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Potential impacts of electric vehicles on air quality in Taiwan

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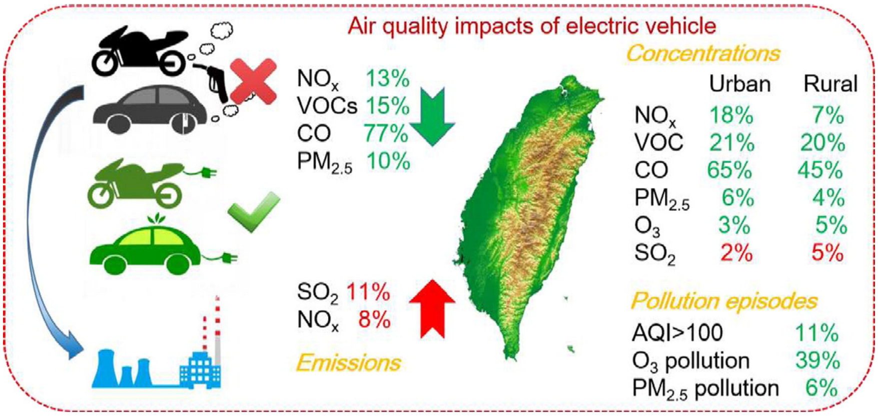
HIGHLIGHTS

- Air quality impact of EV is evaluated with WRF-CMAQ model under different scenarios.
- Net emissions of NO_x, VOCs, CO and $PM_{2.5}$ would be reduced by introducing EV to Taiwan.
- EV penetration would reduce pollution episodes in Taiwan's major cities by up to 60%.

GRAPHICAL ABSTRACT



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ABSTRACT

The prospective impacts of electric vehicle (EV) penetration on the air quality in Taiwan were evaluated using an air quality model with the assumption of an ambitious replacement of current light-duty vehicles under different power generation scenarios. With full EV penetration (i.e., the replacement of all light-duty vehicles), CO, VOCs, NO_x and $PM_{2.5}$ emissions in Taiwan from a fleet of 20.6 million vehicles would be reduced by 1500, 165, 33.9 and 7.2 Gg yr^{-1}, respectively, while electric sector NO_x and SO_2 emissions would be increased by up to 20.3 and 12.9 Gg yr^{-1}, respectively, if the electricity to power EVs were provided by thermal power plants. The net impacts of these emission changes would be to reduce the annual mean surface concentrations of CO, VOCs, NO_x and $PM_{2.5}$ by about 260, 11.3, 3.3 ppb and 2.1 μg m^{-3}, respectively, but to increase SO_2 by 0.1 ppb. Larger reductions tend to occur at time and place of higher ambient concentrations and during high pollution events. Greater benefits would clearly be attained if clean energy sources were fully encouraged. EV penetration would also reduce the mean peak-time surface O_3 concentrations by up to 7 ppb across Taiwan with the exception of the center of metropolitan Taipei where the concentration increased by <2 ppb. Furthermore, full EV penetration would reduce annual days of O_3 pollution episodes by ~40% and $PM_{2.5}$ pollution episodes by 6–10%. Our findings offer important insights into the air quality impacts of EV and can provide useful information for potential mitigation actions.

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1. Introduction

The rapid growth of transportation via automobiles is raising worldwide concerns about the associated fossil energy crisis and environmental pollution. Taiwan is one of the most high-traffic places in the world with vehicle ownership (including motorcycles) having reached ~900 vehicles/1000 people in the year 2010. To drive these vehicles, about 9.7 billion liter gasoline and 4.4 billion liter diesel are consumed each year. Additionally, large amounts of exhaust gases are emitted into the atmosphere. According to the Taiwan Environmental Protection Administration, 50% of NO_x emissions in Taiwan were caused by a fleet of 21.7 million vehicles (EURO IV) in 2010 (MTC, 2010a; TWEPA, 2015), and the situation was even worse in large cities such as the Taipei metropolis, where 85% of NO_x were emitted by on-road traffic (TWEPA, 2015). To address these issues, the electric vehicle (EV) is being considered as a potential option for both energy saving and pollution mitigation (e.g., Brinkman et al. 2010; Helmers and Marx, 2012; Tessum et al. 2014). Compared with conventional vehicles, EVs are more energy efficient and have zero exhaust emissions in street canyons. However, generating electricity to power these vehicles would engender additional emissions from power plants.

Current studies have predicted a wide range of emission changes from the introduction of EVs, depending on assumptions about EV penetration percentage and charging scenarios as well as local emission characteristics (Sioshansi and Denholm 2009; Huo et al. 2010, 2013; Wu et al. 2012; Lang et al. 2013; Nichols et al. 2015). Sioshansi and Denholm (2009) assumed a low penetration (<15%) of plug-in hybrid electric vehicles (PHEVs) and the flexible charging of vehicles under smart grid controls in Texas, USA. They suggested that a PHEV fleet could actually reduce electric sector NO_x emissions during the ozone season, despite the additional charging load. In contrast, Huo et al. (2010) pointed out that EV penetration in China would increase SO_2 and NO_x emissions per vehicle-kilometer by two- to tenfold if the electricity were sourced from the current grid. Lang et al. (2013) agreed that net emission would increase in China, and suggested that increments in SO_2 and NO_x emissions would result from the high proportion of coal-fired energy generation.

Beyond estimating emission changes, only a limited number of studies have focused on the impacts of EVs on air quality levels, even though this topic is in need of much further detailed analysis in areas including chemistry and transport modeling (Thompson et al. 2009; Brinkman et al. 2010; Soret et al. 2014; Tessum et al. 2014). Brinkman et al. (2010) used an air quality model to explore the potential impacts of PHEVs on O_3 concentration in Denver, USA, in the summer of 2006, by considering different PHEV penetration levels and charging scenarios. They estimated that, under 100% PHEV penetration, peak 8-h average O_3 concentration would be reduced by 2–3 ppb on most days, but that O_3 would increase in specific areas near central Denver. Thompson et al. (2009) assumed that PHEVs replaced 20% of the gasoline vehicles in the northeastern USA and were all charged at night. Their simulated peak 8-h average O_3 concentrations decreased by 2–6 ppb across urban areas under this scenario, but increased by up to 8 ppb in highly localized areas. Tessum et al. (2014) analyzed environmental health impacts of EVs across the entire USA by assuming a replacement of 10% of the vehicle fleet in 2020 under different powering scenarios. They found that powering EVs using electricity from corn ethanol or coal would increase environmental health impacts by >80%, while using low-emitting electricity from natural gas or renewable energy would reduce the impacts by 50% or more.

The purpose of this study is to explore the potential impacts of switching conventional vehicles to EVs on air quality in Taiwan. We used a regional chemical model to simulate gaseous and particulate pollutants in Taiwan in the year 2010, and compared the results with the hourly surface chemical measurements from a network of 69 monitoring sites. We discussed detailed environmental impacts of EVs based on assumptions about ambitious vehicle replacements and different electricity supply scenarios.

