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تحليل أنماط الانبعاثات وتلوث الهواء في المناطق القريبة من مصافي النفط في الكويت

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الخلاصـة

تركز هذه الدراسة على تقييم وتحليل تلوث الهواء في المناطق القريبة من مصافي النفط في دولة الكويت، فقد تم استخدام سجل الانبعاثات لمصافي البترول في برنامج إيرمود للتنبؤ بتراكيز الملوثات، وعلى الجانب الآخر تم قياس تراكيز الملوثات و الأرصاد الجوية كل خمس دقائق لمدة 24 ساعة في اليوم في ثلاثة مناطق سكنية. المنطقة السكنية الأولى هي منطقة الفحاحيل وتقع شمال مصافي النفط، والمنطقة السكنية الثانية هي منطقة أم الهيمان وتقع جنوب مصافي النفط و أما المنطقة السكنية الثالثة فهي منطقة الأحمدي وتقع شمال غرب مصافي النفط. لقد أثبتت هذه الدراسة أن تراكيز جميع الملوثات التي تم قياسها في هذه المناطق أعلى من تراكيز الملوثات التي تم تنبؤها باستخدام البرنامج والتي اعتمدت على مصافي البترول وحدها، مما أظهر أن هذه المناطق متأثرة بملوثات أخرى غير مصافي البترول ألا وهي حقول النفط ثم محطات الطاقة و تليها حركة المرور.

Analysis of air pollution emission patterns in the vicinity of oil refineries in Kuwait

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ABSTRACT

This study focuses on the assessment and analysis of air pollution in the vicinity of oil refineries in Kuwait. The emission inventory obtained for oil refineries was used to predict pollutant concentrations and distributions using the AERMOD software (V5.1), Industrial Source Complex Short-Term model (ISCST3). Pollutant concentrations and meteorological parameters were measured at 5-minutes intervals for 24 hours/day in three regions. The first region was in the Fahaheel residential area (north of the oil refineries), the second region was in the Umm Alhyman residential area (south of the oil refineries), and the third region was in the Ahmadi residential area (northwest of the oil refineries). The measured concentrations of all pollutants are higher than the predicted concentrations generated by the refinery emissions, which is attributed to the effect of other pollution sources, e.g., traffic, power plants, and oil fields. Analysis showed that the strongest contribution comes from the oil fields, followed by traffic or oil refineries.

Keywords: Emission inventory; ISCST3 model; oil refinery.

INTRODUCTION

Air pollution, a major problem throughout the world, is caused by the combustion of fossil fuels. Fossil fuels power motor vehicles and airplanes and are used to generate electric power, which is used in air conditioning, the production of various industrial and agricultural goods, and the operation of household devices, among other things. The measurement and analysis of air pollution in Kuwait is a common research topic. Several studies have been performed over the past two decades to provide a better understanding of air pollution patterns, dispersion, and photochemical mechanisms. This study furthers these efforts by assessing and analyzing the air pollution produced by oil refineries in Kuwait. The following provides a brief overview of recent air pollution studies conducted in Kuwait and around the world, with an emphasis on data assessment, air dispersion models, and artificial neural networks (ANNs).

Elbir (2000) studied the air pollution emissions in Turkey and compared them to those in Europe. The results showed that air emissions per capita and per unit area in Turkey are lower than the European averages and provided planners with guides to mitigate air pollution effects in Turkey. An air-quality assessment for large cities was conducted by Baldasano (2002) using data collected from a number of countries in Europe, North America, Africa, and Asia. The results showed that the sulfur dioxide (SO_2) concentrations remain within the regulatory limits throughout the world, except for in some Central American and Asian cities. In addition, the nitrogen dioxide (NO_2) concentrations throughout the world were within or close to the air-quality limits, except for in Kiev, Beijing, and Guangzhou. Furthermore, the study showed that ozone (O_3) concentrations are high throughout the world. The measured particulate matter (PM_{10}) concentrations were found to be above the regulatory limits in every Asian city studied. Nicks *et al*., (2003) compared the measured carbon monoxide (CO) emissions from several power plants in Texas, USA, against inventory emission data. The study included gas, lignite-coal, and coal-fired power plants. The CO emissions from the lignite-coal-fired plants exceeded the inventory data, whereas the CO emissions from the gas- and coal-fired power plants matched the inventory. Riga-Karandinos & Saitanis (2005) analyzed the ambient air quality in two coastal cities (Patras and Volos) in Greece. The results showed that the concentrations of nitrogen monoxide (NO), NO_2, and SO_2 were higher in Patras than in Volos because of the high traffic in Patras, while the concentration of CO was the same in both cities. In contrast, the ozone concentration was higher in Volos than in Patras, especially during the weekends, because of the reduction in NO_x emissions. The reported O_3 levels were close to the upper limits of the international standards. Al-Hamad & Khan (2008) studied the total emission of primary pollutants from flares in oil fields in Kuwait, finding that the flaring emissions fluctuated during the period of 1997-2005. These fluctuations are caused by several factors, including changes in production rates as well as equipment failure and maintenance. Air-quality data were assessed by Ettouney *et al*., (2010) from two monitoring stations in Kuwait (Al-Jahra and Umm-Alhyman). The data covered a period of four years (2001-2004) and reported the average concentrations of CO, carbon dioxide (CO_2), methanated hydrocarbons (MHC), non-methanated hydrocarbons (NMHC), NO_X, SO_2, O_3, and PM_{10}. Moreover, meteorological parameters (wind speed/direction, solar radiation, and temperature) were included in the assessment. It was concluded that all data are within the international limits, except for PM_{10}, which is strongly related to the arid nature of the Kuwaiti environment. Additionally, the increase in NO_X concentrations over the studied period was attributed to the continuous increase in population, motor vehicle density, and industrial activities.

Abdul-Wahab *et al*., (1996) studied O_3 levels in the Shuaiba industrial area in Kuwait. A statistical model was developed from ambient air-quality data. An air pollution mobile monitoring station was used to record the data for a period of one year. It was concluded that a positive correlation existed between O_3 levels and temperatures below 27°C, while a negative correlation existed for temperatures above 27°C. Abdul-Wahab *et al*., (1999) used SO_2 in the Shuiaba industrial area in Kuwait as a model pollutant to compare the predicted ground-level concentrations with the measured concentrations. The ISCST model was used to simulate the dispersion of SO_2 from a large number of emission sources. Good agreement between the measured and predicted data was reported for most of the measured values. However, the use of a constant emission rate for SO_2 provided a poor prediction for a portion of the measured data. Measurements and analysis of air pollution over a period of one year were conducted in the Shuaiba industrial area in Kuwait by Abdul-Wahab *et al*., (2000). Data analysis showed the existence of two-maximum diurnal variations for the concentration of the primary pollutants, which included NO, SO_2, NMHC, CO, and PM. On the other hand, a single maximum was observed for the secondary pollutants, which included O_3 and NO_2. Sivacoumar *et al*., (2001) compared the measured and predicted concentrations of NO_x in Jamshdpur, India. The ISCST model was used to predict NO_x dispersion from industrial, vehicle, and domestic emission. The results indicated that the contributions to the NO_x emissions were as follows: 53% from industry, 40% from vehicles, and 7% from domestic sources. Bevilacqua & Marcello (2002) evaluated the environmental efficiency of seven oil refineries in Italy (over a period of four years) using the data envelope model. The analysis considered the emission of six pollutants (CO, CO_2, SO_2, etc.) as a function of the amount of oil processed. The model predictions agreed with the available field data. Alameddine & El-Fadel (2005) studied the gas emissions from two desalination plants in the Arabian Gulf. The industrial source complex ISC model was used to assess SO_2 concentrations at sensitive receptors under worst-case meteorological conditions and full load operation. The simulation results showed that several receptors were prone to exposure to concentrations exceeding health standards. Al-Rashidi *et al*., (2005) studied the use of mathematical modeling for the investigation of the efficiency of existing monitoring sites regarding the impact of SO_2 emissions from power stations in Kuwait. The ISCST3 model was used to identify the spatial and temporal variations of SO_2 over residential areas. The model results were 60%-94% accurate relative to the measured results.

