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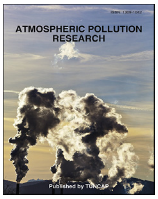

Original article

The phenomena of spreading ambient ozone at the west coast air basin of Taiwan

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ABSTRACT

The total air pollution model (TAPM, www.cmar.csiro.au/research/tapm) was used to explore the phenomena of spreading ambient ozone in the complex 196 km × 196 km terrain of the west coast air basin of Taiwan (including ocean area). The altitude in the air basin ranges from 0 m (sea level) to 3000+ m (high mountain). The data of 2010–2014 from 21 air-quality monitoring stations were used to ensure the accuracy of the simulation results in accordance with an average index of agreement (IOA) > 0.61. Four ozone-spreading phenomena were observed among the air basin: the north–south spreading on the offshore (N–S SOO), north–south spreading around the coast (N–S SAC), east–west spreading from the ocean (E–W SFO), and east–west spreading around the mountain front (E–W SAMF). The results indicate that when two prevailing flows meet and interact at their boundaries, they form a convergence zone. The convergence zone presents distinctive weather conditions and accumulates air pollutants. More than wind direction, the ozone concentration is dependent on the topography and surrounding conditions. The results clearly show that the ozone-spreading phenomena follow certain rules. The N–S SOO, N–S SAC, E–W SFO, and E–W SAMF phenomena are during the northeaster, fore-southwester, southwester, and fore-northeaster monsoon months, respectively. Wind fields are a major factor in the high concentration of ozone and ozone spreading, especially downdraft and onshore winds. The diversion of river valleys and the mountainous barrier between the basin/hill and mountains exert obvious influences on the local wind field, strongly affecting the ozone-spreading phenomena.

1. Introduction

High levels of ambient ozone have become a key environmental concern in recent years, especially in industrialized countries. In Taiwan, the annual mean concentration of ozone is constant, but surface ozone concentration at ozone event days (24 h maximum value of the hour > 120 ppb) have increased significantly attribution ozone event days to reduce (Fig. 1). Some researchers believe this is related to global warming (Langner et al., 2005; Reilly et al., 2007; Joireman et al., 2010; Nema et al., 2012). Ambient ozone is a secondary air pollutant that forms in atmospheric photochemical reactions. Weather and topography exert strong influences on the transmission and formation of ambient ozone (Liang and Liang, 2007). To understand these influences, several studies have estimated the probability density function of the variations in ozone concentration using various photochemical models, such as the California photochemical grid model (Barna and Lamb, 2000), the photochemical box model (Huang et al., 2001), the urban airshed model (Hanna and Davis, 2002), the comprehensive air-quality model with extensions (Pirovano et al., 2007), the Eulerian chemical-weather model (Schürmann et al., 2009), and the community multiscale air-quality model (Shi et al., 2012). Monache and Stull (2003) tested an ensemble approach that used four models (the European monitoring and evaluation programme model, European air pollution dispersion model, long-term ozone simulation model, and regional Eulerian model with three different chemistry schemes), and determined that an ensemble photochemical model resulted in more precise predictions of ozone peak value than a single model deterministic forecast. He and Lu (2012) employed a

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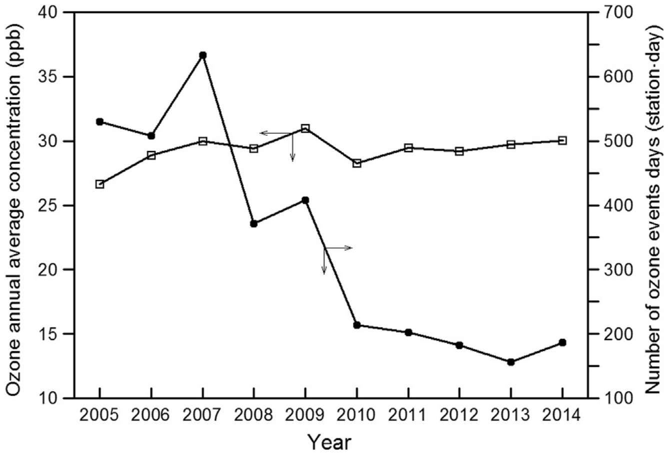

Fig. 1. Ozone annual average concentrations and number of ozone event days in Taiwan. Note that the unit of ozone event days is "station·day" and total of air monitoring stations is 78.

multiple regression and principal component analysis to predict the level of ozone from pollutant data and meteorological variables.