2. Methods and data

2.1. Electric vehicle scenarios

To understand the prospective impact of EV penetration on air quality in Taiwan, we assumed that light-duty vehicles (motorcycles and light-duty passenger cars, which account for 95% of the total vehicles in Taiwan) were 100% replaced by EVs, and that the additional demand for electricity was leveled on power plants as they existed in 2010. Although this ambitious full penetration of EV is not realistic in the short term and the characteristics of both vehicle and power plant fleet would change over time, this hypothetical case provided an insight into the maximum potential benefits from vehicle replacement. Replacements of buses and trucks were not considered in this study, partly due to their minor numbers and partly due to the high uncertainties in estimating their battery efficiency rate. Although some hybrid electric buses are already on the streets, heavy trucks powered by electricity currently remain at the concept stage.

The electricity to power EVs was calculated as follows:

$$ED = \sum_i (VP_i \times VU_i \times VKT_i \times BE_i)/(TE \times CE_i) \quad (1)$$

where ED is the total electricity demand (kWh) by EVs; i is the vehicle type; VP is the vehicle population; VU is the vehicle usage rate (%); VKT is the annual mean vehicle kilometers traveled (km); BE is the average battery efficiency rate (kWh km^{-1}); TE is the electricity transmission efficiency (%); and CE is the electric vehicle charging efficiency (%). VP and VU were sourced from the monthly statistics of transportation and communications in Taiwan (MTC, 2010a). VKT was obtained from the annual reports of motorcycles, private and business light-duty passenger cars in Taiwan (MTC, 2010b, 2011a,b). BE was the average value for typical electric vehicles obtained from the yearbook of energy-saving and new energy vehicles (EBYENEV, 2011). TE was set to 96% following the Taiwan energy statistical yearbook (BEMEA, 2010), and CE was set to 91% following Shi et al. (2013). These details are summarized in Table 1.

EV penetration generally would shift emissions from vehicle exhausts to electric generating units. The resulting additional electricity demand was estimated at 58.1 billion kWh. Providing power plants to meet the electricity demand is hence an important parameter for evaluating the consequent air quality impacts. Table S1 summarizes power generations from different sources in Taiwan 2010. Thermal power (mainly coal-fired) accounts for 80% of the total electricity generation, whereas “clean” powers (nuclear, hydro, geothermal, solar photovoltaic and wind energy) provided the remaining 20%. To better evaluate the prospective impacts of EV, we conducted three scenario simulations in this study: (1) base case (BASE), (2) EV powered by thermal power (EVTP), and (3) EV powered by clean power (EVCP). The first scenario provided a baseline representing 2010 pollutant emissions and air quality levels in Taiwan. The other two scenarios considered the hypothetical adaptation of EV and assumed that the required electricity would be completely sourced from thermal power plants (EVTP) or from clean power sources (EVCP). Comparing these latter two scenarios with the BASE case allowed an evaluation of the degree of environmental impacts under different power generation modes at a high EV penetration level.

2.2. Air quality model

The Community Multi-scale Air Quality model (CMAQ) version 4.7.1 (Binkowski and Roselle 2003; Byun and Schere 2006) was used to simulate gaseous pollutants and aerosols in Taiwan. Meteorological fields to drive CMAQ were obtained using the Weather Research and Forecasting model (WRF) version 3.5.1 (Skamarock et al. 2008). We applied three nested domains (Fig. 1a) with horizontal resolutions of 27, 9 and

Table 1
Vehicle information in Taiwan 2010.

	Light duty passenger car		Motorcycle	
	Private	Business	Heavy	Light
Vehicle population[a]	5,642,969	160,444	11,112,224	3,732,708
Vehicle usage rate	–[b]	–[b]	93.1%[c]	78.6%[c]
Vehicle kilometers traveled (km)	237.2 [d]	508[e]	54.1[c]	20.6[c]
Battery efficiency rate (kWh/100 km)[f]	34	34	4	4
Electricity demand ($\times 10^8$ kWh)[g]	520.9	31.7	25.6	2.8

[a] From monthly statistics of transportation and communications in Taiwan (MTC, 2010a).
[b] Vehicle usage rates for light-duty passenger cars are not available, and are assumed be 100%.
[c] From annual report of motorcycle in Taiwan (MTC, 2011a).
[d] From annual report of private light duty passenger car in Taiwan (MTC, 2010b).
[e] From annual report of business light duty passenger car in Taiwan (MTC, 2011b).
[f] From yearbook of energy-saving and new energy vehicles (EBYENEV, 2011).
[g] Calculate electricity demand using Eq. 1, setting charge efficiency to be 91% (Shi et al. 2013) and power transmission efficiency to be 96% (BEMEA, 2010).

3 km, respectively. Fourteen vertical layers were applied, and eight were assigned to the bottom 1.5 km to emphasize boundary layer processes. The simulation was conducted for a period of one year, from January to December 2010.

SAPRC-99 (Carter 2000; Carlton et al. 2010) was used to represent gas-phase chemical mechanisms. Photolysis rates were estimated by simulated clear-sky photolysis ratio, and then corrected for cloud cover (Byun and Schere 2006). We also simulated Asian and local dust as per Chen et al. (2004) and Lin et al. (2015). Removal of gases and aerosols was implemented with both wet and dry deposition mechanisms following Byun and Schere (2006). In addition, secondary organic aerosol (SOA) formation via the irreversible uptake of dicarbonyls (glyoxal and methylglyoxal) by wet aerosols and cloud droplets was included following Fu et al. (2008). This formation pathway was implemented into CMAQ by Li et al. (2013), and might constitute an important source of SOA in Taiwan (Tsai et al. 2015).

2.3. Emission inventories

This study considered emissions of SO_2, NO_x, VOCs, CO, NH_3 and $PM_{2.5}$ from power plants, transportation and other source sectors. Table 2 summarizes the annual emissions in Taiwan during 2010 in the BASE case and the changes associated with the EV scenarios. Domestic emissions from power plants, transportation and other anthropogenic source sectors (including industry, residential, agriculture and open biomass burning) for the year 2010 were obtained from Taiwan Emission Data System (TEDS) version 8.1 (TWEPA, 2015). This emission inventory has a spatial resolution of 1 × 1 km. We applied diurnal and seasonal variations to the emissions based on activity statistics and surface measurements. Emissions from anthropogenic sources for the rest of Asia were taken from the inventories developed by Li et al. (2015) and Wiedinmyer et al. (2011). Emissions from biogenic sources for both Taiwan and the rest of the model domain were calculated using the MEGAN algorithm (Guenther et al. 2006), driven by meteorological fields simulated by WRF, and land cover and vegetation data from MODIS. Total annual emissions in Taiwan were estimated as follows: 120 Gg SO_2, 263 Gg NO_x, 1110 Gg VOCs, 1940 Gg CO, 188 Gg NH_3 and 72.8 Gg $PM_{2.5}$. Power generation was an important contributor of SO_2 (37%) and NO_x (27%) emissions, but played a minor role for other pollutants (<5%). Transportation sources dominated CO emissions (91%) and also contributed 19–48% to NO_x, VOCs and $PM_{2.5}$ emissions.

Fig. 2 shows the spatial distributions of total emissions and emissions from light-duty vehicles in Taiwan. Light-duty vehicles strongly contributed to emissions mostly in major cities (Fig. 2b), such as Taipei (northern Taiwan), Taichung (central Taiwan) and Kaohsiung (southern Taiwan); however rural areas also showed significant emissions, due to the dense network of county routes and express way systems around these regions. Major thermal power plants in Taiwan are located in the coastal areas (Fig. S1) because electricity generation requires a large quantity of cooling water. The plant located in Taichung (TC, 120.46°E, 24.19°N) is currently the largest coal-fired power plant in the world, contributing 35% to electric sector SO_2 and NO_x emissions in Taiwan. Details of each thermal power plant are summarized in Table S2.

