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ORIGINAL PAPER

Modelling the trends of vehicle-emitted pollutants in Salalah, Sultanate of Oman, over a 10-year period

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Abstract From 2004 to 2014, a significant increase in the number of vehicles in Salalah, Oman, has been observed and is related to the fact that the city has become a more popular tourist destination. Due to this rise in the number of vehicles, traffic jams have become a serious problem in Salalah. Therefore, this study aims to assess carbon monoxide (CO), nitrogen oxides (NO_x), and carbon dioxide (CO_2) from 2004 to 2014 for the Salalah region using the CALPUFF modelling system. Although the number of vehicles gradually increased in the area, the pollutant concentration levels fluctuated. CALPUFF results illustrated that CO levels were within the allowable concentrations assigned by the U.S. Environmental Protection Agency (EPA) standards, but NO_x and CO_2 concentrations were higher than the criterion limits set by the EPA and the Ontario Ministry of the Environment and Climate Change's emission standards. Since Salalah is a coastal city, wind blowing toward the land from the sea significantly affects the dispersion of pollutants. Additionally, most of the maximum concentrations of the three pollutants were located near the centers of the streets. Replacing roundabouts with flyovers might significantly reduce traffic jams and vehicle-emitted pollutants in Salalah.

Keywords Vehicle-emitted pollutants · CALPUFF · Salalah · Sultanate of Oman · Line source

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1 Introduction

Developed by the Atmospheric Studies Group, CALPUFF is considered one of the most powerful environmental modelling programs. The fact that CALPUFF can be run for any location worldwide and for any modelling period has attracted researchers wishing to simulate the dispersion of selected pollutants or model pollutant concentration levels associated with investigating geophysical and meteorological conditions.

In recent years, a tremendous amount of research has been published on CALPUFF modelling and different pollutant concentrations (Liao et al. 2014; Feng et al. 2014; Wu and Nelson 2014). Abdul-Wahab et al. (2013) focused on an examination of the impact of geophysical and meteorological conditions on the dispersion of nitrogen dioxide (NO_2) emitted from a proposed refinery located in Canada. Abdul-Wahab et al. (2014a) also employed CALPUFF to examine the effect of meteorological conditions on the dispersion of an accidental release of hydrogen sulfide (H_2S). CALPUFF software has also been applied for modelling greenhouse gas emissions from the steady and non-steady state operations of a combined cycle power plant located in Ontario, Canada (Abdul-Wahab et al. 2014b). Examining the dispersion of vinyl chloride (C_2H_3Cl) from a renewable energy facility located in

Ontario, Canada was the main aim of a study by Obaid et al. (2014). Other case studies, for which CALPUFF software was used to study concentrations for multiple pollutants include Ghannam and El-Fadel (2013), Tian et al. (2013) and Abdul-Wahab et al. (2015).

Salalah, considered Oman's second largest city and the capital of Dhofar region, experiences a monsoon season from mid-June to mid-August. During this season, Salalah's surroundings and its landscape is transformed completely from brown to shiny green misty pastures. Due to Salalah's monsoon season that attracts tourists, vehicle activities increased drastically over the past years. This certainly triggered health related concerns in the long run since vehicular traffic is considered as one of the major source of CO, NO_x, and CO_2. The high levels of these pollutants cause damage to both human health and the environment.

Despite the fact that considerable amount of studies have taken into consideration the vehicle emissions and the dispersion of line source-emitted pollutants (Oettl et al. 2003; Hong-di and Wei-Zhen 2012; Rosemont Copper Company 2011), no studies have focused on investigating the trends of line source-emitted pollutants for Salalah for the past years. Thus, this paper focuses on employing CALPUFF modelling software for estimating the trends for the dispersion of CO, NO_x, and CO_2. As the number of cars in Salalah has increased significantly within the past years, the main objective of this study was to assess the concentration levels of CO, NO_x, and CO_2 from 2004 to 2014. The developed knowledge from this study will provide a strong evidence to convince Salalah's decision-makers to take the necessary action regarding traffic jams to reduce environmental stresses and also plan vehicle type, routing, and city planning now before the problem becomes out of control in the future.

2 Materials and methods

2.1 Area of study description

Located in the southern region of the Sultanate of Oman, Salalah is Oman's second largest city and the capital of the Dhofar region. Figure 1 represents the location and terrain map of Salalah and the more specific location for the case study. The city generally has an arid climate, although summers are cooler than in more northern or inland parts of Oman. Additionally, Salalah is one of the only places on the Arabian Peninsula, along with Yemen, that experiences a monsoon season (Salalah, http://en.wikipedia.org/wiki/Salalah). From mid-June to mid-August, monsoon clouds from the Indian Ocean bring a constant drizzle to the area, transforming Salalah's surroundings into an oasis of misty pastures (Salalah, http://www.lonelyplanet.com/oman/dhofar/salalah). During this time, Salalah's landscape is transformed from brown and dry to shiny, green and lush. As a result, tourists from other parts of Oman as well as from all over the globe arrive to Salalah to enjoy the scenery.

From 2004 to 2014, a significant increase in the number of tourists resulted in an increase in the number of vehicles in Salalah. Due to this rise in vehicle numbers, traffic jams were recorded as well (Fig. 2). The street of interest in the current study is divided into three main sections, with each representing an active area within Salalah. Based on Google Earth satellite images of the specified street, statistical data (Table 1) were collected in order to estimate the average number of vehicles passing through this street's three sections. Data collection was conducted for 2004–2006, 2008, 2009 and 2012–2014. The days were selected based on image availability and the maximum number of vehicles recorded within the provided days. According to the data collected (Fig. 3), there was a significant increase in the number of vehicles in all three street sections. As expected, Section 1 had the highest number of vehicles for many reasons:

- Section 1 is the longest section of road;
- It intersects with a large number of streets and has the highest accessibility from other exits and entrances as compared to Sections 2 and 3;
- Section 1 connects a large number of residential areas in Salalah (Fig. 2);
- Section 1 is the main road connecting Salalah's city center and its industrial region;
- It connects Central Salalah with West Salalah (Uwqad), Salalah Port, and the Free Zone.
- As the acquisition times in all images were in the morning, most industrial activities would logically be in Section 1.

Section 2, as demonstrated in Fig. 3, had the lowest record of activity since the exits and entrances connecting this road are limited. However, Section 3 also had a high rate of vehicle use since most of the governmental buildings are located in Al-Saadah, which is in the northeast of Salalah.

For this study, the three sections of the selected street were considered, and the total number of vehicles for each selected day was calculated. It was assumed that the number of vehicles extracted from Google Earth images was for a 5-min time period, which is approximately the time required for each batch of vehicles to be replaced by another batch. Table 1 lists the hourly variation in the number of vehicles for the selected years associated with the days where the maximum number of vehicles was recorded. Figure 4 represents the recorded variation starting from 2004, with approximately 3708 vehicles, and ending in 2014 with a total of approximately 12,996 vehicles.

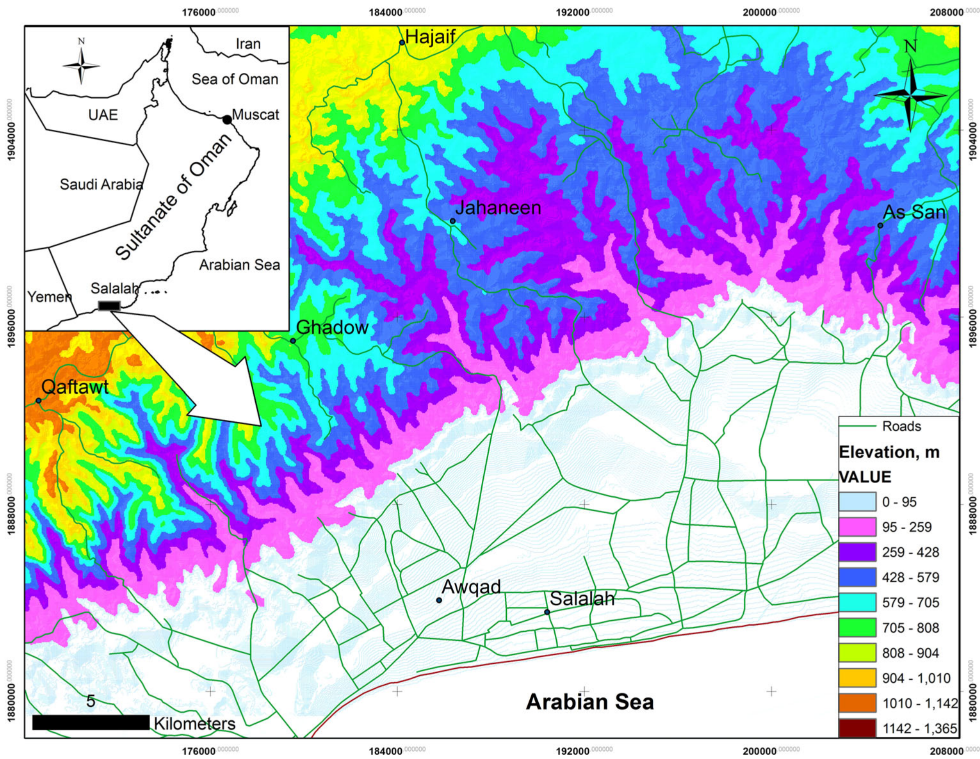


Fig. 1 Location and terrain map of Salalah region on the map of Oman

Fig. 2 Case study street location with major sections in Google maps

Table 1 Statistical data collection for average number of vehicles entering the domain for the three sections

