Air quality modelling: an investigation of the merits of CMAQ in the analysis of trans-boundary air pollution from continents to small islands

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Abstract: The purpose of this study is to conduct an air quality modelling assessment of trans-boundary air pollutants from the Asian continent by applying an advanced modelling system – the Community Multi-scale Air Quality (CMAQ) – developed by the US Environmental Protection Agency (USEPA). The focus of the study is trans-boundary ozone, Particulate Matter (PM), and acid deposition, using selected episodes of both non-trans-boundary and trans-boundary scenarios in order to provide an understanding of the characteristics of air pollutants for decision- and policy-makers in Taiwan and its islands. The study demonstrates that the Models-3/CMAQ system is capable of simulating key criteria pollutants reasonably well during a typical day, and within an acceptable run time. The CMAQ system has been designed to simulate air quality, as a whole, by including state-of-the-science capabilities for tropospheric ozone, fine particles, toxics, acid deposition and visibility degradation. It provides additional profiles for decision- and policy-makers, and assists the Taiwan Environmental Protection Administration (TEPA) in developing control strategies to improve air quality in the Taiwan Islands. We conclude that the methods used in this paper are readily transferable to most air quality data sets, and that the CMAQ system can be applied to other small islands around the world.

Keywords: air quality; Models-3/CMAQ; Sparse Matrix Operator Kernel Emissions; SMOKE; trans-boundary; small islands.

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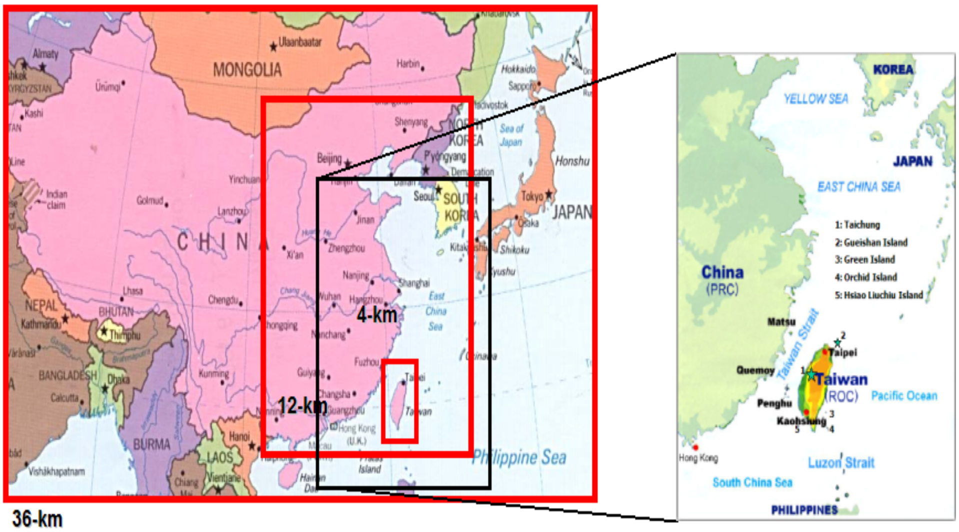
1 Introduction: derivation and role of air quality standards

The main island of Taiwan, Formosa, is surrounded by small islands comprising the Penghu Islands, Hsiao Liuchiu Island, Green Island, Orchid Island, Gueishan Island, Quemoy Island and the Matsu Islands (Figure 1). The environmental loadings of the islands of Taiwan are among the highest in the world, and air quality improvement is a major challenge in the Taiwan islands. The Air Pollution Control Act (APCA) is the legal foundation for all air quality protection policies in Taiwan. The Taiwan Environmental Protection Administration (TEPA) is responsible for implementing policies and measures authorised by the APCA. The original APCA, enacted in 1975, authorised only command-and-control regulation. It has been amended three times to provide legal bases for a comprehensive air quality protection policy. An economic incentive scheme was adopted in the second amendment of the APCA in 1992. TEPA started to collect Air Pollution Fee (APF) in 1995. The APF collection provides economic incentives for the private sector, and funding for TEPA to further improve air quality. Taiwan's air quality has shown much improvement since the collection of the APF (Chen and Chiang, 2000). Currently, TEPA has implement policy tools to control air pollution, including the following:

- tighten emission standards
- stipulate permission regulations
- collect air pollution fees

- promote total capacity control programme
- provide economic incentives for pollution reduction.

Figure 1 Geographical location of Taiwan Islands (see online version for colours)



TEPA adopted the concept of total capacity (CAP) control, and amended APCA for the third time in 1999. TEPA has been implementing a pilot CAP control project in the central Taiwan air basin since 1999, and has expanded the project to the southern Taiwan air basin – including several small islands – which has the worst air quality level among the Taiwan islands. The CAP control provides the flexibility for enterprises (public and private sectors) to select the most cost-effective way to reduce emission. The Air Pollution Fees (APF) fund finances TEPA in various air quality improving projects. These projects include motor vehicles inspection and maintenance, promotion of low-polluting vehicles, compensating new cars to replace old cars, subsidising public transportation, providing free consulting to major emission sources, and subsidising landfill gas power generation. These projects provide even more incentives for air quality improvement.

2 Overview of pollutant characteristics, sources and effects

Sulphur dioxide (SO_2) is formed when fuel-containing sulphur, such as coal and oil, is burned, and when gasoline is extracted from oil, or when metals are extracted from ore. Nitrogen Oxides (NO_x) is a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts, such as NO_2 and NO. Volatile Organic Compounds (VOCs) are emitted as gases from certain solids or liquids. VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. VOCs also are from natural sources, such as isoprene and monterpin emitted from trees and grasses. Natural sources cannot be reduced by environmental conservation, though they have been taken into account in model simulations. VOCs react with NO_x in the presence of heat and sunlight to form ground-level ozone, so called 'bad ozone' or smog. Particulate Matter (PM_{10}) is a particulate with a diameter less than or equal to 10 micrometers (μm), $PM_{2.5}$ describes the 'fine' particles that are less than or equal to 2.5 micrometers in diameter. 'Primary' particles, such as dust from roads or elemental carbon (soot) from wood combustion, are emitted directly into the atmosphere. 'Secondary' particles are formed in the atmosphere from primary gaseous emissions. Examples include sulphate, formed from SO_2 emissions from power plants and industrial facilities, and nitrates, formed from NO_x emissions from power plants, automobiles, and other types of combustion sources. The chemical composition of particles depends on location, time of year, and weather. Generally, fine PM is mostly composed of secondary particles, and coarse PM is largely composed of primary particles. Visibility has been defined as the greatest visual distance at which an observer can see a black object viewed against the horizon sky. Visibility is more closely associated with conditions that allow appreciation of the inherent beauty of landscape features. These pollutants and their sources and effects, as well as Taiwan air quality standards, are summarised in Table 1.

