperature inversions easily occur under low ground temperature conditions, which will impede the dispersion of air pollutants and lead to elevations in atmospheric $\text{PM}_{2.5}$ in cold seasons (Tang *et al.*, 2017; Xing *et al.*, 2017; Lee *et al.*, 2018; Wang *et al.*, 2018a).

The primary sources of fuel combustion, including industrial facilities, vehicle emissions, and power plants can release fine particles, and secondary atmospheric gaseous emissions, such as VOCs, NO_x , and SO_2 , also transform $\text{PM}_{2.5}$ (Mao *et al.*, 1997; Yang *et al.*, 1997; Liu *et al.*, 2002). This universal source of $\text{PM}_{2.5}$ determines its crucial effect on regional air quality. Therefore, it is of great significance to reduce the level of $\text{PM}_{2.5}$ by reducing the number of automobiles and promoting clean energy in order to improve overall air quality.

PM_{10} Concentration

PM_{10} comprises inhalable particles. These coarse particles are usually derived from motor vehicles running on unpaved asphalt and cement roads, the crushing and grinding of materials, as well as dust from the wind. PM_{10} can be inhaled by humans and is deposited in the upper respiratory tract and pulmonary alveoli and causes related diseases (Song *et al.*, 2008; Tao *et al.*, 2009; Matus *et al.*, 2012; Sun *et al.*, 2014; Liang *et al.*, 2016). PM_{10} can affect residents' health and the air quality of a region (Liu *et al.*, 2002). For the period from 2015–2017, the monthly average PM_{10} concentrations in the ambient air in Puzih City, Singang Township, and Chiayi County are presented in Tables 1(a)-1, 1(b)-1, and 1(c)-1, and those in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township are presented in Tables 1(a)-2, 1(b)-2, 1(c)-2, respectively.

It can be seen in Tables 1(a)-1 and 1(a)-2 that Mailiao Township ($72 \mu\text{g m}^{-3}$) has the maximum levels of PM_{10} , ranging from $36\text{--}149 \mu\text{g m}^{-3}$, while Taisi Township ($47 \mu\text{g m}^{-3}$) has the minimum values, ranging from $20\text{--}94 \mu\text{g m}^{-3}$ in 2015. Table 1(b)-1 and 1(b)-2 shows that the highest PM_{10} concentration occurred in Mailiao Township ($66 \mu\text{g m}^{-3}$) and ranged from $31\text{--}125 \mu\text{g m}^{-3}$, while the lowest PM_{10} concentration occurred in Taisi Township ($45 \mu\text{g m}^{-3}$) and ranged from $19\text{--}85 \mu\text{g m}^{-3}$ in 2016. For 2017, Tables 1(b)-1 and 1(b)-2 demonstrate that the highest annual average PM_{10} concentration was found in Mailiao

Township ($71 \mu\text{g m}^{-3}$), which ranged from $36\text{--}144 \mu\text{g m}^{-3}$, and that the lowest values occurred in Taisi Township ($49 \mu\text{g m}^{-3}$), with a range of $24\text{--}104 \mu\text{g m}^{-3}$. Among the seven observation areas, due to the establishment of some factories and an industrial zone in Mailiao Township, it has gradually become a major industrial township in Taiwan and has been accompanied with the highest PM_{10} levels. Taisi Township is located in the western part of Taiwan, which is close to the sea, where the strong winds and rain from the sea favor the dispersion and deposition of PM_{10} , thus it has the lowest PM_{10} levels. The average PM_{10} concentrations for the three years under observation were 65, 58, 57, 52, 47, 54, and $70 \mu\text{g m}^{-3}$ in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township, respectively. Although the observed PM_{10} levels in western Taiwan were lower than those in Wuhu ($82 \mu\text{g m}^{-3}$) and Bengbu ($95 \mu\text{g m}^{-3}$), two central cities in China, they were still approximately 2.35–3.50 times higher than the WHO standard ($20 \mu\text{g m}^{-3}$). A previous study indicated that PM_{10} is an important major atmospheric air pollutant that has a large regional impact on AQI (Liu *et al.*, 2002). Thus, further control of PM_{10} is of great significance to improve the air quality in western Taiwan.

An examination of the seasonal PM_{10} concentration characteristics indicated that the values were between 44 (Taisi Township) and $70 \mu\text{g m}^{-3}$ (Mailiao Township) in spring, were between 29 (Taisi Township) and $46 \mu\text{g m}^{-3}$ (Mailiao Township) in summer, ranged from 52 (Taisi Township) to $78 \mu\text{g m}^{-3}$ (Mailiao Township) in fall, and were between 65 (Taisi Township) and $96 \mu\text{g m}^{-3}$ (Mailiao Township) in winter, respectively, in 2015. These values ranged between 51 (Taisi Township) and $66 \mu\text{g m}^{-3}$ (Mailiao Township) in spring, were between 31 (Taisi Township) and $47 \mu\text{g m}^{-3}$ (Mailiao Township) in summer, ranged from 45 (Taisi Township) to $70 \mu\text{g m}^{-3}$ (Mailiao Township) in fall, and were between 54 (Taisi Township) and $80 \mu\text{g m}^{-3}$ (Mailiao Township) in winter, respectively, in 2016. These values ranged between 53 (Taisi Township) and $72 \mu\text{g m}^{-3}$ (Mailiao Township) in spring, were between 29 (Taisi Township) and $41 \mu\text{g m}^{-3}$ (Mailiao Township) in summer, ranged from 52 (Douliou City) to $77 \mu\text{g m}^{-3}$ (Mailiao Township) in fall, and were between 59 (Taisi Township) and $93 \mu\text{g m}^{-3}$ (Mailiao Township) in winter, respectively, in 2017. PM_{10} levels exhibit notable seasonal distinctions. The average values in summer with the lowest levels ($36 \mu\text{g m}^{-3}$) were 52.0% in magnitude lower than those in winter, when the highest levels ($75 \mu\text{g m}^{-3}$) were observed. Spring had similar levels to those in the fall, and both were in the middle levels ($60 \mu\text{g m}^{-3}$ in spring and $61 \mu\text{g m}^{-3}$ in fall, respectively). In Taiwan, the airflow with low temperature and moisture from the north in winter favors enhancement of the level of PM_{10} . This result was consistent with the seasonal distribution of PM_{10} found in Wuhu and Bengbu (Shang *et al.*, 2018; Wang *et al.*, 2018b). Taiwan is surrounded by the sea and has abundant rainfall, which is very beneficial to the removal of PM_{10} from the atmosphere by wet deposition; thus its overall PM_{10} levels were lower than those for Wuhu and Bengbu.

Table 1(a)-1. Monthly average atmospheric PM₁₀ concentrations in Puzih City, Singang Township, and Chiayi County in 2015.

Month	Puzih City			Singang Township			Chiayi County		
	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)
Jan.	29–147	100	27	29–147	93	29	30–147	91	25
Feb.	50–176	91	36	51–164	85	35	45–136	91	30
Mar.	41–115	79	25	43–112	73	28	45–118	75	27
Apr.	40–103	66	28	29–89	58	31	28–101	57	32
May	21–107	49	40	9–77	39	51	12–77	39	44
June	29–54	42	13	20–61	33	27	21–41	30	16
July	21–75	43	28	14–61	35	34	18–67	33	35
Aug.	20–122	43	51	8–77	33	53	13–84	35	47
Sep.	39–88	61	24	22–73	47	35	18–72	46	37
Oct.	31–114	73	22	21–96	62	26	25–103	65	27
Nov.	54–139	85	23	46–117	81	23	46–115	75	22
Dec.	24–167	78	32	25–142	72	29	29–139	79	28
Annual	33–117	68	29	26–101	59	34	28–100	60	31

Table 1(a)-2. Monthly average atmospheric PM₁₀ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2015.

