



Photochemical Smog Modelling Using the Air Pollution Chemical Transport Model (TAPM-CTM) in Ho Chi Minh City, Vietnam

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Abstract

This paper describes the application of the air pollution model (TAPM-CTM) for photochemical airshed modelling in the Ho Chi Minh region. The model was developed by the Commonwealth Scientific and Research Organisation (CSIRO), Australia, and incorporates both a prognostic meteorological component and photochemical component. Based on the emission inventory developed by Vietnam National University, simulation of meteorological and chemical transport dispersion processes for air quality in Ho Chi Minh City (HCMC) is performed using TAPM-CTM. The model performance is evaluated using publicly available measured meteorological data at Ho Chi Minh City airport and air quality data as measured by the Hydro-meteorological Center of Southern Region and our research team at the Ho Chi Minh City University of Science. The model is then applied to simulate a 1-month period in the dry season to determine the extent of the photochemical pollution in Ho Chi Minh City and the surrounding areas. The results show that under the north easterly prevailing wind in this period, the high pollution is more likely to be experienced in the south west of Ho Chi Minh in the Long An, Tien Giang, Ben Tre and Vinh Long provinces. It is recommended that monitoring stations should be set up in these provinces to monitor the peak ozone events that are formed due to transport of precursors from Ho Chi Minh City. The results show that TAPM-CTM performed well as applied to the Ho Chi Minh City airshed region and is a promising tool to study scenario emission for air quality management in this city and the surrounding areas.

Keywords Air quality model · Photochemical smog · Ozone · Ho Chi Minh air pollution

1 Introduction

Ho Chi Minh City (HCMC) is the largest city in Vietnam in terms of population and its importance in economic output. In recent years, as the population increases rapidly with an increasing number of cars and motorcycles causing frequent traffic congestions, the air quality in HCMC is becoming a

more pressing problem to manage for the city authority. The city's population in 2015 is 8,247,829 inhabitants [1]. The actual population of the city in recent years has increased by about 110,000 people every year, causing great pressure on the environment the city in general and in particular the transport infrastructure. HCMC has over 8.5 million motorcycles (among that there are 7.43 million motorcycles are registered in HCMC, the rest 1.07 million motorcycles come from the neighbouring provinces to work and circulate in HCMC) and nearly 508 thousand cars with an increase rate of 14.5%/year, motorcycle with an increase rate of about 5.4%/year and more than 1 million bicycles [1]. The sharing mode of transportation in HCMC is as follows: public transport is about 3.7%, about 96.3% of the remaining is for the use of private vehicles which consists mainly of motorcycles [2].

In a recent study of the relationship between air pollution and human health, over 90% children less than 5 years old in HCMC were suffering from respiratory diseases [3]. According to the World Economic Forum in 2012, Vietnam is one of the 10 countries which have the worst air pollution in the world [4]. And in the urban area such as HCMC, traffic is the major contributor to air pollution [5]. According to the

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World Health Organization (WHO) [6], the air pollutants due to emission from traffic activities are very dangerous, especially super fine particle $PM_{2.5}$. They cause respiratory diseases, lung cancer and mortality. $PM_{2.5}$ concentration in HCMC (129 micrograms/ m^3) is 3.5 times higher than the national standard [7]. Roadside NO_2 monitoring concentration is also several times higher than Vietnam National Guideline for ambient air (QCVN 05 2013, namely QCVN from now). For example, the average of NO_2 in 2015 ranged from 30.12 to 128.73 $\mu g/m^3$, 99.33% of the monitoring values are lower than QCVN. Especially, at the busy An Suong road intersection, 10% of the monitoring value is higher than QCVN for NO_2 . The PM_{10} concentrations were also regularly higher than QCVN, with the concentration of the pollutants in the air is so high that they can cause extremely severe impact on the human health and the younger generation of HCMC future. The monitoring data showed that the ozone concentration in HCMC also exceeded the QCVN almost 2 times. In 2012, International Agency for Research on Cancer (IARC) has classified diesel engine emission to Group 1 *Carcinogenic to humans*. The IARC also reported that emissions from diesel engines from trucks, cars, train or boat were one of the major causes of lung and bladder cancer [8]. Thus, we have sufficient evidence about the impact of air pollution on human health, and we have sufficient evidence that the current air quality in HCMC is extremely polluted.

Ho Chi Minh City urgently needs to conduct air quality studies for developing abatement strategies to reduce pollution level. However, air pollution problems are complex; therefore, air quality model is an essential tool to calculate the dispersion of air pollutant emissions and study the chemical process in the atmosphere in HCMC. The objectives of this research are the following: (i) Prepare air emission inventory for several sources such as traffic, industrial and household sources of primary pollutants or precursors of photochemical products such as nitrogen oxides, carbon monoxide and volatile organic compounds (VOCs); (ii) simulation of meteorological and chemical transport dispersion processes for air quality in Ho Chi Minh City by using TAPM-CTM model. Evaluation of the simulation was carried out to determine the appropriate simulation method; (iii) and finally, predict photochemical smog over Ho Chi Minh City and the surrounding provinces.

2 Material and Methods

2.1 Methods

2.1.1 Method for Development of an Air Emission Inventory

Traffic Source The EMISENS model was applied to calculate air emission from traffic activities [9]. EMISENS mode divides emission into hot emission, cold-start emission and extra

emission as in Eq. 1. Generally, the total emissions are the sum of hot emissions (the emissions when a vehicle is running, with the engine thermally stabilised), cold emissions (the emissions when a vehicle is running, during engine warm-up) and evaporative emissions (the emissions from fuel due to the difference between the temperature of engine and ambient temperature). The equation for total emissions is shown below:

$$E_{\text{total}} = E_{\text{hot}} + E_{\text{cold}} + E_{\text{extra}} \quad (1)$$

where E_{total} is total emissions of pollutant I; E_{hot} is hot emissions; E_{cold} is cold emissions; E_{extra} is evaporation emissions, tire and brake wear.

Industrial Source Industrial air emission was estimated from 282 major sources (such as iron, steel, cokes, refinery and cement, among others) as boilers, chimneys, generators, etc. in HCMC. Activity data for each source were collected as fuel consumption, fuel type, treatment methods, etc. The small industrial sources using charcoal emit small emissions and were estimated in area source. Main information required is fuel consumption for each source and also conducted in study from stationary emission sources of Ho Chi Minh Environmental Protection Agency (HEPA)/HCMC DoNRE (Department of Natural Resources and Environment).

Air emission for industrial sources was estimated (Eq. 2) using the emission factors

$$G_i = \sum_{i=1}^{282} (K_i + N_i) \quad (2)$$

Where G_i is air emission ($kg \text{ day}^{-1}$); K_i is emission factor of fuel ($kg \text{ kg}^{-1}$ or $kg \text{ m}^{-1}$); and N_j fuel consumption of type j ($kg \text{ day}^{-1}$ or $m^3 \text{ day}^{-1}$).

Area Sources Air emission generated from area sources are household activities and small restaurants from fuel combustion (gases, LPG, charcoal and firewood). To estimate PM_{10} emission, we used Eq. 3 and emission factors.

$$E_i = e_i \times P \quad (3)$$

where E_i is emission of pollutant i ($kg_i \text{ day}^{-1}$), e_i emission rate of pollutant i ($kg_i \text{ day}^{-1} \text{ person}^{-1}$) and P population (number of persons).

Biogenic Source Air emission from biogenic source was estimated based on the area of vegetation over HCMC and the air emission factor. The area of vegetation was calculated by the land use map of HCMC.

2.2 Method for Meteorological and Air Quality Modelling

Simulation of air pollution over an urban area such as Ho Chi Minh City is performed by using an air quality model. The TAPM model, a three-dimensional prognostic meteorological

and air pollution model, was developed by the Commonwealth Scientific and Research Organisation (CSIRO) in Australia for use in air quality studies on a local, regional or inter-regional scale [10]. Recently, an enhanced version of TAPM called TAPM-CTM was also developed by CSIRO to include options to use the Lurman, Carter and Coyner (LCC) or the Carbon Bond 4 and 5 (CB4, CB5) photochemical mechanisms [11]. The original TAPM only has the simplified generic reaction set (GRS) photochemical component, which was based on smog chamber studies.

The meteorological component of TAPM is an incompressible, optionally non-hydrostatic, equation model with a terrain-following vertical coordinate for three-dimensional simulations. Cloud/rain/snow micro-physical processes, turbulence closure, urban/vegetative canopy and soil and radiative fluxes are modelled and parameterized in equations. The model solution for winds, potential virtual temperature and specific humidity is weakly nudged with a 24-h e-folding time towards the synoptic-scale input values of these variables [9].

