Environmental Pollution 236 (2018) 699–705

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Air quality impacted by local pollution sources and beyond – Using a prominent petro-industrial complex as a study case[☆]

Sheng-Po Chen [a, *], Chieh-Heng Wang [b], Wen-Dian Lin [c], Yu-Huei Tong [c], Yu-Chun Chen [c], Ching-Jui Chiu [c], Hung-Chi Chiang [c], Chen-Lun Fan [c], Jia-Lin Wang [d, **], Julius S. Chang [a]

[a] *Atmospheric Sciences Research Center, University at Albany, State University of New York, Albany, NY, USA*
[b] *Center for Environmental Studies, National Central University, Taoyuan, Taiwan*
[c] *Environmental Simulation CO. LTD., Taipei, Taiwan*
[d] *Department of Chemistry, National Central University, Taoyuan, Taiwan*

ARTICLE INFO

Article history:
Received 17 October 2017
Received in revised form
26 January 2018
Accepted 27 January 2018

Keywords:
Sulfur dioxide
Coastal air quality
Monitoring network
Model simulation

ABSTRACT

The present study combines high-resolution measurements at various distances from a world-class gigantic petrochemical complex with model simulations to test a method to assess industrial emissions and their effect on local air quality.

Due to the complexity in wind conditions which were highly seasonal, the dominant wind flow patterns in the coastal region of interest were classified into three types, namely northeast monsoonal (NEM) flows, southwest monsoonal (SEM) flows and local circulation (LC) based on six years of monitoring data. Sulfur dioxide (SO_2) was chosen as an indicative pollutant for prominent industrial emissions. A high-density monitoring network of 12 air-quality stations distributed within a 20-km radius surrounding the petrochemical complex provided hourly measurements of SO_2 and wind parameters. The SO_2 emissions from major industrial sources registered by the monitoring network were then used to validate model simulations and to illustrate the transport of the SO_2 plumes under the three typical wind patterns. It was found that the coupling of observations and modeling was able to successfully explain the transport of the industrial plumes. Although the petrochemical complex was seemingly the only major source to affect local air quality, multiple prominent sources from afar also played a significant role in local air quality. As a result, we found that a more complete and balanced assessment of the local air quality can be achieved only after taking into account the wind characteristics and emission factors of a much larger spatial scale than the initial (20 km by 20 km) study domain.

1. Introduction

Due to social and economic reasons, coastal regions are often the preferred choices for urban and industrial developments. Air quality in a coastal region with industrial sources can be controlled not only by emissions but also by meteorology (Nester, 1995). For instance, many studies have explored the wind flows and boundary layer structures (Cheng et al., 2012; Liu et al., 2001; Melas et al., 1995; Ohara et al., 1989; Srinivas et al., 2007), topography (Cai and Steyn, 2000), sea surface temperature (Lee et al., 2011), urban heat-island effect (Lin et al., 2008). Several studies also discussed the impact of land-sea breeze on air quality for coastal urban centers (Angevine et al., 2004; Cheng et al., 2012; Cheng, 2002; Clappier et al., 2000; Ding et al., 2004; Lalas et al., 1983; Lee et al., 2011; Lin et al., 2008; Liu and Chan, 2002; Liu et al., 2001; Ohara et al., 1989). The interplay between emissions and wind field could decide the overall air quality of a region. While episodes of strong land-sea interchanges were of obvious research interest, they by no means provided the sole perspective of the interplay between meteorology and air quality. The cause-and-effect relationship would be straightforward if the controlling wind field is monotonous to disperse a prominent emission source. However, the issue may not be trivial if the controlling wind field is complex, and the affecting parameters on air quality can extend far beyond the local domain. As a result, a systematic approach with the right tools of both observation and simulation with sufficient temporal

---

[☆] This paper has been recommended for acceptance by Dr. Hageman Kimberly Jill.
* Corresponding author.
** Corresponding author.
E-mail addresses: schen21@albany.edu (S.-P. Chen), cwang@cc.ncu.edu.tw (J.-L. Wang).

https://doi.org/10.1016/j.envpol.2018.01.091
0269-7491/

and spatial resolution, as well as geophysical scale, can be advantageous.

To test the approach of measurement-modeling coupling to study local air quality affected by major stationary sources, a rural coastal region with a gigantic petrochemical industrial complex (hereafter called the Complex) was chosen as the test ground. Refinery and associated processes within the Complex overwhelmed other possible sources in the region such as traffic due to the rural nature and scarce population. To give an idea of the prominence of the Complex and the contrast to other minor sources within the region, the Complex ranked among the world's top ten similar complexes in 2008, on a par with other major petrochemical companies in Germany, USA, Netherlands, UK, Saudi Arabia, and Japan (ArabianOilandGas.com). The Complex accommodated 70 associated plants, contributing approximately 10% to Taiwan's gross domestic product (GDP) in 2012 (National Statistics, 2013).

Due to the prominence of emissions, both air quality and wind parameters were intensively monitored surrounding the Complex to closely watch its emissions and to facilitate air-quality assessment in the area.

