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Impact of Air Pollutants Emitted by Taichung Power Plant on Atmospheric $PM_{2.5}$ in Central Taiwan

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ABSTRACT

The Taichung Power Plant (TCPP) is the second largest thermal power plant in the world and has been a highly controversial source of $PM_{2.5}$ emissions. In this study, the CMAQ/MM5 model was validated and used to simulate the $PM_{2.5}$ levels of the 11 stations in central Taiwan. The Base Case with all emission sources and the Control Case without TCPP emission were simulated. The difference between the two simulated results determines the contribution of TCPP emission. The results showed that most of the daily average contribution was less than 5 µg m^{-3} at each station in year. However, outlier contribution, representing the extreme episode, could reach to 15 µg m^{-3} in autumn. Although the maximum annual average contribution of TCPP to a single station was 2.0%, the maximum daily and hourly average contribution could be as high as 17% and 60%, respectively. In most stations, the contribution of the red-grade days (> 54 µg m^{-3}) accounted for less than 10% in a year. The contribution might be underestimated as the temporal variation was not considered particularly in the peak-power operation of summer.

Keywords: $PM_{2.5}$, CMAQ, Taichung Power Plant, Air pollution

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1 INTRODUCTION

The Taichung Power Plant (TCPP) is located in central Taiwan. It is equipped with 10 coal-fired units and 4 gas turbine units. The total installed capacity is 5.78 GW. It is the largest thermal power plant in Taiwan and the second largest thermal power plant in the world. TCPP provides approximately 19% of the country's electricity (Chen, 2017). Due to the largest power generation and the largest $PM_{2.5}$ emissions, TCPP has been a highly controversial emission source between the Taiwan's central government and local governments. The central government claims that if TCPP was closed, it would only improve the air quality of $PM_{2.5}$ in the central Taiwan by 2–3% on annual average. Overseas sandstorms and local traffic emissions are more important sources of contribution. This statement is supported by many researchers. One of these studies used a Community Multi-scale Air Quality (CMAQ) model to simulate the impact of TCPP on the air quality in Tainan. The results showed that the annual average contribution of $PM_{2.5}$ was only 2.8%, which was lower than the 3.5% of diesel vehicles in Tainan (Lu *et al.*, 2019). Another study used a hybrid model of CMAQ and AERMOD. The study concluded that a 40% reduction in TCPP power generation could only reduce the $PM_{2.5}$ concentration by 1.25% based on daily average. On the other hand, reducing traffic flow by 30% could reduce the $PM_{2.5}$ daily average in Taichung by 6.6% (Lai *et al.*, 2019). However, these studies only explored the impact of TCPP over this dispute in a single city or on a single episode.

The International Agency for Research on Cancer (IARC) determines outdoor $PM_{2.5}$ as Group 1 that is carcinogen to human (IARC, 2013, 2015). Studies have shown that for every 10 µg m^{-3} increase in the annual average concentration of $PM_{2.5}$, the mortality of all-cause, cardiopulmonary, and lung cancer will increase by 4%, 6%, and 8%, respectively (Pope *et al.*, 2002, 2009). More notably, many studies have indicated that short-term exposure to $PM_{2.5}$ increases the risk of

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hospitalization for cardiovascular and respiratory diseases (Dominici *et al.*, 2006; Wellenius *et al.*, 2012; Shah *et al.*, 2016). Based on epidemiological studies, the American Heart Association (AHA) found that when the daily average of $PM_{2.5}$ increases by 10 µg m^{-3}, the relative risk of cardiovascular mortality increases by 0.4–1.0% (Brook *et al.*, 2004, 2010). This indicates that the short-term adverse effect of $PM_{2.5}$ exposure cannot be ignored by the central authority as the mode of public perception is inextricably tiered to local context (Bickerstaff and Walker, 2001; Huang, 2015). The annual average assessment alone was not adequate to clarify this major controversy.

The purpose of this study was to evaluate the contribution of TCPP emissions on the increase in the atmospheric $PM_{2.5}$ in central Taiwan. Firstly, two simulation scenarios of Base Case and Control Case were performed at the study 11 stations in central Taichung. Then, the difference of the two simulated concentrations at each station was determined as the contribution of TCPP. The focus of this study was to evaluate the different contribution of yearly, daily, and hourly averages in a year.