TAPM uses the coarse resolution (~80 km) global meteorological data output from The Australian Community Climate and Earth-System Simulator (ACCESS) model developed by the Australian Bureau of Meteorology (BOM) to downscale in higher resolution, such as 3 km by 3 km, to any region of interests in the world. The ACCESS models, as developed by The Australian Bureau of Meteorology (BOM), are based on the UK Meteorological Office's Unified Model (UM). Other global reanalysis meteorological host data such ERA-interim or NCEP (National Centers for Environmental Prediction) can be adapted to be used with TAPM.

The governing equation for pollutant concentration (C) includes the advection, diffusion of pollutants and terms to represent pollutant emissions S_C and chemical reactions R_C

$$\frac{dC}{dt} = \frac{\partial}{\partial x} \left(K_{HC} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{HC} \frac{\partial C}{\partial y} \right) - \left(\frac{\partial \sigma}{\partial z} \right) \frac{\partial}{\partial \sigma} (\overline{w' C'}) + S_C + R_C \quad (4)$$

where

$\overline{w' C'}$ = $-K_C \frac{\partial C}{\partial \sigma} \frac{\partial \sigma}{\partial z}$ is the vertical flux and with diffusion coefficients $K_{HC} = \min(10, K_C)$, $K_C = 2.5 K$ and K is the eddy diffusivity.

The chemical reaction component is a separate module from TAPM and was developed to account for different advanced chemical mechanism such as the LCC, CB4 or CB5 chemical mechanism. This module, called the chemical transport module (CTM), replaces the built-in GRS chemical mechanism in TAPM. The CTM chemical mechanism used in this study is based on the Carbon Bond 5 (CB5) mechanism with two-bin aerosol module ($PM_{2.5}$ and PM_{10}). The combined TAPM-CTM, which integrates the meteorological prognostic TAPM output with the CTM CB5 photochemical smog

model component, allows the model to be run for a long period. TAPM-CTM has been used widely in Australia and the results have been verified in various meteorological and air quality studies [12–14]. A schematic diagram of the TAPM-CTM modelling system is shown in Fig. 1.

The TAPM-CTM is a Windows-based PC desktop system which integrates both the meteorological component and the CTM component. It has a simple GUI interface to define the modelling domains and take input data from the downloadable global meteorological ACCESS data and emission data in CIT (California Institute of Technology) model standard text-formatted file. The CIT model is based on LCC chemical mechanism and mostly used by researchers in the US state of California.

2.3 Data

TAPM's standard data sets include global terrain height with a resolution of 30 s (~1 km), vegetation and soil type with a resolution of 3 min (~5 km) and 30 s (~1 km), respectively. A higher terrain height resolution of 9 s (~0.3 km) can be obtained from the Australia National Mapping Agency, AUSLIG, for use in the model. Global reanalysis meteorological host data from 2011 to 2016 are available online and can be downloaded from CSIRO ftp site ftp://ftp.csiro.au/TAPM/SYNOPTIC_DATA/.

In addition to the standard data sets provided within the TAPM system and synoptic data from ACCESS, the simulation of photochemical events requires point source and gridded emission data within the region under consideration. For Ho Chi Minh City, we use the emission inventory as developed by Institute for Environment and Resources, Vietnam National University, Ho Chi Minh City.

Meteorological data from Tan Son Nhat airport in Ho Chi Minh City for 2015 is used for evaluating the TAPM meteorological prediction. The meteorological data are obtained from the publicly available automated airport weather observation network (ASOS or METAR data). Monitored air quality data from 04 sites located at the University of Natural Science (UNS), Nha Be, site 1 and site 2 in Ho Chi Minh City as measured by our team and from the local government are used to evaluate the TAPM-CTM modelling system.

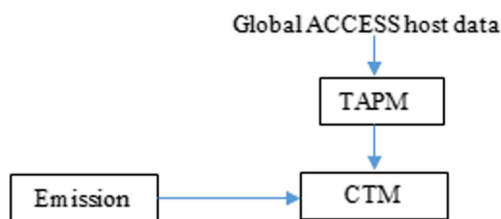


Fig. 1 TAPM-CTM modelling system

2.4 Definition of Study Area

The TAPM-CTM simulation is based on 3 grid configurations with the outer most grid for meteorological simulation only and the two inner grids for both meteorological and chemical simulation (provided with emission grid sources).

The inner most grid configuration is 90 by 90 grid points with 2 km grid size in both the x and y direction (see Fig. 1). The outer grids are also 90 by 90 grid points with 3 km grid size and 4 km grid size, respectively. The simulation results in the outer most grid configuration, which is in coarse resolution and runs faster, provide the meteorological boundary conditions for the next inner grid. The results from this grid in turn provide the boundary condition for the inner most grid. The centre coordinate of these grids is set to be the same as the Ho Chi Minh emission inventory domain (Fig. 2).

The Ho Chi Minh City emission inventory domain is 90 km by 90 km with grid resolution at 1 km. The domain has the centre coordinate at 10.759° latitude and 106.641° longitude (or 679,380 m Easting and 1,189,899 m Northing for UTM projection).

There are 25 vertical levels with heights (in meters) of 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 750, 1000, 1250, 1500, 1750, 2000, 2500, 3000, 3500, 4000, 5000, 6000, 7000 and 8000.

The biogenic emission calculation for NO_x , isoprene, monoterpene and cineole is an updated version of the canopy and grass emission based on the algorithms used for the CIT (California Institute of Technology) model [10].

2.5 Emission Inventory

A complete air emission inventory was developed over HCMC for many sources in HCMC, including key sources such as traffic sources, industrial sources, household sources and biogenic sources. The emission inventory (EI) is calculated with a temporal resolution of 1 h and a spatial resolution of 1 km \times 1 km. The EI is calculated for NO_x , SO_2 , CO, NMVOC and CH_4 and not include the particle matter (PM) because modelling of particulate, such as PM_{10} and $\text{PM}_{2.5}$ including secondary organic aerosols (SOA), requires a more comprehensive emission inventory with much more species to be accounted for than the current emission inventory allows and the use of better models such as CMAQ (Community Multi-scale Air Quality Model) or CAMx (Comprehensive Air Quality Model with Extension).

Table 1 presents the results of total EI for all emissions sources in HCMC and the percentage of contribution of each emission source towards the total emissions in HCMC. The column “total emissions” represents the total emissions (in ton

Fig. 2 The TAPM modelling domain (inner most grid) shows Ho Chi Minh City and the surrounding area. The emission inventory grid is yellow-shaded. The coordinate is in UTM projection (zone 48P)

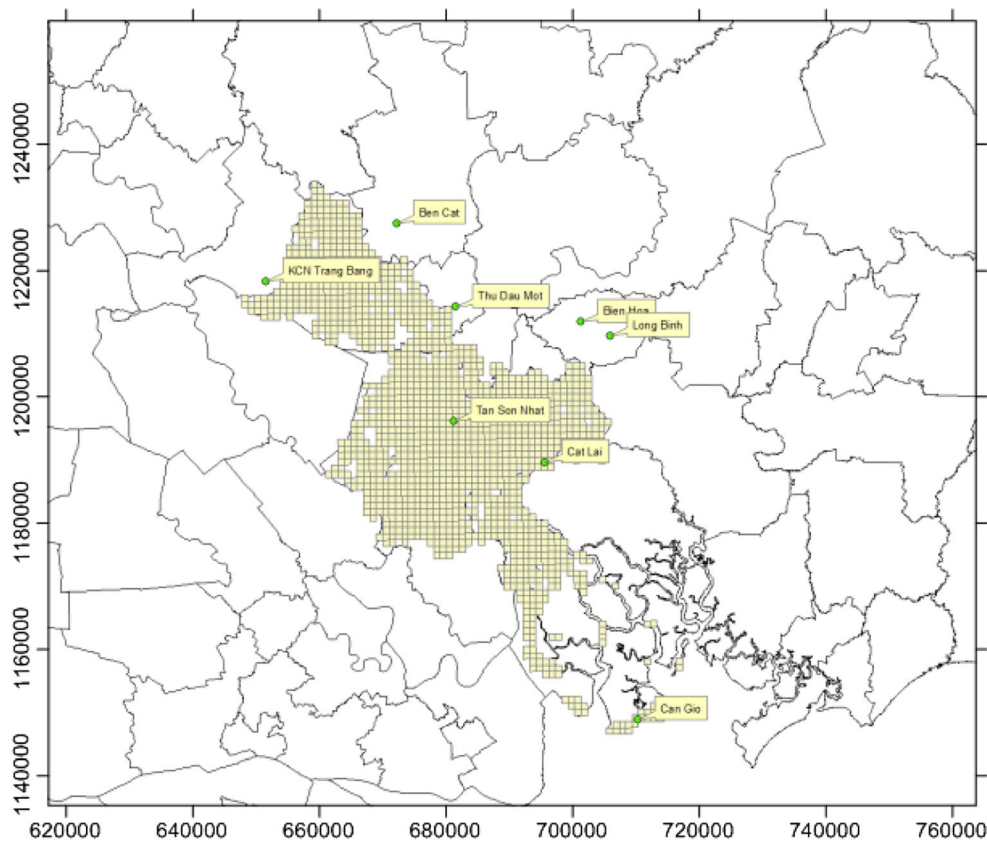


Table 1 Total emissions in HCMC [ton day⁻¹] and the contribution of each emission source on the total emissions in HCMC (in %)