Month	Douliou City			Taisi Township			Lunbei Township			Mailiao Township		
	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)
Jan.	23–133	80	28.4	28–143	71	40.6	23–119	79	30.9	40–202	105	32.6
Feb.	39–139	81	32.6	31–163	67	48.6	36–176	77	46.1	52–224	97	45.8
Mar.	42–118	70	28.6	28–85	54	34.1	33–104	64	30.8	40–160	85	30.8
Apr.	32–88	55	28.9	22–73	44	35.4	25–80	54	32.5	40–134	72	29.9
May	14–78	40	44.2	8–64	34	45.3	8–72	37	45.5	23–90	54	32.4
June	21–53	32	22.6	16–43	26	23.8	17–49	27	25.3	33–55	41	13.5
July	19–66	35	39.9	16–49	33	28.7	15–69	37	40.1	26–99	50	30.0
Aug.	13–62	27	43.1	9–59	26	54.0	9–63	27	50.0	12–217	45	83.9
Sep.	21–67	45	31.6	18–63	41	29.1	20–104	48	37.9	30–122	66	33.0
Oct.	26–94	60	28.4	20–90	56	28.7	22–88	58	25.5	42–127	81	22.5
Nov.	35–131	76	28.7	25–139	59	36.1	42–227	74	44.7	62–190	86	27.5
Dec.	27–117	65	30.4	17–158	56	51.0	23–181	65	44.5	32–169	86	36.6
Annual	26–95	56	32.3	20–94	47	38.0	23–111	54	37.8	36–149	72	34.9

Table 1(b)-1. Monthly average atmospheric PM₁₀ concentrations in Puzih City, Singang Township, and Chiayi County in 2016

Month	Puzih City			Singang Township			Chiayi County		
	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)
Jan.	35–109	63	31	32–101	58	34	28–102	61	32
Feb.	34–179	81	41	25–151	70	45	26–143	72	39
Mar.	32–135	78	32	20–140	74	36	25–113	71	33
Apr.	34–169	68	42	35–157	69	42	29–137	61	49
May	35–103	52	33	28–99	49	35	25–89	45	37
June	28–55	40	16	15–57	35	29	17–39	29	19
July	22–61	38	25	13–56	32	34	15–49	31	27
Aug.	27–81	48	32	20–75	40	36	18–67	40	31
Sep.	14–78	45	42	12–68	37	45	20–74	41	46
Oct.	25–139	63	39	24–121	58	38	18–94	55	33
Nov.	26–141	74	38	24–146	72	44	17–111	66	38
Dec.	40–168	83	29	29–95	73	22	37–113	79	21
Annual	29–118	61	33	23–106	56	37	23–94	54	34

Table 1(b)-2. Monthly average atmospheric PM₁₀ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2016.

Month	Douliou City			Taisi Township			Lunbei Township			Mailiao Township		
	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)
Jan.	21–87	48	34.9	23–76	46	34.2	24–85	49	35.7	35–115	65	31.4
Feb.	18–119	57	44.5	24–114	54	45.0	19–143	64	46.3	36–191	76	44.5
Mar.	21–105	62	35.6	19–106	58	35.9	19–122	63	36.8	27–138	75	33.7
Apr.	30–127	58	46.3	28–113	52	38.4	33–160	59	46.0	40–145	68	34.3
May	25–78	42	33.4	21–83	43	35.1	21–82	42	36.1	32–90	55	28.8
June	17–44	30	20.5	10–44	29	26.0	15–47	31	24.2	22–61	42	18.9
July	14–52	31	29.3	14–52	30	30.9	13–60	32	33.8	25–81	44	29.0
Aug.	19–68	38	32.3	17–62	35	34.8	19–65	37	35.8	32–105	54	31.2
Sep.	13–64	37	46.0	8–57	31	44.9	11–62	38	44.9	12–91	53	39.6
Oct.	22–94	53	34.1	17–92	47	40.7	22–128	57	44.0	34–128	74	30.6
Nov.	18–101	60	39.6	19–105	57	41.6	17–124	63	42.9	34–143	82	36.1
Dec.	27–93	65	22.9	34–114	61	34.0	31–238	71	50.9	48–217	99	39.6
Annual	20–86	48	35.0	19–85	45	36.8	20–110	50	39.8	31–125	66	33.1

Table 1(c)-1. Monthly average atmospheric PM₁₀ concentrations in Puzih City, Singang Township, and Chiayi County in 2017.

Month	Puzih City			Singang Township			Chiayi County		
	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)
Jan.	50–115	82	22	40–109	74	25	43–108	75	23
Feb.	37–138	87	28	31–126	77	31	39–109	75	25
Mar.	50–140	83	24	46–115	78	24	46–107	76	19
Apr.	33–106	65	29	28–111	59	35	29–107	56	31
May	33–110	58	30	24–104	54	32	26–82	50	31
June	24–53	37	20	19–61	33	31	17–41	29	23
July	27–56	40	21	20–56	37	24	19–54	35	27
Aug.	26–74	38	29	16–74	31	38	22–76	35	32
Sep.	29–99	54	35	22–80	46	38	25–78	46	31
Oct.	17–189	81	47	19–110	60	33	16–104	60	33
Nov.	45–170	86	37	37–121	72	33	42–108	68	27
Dec.	38–186	93	36	40–126	76	31	40–116	72	28
Annual	34–120	67	30	28–99	58	31	30–91	56	28

Table 1(c)-2. Monthly average atmospheric PM₁₀ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2017.

Month	Douliou City			Taisi Township			Lunbei Township			Mailiao Township		
	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)	Range ($\mu\text{g m}^{-3}$)	Mean ($\mu\text{g m}^{-3}$)	R.S.D (%)
Jan.	30–98	61	27.3	35–80	52	26.2	30–96	61	26.3	61–192	96	32.7
Feb.	28–109	66	31.5	24–122	60	34.3	20–104	65	31.0	36–185	97	36.6
Mar.	38–96	67	22.6	32–104	60	32.8	39–107	67	26.7	47–194	87	32.0
Apr.	26–114	54	34.1	25–90	53	34.4	23–89	56	32.5	37–110	68	28.3
May	25–84	50	28.8	19–121	47	42.9	19–98	47	36.5	31–117	61	31.1
June	14–47	28	27.4	11–45	24	33.1	19–59	30	34.2	22–55	34	23.2
July	22–60	33	28.8	21–44	33	20.7	19–59	35	27.3	28–67	43	23.8
Aug.	20–59	34	27.9	17–63	31	38.2	19–60	32	34.1	27–140	45	46.4
Sep.	26–74	45	30.3	20–111	45	43.5	21–127	49	45.1	33–109	59	34.0
Oct.	15–78	53	28.4	26–154	65	49.4	16–239	82	73.6	28–208	85	42.9
Nov.	36–112	58	33.9	26–167	52	54.4	35–211	77	52.2	45–190	86	41.4
Dec.	30–108	63	34.8	27–142	65	43.7	31–184	88	48.0	40–165	85	33.6
Annual	26–87	51	29.6	24–104	49	37.8	24–119	57	39.0	36–144	71	33.8

Coarse particles (PM_{10}) are mainly due to natural and anthropogenic processes, including dust storms, local soil re-suspension, road dust, and various industrial processes (Querol *et al.*, 2004; Xu *et al.*, 2017). The $PM_{2.5}/PM_{10}$ ratio is a useful index by which to determine the most likely atmospheric processes leading to accumulation due to the diverse sources of $PM_{2.5}$ and PM_{10} . It can thus be used to reflect the status of air quality (Speranza *et al.*, 2014; Blanco-becerra *et al.*, 2015; Xu *et al.*, 2017; Wang *et al.*, 2018b). Previous studies have found that the $PM_{2.5}/PM_{10}$ ratio varies from seasons to season, where the dry season is lower than the wet season, which is mainly due to the contribution of dust re-suspension (Akinlade *et al.*, 2014; Speranza *et al.*, 2014; Wang *et al.*, 2018a). Some studies have also reported that due to the effect of re-suspended coarse road dust, there is negative correlation between the number of vehicles and the $PM_{2.5}/PM_{10}$ ratio (Querol *et al.*, 2001; Evagelopoulou *et al.*, 2006).

SO₂ Concentration

Anthropogenic activities (including the burning of biomass, fossil fuel combustion, and metal smelting) and natural processes (including volcanic eruption, soil oxidation, and hydrogen sulfide oxidation) generate and emit sulfur dioxide (SO_2) into the atmosphere (Kettle and Andreae, 2000; Dong *et al.*, 2002; Halmer *et al.*, 2002; Vijay *et al.*, 2004; Dentener *et al.*, 2006; Lee *et al.*, 2008; Lin *et al.*, 2010; Khattak *et al.*, 2013). Thus, atmospheric SO_2 irritates the respiratory tract and injures the cardiovascular system of living things (Lovati *et al.*, 1996). SO_2 in the atmosphere is absorbed by water aerosol droplets, such as clouds, fog, and rains, where acid rain forms in this process and increases the risk of harm to ecological systems (Ferrari and Salisbury, 1999; Chen *et al.*, 2001; Goncalves *et al.*, 2002; Chen *et al.*, 2011). SO_2 is a noticeable air pollutant that will damage human health and the environment (Aneja *et al.*, 2001; Chen *et al.*, 2011). Figs. 2(a)-1, 2(b)-1, 2(c)-1 show the monthly average SO_2 concentration from 2015–2017 in Puzih City, Singang Township, and Chiayi County, respectively, and Figs. 2(a)-2, 2(b)-2, 2(c)-2 show the monthly average SO_2 concentration in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township, respectively.