2 METHODS

2.1 The Study Site

Fig. 1 is the map of the study site of TCPP, showing the enlarged 11 stations in central Taiwan. These stations were built and managed by the Taiwan Environmental Protection Agency (TEPA) for the routine monitoring of $PM_{2.5}$. The nested gridding method is normally used to balance the simulation efficiency and performance (Byun and Ching, 1999; Byun and Schere, 2006). In this study, a nesting ratio of 3 was used with the largest domain of 81 km × 81 km in the first layer covering the most areas of East Asia. The fourth layer of 3 km × 3 km covers the entire Taiwan.

2.2 The CMAQ Modeling System

The CMAQ system developed by the U.S. Environmental Protection Agency (U.S. EPA, 2018) was used in this study. The system is consisted of: (1) Four-dimensional meteorological data

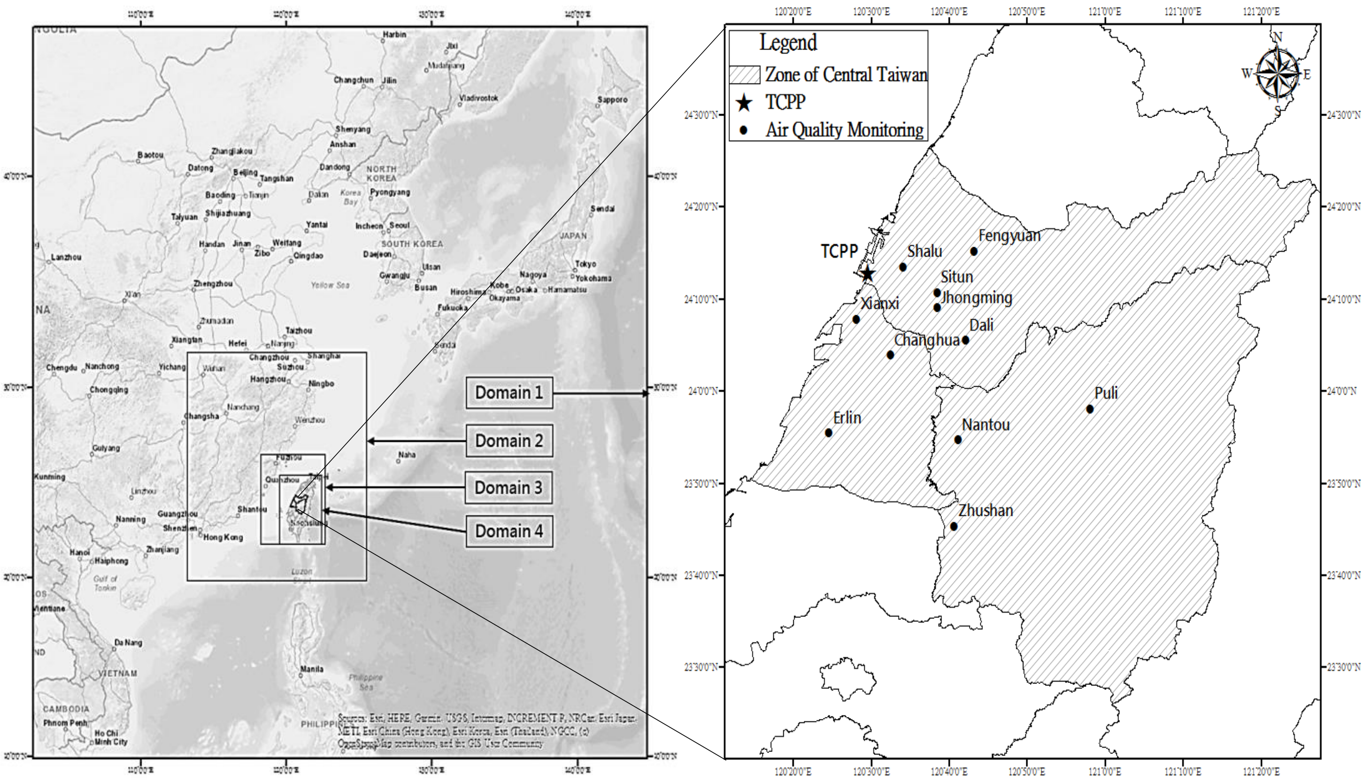

Fig. 1. Site map of the 4-layer nested simulation domain of the Taichung Power Plant (TCPP) and 11 monitoring stations in central Taiwan.