Pollutant	Total emissions	Industry (%)	Residential + other (%)	Biogenic (%)	Traffic (%)
NO _x	106.27	15.79	6.46	–	77.75
CO	8860.25	5.45	4.78	–	89.77
SO ₂	1603.37	80.42	18.49	–	1.10
NM VOC	1241.45	1.90	8.33	0.38	89.39
CH ₄	214.81	27.02	33.19	16.98	22.80

per day). The last four columns correspond to the percentage of contribution of each emission source on total EI.

The traffic sources in Table 1 contribute with the highest percentage of total emissions (CO accounted for 89.77%; NMVOC 89.39% and NO_x 77.75%). Among that, the emissions from motorcycle for CO, NMVOC, SO₂ and NO_x occupy more than 94, 68, 61 and 29%, respectively of total road traffic emissions. The motorcycle category is the most important source of emissions from traffic (except NO_x because the heavy truck category is the most important source of NO_x emissions). The main reason for this is because motorcycles constitute more than 86% of the total vehicles in HCMC. A large number of motorcycles have low-quality engine and are not maintained properly and regularly. In addition, motorcycles in Vietnam have not been inspected periodically for smoke.

The emissions of SO₂ from industrial sources are very important and accounting for 80.42% of the total emission of SO₂ because the industry in HCMC uses a lot of diesel oil, mazut oil and fossil coal which contain high percentage of sulphur as fuel.

Figure 3 shows the spatial distribution of the total emissions of CO, NO_x, formaldehyde and isoprene. The patterns of the total emissions of CO are similar to the emissions of NO_x with the highest emission in the centre of HCMC because the emissions of traffic occupy more than 77% of total emission in case of CO and NO_x. The highest emissions are in the city centre where we find the highest-density streets.

The TAPM model provides a number of different pollutant emission types to be used as input to the model. These include point sources, line sources, area sources and gridded surface sources. The seven optional gridded surface emission files are gridded surface emissions (GSE) which is independent of meteorology; biogenic surface emissions (BSE), at T_{vege} = 30 °C, PAR (photo-synthetically active radiation) = 1000 μmol m⁻² s⁻¹ for VOC, and at T_{soil} = 30 °C for NO_x; wood heater emissions (WHE), at T_{screen24} = 10 °C for all pollutant species; vehicle petrol exhaust emissions (VPX), at T_{screen} = 25 °C for VOC, NO_x and CO; vehicle diesel exhaust emissions (VDX), independent of meteorology; vehicle LPG exhaust emissions (VLX), at T_{screen} = 25 °C for VOC, NO_x and CO and vehicle petrol evaporative emissions (VPV), at T_{screen} = 25 °C for VOC.

As the emission data are given in tons/day for all species (CO, CH₄, CO₂, NO₂, NO_x, PM, SO₂, VOC) from all combined sources at each grid point, the gridded surface emission (GSE) is used for input to TAPM. The total emission is dominated by anthropogenic sources. Time resolving the emission into hourly is done by scaled weighting of the total daily into an hourly diurnal pattern with peak emission at 8 a.m. and 9 a.m. in the morning and 5 p.m. and 6 p.m. in the afternoon which coincide with the traffic pattern emission in Ho Chi Minh City.

As the CB4 or CB5 photochemistry mechanism requires the emission values of some important species rather the lumped VOC as given in the emission data, an assumption is made to segregate the total VOC into these individual species. This assumption is based on the box model testing of CB4 and CB5 implementation in CMAQ under an MIR (maximum incremental reactivity) condition with an urban emissions mix of VOCs and NO_x where the VOC/NO_x ratio is low, and hence, VOC has the greatest incremental impact on the ozone production rate [15]. For CB5 mechanism, the VOC composition has the following fractional contribution to moles carbon of these species: PAR (0.675), ETH (0.045), OLE (0.034), TOL (0.116), XYL (0.078), MEOH (0.001), ETOH (0.009), ISOP (0.5), CRES (0.002), FORM (0.009), ALD2 (0.006), IOLE (0.018), ALDX (0.003).

2.6 Model Evaluation

Model validation should include both spatial pattern and temporal patterns of key variables. Temporal pattern comparison can be achieved with the use of the Taylor diagram which encapsulates 3 temporal indices: variances (model and observation), root mean square (RMS) errors and correlation [16]. Another temporal comparison index is the index of agreement (IOA). The refined Willmott IOA d_1 is defined as [17].

$$d_1 = 1 - \frac{\sum_{i=1}^n |P_i - O_i|}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)} \quad (5)$$

where P_i and O_i as the predicted and observed values at time i .

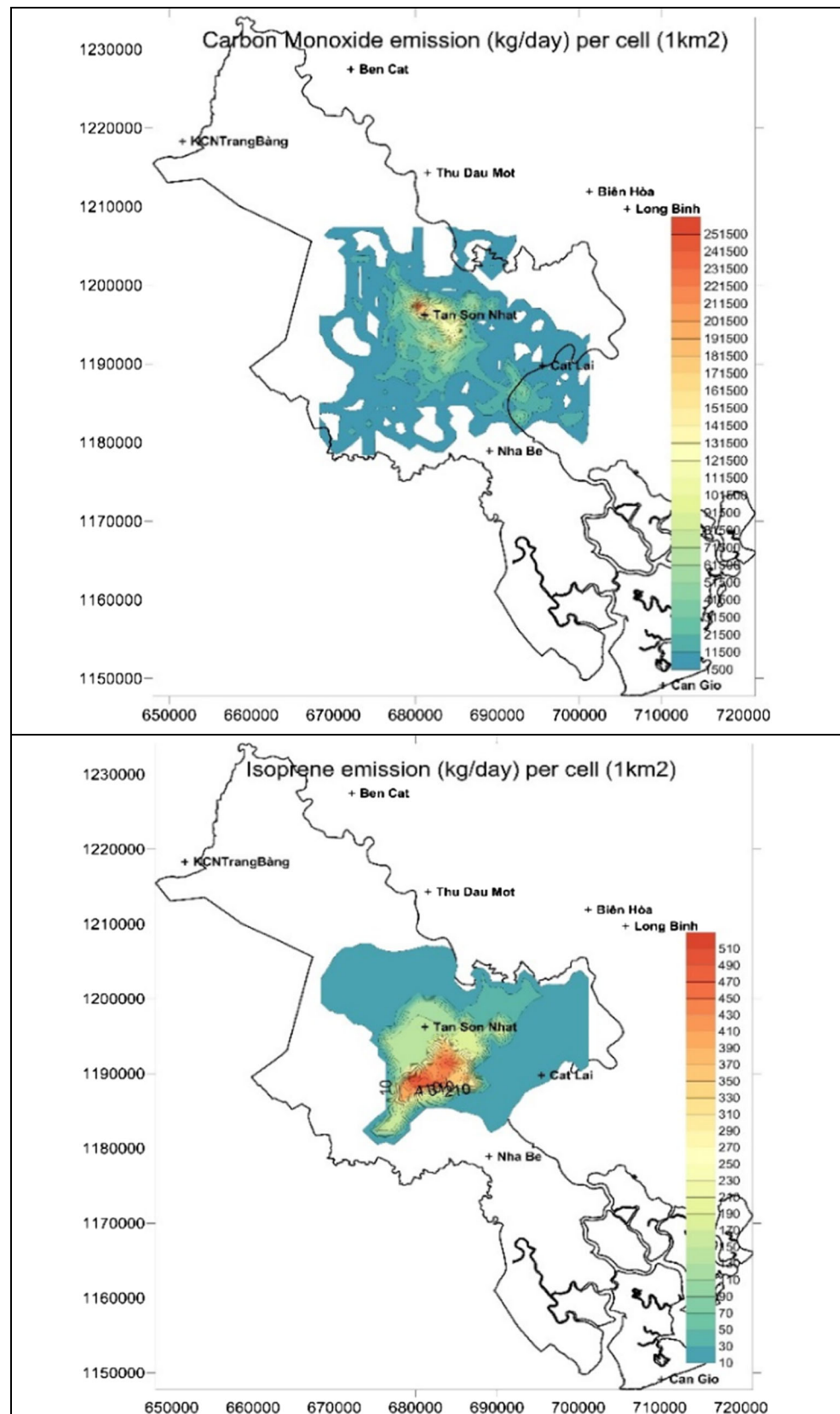
While the original index is

$$d = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (6)$$

(with 1 as perfect match and 0 as zero match)