Grivas & Chaloulakou (2006) developed artificial neural network (ANN) models using a combination of metrological and time-scale input variables to predict the hourly concentration of PM_{10} in Athens. The PM_{10} data covered a period of two years. The analysis of the predicted data of particulate matter showed that the ANN model performed well, yielding acceptable probabilities. Kurt *et al*., (2008) developed an online air pollution forecasting system using neural networks for Istanbul. SO_2, PM_{10}, and CO levels were predicted for the next three days. The results showed that the use of day of the week as an input parameter to the ANN system provided forecasts with high accuracy. Al-Alawi *et al*., (2008) developed models to predict O_3 concentrations in Kuwait in the lower atmosphere. The data were collected in the summer. Three models were used: principle component regression (PRC), artificial neural network (ANN), and a combination of PRC and ANN. The results showed that the combination method provided the best forecast accuracy for O_3 concentration levels in a 24-hours period, followed by the ANN model and then the PCR model. Pfeiffer *et al*., (2009) used diffusive sampling measurements and an artificial neural network to calculate the average spatial distribution of NO_2 in Cyprus. The best input data were found to be emission inventory and population density. The results showed that the neural network give realistic maps of the annual average distribution of NO_2. Ettouney *et al*., (2009a; 2009b) estimated the emission inventory of SO_2, CO, and NO_x in Kuwait. The emission sources were power plants, motor vehicles, oil fields, and oil refineries. A pollutant database for 2003 in Al-Jahra was simulated using the ISCST dispersion model, and the O_3 concentration was forecasted using two feed-forward artificial neural networks (ANNs). The emission inventory showed that the major sources of SO_2, CO, and NO_x are power plants, motor vehicles, and oilfields. Additionally, the predictions of the ISCST3 model and the database were nearly identical for the hourly average but differed for the hourly maxima.

The present work focuses on measurements of pollutant concentrations in urban areas in the vicinity of oil refineries in Kuwait. The measurements were conducted over a period of one year and included emission inventories and pollutant concentrations. In addition, pollutant patterns were predicted using the AERMOD software, ISCST3 model. Several numerical experiments were conducted to determine the conditions under which the emission rates and resulting pollutant dispersion would be below the maximum allowable limits. In addition, the model and measured results were used to assess the health risks in urban areas in the vicinity of oil refineries.

MEASUREMENTS AND LOCATIONS

Air pollution measurements were taken for sixteen days over three periods in different areas, as shown in Figure 1: in the Fahaheel residential area from 21/12/2010 to 5/01/2011, in the Umm Alhyman residential area from 10/04/2011 to 25/04/2011, and in the Ahmadi residential area from 25/06/2011 to 10/07/2011. The details of the mobile laboratory instruments are provided in Table 1. Pollutants and meteorological parameters were measured in 5-minutes intervals for 24 hours/day. The pollutants included CO, CO_2, SO_2, NO, NO_2, O_3, PM_{10}, hydrogen sulfide (H_2S), ammonia (NH_3), methane (CH_4), NMHC, and total hydrocarbons (THC). The recorded meteorological conditions were relative humidity, wind speed, wind direction, ambient temperature, and solar intensity.

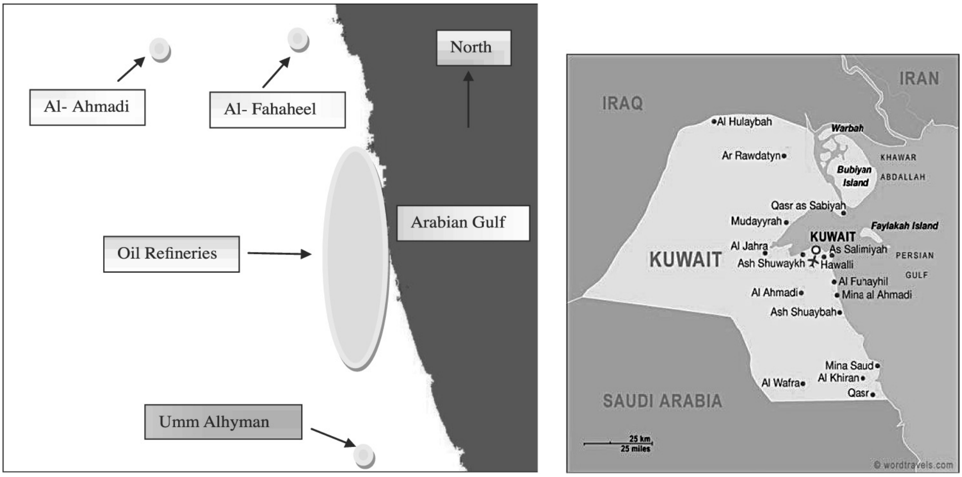


Fig. 1. Location of the oil refineries and three residential areas where measurements were taken. Map (a) shows the location of the study area, and Map (b) shows the state of Kuwait and the relative location of the study area.

Table 1. Characteristics and types of measuring devices used in air pollution laboratory.

Parameter	Apparatus	Range	Minimum Detectable Limit
Carbon monoxide (CO)	Infrared Analyzer, IR	0 - 1,000 ppm	0.04 ppm
Carbon dioxide (CO_2)	Infrared Analyzer, IR	0 - 1,000 ppm	0.1 ppm
nitrogen oxide (NO, NO_2 and NO_X)	Chemiluminance Analyzer	0 - 20,000 ppb	0.4 ppb
Sulfur dioxide (SO_2)	Florescence Analyzer	0 - 20,000 ppb	0.4 ppb
Methane and non-methane hydrocarbons	Gas Chromatograph with FID (Flame Ionization Detector)	0 - 20 ppm	0.1 ppm
Ozone (O_3)	Ultra-violet Analyzer	0 – 1,000 ppb	1 ppb
Particulate matter, PM_{10}	Standard Gravimetric Method	0 - 5,000 µg/m^3	5 µg/m^3
Solar radiation	Solar Radiation Sensor	0 - 2,000 W/m^2	20 W/m^2
Air temperature	Thermometer	-30 to 60ºC	0.1%
Wind speed	Anemometer	0.46 - 76 m/s	0.2 m/s
Wind direction	Direction Sensor	0º to 360º	5º

EMISSION INVENTORY

There are three large oil refineries in Kuwait; Ahmadi, Shuaiba, and Mina Abdullah, with production capacities of 460,000, 200,000, and 270,000 BPD (barrels per day), respectively, as per Kuwait National Petroleum Company (KNPC) records.