Table 1. Annual emission rates (1,000 metric tons per year) of TCPP and all the emissions sources in Taiwan used for the CMAQ simulation in this study.

Annual emission rate	$PM_{2.5}$	SO_X	NO_X	VOCs
TCPP	1.2	14.9	23.2	0.003
All the sources	77.2	116.9	399.4	457.2
Ratio (%)	1.6	12.7	5.8	0.0

generated by the fifth-generation Penn State / NCAR Mesoscale Model (MM5) and assimilated by the weather data collected in Taiwan; (2) Taiwan emission data of anthropogenic and biological sources from Taiwan Emission Data System (TEDS 9.0) (TEPA, 2016b) and Taiwan Biogenic Emissions Inventory System (TBEIS), respectively (Chang *et al.*, 2009). Table 1 gives the annual emissions of $PM_{2.5}$, SO_x, NO_x and VOC of TCPP and all emission sources in Taiwan; (3) Multi-resolution Emission Inventory for Chinese anthropogenic emissions (MEIC) (Li *et al.*, 2014; Zheng *et al.*, 2014; Liu *et al.*, 2015); (4) Anthropogenic emissions of Intercontinental Chemical Transport Experiment-Phase B (INTEX-B) for other areas of East Asia (Zhang *et al.*, 2009); and (5) Biomass emissions of East Asia Biogenic Emissions Inventory System (EABEIS) (Chang *et al.*, 2005).

2.3 Performance Evaluation

The TEPA's "Guideline for Simulation of Air Quality Model in Taiwan" (TEPA, 2015), was followed for the performance evaluation of the CMAQ modeling system of this study. The monitored data are required to validate with all the monitored data at all the relevant stations of interest. The mean fractional bias (MFB) and the mean fractional error (MFE) were used as the evaluation indicators as defined below:

$$MFB = \frac{2}{M \times N}\sum_{k=1}^{M}\sum_{i=1}^{N}\left(\frac{P_{i,k} - O_{i.k}}{P_{i,k} + O_{i,k}}\right) \tag{1}$$

$$MFE = \frac{2}{M \times N}\sum_{k=1}^{M}\sum_{i=1}^{N}\left|\frac{P_{i,k} - O_{i.k}}{P_{i,k} + O_{i,k}}\right| \tag{2}$$

where, M = the number of all stations, N = the number of simulated days, $P_{i,k}$ = the predicted value of the k-th station on the i-th day, $O_{i,k}$ = the monitored value of the k-th station on the i-th day. The acceptable goals were MFB $\leq \pm 30\%$ and MFE $\leq 50\%$, while the acceptable criteria were MFB $\leq \pm 60\%$ and MFE $\leq 75\%$ (Boylan and Russell, 2006). At least 60% of the stations must meet the following criteria: (1) correlation coefficient (R) $>$ 0.55, (2) MFB $< \pm$ 35%, (3) MFE $<$ 55%.

2.4 Contribution of the TCPP

The Base Case simulation was first performed with all the emissions of Taiwan and the relevant foreign countries. The TCPP-Control Case was then performed by using all the emissions, meteorological, initial and boundary conditions same as in the Basic Case, except for the TCPP emissions. Four seasons of January, April, July, and October in 2013 were simulated, representing winter, spring, summer, and autumn, respectively. The simulated concentration of the Control Case was subtracted from that of the Control Case to obtain the $PM_{2.5}$ contribution of the TCPP emissions at the 11 stations in central Taiwan.