(Day/month/year)	Section 1 (veh)	Section 2 (veh)	Section 3 (veh)	Total number of vehicles for every 5 min (veh)	Total number of vehicles for every hour (veh)
26/5/2004	184	46	79	309	3708
27/9/2005	239	98	142	479	5748
3/8/2006	247	107	148	502	6024
22/8/2008	254	113	156	523	6276
21/6/2009	365	169	254	788	9456
5/9/2012	415	189	348	952	11,424
7/11/2013	521	236	292	1049	12,588
22/1/2014	506	276	301	1083	12,996

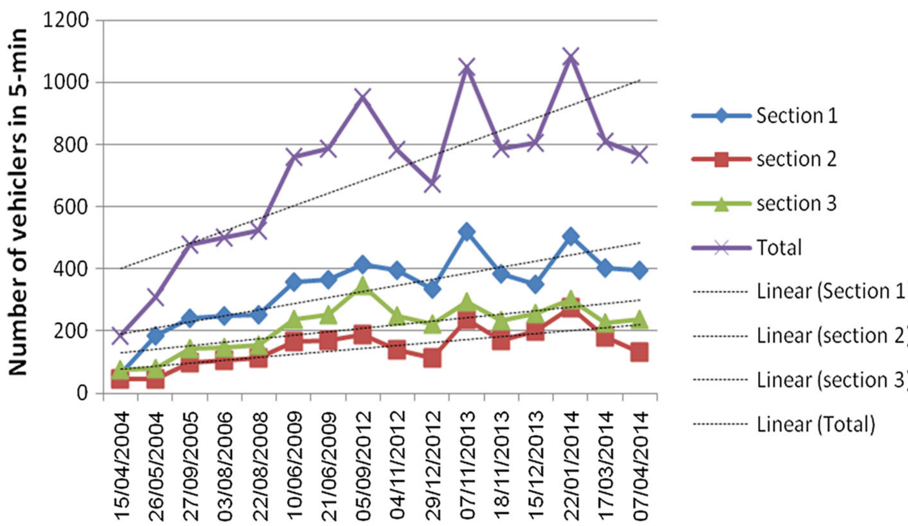


Fig. 3 The trend of number of vehicles entering the domain for the three sections

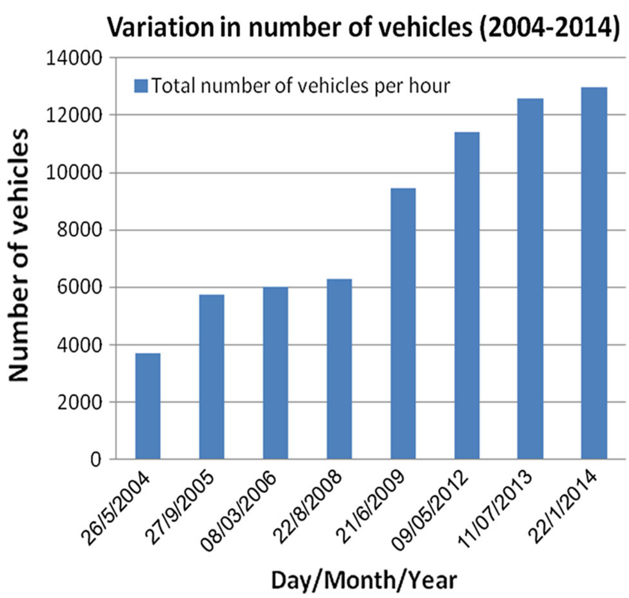


Fig. 4 Hourly recorded variation in vehicle numbers from 2004 to 2014

2.2 CALPUFF modelling system

CALPUFF modelling system, also known as CALPro software, is a meteorological and air quality modelling software designed by the Atmospheric Studies Group (ASG) and got approved by U.S. Environmental Protection Agency (EPA). Taking into account the area of interest's geography and climate factors as coastal and wind conditions, dispersion and concentration levels of air pollutants that are emitted from various sources such as landfills, traffic, and industrial plants can be predicted and investigated by employing CALPUFF software. In addition to a pre-processing package, the software mainly consists of three dominant components: CALMET, CALPUFF, and CALPOST. Additional information related to CALPro software can be found in Scire et al. (2000) and Abdul-Wahab and Fadlallah (2014). As a start, the meteorological grid shared information for Salalah was inserted into a common file, before running the CALPUFF pre-processors, using the Identify Shared Information module listed in

Table 2. For this study, starting at 00h00 till 23h00, the model was simulated for selected modelling periods (i.e. 25–27/05/2004, 26–28/09/2005, 2–4/08/2006, 21–23/08/2008, 20–22/06/2009, 4–6/09/2012, 6–8/11/2013, 21–23/01/2014). Considering the line source emission rates shown in Table 4 and the data files produced by CALMET, CALPUFF was run for the pollutants CO, NO_x, and CO_2 for the selected modelling periods. For the CALPUFF modelling system, the fractional convergence criteria for numerical slug sampling integration and numerical area source integration were set at 1.0E−04 and 1.0E−6, respectively. Concentration levels simulation results and plume trajectories were produced by activating CALPOST. For a visualized simulation of the pollutants plume trajectories and concentration levels, CALVIEW was operated. The selected layer for assessing the effect of CO, NO_x, and CO_2 on humans distributed within the desired area of interest was the first layer, which is in the range of 0–20 m.

2.3 Upper air and surface meteorological data

The upper air meteorological data information was extracted from the listed radiosonde stations on the National Oceanic and Atmospheric Administration's (NOAA) official website (https://esrl.noaa.gov/raobs/). For a representation of a full time period, 12-h interval data were obtained from the upper air climate station for the selected years associated with the modelling days mentioned earlier. The extracted data were processed in a compatible format that can be run using CALPro's READ62 program to produce UP.DAT file suitable as an input to CALMET.

On the other hand, the surface meteorological data used in this study were obtained from Oman's Directorate General of Meteorology and Air Navigation (www.met.gov.om). The hourly meteorological data consist of the following information: precipitation (mm), temperature (°C), station pressure (mbar), wind direction (°), wind speed (m/s), relative humidity (%), cloud cover (tenths), and cloud height (ft). For a full period similar to that of the upper air data period, the obtained data were prepared in a format that could be run using CALPro's SMERGE program to produce a SURF.DAT file suitable for input into CALMET. The extracted information related to upper air and surface stations is summarized in Table 3.

2.4 Emission data

In order to calculate the emission rates for a line source, emission factors are required. As vehicles come in different types, emission rates differ according to vehicle specifications such as engine capacity, fuel type, vehicle speed, vehicle weight, and so on. Numerous environmental institutes and research papers have concentrated on calculating emission rates. Abdul-Wahab and Fadlallah (2014) made a comparison between various research studies in terms of CO, NO_x, and CO_2 emission rates. A conclusion was reached based on the fact that Muscat suffers from the absence of information related to vehicle emissions; thus, the emission factors set by the Transport Research Laboratory (TRL) were compared to those found through other studies. In the current study, an Excel sheet developed by the TRL which categorizes vehicles based on certain specifications (e.g., weight, engine capacity, etc.) was used (TRL, https://www.gov.uk/government/publications/road-vehicle-emission-factors-2009). Assuming an average vehicle speed of 34.5 km/h with the following specifications: petrol fuel type, pre-euro emission standard, < 1400 cc engine capacity, and < 2.5 t vehicle weight, CO, NO_x, and CO_2 emission factors were determined to, respectively, be 15.74, 1.29 and 182.35 g/veh km.

Moving to the calculation related to emission rates, Table 4 demonstrates the calculation of CO, NO_x, and CO_2 emission rates by taking into consideration the number of vehicles passing through the specified street for the

Table 2 Meteorological domain of study model input information

Parameter	Salalah
Projection type	LLC
LCC latitude of origin	17.023466°N
LCC longitude of origin	54.101037°E
Latitude 1	5 N
Latitude 2	45 N
False easting	0
False northing	0
Continent/ocean	Global
Geoid–ellipsoid	WGS-84:WGS84
Region	WGS-84
DATUM code	WGS-84
X (easting)	− 100 km
Y (northing)	− 100 km
Number of grid cells (X)	200
Number of grid cells (Y)	200
Grid spacing	1 km
Number of vertical layers	9
Cell face heights	0, 20, 50, 100, 150, 200, 300, 500, 1000, 2000 m
Base time zone	UTC + 04:00

Table 3 Upper air and surface stations information

Parameter	Radiosonde station (upper air meteorological data)	Surface station (surface meteorological data)
Station name	ABU DHABI INTL 99 AE	SEEB INTL/MUSCAT 99 OM
Station initials (INIT)	OMAA	OOMS
Universe transverse mercator (UTM) latitude	24.43°N	23.58°N
Universe transverse mercator (UTM) longitude	54.65°E	58.28°E
Location X on grid	− 400 km	10 km
Location Y on grid	60 km	12 km
Station elevation	27 m	17 m
World Meteorological Organization (WMO) identifier (ID)	41,217	41,256
Weather Bureau Army Navy (WBAN) station number	99,999	99,999

modelling days selected for the study. CALPUFF line source input parameters, including the street coordinates with respect to the located origin, emission height, car width, building dimensions, and the separation between each building, are listed in Table 5.