Since the APFs were levied in 1995, the monthly average concentrations of SO_2), NO_x, suspend particulate (PM_{10}, a particulate with a diameter less than or equal to 10 micrometers, 10 μm), and $PM_{2.5}$ (a particulate with a diameter less than or equal to 2.5 micrometers, 2.5 μm) have been decreasing (Chen and Chiang, 2000). The APF scheme helps to establish Taiwan's emission inventory database. More than 5400 factories reported their emission data quarterly, and more than 20 000 reported annually. These data provide the TEPA with a very clear picture of Taiwan's air pollution, and serve as a useful tool towards TEPA's (2001) policy-making.

While APF and CAP rules have successfully helped to decrease air pollution, trans-boundary air pollutants from the Asian continent have hindered TEPA efforts to further improve air quality after the year 2000 (TEPA, 2001). The maximum level reported (Chang and Lee, 2007) over the last decade was 53 ppb in 2003, and that the maximum level reported prior to that was 164 ppb in 1995. However, both the maximum annual mean of O_3, an average of 27 ppb, and the maximum of O_3, an average of 66 ppb, occurred in 2003, indicating an upward trend (Chang and Lee, 2007) in the south Taiwan area, including Hsiao Liuchiu Island. The dust storm from Mongolia caused high PM_{10} levels in January, February and April of 1999. Lin (2001) observed yellow dust events and found high concentrations of yellow sand transported over the Taiwan area including most of the small islands. Lee *et al.* (2006) divided the influences of yellow dusts into three phases, 'before period', 'during period', and 'after period', to identify the dusts from local sand versus those from outside the islands. They found that hourly average density levels of PM_{10} and $PM_{2.5-10}$ were much higher in the 'during period', as compared to those in the 'before period', while finer particles dominated the 'during period', and $PM_{2.5}$ particles were predominant in the 'before and after periods'. In addition, they found the time lapse in the 'during period' was well correlated with the maximum level of both PM_{10} and $PM_{2.5-10}$. Chuang *et al.* (2007) simulated the long-ranged transport episodes and found that major industries along the coastal region in China contributed major particulate concentration with the advection of the high-pressure system to the Taiwan main island and small islands, including the Penghu Islands, Hsiao Liuchiu Island, Green Island, Orchid Island, Gueishan Island, Quemoy Island, and the Matsu Islands. It is noted that there are no obvious emission sources on these small islands. Ozone concentrations are higher in the seasons of spring and autumn when the Asian high pressure systems move from Asian continent southwardly. In winter, the ozone concentration is low since temperature is lower and prevailing wind is faster than other seasons. While in summer, the dominative weather system is mainly local thermal circulation and the Pacific high pressure, ozone concentrations at those selected small island sites are not apparently influence by China mainland (Figure 2). Because quasi-periodic Asian high pressure systems move from Asian continent to the west and south of the Pacific Oceans during cold seasons (autumn, winter, and spring), $PM_{2.5}$ level is always high due to long-range transport. Relatively, $PM_{2.5}$ concentration in summer is low since the main source is local pollution (Figure 2).

In the past, most local air quality issues focused on the three most polluted areas – the greater Taipei, Taichung, and Kaohsiung metropolitan areas (Figure 1) and influenced surrounding islands. It is known that vehicle emission influences the particulate levels of the three major cities in Taiwan (Chen *et al*., 1999). In addition, the effects brought by the posterior factors, such as sea salt, soil, or dust, did bring reactions to the Taipei region (Lee and Hsu, 1996; Chen *et al*., 2001). Liu *et al*. (2002) simulated the distribution of the ozone concentrations in North Taiwan under weak prevailing winds, and concluded that sea-land breeze and mountain-valley wind tended to transport urban ozone and precursor gases to clean coastal and mountain regions. Cheng (2001) concluded that the ozone levels would rise in Taichung City when there was an anticyclone move toward the West Pacific Ocean. Additionally, in the experiment held by Fang *et al*. (2006) from March 2004 to January 2005 in Taichung City, the average mass concentration of Total Suspended Particulates (TSP) $PM_{2.5}$ and $PM_{2.5–10}$ could be 154 μg m^{-3}, 54 μg m^{-3} and 30 μg m^{-3}, respectively. The possible emission sources of particulates were air-slake of crust surface, sea-salt aerosols, agriculture activities, coal combustion and mobile vehicles.