The refineries were established and commissioned during 1949-1988. Examples of units found in the Ahmadi refinery include crude distillation, naphtha reforming, desulphurization, vacuum distillation, fluid catalytic cracking, hydrogen recovery and production, etc. The other two refineries contain similar units; however, Mina Abdullah also has a delayed coker unit that generates light fractions from vacuum distillation residuals.

Emission inventories were collected for four flares in the Ahmadi refinery, two flares in the Shuaiba refinery, and six flares in the Mina Abdullah refinery during 2007. Data were measured continuously in 10-minutes intervals, and the measured data were averaged on a monthly basis. The data included SO_2, volatile organic compounds (VOCs), NO, CO, and CO_2. The emission inventories for all pollutants in all flares fluctuate around similar average values throughout the entire year, as shown in Tables 2, 3, and 4.

Table 2. *Emission inventory in gm/s in 2007 from flares in Mina Ahmadi refinery.

Month	SO_2	VOCs	NO	CO	CO_2
January	24.35	36.20	1.35	34.98	1050.10
February	21.85	22.26	1.13	32.44	819.97
March	16.16	23.63	0.82	27.08	736.84
April	12.57	19.12	0.90	25.13	710.32
May	18.94	27.53	0.76	26.25	728.77
June	13.40	26.65	0.76	29.81	883.58
July	12.32	32.69	1.16	31.36	881.36
August	22.06	27.62	0.85	39.34	1081.02
September	19.73	34.64	0.75	34.22	988.66
October	20.93	35.17	0.56	30.36	926.81
November	16.67	32.05	0.63	30.03	913.86
December	16.04	32.75	0.56	29.37	888.23

*(www.knpc.com)

Table 3. *Emission inventory in gm/s in 2007 from flares in Mina Shuaiba refinery.

Month	SO_2	VOCs	NO	CO	CO_2
January	44.18	20.16	0.44	16.26	380.50
February	42.40	18.39	0.40	13.46	300
March	27.40	13.29	0.30	10.30	374
April	24.60	7.50	0.30	15.20	283
May	38.22	10.71	0.23	8.68	259.31
June	17.10	7.09	0.22	11.30	174.32
July	31.80	12.60	0.30	9.55	285.15
August	36.40	8.70	0.22	14.30	204.19
September	22	8.51	0.24	7.12	212.61
October	35.40	7.77	0.24	16	208.93
November	24.80	12.60	0.37	10.45	274
December	28	13.03	0.31	18	287
Average	31.03	11.69	0.29	12.55	270.25

*(www.knpc.com)

Table 4. *Emission inventory in gm/s in 2007 from flares in Mina Abdullah refinery.

Month	SO_2	VOCs	NO	CO	CO_2
January	8.92	21.77	2.57	14	450.17
February	9.95	17.77	2.31	14.05	431.57
March	8.06	20.80	2.57	13.15	450.17
April	7.86	18.39	2.49	12.25	441.90
May	7.10	19.81	2.57	12.30	450.17
June	8.36	18.21	2.49	12.60	441.79
July	7.73	21.31	2.57	12.50	450.08
August	8.92	23.35	2.57	14.75	450.17
September	8.23	19.18	2.49	12.85	441.89
October	8.92	21.31	2.57	13.30	450.17
November	8.06	17.38	2.49	13.50	441.60
December	8.13	22.26	2.57	14.60	450.06
Average	8.35	20.12	2.52	13.32	445.81

*(www.knpc.com)

METHODOLOGY

The industrial source complex short-term model (ISCST3) provides options to model emissions from various sources that could be presented in a typical industrial source complex. The performance of the ISCST model was investigated in several studies done by Al-Rashidi *et al*. (2005), Arslan *et al*. (2009), Baldasano (2002) and Bevilacqua & Marcello (2002). Lingjuan *et al*., (2006) compared the performance of the CALPUFF and ISCST3 models for predicting downwind odor and source emission rates. The study showed that the ISCST3 model under predicted downwind odor concentrations compared to the measured concentrations. Additionally, both models failed to predict the peak odor concentrations using the constant average emission rate. In this study, the AERMOD software, ISCST3 model was used to predict the measured SO_2, NO, CO, and VOCs. The calculations were based on the hourly averages of the measured data over a period of 24 hours/day. Kenneth *et al*., (2006) applied two steady-state air dispersion models, ISCST3 and AERMOD, to predict hydrogen cyanide concentrations. Hydrogen cyanide samples were collected at monitoring stations located on the opposite sides of a gold heap leach field. The results showed that the ISCST3 over predicted hydrogen cyanide concentrations relative to the measured concentrations by a factor of 2.4 on average. However, the AERMOD under predicted hydrogen cyanide concentrations relative to the measured concentrations by a factor of 0.76 on average. Arslan *et al*., (2009) modeled the atmospheric dispersion of hydrogen sulfide and volatile organic compound emissions from a landfill area in Istanbul. The ISCST3 model was used to predict the hourly pollutant concentrations over the closest residential area. The study shows that the ISCST3 predicted concentrations of ethyl mercaptan, methyl mercaptan, and hydrogen sulfide that exceeded odor thresholds at several points within the study domain. The performance of the (EPA) non-reactive Gaussian air-quality dispersion model, the industrial source complex short-term model (ISCST3), was examined by Matthew *et al*., (2000). The model was used to predict polychlorinated dibenzodioxin and polychlorinated dibenzofuran concentrations in air and soil near the Columbus Municipal Solid Waste-to-Energy Facility. The results showed that the predicted values were within a factor of 10 of the measured values, which was considered to be reasonable because of the small number of measured data and the uncertainties involved in the study, including the stack emission rate, meteorological data, and reactions/transformation of dioxins.

METEOROLOGICAL DATA ANALYSIS

The temperature variations are shown in Figure 2. The collected data vary over ranges of 10-24°C, 19-35°C, and 29-52°C during the first, second, and third measurement periods, respectively. Moreover, the temperature profiles are consistent with the daily norms, in which the maximum occurs at approximately 3 pm. Figure 3 shows that the wind speed varies within 1-8.8 m/s, 1.8-9.8 m/s, and 1-6 m/s for the first, second, and third periods, respectively. These values correspond to light to fresh breeze conditions on the Beaufort scale (Brebbia, 2007). As shown, the wind speed peaks around midday, which is due to the rapid increase in the land temperature, which causes the adjacent air mass to rise and induces the sea breeze phenomenon. The wind speed continues to decrease until approximately midnight, at which point the land temperature is lower than the sea temperature and the opposite of the sea breeze phenomenon (land breeze) occurs, causing air turbulence and increasing the wind speed (Ettouney *et al*., 2010). Figure 4 shows the wind roses for the three study periods, which indicate that January and July feature less turbulent wind conditions than April. The change in the climate conditions from cold to warm during April resulted in uniform wind speeds in all directions. However, in January and July, most of the wind comes from the northwest, which is the dominant direction for wind in Kuwait (Al-Rashidi *et al*., 2005).