2.5 The Pollution Grades

The simulated $PM_{2.5}$ daily averages of each station were grouped into yellow ($<$ 35µg m^{-3}), orange (35–54 µg m^{-3}), or red ($>$ 54 µg m^{-3}), respectively (TEPA, 2012, 2016a). The yellow grade indicates that the air quality meets the standard, but may have a slight effect on a very small number of extremely sensitive people. The orange grade means that the air quality exceeds the standard, which may affect the health of sensitive people, but the effect on the general public is not obvious. The red grade means that it has an effect on the health of all people, and may have a serious health impact on sensitive people.

3 RESULTS AND DISCUSSION

3.1 Performance Evaluation

Fig. 2 is the Base Case simulation result of $PM_{2.5}$ annual averages of the entire Taiwan. As expected, the high-level contours were found in the western part of the highly industrialized and urbanized area, while low concentrations appeared in eastern part of the underdeveloped area. A hot spot of annual averages (21–42 $\mu g\ m^{-3}$) was found in the southwestern area of Kaohsiung and Pingtung (27–45 $\mu g\ m^{-3}$). The inland areas of Yunlin, Chiayi and Tainan had higher concentrations than their coastal areas. This finding is generally consistent with many previous studies (Lai *et al.*, 2019; Lu *et al.*, 2019).

The simulated and monitored $PM_{2.5}$ daily averages of all the 11 stations were fairly correlated (Fig. 3). As further analyzed in Fig. 4, a few points at Dali, Jhongming, and Situn stations were found to be highly overestimated in January and October. This was probably due to the imperfect wind field simulations associated with the complex terrain of the study area in these seasons. Nevertheless, the validated R = 0.62–0.74, MFB = -1.3–5.3% and MFE = 34–53% (n = 1,342) all meet the performance requirements (R > 0.55, MFB < ± 35%, and MFE < 55%).

3.2 Contribution of Daily Average

To analyze the central tendency and the outlier of the simulated daily average of each station, the whisker box plot was used. The inner line of the box is the median. The bottom and top values of the box are P25 and P75, respectively, which are the larger value of {minimum value of all data, P25 – 1.5 × (P75 – P25)}, and the smaller value of {maximum value of all data, P75 + 1.5 × (P75 – P25)}, respectively. The two ends of the whisker drawn in straight are the minimum and the maximum. The solid dot of the whisker is the outlier.

As shown in Fig. 5 (a) for Base Case, spring (April) and summer (July) generally had better $PM_{2.5}$ air quality from the prospective of lower P75 values and much lower extremes. Except for autumn (October), as shown in Fig. 5 (b), the contribution of most TCPP operations was less than 5 $\mu g\ m^{-3}$. The outlier contribution of $PM_{2.5}$, representing the extreme episode, in autumn was the highest, which could reach to greater than 15 $\mu g\ m^{-3}$. The variation of seasonal outlier contribution could be due to the different prevailing winds in different seasons in the study area. By contract, as shown in Fig. 5 (c), the highest percentage contribution (> 15%) was only occurred in summer (Jul) due primarily to its low base case levels of $PM_{2.5}$. When the temporal TCPP emission was considered, the percentage contribution could be even higher in the peak-power generation in summer (Farkas *et al.*, 2015, 2016).

As further analyzed in Fig. 6, the contribution of the yellow-grade days was quite limited by 1.1%, 2.6%, 1.0%, and 2.6% in winter, spring, summer, and autumn, respectively. The percent contribution of the red grade days was also marginal. Surprisingly, the relative contribution of the red grade days in summer (July) was as high as 33% due to a low Base Case percentage (1.8%) of

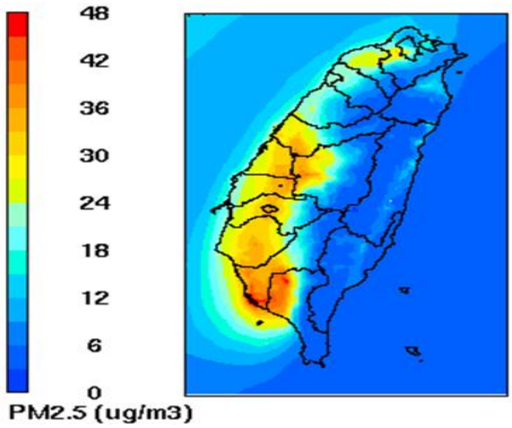

Fig. 2. Spatial distribution diagram of the annual $PM_{2.5}$ concentration simulated in January, April, and October 2013 for the Base Case of this study.