The highest annual average SO_2 concentration among the seven cities and townships occurred in Taisi Township (9.89 ppb), ranging from 4.44–14.4 ppb, and the lowest level occurred in Douliou City (5.54 ppb), ranging from 4.19–6.58 ppb in 2015. In 2016, the maximum annual SO_2 value was found in Taisi Township (8.49 ppb), ranging from 4.60–12.2 ppb, and the lowest value was found in Douliou City (5.25 ppb), ranging from 4.00–5.92 ppb. In 2017, the maximum annual SO_2 level was found in Taisi Township (7.28 ppb), ranging from 4.30–10.0 ppb, and the lowest value was found in Douliou City (4.94 ppb), ranging from 3.98–5.96 ppb. During the period 2015–2017, the highest concentration of SO_2 always was in Taisi Township, and the lowest values were always in Douliou City. The three-year mean SO_2 concentrations in Puzih City, Singang Township, Chiayi County, Douliou City,

Taisi Township, Lunbei Township and Mailiao Township were 5.51, 5.66, 6.20, 5.24, 8.55, 5.85, and 6.69 ppb, respectively. With the exception of Taisi Township, the levels of SO_2 in other six observed regions were slightly lower than the WHO standard of 7.00 ppb. This result was similar to that found for Wuhu City (6.54 ppb) and Bengbu City (7.88 ppb) (Wang *et al.*, 2018b). Some studies have indicated that volcanic eruptions are the major contributors to the natural sources of SO_2 in the atmosphere (Andres and Kasdnoc *et al.*, 1998; Halmer *et al.*, 2002; Kato *et al.*, 2016). Although there are several volcanoes in Taiwan, including Datunshan volcano, Keelung volcano, and Penghu volcano, these are all extinct volcanoes and will not increase atmospheric SO_2 concentration in the region.

The seasonal variations in atmospheric SO_2 are discussed as follows: In 2015, the average SO_2 concentrations were 4.71 ppb (Puzih City)–8.16 ppb (Taisi Township), 4.23 ppb (Lunbei Township)–6.69 ppb (Taisi Township), 5.79 ppb (Singang Township)–13.07 ppb (Taisi Township), 6.44 ppb (Douliou City)–11.7 ppb (Taisi Township) in spring, summer, fall, and winter, respectively. In 2016, these values were 5.52 ppb (Douliou City)–10.2 ppb (Taisi Township), 4.05 ppb (Lunbei Township)–5.26 ppb (Singang Township), 5.48 ppb (Puzih City)–9.06 ppb (Taisi Township), 5.18 ppb (Douliou City)–8.73 ppb (Taisi Township) in spring, summer, fall, and winter, respectively. In 2017, these values were 5.46 ppb (Douliou City)–8.29 ppb (Taisi Township), 3.91 ppb (Lunbei Township)–6.18 ppb (Taisi Township), 5.13 ppb (Douliou City)–8.01 ppb (Taisi Township), 4.75 ppb (Douliou City)–7.79 ppb (Chiayi County) in spring, summer, fall and winter, respectively. This indicated that summer had the minimum SO_2 values, followed by spring, fall and winter, when similar levels were observed. Generally, the average SO_2 concentration of these seven areas in summer (4.86 ppb) was 26.1% lower than that in other seasons (6.40, 6.58, and 6.75 ppb in spring, fall and winter, respectively). This may be attributed to the fact that Taiwan has a monsoon climate with strong rainfall intensity in summer, so some of the SO_2 was scavenged from the ambient air through wet deposition (Chen *et al.*, 2011). This result was compared with those found for Wuhu and Bengbu, where the SO_2 concentrations in winter were slightly higher than in the other seasons, and where without the requirement of fuel combustion for heating and less effect of polluted airflow from north China in the winter in Taiwan lead to this distinction.

NO₂ Concentration

Anthropogenic activities of industrial facilities and traffic emissions are the main sources of atmospheric nitrogen dioxide (Cheng *et al.*, 2018). NO_2 participates in a complex photochemical reaction, where as the corresponding oxidation products are incorporated into ambient aerosols, they have adverse effects on visibility (Anttila *et al.*, 2011; He *et al.*, 2014). NO_2 is also the crucial precursor of ozone and acid rain, which can acidize ecosystems and impact the human respiratory system (Bowman *et al.*, 1994; Plaisance *et al.*, 2002; Cox *et al.*, 2003; An *et al.*, 2006; Khokhar *et al.*, 2016). Based on air quality guidelines established by WHO,

Fig. 2(a)-1. Monthly average atmospheric SO₂ concentrations in Puzih City, Singang Township, and Chiayi County in 2015.

Fig. 2(a)-2. Monthly average atmospheric SO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2015.

Fig. 2(b)-1. Monthly average atmospheric SO₂ concentrations in Puzih City, Singang Township, and Chiayi County in 2016.

Fig. 2(b)-2. Monthly average atmospheric SO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2016.

Fig. 2(c)-1. Monthly average atmospheric SO₂ concentrations in Puzih City, Singang Township, and Chiayi County in 2017.

Fig. 2(c)-2. Monthly average atmospheric SO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2017.

when evaluating the air quality index of a region, NO₂ is classified as a monitored air pollutant (He *et al.*, 2014). From 2015 to 2017, the monthly average NO₂ concentrations in Puzih City, Singang Township, and Chiayi County are

plotted in Figs. 3(a)-1, 3(b)-1, 3(c)-1, respectively, and the monthly average NO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township are plotted in Figs. 3(a)-2, 3(b)-2, 3(c)-2, respectively.

Fig. 3(a)-1. Monthly average atmospheric NO₂ concentrations in Puzih City, Singang Township, and Chiayi County in 2015.

Fig. 3(a)-2. Monthly average atmospheric NO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2015.

Fig. 3(b)-1. Monthly average atmospheric NO₂ concentrations in Puzih City, Singang Township, and Chiayi County in 2016.

Fig. 3(b)-2. Monthly average atmospheric NO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2016.

Fig. 3(c)-1. Monthly average atmospheric NO₂ concentrations in Puzih City, Singang Township, and Chiayi County in 2017.

Fig. 3(c)-2. Monthly average atmospheric NO₂ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2017.

Comparing the annual mean NO₂ concentration in the seven observed areas during the period 2015–2017, Douliou was the city with the highest levels of NO₂, which were

24.3, 24.7, and 22.6 ppb in 2015, 2016, and 2017, for which the corresponding ranges were 14.6–34.3 ppb, 14.5–35.5 ppb, and 13.2–30.1 ppb, respectively. The lowest levels were

found in Singang Township (18.9 ppb), Lunbei Township (18.1 ppb), and Puzih City (16.8 ppb) in 2015, 2016, and 2017, for which the corresponding ranges were 13.2–23.6 ppb, 12.3–24.8 ppb, and 13.2–20.8 ppb, respectively. In general, with the exception of Chiayi County and Douliou City, where the NO₂ concentration rose slightly in 2016 (the annual mean values of Chiayi County were 22.9, 23.3 and 22.4 ppb in 2015, 2016, and 2017, respectively, those of Douliou City were 24.3, 24.7 and 22.6 ppb in 2015, 2016, and 2017, respectively), the other five showed a clear annual tendency to decline, decreasing by 0.524%–4.23% from 2015 to 2016, and by 3.85%–11.6% from 2016 to 2017.

As a whole, during these recent three years (2015–2017), the average NO₂ concentration in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 18.0, 18.4, 22.9, 23.9, 18.3, 18.2 and 18.2 ppb, respectively. It can be seen that the NO₂ levels in Chiayi County and Douliou City were slightly higher than the WHO standard of 19.6 ppb and that the others were slightly lower than the WHO standard. The overall levels in the surveyed regions were comparable to those of Wuhu (21.4 ppb) and Bengbu (18.0 ppb) (Wang *et al.*, 2018b). Fu *et al.* (2000) and Cheng *et al.* (2018) pointed out that due to recent economic development and rapid urbanization, motor vehicles have become the major emission source of NO₂. The human population of Chiayi County (274,051) and Douliou City (108,231) is far above that of Puzih City (44,234), Singang Township (35,347), Taisi Township (25,116), Lunbei Township (28,003), and Mailiao Township (34,014), where it can be inferred that the former urbanization rate was higher than that occurring later. Thus, a larger number of vehicles are emitting NO₂ into the ambient air, which results in the higher NO₂ concentration in Chiayi County and Douliou City.

In 2015, the seasonal NO₂ concentrations were 18.4 ppb (Taisi Township)–24.9 ppb (Douliou City), 12.3 ppb (Lunbei Township)–15.2 ppb (Douliou City), 18.2 ppb (Singang Township)–25.0 ppb (Douliou City), 22.2 ppb (Taisi Township)–32.2 ppb (Douliou City) in spring, summer, fall, and winter, respectively. In 2016, these values were 19.0 ppb (Mailiao Township)–28.0 ppb (Douliou City), 12.7 ppb (Chiayi County)–15.7 ppb (Singang Township), 17.0 ppb (Lunbei Township)–24.3 ppb (Douliou City), 20.3 ppb (Taisi Township)–32.0 ppb (Chiayi County) in spring, summer, fall, and winter, respectively. In 2017, these values were 17.9 ppb (Puzih City)–24.7 ppb (Douliou City), 12.6 ppb (Lunbei Township)–14.0 ppb (Douliou City), 15.8 ppb (Puzih City)–24.2 ppb (Douliou City), 17.8 ppb (Taisi Township)–28.2 ppb (Chiayi County) in spring, summer, fall, and winter, respectively. As for the spatial distribution, Douliou City usually had with the maximum NO₂ levels, which may be tightly related to vehicle emissions. In terms of the temporal distribution, the minimum NO₂ concentration always occurred in summer, and the maximum values occurred in winter, with three-year average values in summer (13.7 ppb) that were 43.2% lower than those in winter (24.1 ppb), while the NO₂ levels for spring and fall were between those of summer and

winter, and that of spring (21.1 ppb) was slightly higher than fall (19.9 ppb). This seasonal distribution is attributed to distinct meteorological conditions in different seasons, where there is a hot summer and a cold winter. The high ground temperature in summer and the severe winter are conducive to the transport of NO₂, and the abundant rainfall favors the deposition of NO₂ (Wang *et al.*, 2018b). Thus, the NO₂ levels are lowest in summer and highest in winter.