2.5 CALPUFF operation

Figure 5 represents CALPUFF operation flow diagram. Simulations were run on a 16-bit Windows XP computer with an Intel Pentium 4 3.4 GHz processer, 1 GB RAM. As a start, the identified shared information common file that includes meteorological and geophysical data for the domain of study, listed in Table 2, were processed before proceeding with CALMET. The geophysical data: terrain, land use, and coastline data were obtained from the ASG official website (www.src.com/datasets/datasets_main.html). The extracted geophysical data were employed to activate terrain (TERREL) and land use (CTGPROC) processing packages. TERREL.DAT and LU.DAT are the resultant data set files from the previous process. These files are essential in running geophysical (MAKEGEO) processing package producing GEO.DAT. As previously mentioned, the meteorological data for both surface and upper air data were extracted and processed with an assistance of SMERGE and READ62 respectively producing SURF.DAT and UP.DAT data files. All the previously produced data files with an extension (.DAT) are considered as CALMET inputs. For this study, starting at 00h00 till 23h00, the model was simulated for the selected modelling periods. Considering the line source emission rates shown in Table 4 and the data files produced by CALMET, CALPUFF was run for the pollutants CO, NO_x, and CO_2 for the selected modelling periods. Concentration levels simulation results and plume trajectories were produced by activating CALPOST. For a visualized simulation of the pollutants plume trajectories and concentration levels, CALVIEW was operated. The selected layer for assessing the effect of CO, NO_x, and CO_2 on humans distributed within the desired area of interest was the first layer, which is in the range of 0–20 m.

3 Results and discussions

According to the CALPUFF-simulated terrain map of Salalah (Fig. 6), the domain consists of various elevation ranges since Salalah's terrain is mountainous. Additionally, as Salalah is a coastal city, the ocean has a significant influence over its meteorological conditions. Figure 7 represents a wind rose for each of the selected modelling days investigated in this study. Each wind rose shows the distribution of wind direction and speed at the study location. The wind speed ranges are indicated by colored bands, while the frequency of the wind that blows from specific directions is demonstrated by the length of the spoke. A spoke with multi-coloured bands represents various ranges of wind speed which occurred in the indicated direction of the spoke. The analysis of the simulation results is divided into two main parts: results analysis based on the selected modelling periods, and emissions trends for the pollutants CO, NO_x, and CO_2.

3.1 Modelling periods

3.1.1 Period 1 (May 26, 2004)

For May 26, 2004, wind blew from the southwest (SW) and the south-southwest (SSW), with gusts predominantly from the SSW (Fig. 7). For the majority of the day, the wind

Table 4 Line source emission rate calculations for the desired pollutants

Selected date (day/month/ year)	Emission factor g/ (veh km)	Average speed (km/h)	Number of vehicles for selected day (veh)	Emission rate (g/s)
CO				
26/05/2004	15.535	35	3708	560.03675
27/09/2005			5748	868.14758
03/08/2006			6024	912.55179
22/08/2008			6276	947.89391
21/06/2009			9456	1428.18433
05/09/2012			11424	1725.42066
07/11/2013			12,588	1901.22,508
22/01/2014			12,996	1962.84725
NO_x				
26/05/2004	1.3008	35	3708	46.89384
27/09/2005			5748	72.69304
03/08/2006			6024	76.18352
22/08/2008			6276	79.37048
21/06/2009			9456	119.58688
05/09/2012			11,424	144.47552
07/11/2013			12,588	159.19624
22/01/2014			12,996	164.35608
CO_2				
26/05/2004	181.668	35	3708	6549.1314
27/09/2005			5748	10,152.2134
03/08/2006			6024	10,639.6892
22/08/2008			6276	11,084.7758
21/06/2009			9456	16,701.3448
05/09/2012			11,424	20,177.2592
07/11/2013			12,588	22,233.1354
22/01/2014			12,996	22,953.7518

Table 5 CALPUFF line source input parameters

Parameter	Values
X (start)	4.5 km
Y (start)	0 km
X (end)	− 4.51 km
Y (end)	0 km
Emission height	0.35 m
Car width	1.4 m
Building height	35 m
Separation between buildings	50 m
Base elevation	14 m
Building width	27.5 m
Building length	68.41 m

from the SSW had a speed ranging from 1.8 to 3.3 m/s. As for the wind blowing from the SW, the most frequent wind speed ranged from 3.3 to 5.4 m/s. Table 6 lists the day's top five CO, NO_x, and CO_2 concentration levels with their corresponding allowable limits. For the three investigated pollutants, the maximum concentration occurred (− 0.5, 0.5 km) away from the defined origin at 05h00 LST. According to CO simulation results for this modelling period, the maximum concentration recorded was 22,542 $\mu g/m^3$. This concentration level was within the criterion limits assigned by U.S. EPA standards. As for nitrogen oxides (NO_x), the top five recorded concentration levels exceeded the limits set by the EPA. At 05h00 LST, two of the top recorded concentrations occurred simultaneously but in different locations close to the study area's center. On the other hand, allowable CO_2 concentrations set by the Ontario Ministry of the Environment and Climate Change (MOE) emission standards for a 0.5-h average period were exceeded by simulation results.

3.1.2 *Period 2 (September 27, 2005)*

On September 27, 2005, wind blew from the west, east, SW, and SSW (Fig. 7).The dominant wind direction was from the SW, with a speed ranging from 5.4 to 8.5 m/s. The same speed was recorded for wind from the SSW direction, which displayed the second highest gust frequency. Table 6 illustrates the top five maximum concentration levels of CO, NO_x, and CO_2 along with their allowable concentrations. The maximum concentration occurred (−4.5, −0.5 km) from the origin at 03h00 LST. As for the remaining peak values, they all occurred at 04h00 LST in multiple locations within the study domain. The highest recorded CO concentration, 5533 $\mu g/m^3$, was located (−4.5, −0.5 km) from the origin, and was far below the EPA-assigned value for CO concentration levels. As for NO_x, the five recorded concentration levels exceeded the EPA's recommended limit for 1-h NO_2 average concentration standards. Similar to what was observed for the dispersion of NO_x, CO_2 concentrations exceeded the concentration limits set by Ontario's MOE emission standards.

3.1.3 *Period 3 (August 3, 2006)*

From Fig. 7, it can be noticed that for the modelling day August 3, 2006, wind blew from the SW and southeast (SE), but it gusted predominantly from the south-southeast (SSE). The wind speed ranged from 1.8 to 3.3 m/s. As for the wind from the SE, which was the second most frequent direction from which wind blew during the specified