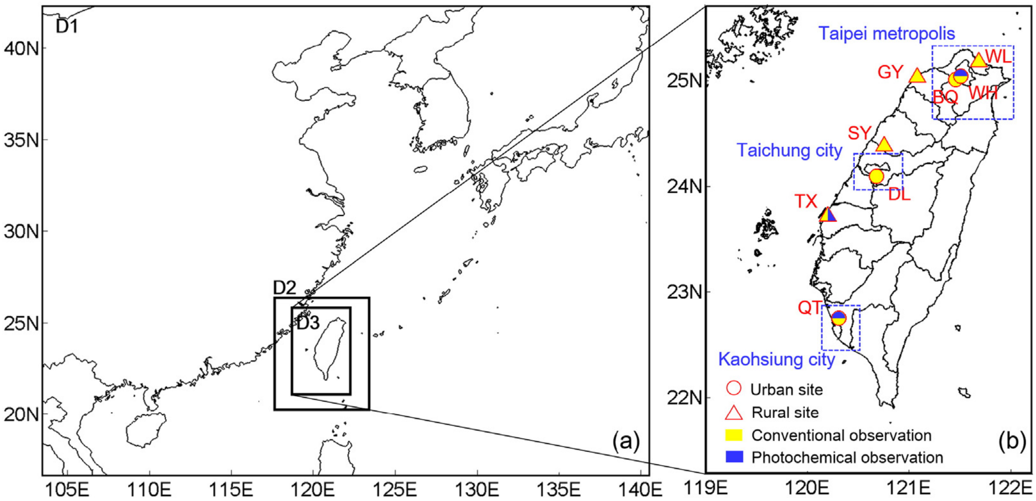

Fig. 1. The simulation domain and locations of the eight selected surface observation sites in Taiwan, including four urban sites (circles) and four rural sites (triangles). The yellow indicates conventional observations of SO_2, NO_x, O_3, CO and $PM_{2.5}$ concentrations, and the blue indicates photochemical observations of VOCs concentrations.

Table 2
Total base case emissions in Taiwan 2010 and changes in emissions in the EV scenarios (Gg yr^{-1}).

Pollutant	Source sector	Scenario		
		BASE	EVTP	EVCP
SO_2	Power generation	44.6	+12.9 (+29%)[a]	0
	Transportation	8.6	−0.2 (−3%)	−0.2 (−3%)
	Total[b]	120	+12.7 (+11%)	−0.2 (0%)
NO_x	Power generation	70.1	+20.3 (+29%)	0
	Transportation	126	−33.9 (−27%)	−33.9 (−27%)
	Total[b]	263	−13.6 (−5%)	−33.9 (−13%)
VOCs	Power generation	0.6	+0.2 (+29%)	0
	Transportation	209	−165 (−79%)	−165 (−79%)
	Total[b]	1110	−165 (−15%)	−165 (−15%)
CO	Power generation	12.5	+3.6 (+29%)	0
	Transportation	1770	−1500 (−85%)	−1500 (−85%)
	Total[b]	1940	−1500 (−77%)	−1500 (−78%)
NH_3	Power generation	9.0	+2.6 (+29%)	0
	Transportation	1.5	0	0
	Total[b]	188	+2.6 (+1%)	0
$PM_{2.5}$	Power generation	2.9	+0.8 (+29%)	0
	Transportation	26.4	−7.2 (−27%)	−7.2 (−27%)
	Total[b]	72.8	−6.3 (−9%)	−7.2 (−10%)

[a] Values in brackets are relative changes to the corresponding sectors.
[b] Including emissions from power generation, transportation, industrial, residential, agricultural, open biomass burning, and biogenic sources.

Introducing EV significantly changed the emissions. Emissions from light-duty vehicles were completely removed in both EV scenarios, while emissions from power plants were increased by 29% in EVTP and 0% in EVCP. In the EVTP scenario, NO_x emissions from transportation were reduced by 33.9 Gg yr^{-1} (27% of transportation NO_x emissions), but 20.3 Gg yr^{-1} were added from power plants. CO, VOCs and $PM_{2.5}$ emissions from transportation were estimated to be 1500 Gg yr^{-1} (85%), 165 Gg yr^{-1} (79%) and 7.2 Gg yr^{-1} (27%) lower than those in the BASE case, respectively, while the additional power demands from thermal power plants caused <1% increases in these emissions. The percentage reductions in VOCs and CO emissions were significantly larger than those in other pollutants, because light-duty vehicles had larger contributions to these categories than to other pollutants. The change in SO_2 emissions stood out in that it was the only pollutant that increased (by 12.7 Gg yr^{-1} or 11%). This was because conventional vehicles contributed very little to SO_2, but coal-fired power plants were big emitters of SO_2. The change in NH_3 emissions was <1% because neither transportation nor power plants were significant contributors.

3. Results

3.1. Model evaluation

To better evaluate model performance, we selected eight surface stations (Fig. 1b) from a network of 69 available monitoring sites operated by the Taiwan Environmental Protection Administration to provide hourly surface concentrations of SO_2, NO_x, CO, VOCs, O_3 and $PM_{2.5}$ from January to December 2010 (http://taqm.epa.gov.tw/taqm/tw/default.aspx). The eight representative stations include four urban sites (BQ, DL, QT and WH) and four rural sites (GY, SY, TX and WL), with site details given in Table S3. As shown in Fig. S2, our model reproduced the annual mean SO_2, NO_x, O_3 and CO concentrations at most sites well, with normalized mean biases (NMB) below ±16%. The simulated annual mean VOCs and $PM_{2.5}$ agreed well with the measurements at rural sites (biases below ±11%), but were overestimated at urban sites (biases up to ±41%). Seasonal and diurnal patterns are discussed in supplement section S1.

Fig. 3 summarizes the model performance by statistical comparisons between the measured and simulated monthly diurnal concentrations at the eight sites. All pollutants showed high correlations ($r = 0.72$–0.86) between simulation and observation, indicating that our model did fairly well in reproducing the diurnal and seasonal variations at these sites. The regression slopes of SO_2, NO_x, O_3 and CO were within the range of 0.91–1.06; however, our model overestimated the VOCs and $PM_{2.5}$ concentrations, with regression slopes of 1.41 and 1.30, respectively. In general, although not without biases, our model showed a reasonable agreement with the surface observations in Taiwan, which allowed a decent evaluation of EV effects.

3.2. Impacts of EV on surface pollutant concentrations

As stated earlier, replacing current vehicles with EVs would yield substantial reductions in gaseous and particulate pollutant emissions (up to 77%), with the exception of SO_2. In this section, we analyze the consequent impacts on surface pollutant concentrations.

3.2.1. SO_2, NO_x, VOCs, CO and $PM_{2.5}$

Fig. 4 shows the spatial distributions of the simulated annual mean surface concentrations of SO_2, NO_x, CO, VOCs and $PM_{2.5}$ in the BASE case, as well as their changes in the EVTP and EVCP scenarios. Surface SO_2 concentrations evidently increased near the thermal power plants in the EVTP scenario, with the largest changes (up to 3 ppb) occurring near the Talin (TL) power plant in southern Taiwan. The annual mean changes due to EVTP is to increase SO_2 concentration by about 0.1–0.2 ppb across Taiwan (Table 3). It is worth noting that the largest change did not occur at the largest thermal power plant (TC). This is because the chimneys of TL (130 m) are much lower than those of other thermal power plants (200–250 m) (Table S2), so the changes in emissions from TL had a stronger local impact (Fig. S15). For the EVCP scenario, the changes in SO_2 concentration were quite minor due to the low percentage of SO_2 emissions from light-duty vehicles.