The above results indicate that atmospheric NO₂ concentrations are determined by both emissions and meteorological conditions. Therefore, when implementing control of industrial and vehicle emissions, it is necessary to pay attention to restricting NO₂ concentrations during seasons without favorable weather conditions (Cheng *et al.*, 2018).

CO Concentration

During the combustion process, carbon monoxide (CO) is emitted along with NO_x and volatile organic compounds (VOCs) and into the ambient air. CO can exist longer than one month and remain at high concentrations after being transported for a long distance (Kato *et al.*, 2016). Therefore, CO is an important indicator of air pollution to understand the air quality of a region. During the period 2015–2017, the monthly average CO concentrations in Puzih City, Singang Township, and Chiayi County are given in Tables 2(a)-1, 2(b)-1, 2(c)-1, respectively, and the monthly average CO concentrations in Douliou City, Taisi Township, Lunbei Township and Mailiao Township are given in Tables 2(a)-2, 2(b)-2, 2(c)-2, respectively.

From 2015–2017, comparing the annual mean CO concentration among the seven districts, the highest levels of CO were found in Chiayi County, which were 0.514, 0.506, and 0.478 ppm in 2015, 2016, and 2017, for which the corresponding ranges were 0.295–0.793 ppm, 0.307–0.797 ppm, and 0.293–0.899 ppm, respectively. Taisi was the Township with the lowest CO levels, which were 0.332, 0.324, and 0.296 ppm in 2015, 2016, and 2017, for which corresponding ranges were 0.151–0.611 ppm, 0.168–0.567 ppm, and 0.145–0.498 ppm, respectively. Generally, it can be inferred that the CO levels of these studied locations were significantly lower than those in Wuhu (0.532–1.21 ppm, with an average of 0.831 ppm) and Bengbu (0.465–1.16 ppm, with an average of 0.720 ppm), two middle latitude cities in China. Furthermore, a comparison the annual average CO concentration of the seven areas during the three years under observation (2015–2017) indicates that these values all decreased annually. The levels in 2015 reduced by 1.10–7.15% as compared with those observed in 2016 and went down by 5.62–10.8% from 2016 to 2017. As a whole, during the three years under observation (2015–2017), the mean CO concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 0.384, 0.413, 0.499, 0.437, 0.317, 0.377, and 0.374 ppm, respectively. The WHO air quality eight-hour average regulated standard of CO is 8.00 ppm, while the CO concentrations in these seven

Table 2(a)-1. Monthly average atmospheric CO concentrations in Puzih City, Singang Township, and Chiayi County in 2015.

Month	Puzih City			Singang Township			Chiayi County		
	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)
Jan.	0.340–0.856	0.531	24.7	0.318–0.889	0.578	25.6	0.459–0.918	0.742	14.7
Feb.	0.285–0.760	0.518	26.1	0.323–0.804	0.567	23.6	0.469–1.038	0.723	22.1
Mar.	0.330–0.775	0.501	21.4	0.293–0.815	0.536	20.6	0.319–1.015	0.660	20.5
Apr.	0.278–0.577	0.385	19.0	0.161–0.670	0.383	25.1	0.210–0.718	0.449	26.2
May	0.220–1.410	0.374	57.4	0.164–0.690	0.343	33.4	0.185–0.671	0.371	43.9
June	0.193–0.388	0.267	15.6	0.148–0.537	0.258	32.5	0.168–0.495	0.237	25.5
July	0.153–0.373	0.262	21.5	0.148–0.354	0.251	22.6	0.139–0.410	0.282	26.6
Aug.	0.166–0.580	0.323	32.5	0.100–0.544	0.291	32.0	0.146–0.753	0.335	32.7
Sep.	0.190–0.486	0.364	17.2	0.239–0.499	0.402	16.1	0.236–0.591	0.461	17.9
Oct.	0.259–0.634	0.408	25.8	0.289–0.630	0.430	21.0	0.304–0.860	0.548	22.7
Nov.	0.274–0.668	0.467	21.8	0.294–0.775	0.542	23.9	0.429–0.860	0.630	19.3
Dec.	0.225–0.830	0.491	26.0	0.230–0.918	0.557	26.9	0.483–1.193	0.735	21.4
Annual	0.243–0.695	0.408	25.7	0.225–0.677	0.428	25.3	0.295–0.793	0.514	24.4

Table 2(a)-2. Monthly average atmospheric CO concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2015.

Month	Douliou City			Taisi Township			Lunbei Township			Mailiao Township		
	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)
Jan.	0.337–0.799	0.621	18.5	0.176–0.906	0.461	38.7	0.370–0.945	0.585	24.2	0.224–0.945	0.512	32.6
Feb.	0.366–0.829	0.590	23.2	0.185–0.663	0.427	30.9	0.289–0.780	0.549	22.7	0.240–0.704	0.491	26.9
Mar.	0.404–0.884	0.559	23.0	0.157–0.733	0.389	31.2	0.238–0.880	0.546	20.3	0.280–0.675	0.457	24.7
Apr.	0.301–0.563	0.416	13.9	0.151–0.554	0.303	33.0	0.134–0.633	0.389	29.5	0.190–0.620	0.363	27.4
May	0.269–0.667	0.402	26.7	0.110–0.780	0.257	48.3	0.148–0.747	0.322	41.2	0.169–0.763	0.325	34.2
June	0.231–0.434	0.325	13.7	0.123–0.361	0.178	32.1	0.152–0.373	0.220	27.0	0.189–0.486	0.263	25.7
July	0.204–0.444	0.316	17.7	0.111–0.308	0.190	23.4	0.125–0.319	0.211	26.3	0.150–0.409	0.248	23.0
Aug.	0.108–0.668	0.350	28.1	0.055–0.326	0.187	34.3	0.080–0.344	0.219	31.9	0.170–0.500	0.280	27.1
Sep.	0.326–0.539	0.421	14.7	0.169–0.541	0.334	27.8	0.203–0.488	0.361	21.9	0.182–0.545	0.376	22.1
Oct.	0.344–0.735	0.490	20.7	0.185–0.625	0.372	28.8	0.244–0.624	0.418	26.2	0.238–0.698	0.430	25.6
Nov.	0.315–0.765	0.542	20.2	0.209–0.727	0.446	29.1	0.271–0.735	0.504	24.4	0.301–0.765	0.476	25.1
Dec.	0.362–0.909	0.601	24.6	0.183–0.805	0.441	31.5	0.240–0.904	0.522	27.3	0.245–0.867	0.474	29.6
Annual	0.297–0.686	0.469	20.4	0.151–0.611	0.332	32.4	0.208–0.648	0.404	26.9	0.215–0.665	0.391	27.0

Table 2(b)-1. Monthly average atmospheric CO concentrations in Puzih City, Singang Township, and Chiayi County in 2016.

Month	Puzih City			Singang Township			Chiayi County		
	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)
Jan.	0.319–0.831	0.501	26.8	0.351–0.736	0.529	20.6	0.412–1.010	0.733	20.2
Feb.	0.315–0.690	0.504	20.5	0.301–0.803	0.545	21.8	0.388–1.024	0.675	20.8
Mar.	0.282–0.766	0.482	24.7	0.286–0.771	0.540	22.7	0.479–1.211	0.701	22.2
Apr.	0.266–0.863	0.458	27.7	0.251–2.968	0.596	82.3	0.256–0.810	0.522	30.5
May	0.217–0.753	0.385	34.7	0.153–0.725	0.393	40.1	0.167–0.845	0.390	47.4
June	0.190–0.331	0.266	13.3	0.158–0.371	0.258	24.3	0.163–0.465	0.251	27.1
July	0.139–0.332	0.231	20.2	0.165–0.429	0.245	24.7	0.141–0.414	0.258	27.8
Aug.	0.166–0.531	0.299	25.4	0.178–0.526	0.321	24.1	0.208–0.529	0.358	22.8
Sep.	0.074–0.446	0.321	27.3	0.114–0.475	0.329	26.2	0.206–0.536	0.389	24.7
Oct.	0.220–0.620	0.349	27.8	0.220–0.634	0.387	25.5	0.346–0.793	0.503	21.2
Nov.	0.265–0.644	0.429	23.2	0.278–0.715	0.464	25.7	0.433–0.958	0.626	20.3
Dec.	0.268–0.693	0.434	26.8	0.274–0.836	0.475	26.0	0.488–0.971	0.667	18.4
Annual	0.227–0.625	0.388	24.9	0.227–0.832	0.424	30.3	0.307–0.797	0.506	25.3

Table 2(b)-2. Monthly average atmospheric CO concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2016.