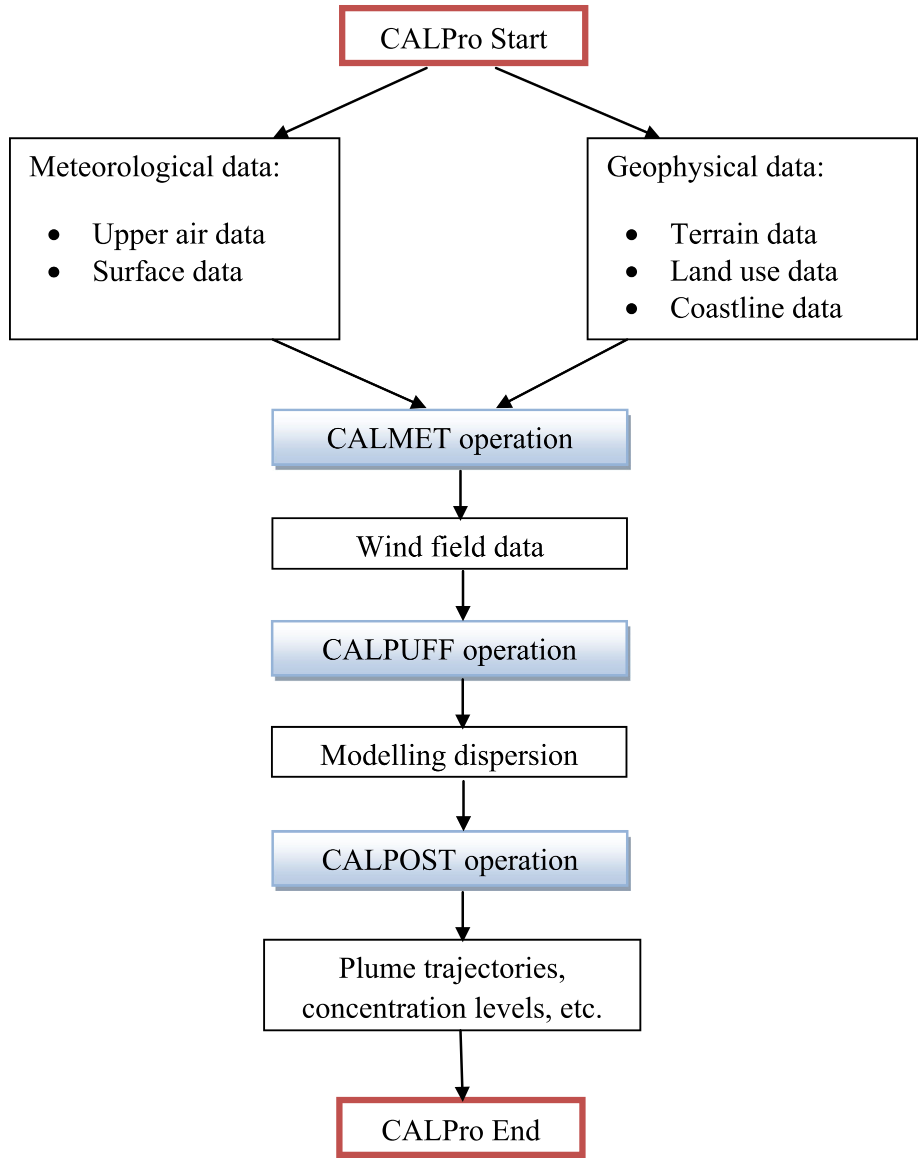


Fig. 5 CALPUFF operation flow diagram

period, the most frequent wind speed ranged from 0.5 to 1.8 m/s. Table 6 displays the allowable and top five average CO, NO_x, and CO_2 concentrations simulated on August 3, 2006 and shows that the maximum concentrations of CO were within the prescribed limits. On the other hand, both NO_x, and CO_2 clearly exceeded allowable concentrations. The maximum concentrations were recorded (−1.5, −0.5 km) from the origin at 20h00 LST. For NO_x, the two highest concentrations occurred at the same time but in different locations near the domain origin. As for CO_2, the maximum concentration level was 305,661.4 μg/m^3, which is far beyond the criterion limit of 63,000 μg/m^3.

3.1.4 Period 4 (August 22, 2008)

The wind rose associated with the modelling day August 22, 2008 shows that wind blew in directions ranging from the SW to the SE (Fig. 7). Specifically, most of the gusts blew from the SSW and SSE. The wind predominantly blew from the SSW direction with speeds ranging from 3.3 to 5.4 m/s for the majority of the day. The wind from the SSE direction blew second most frequently, with the most frequent wind speed ranging from 1.8 to 3.3 m/s. Table 6 lists the maximum five concentration levels for CO, NO_x, and CO_2 against their respective criterion limits on August 22, 2008. For the three pollutants, the maximum concentrations were recorded from 19h00 to 22h00 LST. The highest concentration occurred at 22h00 LST, and the second and fourth highest concentrations occurred at 21h00

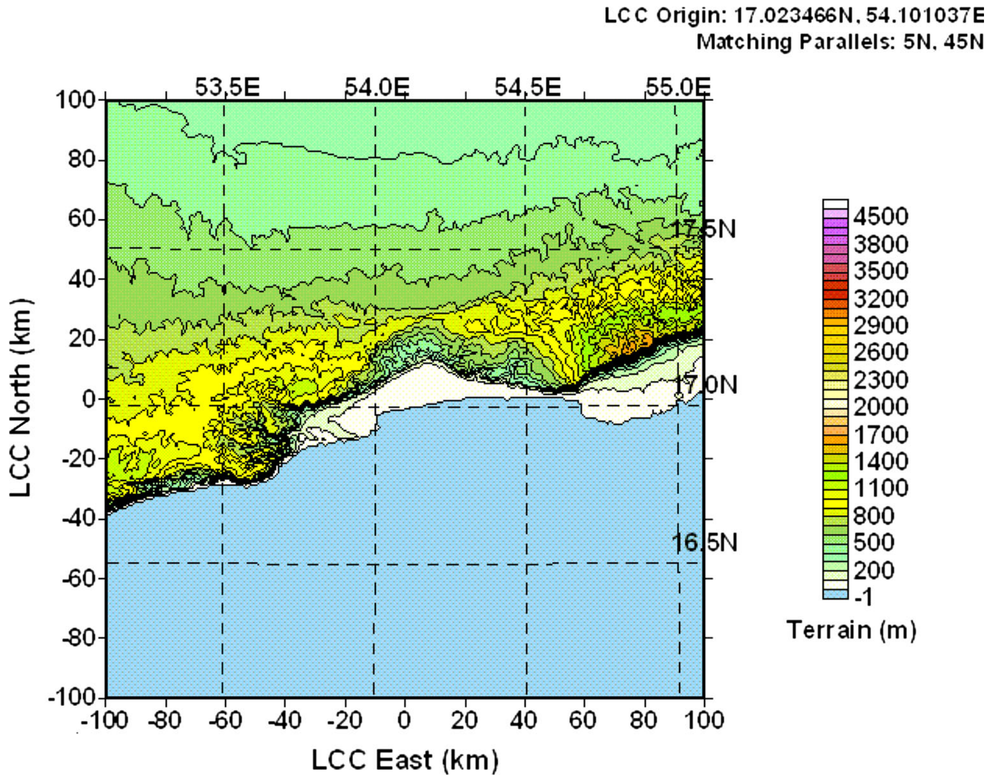


Fig. 6 Terrain map of Salalah domain of study

LST. The third highest concentration occurred at 19h00 LST, and the fifth highest concentration occurred at 20h00 LST. It is worth mentioning that four of the maximum concentrations occurred at the same coordinate (3.5, 0.5 km), which was close to the origin of the study domain. Although the maximum concentration of CO reached 19,217 $\mu g/m^3$, it was still within the criterion limits. In contrast, the NO_x, and CO_2 maximum concentration levels clearly exceeded the allowable concentration standards.

3.1.5 Period 5 (June 21, 2009)

The wind rose associated with the modelling day June 21, 2009 demonstrates that wind only blew in directions ranging from the west to the south (Fig. 7). Specifically, most of the wind blew from the SW to the SSW. For the majority of the day, the wind came from the SSW with a speed ranging from 5.4 to 8.5 m/s. The second most frequent direction from which the wind came, the SW, blew from 1.8 to 3.3 m/s, while the second most noticeable wind speed ranged from 5.4 to 8.5 m/s. Table 7 shows the top five maximum concentrations of CO, NO_x, and CO_2 for a 1-h average for June 21, 2009. The simulation results demonstrate the fact that all maximum concentrations occurred at 05h00 LST. The highest 1-h average concentration occurred 1.5 km east and 0.5 km north of the center of the street. The second highest concentration was located 3.5 km west and 0.5 km north of the center of the street. The third highest concentration occurred 2.5 km west and 0.5 km north of the street. The fourth highest concentration occurred at a location 0.5 km east and north of the defined street. Finally, the fifth highest concentration was 1.5 km west and north of the selected domain origin. Based on CO simulation results, the maximum concentrations were within the criterion limits for all levels. As for NO_x, the maximum concentration for a 1-h period reached within the simulated model was found to be approximately 2644.4 $\mu g/m^3$. According to U.S. EPA standards, the top five concentrations exceeded the allowable concentrations for NO_x. As for CO_2, all top five concentrations were significantly greater than 63,000 $\mu g/m^3$, which is the allowable concentration limit assigned by the Ontario MOE's emission standards.

3.1.6 Period 6 (September 5, 2012)

The wind rose associated with the modelling day of September 5, 2012 (Fig. 7), shows that the wind blew from the NW, the south and the SW. The wind predominantly came from the SSW with a speed that varied between 1.8–3.3 and 3.3–5.4 m/s for the majority of the day. As for the wind from the SW, which was the second most frequent direction from which the wind blew, the most frequent wind speed ranged from 1.8 to 3.3 m/s. Table 7 lists the allowable concentration according to Ontario's MOE and the top five average concentrations of CO, NO_x, and CO_2