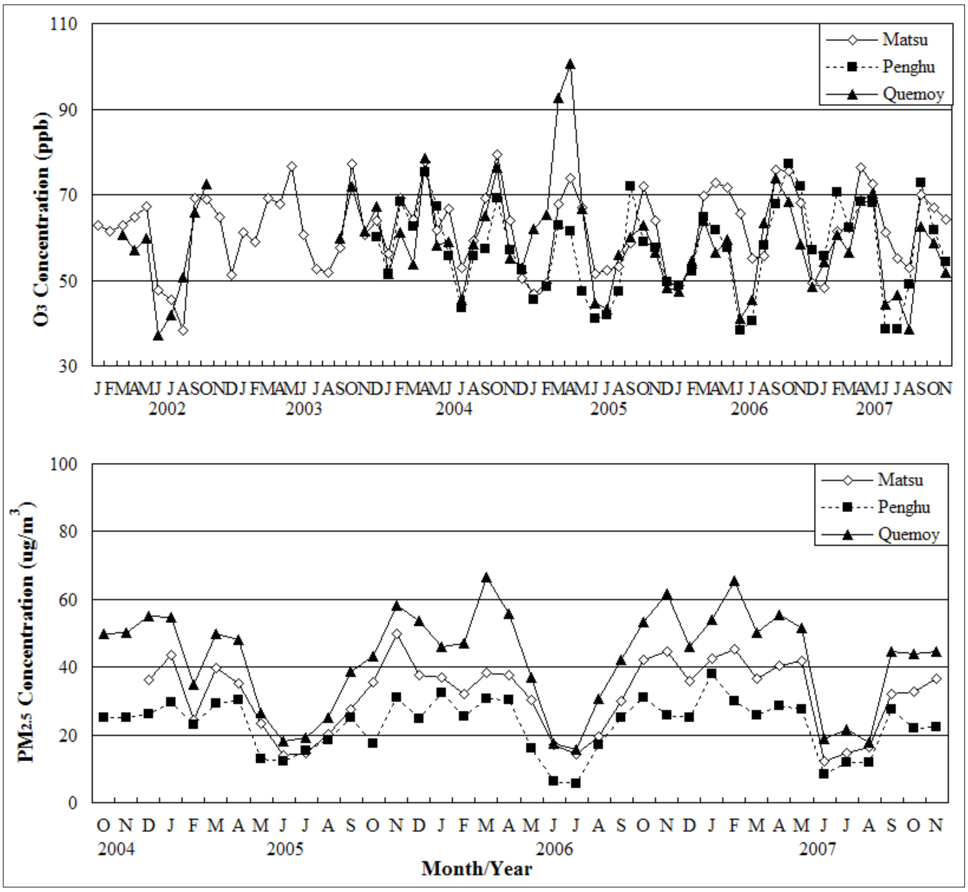
The air quality in the greater Kaohsiung area is the worst in Taiwan. Lin (2002) analysed $PM_{2.5}$ samples in Kaohsiung city and found that ions, sulphate ($SO_4^{2=}$), nitrate (NO_3^-), and ammonium (NH_4^+), and carbon occupied 42.2% and 20.8% of $PM_{2.5}$ mass concentrations. He also suggested that gas-to-particles conversion is significant for the formation of secondary aerosols. Yuan *et al*. (2000) used the Chemical Mass Balance (CMB) method to statistically estimate emission sources in metro Kaohsiung city, such as transportation sources (35±12%), paved road dust (15±6%), nitrate (14±8%), sulphate (13±6%), cement (10±5%), sea salt (7±3%) and others (5±2%). Yu and Chang (2000) stated that most ozone pollution days occur between October and March due to high ozone seasons in south Taiwan and a small island, Hsiao Liuchiu Island. According to those studies above, how to simulate the pollutants transported from the Asian continent needs to be addressed. We first attempt to depict the effects of air pollutants transported from the Asia continent to the Taiwan main island and small islands. Though ozone concentration levels at those small islands do not exceed the ozone standard at 100 ppb except two higher ozone in 2005, many exceedances of $PM_{2.5}$ at 65 μg m^{-3} daily average and 15 μg m^{-3} annual average are based on USA's air quality standards (Taiwan has not had $PM_{2.5}$ standards yet). Matsu and Quemoy islands are closed to the Asia continent, therefore, their ozone and $PM_{2.5}$ concentrations are higher than Penghu islands as shown in Figure 2. An air quality modelling system should be used to identify and quantify trans-boundary pollutants to the Taiwan main and small islands when higher ozone and $PM_{2.5}$ occurred. The Models3/CMAQ has been applied to assess the air quality in Asian countries (Fu *et al*., 2003). Various air pollutants do impact the air quality in the studied region, and their characteristics play important roles within the air quality modelling system.

Table 1 Definitions of air pollutant characteristics

Key pollutants	*Sources*	*Effects*	*Standards*
Sulphur dioxide (SO_2)	Formed when fuel-containing sulphur, such as coal and oil, is burned, and when gasoline is extracted from oil or metals are extracted from ore.	Effects on respiratory illness, breathing, alterations in pulmonary defenses, aggravation of existing cardiovascular disease and a precursor to sulphates associated with acidification of lakes and streams, reduced visibility, accelerated corrosion of buildings and monuments, and adverse health effects.	250 ppb[1] 100 ppb[2] 30 ppb[3]
Nitrogen Oxides (NO_x)	The primary manmade sources of NO_x are electric power plants, motor vehicles, and other industrial, commercial, and residential sources that burn fuels. NO_x can also be formed naturally.	Formation of ground-level ozone, which can trigger serious respiratory problems and form nitrate particles, acid aerosols, as well as NO_2, which also cause respiratory problems. Contributes to formation of acid rain, deposit to nutrient overload that deteriorates water quality, atmospheric particles, that cause visibility impairment most noticeable in national parks, and global warming.	250 ppb[1] 50 ppb[3]
Volatile Organic Compounds (VOCs)	Vehicles are the largest source of VOC emissions, and other significant sources include industrial combustion and petroleum production and its distribution and from natural sources or called 'biogenic' from trees and other vegetation.	VOCs react with oxides of nitrogen (NO_x) in the presence of heat and sunlight to form ground-level ozone, so call 'bad ozone' or smog. VOCs include conjunctival irritation, nose and throat discomfort, headache, allergic skin reaction, dyspnea, declines in serum cholinesterase levels, nausea, emesis, epistaxis, fatigue, dizziness.	
Ozone	It is not usually emitted directly into the air, but at ground-level is created by a chemical reaction between NO_x and VOC in the presence of sunlight.	Ozone causes human health including chest pain, coughing, throat irritation, congestion, bronchitis, emphysema, asthma, reduce lung function and inflame the linings of the lungs and public welfare (*e.g.*, crops, buildings and vegetation).	120 ppb[1] 60 ppb[4]
Particulate Matter PM_{10}	Dust from roads, emission from vehicles, open or wood burning, construction, agriculture, or as a secondary pollutant transformed from other air pollutants.	PM_{10} can easily penetrate into the bronchus of the human lungs such as asthma.	$125 \mu g/m^3$ [2] $65 \mu g/m^3$ [3]
Particulate Matter $PM_{2.5}$	Dust from roads, emission from vehicles, open or wood burning, construction, agriculture, or as a secondary pollutant transformed from other air pollutants.	Health effects for heart and lung disease, increased respiratory disease and symptoms such as asthma, decreased lung function, and even premature death, cardiopulmonary disease.	$65 \mu g/m^3$ [2] $15 \mu g/m^3$ [3] (USA*)
Visibility	PM is the major cause of degraded visibility.	Visibility is more closely associated with conditions that allow appreciation of the inherent beauty of landscape features. It is important to recognise and appreciate by visitors who are from inside and outside of the Taiwan Island.	

