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Modeling study of three consecutive high ozone episodes over Taiwan in spring 2007

Fujung Tsai [a,*], Tsun-Hsien Liu [b]

[a] Department of Marine Environmental Informatics, National Taiwan Ocean University, #2 Peining Road, Keelung 202, Taiwan
[b] Department of Atmospheric Physics, National Central University, Taiwan

HIGHLIGHTS

- We analyzed three continuous high O_3 episodes in Taiwan in spring 2007.
- We found the different sources of these three high ozone episodes.
- We found high O_3 forms under different synoptic conditions.
- We quantify the processes contributing to the high ozone episodes.
- We quantify the contribution of different sources during the episodes.

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ABSTRACT

A three-dimensional photochemistry model is applied to analyze three unusual high O_3 episodes that occurred continuously in Taiwan from May 1 to 11, 2007. During this period, the first high ozone episode was observed in northern and central western Taiwan on May 4. Following this episode, the second episode was observed throughout Taiwan on May 7, and continued for several days until May 10, when the third episode was observed in central western and southwestern Taiwan. This was the worst O_3 period in Taiwan over the past two decades. During this period, 70% of the local air quality station reported an O_3 concentration of over 120 ppb, and a maximum O_3 concentration of 175 ppb was observed in background Taiwan.

Based on model analyses, the sources of the three high O_3 episodes differ. The high O_3 concentration observed during the first episode is mainly attributed to the northeastward transport of O_3 precursors and concentrations from northern and central western Taiwan under southwesterlies prior to frontal passage, chemically producing O_3 over 30 ppb h^{-1} in northern Taiwan. During the second episode, horizontal advection of Asian outflow during the passage of an anticyclone and front contributes a maximum of 25 ppb h^{-1} in both northern and southern tip of Taiwan, respectively, increasing to more than 75 ppb h^{-1} in southwestern Taiwan because of the combination with the local source. During the third episode when the prevailing easterlies associated with a departing anticyclone to the east of Taiwan is blocked by the high central mountain, local O_3 chemical production and horizontal transport contribute a maximum of 25 ppb h^{-1} and 35 ppb h^{-1} in central and southwestern Taiwan, respectively, under a calm and high background O_3 condition.

Source from Taiwan contributes more than half of the high O_3 concentration over northwestern Taiwan prior to frontal passage during the first episode, but decreases to mostly below 40% over western Taiwan during the second episode when Asian outflow occurs, and increases to more than 60% over central and southwestern Taiwan due to pollution accumulation under an anticyclonic departure.

1. Introduction

Ozone is an important air pollutant that affects air quality. High concentrations of surface O_3 are of great concern because of their effect on human health and ecosystems (Lippmann, 1991). Problems on O_3 are challenging because O_3 is a secondary pollutant

* Corresponding author. Tel.: +886 2 24622192x6313; fax: +886 2 24621047.
E-mail addresses: fujung@mail.ntou.edu.tw (F. Tsai), tsunhsien.liu@gmail.com (T.-H. Liu).

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generated through a series of complex chemical reactions involving nitrogen oxide (NO_x) and non-methane hydrocarbon (NMHC) (Haagen-Smith, 1952; Leighton, 1961). The generated O_3 may be transported downwind under favorable meteorological conditions. Advection, diffusion, and deposition aside from chemical reactions also influence the overall O_3 concentration over the downwind areas.

Taiwan is an island located offshore of East Asia and downwind of the eastern coast of China (Fig. 1). Air pollutants such as O_3 can be transported from China and affect the local air quality (Chou et al., 2006; Liu et al., 2008). In addition, with an extremely high population density in the world, Taiwan also suffers from a local O_3 issue (Cheng, 2001; Lin et al., 2004a). Previous studies demonstrated that the maximum O_3 concentrations in Taiwan mainly occur from autumn to next spring, when winter monsoon prevails (Lee et al., 2000). During this period, i.e., from October to May of the following year, the anticyclones associated with the frontal system frequently form at a rate of about one per week (Bachmeier et al., 1996), and their movement across the continent affect the air quality. When the weather in Taiwan is dominated by anticyclonic weather between the two frontal passages, the weak surface winds and warmer surface temperature are favorable for the local pollution to accumulate in Taiwan, and the condition can result in high O_3 concentration. This weather condition accounts for 70% of the day during winter monsoon (Lin et al., 2004b). In the remaining 30%, Taiwan is under the passage of an anticyclonic system behind a surface front, when the prevailing northeasterlies with either clean or polluted continental outflow can also be carried to Taiwan. The contributions of Asian outflow and local emission on O_3 concentration are both found to be significant. For example, Chou et al. (2006) found that the O_3 concentration in the metropolis of northern Taiwan increased by an annual average of about 1 ppbv yr^{-1} from 1994 to 2003, and this increase is partially attributed to Asian outflows. Bey et al. (2001) and Liu et al. (2002) found that Asian outflow of O_3 pollutants significantly affects the air quality over the downwind area. On the other hand, Cheng (2001) and Lin et al. (2004a) found that during the winter monsoon when an anticyclone east of Taiwan dominates the local air quality, the prevailing easterly wind blocked by the high central mountain in Taiwan has resulted in local pollutant accumulation and a high O_3 concentration over central western and southwestern cities in Taiwan. Chiang et al. (2009) quantified the contribution of Asian and local emission through simulating springtime O_3 concentration in northern Taiwan in 2003 and reported that Asian outflow could contribute up to 35% of the O_3 concentration in northern Taiwan during anticyclonic passage. Prior to the approach of a front when southwesterlies prevail over the western plain, they found that the local emission dominates the air quality, and the contribution of Asian outflow decreases to less than 10%. Thus, the contribution of local sources and Asian outflow on O_3 concentration in Taiwan during winter monsoon strongly depends on the frontal and anticyclonic condition.