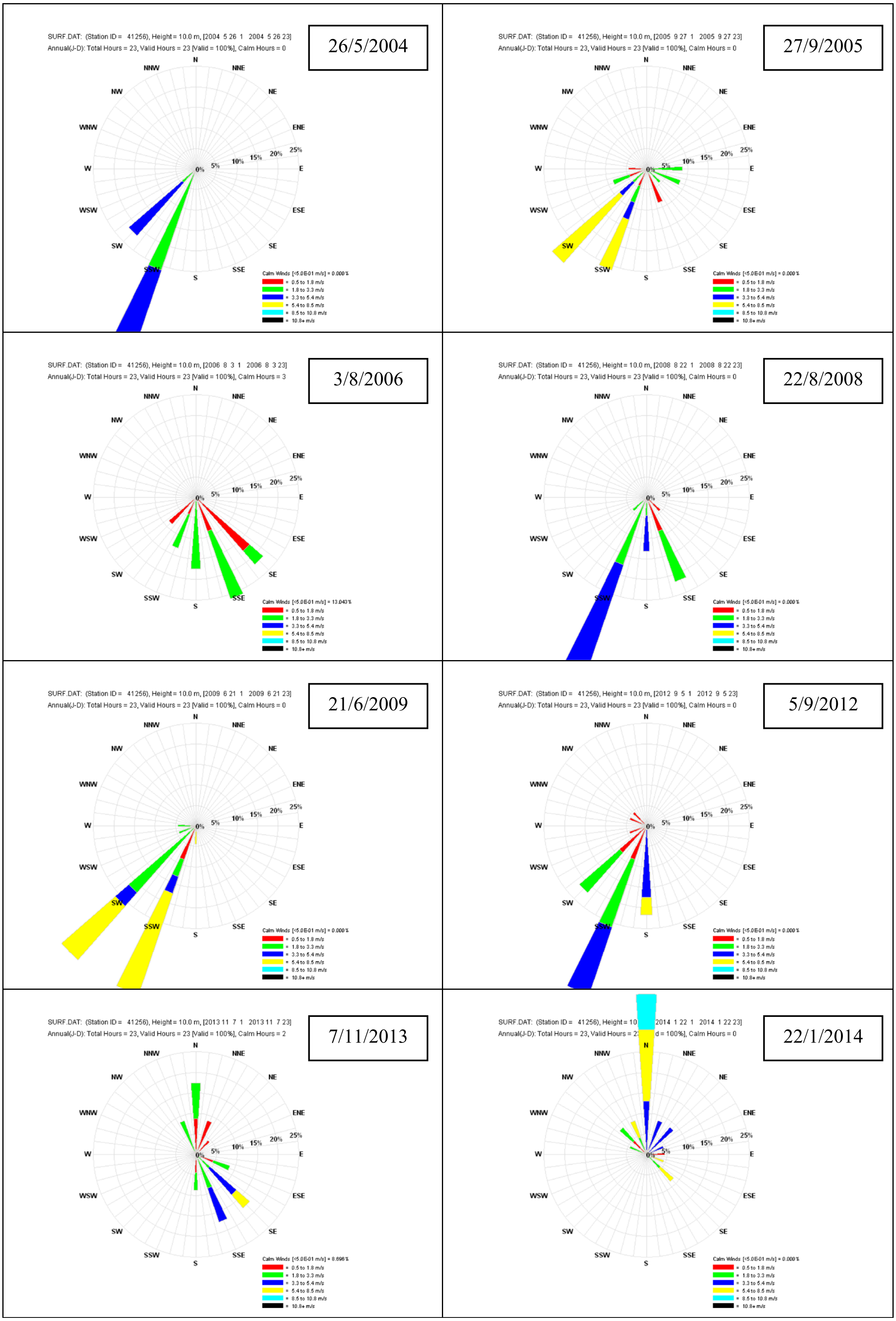


Fig. 7 Salalah windrose for the selected simulation periods

Table 6 Line source allowable and top 5 average CO, NO_x, and CO_2 concentrations simulated on May 26, 2004; September 27, 2005; August 3, 2006; August 22, 2008 from 00:00 to 23:00

		May 26, 2004			September 27, 2005			August 3, 2006			August 22, 2008		
		Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)	Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)	Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)	Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)
		CO											
Allowed 1-h CO average concentration[a] (μg/m^3)	40096.1 μg/m^3 (35 ppm)	−0.5, 0.5	05:00	22,542	−4.5, −0.5	03:00	5533.0	−1.5, −0.5	20:00	21,590	3.5, 0.5	22:00	19,217
		4.5, 0.5	05:00	21,387	0.5, −0.5	04:00	4896.4	2.5, −0.5	20:00	19,668	3.5, 0.5	21:00	18,227
		4.5, 0.5	01:00	21,152	1.5, −0.5	04:00	4837.0	−2.5, −0.5	19:00	19,296	3.5, 0.5	19:00	17,903
		0.5, 0.5	04:00	16,023	−4.5, −0.5	04:00	4671.7	−4.5, −0.5	01:00	18,361	−0.5, 0.5	21:00	16,175
		−0.5, 0.5	01:00	13,787	−3.5, −0.5	04:00	4667.7	3.5, −0.5	20:00	17,905	3.5, 0.5	20:00	16,000
		NO_x											
Allowed 1- hour NO_2 average concentration[a] (μg/m^3)	188.2 μg/m^3 (100 ppb)	−0.5, 0.5	05:00	1887.5	−4.5, −0.5	03:00	463.29	−1.5, −0.5	20:00	1802.5	3.5, 0.5	22:00	1609.1
		4.5, 0.5	05:00	1790.8	0.5, −0.5	04:00	409.99	2.5, −0.5	20:00	1641.9	3.5, 0.5	21:00	1526.2
		4.5, 0.5	01:00	1771.1	1.5, −0.5	04:00	405.02	−2.5, −0.5	19:00	1610.9	3.5, 0.5	19:00	1499.1
		0.5, 0.5	04:00	1341.6	−4.5, −0.5	04:00	391.17	−4.5, −0.5	01:00	1532.9	−0.5, 0.5	21:00	1354.4
		−0.5, 0.5	01:00	1154.4	−3.5, −0.5	04:00	390.84	3.5, −0.5	20:00	1494.8	3.5, 0.5	20:00	1339.7
		CO_2											
Allowed 0.5-h CO_2 average concentration[b] (μg/m^3)	63,000 μg/m^3	−0.5, 0.5	05:00	320,061.7	−4.5, −0.5	03:00	78,560.8	−1.5, −0.5	20:00	305,661.4	3.5, 0.5	22:00	272,878.1
		4.5, 0.5	05:00	303,670.1	0.5, −0.5	04:00	69,522.4	2.5, −0.5	20:00	278,439.2	3.5, 0.5	21:00	258,805.6
		4.5, 0.5	01:00	300,331.1	1.5, −0.5	04:00	68,678.5	−2.5, −0.5	19:00	273,181.7	3.5, 0.5	19:00	254,215.9
		0.5, 0.5	04:00	227,503.7	−4.5, −0.5	04:00	66,331.4	−4.5, −0.5	01:00	259,934.8	−0.5, 0.5	21:00	229,677.1
		−0.5, 0.5	01:00	195,752.4	−3.5, −0.5	04:00	66,275.6	3.5, −0.5	20:00	253,487.4	3.5, 0.5	20:00	227,188.0

[a]U.S. Environmental Protection Agency (2012)

[b]Ontario Ministry of the Environment (2008)

Table 7 Line source allowable and top 5 average CO, NO_x, and CO_2 concentrations simulated on June 21, 2009; September 5, 2012; November 7, 2013; January 22, 2014 from 00:00 to 23:00

		June 21, 2009			September 5, 2012			November 7, 2013			January 22, 2014		
		Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)	Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)	Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)	Coordinates (km)	Time (HH:MM)	Peak value (μg/m^3)
		CO											
Allowed 1-h CO average concentration[a] (μg/m^3)	40,096.1 μg/m^3 (35 ppm)	1.5, 0.5	05:00	31,581	−3.5, −0.5	05:00	11,834	−2.5, −0.5	19:00	4359.1	−2.5, −0.5	03:00	20,291
		−3.5, 0.5	05:00	18,918	−2.5, −0.5	05:00	11,190	−2.5, −0.5	20:00	4302.7	2.5, −0.5	03:00	19,107
		−2.5, 0.5	05:00	16,397	−3.5, −0.5	03:00	10,918	−2.5, −0.5	18:00	4289.2	1.5, −0.5	03:00	14,417
		0.5, 0.5	05:00	15,489	3.5, −0.5	04:00	10,835	−1.5, −0.5	02:00	4050.3	−1.5, −0.5	03:00	14,123
		−1.5, 1.5	05:00	12,746	−1.5, −0.5	04:00	10,781	−3.5, −1.5	18:00	4032.7	−3.5, −0.5	18:00	12,681
		NO_x											
Allowed 1- hour NO_2 average concentration[a] (μg/m^3)	188.2 μg/m^3 (100 ppb)	1.5, 0.5	05:00	2644.4	−3.5, −0.5	05:00	991.33	−2.5, −0.5	19:00	365.01	−2.5, −0.5	03:00	1699.1
		−3.5, 0.5	05:00	1584.1	−2.5, −0.5	05:00	937.04	−2.5, −0.5	20:00	360.29	2.5, −0.5	03:00	1600.0
		−2.5, 0.5	05:00	1373.0	−3.5, −0.5	03:00	914.25	−2.5, −0.5	18:00	359.16	1.5, −0.5	03:00	1207.3
		0.5, 0.5	05:00	1297.0	3.5, −0.5	04:00	907.32	−1.5, −0.5	02:00	339.16	−1.5, −0.5	03:00	1182.6
		−1.5, 1.5	05:00	1067.3	−1.5, −0.5	04:00	902.81	−3.5, −1.5	18:00	337.69	−3.5, −0.5	18:00	1061.9
		CO_2											
Allowed 0.5-h CO_2 average concentration[b] (μg/m^3)	63,000 μg/m^3	1.5, 0.5	05:00	448,402.1	−3.5, −0.5	05:00	168,093.1	−2.5, −0.5	19:00	61,894.8	−2.5, −0.5	03:00	288,128.4
		−3.5, 0.5	05:00	268,604.2	−2.5, −0.5	05:00	158,889.5	−2.5, −0.5	20:00	61,094.6	2.5, −0.5	03:00	271,311.8
		−2.5, 0.5	05:00	232,809.7	−3.5, −0.5	03:00	155,028.4	−2.5, −0.5	18:00	60,901.6	1.5, −0.5	03:00	204,725.4
		0.5, 0.5	05:00	219,927.1	3.5, −0.5	04:00	153,850.6	−1.5, −0.5	02:00	57,510.3	−1.5, −0.5	03:00	200,536.4
		−1.5, 1.5	05:00	180,975.7	−1.5, −0.5	04:00	153,085.7	−3.5, −1.5	18:00	57,260.2	−3.5, −0.5	18:00	180,065.1