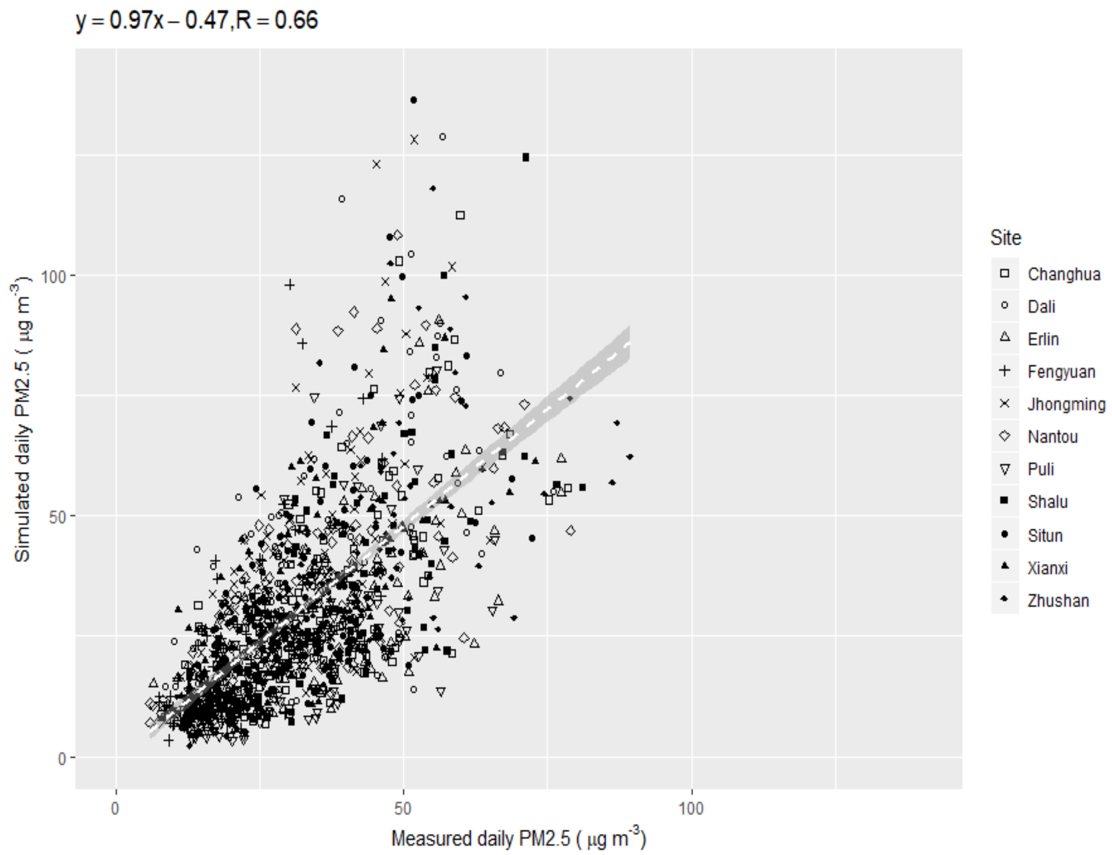

Fig. 3. Performance evaluation of the CMAQ model, showing the linear correlation (R = 0.66) between the simulated vs. monitored daily $PM_{2.5}$ concentrations at 11 stations in January, April, July and October 2013.