The Air Pollution Model (TAPM) is a PC-based, nestable, prognostic meteorological and air pollution model (with photochemistry) driven by a graphical user interface, and is a viable tool for year-long simulations (Hurley et al., 2005). Zawar-Reza et al. (2005) compared the meteorology and PM_{10} dispersion results from TAPM modeling and an air pollution monitoring station for Christchurch, New Zealand. Statistical measures between modeled and measured data indicate that the model performs well. Wilson and Zawar-Reza (2006) used TAPM simulating PM_{10} and comparing with a dense intraurban monitoring network in Christchurch, New Zealand. The model performed satisfactorily overall, with mean observed and modeled concentrations of 42.9 and 43.4 $\mu g\ m^{-3}$, respectively. Peng et al. (2008) predicted the surface ozone concentrations using TAMP. Both measurements and simulations indicate that daytime ozone concentrations decreased quickly with increasing height at altitudes below 300 m; while nighttime ozone concentrations were lower at low altitudes (50–300 m) than at higher altitudes. Zoras et al. (2010) developed an air quality forecasting system via linking up TAPM with SKIRON model to predict next day's weather forecast and PM_{10} concentration in north–western Greece. Luhar and Hurley (2012) employed TAPM model to generate input meteorological data to simulate atmospheric transport and risk of pollutant emissions from a potential post-combustion carbon capture project. Cheng et al. (2014) used TAPM to simulate wind fields and trajectories of air masses. It was determined that typhoon position affected O_3 concentration, temporal and spatial patterns of O_3 titration and vertical meteorological characteristics.

TAPM demonstrates many advantages such as three-dimensional prognostic modeling, predicting both meteorological and air pollution fields, predicting hour by hour pollution concentrations for periods of up to a year, and predicting the flows important to local-scale air pollution such as sea breezes and terrain induced flows. But TAPM has a tendency to overestimate surface wind speed over urban areas during stagnant nocturnal conditions, resulting in quick flushing of pollutants (Zawar-Reza et al., 2005).

Ground level ozone concentrations can be determined by source and sink mechanisms, which primarily rely on meteorological conditions (Pudasainee et al., 2006). Diem (2000) reported that the transition from the relatively dry atmosphere during the arid pre-summer months of May and June to the relatively moist atmosphere during the monsoon months of July and August appeared to explain the changes in ozone concentration. Lam et al. (2001) demonstrated that the fall maximum surface ozone was caused by weak, slowly moving high-pressure systems that created favorable photochemical production conditions and transported aged air masses with high levels of ozone and its precursors (nitrogen oxide and Volatile organic compounds). Cheng (2001) noted the lack of a clear statistical correlation between a single meteorological variable and ozone concentration. The orographic effect and the long-range transport of ozone are critical factors in studying ambient ozone levels. Glavas and Sazakli (2011) reported that in cold months, the concentration of transported ozone was larger than locally formed ozone, whereas in the warm months, more ozone formed locally. Gao (2007) applied functional data analysis techniques to hourly resolved ozone and nitrogen oxide (NO_x) measurement data, examining diurnal ozone cycles and their functional characteristics (ozone accumulation and destruction rates), and closely linking them to transportation emissions. The results supported the findings of previous researchers.

High concentration of ozone is a major environmental concern because of its adverse impacts on human health and a key position in the processes and cycles affecting the formation and fate of other pollutants Taiwan, with warm and high humidity climates, is especially likely to experience high ozone concentrations (Liang and Liang, 2007). The west coast air basin of Taiwan has a complex terrain and an altitude ranging from 0 m (sea level) to 3000+ m (high mountain), which is similar to the complex terrains in other countries. The air basin is comprised of three air quality areas: the Chu-Miao, Central, and Yun-Chia-Nan Air Quality Areas, which consists of eight cities/counties. Brönnimann et al. (2000) indicated that the estimated annual average ozone concentration depended on altitude, and differences in background ozone were found to depend on the type of synoptic weather. To understand the influences of weather and terrain on spreading ambient ozone, four areas in the air basin (the ocean, coast, basin/hill, and mountains) were examined. Data from 21 Taiwan Environmental Protection Administration (EPA) air-quality monitoring stations were analyzed. The simulated results from TAPM (version 4.0) were also analyzed. The TAPM is an atmospheric photochemical grid model that solves approximations to the fundamental fluid dynamics and scalar transport equations predicted for meteorology and pollutant concentrations. The TAPM was used in this study because it can accurately simulate a range of pollutants, especially secondary air pollutants.

2. Materials and methods

2.1. Study area and monitoring data

Fig. 2 shows the sites of 21 Taiwanese EPA air-quality monitoring stations (S1 to S21) and nine major rivers (R1 to R9) in the air basin. The terrain in the air basin is the most varied in the country, with straits, coasts, basins, hills, and mountains all present. The land area is approximately 16,200 km^2. The length from the north (Hsinchu County) to south (Chiayi County) is approximately 196 km and the width ranges from 37 km to 128 km. The area includes one municipality, two cities, and six counties, with a total population of 7.54 million. In this study, the area was divided into four geographical regions: ocean (Taiwan Strait), coast, basin/hill (Hsinchu Hill, Miaoli Hill, Taichung Basin, and Gukeng Hill), and mountains (Snowy and Central Mountain Ranges). In Fig. 1, the altitudes are differentiated by color.

Monitoring data (http://taqm.epa.gov.tw/taqm/zh-tw/default.aspx) for 2010, 2012, and 2014 from S1 to S21 were used to

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