Month	Douliou City			Taisi Township			Lunbei Township			Mailiao Township		
	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)
Jan.	0.358–0.881	0.608	21.4	0.270–0.714	0.428	26.4	0.312–0.819	0.500	22.6	0.320–0.743	0.472	24.8
Feb.	0.420–0.895	0.573	23.5	0.210–0.568	0.388	25.7	0.305–0.644	0.500	17.3	0.220–0.598	0.430	24.6
Mar.	0.339–0.928	0.585	22.3	0.250–0.701	0.422	26.0	0.250–0.746	0.505	24.3	0.285–0.789	0.467	24.9
Apr.	0.305–0.725	0.513	22.3	0.179–0.898	0.388	36.6	0.191–0.937	0.434	36.5	0.274–0.923	0.441	30.5
May	0.254–0.739	0.393	26.9	0.136–0.699	0.333	46.8	0.140–0.791	0.354	47.3	0.158–0.758	0.378	41.8
June	0.208–0.535	0.289	22.8	0.106–0.303	0.191	27.4	0.108–0.313	0.203	25.5	0.166–0.335	0.257	17.4
July	0.185–0.414	0.284	19.2	0.094–0.270	0.170	28.8	0.106–0.277	0.185	24.7	0.151–0.323	0.224	18.7
Aug.	0.211–0.519	0.343	21.3	0.133–0.458	0.242	32.0	0.130–0.516	0.279	32.4	0.141–0.521	0.303	27.1
Sep.	0.135–0.525	0.364	21.8	0.090–0.449	0.259	36.5	0.090–0.465	0.285	38.2	0.060–0.489	0.323	31.5
Oct.	0.265–0.689	0.407	23.0	0.182–0.506	0.321	24.1	0.188–0.639	0.362	29.0	0.228–0.626	0.379	24.3
Nov.	0.269–0.711	0.468	23.7	0.184–0.638	0.391	29.0	0.258–0.704	0.436	23.5	0.225–0.654	0.425	24.6
Dec.	0.339–0.716	0.509	19.1	0.178–0.605	0.359	33.2	0.288–0.705	0.454	26.1	0.245–0.690	0.422	26.5
Annual	0.274–0.690	0.445	22.3	0.168–0.567	0.324	31.0	0.197–0.630	0.375	29.0	0.206–0.621	0.377	26.4

Table 2(c)-1. Monthly average atmospheric CO concentrations in Puzih City, Singang Township, and Chiayi County in 2017.

Month	Puzih City			Singang Township			Chiayi County		
	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)
Jan.	0.265–0.659	0.446	23.0	0.305–0.618	0.483	22.3	0.410–0.864	0.640	16.9
Feb.	0.249–0.600	0.429	22.8	0.284–0.618	0.470	22.0	0.429–0.826	0.626	14.4
Mar.	0.296–0.684	0.462	18.8	0.324–0.918	0.529	23.4	0.476–1.098	0.630	20.1
Apr.	0.231–0.736	0.407	26.8	0.210–0.718	0.452	32.1	0.233–0.866	0.505	35.7
May	0.226–0.520	0.332	24.6	0.178–0.518	0.366	26.6	0.230–0.618	0.433	27.1
June	0.155–0.392	0.254	27.6	0.106–0.418	0.242	34.6	0.116–2.690	0.339	134.0
July	0.150–0.373	0.252	20.3	0.176–0.418	0.276	23.2	0.195–0.483	0.305	26.1
Aug.	0.137–0.425	0.247	25.0	0.159–0.318	0.250	21.9	0.136–0.442	0.261	32.2
Sep.	0.211–0.498	0.304	25.1	0.190–0.518	0.337	27.1	0.224–0.526	0.396	19.4
Oct.	0.181–0.504	0.332	20.6	0.215–0.518	0.362	23.7	0.236–0.737	0.461	22.6
Nov.	0.283–0.526	0.383	21.8	0.263–0.518	0.414	23.0	0.386–0.794	0.547	18.5
Dec.	0.277–0.678	0.426	28.8	0.284–0.718	0.470	31.4	0.445–0.843	0.587	18.9
Annual	0.222–0.550	0.356	23.8	0.224–0.609	0.388	25.9	0.293–0.899	0.478	32.2

Table 2(c)-2. Monthly average atmospheric CO concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2017.

Month	Douliou City			Taisi Township			Lunbei Township			Mailiao Township		
	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)	Range (ppm)	Mean (ppm)	R.S.D (%)
Jan.	0.328–0.727	0.496	20.3	0.163–0.601	0.345	32.3	0.281–0.694	0.465	21.9	0.222–0.645	0.400	30.4
Feb.	0.270–0.636	0.477	18.8	0.179–0.618	0.381	30.4	0.284–0.627	0.448	23.2	0.193–0.705	0.424	29.5
Mar.	0.333–0.745	0.489	16.8	0.223–0.698	0.406	25.6	0.343–0.759	0.503	19.5	0.275–0.760	0.470	25.9
Apr.	0.294–0.835	0.447	29.6	0.153–0.601	0.370	31.1	0.166–0.681	0.426	31.7	0.244–0.696	0.427	27.4
May	0.243–0.584	0.389	21.1	0.138–0.540	0.307	35.3	0.158–0.559	0.356	29.4	0.180–0.541	0.354	28.9
June	0.216–0.468	0.284	19.4	0.086–0.293	0.151	40.0	0.096–0.358	0.189	34.6	0.101–0.400	0.230	30.2
July	0.190–0.340	0.255	14.0	0.090–0.303	0.205	28.4	0.128–0.290	0.217	19.7	0.123–0.343	0.249	21.9
Aug.	0.211–0.436	0.286	20.1	0.091–0.294	0.173	31.0	0.105–0.324	0.199	26.4	0.148–0.384	0.245	25.4
Sep.	0.225–0.539	0.343	22.5	0.124–0.375	0.242	29.1	0.126–0.485	0.281	27.7	0.179–0.629	0.310	30.1
Oct.	0.244–0.628	0.391	24.2	0.157–0.530	0.311	29.0	0.186–0.517	0.328	26.0	0.196–0.518	0.375	23.2
Nov.	0.286–0.599	0.426	20.9	0.154–0.507	0.286	31.7	0.274–0.541	0.380	21.5	0.230–0.519	0.344	23.6
Dec.	0.328–0.668	0.480	22.5	0.183–0.620	0.373	29.8	0.259–0.751	0.446	24.9	0.220–0.659	0.427	25.8
Annual	0.264–0.600	0.397	20.9	0.145–0.498	0.296	31.1	0.200–0.549	0.353	25.5	0.192–0.566	0.355	26.9

investigated regions were all significantly lower than WHO standard, which demonstrated that atmospheric CO does not have a serious impact on the air quality in these areas.

As for variations in atmospheric CO concentration by season, in 2015, these values were 0.316 ppm (Taisi Township)–0.493 ppm (Chiayi County), 0.185 ppm (Taisi Township)–0.330 ppm (Douliou City), 0.384 ppm (Taisi Township)–0.546 ppm (Chiayi County), 0.443 ppm (Taisi Township)–0.733 ppm (Chiayi County) in spring, summer, fall, and winter, respectively. In 2016, the values were 0.381 ppm (Taisi Township)–0.537 ppm (Chiayi County), 0.201 ppm (Taisi Township)–0.305 ppm (Douliou City), 0.324 ppm (Taisi Township)–0.506 ppm (Chiayi County), 0.392 ppm (Taisi Township)–0.692 ppm (Chiayi County) in spring, summer, fall, and winter, respectively. In 2017, the values were 0.361 ppm (Taisi Township)–0.523 ppm (Chiayi County), 0.176 ppm (Taisi Township)–0.301 ppm (Chiayi County), 0.280 ppm (Taisi Township)–0.468 ppm (Chiayi County), 0.366 ppm (Taisi Township)–0.618 ppm (Chiayi County) in spring, summer, fall, and winter, respectively. Generally, it can be seen that the hot summer had the minimum values and the cold winter had the maximum values, while spring and fall had levels in the middle, which indicated that the CO values in spring were slightly higher than those in fall, especially in 2016 and 2017. The average CO concentrations in the seven researched areas in spring were all higher than those in fall. Wang *et al.* (2018b) reported the same result for Wuhu (0.867, 0.651, 0.770, with 1.04 ppm in spring, summer, fall, and winter, respectively) and for Bengbu (0.723, 0.513, 0.670, and 0.960 ppm in spring, summer, fall, and winter, respectively). The seasonal variation may be a result of the distinct meteorological conditions occurring in different seasons, where a higher air temperature is conducive to the long-range transport of CO in the summer (Kato *et al.* 2016), and the lower ground air temperature in the winter can lead to an accumulation of CO, which concurs with the seasonal distribution of NO₂.