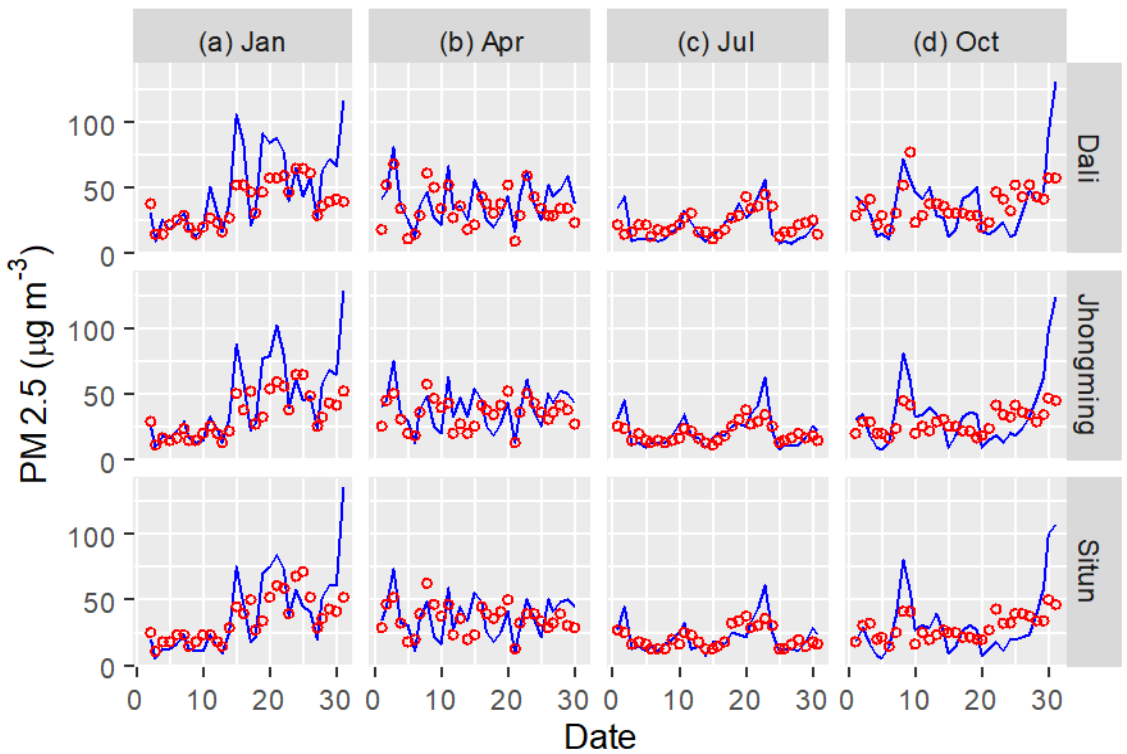

Fig. 4. Comparison of the temporal trend of the simulated (line) and monitored (circle) daily $PM_{2.5}$ concentrations at Dali, Jhongming and Situn stations in January, July, April, and October 2013.

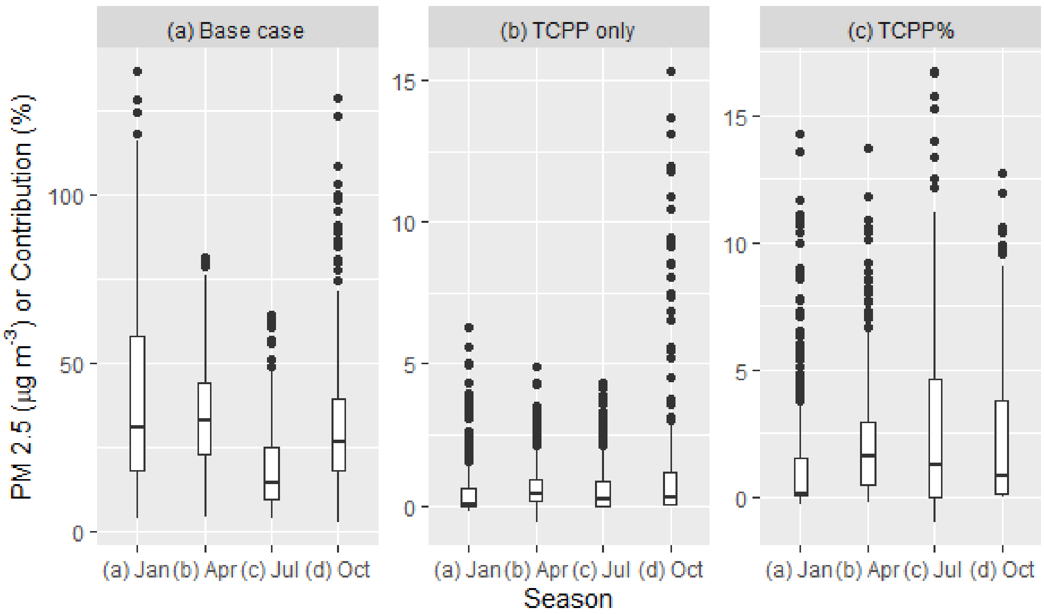

Fig. 5. Simulated $PM_{2.5}$ daily averages in each season 2013: (a) Concentration of Base Case; (b) Contribution of TCPP; and (c) Percentage contribution of TCPP; showing the median, the bottom, top, P25, P75, minimum and maximum (line) and outlier (dot) values of the Whisker box.