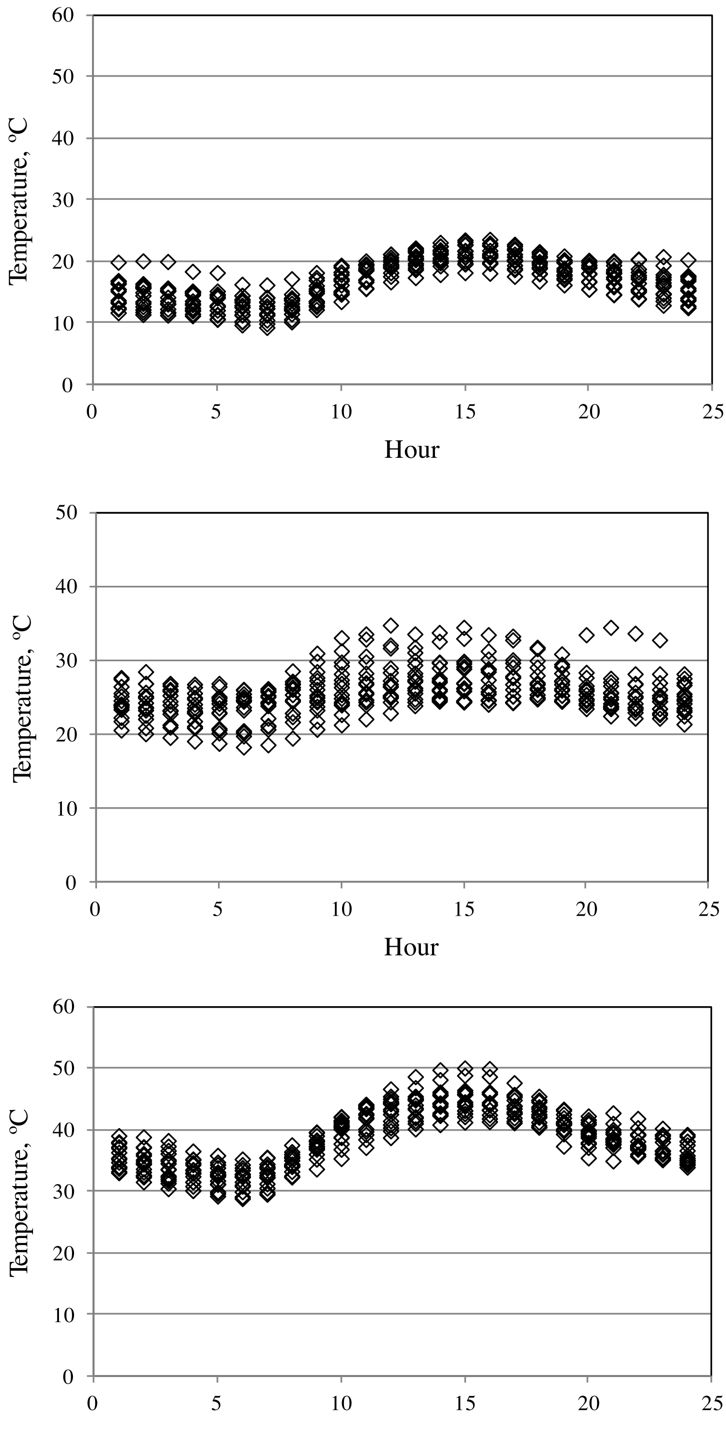


Fig. 2. Variation in measured temperature during the 1st, 2nd, and 3rd periods of the study.

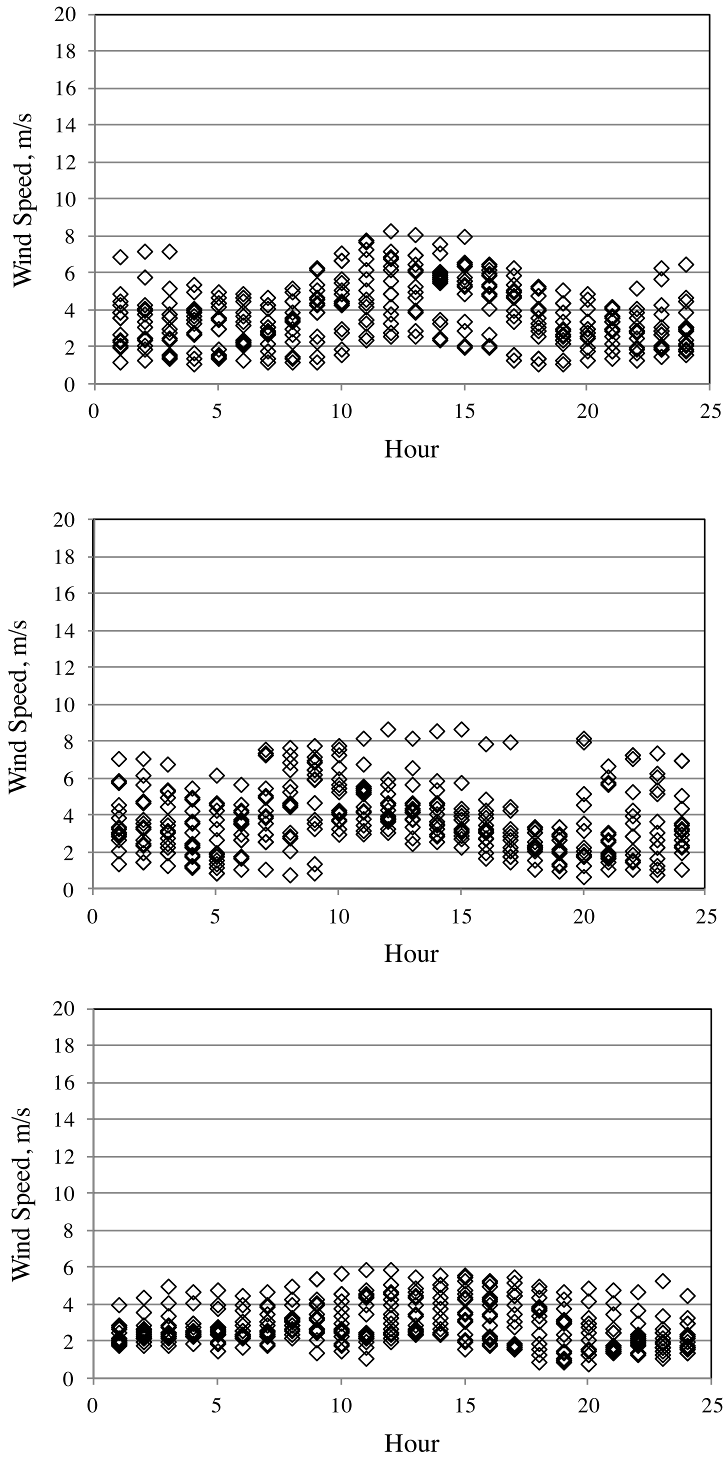


Fig. 3. Variation in measured wind speed during the 1st, 2nd, and 3rd periods of the study