O₃ Concentration

Ozone (O₃) is a secondary source of pollution that is generated through natural or anthropogenic photochemical reactions of oxides of nitrogen (NO_x), volatile organic compounds (VOCs), carbon monoxide (CO), methane (CH₄), and nonmethane hydrocarbons (NMHCs) (Seinfeld and Pandis, 1998; Tu *et al.*, 2007; Lan *et al.*, 2015; Wu *et al.*, 2015; Gong *et al.*, 2018). Atmospheric NO_x and VOCs play a dramatic role in the formation of O₃ in polluted atmospheres, especially unsaturated VOCs (Wang *et al.*, 2018b). From the Air Quality Guidelines of WHO₂₀₀₅, the simplified photochemical reactions can be summarized as follows:

Nitrogen dioxide dissociates to form nitric oxide (NO) and an atomic oxygen radical:

Atomic oxygen radical combines with molecular oxygen to form ozone:

Ozone is decomposed by reacting with nitric oxide, forming nitrogen dioxide and molecular oxygen:

The reaction of nitric oxide with atmospheric peroxides (RO₂) is the main cause of disturbances in the photochemical equilibrium, as presented in reaction (6):

Atmospheric peroxides are formed by the oxidation of VOCs as represented in the equations below, which describe the oxidation of an alkene:

The intensity of the sun and the concentration of NO_x and VOCs are all key factors that influence ambient ozone concentrations. Some studies have also indicated that the ratio of VOCs to NO_x also has an effect on the O₃ formation mechanism. These studies reported that ratios in a range of 4:1 to 10:1 are most favorable for formation of O₃. Furthermore, meteorological factors, including air temperature, humidity, and wind speed, play an important role in the process of dispersion, transport, and dilution of O₃ (Seaman, 2000; Tu *et al.*, 2007; Jin *et al.*, 2013; Cheng *et al.*, 2015).

Tropospheric O₃ is a crucial greenhouse gas and has a direct adverse impact on ecosystems and human health (Solomon *et al.*, 2000; Silva *et al.*, 2013; Lelieveld *et al.*, 2015; Kato *et al.*, 2016). With the impact of anthropogenic activities, including industrial emissions and transportation and meteorological conditions, the dramatic increase O₃ has made it a concern, and it has become an important criteria air pollutant. From 2015 to 2017, the monthly average O₃ concentration in Puzih City, Singang Township, and Chiayi County are plotted in Figs. 4(a)-1, 4(b)-1, 4(c)-1, respectively, and the monthly average O₃ concentration in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township are plotted in Figs. 4(a)-2, 4(b)-2, 4(c)-2, respectively.

In 2015, the highest annual mean O₃ level among the seven cities and townships was found in Taisi Township (50.3 ppb), and the lowest value was in Lunbei Township (42.2 ppb), which ranged from 29.4–63.3 ppb and 27.8–55.9 ppb, respectively. In 2016, the highest annual mean O₃ level among the seven cities and townships was found

Fig. 4(a)-1. Monthly average atmospheric O₃ concentrations in Puzih City, Singang Township, and Chiayi County in 2015.

Fig. 4(a)-2. Monthly average atmospheric O₃ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2015.

Fig. 4(b)-1. Monthly average atmospheric O₃ concentrations in Puzih City, Singang Township, and Chiayi County in 2016.

Fig. 4(b)-2. Monthly average atmospheric O₃ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2016.

Fig. 4(c)-1. Monthly average atmospheric O₃ concentrations in Puzih City, Singang Township, and Chiayi County in 2017.

Fig. 4(c)-2. Monthly average atmospheric O₃ concentrations in Douliou City, Taisi Township, Lunbei Township, and Mailiao Township in 2017.

in Douliou City (48.1 ppb), and the lowest value was in Lunbei Township (44.7 ppb), which ranged from 33.5–58.8 ppb and 32.2–52.5 ppb, respectively. In 2017, the highest annual mean O₃ level among the seven cities and townships was found in Douliou City (52.3 ppb), and the lowest value was in Mailiao Township (45.6 ppb), which ranged from 36.3–63.2 ppb and 28.4–57.7 ppb, respectively. A comparison of the variation in O₃ concentrations from 2015 to 2016 showed that O₃ concentrations in Puzih City and Lunbei Township increased by 1.91% and 5.60%, respectively, while in the others, concentrations declined by 3.07–7.76%. However, the values in all the observed cities rose by 0.43–7.93% in 2016 compared with those observed in 2017. This trend toward increases in O₃ levels poses a serious challenge in terms of air quality and should generate more public attention.

Generally, the recent three-year (2015–2017) average O₃ concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 47.7, 47.5, 48.0, 50.0, 48.7, 45.0 and 46.1 ppb, respectively. The average O₃ levels in Lunbei Township and Mailiao Township met the WHO standard of 46.6 ppb, but the others were all slightly higher than WHO standard and were also higher than in Wuhu City (35.9 ppb) and Bengbu City (44.7 ppb) (Wang *et al.*, 2018b). This result can be attributed to the sunshine intensity. The latitude of Taiwan is significantly lower than that of Wuhu and Bengbu, and with a higher solar altitude angle, low latitude areas have stronger UV radiation, which leads to the formation of O₃.

As for the seasonal variations in O₃, the average O₃ concentrations were 38.8 ppb (Puzih City)–51.6 ppb (Taisi Township), 32.5 ppb (Mailiao Township)–40.7 ppb (Chiayi County), 52.2 ppb (Lunbei Township)–63.3 ppb (Chiayi County), 40.3 ppb (Lunbei Township)–51.6 ppb (Taisi Township) in spring, summer, fall, and winter, respectively, in 2015. In 2016, these values were 47.3 ppb (Chiayi County)–52.2 ppb (Taisi Township), 38.3 ppb (Mailiao Township)–46.2 ppb (Douliou City), 47.3 ppb (Mailiao Township)–53.9 ppb (Douliou City), 38.9 ppb (Lunbei Township)–48.4 ppb (Taisi Township) in spring, summer, fall, and winter, respectively. In 2017, these values were 55.0 ppb (Chiayi County)–60.1 ppb (Puzih City), 33.6 ppb (Mailiao Township)–43.5 ppb (Douliou City), 47.6 ppb (Mailiao Township)–58.8 ppb (Douliou City), 44.1 ppb (Chiayi County)–50.1 ppb (Taisi Township) in spring, summer, fall, and winter, respectively. Overall, the seasonal O₃ concentration exhibited different patterns in the three years under observation. Firstly, all the observed cities achieved their maximum levels in fall and their minimum in summer, while spring and winter exhibited intermediate levels in 2015. Previous studies reported there to be a negative correlation between the atmospheric relative humidity and O₃ concentration (Kato *et al.*, 2016; Li *et al.*, 2017b; Gong *et al.*, 2018; Wang *et al.*, 2018b), where during a dry fall season, the lower relative humidity results in higher O₃ levels than those in summer and spring, and the stronger sun radiation leads to higher O₃ levels than those in winter. During the summer, the high atmospheric relative humidity

and low precursor concentrations are not favorable to the formation of O₃. Thus, the summer in these observed areas exhibited the lowest O₃ levels. Secondly, as for 2016, the maximum O₃ levels typically occurred in spring or fall, and the minimum O₃ levels typically occurred in summer or winter. This may be attributed to the fact that during spring and fall, the UV radiation strength in the monitored areas is stronger than in winter, and the concentrations of precursors (including NO_x and VOCs) are higher than in summer in monitored areas, so the strong UV radiation and increasing precursors enhance the production of O₃. Thirdly, as seen in 2017, the O₃ concentrations in both spring and fall were at high levels, and those in spring were higher than those in fall, followed by winter, with the lowest in summer. This may be analyzed from the perspective of air temperature, sunshine intensity, and precursor concentrations. The temperature and sun intensity in spring and fall were higher than those in winter, which directly increases O₃ production rates and thus leads to higher O₃ levels. While high temperatures and wind speeds in summer are favorable to the dispersion and dilution of air pollutants, a significant lack of precursors will hinder the formation of O₃. Therefore, the summer had the minimum O₃ level among the four seasons. The differences in seasonal ozone distribution over the three years under observation may have been related to the different contributions of various influencing factors at different ozone levels, including the concentration of NO_x and VOCs, air temperature, humidity, and wind speed.

AQI Analysis

The Air Quality Index (AQI) is a useful index for evaluating daily air quality and its health effects, which can be used to inform the government and the public about the current air quality and thus help them take proper health protection measures when necessary. From 2015–2017, the day fractions of the six AQI categories in different seasons for Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township are plotted in Figs. 5(a)–1 to 5(g)–3, respectively, and the corresponding cumulative number of days of primary pollutants are shown in Tables 3(a)–3(g).

In 2015, the daily AQI of Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 77 (19–194), 77 (15–188), 84 (19–190), 89 (17–176), 78 (18–187), 88 (20–173), and 80 (18–179), respectively. In 2016, these values were 80 (22–202), 77 (17–198), 82 (18–189), 85 (19–204), 76 (22–213), 85 (27–203), and 77 (23–210), respectively. In 2017, these values were 76 (17–176), 78 (18–169), 83 (16–171), 88 (18–184), 79 (26–171), 83 (25–169), and 85 (21–160), respectively. Generally, during the three-year observation period, the annual mean levels of AQI in these observed areas were Grade II, but the daily AQI values obviously fluctuated, which may be attributed to the seasonal characteristics of air pollutant emissions and meteorological conditions.

