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Analysis of observed surface ozone in the dry season over Eastern Thailand during 1997–2012

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ABSTRACT

This study analyzed observed surface ozone (O_3) in the dry season over a long-term period of 1997–2012 for the eastern region of Thailand and incorporated several technical tools or methods in investigating different aspects of O_3. The focus was the urbanized and industrialized coastal areas recently recognized as most O_3-polluted areas. It was found that O_3 is intensified most in the dry-season months when meteorological conditions are favorable to O_3 development. The diurnal variations of O_3 and its precursors show the general patterns of urban background. From observational O_3 isopleth diagrams and morning ratios of non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NO_x), the chemical regime of O_3 formation was identified as VOC-sensitive, and the degree of VOC sensitivity tends to increase over the years, suggesting emission control on VOC to be suitable for O_3 management. Both total oxidant analysis and back-trajectory modeling (together with *K*-means clustering) indicate the potential role of regional transport or influence in enhancing surface O_3 level over the study areas. A meteorological adjustment with generalized linear modeling was performed to statistically exclude meteorological effects on the variability of O_3. Local air-mass recirculation factor was included in the modeling to support the coastal application. The derived trends in O_3 based on the meteorological adjustment were found to be significantly positive using a Mann–Kendall test with block bootstrapping.

1. Introduction

Tropospheric ozone (O_3), is a secondary air pollutant, photochemically forms in the atmosphere through a series of complex reactions in the presence of its precursors mainly nitrogen oxides (NO_x), volatile organic compounds (VOC), and carbon monoxide (CO) (Seinfeld and Pandis., 1998; Sillman, 1999). It can be harmful and negatively affect human health and the environment (US EPA, 2013). In context of climate change, O_3 directly contributes to the greenhouse effect (IPCC, 2007). O_3 pollution exists in many parts in the world (Molina and Molina, 2004 and references therein), including Thailand, a country in Southeast Asia. Deterioration of air quality has been found in a number of areas or cities in Thailand (PCD, 2012 and , 2013), generally as a result of industrialization, urbanization, and public infrastructure expansion following the nation's economic growth. The O_3 pollution has received most attention for Bangkok (Thailand's capital) (e.g., Limpaseni et al., 2003; Milt et al., 2009; PCD, 2001; Zhang and Oanh, 2002). Nevertheless, some other rapidly developing cities or areas have emerged to be highly polluted with O_3 (PCD, 2013), requiring an effort to understand the problem. One of such areas is the urbanized and highly industrialized eastern region, specifically, along the coastal areas of Chon Buri and Rayong provinces (shortly, CC and RC, respectively) (Fig. 1). In terms of severity, observed O_3 in both areas has shown to exceed the national O_3 standards several times a year (100 ppb for 1-h average and 80 ppb for 8-h average) (Supplemental Information, Fig. S1).

Each of Chon Buri and Rayong provinces has an overall positive economic growth in recent years, which can be seen from gross provincial production (GPP) (Fig. 2a and c) (NESDB, 2014). GPP shares the same definition as the gross domestic product (GDP) but scaled to a provincial level instead (as opposed to a national level). Industry is the largest contributor to total GPP, followed by transportation, residential & commercial, and agriculture. Fuel consumption in each province also has an increasing trend over time (Fig. 2b and d) (ETE, 2015). Pham et al. (2008) estimated total emissions from the industrial and power plant sectors in the year 2004 over the five different regions, finding that the eastern region emitted large amounts of NO_x, NMVOC, and CO compared to most of the other regions, despite its size being the smallest (Fig. 1a). Until now, air pollution and related health effects in

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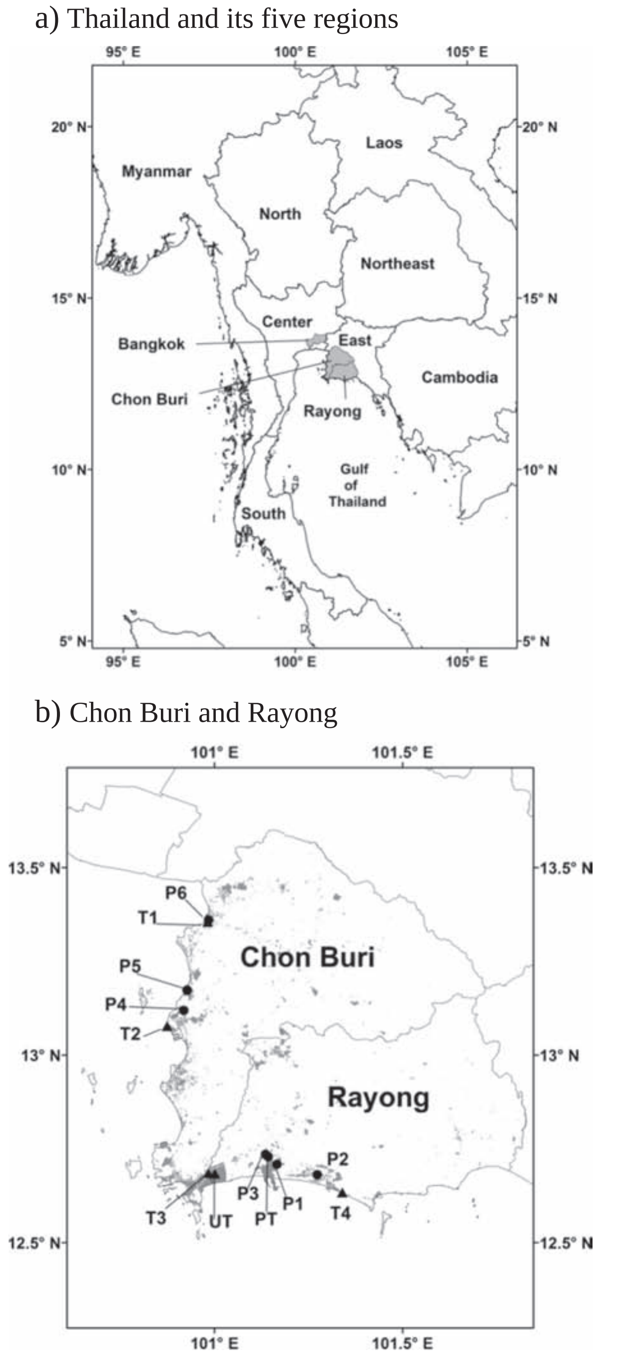