The results of NO_x simulation suggest that EV penetration could be effective in reducing surface NO_x concentrations. The largest NO_x reductions for both the EVTP and EVCP scenarios were associated with on-road emission mitigation in the Taipei metropolis, where annual mean concentration decreased by up to 16 ppb. On the other hand, surface NO_x concentrations increased slightly near the TC, HT and TL power plants for the EVTP scenario. Overall, the net effect was to create obvious surface NO_x reductions over the Taipei metropolis and Taichung city. However, for Kaohsiung city, the effect of EV on emission reduction was nearly offset by the low chimneys in the nearby power plants. Another important reason for the relative smaller NO_x changes in Kaohsiung was that heavy industries, who would not be subject to on-road emission reduction, were major contributors of NO_x emissions in this area.

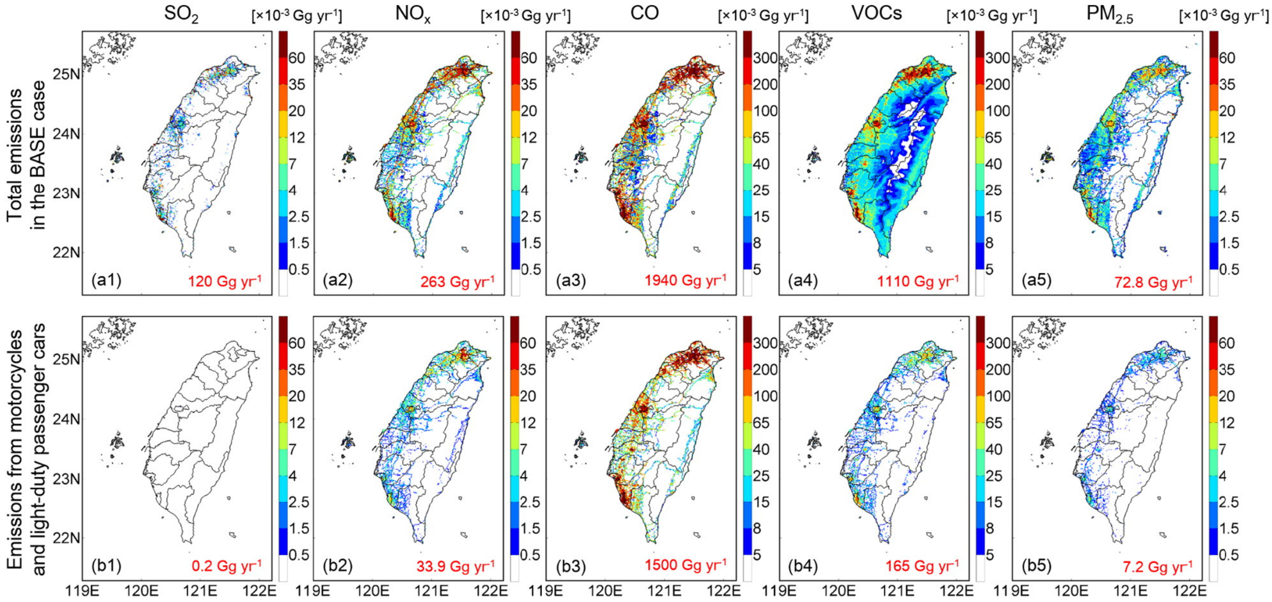

Fig. 2. Annual mean emissions of SO_2, NO_x, CO, VOCs and $PM_{2.5}$ (from left to right) in Taiwan from all sectors (top) and from motorcycles and light-duty passenger cars only (bottom). The domain-average annual emissions of each pollutant from Taiwan are shown at the lower right corner in red.

For CO and VOCs, we found substantial reductions over large cities, with surface concentrations decreased by up to 850 ppb for CO and 35 ppb for VOCs. Reductions in CO and VOCs were unchanged for different electricity supply modes, since electric generating units emitted low quantities of these pollutants. The reduction of CO concentration was the most prominent effect among pollutants, as light-duty vehicles are the dominant sources (77%) of CO emissions in Taiwan. The spatial distribution of $PM_{2.5}$ changes was similar to those of CO and VOCs, but appeared to cover a wider area, likely due to the time required for secondary aerosol formations and thus further dispersion. The degree of $PM_{2.5}$ reduction was somewhat smaller in the EVTP scenario (up to 6 μg m^{-3}) compared to that in the EVCP scenario (up to 7 μg m^{-3}). The smaller changes were due to be offset by increased emissions of SO_2 and NO_x, which can convert into sulfate and nitrate aerosols, from the electrical sector.

Fig. 5 shows the annual mean diurnal pattern of changes in surface pollutant concentrations associated with EV penetration. Full EV penetration reduced the surface concentrations of NO_x, CO, VOCs and $PM_{2.5}$