Other metrics can also be used in addition to the IOA and 3 key temporal indices as described above. In particular, biases should be included. The model bias (MB), normalised mean bias (NMB), normalised mean error (NME), mean fractional

Fig. 3 The total daily emission contours of carbon monoxide (CO) and isoprene as extracted from the Ho Chi Minh City emission inventory



bias (MFB) and mean fractional error (MFE) are used for model evaluation. The mean bias (MB) and normalised mean

bias (NMB) assume that observations are the absolute truth and these metrics can be dominated by a few outlier data

points, while the MFB and MFE consider prediction and observation on equal footing and bound the maximum bias and error with MFB in the range of from -200% (extreme under-prediction) to $+200\%$ (extreme over-prediction) and MFE from 0% to $+200\%$. Most studies, Boylan and Russell [18] and guidance such as that provided by the US-EPA [19] use the MFB or MFE for bias evaluation.

3 Results

3.1 Performance of Meteorological Output

Meteorological observation data from Tan Son Nhat airport (10.8167° lat, 106.6667° lon) automated surface observation system (ASOS) are obtained from Vietnam ASOS network. The data are used to verify the performance of the TAPM-CTM prediction. Temperature is the surrogate for solar radiation which is the important factor in the production of ozone. Temperature and wind (wind speed and direction) are parameters that are evaluated with observed data. The most commonly referenced meteorological benchmarks in the literature were established by Emery et al. [20] who conducted the modelling over the eastern and mid-west of the USA where the terrain is considered flat and “simple”. For more complex terrain, the benchmarks provided by McNally, 2009 and Kemball-Cook et al., 2005 are more appropriate [21, 22]. We use the Emery et al., 2001 benchmark reference where the metrics are specified in this study [20].

3.1.1 Surface Temperature Comparisons

At Tan Son Nhat Airport site, the predicted temperature for January to June 2015 correlates well with observed temperature as shown in the time series plots and the regression analysis (Fig. 4). The regression of paired hourly predicted and observation temperature gives the regression equation as y (pred.) = $0.9964 \times$ (observation) and $R^2 = 0.76$. The index of agreement (IOA) is 0.92.

From Fig. 4, the predicted temperature is generally good for maximum temperature during the day with some over predicted values in the range between 25 and 30 °C. For minimum temperature during the day, the predicted values are mostly less than the observed values (between 17 and 23 °C). The overall correlation coefficient for the period from January to June 2015 is 0.87 which is acceptable. Note that the observed temperature data as measured at Tan Son Nhat airport is in 1 °C resolution as shown by the discontinuities in the regression and Q-Q plots of Fig. 4b, c. The IOA metric is 0.92 which satisfies the recommended range (>0.8) by Emery et al. (2001). The mean bias (MB) and normalised mean bias (NMB) are 0.39 and 0.014, respectively while the MFB and MFE are 2.7 and 8.9%. The MB is conforming to the Emery et al., 2001 recommended range of less than ± 0.5 [20].

3.1.2 Surface Wind Comparison Analysis

The surface wind as predicted by TAPM-CTM for the period of January to June 2015 is compared with observed wind at the meteorological stations at Tan Son Nhat airport monitoring station (Fig. 5).

Note that the resolution of observed wind speed is 0.5 m/s which explains the discontinuity in the Q-Q (quantile to quantile) plot as shown in Fig. 5c. The Q-Q plot shows the predicted wind speed performs well. Over prediction only occurs in high wind condition. The root mean squared error (RMSE) and MB for wind speed are 1.3 and 0.003 m/s which conform to the recommended range <2 m/s and $<\pm 0.5$ m/s of Emery et al. [20].

Re-plotting the predicted and observed wind (Jan to June 2015) using wind rose to incorporate wind direction for comparison, as shown in Fig. 6, shows that the predicted surface wind at Tan Son Nhat airport monitoring station corresponds reasonably well to the observed data in the dominant south east wind direction at the site, except in the north east direction the predicted wind is higher than observation and in the south west the predicted wind speed is less than observation.

The overall IOA for wind speed is 0.55 which is less than that for temperature. The recommended IOA range by Emery et al. for wind speed is greater or equal to 0.6 (≥ 6) [20]. The IOA for wind speed is therefore a little less than the recommended range. One of the reasons for this is that the surface roughness length for the urban area near the airport is not accounted for in the model.

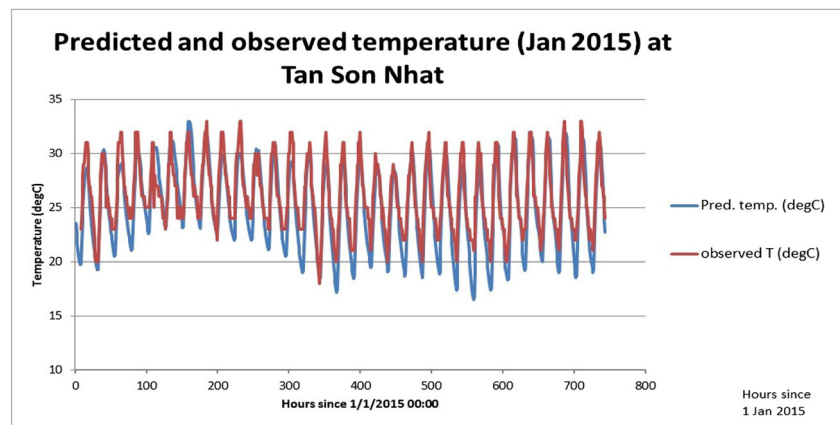
The mean absolute error (MAE) for the wind direction is 52.36 degrees which is not in the recommended range of Emery et al. [20] which has the range as <30 degrees. However, for the more complex terrain benchmarks from McNally [21] and Kemball-Cook et al. [22], the wind direction MAE is within the range of less than 55 degrees.

3.2 Comparison of Observed Air Quality Monitoring Data and Prediction

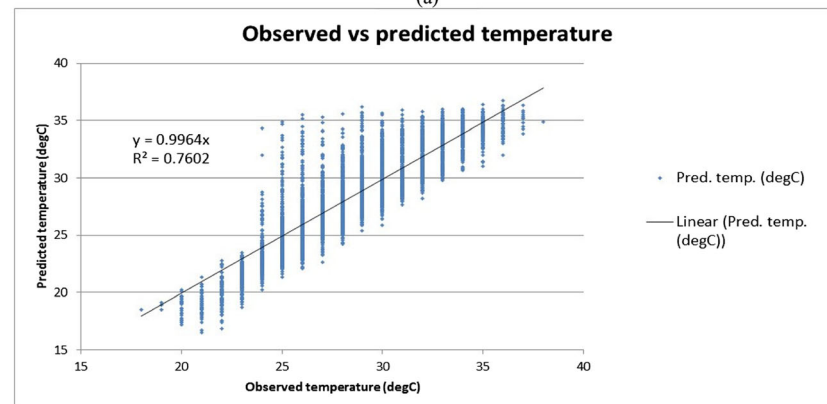
The comparison of observed air quality monitoring data and prediction at 04 sites in the study domain is as follows:

- The site UNS is located at 227 Nguyen Van Cu Street, District 5 with latitude of $10^\circ.762549$ and longitude of $106^\circ.682428$.
- The Nha Be site is located at 10.6500° latitude and 106.7167° longitude
- The site 1 is located at 110D Dinh Tien Hoang Street, Ward 3, Binh Thanh District, Ho Chi Minh City, Vietnam, with latitude of $10^\circ.47423$ and longitude of $106^\circ.41842$.
- The site 2 is located at Hang Xanh—Dien Bien Phu roundable, Ward 25, Binh Thanh District, Ho Chi Minh City, Vietnam, with latitude of $10^\circ.48109$ and longitude of $106^\circ.42652$.