[a]U.S. Environmental Protection Agency (2012)

[b]Ontario Ministry of the Environment (2008)

Table 8 Maximum highest concentrations of CO, NO_x, and CO_2 with their corresponding criterion limits

CO		
Selected date (day/month/year)	Maximum highest 1-h concentration ($\mu g/m^3$)	1-h criterion limit[a] ($\mu g/m^3$)
26/05/2004	22,542	40096.1 $\mu g/m^3$ (35 ppm)
27/09/2005	5533.0	
03/08/2006	21,590	
22/08/2008	19,217	
21/06/2009	31,581	
05/09/2012	11,834	
07/11/2013	4359.1	
22/01/2014	20,291	
NO_x		
Selected date (day/month/year)	Maximum highest 1-h concentration ($\mu g/m^3$)	1-h criterion limit[a] ($\mu g/m^3$)
26/05/2004	1887.5	188.2 $\mu g/m^3$ (100 ppb)
27/09/2005	463.29	
03/08/2006	1802.5	
22/08/2008	1609.1	
21/06/2009	2644.4	
05/09/2012	991.33	
07/11/2013	365.01	
22/01/2014	1699.1	
CO_2		
Selected date (day/month/year)	Maximum highest 0.5-h concentration ($\mu g/m^3$)	0.5-h criterion limit[b] ($\mu g/m^3$)
26/05/2004	320061.7	63,000 $\mu g/m^3$
27/09/2005	78560.8	
03/08/2006	305661.4	
22/08/2008	272878.2	
21/06/2009	448402.2	
05/09/2012	168093.1	
07/11/2013	61894.8	
22/01/2014	288128.4	

[a]U.S. Environmental Protection Agency (2012)

[b]Ontario Ministry of the Environment (2008)

for September 5, 2012. According to the simulation results, the maximum concentration occurred 3.5 km west and 0.5 km north of the defined origin at 05h00 LST. The first and the third highest 1-h average concentrations all occurred at the same location, 2 h apart from each other. Similar to the previous simulation analysis, CO concentrations were below the EPA's threshold concentration levels. As for NO_x, the maximum concentration was five times greater than the allowable concentration set by EPA standards. CO_2 concentrations, on the other hand, were far beyond the criterion limits. The maximum value was 168,093.1 $\mu g/m^3$ compared to 63,000 $\mu g/m^3$ as an allowable a 0.5-h average period concentration.

3.1.7 *Period 7 (November 7, 2013)*

Based on Fig. 7, it can be observed that for the modelling period November 7, 2013, wind blew from directions ranging from the south to the NNW, with the three most predominant gust directions being the SSE, SE, and the north. The wind from the SSE and SE directions had a speed ranging from 3.3 to 5.4 m/s for the majority of the day. As for the wind from the north, the most frequent wind speeds were between 1.8 and 3.3 m/s. Table 7 summarizes the top five concentration levels of CO, NO_x, and CO_2 for November 7, 2013, with their allowed concentrations. The maximum concentration of the three pollutants occurred at 19h00 LST, 2.5 km west and 0.5 km south of the domain origin. CO concentrations were within the limits set by the U.S. EPA. Similarly, CO_2 levels were also below the allowed 0.5-h average concentrations. On the other hand, nitrogen oxides simulation results showed a violation in concentration levels. Occurring at 19h00 LST, the maximum concentration was 365.01 $\mu g/m^3$, which is higher than the criterion limit.

3.1.8 *Period 8 (January 22, 2014)*

The wind rose on January 22, 2014 (Fig. 7) shows that wind blew in directions ranging from the WNW to the SE, although it blew predominantly from the north with a speed between 5.4 and 8.5 m/s for the majority of the day. For the remainder of the day, the wind speed varied between the ranges (3.3–5.4 m/s) and (8.5–10.8 m/s). Table 7 lists the top five CO, NO_x, and CO_2 concentration levels on this particular day with their corresponding allowable limits. For the three investigated pollutants, the maximum concentration occurred at (−2.5, −0.5 km) away from the defined origin at 03h00 LST. According to CO simulation results for this modelling period, the maximum concentration recorded was approximately 20,291 $\mu g/m^3$, which is within the criterion limits set by U.S. EPA. On the other hand, the maximum concentration of NO_x for a 1-h period reached within the simulated model was found to be 1699.1 $\mu g/m^3$. According to the U.S. EPA's standards, the top five concentrations exceeded the allowable limits for NO_x. For CO_2, the maximum concentration level was approximately 288,128.4 $\mu g/m^3$, which is beyond the criterion limit for a 0.5-h period (63,000 $\mu g/m^3$).

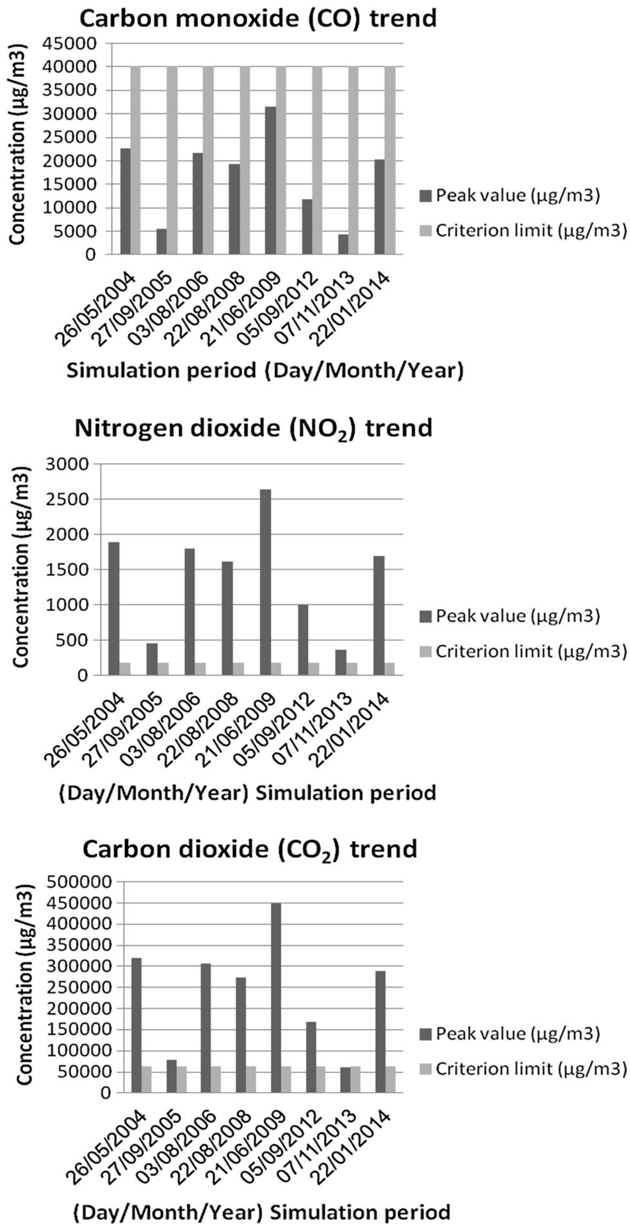


Fig. 8 Comparison between allowed and simulated concentration trends of CO, NO_x, and CO_2

3.2 Emission trends

Table 8 lists the maximum concentrations of CO, NO_x, and CO_2 with their corresponding criterion limits for the simulation periods associated with this study. For more visualization regarding the trends of these line source emitted pollutants for the past 10 years, Fig. 8 summarizes the comparison between allowed and simulated concentration trends of CO, NO_2, and CO_2.