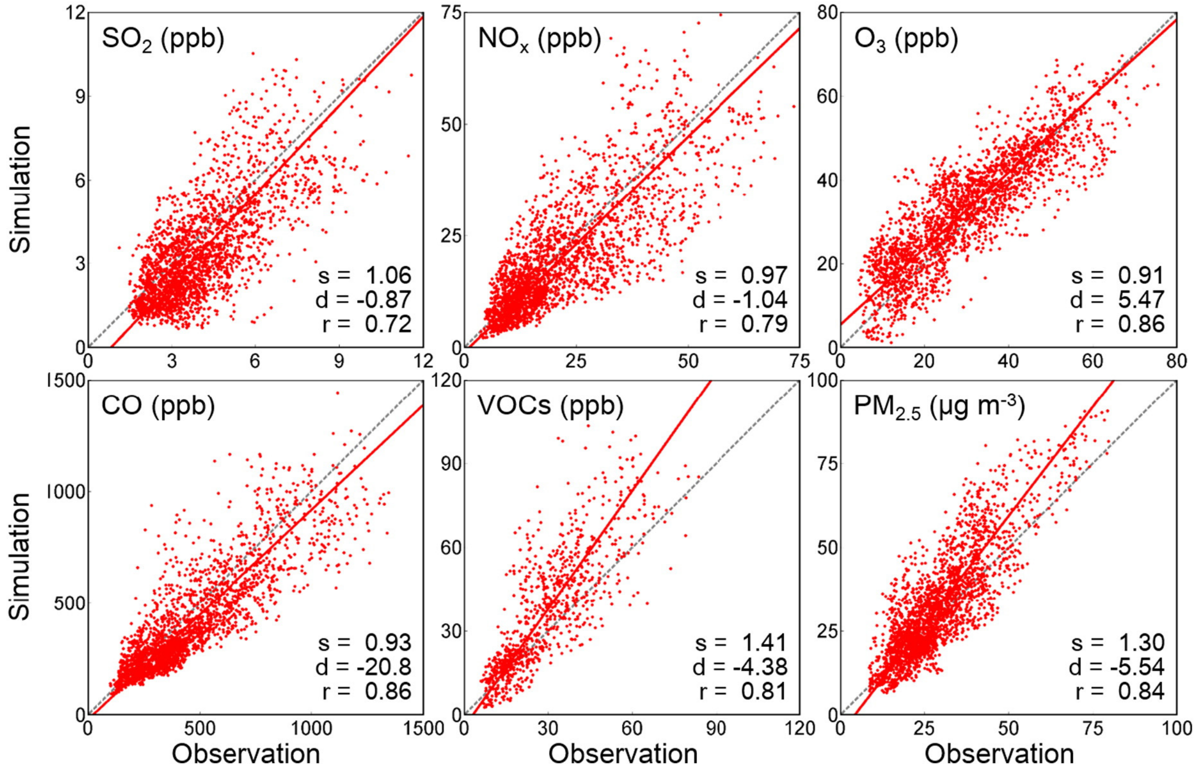

Fig. 3. Simulated versus observed surface pollutant concentrations at the eight selected sites. Each dot represents the monthly mean concentration at a particular hour of the day, so diurnal variations are included. Also shown are the reduced-major axis regression lines (solid lines), the regression slopes (s), intercepts (d) and correlation coefficients (r). Grey dashed lines indicate the 1:1 ratio.

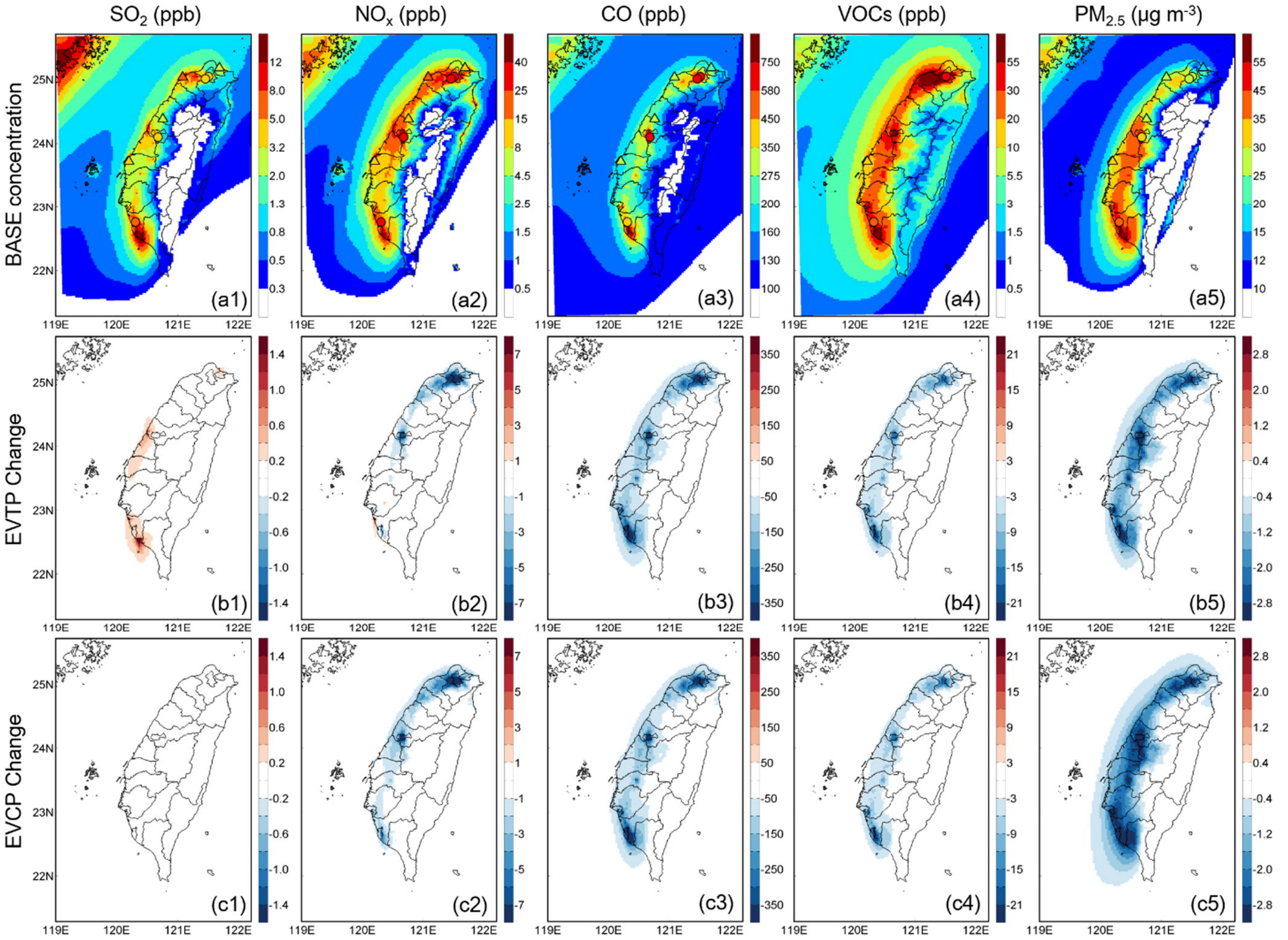

Fig. 4. Spatial distributions of simulated annual mean surface concentrations of SO_2, NO_x, CO, VOCs and $PM_{2.5}$ in Taiwan 2010 for the BASE case (a1–a5), overlaid with observed annual mean concentrations at the urban (circles) and rural (triangles) sites. Also shown are the changes in concentrations for the EVTP (b1–b5) and EVCP (c1–c5) scenarios.

around the clock, and reductions were more substantial in urban than in rural sites. Concentration reductions were particularly prominent during the morning and evening rush hours, synchronized with the peaks in the baseline case. Combined with the spatial patterns discussed above, our results suggest that large reductions in NO_x, CO, VOCs and $PM_{2.5}$ concentrations tend to occur at times and places with high pollutant concentrations. The SO_2 concentration behaved rather differently, showing diurnally flat increases for both urban and rural sites in the EVTP scenario, but changing little in the EVCP scenario. Note that the diurnal patterns of the concentration changes showed little seasonal differences in most sites (see Figs. S16–S21).

Table 3 summarizes the air quality impacts of EV penetration averaged for all 69 sites (46 urban and 23 rural sites). Replacement with EV could markedly reduce annual mean concentrations of NO_x (7–21%), CO (45–65%), VOCs (20–21%) and $PM_{2.5}$ (4–8%) in both EVTP and EVCP scenarios, with more substantial effects in urban than in rural areas. SO_2 generally increased by 2–5% due to the extra burden of electric power generation in the EVTP scenario.

Table 3
Observed and simulated annual mean surface pollutant concentrations averaged for the 69 sites in Taiwan 2010 and the changes in concentrations in the EV scenarios.