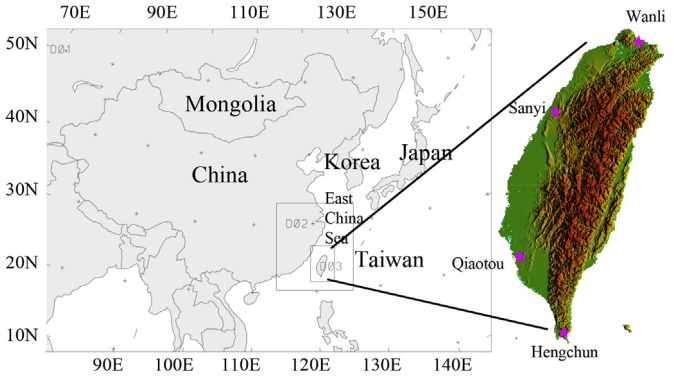

Fig. 1. CMAQ modeling domain and the observed background stations, including Wanli, Sanyi, Qiaotou, and Hengchun in Taiwan.

During the spring of 2007, a series of unusually high O_3 concentrations was continuously observed over most of Taiwan. Among these concentrations, three episodes were identified. Prior to the frontal passage on May 4, high O_3 concentration was observed over a large area in northern to central western Taiwan. Following the anticyclone passage on May 7, a second high O_3 episode was observed throughout Taiwan. This episode extended for several days until around May 9–10, when the O_3 concentration increased again because of the departure of an anticyclone as well as the approach of another system. May 10 is selected as the third episode for discussion because the elevated concentration was observed by more station. These episodes were the worst O_3 period in Taiwan in the past two decades. More than 70% of the local Environmental Protection Administration (EPA) stations (about 70 stations in total) reported an O_3 concentration of over 120 ppb during the period, and the maximum concentrations of around 200 ppb and 175 ppb were observed in urban and background stations, respectively. In addition to its severeness, this extreme event also covers a whole period of a frontal and anticyclonic cycle. Thus, it provides us a good opportunity to understand the high O_3 distribution associated with the synoptic condition during winter monsoon in Taiwan and the processes contributing to the high O_3 concentrations, which were not explored in previous studies.

In this study, a three-dimensional photochemical model is applied to analyze the high O_3 concentrations during these three episodes. Different emission experiments were performed to understand the contribution of high O_3 from either the Asian outflow or the local source. The distribution of O_3 and its precursors, including NO_x and NMHC, is analyzed, and the effects of these precursors on the high O_3 concentrations are discussed. The contributions of the high surface O_3 concentration in Taiwan from different physical and chemical processes such as advection, diffusion, and chemical reactions, during the three episodes are quantified. The contribution of the Asian and local sources on the elevated O_3 concentrations is also calculated.

2. Methodology

2.1. Model descriptions and methods

The three-dimensional regional chemistry model applied in this study is the Community Multiscale Air Quality Model (CMAQ) version 4.6 (Byun and Schere, 2006). CMAQ was developed by the US EPA and has been widely applied in air-quality studies. Three nesting model domains are used. The largest model domain (D1) with a horizontal grid of 81 km × 81 km covers East Asia. The inner domain (D2) has a grid of 27 km × 27 km. The smallest model domain (D3) with a grid of 9 km × 9 km covers Taiwan (Fig. 1). The model is vertically divided into 15 layers by using a sigma coordinate, with denser layers located near the surface.

Emissions of gaseous species in Asia and Taiwan are compiled based on several emission inventories, including anthropogenic and natural sources. The anthropogenic gas phase emissions of NO_x ($NO + NO_2$), CO, and NMHC in Asia are based on the 1° × 1° emission inventory of Streets et al. (2003) and Olivier et al. (1999). Anthropogenic emissions in Taiwan are based on the Taiwan Emission Data system for 2007. Natural sources of NO_x and NMHC in Asia emitted from soil or biological matter are based on the monthly global inventory of the Global Emission Inventory Activity