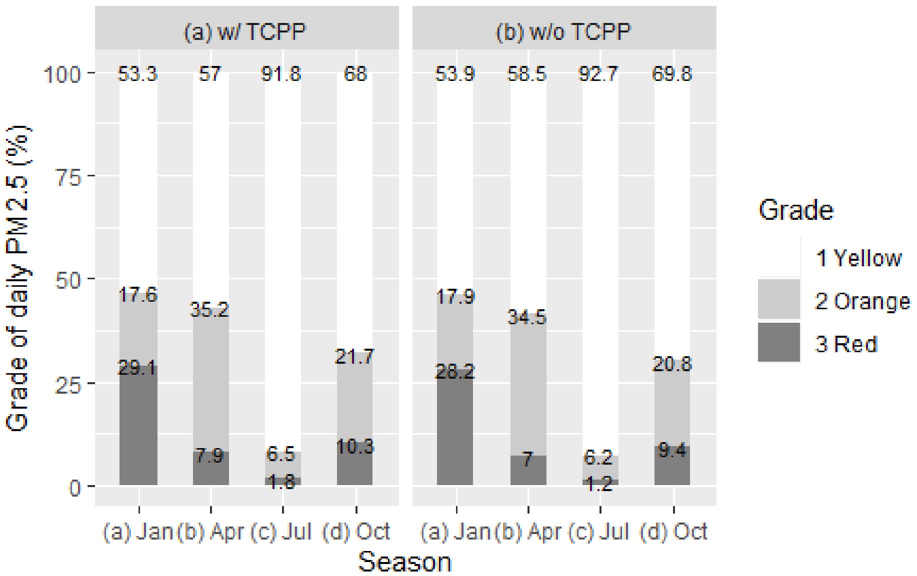

Fig. 6. Percentages of the yellow-grade, orange-grade, and red-grade days in central Taiwan: (a) Normal operation of TCPP of Base Case; (b) Closure of TCPP of Control Case.

the red-grade days. In the other three seasons, the relative contribution of the red-grade days was 11%, 8.7%, and 3.1% in spring, autumn, and winter, respectively. It was further found in Table 2 that most stations had a low relative contribution of the yellow grade days (< 3%) and the red-grade days (< 10%) in a year. Erlin station had the highest relative contribution (4.4%) of the yellow grade days in a year. Situn (11%) and Changhua (13%) had a relative contribution of the red grade days of greater than 10%. The highest relative improvement of the red grade days was located at Erlin station (25%) due to a low Base Case percentage (6.6%) of the red grad days in a year.

3.3 Contribution of Different Averaging Times

As shown in Table 3, the simulated maximum contribution in a year for each station ranged

Table 2. Relative improvement of the yellow grade days and the red grade days at each station in the study area of central Taiwan.

Grade	Yellow grade			Red grade		
Site	w/ TCPP	w/o TCPP	Relative Contritution	w/ TCPP	w/o TCPP	Relative Contribution
Dali	56	57	1.5	17	16	9.5
Fengyuan	75	76	2.2	9.0	9.0	0
Jhongming	65	65	0	16	16	0
Shalu	69	70	2.4	12	11	6.7
Situn	68	68	0	15	13	11
Changhua	69	69	0	13	11	13
Xianxi	70	72	2.3	8.2	8.2	0
Erlin	74	77	4.4	6.6	4.9	25
Nantou	57	58	1.4	15	14	5.6
Puli	84	85	1.0	5.7	5.7	0
Zhushan	58	61	4.2	16	15	5.3

Table 3. Maximum contributions of different averaging time periods of TCPP at each station in central Taiwan; Nx in brackets representing the multiplier to the annual average contribution; @month representing the season in which the maximum contribution occurs.