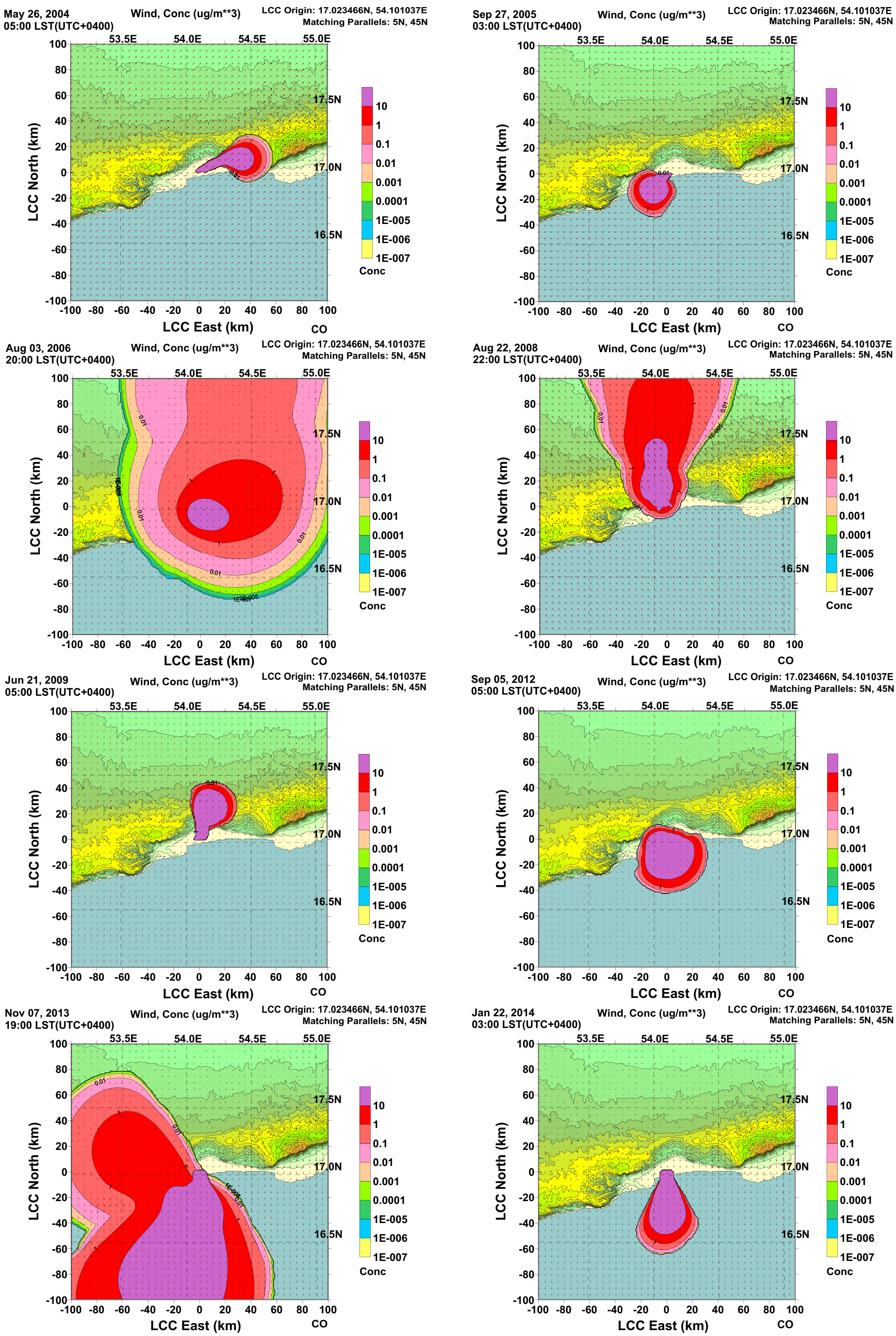
Fig. 9 Plume trajectories of the highest 1-h CO concentration levels ▶ for the selected simulation periods

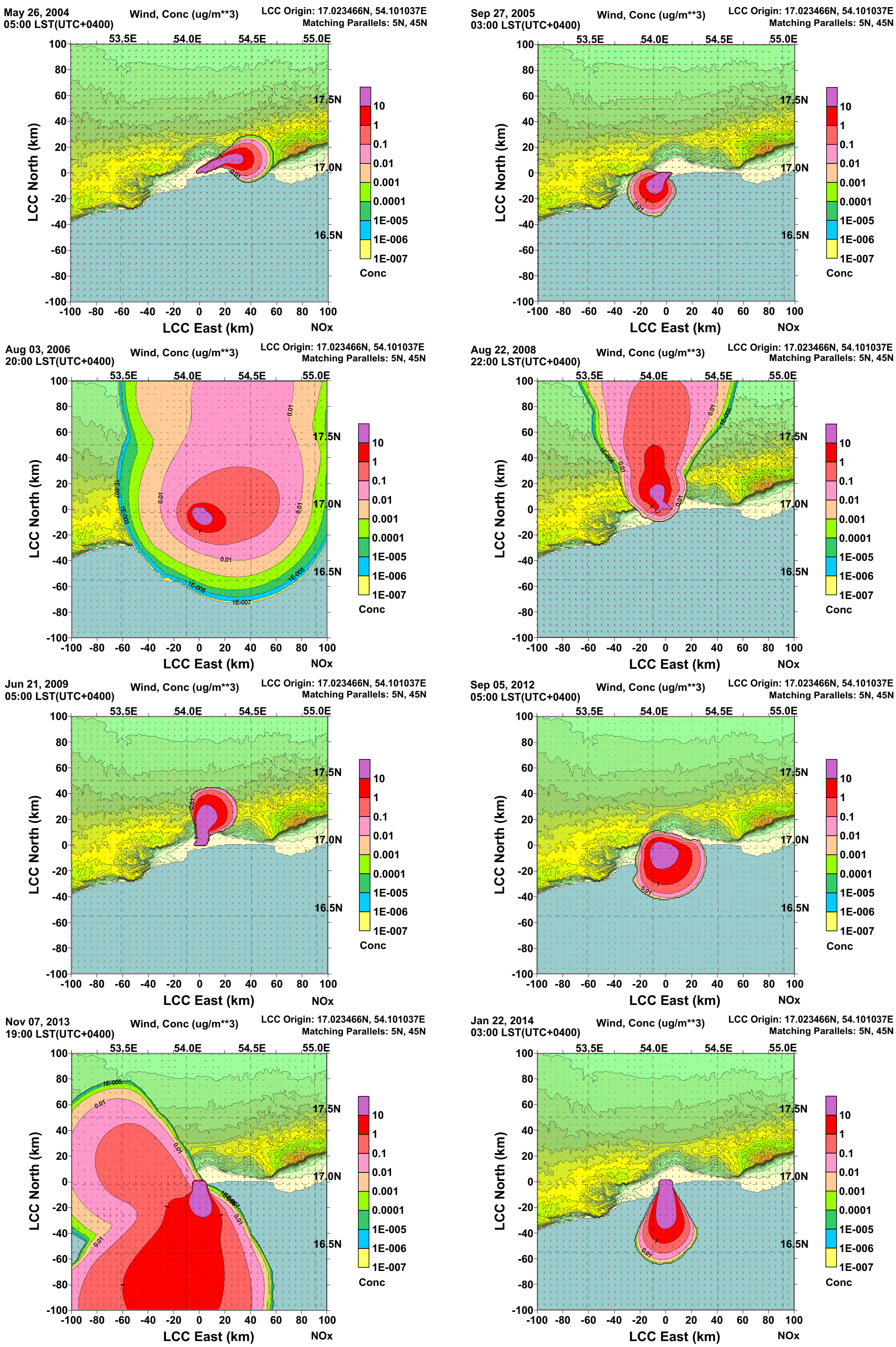
3.2.1 Carbon monoxide (CO)

Starting with the first modelling period, May 26, 2004, the maximum CO concentration reached 22,542 $\mu g/m^3$. This concentration significantly decreased the next modelling day, September 27, 2005, to 5533 $\mu g/m^3$. Figure 9 represents the plume trajectories of the highest 1-h CO concentration levels, which dropped due to wind blowing from the land toward the sea. The simulated wind vectors showed the winds shifting to the southwest. Comparing this value to the concentration level simulated on August 3, 2006, a tremendous increase of around 21,590 $\mu g/m^3$ can be observed. Although the number of vehicles increased through the 10-year study, a slight decrease occurred in the concentration of CO on August 22, 2008. For the next year, the concentration of carbon monoxide increased to 31,581 $\mu g/m^3$. Based on the visualized trend, this value is the maximum concentration level which occurred in the past 10 years. From September 5, 2012, to January 22, 2014, the trend was that of fluctuating in the concentration levels, which started at approximately 11,834 $\mu g/m^3$, decreased to 4359.1 $\mu g/m^3$, and finally settled with a value of 20,291 $\mu g/m^3$ in 2014. All these fluctuations in concentration levels were due to the wind direction associated with each modelling day. Despite the fact that the concentration levels listed for CO were high in general, these concentration levels were within the criterion limits assigned by the U.S. EPA.