Based on the ranges of the AQI values, air quality can be classified into six classes: Grade I: 0–50; Grade II: 51–100; Grade III: 101–150; Grade IV: 151–200; Grade V: 201–300;

Fig. 5(a)-1. The fractions of the six AQI categories for Puzih City in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(a)-2. The fractions of the six AQI categories for Puzih City in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(a)-3. The fractions of the six AQI categories for Puzih City in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Fig. 5(b)-1. The fractions of the six AQI categories for Singang Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(b)-2. The fractions of the six AQI categories for Singang Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(b)-3. The fractions of the six AQI categories for Singang Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Fig. 5(c)-1. The fractions of the six AQI categories for Chiayi County in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(c)-2. The fractions of the six AQI categories for Chiayi County in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(c)-3. The fractions of the six AQI categories for Chiayi County in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Fig. 5(d)-1. The fractions of the six AQI categories for Douliou City in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(d)-2. The fractions of the six AQI categories for Douliou City in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(d)-3. The fractions of the six AQI categories for Douliou City in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Fig. 5(e)-1. The fractions of the six AQI categories for Taisi Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(e)-2. The fractions of the six AQI categories for Taisi Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(e)-3. The fractions of the six AQI categories for Taisi Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Fig. 5(f)-1. The fractions of the six AQI categories for Lunbei Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(f)-2. The fractions of the six AQI categories for Lunbei Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(f)-3. The fractions of the six AQI categories for Lunbei Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Fig. 5(g)-1. The fractions of the six AQI categories for Mailiao Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2015.

Fig. 5(g)-2. The fractions of the six AQI categories for Mailiao Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2016.

Fig. 5(g)-3. The fractions of the six AQI categories for Mailiao Township in (A) Spring, (B) Summer, (C) Fall, and (D) Winter in 2017.

Grade VI: 300–500. In terms of the seasonal proportions of different AQI classes, in the spring of 2015, the percentages of Grade I, II, III, IV, V, and VI levels ranged from 14% (Mailiao Township)–31% (Taisi Township), 37% (Taisi Township)–57% (Singang Township), 17% (Singang Township)–26% (Lunbei Township), 1% (Puzih City)–10% (Douliou City), 0% and 0%, respectively. In 2016, the Grade I, II, III, IV, V, and VI ranged from 9% (Lunbei Township)–26% (Chiayi County), 30% (Chiayi County)–50% (Mailiao Township), 29% (Lunbei Township)–35% (Chiayi County), 5% (Mailiao Township)–12% (Douliou City and Lunbei Township), 0%–1% (Puzih City, Taisi Township and Mailiao Township) and 0%, respectively. In 2017, the percentages of Grade I, II, III, IV, V, and VI ranged from 3% (Mailiao Township)–27% (Singang Township), 38% (Douliou City)–51% (Puzih City), 22% (Singang Township)–46% (Chiayi County), 5% (Chiayi County)–12% (Taisi Township), 0% and 0%, respectively. From 2015–2017, the AQI Grade I classes showed a decreasing tendency, the Grade II had relatively large fractions, and the Grade IV rose slowly, while both Grade V and VI remained constant at 0% and 1%. It can be seen that the air quality of these seven districts was evenly distributed in the Good (Grade I), Moderate (Grade II) and Unhealthy for Sensitive Groups (Grade III) categories; furthermore, the Moderate (Grade II) level comprised the highest proportion among the areas under consideration. The decline in the fraction of Grade I and the increasing fraction of Grade IV demonstrated that the air quality in these districts gradually deteriorated in

spring. However, occurrences of Unhealthy (Grade V) and Hazardous (Grade VI) conditions were extremely rare.

In general, $PM_{2.5}$ was the most frequent primary air pollutant during the three year study period, but the levels declined annually. This was followed by O_3 , where the days with this gaseous species as the primary air pollutant increased in various AQI classes. In 2016, Grade V levels, with O_3 as the primary air pollutant, was observed in all seven areas, which means that the impact of O_3 on spring pollution is increasing. Among the other four air pollutants, PM_{10} was an occasional primary pollutant, and none of the other pollutants were primary pollutants in spring in these regions.

In the summer of 2015, the percentages with Grade I, II, III, IV, V, and VI ranged from 53% (Mailiao Township)–76% (Taisi Township), 21% (Taisi Township)–41% (Lunbei Township), 0% (Puzih City)–6% (Douliou City and Lunbei Township), 0%, 0% and 0%, respectively. In 2016, the percentages with Grade I, II, III, IV, V, and VI ranged from 38% (Lunbei Township)–70% (Chiayi County), 25% (Chiayi County)–54% (Lunbei Township), 3% (Singang Township and Mailiao Township)–10% (Douliou City), 1%–2% (Singang Township, Douliou City and Lunbei Township), 0% and 0%, respectively. And in 2017, the percentages with Grade I, II, III, IV, V, and VI ranged from 41% (Mailiao Township)–74% (Puzih City), 25% (Puzih City)–57% (Mailiao Township), 0% (Chiayi County and Taisi Township)–6% (Douliou City), 0%, 0% and 0%, respectively. From 2015 to 2017, obviously, Grade I comprised the

Table 3(a). Cumulative number of days of major pollutants for Puzih City from 2015–2017.

[illegible]

Table 3(b). Cumulative number of days of major pollutants for Singang Township from 2015–2017.

[illegible]

Table 3(c). Cumulative number of days of major pollutants for Chiayi County from 2015–2017.

[illegible]

Table 3(d). Cumulative number of days of major pollutants for Douliou City from 2015–2017.

[illegible]

Table 3(e). Cumulative number of days of major pollutants for Taisi Township from 2015–2017.

[illegible]

Table 3(f). Cumulative number of days of major pollutants for Lunbei Township from 2015–2017.

[illegible]

Table 3(g). Cumulative number of days of major pollutants for Mailiao Township from 2015–2017.

Year	AQI Class	Spring				Summer				Fall				Winter			
		PM _{2.5}	PM ₁₀	SO ₂	O ₃	PM _{2.5}	PM ₁₀	SO ₂	O ₃	PM _{2.5}	PM ₁₀	SO ₂	O ₃	PM _{2.5}	PM ₁₀	SO ₂	O ₃
2015	51–100	38	4	0	6	9	9	0	3	20	21	0	11	30	16	0	0
	101–150	19	1	0	2	1	0	0	1	13	1	0	10	27	3	0	0
	151–200	4	0	0	2	0	0	0	0	2	0	0	4	12	0	0	0
	201–300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2016	51–100	40	0	0	6	16	2	0	6	35	10	0	0	50	3	0	1
	101–150	23	0	0	6	2	0	0	1	11	3	0	4	26	4	0	0
	151–200	5	0	0	0	0	0	0	1	4	0	0	0	1	0	0	0
	201–300	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	>300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2017	51–100	39	0	0	4	51	0	0	1	51	16	0	3	35	17	0	0
	101–150	27	0	0	11	1	0	0	1	12	5	0	2	25	7	0	0
	151–200	7	0	0	1	0	0	0	0	0	0	0	0	6	0	0	0
	201–300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

largest fraction among the six AQI classes but had the lowest proportion in 2016, when the fraction of Grade II increased obviously. Grade III had the highest proportion in 2016, but the total fractions were relatively low in the different AQI classes. The levels of Grade IV, V, and VI, with the exception of Grade IV, had fractions from 1%–2% in 2016, and the other classes remained constant at 0% over the study period. Therefore, the air quality exhibited a marked Good (Grade I) condition, and the lowest Good level and highest Unhealthy for Sensitive Groups levels reflected the worst air quality in 2016 during the study period in the summer among all seven districts.

The total polluted days in summer were much lower than other seasons, PM_{2.5} was the most frequent primary air pollutant at the Grade II level, while the fraction of O₃ as the primary air pollutant rise significantly compared with that in spring. The number of days of PM_{2.5} and O₃ as primary air pollutant were equivalent, and both occurred at extremely low levels as Grade III pollutants. As in spring, Grade IV pollution occurred in 2016, where the primary air pollutant was all O₃ at the monitored stations, indicating that O₃ has a greater impact on the unhealthy situation occurring during the summer. It was also found that PM₁₀ and NO₂ occasionally acted as the primary pollutants.

In the of 2015, the percentages with Grade I, II, III, IV, V, and VI ranged from 5% (Lunbei Township)–15% (Chiayi County), 39% (Douliou City)–57% (Mailiao Township), 26% (Mailiao Township)–36% (Douliou City), 7% (Mailiao Township)–18% (Douliou City), and 0% and 0%, respectively. In 2016, the percentages with Grade I, II, III, IV, V, and VI were 19% (Lunbei Township)–45% (Mailiao Township), 34% (Douliou City)–57% (Taisi Township), 13% (Taisi Township)–28% (Douliou City), 4% (Mailiao Township)–14% (Douliou City), and 0% and 0%, respectively. And in 2017, the percentages with Grade I, II, III, IV, V, and VI were 2% (Mailiao Township)–31% (Puzih City), 52% (Puzih City)–77% (Mailiao Township), 15% (Taisi Township)–34% (Chiayi County), 0% (Mailiao Township)–6% (Douliou City), and 0% and 0%, respectively.