Notes: [1] Hourly average; [2] Daily average; [3] Annual average; [4] 8-hour average; * United States of America Air Quality Standards.

Figure 2 Ozone and PM2.5 concentration trends at Matsu, Penghu and Quemoy Islands



3 Aims and objectives

In recent years, TEPA has been seeking air quality management tools such as the development of cost-effective control strategies and decision support. In order to quantify the impacts from the Asian continent to the Taiwan islands, TEPA has been designing the feasibility of rulemaking to resolve current ozone and PM issues in the Taiwan islands. The purpose of this study is to investigate the merits of Community Multi-scale Air Quality (CMAQ) in the analysis of trans-boundary air pollution from continents to small islands by applying an advanced modelling system – CMAQ – developed by the USEPA. The focus of the study is trans-boundary ozone, PM, and acid deposition, using selected episodes of both non-trans-boundary and trans-boundary scenarios in order to provide an understanding of the characteristics of air pollutants for decision- and policy-makers in the Taiwan islands. The Taiwan air quality standards (Table 1) include a daily maximum of 120 ppb, and a daily average of 100 µg m^{-3}, for O_3 and PM_{10}, respectively. At present, there is no standard in Taiwan for $PM_{2.5}$.

The US PM standards (Table 1) include an annual average $PM_{2.5}$ standard of 15 μg m^{-3} and a daily average $PM_{2.5}$ standard of 65 μg m^{-3}. Since $PM_{2.5}$ and O_3 appear to cause health effects, this study included $PM_{2.5}$ and O_3 as two main factors within the multi-modelling processes. The two sets of boundary conditions of clean air concentrations (mainly local pollutants) and transported concentrations (trans-boundary pollutants) from outside the Taiwan region were employed in the modelling simulations separately. The clean air boundary conditions were not considered to react with NO_x, VOCs, SO_2 and aerosol transported from outside of the Taiwan islands area. In the other word, trans-boundary pollutants reacted with local pollutants.

This study gives a description of the model configuration and setup, and presents examples of the preliminary model simulation results. This application provides an understanding of the formation of the trans-boundary ozone and haze problems for the policy-makers in Taiwan islands in the transport season, especially when higher concentrations occurred in January 2001 according to available Asia emission inventory in 2001 (Streets *et al*., 2003). The high pressure went southward and with the wind directions shown in Figure 4. The pollutants were pushed, and moved to the south China area, including the Taiwan islands. These effects have been shown in the literature presented in previous sections. The outcomes of this study providedvaluable recommendations for the TEPA to refine the model and adapt it more thoroughly to conduct air quality management in the Taiwan islands.

4 Methods

4.1 USEPA's models-3/CMAQ modelling system

In this study, we employ the Taiwan Emission Database System (TEDS), a comprehensive emission database in the Taiwan islands, with meteorological data sets as the main input sources. The Mesoscale Model Version 5 (MM5) provides meteorological input fields for the CMAQ model simulations. As shown in Figure 1, nesting grids at 36 km × 36 km (D1), 12 km × 12 km (D2), and 4 km × 4 km (D4) resolution are set up by the MM5 meteorological processing model for the episodes during wintertime in 2001. USEPA has been devoting major resources to develop an advanced modelling system integrated with a 'one-atmosphere' perspective, such as the USEPA's Models-3/CMAQ modelling system (Byun and Ching, 1999; Byun and Schere, 2006). Models-3/CMAQ is a numerical modelling system that can simultaneously simulate the transport, physical transformation, and chemical reactions of multiple pollutants across large geographic regions. The system is useful to both state governments and international agencies making regulatory decisions on air quality management, as well as to scientists in the field of atmospheric research. It is a combination of Models-3, a flexible software framework, and the CMAQ modelling system, to support air quality applications ranging from regulatory issues to scientific research into atmospheric processes. The modular design of CMAQ allows the user to build different chemistry-transport models and analyse various air quality problems. The Models-3/CMAQ system was designed to approach air quality as a whole by including state-of-the-science capabilities to model multiple air quality issues including ozone, particulate matter, visibility degradation, acid deposition, and air toxics, at multiple scales. The Models-3/CMAQ system was first released to the public in July 1998, and has been used broadly for air quality assessments. Through Taiwan-USA bilateral collaborations, TEPA utilised the advanced air quality-modelling tool to assess trans-boundary issues and evaluate Taiwan islands' air pollution control strategies.

5 Model configuration and setup

5.1 Model domain

In this Models-3/CMAQ application, the model domain covered East Asia, as shown in Figure 1. The domains that had 130×94 horizontal grid cells use a 36 km resolution, while 135×198 horizontal grid cells use a 12-km resolution, and 59×114 horizontal grid cells use a 4 km resolution (Figure 1). The resolutions were based on the Lambert Conformal map projection system centred at 34°N, 110°E. The research team configured 14 vertical layers that were initially configured following the Sigma (σ) layer structure with denser grids at lower levels to better resolve the boundary layer. The σ-layer interfaces occurred at: 1 (0 m), 0.995 (38 m), 0.988 (92 m), 0.98 (153 m), 0.97 (230 m), 0.956 (340 m), 0.938 (482 m), 0.893 (846 m), 0.839 (1300 m), 0.777 (1850 m), 0.702 (2557 m), 0.582 (3806 m), 0.400 (6083 m), 0.20 (9511 m) and 0.00 (16,262 m).