	Urban sites (n = 46)				Rural sites (n = 23)			
	Observation	BASE	EVTP	EVCP	Observation	BASE	EVTP	EVCP
SO_2 (ppb)	4.6	5.2	+0.1 (+2%)	<±0.1 (<±1%)	3.7	4.3	+0.2 (+5%)	<±0.1 (<±1%)
NO_x (ppb)	26.9	24.7	−4.5 (−18%)	−5.3 (−21%)	16.0	13.6	−1.0 (−7%)	−1.8 (−13%)
CO (ppb)	541	506	−328 (−65%)	−329 (−65%)	342	274	−123 (−45%)	−123 (−45%)
VOC (ppb)	39.8[a]	68.7	−14.1 (−21%)	−14.1 (−21%)	19.7[a]	28.7	−5.6 (−20%)	−5.6 (−20%)
$PM_{2.5}$ (μg m^{-3})	31.9	39.3	−2.5 (−6%)	−3.1 (−8%)	29.9	30.6	−1.2 (−4%)	−1.8 (−6%)
O_3 (ppb)								
24-h average	26.6	31.0	+0.8 (+3%)	+1.2 (+4%)	30.8	36.4	−0.5 (−1%)	<±0.1 (<±1%)
Peak time[b]	45.7	48.7	−1.7 (−3%)	−1.3 (−3%)	48.7	48.1	−2.2 (−5%)	−1.7 (−4%)
Rush hours[c]	23.8	28.5	+1.4 (+5%)	+1.7 (+6%)	28.8	35.1	−0.3 (−1%)	−0.2 (−1%)

[a] For VOC observation, the values are averaged for 5 urban photochemical sites and 3 rural photochemical sites, respectively.
[b] O_3 peak time: 12:00–14:00 local time.
[c] Rush hours: 6:00–9:00 and 17:00–20:00 local time.

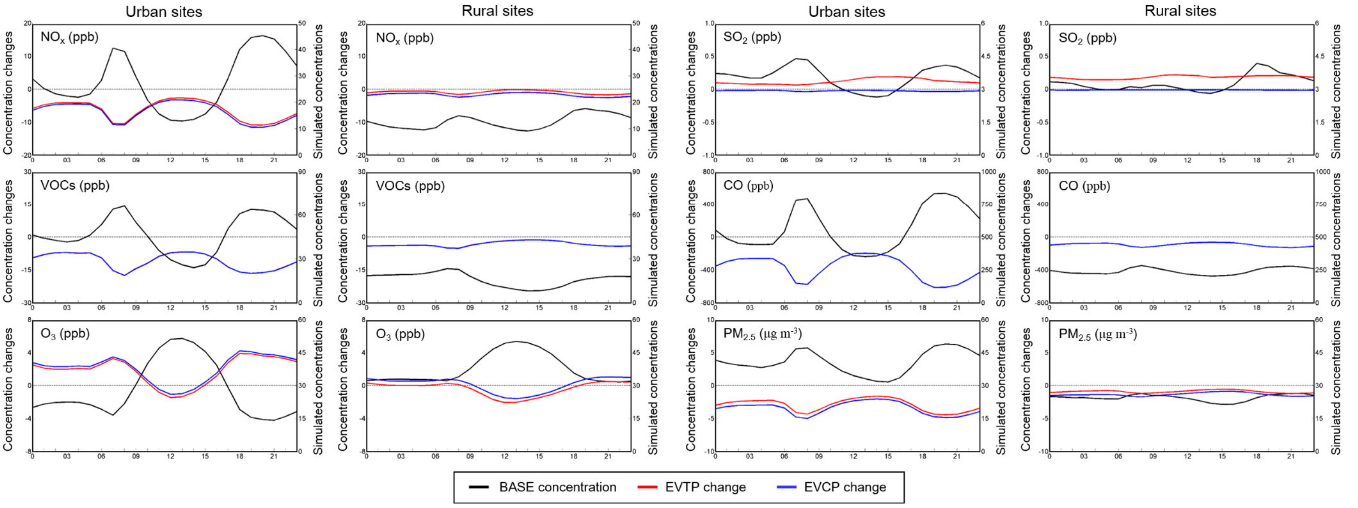

Fig. 5. The diurnal variations of simulated annual mean surface concentrations of NO_x, VOCs, O_3, SO_2, CO and $PM_{2.5}$ averaged for the eight selected urban and rural sites in Taiwan 2010 (black). Also shown are the changes in concentrations for the EVTP (red) and EVCP (blue) scenarios.

3.2.2. Ozone

O_3 is a secondary pollutant formed through nonlinear reactions of NO_x and VOCs in the presence of sunlight. O_3 production is most efficient when there is sufficient solar radiation. At night, however, the titration effect of freshly emitted NO dominates and the O_3 concentration tends to drop to a lower level. Fig. 6 shows the spatial distributions of the simulated annual mean concentrations of surface O_3. During O_3 peak time (12:00–14:00 local time), simulated surface O_3 concentrations were higher in western and central Taiwan, consistent with the observations in the same time (NMB = 2%). Replacement with EV could evidently reduce peak O_3 concentrations by up to 7 ppb over almost all of Taiwan, except for a slight increase (<2 ppb) over downtown Taipei. It should be noted that O_3 production regime varies depending on the ratio of ambient VOCs and NO_x (Stockwell and Goliff 2004). For the NO_x-sensitive regime, O_3 concentration tends to decrease in response to reductions in on-road NO_x emissions; however, in the high NO_x emission areas, O_3 concentration reacts in the opposite direction of NO_x emission change.

The inverse response of O_3 concentration to NO_x emission (i.e., the titration effect) is even more obvious during rush hours and at night. Figures 6b3 and 6c3 show that, during the morning and evening rush hours, surface O_3 concentration increased over a much broader area around the Taipei metropolis (up to 6 ppb) and downwind of prevailing winds, as well as over a small portion of Taichung city. For Kaohsiung city, however, there were no significant O_3 increases in the EVTP scenario because the on-road NO_x reduction was offset by the increased emissions from nearby power plants. Daily O_3 concentration was determined by values somewhere between those during the O_3 peak time and rush hours. Fig. 5 suggests that the diurnal patterns of O_3 changes due to the EV effect were negatively correlated with the ambient O_3 concentrations. In the urban areas, reduced NO_x emissions caused O_3 to increase (especially near rush hours), except around noon when O_3 photochemical production is the strongest. Across the rural areas, O_3 concentrations reduced during daytime and stayed the same during nighttime. Overall, EV penetration reduced the averaged O_3 peak value by 1.3–2.2 ppb in both scenarios. The magnitudes of these changes are summarized in Table 3.

3.3. Impacts of EV on pollution episodes

Compared with the impacts on the annual scale, we found that EV penetration would produce even higher benefits in pollution episode mitigation than in mean concentrations. We applied the Air Quality Index (AQI) to define the days of pollution episodes (AQI > 100), and evaluated the influences caused by EV. As shown in Fig. 7, the simulated annual number of days with AQI > 100 was 62 (averaged for the regions with at least one day of AQI > 100; this criterion was used for all further evaluations), which is consistent with the observations (see Table S4). All pollution episodes (simulated and observed) in Taiwan were caused by $PM_{2.5}$ and O_3. A total of 52 annual pollution episode days were caused by excessive $PM_{2.5}$ (24-h average $PM_{2.5}$ concentration exceeded 35 μg m^{-3}) (USEPA, 2012), and a total of 18 days were caused by excessive O_3 (peak 8-hour average O_3 concentration exceeded 70 ppb) (USEPA, 2012). Western and southwestern Taiwan are the most seriously polluted areas; for example, Taichung and Kaohsiung stand out with over 150 d yr^{-1} of episode incidence.