Contrary to summer, the fraction of Grade I with the highest values and Grade III with the lowest values occurred in 2016, and Grade II had a larger fraction than other classes, and the values significantly increased in 2017. The fraction of Grade IV declined from 2015–2017, with the highest values always occurring in Douliou City, and the lowest values always occurring in Mailiao Township. Compared with the other seasons, the lowest Good level and the highest Unhealthy for Sensitive Groups level indicated that the air quality in the fall of 2016 was not the worst in these study areas. It also could be observed that the air quality remained for the most part at Moderate (Grade II) levels in the fall in the seven districts. Furthermore, among the seven areas, Unhealthy (Grade IV) condition was the most serious in Duliou City and the least serious in Mailiao Township.

PM_{2.5} was still the most important primary air pollutant in fall, followed by O₃, and the number days it was the primary pollutant was significantly higher in fall than in spring and summer. It is worth noting that the number of days in which PM₁₀ was the primary air pollutant at of Grade II and III was also significantly higher than in spring and summer. This means PM₁₀ had a more significant influence on autumn pollution.

In winter, during 2015, the percentages of Grade I, II, III, IV, V, and VI ranged from 2% (Puzih City, Douliou City and Mailiao Township)–12% (Taisi Township), 38% (Chiayi County)–52% (Puzih City), 30% (Taisi Township)–40% (Chiayi County), 11% (Taisi Township)–22% (Douliou City), 0% and 0%, respectively. In 2016, the percentages with Grade I, II, III, IV, V, and VI ranged from 3% (Lunbei Township)–11% (Singang Township), 41% (Chiayi County)–62% (Taisi Township), 24% (Puzih City)–34% (Chiayi County), 1% (Mailiao Township)–15% (Chiayi County), 0% and 0%, respectively. In 2017, the percentages with Grade I, II, III, IV, V, and VI ranged from 0% (Mailiao Township and Chiayi County)–5% (Puzih City), 44% (Chiayi County)–67% (Puzih City), 27% (a Puzih City and Taisi Township)–41% (Chiayi County), 1% (Puzih City)–15% (Chiayi County), 0% and 0%, respectively. Compared

with spring, summer, and fall, winter was accompanied with the lowest percentages of Grade I, and the lowest values occurred in 2017 during the study period. While Grade II and Grade III occupied the majority, and the former is slightly higher than the latter. The levels of Grade IV in 2015 were significantly higher than those in 2016 and 2017, but the V and VI classes remained constant at 0%. The winter in the studied districts had few with Good (Grade I) conditions, but Moderate (Grade II) and Unhealthy for Sensitive Groups (Grade III) conditions occurred frequently. In addition, Unhealthy (Grade IV) conditions in winter was the most serious in 2015.

Generally, $PM_{2.5}$ was the most important primary air pollutant, followed by PM_{10} and O_3 occasionally being the primary air pollutants in winter. This indicates that particulate matter played a decisive role in the winter AQI in these seven districts. Moreover, the most frequent primary pollutant lead to a Grade IV was $PM_{2.5}$ in all the study areas, which means $PM_{2.5}$ has a huge impact on unhealthy winter air quality.

Similar to the results of previous studies (Shen *et al.*, 2017; Wang *et al.*, 2018b), when observing the seasonal variations in air quality in these areas, summer had the best air quality, with a marked Good (Grade I) condition, and winter had the worst, with typically Moderate (Grade II) and Unhealthy for Sensitive Groups (Grade III) rankings, while the spring was similar to fall at the Moderate (Grade II) level. As for the primary air pollutants, $PM_{2.5}$ was the typical primary air pollutant in all four seasons, while the frequency of O_3 as the primary air pollutant rose annually in spring, and the fraction of O_3 as the primary air pollutant in summer was higher than that in spring. It should be noted that O_3 had a significant impact on the occurrence of pollution, which were Unhealthy (Grade V) in spring and Unhealthy for Sensitive Groups in summer (Grade IV). The number of days of both O_3 and PM_{10} as the primary pollutant in autumn was significantly higher than that in spring and summer. Finally, in winter, $PM_{2.5}$ was the most important primary air pollutant, followed by PM_{10} , and the frequency of O_3 as the primary air pollutant was extremely low.

CONCLUSION

The results of this study on air quality index in southwestern Taiwan can be summarized as follows:

1. The $PM_{2.5}$ concentrations fluctuate significantly in the study areas, where the focal three-year mean $PM_{2.5}$ concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township and Mailiao Township were 24.1, 24.9, 27.2, 27.5, 25.0, 29.2 and 25.7 $\mu g m^{-3}$, respectively. It can be seen that Lunbei Township had the $PM_{2.5}$ highest values, and Puzih City had the lowest. The seasonal characteristic of $PM_{2.5}$ generally are in the following order: winter > spring > fall > summer.
2. The three-year mean PM_{10} concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 65, 58, 57, 52, 47, 54 and 70 $\mu g m^{-3}$, respectively, which were lower than those in Wuhu (82 $\mu g m^{-3}$) and Bengbu (95 $\mu g m^{-3}$). As a whole, of these seven observed districts, the average PM_{10} values in summer (36 $\mu g m^{-3}$) were 52.0% lower than those in winter (75 $\mu g m^{-3}$), and spring (60 $\mu g m^{-3}$) had the similar levels to those observed in fall (61 $\mu g m^{-3}$).
3. From 2015–2017, Taisi Township always had the highest concentration of SO_2 , and Douliou City had the lowest values, and the three-year average SO_2 concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 5.51, 5.66, 6.20, 5.24, 8.55, 5.85 and 6.69 ppb, respectively. In summer (4.86 ppb) the minimum SO_2 levels were observed, which were 26.1% lower than that found for the other seasons (6.40, 6.58 and 6.75 ppb in spring, fall and winter, respectively).
4. The average NO_2 concentration in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 18.0, 18.4, 22.9, 23.9, 18.3, 18.2 and 18.2 ppb, respectively, during the three-year study period. These values were comparable to those of Wuhu (21.4 ppb) and Bengbu (18.0 ppb). In terms of seasonal variations, Douliou City usually had the maximum NO_2 levels in terms of spatial distribution, while summer always had the minimum values. Winter had the maximum values in terms of temporal distribution, for which the three-year average values in summer (13.7 ppb) were 43.2% lower than those in winter (24.1 ppb).
5. The mean CO concentrations in the three year study period in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 0.384, 0.413, 0.499, 0.437, 0.317, 0.377 and 0.374 ppm, respectively, which were significantly lower than the WHO standard (8.00 ppm), while the seasonal CO characteristics generally occurred in the following order: winter > spring > fall > summer.
6. The O_3 concentration in all observed cities rose by 0.43–7.93%. This increasing tendency poses a serious challenge in terms of air quality. The three-year average O_3 concentrations in Puzih City, Singang Township, Chiayi County, Douliou City, Taisi Township, Lunbei Township, and Mailiao Township were 47.7, 47.5, 48.0, 50.0, 48.7, 45.0 and 46.1 ppb, respectively. The O_3 concentrations in most of these places were slightly higher than the WHO standard (46.6 ppb).
7. Due to meteorological conditions, there were three O_3 seasonal distribution patterns in the study period. Firstly, all the observed cities had their maximum levels in fall and their minimum levels in summer, while spring and winter were at intermediate levels in 2015. Secondly, the maximum O_3 level normally occurred in spring or fall, and the minimum O_3 level normally occurred in summer or winter in 2016. Thirdly, the O_3 concentrations in spring and fall were both at high levels and those in spring were higher than those in fall, followed by winter, with the lowest in summer in 2017.
8. The percentages of air quality at the Moderate level were greatest in spring in the study areas, after which

they gradually deteriorated. PM_{2.5} was the most frequent primary pollutant, followed by O₃, which increased in different AQI classes. PM₁₀ was an occasional primary pollutant.

9. The air quality exhibited a marked Good (Grade I) condition in the summer in the study areas. PM_{2.5} was the most frequent primary air pollutant, and the fraction of O₃ as the primary air pollutant was significantly higher in summer than in spring. Furthermore, O₃ had a greater impact on unhealthy summer conditions.
10. The air quality mostly remained at Moderate levels in the fall in the study areas, and Unhealthy conditions were the most serious in Duliou City and the least serious in Mailiao Township. PM_{2.5} was still the most important primary air pollutant in fall, followed by O₃, and the number of days of PM₁₀ as the primary air pollutant significantly increased in the fall as compared with spring and summer.
11. Some of the studied districts had Good conditions in winter, but Moderate and Unhealthy for Sensitive Groups occurred frequently. PM_{2.5} was the most important primary air pollutant, followed by PM₁₀ and occasionally O₃ as the primary air pollutants, and particulate matter played a decisive role in the winter AQI in these seven districts.
12. The results of this study provide useful information for the establishment of air pollution control strategies and for future studies conducted by the scientific community.

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