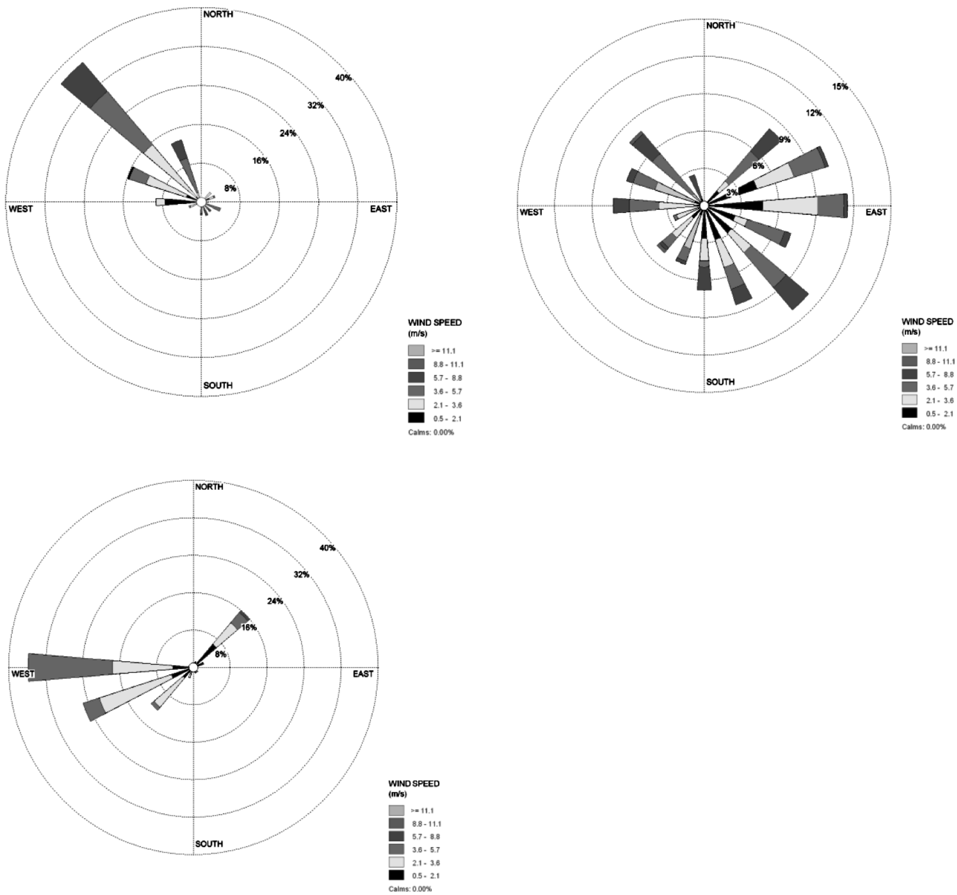


Fig. 4. Wind rose graphs for the 1st, 2nd, and 3rd periods of the study, corresponding to January, April, and July.

AIR POLLUTION DATA ANALYSIS

Figure 5 shows the SO_2 variations. Most of the data fall between 5 ppb to 25 ppb. However, higher concentrations of 40-120 ppb were measured in the first period in the Fahaheel residential area from 21/12/2010 to 05/01/2011, which is attributed to the high emission rates in the Ahmadi and Shuaiba refineries, as shown in Tables 2 and 3. Contrary to the findings of Abdul-Wahab *et al*., (2000), the data show a base concentration for SO_2, which is similar for the three study periods. Additionally, it was difficult to discern a two-maximum diurnal variation, as reported in Abdul-Wahab *et al*., (2000), which is explained by the strict emission regulations recently practiced in the refineries, unlike those practiced 10 years earlier.

The measured NO and CO data are shown in Figures 6 and 7, respectively. The daily patterns for NO show bi-diurnal variations during the early morning and evening rush hours. This finding is consistent with the CO results, which are attributed to the increase in traffic volume or heavy use of construction vehicles and machinery in these periods. The same results were reported by Ettouney *et al*., (2010), while diurnal variations in CO are consistent with the behavior of non-reactive photochemical components featuring two maxima: one during the early morning hours and one during the late evening hours. Similar patterns are also observed for nitrogen oxides.

Figure 8 shows the variations of the THCs. As shown, a minimum occurs at midday, while higher values occur in the morning and evening. This occurrence is related to the reaction of hydrocarbon with nitrogen oxides in the air in the presence of sunlight to form ozone, as reflected in O_3 variation, which peaks between 10 am and 4 pm. These conclusions are supported by the results of Ettouney *et al*., (2010).

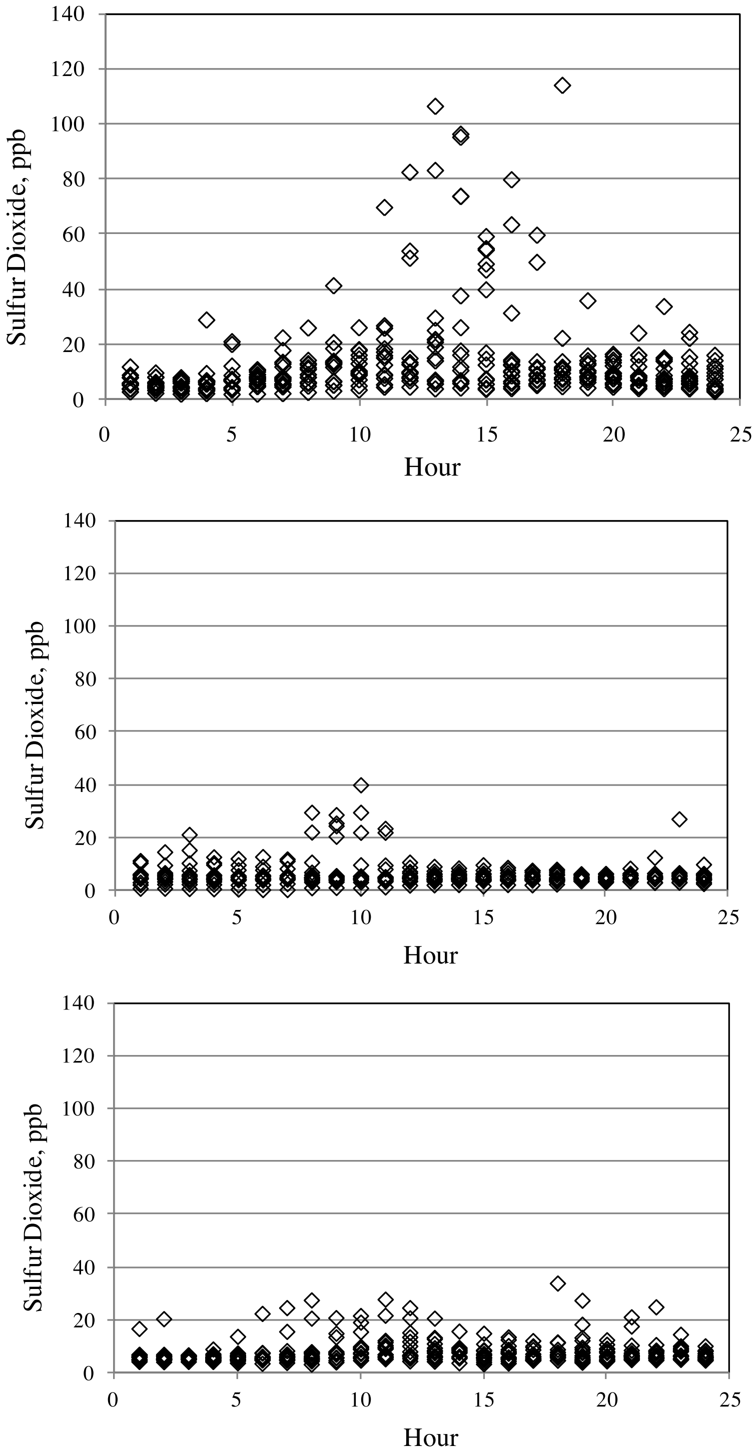


Fig. 5. Variation in measured sulfur dioxide during the 1st, 2nd, and 3rd periods of the study.