5.2 Model configuration

The September 2003 version of the Models-3/CMAQ system was used in this modelling work. Further details of model configurations and science modules were given in Models-3/CMAQ science documents (USEPA, 1999). The key science modules used in this modelling work are given below. Note that the selected science modules (*e.g.*, initial conditions and boundary conditions, *etc.*) are the default options given within the September 2003 Models-3/CMAQ version.

5.3 Model inputs and setup

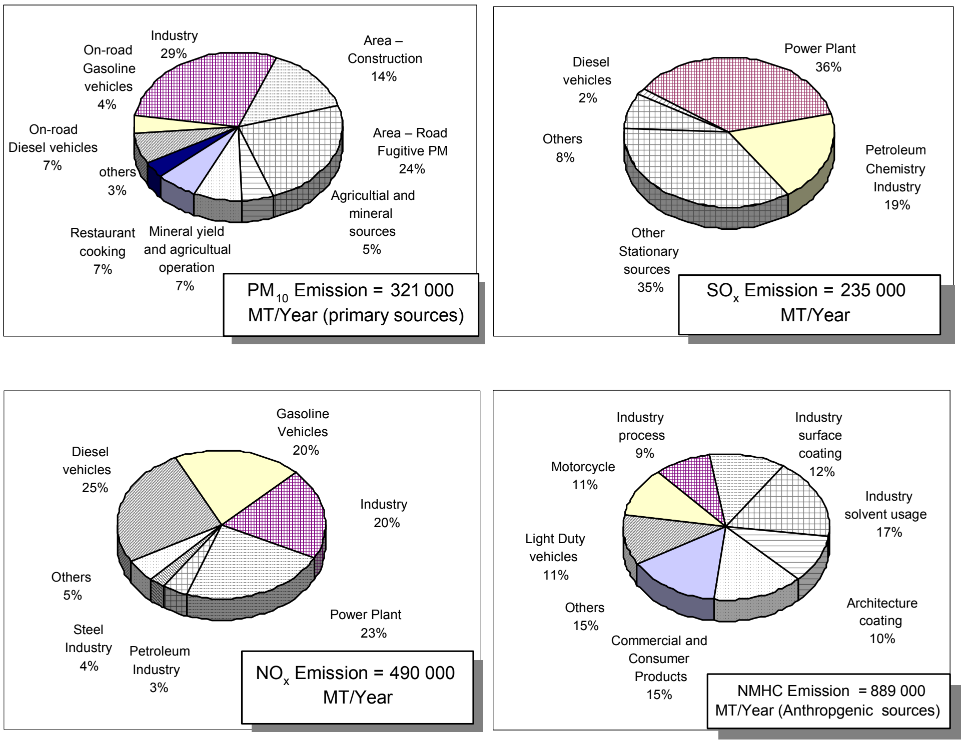
The Mesoscale Model Version 5 (MM5) v.3.7 was used to provide meteorological input fields for the model simulations. The 36-, 12- and 4-km domains and their meteorological outputs simulated by MM5 in these modelling efforts were included during the simulations. The newest Meteorology/Chemistry Interface Processor (MCIP) 2.2 released in June 2003 was used to process the raw MM5 output data into the format and structure required by the Models-3/CMAQ modelling.

5.4 Emission estimates

From the 1970s to the 1990s, Taiwan's economic growth rate has been more than 10% yearly. In 1991, TEPA established the first version of the Taiwan emission database based on 1987 emission measures, Taiwan Emission Data System, Version 1.0 (TEDS1.0). TEDS is the nationwide emission data system of Taiwan. Most information necessary to produce National-wide emission inventory within the TEDS is obtained from the Taiwan EPA and local government agencies of Environmental Protection. Subsequently, TEPA updated TEDS2.0, TEDS3.0, TEDS4.0 and TEDS5.0 based on

1991, 1994, 1997 and 2000 emission measures in 1994, 1995, 1998 and 2001, respectively. The latest version of TEDS is TEDS 5.1 (CTCI Corporation, 2003) for the year 2001 emissions simulation.

Figure 3 Taiwan's emission inventory of year 2001 (see online version for colours)



Pollutants included in TEDS5.1 are Total Suspended Particulates (TSP), fine suspended particulates (PM_{10}), oxides of sulphur (SO_x), oxides of nitrogen (NO_x), Non-Methane Hydrocarbon (NMHC), carbon monoxide (CO), and lead (Pb). Inventory Source Category of TEDS includes point sources, mobile sources, area sources, and biogenic sources. The difference between point sources and area sources is that point sources are one or more permitted pieces of equipment in a fixed and identifiable location, and area sources consist of numerous small facilities or pieces of equipment such as gasoline-dispensing facilities, residential water heaters, and architectural coatings for which locations are not specifically identified in the database. Most of the emissions for air pollution fee were based on results of stack measurements or Continuing Emission Monitoring System (CEMS), and there were independent validation measures conducted by Taiwan EPA. Therefore, the emissions of SO_x and NO_x from stationary sources in TEDS have been replaced by air pollution fee data. In the present research, the biogenic emission is estimated by BEIS II (Birth and Geron, 1995). Although the classifications of land use were in more detail from the Taiwan Forestry Bureau (TFB),[1] this database did not cover urban areas and some rural areas. Thus, the classifications from TEDS were used for these areas. In order to have better representation of land usages, we used 75 types of land usages in TFB, and the other seven types arranged in this study.

Data in TEDS are processed by Sparse Matrix Operator Kernel Emissions (SMOKE) (Houyoux and Vukovich, 1999). The SMOKE system provides a mechanism and prepares specialised inputs for air quality modelling research. SMOKE includes biogenic emissions modelling and supports area, mobile, and point source emission processing. The SMOKE has been modified to change the time zone in order to be feasibly used in the Taiwan islands or Asian region. Some basic files such as Taiwan census data, road types, vehicle types, and county boundary are switched from the USEPA's default to Taiwan's data. Corresponding spatial and temporal files are all retrieved from CTCI Corporation (2003). The preparation of the SMOKE is to fit the required CMAQ model input format.