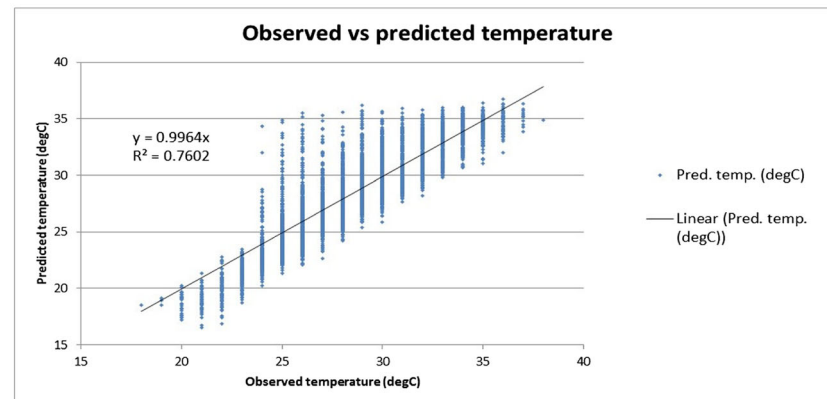
Fig. 4 **a** Predicted and observed temperature (Jan 2015) at Tan Son Nhat: Time series of observed (red) and predicted (blue) temperature shown only for January 2015. **b** Observed vs predicted temperature: Regression analysis of observed (x -axis) and predicted (y -axis) surface temperature at Tan Son Nhat airport from January to June 2015. **c** Temperature quantile-quantile at Tan Son Nhat: Q-Q plot of observed versus predicted temperature from January to June 2015



(a)



(b)



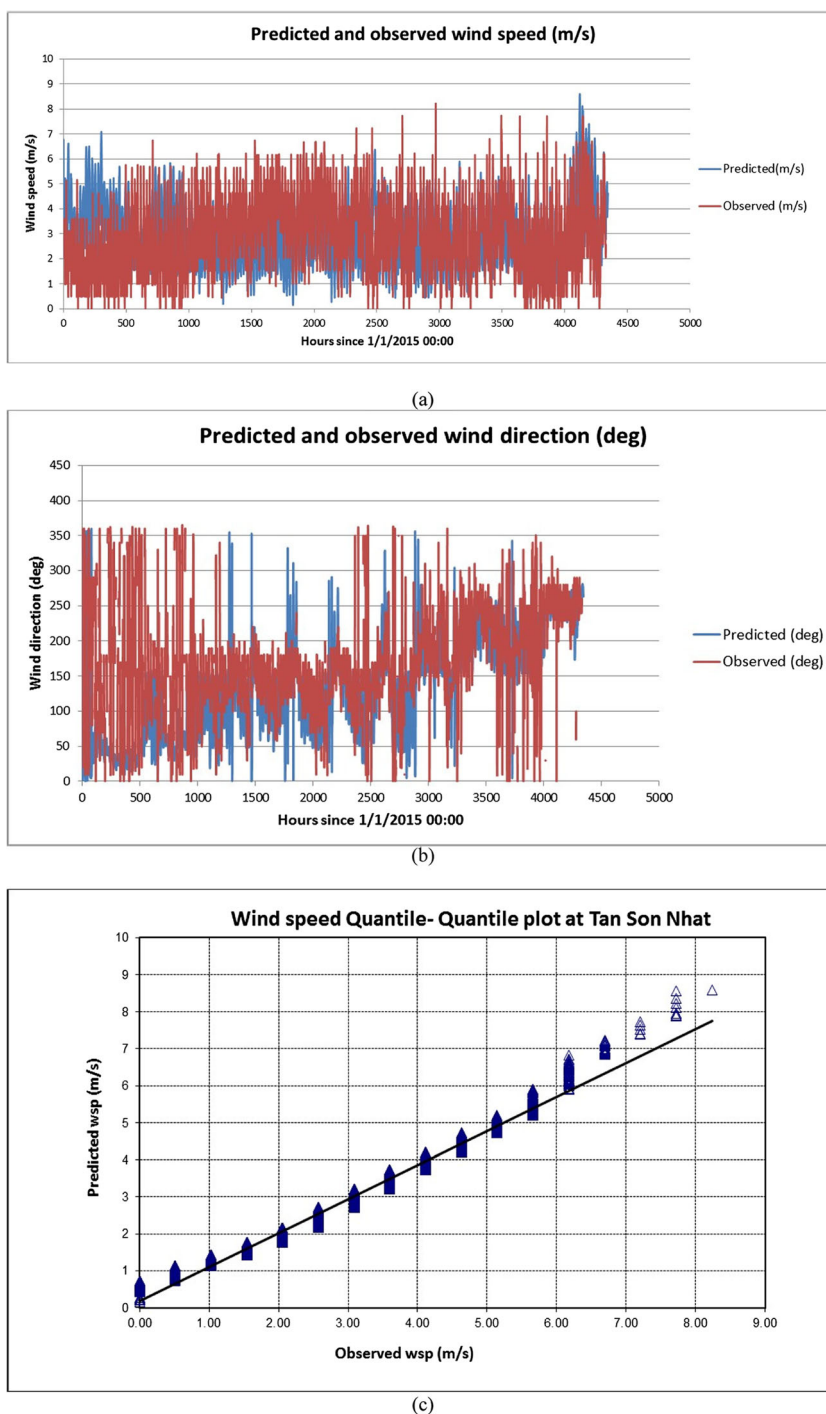
(c)

Time series plot of predicted ozone at a monitoring station located at Nha Be, a southern suburb of Ho Chi Minh City (shown in Fig. 3) and the other located at the University of Natural Science (UNS), Ho Chi Minh City, is compared with observed data. The data from Nha Be was provided by the Hydro-meteorological Center (Southern Region) and cover the period from 1/3/2015 to 31/3/2015 while the measured ozone data at the UNS site is from 7/12/2015 to 9/12/2015, and the UNS site at 227 Nguyen Van Cu Street, District 5 with latitude of 10.762549° and longitude of 106.682428° . The time series plot of predicted and observed ozone is shown in

Fig. 7. These days are typical dry season days after the wet monsoon period of late April to late October ends and the high pollution usually happens in Ho Chi Minh City.

The index of agreement (IOA) for the predicted ozone as compared with observed observation for the Nha Be site is calculated to be 0.96 for March 2015 and for the UNS site the IOA is 0.9 for the 3 days period from 7/12/2015 00:00 to 9/12/2015 23:00. Adeeb [29], in a study of ozone simulation using TAPM in Adelaide, considered the IOA for ozone of 0.82 as very good. Nath and Patil [30] in the study of ozone simulation using IMG-BM (in situ mixing growth-box model) considered the IOA of

Fig. 5 Predicted (red) wind speed (a) and direction (b) compared to observation (blue) at Tan Son Nhat for January to June 2015 (c) wind speed quantile-quantile plot at Tan Son Nhat



0.9 as good model performance. Our IOA of 0.9 using TAPM for ozone performance evaluation is considered as good.

Comparison of observed air quality monitoring data and prediction at the site 1 and site 2 in March 2015 having mean absolute percentage error (MAPE) values are 11.7 and 12.1%, respectively.