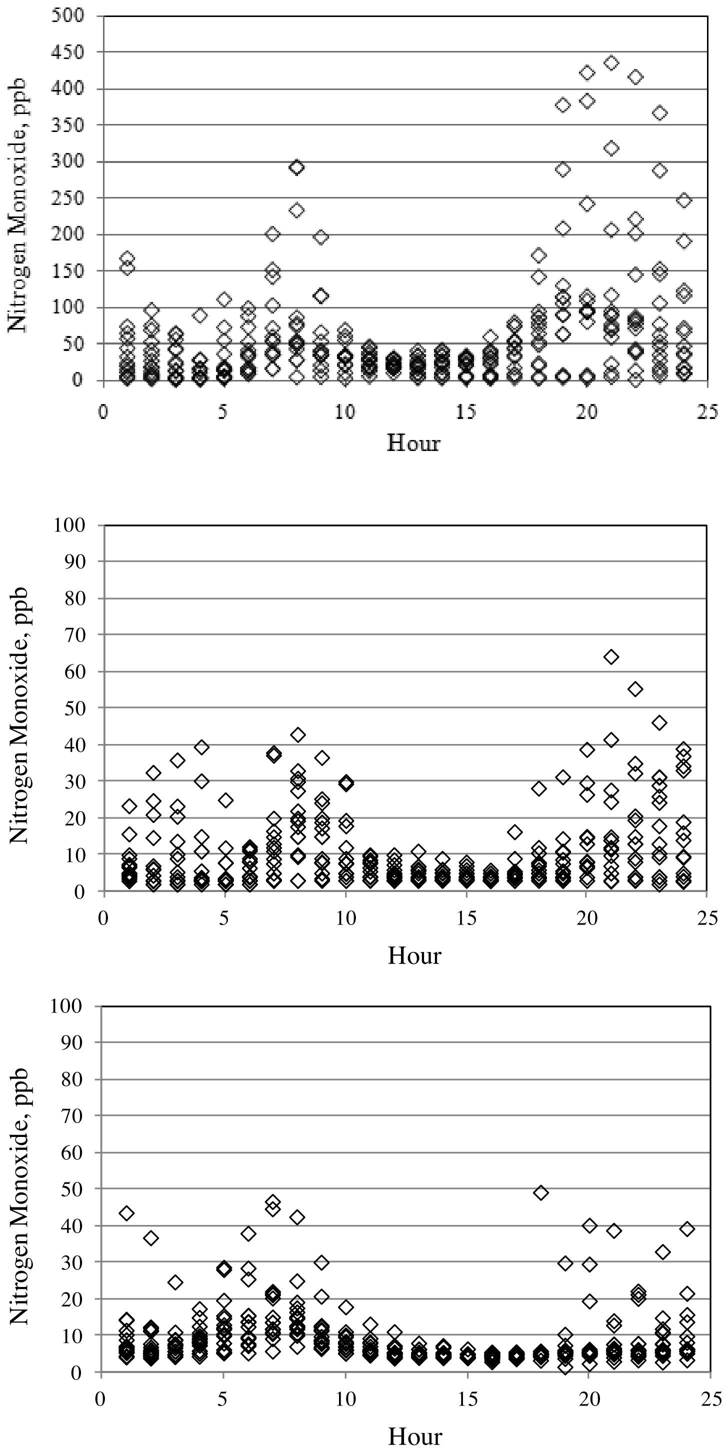
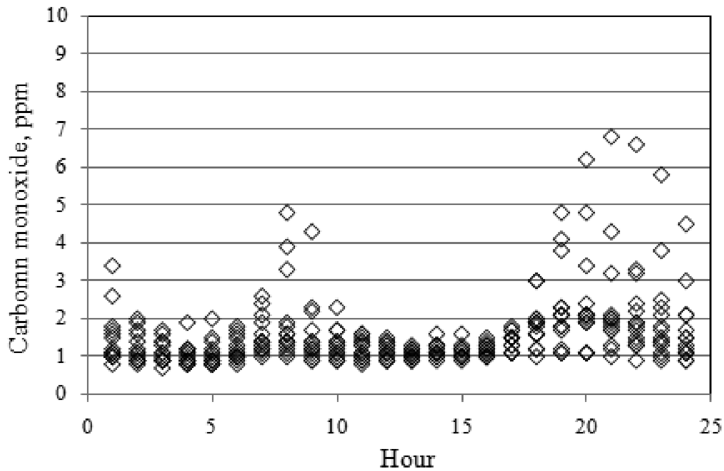
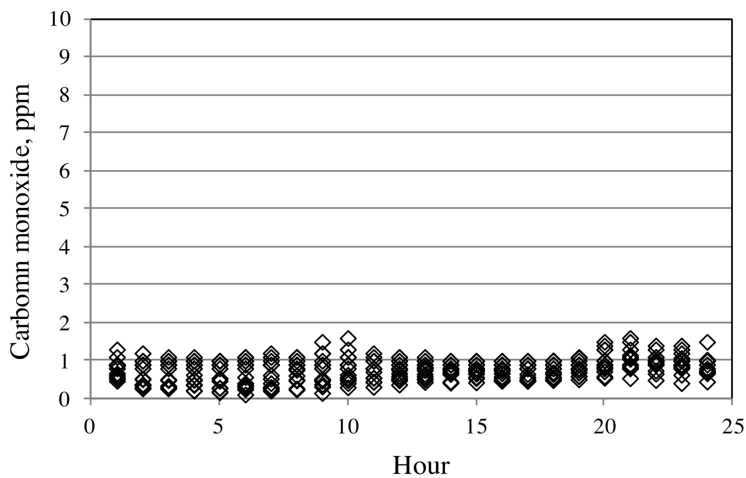


Fig. 6. Variation in measured nitrogen monoxide during the 1st, 2nd, and 3rd periods of the study.





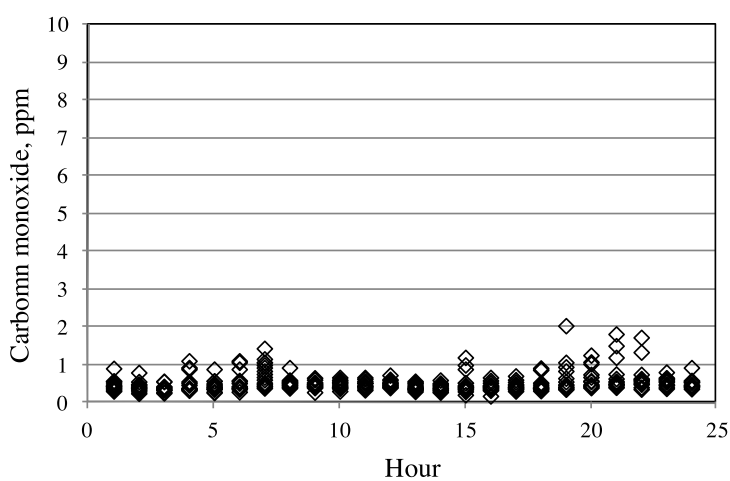


Fig. 7. Variation in measured carbon monoxide during the 1st, 2nd, and 3rd periods of the study.