The emission measures of Street *et al*. (2003) were used for Domain 1 and those of TEDS-SMOKE were used for Domain 2. The combination of TEDS emission database and the SMOKE was successfully prepared as the emission input file for CMAQ. Hereafter, the combined system is referred to as 'TEDS-SMOKE'. It is noted that the results of TEDS-SMOKE are the most accurate emissions obtained so far in the literature. Figure 3 shows the contributions of the various source categories to the emissions of the individual contaminants for the year of 2001 in Taiwan (TEPA, 2001).

6 Results of air quality modelling

Figure 4 shows the results of the nesting domains at 36-km, 12-km, and 4-km. The wind fields of the MM5 outputs are shown in Figure 5. Winter outflows typically exhibit south to southwesterly directions over the eastern part of north-to-south Taiwan Islands including Matsu, Quemoy, and Penghu islands. During the wintertime, the high-pressure system moved from China to the West Pacific Ocean. When the leading edge of the anti-cyclonic system arrives in Taiwan and its small islands, the pollutant concentration levels increase with the increased wind speed. The winter breeze, on the other hand, is prevalent in north to northwesterly flows from the East Sea of China. The adverse pollutants moved from China to the West Pacific Ocean, Taiwan Island, and its small islands. Figure 6 displays the spatial allocations of several pollutants including nitrogen oxide (NO), paraffin (PAR) of very reactive pollutants of VOC and ammonia (NH_3) in January 2001. High NO and PAR emissions are shown in Taipei and Kaohsiung cities and along the main Taiwan Freeway. Mainly, those (NO and PAR) were emitted by the road traffic. As shown in Figure 6, higher PAR concentrations appeared in the Kaoshiung area because of the existences of various industries including petroleum and chemical plants.

Ammonium is spatially allocated in the western parts of Taiwan Island where major agriculture activities are present. The Boundary Conditions (BC) of ozone are set at 35 ppb within the first layer when we assumed no transported pollutants were from outside of Taiwan Island. Results from the Models-3/CMAQ simulation found that the effects of transported pollutants, such as fine $PM_{2.5}$, on the levels of visibility and major constituents of $PM_{2.5}$, such as sulphate PM and nitrate PM, on the levels of air quality were performed well. The results of the study demonstrate that the Models-3/CMAQ system was capable of simulating key criteria pollutants reasonably well during a typical day and within an acceptable run time.

Figure 4 PM2.5 model nesting domains (see online version for colours)

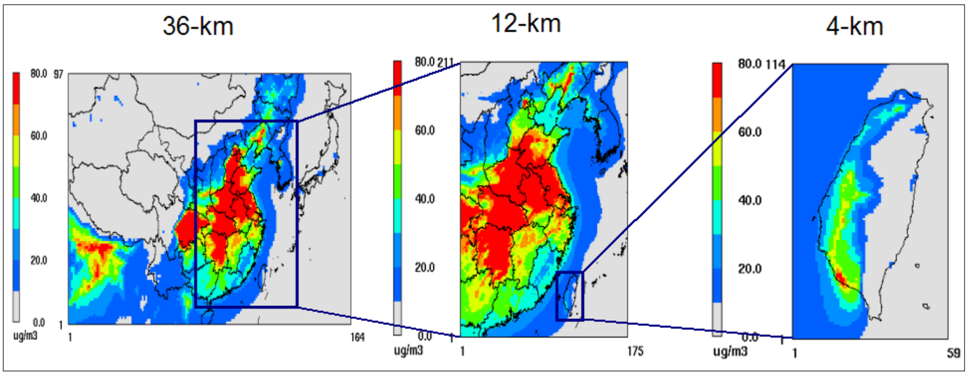


Figure 5 Wind fields (see online version for colours)

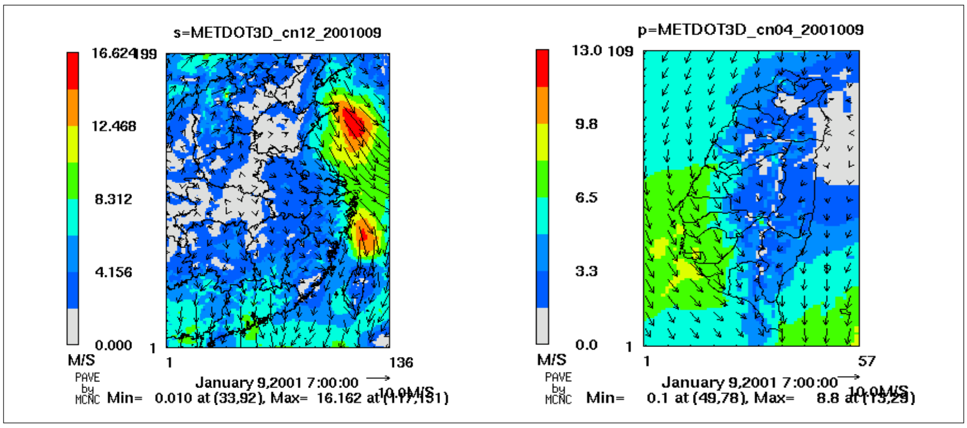


Figure 6 NO, PAR and NH_3 emissions (see online version for colours)