Site	Yearly	Max. monthly	Max. daily	Max. hourly
Dali	1.5% (1x)	2.3% (1.5x)@Jul	10% (6.7x)@10/31	60% (40x)@7/13 6h
Fengyuan	1.6% (1x)	2.5% (1.6x)@Jul	13% (8.1x)@10/31	43% (27x)@4/6 3h
Jhongming	1.4% (1x)	1.9% (1.4x)@Jul	10% (7.1x)@4/25	44% (31x)@4/25 2h
Shalu	2.0% (1x)	3.9% (2.0x)@Jul	12% (6.0x)@10/30	38% (19x)@7/3 14h
Situn	1.4% (1x)	2.0% (1.4x)@Apr	10% (7.1x)@4/25	42% (30x)@4/6 5h
Changhua	1.8% (1x)	2.4% (1.3x)@Jul	16% (8.9x)@7/10	56% (31x)@7/13 2h
Xianxi	4.0% (1x)	4.5% (1.1x)@Jul	17% (4.2x)@7/1	57% (14x)@7/16 6h
Erlin	4.3% (1x)	6.1% (1.4x)@Jan	14% (3.2x)@1/3	53% (12x)@4/25 10h
Nantou	1.6% (1x)	2.1% (1.3x)@Jul	11% (6.9x)@7/10	56% (35x)@7/13 2h
Puli	2.1% (1x)	3.2% (1.5x)@Jul	10% (4.8x)@10/14	53% (25x)@7/13 5h
Zhushan	2.2% (1x)	3.4% (1.5x)@Jul	11% (5.0x)@7/10	56% (25x)@7/13 0h

1.5–4.3%, 1.9–6.1%, 10–17%, and 38–60% for the yearly, monthly, daily, and hourly average. For better comparison, the annual average contribution of each station was used as the reference to calculate the maximum contribution multiplier (Nx). Their occurrence seasons were also identified. It could be seen when the averaging time period was shortened, the maximum contribution by TCPP operation at each station increased. The annual average contribution of TCPP was as much as 3.0%. But on the basis of the hourly average, the maximum contribution could be as high as 60%. This suggests that, in evaluating the contribution of specific emission sources, use of the annual average or daily average alone (Lai *et al.*, 2019; Lu *et al.*, 2019;) could sometimes be misleading.

From the aspect of toxicological effect of $PM_{2.5}$, short-term exposure cannot be ignored by the quality authority (Bickerstaff and Walker, 2001; Huang, 2015). In addition, the public is more perceived to the hourly average or even the hourly peak measurements and the mode of public perception is inextricably tiered to local context (Bickerstaff and Walker, 2001; Brook *et al.*, 2004; 2010; Huang, 2015). According to the public IoT data service platform (TMOST, 2020), the TEPA currently collects the continuous $PM_{2.5}$ monitoring of about 3,000 micro-sensors in the entire Taiwan in every 3 minutes. It is speculated that the short-term continuous monitoring data may provoke more public attention, although the reliability of the data is often questioned.

4 CONCLUSIONS AND RECOMMENDATIONS

Several important conclusions and recommendations obtained in this study were as follows:

1. From the whisker-box analysis, except for autumn, the daily average contribution of most TCPP operations was less than 5 µg m^{-3}. The outlier contribution of $PM_{2.5}$, representing the

extreme pollution episode, was the highest in autumn and could reach to greater than 15 µg m^{-3}.
2. Although the maximum annual average contribution of TCPP to a single station was only 2.0%, their corresponding maximum daily and hourly average contributions could be as high as 17% and 60%, respectively.
3. The contributions of the yellow grade days and the red grade days in a year were < 3% and < 19%, respectively. Surprisingly, the relative contribution in summer of the red grad days was as high as 33%. However this was associated with their low Base Control of the red grade days (1.8%).
4. It is recommended that the air pollution authority collect the temporal emission data of SO_x, NO_x, VOCs, and primary $PM_{2.5}$ to improve the simulation of the diurnal and seasonal variation of $PM_{2.5}$.

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