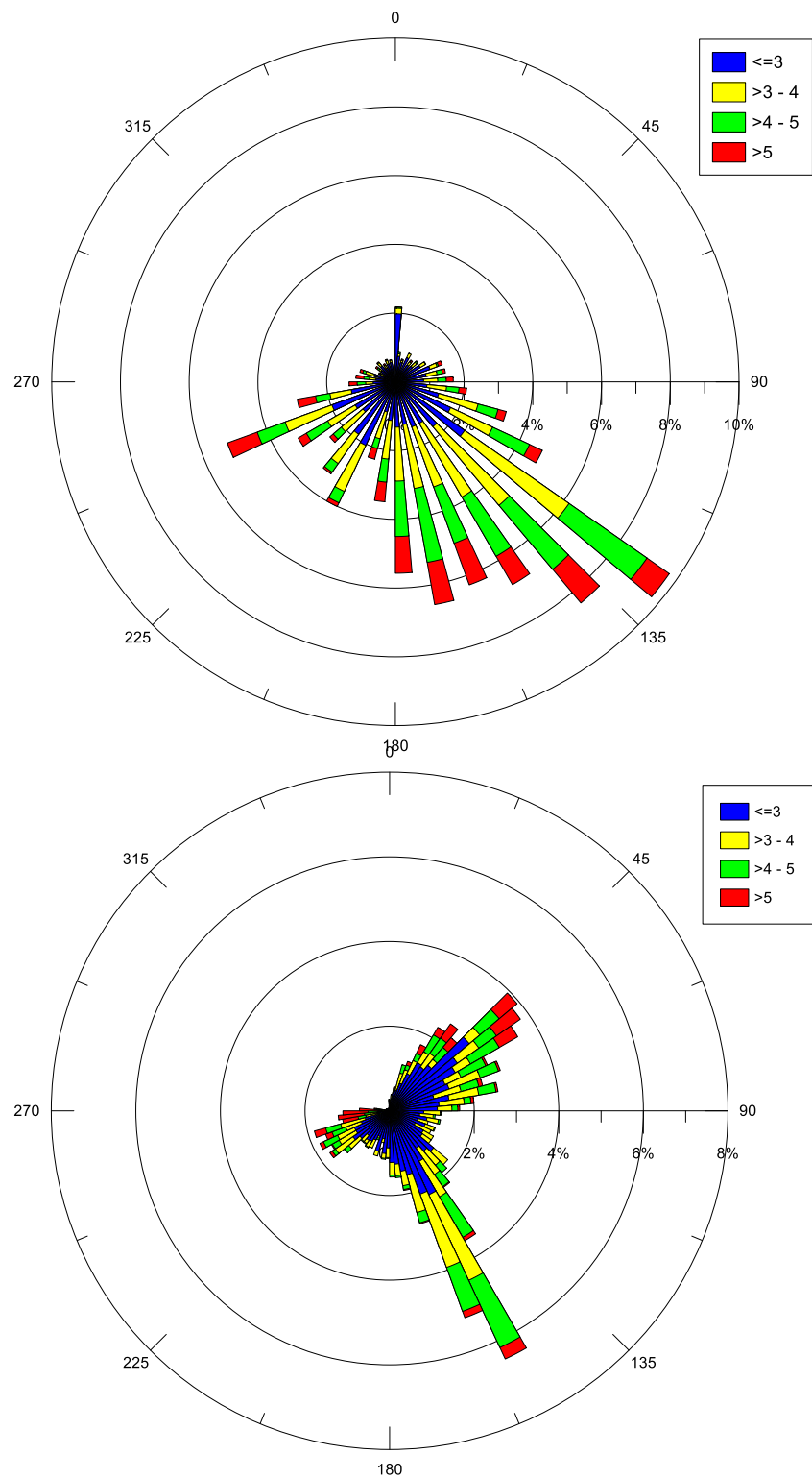
The spatial and temporal patterns, as well as the magnitude and the phase of the predicted ozone concentrations, are equally important when evaluating model performance. For this reason, reliance on summary statistics of each series is not

considered adequate. These analyses should be supplemented with some form of correlation method and root mean square errors such as that used in the Taylor diagram [16].

A summary statistics including the correlation coefficient, root mean square error (RMS), mean bias (MB) mean fractional bias (MFB) and mean fractional error (MFE) of the observed and predicted ozone for the UNS site is shown in Table 2.

The mean bias, normalised bias and mean fractional bias are negative and indicate that the model overall underpredicts

Fig. 6 Tan Son Nhat observed surface winds (top) and TAPM predicted winds (bottom) for the period from January to June 2015

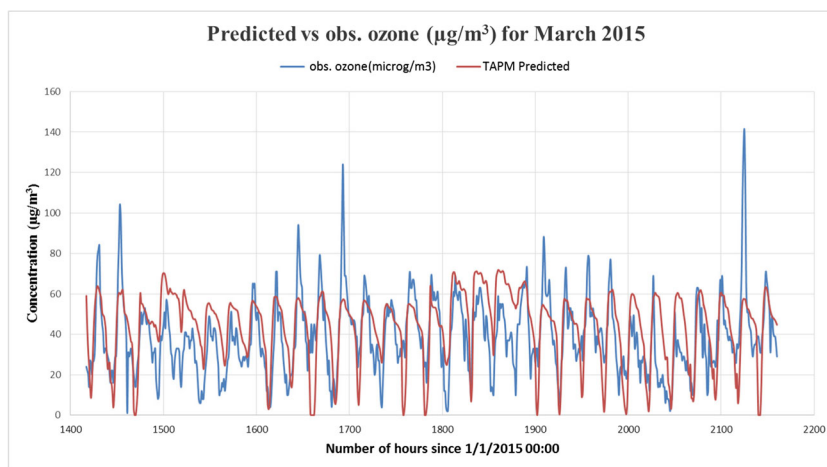


the ozone at UNS site. The ozone prediction at Nha Be site also underpredicts the very highest peaks. But at some days where the daily ozone is not so high, the prediction is higher than the observed.

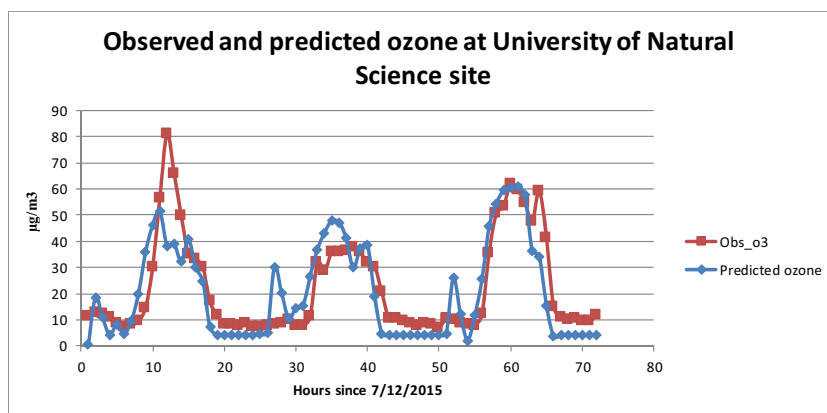
There are a large number of methods for evaluation of air quality modelling in literature, the guidance provided by the US-

EPA [19] for ozone species is followed in this study. According to the US EPA [19], the benchmarks of MFB and MFE are ± 15 and 35%, respectively for ozone. The MFB and MFE in our case (11 and 43%) for Nha Be and (-25 and 56%) for UNS are just outside these ranges. The reason for this is the ozone prediction for minimum values at UNS site during night time is too low.

Fig. 7 Predicted ozone versus observation at monitoring station (a) Nha Be for 1/3/2015 00:00 to 31/3/2015 23:00 and (b) UNS (University of Science) site (starting date time of 7/12/2015 00:00 to ending date time of 9/12/2015 23:00)



(a)



(b)

But we are more concerned with the high or peak ozone values during daytime, and the high ozone prediction during daytime is reasonably good at UNS site. Gao et al. [23] in their study of climate change impact on ozone in the USA has used the cutoff values of 40 and 80 ppb for observation to calculate the NMB, NME, MFB and MFE to reduce the biases of small observed values according to US EPA guidance [19]. Using the cutoff values of 5 ppb (or 10 $\mu\text{g m}^{-3}$) at our site, i.e. ozone less than the cutoff values not used in the evaluation, the MFB are +10 and -10% for Nha Be and UNS site, respectively and are within the guideline. The corresponding values for MFE are 38 and 42% for Nha Be and UNS site, respectively. This means they are still outside the guideline range for MFE.

In any air quality model, there are several aspects that could be contributing to the differences between the simulations and the observations. Uncertainties in the meteorological component of the simulation have a significant impact on the model performance. It should also be noted that there are considerable uncertainties in the emissions inventory used.

In addition, sensitivity analysis showed that the choice of VOC reactivity was important in influencing the results. Relatively small changes in the specified background levels of VOC and NO_x also resulted in significant changes to the

predicted maximum ozone concentration. The HCMC emission inventory covers only the metropolitan urban area, and

Table 2 Summary statistics of predicted and observed ozone, correlation, RMS, mean bias (MB), normalised mean bias (NMB) and mean fractional bias (MFB) at the sites is shown in this table. Unit is in $\mu\text{g/m}^3$

Metric	Nha Be		University of Science	
	Observed ozone	Predicted ozone	Observed ozone	Predicted ozone
Mean	38.58	43.80	22.3	20.64
Standard deviation	18.81	17.43	18.5	18.23
Correlation	0.58		0.82	
RMSE	14.23		10.41	
Mean bias (MB)	5.22		-1.66	
Normalised mean bias (NMB)	0.0		-0.01	
Mean fractional bias (MFB)	0.11		-0.25	
Mean fractional error (MFE)	0.43		0.56	
Index of agreement (IOA)	0.96		0.9	

hence underestimate the contribution of biogenic emission outside the urban area. However, on the basis of these comparisons as shown in Table 2, the TAPM-CTM model does perform reasonably well with respect to the ozone prediction.