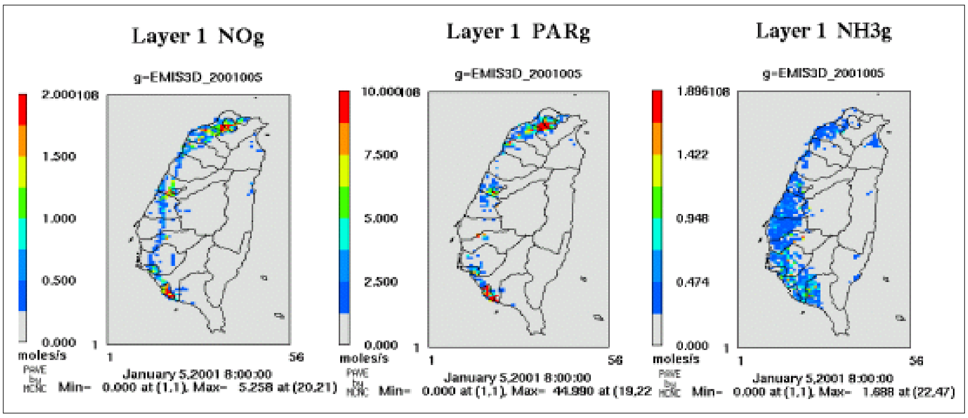
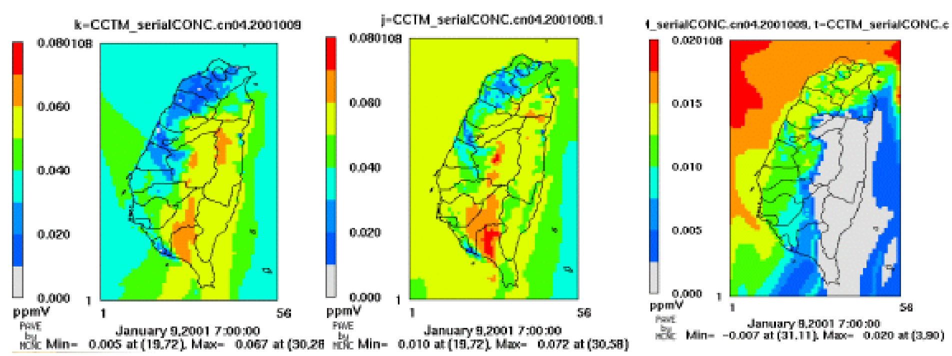


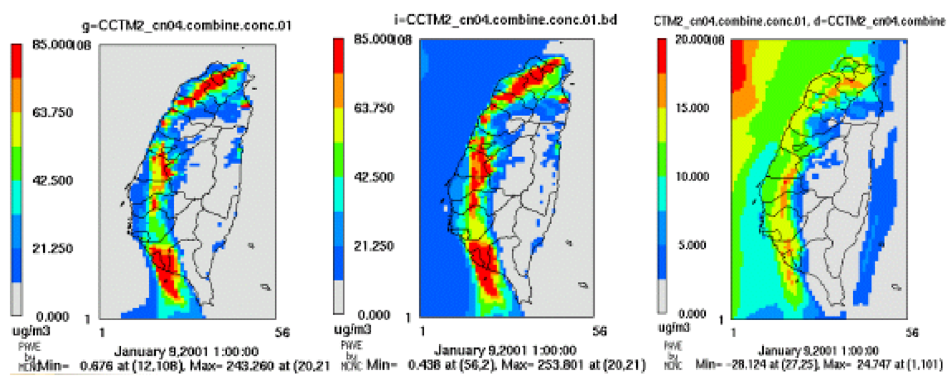
Figure 7 shows that the left panel (a) used clean air (no transported pollutants were from outside of the island), the middle panel (b) considered pollutants transported from China, and the right panel (c) is the difference of panel (b) from panel (a). The impact of the ozone concentrations is up to 20 ppb (26%) in the northwest direction and 15 ppb (19%) in the north and central of Taiwan. It occurred the higher ozone concentrations is up to 16 ppb (20%) at Penghu islands and Gueishan Island and 6 ppb (9%) at Hsiao Liuchiu Island. Though Green Island and Orchid Island are not impacted by the transported pollutants from the Asia continent but the impact of the concentrations is up 12 ppb (15%) from Taiwan Island. High $PM_{2.5}$ concentrations are shown in Figure 8. The levels of $PM_{2.5}$ are way beyond the US standard of 65 ppb daily averages. High levels of the $PM_{2.5}$ occurred along the western part of Taiwan Island. Most pollutants spatially accumulated in the west plain of Taiwan Island, following the north-to-south direction. The $PM_{2.5}$ concentrations contributed from outside of Taiwan are up to 20 μg m^{-3} in the northwest direction and 15–20 ppb in the Taipei, Taichung and Kaohsiung metropolitan areas. The impact of PM concentrations is more significant than ozone's at those small islands. At Matsu, and Guemoy islands, the impact of PM concentrations is up to 25 μg m^{-3}P (not shown in figures). Penghu islands's impact of the PM concentrations is up to 22 μg m^{-3} and 13 μg m^{-3} at Hsiao Liuchiu Island.

Figure 7 O_3 Concentrations (see online version for colours)



(a) Background BC (b) Nested BC (c) Effects of O_3

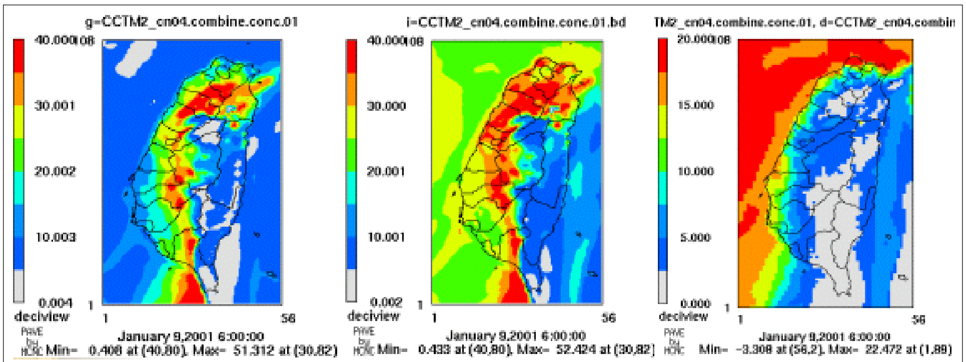
Figure 8 $PM_{2.5}$ concentrations (see online version for colours)