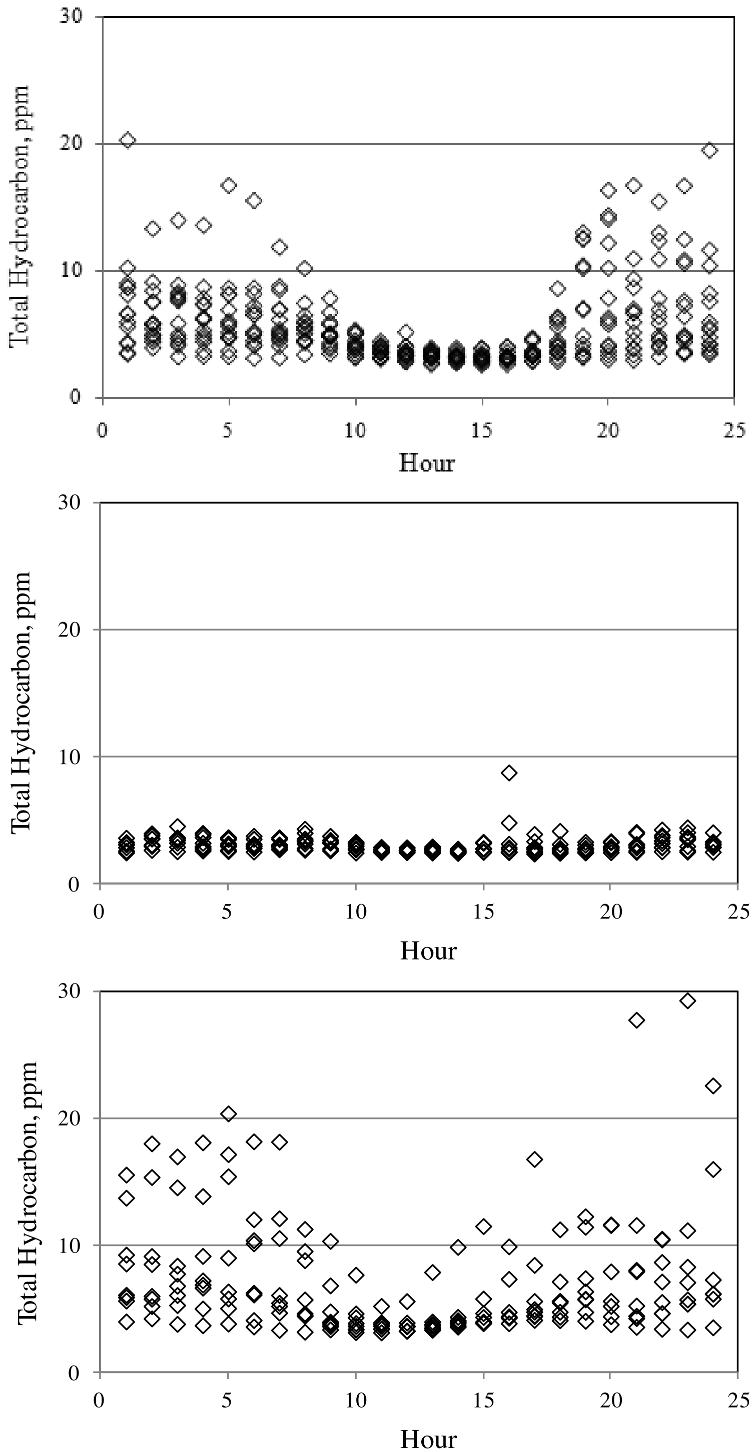


Fig. 8. Variation in measured total hydrocarbons during the 1st, 2nd, and 3rd periods of the study.

MEASURED AND PREDICTED DATA

The contour maps generated by the AERMOD software, ISCST3 model show that the pollutants are uniformly distributed and that there is a strong dependence on the wind direction, as illustrated in the wind roses provided in the previous section. The maps indicate that during the first measurement period, from 21/12/2010 to 5/01/2011, the Ahmadi residential area is mainly affected by the Ahmadi refinery. Zero concentrations in Ahmadi were obtained when simulating emissions from the Shuaiba refinery and Abdullah refinery individually. Moreover, the contour maps show that, when considering emissions from the Abdullah refinery only, contours with higher values are concentrated around the Umm Alhyman residential area. The maps show that during the second measurement period, the three residential areas are affected by the Ahmadi, Shuaiba, and Abdullah refineries for the cases of simulating refinery emissions individually or together. This occurrence is due to the wind, as discussed, which was blowing from almost all directions during 10/04/2011 to 25/04/2011. The maps for the third measurement period illustrate that the Ahmadi residential area is mainly affected by the Ahmadi refinery, while the Umm Alhyman residential area is affected by all refineries. However, the Fahaheel residential area is not affected by the emissions from any of the three oil refineries. Examples of the pollutant contour maps are shown in the figures below.