In this study, sulfur dioxide was selected as the target pollutant for both modeling and observations to track industrial emissions from and beyond this region due to the greater specificity of its source locations and amounts, as well as the sharp contrast between emissions and background than other pollutant species. The approach was to first validate the accuracy of the model simulations with the network observations, the simulations in turn provided the complete picture of the transport of industrial plumes. Therefore, the objective of this study is to use the tools of network observations and model simulations to approach the problem of how a major industrial source affects a rural area where the wind characteristics are highly seasonal. While most air-quality studies are urban-oriented with the widespread traffic as the major emission source to affect air quality, this study chooses a very different setting as a contrast; that is, an agricultural area with minimal traffic but a single major industrial source. Since the spatial coverage of the monitoring sites is believed to be unprecedented worldwide, the coupling of observations of high spatial-temporal resolution with the Eulerian model simulations presented here allows the air-quality assessment to be a benchmark for any region with major stationary emission sources.

2. Wind flow patterns at the coastal region

2.1. Monitoring sites (data source)

A network of more than 70 air quality stations are currently operated by Environmental Protection Administration of Taiwan (EPA-AQS) across the island reporting hourly concentrations (mixing ratios by volume) of NO_x, SO_2, CO, PM_{10} and O_3. The AQS also report hourly wind data (wind speed and wind direction), temperature, humidity, rainfall, etc. In the study domain of interest, there are three EPA-AQS (E1-E3) situated at 3 km, 10 km, and 40 km towards inland from the coastline (Fig. 1).

In mid-2012, due to the prominence of the Complex, an additional network of nine continuous AQS were added within a radius of 20 km area (dubbed Petro-AQS) to closely watch the local air quality, forming a high-density network to synergistically characterize wind patterns and key pollutants with high temporal and spatial resolutions. One of the nine Petro-AQS was inside the Complex. The monitoring instruments at the nine Petro-AQS were maintained in accordance with the Taiwan EPA-AQS operation protocols (Table S1). As a result, data from the two different agencies can be directly inter-compared.

The following categorization of wind flow pattern is used to systematically classify the daily wind field characteristics for the observations in this coastal area. The six-year worth of the EPA-AQS dataset from 2008 to 2013 were used to study the characteristic wind flow patterns over a broader coastal region (Section 2.3), whereas the observations from the more densely deployed Petro-AQS from Aug. 2013 to Jul. 2014 were utilized (Section 2.4) to gain more spatially resolved wind features in the vicinity of the Complex.

2.2. Categorization of surface wind patterns

In this coastal region of interest, the prevailing synoptic weather patterns are mostly determined by winter and summer monsoons (Chang et al., 2000; Chen et al., 2014; Chiang et al., 2009). The most dominant wind flows are northeasterlies mainly occurring in colder months. In summer, southwesterly winds are frequent; however, the land-sea breeze or more generally described as the local circulation (LC) can also be important. It was noted that high pollution events could occur during the land-sea breeze events in coastal areas (Angevine et al., 2004; Boucouvala and Bornstein, 2003; Ding et al., 2004; Kalthoff et al., 2005; Klausner and Fattal, 2011; Lin and Chang, 2002; Talbot et al., 2007).

To unravel the pollution phenomena in the study region of interest in a more systematic way which is largely wind driven, the three types of wind flows were categorized based on the perennial wind data obtained by the networks mentioned earlier (Fig. 2):

(1) Northeast monsoonal (NEM)
(2) Southwest monsoonal (SWM)
(3) Local circulation (LC)

The monsoonal flow patterns are defined as the changes in wind direction confined within 90° within 24 h, which are manifested as higher wind speeds and rather monotonous wind directions over a fairly long period of days. Under this wind pattern, pollutants from afar can traverse long distances to affect downwind air quality.

For LC, including land-sea-breeze, the changes in wind direction are confined within 90°–270°. Under this flow pattern, pollutants from the coastal region tend to spread over a large area into inland.

Within each of the three wind flow types, most of the pollution episodes can be unambiguously described for the source origins and transport routes. Details of the analysis of area-wide wind flow patterns will be shown in section 2.4.

2.3. Wind fields in a broader region

As seen in Fig. 1, the three EPA-AQS (E1, E2 and E3) provided a lengthy meteorological dataset (2008–2013) not only in the coastal area, but also stretching far into the inland areas to the east (i.e., the E3 site). These hourly wind data revealed the overall wind characteristics for the entire region. In Fig. 3 the statistics of the three wind flow patterns at these three EPA-AQS reveals that the percentages of the NEM pattern decreased from coast to inland. It ranged from 30% to 46% at the E1 site (coastal), but dropped to 22%–27% at E3 (inland). Likewise, the SWM pattern ranged from 7% to 12% at the E1 or E2 site, but reduced to 1%–4% at E3, suggesting that the monsoonal flows affect more in coastal areas than inland, but more so for NEM than for SWM. In contrast, for the LC flows, their percentages increased from 43% to 54% at E1 (coastal) to 69%–75% at E3 (inland), suggesting that the more inland areas are less affected by the monsoonal flows and more by the LC flows.

2.4. Wind fields within the target coastal region

When narrowing from the broader region down to the more