(a) Background BC (b) Nested BC (c) Effects of $PM_{2.5}$

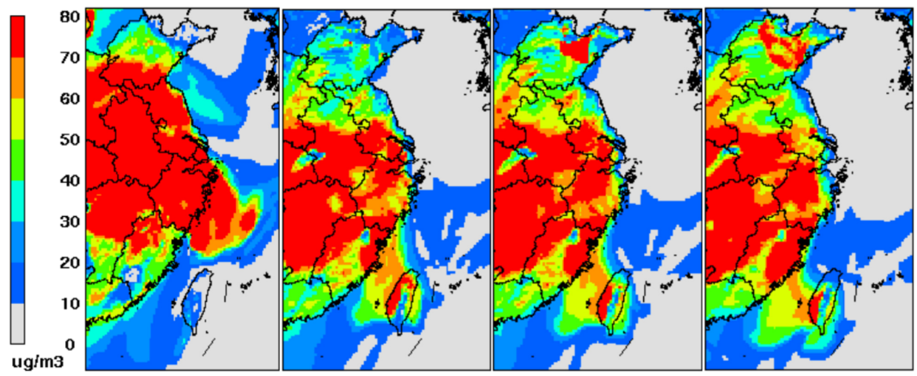
Nitrate PM concentrations are affected by the pollutants from outside of Taiwan, and showed significant impacts in North Taiwan. The peak $PM_{2.5}$ levels can be as high as 250 μg m^{-3} and exceed the standard of 65 μg m^{-3}. In the cities of Taipei and Kaoshiung, the monthly average levels were 49 μg m^{-3} and 73 μg m^{-3}, exceeding the 15 μg m^{-3} annual standard, respectively. The highest sulphate PM is in the Kaohsiung area. The visibility shown in Figure 9 is reduced in North Taiwan to a distance of 10 km. The local and transported pollutants degraded visibility conditions. Visibility impairment is caused by the secondary $PM_{2.5}$, such as nitrate PM, sulphate PM, and organic PM. The nitrate PM affected visibility impairment in January and was caused more by transported pollutants from outside of Taiwan small islands than other secondary PM pollutants.

Figure 9 Visibility (see online version for colours)



(a) Background BC (b) Nested BC (c) Effects of $PM_{2.5}$

Figure 10 $M_{2.5}$ concentrations in a series time on 20 December 2004: (a) 6:00, (b) 18:00, (c) 21:00, (d) 0:00 on 21 December 2004 (see online version for colours)



(a) (b) (c) (d)

7 Discussion – transferability to small island context

The APF fund finances TEPA in various air quality improving projects. These projects include motor vehicles inspection and maintenance and promotion of low-polluting vehicles. Compensating new cars to replace old cars, subsidising public transportation, providing free consulting to major emission sources, and subsidising landfill gas power generations are also well included within the APF/TEPA projects. More specifically, these projects provide more incentives for air quality improvement. However, since 2000, trans-boundary air pollution is hindering the efforts to further improve the air quality in the Taiwan islands. Using an advanced air quality modelling system that needs meteorological data from MM5/MCIP models' outputs and emission inputs from SMOKE/TEDS models' outputs, now we are able to assess multi-pollutants including ozone, particulate matter, acid deposition, and visibility.

As mentioned previously, this study used Models-3/CMAQ over Asia (36 km), regional (12 km), and Taiwan (4 km) to investigate the relations among transported and non-transported pollutants and to simulate multi-pollutants, including primary and secondary pollutants (*e.g.*, ozone, PM, acid deposition, visibility, SO_2 and NO_x). The preliminary results (from the January case) showed a lower level of O_3 concentration than previous expectations. High $PM_{2.5}$ was simulated over metropolitan areas with significant secondary constituents. When TEPA considers the cap quantity control, the local transported pollutants, and trans-boundary pollutants, further air quality studies, integrated with the considerations of seasonality in metropolitan areas, need to be assessed.

The air quality model has been recognised as a tool to predict ozone and PM concentrations for those mentioned islands. An investigation of the merits of CMAQ in the analysis of trans-boundary air pollution from continents to Taiwan Island and its small islands has been conducted in this study. Major applications of CMAQ have been reviewed in the introduction section. Various impacts on small islands are often ignored by the closed continent and bigger islands. In this study, we depict the impact of transported air pollutants toward small islands that are closed to the Asia continent and Taiwan Island. In the recent study, $PM_{2.5}$ concentrations shown in time series maps in Chuang *et al*. (2007) indicated that pollutants did move from mainland to south China and generated impacts on Matsu Island, Quemoy Island, Gueishan Island, and the Penghu Islands. Concentrations increased from 10 $\mu g\ m^{-3}$ to 75 $\mu g\ m^{-3}$ when high pressure and wind direction were southward from 6am on 20 December to 12am on 21 December 2004. Hsiao Liuchiu Island also was influenced by the Taiwan main island's pollutants. Due to topographical factors, the concentrations in Green Island and Orchid Island only increased 5 $\mu g\ m^{-3}$ shown in Figure 10. This study demonstrated that most of the Air quality data sets can be used to analyse the impacts of air pollutant concentrations on the surrounding Taiwan small islands.

8 Conclusions

The CMAQ system is a useful research and management tool for regional and urban air quality assessment over the Taiwan Islands and its small islands. The system has been designed to simulate air quality as a whole by including state-of-the-science capabilities for tropospheric ozone, fine particles, toxics, acid deposition, and visibility degradation.

The system has been widely used to evaluate trans-boundary air pollutants in regional studies (Streets *et al*., 2007). The CMAQ has now performed well in a regional study and in other studies worldwide. Fu *et al*. (2007) have shown that the CMAQ model outperformed other models.

The CMAQ system used in this study continually strives to improve the quality of the input data sets and parameters, with an emphasis on compiling appropriate atmospheric and geographic data and parameters, and to ensure that the interpretation and characterisation of the results comply with best-practice scientific principles. This system provides additional profiles to decision- and policy-makers in Taiwan, and assists the TEPA in developing control strategies to improve air quality in the Taiwan Island and its small islands. We conclude that the methods used in this paper are readily transferable to most air quality data sets. The CMAQ system can be applied to any other small, medium, and large islands around the world with their own meteorological conditions and emissions inputs.

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Note

1 http://www.forest.gov.tw/