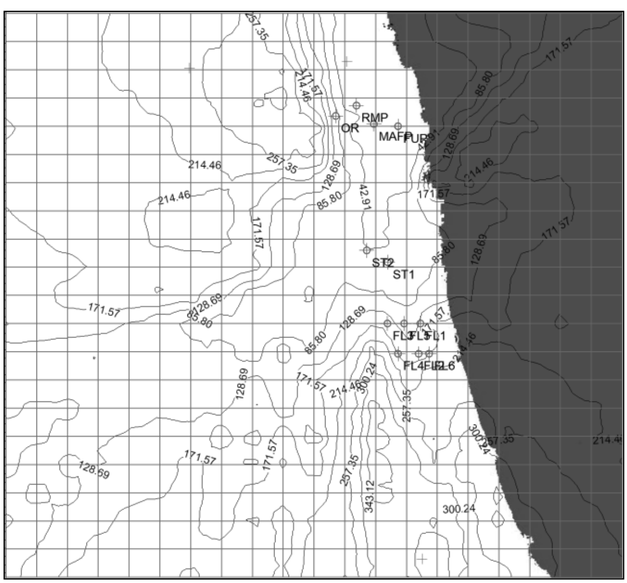


Fig. 9. Contour map of SO_2 concentrations during the 2[nd] period

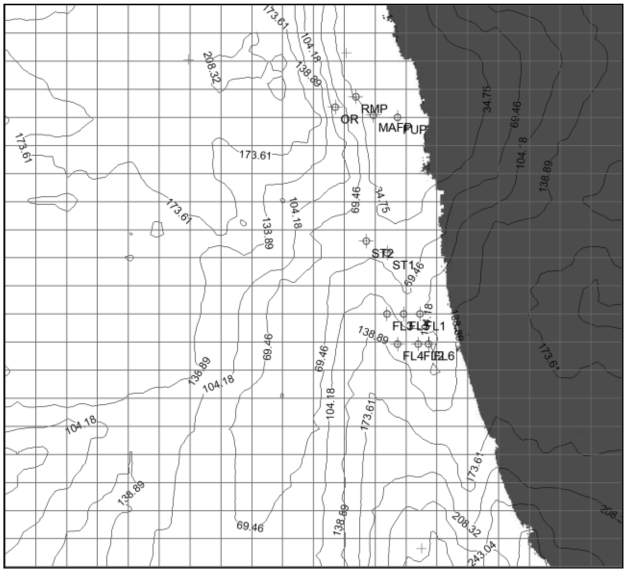


Fig. 10. Contour map of NO concentrations during the 2nd period

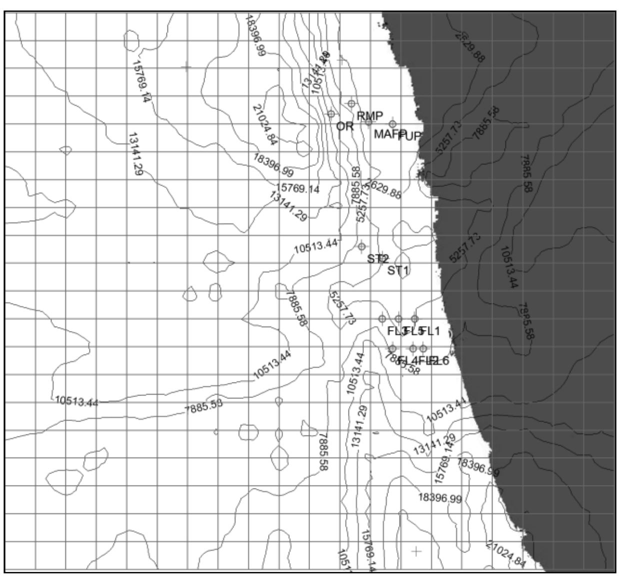


Fig. 11. Contour map of CO concentrations during the 2nd period

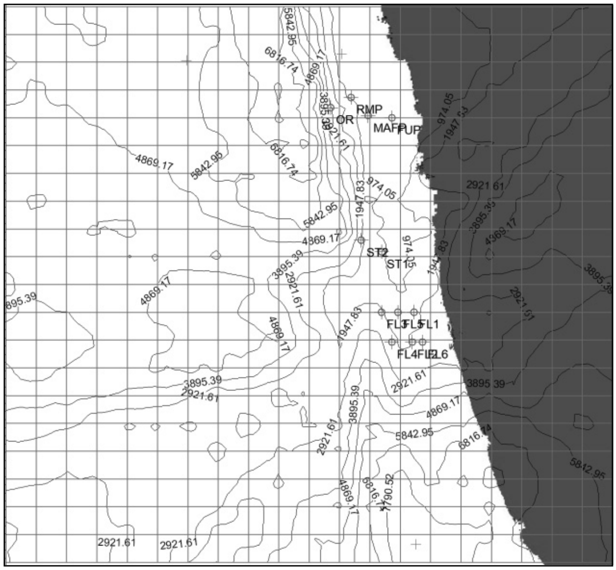


Fig. 12. Contour map of VOC concentrations during the 2nd period

COMPARISON WITH EPA STANDARDS

Table 5 shows the predicted concentrations of SO_2, NO, CO, and VOCs generated from the AERMOD software, ISCST3 model. As shown, the predicted concentrations of all pollutants are lower than the measured concentrations in the Fahaheel, Umm Alhyman, and Ahmadi residential areas during the measured periods when considering the refineries individually and together. This result shows that these areas are affected by other sources of emissions in addition to the oil refineries. Table 6 shows the measured pollutant concentrations along with the corresponding international standards. Comparing the measured concentrations in the Fahaheel area during the first measurement period with the international standards given by the USEPA illustrates that only the CO concentration is below the EPA limits, which is attributed to the limited number of motor vehicles and the high ambient temperature in Kuwait, while the SO_2 and NO concentrations exceed the limits. In contrast, the SO_2, NO, and CO measured concentrations during the second and third measurement periods in the Umm Alhyman and Ahmadi areas are below the international limits. However, the measured data show that the VOC concentrations are higher than expected in Fahaheel, Umm Alhyman, and Ahmadi residential areas, which indicates that there are other sources of VOC emissions that should be included in the next study.

Table 5. Predicted concentrations of pollutants in ppm in three residential areas in Kuwait.

Receptor	Pollutants	Ahmadi Refinery	Shuaiba Refinery	Mina Abdullah Refinery
Fahaheel residential area (21/12/2010-5/01/2011)	SO_2	2.5×10^{-4}	1.6×10^{-3}	3.3×10^{-6}
	NO	1.6×10^{-6}	1.4×10^{-4}	2.7×10^{-5}
	CO	6.2×10^{-5}	6.3×10^{-2}	2.0×10^{-3}
	VOCs	1.5×10^{-5}	2.1×10^{-2}	2.6×10^{-3}
Ahmadi residential area (25/06/2011-10/07/2011)	SO_2	5.8×10^{-4}	0.0	0.0
	NO	1.6×10^{-2}	0.0	0.0
	CO	2.5×10^{-2}	0.0	0.0
	VOCs	0.0	0.0	0.0
Umm Alhyman residential area (10/04/2011-25/04/2011)	SO_2	2.4×10^{-4}	1.5×10^{-3}	5.5×10^{-3}
	NO	2.1×10^{-3}	4.4×10^{-4}	6.6×10^{-3}
	CO	9.5×10^{-2}	0.13	0.53
	VOCs	3.1×10^{-2}	0.75	0.89

Table 6. Predicted, Measured and EPA standard concentrations of pollutants in ppm in three residential areas in Kuwait.

Receptor	Pollutants	All Refineries	Measured	*EPA
Fahaheel residential area (21/12/2010-5/01/2011)	SO_2	2.0×10^{-3}	0.21	0.14
	NO	2.0×10^{-4}	0.44	0.15
	CO	6.5×10^{-2}	6.80	35
	VOCs	2.3×10^{-2}	5.80	0.24
Ahmadi residential area (25/06/2011-10/07/2011)	SO_2	5.8×10^{-4}	0.05	0.14
	NO	1.6×10^{-2}	0.05	0.15
	CO	2.5×10^{-2}	2.04	35
	VOCs	0.31	7.14	0.24
Umm Alhyman residential area (10/04/2011-25/04/2011)	SO_2	6.5×10^{-3}	0.04	0.14
	NO	7.2×10^{-3}	0.06	0.15
	CO	0.82	1.60	35
	VOCs	0.60	2.91	0.24

*(http://www.epa.gov/air/criteria.html)

CONCLUSION

Previous studies have been conducted to investigate the air pollution patterns, dispersion, and photochemical mechanisms in Kuwait, and this study continues these efforts. The results show that the predicted concentrations of all pollutants are lower than the measured concentrations in the Fahaheel, Umm Alhyman, and Ahmadi residential areas during the measured periods when considering the refineries individually and together. This finding indicates that these areas are affected by other sources of emissions in addition to the oil refineries. A comparison of the measured data against international limits shows that for the Fahaheel area, all pollutants exceeded the international limits, except for CO during the first measurement period, which is attributed to the low traffic volume and high ambient temperature in Kuwait. The measured concentrations of SO_2, NO, and CO during the second and third measurement periods in the Umm Alhyman and Ahmadi areas are below international standards. The measured data show that the VOC concentration is higher than expected in the Fahaheel, Umm Alhyman, and Ahmadi residential areas, which is caused by emissions from several small-scale industrial sites that are poorly regulated and provide little or no emission treatment. It is highly recommended to perform measurements of extensive emission rates in other industrial locations in the vicinity of the study area. This is necessary to obtain a clear picture for the pollution pattern and dispersion in these areas.

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