Under EV penetration, O_3 episode days were significantly reduced by as much as 7 d yr^{-1} (39%), averaged for the polluted areas. The largest reductions (up to 35 d yr^{-1}) occurred around the most O_3-polluted areas (i.e., cities of Taichung and Kaohsiung; cf. Fig. 7). Compared with O_3 pollution mitigation, EV penetration had a smaller mitigation effect on $PM_{2.5}$ pollution, reducing annual $PM_{2.5}$ episode days by 3–5 d yr^{-1} (6–10%). The spatial distributions of reductions in $PM_{2.5}$ episode days (Fig. 7) were similar to the patterns of $PM_{2.5}$ concentration changes (Fig. 4). For episodes with AQI > 100 in general, annual mitigation was estimated to be 7–9 d yr^{-1} (population). The mitigation effect was much more prominent over urban areas, because air pollutions in urban areas are mostly caused by transportation sources. Our results suggest that EV penetration could considerably reduce pollution episodes by up to 34 d yr^{-1} (62%) and 44 d yr^{-1} (66%) in the cities of Taipei and Taichung, respectively. However, the improvements over Kaohsiung city (the other most polluted area) would be less significant because the area is influenced strongly by heavy industry and thus would benefit less from EV penetration.

4. Discussion

It should be noted that in addition to uncertainties pertaining to the emission inventory data and the simulations of meteorological fields, some uncertainties also remain with regard to the assumptions used in this study. Firstly, we assumed that the additional electricity to power EVs were proportionately provided by power plants according to their original diurnal patterns. However, previous studies have suggested that charging EVs under smart grid controls (using efficient units and during low electricity demand periods) might significantly reduce the additional emissions from power plants (Sioshansi and Denholm 2009; Thompson et al. 2009). Secondly, we did not consider

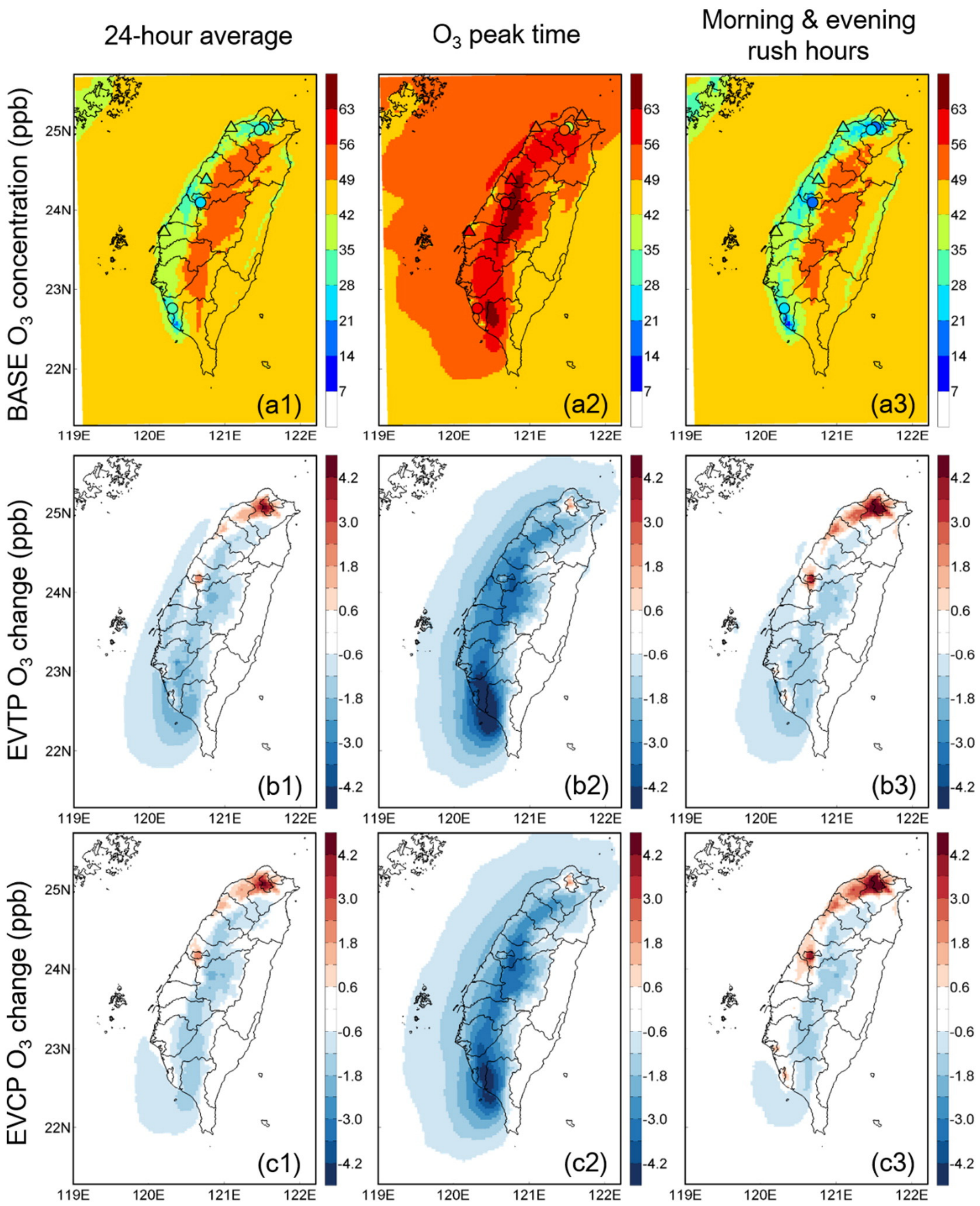

Fig. 6. The spatial distributions of simulated annual mean surface O_3 concentrations (top) and the changes for the EVTP (middle) and EVCP (bottom) scenarios. From left to right are for 24-hour average, O_3 peak time (12:00–14:00 local time) and rush hours (6:00–9:00 and 17:00–20:00 local time), respectively. Also overlaid on the top panels are the observed annual mean concentrations at the urban (circles) and rural (triangles) sites.

the manufacturing process of EV batteries, which would produce considerable emissions of SO_2, NO_x and $PM_{2.5}$ (Tessum et al. 2014). Thirdly, the limitations of the current chemical model (e.g., imperfect understanding of the precursors and formation pathways of SOA) are also likely to have introduced uncertainties into our results.

Our study is the first attempt to explore the potential impacts of EV on air quality in Taiwan. The findings are generally comparable to results from other similar studies. For example, Thompson et al. (2009) found that with PHEVs replacing 20% of the gasoline vehicles and charged overnight could lead to reductions in peak 8-h O_3 concentrations by 2–6 ppb across the northeastern USA, except around Newark and Philadelphia where significant O_3 increase may occur in certain summer days. Brinkman et al. (2010) estimated that, under the 100% PHEV penetration condition, peak 8-h O_3 concentration in Denver would be reduced by 2–3 ppb on most days during summer, except for a small area near central Denver that experienced elevated O_3. In comparison, our results showed decreases in peak 8-h O_3 concentrations by 1.3 to 2.2 ppb annually across Taiwan. Exceptions (elevated O_3) near urban centers also occurred in our simulation but only in the Taipei City. Brinkman et al. (2010) further calculated the associated changes in the frequency of O_3 pollution episode associated with EV penetration, and they fund that the number of 8-h O_3 exceeding the 75 ppb standard would reduce by 20.5% and 17.1% for all-day charging and night charging scenarios, respectively. Our results showed a general improvement in O_3 episode days by 11–15% across Taiwan; the improvement is more significant over the cities, with over 60% reduction in episode days in the cities of Taipei and Taichung. Instead of changes in episode days, Thompson et al. (2009) calculated the changes in