4 Discussion

TAPM-CTM has been applied to study the extent of the pollution from the HCMC and the surrounding areas as the prevailing wind in a rather flat landscape can carry pollutant plume in HCMC to affect the downwind areas. For example, the extent of the pollution plume from HCMC can cover the surrounding areas in the neighbouring provinces as the wind usually persist in one particular direction for a number of hours, as shown in Fig. 8 for the nitrogen dioxide plume on the typical high dry season day of 1st March 2015 at 2 a.m. The south west and west immediately to HCMC are mostly affected by the nitrogen dioxide plume.

We have performed a simulation for the entire 1-month period of January 2015 during the dry season to study the extent of pollution in HCM City and the surrounding areas. The impact of emission in HCM City on the pollution in the south west during January 2015 when the prevailing wind is north easterly is evident from the results of the photochemical smog simulation using TAPM-CTM. High ozone level is experienced in the south west in Long An and Tien Giang provinces as shown in Fig. 9 for ozone and precursors of nitrogen oxides and VOC.

High ozone level is experienced in the south west in Long An, Tien Giang, Ben Tre and Vinh Long provinces as shown in

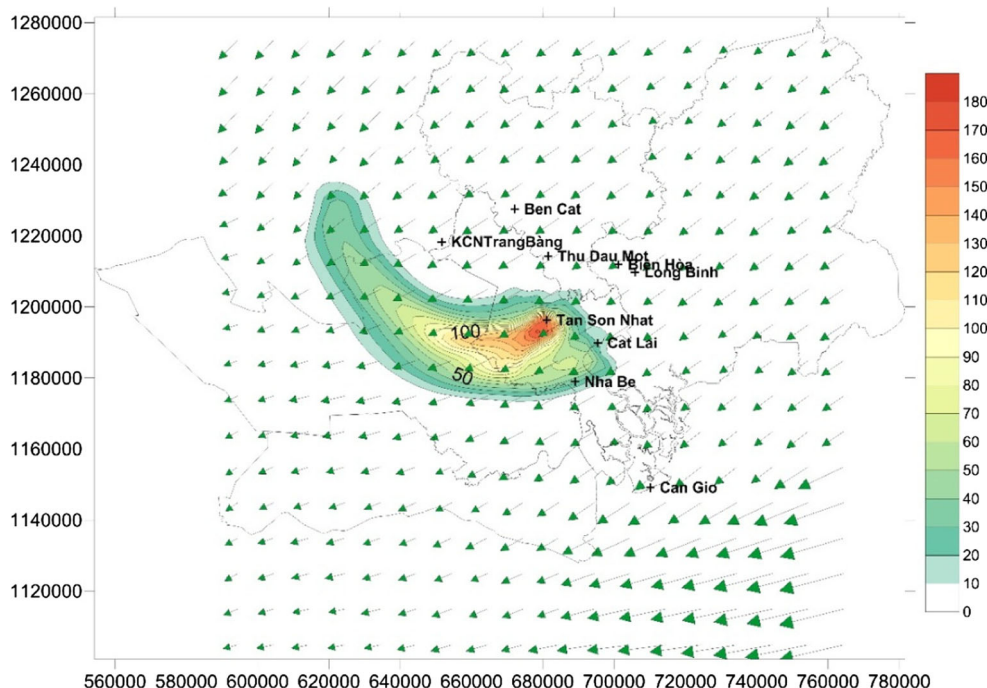
Fig. 9 which depicts the contours of maximum ozone, nitrogen oxides (NO, NO₂) and VOC (toluene) precursors. These provinces are downwind from the main sources of precursor emission in the urban area of Ho Chi Minh City. The maxima of NO₂, NO and toluene precursor concentration occur within the HCM centre with NO₂ at 135.5 ppb, NO 181 ppb and toluene 15.3 ppb. The maximum ozone concentration of about 65 ppb occurs in the provinces of Tien Giang, Ben Tre and Vinh Long.

Many studies [7, 24, 25] have shown that downwind areas experience high ozone pollution from precursor sources upwind at distances of hundreds of kilometres. These downwind non-urban or rural areas with high ozone concentrations can lead to low productivity of some crops as high ozone is known to damage and reduce plant growth [26].

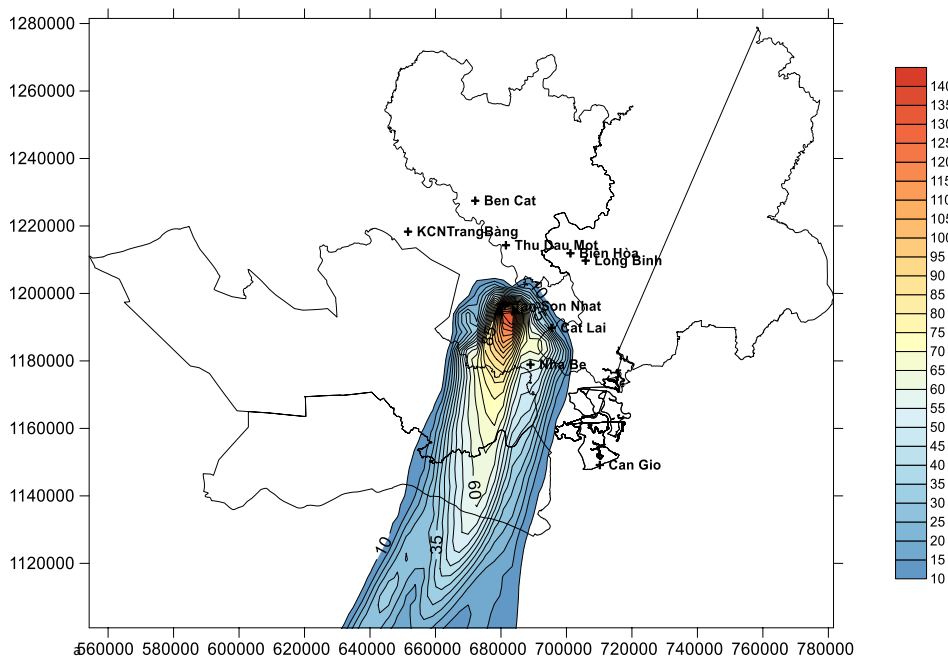
Currently, there are no monitoring sites in the neighbouring provinces in the south west of HCMC. It is expected that downwind from emission of ozone precursors will experience high level of ozone in the afternoon when the photochemical process is at peak. The TAPM-CTM has shown that this is the case. For this reason, we recommend the Department of Natural Resources and Environment of the provinces of Long An and Tien Giang to conduct a study to monitor the ozone level to ascertain the degree of ozone transport from Ho Chi Minh City.

The results of ozone simulation in this research are similar with those from the previous study of Le and Nguyen [27] over HCMC which showed that the predicted ozone levels are about 50 ppb and the ozone plume was moving to southwestern during January 2005. Le and Nguyen applied MM5 and CMAQ models for air quality modelling over the continental South East Asia. Besides the similar ozone plume

Fig. 8 Nitrogen dioxide plume on 1 March 2015 at 2 a.m. (ppb)