Fig. 1. Maps of Thailand and Chon Buri and Rayong provinces. In b), grey shading denotes urban, residential, industrial, and commercial areas combined (LDD, 2007), and the solid circles and triangles denote the monitoring stations considered in the study (see text).

this region have been studied by many researchers (e.g., Chusai et al., 2012; Khuntong et al., 2010; Pimpisut et al., 2005; Thepanondh et al., 2011; Guo et al., 2014; Kongtip et al., 2013; Tanyanont and Vichit-Vadakan, 2012) whereas O_3 has been much less addressed. A first dedicated O_3 work was only recently conducted by Prabamroong et al. (2012) in which the nature of O_3 formation and potential roles of emissions were considered using simplified photochemical box modeling. Nevertheless, the scope of investigation was limited to a short-term period in the year 2006 over CC alone, and other aspects of the problem still largely remain elusive, which have become the motivation of the current study for continuation.

O_3 formation depends on both precursor emissions and meteorological conditions, and, as a result of changes in these factors, O_3 varies with time differently at a different temporal scales (e.g., hourly, monthly, seasonal, and yearly). Its response to emitted precursors may be linear or nonlinear, governed by photo-chemistry (Seinfeld and Pandis., 1998; Sillman, 1999), complicating the development of suitable control strategies for managing the pollutant. In this study, O_3 over CC and RC was investigated using long-term observation data of O_3, the precursors, and meteorology. The data available to the study covers a period of 16 years (1997–2012), thus offering an opportunity to analyze O_3 characteristics in an integrative and statistically robust manner as well as enabling us to address some policy-related issues. To our knowledge, no previous studies have been dedicated to a long-term observational analysis of surface ozone for Thailand and Upper Southeast Asia. We began with examining the diurnal and monthly variations of O_3 and its precursors for the coastal areas. We then inspected the underlying chemical regime of O_3 formation for each area. Prabamrong et al. previously suggested the regime over CC as VOC-sensitive, we here re-assessed it with the long-term data for both CC and RC, and extended to whether there had been any shift or change in the regime over the long-term period. The dry season of the region was specifically considered due to its meteorological conditions generally being favorable for O_3 formation and elevate (see Section 4). The regionality and locality aspects of O_3 (i.e., whether regional sources or transport influencing O_3 observed over an area) was also investigated by means of a total oxidant concept and air-mass back trajectories, which will offer useful perspectives to air quality workers in terms of O_3 management. Lastly, a trend analysis was also performed to find whether O_3 has declined or increased over the long-term period for each area. In a policy-based context, a pollutant trend with effects of weather or meteorology removed is in fact more relevant and useful because an original trend is confounded by both the variability of emissions and that of meteorology. To relate or account for effects of meteorological factors, meteorological adjustment was performed (Thompson et al., 2001; Zheng et al., 2007) using generalized linear modeling. It is our hope that the findings from the above investigation will help enhance the existing understanding of the O_3 pollution and be useful to its management much needed for the region.

2. Study areas

Chon Buri and Rayong are the major and largest (in terms of development) provinces in the eastern region, as previously mentioned. They are adjacent to the sea (i.e., Gulf of Thailand) to the west and to the south, respectively (Fig. 1b). The general topography of CC and RC is mostly coastal plains, with mountains (for most, <700 m above mean sea level) sporadically aligned in the north–south direction. The former province has a total land area of about 4400 km^2 (with 17.8% as built-up) while the latter province has about 3600 km^2 (with 12.1% as built-up area) (LDD, 2007). Most of the built-up areas are congested along the coastal areas (i.e., CC and RC), which are urbanized and highly industrialized, as seen in the Fig. 1b. As to population, the former has a total registered population of 1.4 million and the latter has 0.6 million (as of 2012) (DOPA, 2015). Non-registered (or latent) population was reported to be sizable, as high as 90% (of registered population) for Chon Buri (as of 2011) (http://www.chonburi.go.th) and 74% for Rayong (as of 2009) (NESDB, 2010). The industry sector in the two provinces is large, e.g., in 2012, 60% (Chon Buri) and 45% (Rayong) of total GPP (from all sectors combined) was from industry sector (NESDB, 2014). Petrochemical plants (including oil refineries) are well present there, and two major deep seaports (Laem Chabang Port in CC and Map Ta Phut Port in RC) are to facilitate logistics for goods and commodities. A total of about 18 industrial estates exist in these two provinces (about 40% of all industrial estates in Thailand). 15 of them are found in the coastal areas (http://www.ieat.go.th/ieat/index.php; IEAT, 2014). In addition, both provinces also have tourist attractions (beaches, national parks, and cultural sites) (http://www.tourismthailand.org), and good air quality management becomes indispensable. The general climate of the eastern region is seasonally regulated by the northeast