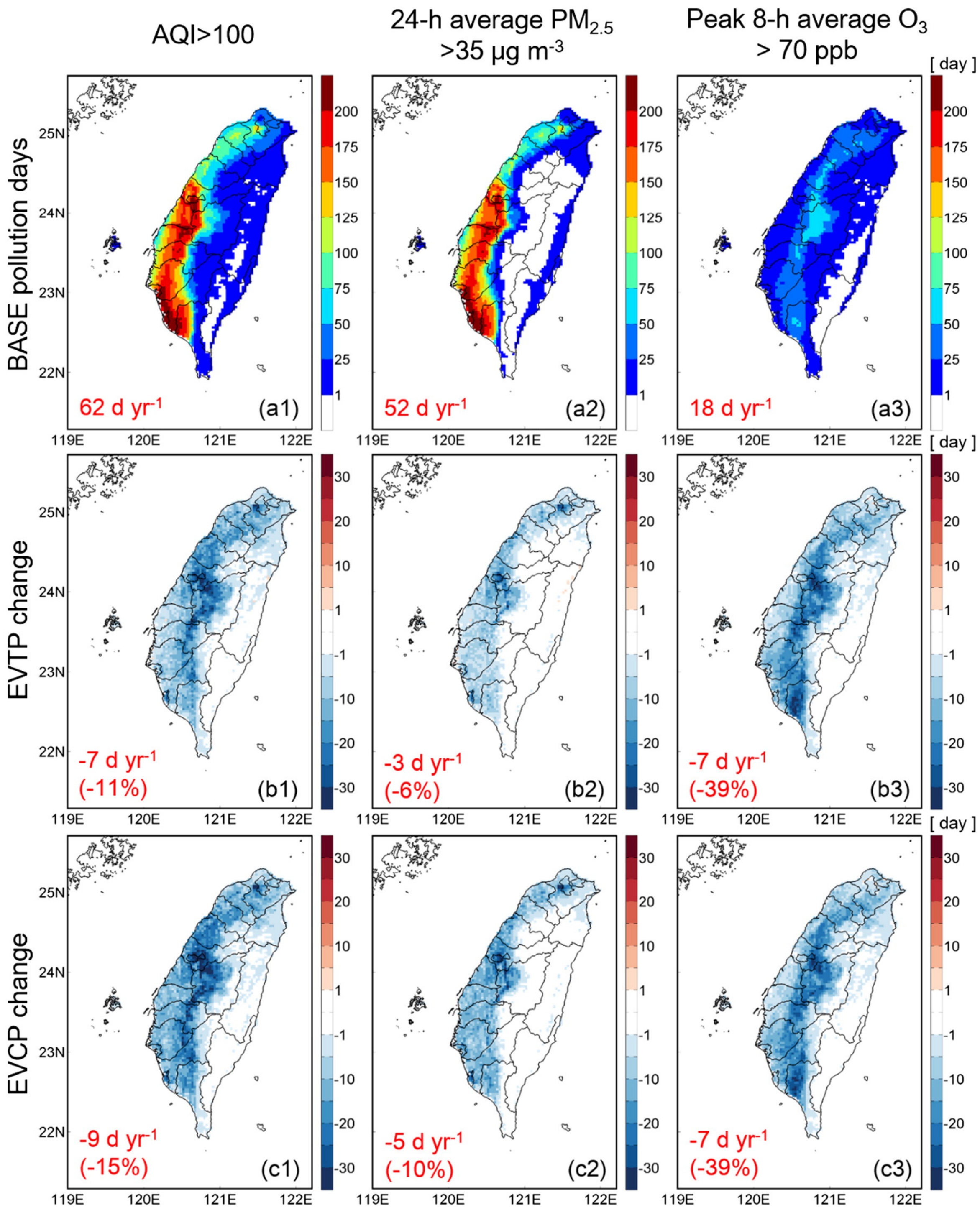

Fig. 7. The spatial distributions of simulated pollution episode days in Taiwan (top), as well as the changes due to the EVTP (middle) and EVCP (bottom) scenarios. From left to right are the frequencies calculated according to Air Quality Index (AQI) > 100, 24-h average $PM_{2.5}$ concentration > 35 μg m^{-3} and peak 8-h average O_3 concentration > 70 ppb, respectively. The regional mean pollution days and changes (averaged for the grids with at least one day of AQI > 100) are shown at the lower left corner in red.

population exposure, showing decreases by 5% and 9%, respectively, in maximum population exposure under the 75 ppb and 85 ppb standards. Such calculations are more pertinent to public health impact assessment, but require high-resolution data on the temporal and spatial distribution of the population which are not available for the studied area. Note that this study assumed full EV penetration, and the associated power demand is evenly distributed among existing power plants; the mitigation benefit could be higher if a smart grid control scheme was implemented. Compared with those studies, our analysis covered a longer period (one-year) to show the patterns in different seasons, and employed a higher spatial resolution (3 km) to compare the characteristic in different regions.

5. Conclusion

Electric vehicles have been identified as a potential option for reducing air pollution, especially over urban areas. In this study, we used a regional air quality model to simulate gaseous and particulate pollutants in Taiwan, aiming at evaluating the prospective impacts of EV penetration on air quality. The simulations were parameterized using the best currently available emission inventories, and the results were compared to the surface chemical measurements.

We assumed a 100% replacement of current light-duty vehicles in Taiwan. The burden of electricity supply (~58.1 billion kWh) was shifted to either coal-fired power plants or clean energy sources. With this ambitious EV penetration, CO, VOCs, NO_x and $PM_{2.5}$ emissions in Taiwan from on-road sources would be reduced by 1500 (85%), 165 (79%), 33.9 (27%) and 7.2 (27%) Gg yr^{-1}, respectively. On the other hand, electric sector NO_x and SO_2 emissions would be increased by up to 20.3 (29%) and 12.9 (29%) Gg yr^{-1} if all electricity were provided by thermal power plants. Overall, total emissions of most pollutants except for SO_2 (which increased by 11%) would be considerably reduced by EV penetration.

We further analyzed the consequent impacts of EV on the level of air quality. Replacement with EV would be effective in reducing annual mean surface concentrations of CO (by 260 ppb), VOCs (by 11.3 ppb), NO_x (by 3.3 ppb) and $PM_{2.5}$ (by 2.1 μg m^{-3}), while SO_2 would increase slightly (by 0.1 ppb). The large reductions tended to occur at times and places with high ambient concentrations. Greater benefits would clearly be attained if clean energy sources were fully encouraged. EV penetration would cause widespread reductions in annual average O_3 peak values (up to 7 ppb) across Taiwan, except for a slight increase (<2 ppb) in downtown Taipei. Further analysis suggests that EV penetration would tend to be of significant benefit to the mitigation of high pollution episodes. Calculated regional mean pollution episode days (AQI > 100) in Taiwan would be reduced by 7–9 d yr^{-1} (11–15%), and the local reductions may reach 44 d yr^{-1} in highly-polluted Taichung city. We found O_3 and $PM_{2.5}$ to be the main causers of air pollution, and attributed at least 70% of the improvements to O_3 reduction. Our findings are important for understanding the potential effects of EV on air quality, and can provide useful information to local governments for use in air pollution strategies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.05.105.

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