Predicted maximum NO₂ concentration (ppb) pattern in Jan 2015



Predicted maximum NO concentration (ppb) pattern in Jan 2015

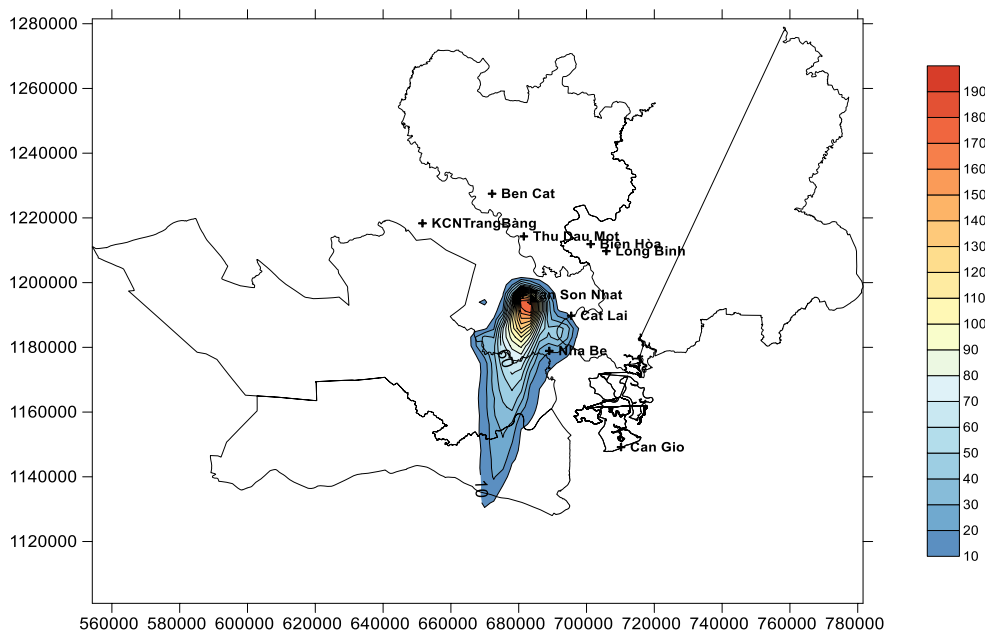


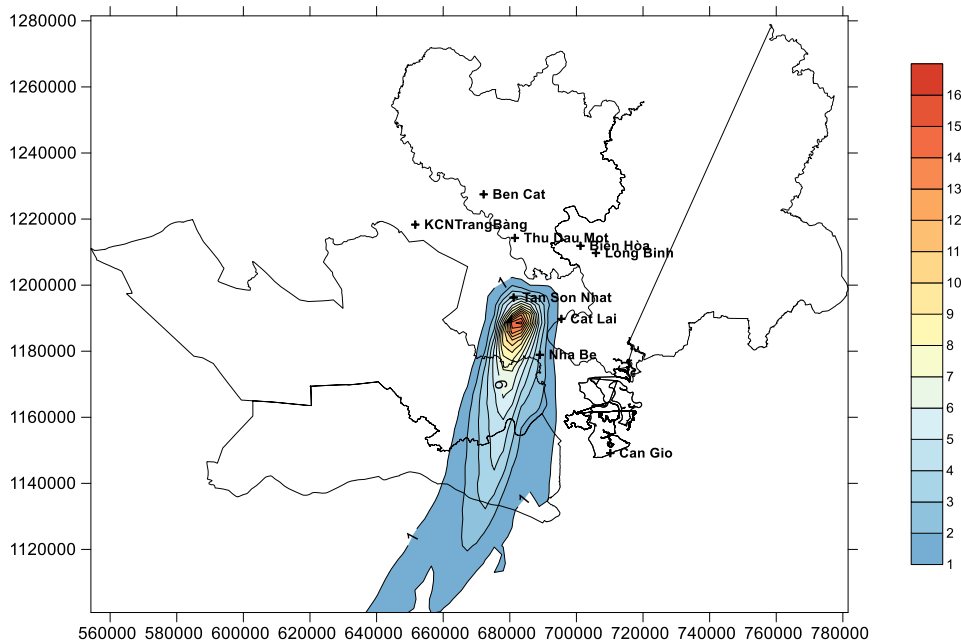
Fig. 9 Spatial pattern of NO₂, NO, VOC (toluene) and ozone as predicted by TAPM-CTM

pattern to ours, their results of ozone in 2005 are about 10 ppb lower than our results in 2015. This difference could also be due to their usage of an air emission inventory derived from satellite image (MODIS) in 2005 and that their simulation was done using an older version of CMAQ model (MM5-CMAQ) which is different from our air quality model.

Another study, by Dung and Thang [28] in 2006 to simulate air quality in HCMC, showed that the ozone level is about 75 ppb and that the ozone plume was moving to south-western

of HCMC during 20 January 2006 which is similar to our ozone plume pattern. Their study used the FVM-TAPM model for air quality modelling and an air emission inventory which was estimated by using a top-down approach. Their results of ozone are higher (about 12 ppb) than those from our study. Again, the difference in magnitude may also be due to the difference in using air emission estimate based on a top-down approach and our approach and the 10 years difference in the corresponding emission estimates.

Predicted maximum Toluene concentration (ppb) pattern in Jan 2015



Predicted maximum ozone concentration (ppb) pattern in Jan 2015

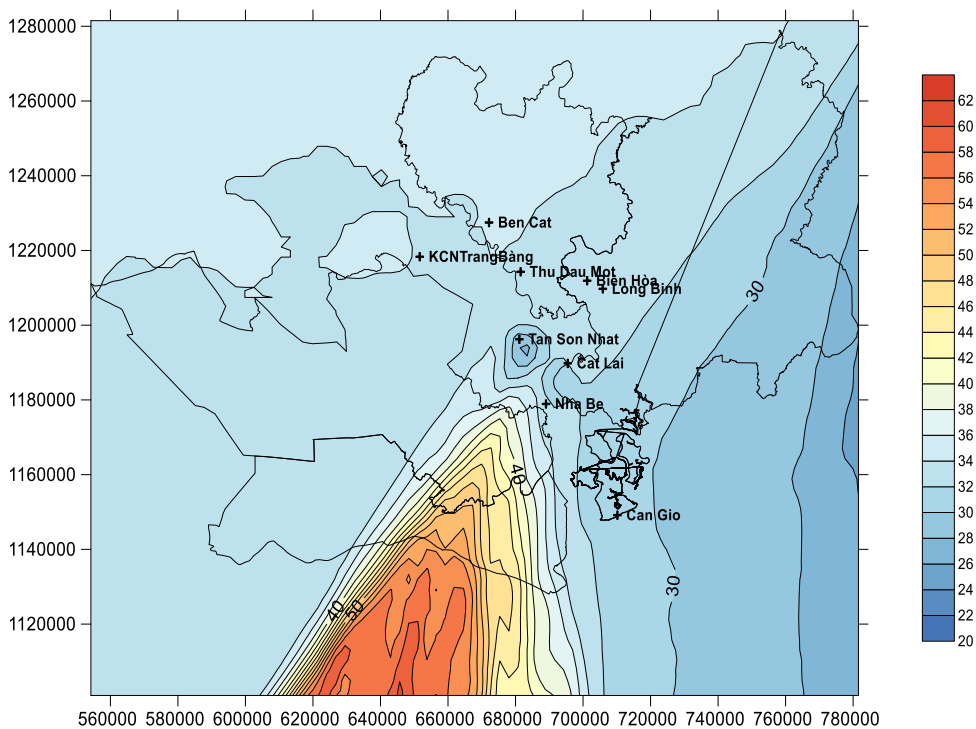


Fig. 9 continued.

Limitations of This Research In the future, the HCMC emission inventory needs to be improved by having a larger spatial dimension to encompass not only the mobile sources, industrial and area sources within Ho Chi Minh city and neighbouring industrial areas but also biogenic and area sources (commercial

and domestic) especially in the east, south and south east of Ho Chi Minh City toward the neighbouring provinces. In addition, a better time resolution such as monthly and weekday/weekend emission variation and more species including PM10, benzene, isoprene, NH₃... are required to improve the accuracy of the

emission inventory. Such an improved emission inventory is being considered by the Institute for Environment and Resources of Vietnam National University in Ho Chi Minh City, and hence, better and more comprehensive modelling systems such as CMAQ and CAMx to model the air quality including PM₁₀, PM_{2.5} and ozone can be utilised.

5 Conclusion

In summary, the meteorological component of TAPM-CTM is performing reasonably well in our validation of meteorological prediction with observed data at Tan Son Nhat airport monitoring station. For the event under consideration, the results of ozone prediction are reasonably good. The predicted values generally follow the pattern of the measured values but there are some differences between the predicted and the observed ozone concentrations. The model underpredicts the high ozone level at the Nha Be and UNS sites and has less variability compared to the observed ozone level.

Overall, for the 31 days simulation at Nha Be and 3 days simulation at the University of Science during the dry season, TAPM-CTM does perform reasonably well in predicting the ozone level. Due to our limited resources at the University to pay for a longer monitoring period to obtain ozone data, only a short period of 3 days are available for our study. This does not validate satisfactorily the TAPM-CTM model for ozone prediction as applied to HCMC compared to other validation of TAPM-CTM that have been done in other cities (Hurley et al. 2003). However, the good validation results for meteorology and the expected change pattern of predicted ozone with observed data give a confidence in the model.

The analyses presented here are based on model results extracted from the model output at the grid points to be matched with observation locations both in space and time. It is acknowledged that the performance of any models would be severely tested using these strict temporal and spatial criteria. However, this performance gives a more realistic expectation from the field workers on comparing the model results with observation data from the monitoring network.

The above results show that the TAPM-CTM model is useful in providing a simulation of airshed photochemical process for a period of time (such as a summer season).

The TAPM-CTM model has been applied to predict the pollutant plumes, such as ozone and nitrogen oxides. From the prevailing north easterly wind during the dry season, it has been predicted that downwind areas of HCMC, such as in Long An or Tien Giang provinces, are more likely to have higher pollution than other provinces in the north and HCMC itself. It is recommended that the monitoring resources should be allocated to these regions to capture the maximum of the ozone and other pollutants rather than concentrate in the metropolitan areas of HCMC.

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