3.2.2 Nitrogen dioxide (NO_2)

On May 26, 2004, the maximum concentration of NO_2 reached 1887.5 $\mu g/m^3$. This concentration level had decreased four-fold by the next modelling day, September 27, 2005, to 463.29 $\mu g/m^3$. Figure 10 represents the plume trajectories of the highest 1-h NO_x concentrations. A notable drop occurred due to the wind blowing from the land toward the sea, and simulated wind vectors shifted to the southwest. Comparing this value to the concentration level simulated on August 3, 2006, it can be observed that the concentration of NO_2 significantly increased, to 1802.5 $\mu g/m^3$. Because the number of vehicles increased in Salalah over the study period, a slight decrease occurred in the concentration of NO_2 on August 22, 2008. However, by the next modelling day, nitrogen dioxide concentration levels had increased to 2644.4 $\mu g/m^3$. Based on that trend, this value is the maximum concentration level that occurred within the past 10 years. Between September 5, 2012,


May 26, 2004
05:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Sep 27, 2005
03:00 LST(UTC+0400)
Aug 03, 2006
20:00 LST(UTC+0400)
Aug 22, 2008
22:00 LST(UTC+0400)
Jun 21, 2009
05:00 LST(UTC+0400)
Sep 05, 2012
05:00 LST(UTC+0400)
Nov 07, 2013
19:00 LST(UTC+0400)
Jan 22, 2014
03:00 LST(UTC+0400)
LCC North (km)
LCC East (km)
CO
53.5E 54.0E 54.5E 55.0E
17.5N 17.0N 16.5N
10 1 0.1 0.01 0.001 0.0001 1E-005 1E-006 1E-007
Conc


May 26, 2004
05:00 LST(UTC+0400)
Sep 27, 2005
03:00 LST(UTC+0400)
Aug 03, 2006
20:00 LST(UTC+0400)
Aug 22, 2008
22:00 LST(UTC+0400)
Jun 21, 2009
05:00 LST(UTC+0400)
Sep 05, 2012
05:00 LST(UTC+0400)
Nov 07, 2013
19:00 LST(UTC+0400)
Jan 22, 2014
03:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
53.5E
54.0E
54.5E
55.0E
17.5N
17.0N
16.5N
LCC North (km)
LCC East (km)
NOx
10
1
0.1
0.01
0.001
0.0001
1E-005
1E-006
1E-007
Conc

◀**Fig. 10** Plume trajectories of the highest 1-h NO_x concentration levels for the selected simulation periods

and January 22, 2014, the trend showed a fluctuation in concentration levels, with NO_2 concentrations of 991.33 μg/m^3 in 2012, which decreased to 365.01 μg/m^3 in 2013, and finally settled with a value of 1699.1 μg/m^3 in 2014. Further examination of Table 8 and Fig. 8 illustrates that all the simulated 1-h average NO_x concentrations were found to significantly exceed their respective 1-h criterion limits.

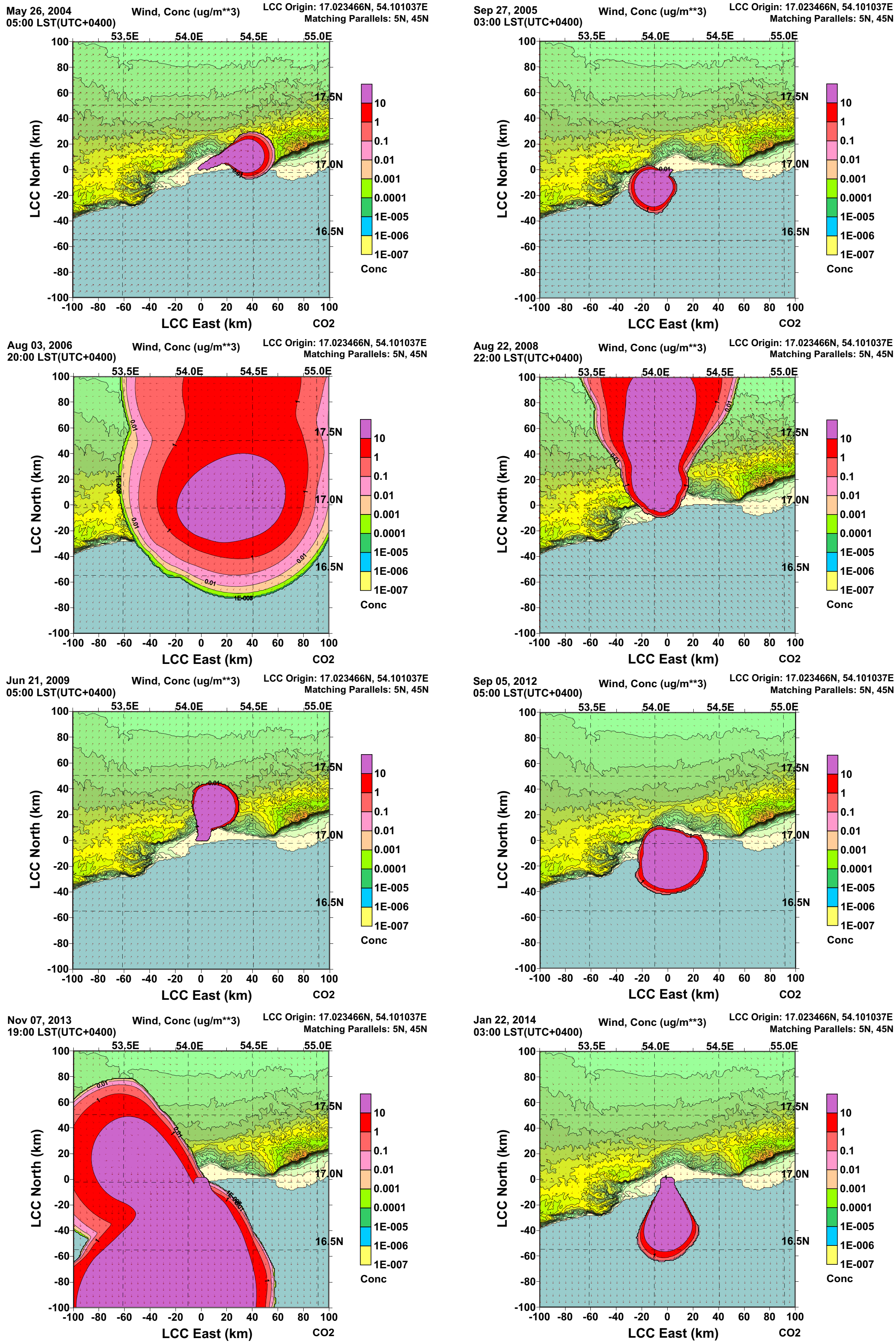
3.2.3 Carbon dioxide (CO_2)

On the first modelling day, May 26, 2004, the simulated maximum concentration of $CO_2$was found to be 320,061.7 μg/m^3. On the next modelling day, September 27, 2005, the concentration of CO_2 significantly decreased to 78,560.8 μg/m^3 (Fig. 11). The reason behind this significant drop is related to the breeze that comes toward the sea from the land. Comparing this result with the results of the simulation period on August 3, 2006, it is clear that CO_2 concentration levels significantly increased to 305,661.4 μg/m^3. A slight decrease occurred in the concentration of CO_2 on August 22, 2008, compared to the increase in the number of vehicles associated with the modelling period. On the next modelling day, CO_2 concentration levels increased to 448,402.2 μg/m^3, which were the maximum concentration levels observed within the 10-year study. Between September 5, 2012, and January 22, 2014, there was a fluctuation in concentration levels. In 2012, the concentration of 168,093.1 μg/m^3 decreased to 61,894.8 μg/m^3 in 2013, and finally settled with a value of 288,128.4 μg/m^3 in 2014. The simulation results related to CO_2 in Table 8 and Fig. 8 demonstrate that all the concentration levels associated with the previously mentioned simulation periods significantly exceeded their respective 0.5-h criterion limits except for the simulation results related to November 7, 2013, where the concentrations of CO_2 were below the allowable concentrations assigned by the Ontario MOE.

4 Conclusions

Employing software models in assessing the effect of the geophysical and meteorological conditions on the dispersion of line source emissions in the environment is consequential. Based on that, the influence of three vehicle pollutants, CO, NO_x, and CO_2 on Salalah's environment was investigated for a 10-year period. The analysis of the simulation results was divided into two main sections: a study of each of the selected modelling days and an assessment of the trends in the concentration levels of CO, NO_x, and CO_2 within a 10-year period. In the first part of the study, the meteorological conditions for each of the selected modelling periods were different and, based on this fact, the variation in concentration levels, coordinates, and timing where maximum concentrations were recorded were noticeable. In the second part of the analysis, the concentration trends of CO, NO_x, and CO_2 for the 10-year study period were investigated. From the results of this study, June 21, 2009, was determined to be the day with the highest 1-h average of CO and NO_x concentrations and 0.5-h average CO_2 concentration within the past 10 years. November 7, 2013, was determined to have had the lowest 1-h average of CO and NO_x concentrations and 0.5-h average CO_2 concentration. On June 21, 2009, the highest 1-h average CO and NO_x concentrations and 0.5-h average CO_2 concentration were determined to, respectively, be 31,581, 2644.4, and 4488,402.2 μg/m^3. These NO_x and CO_2 concentrations significantly exceeded the EPA's NO_x criterion limit of 188.2 μg/m^3 and the Ontario MOE's 0.5-h criterion of 63,000 μg/m^3. Based on the simulation results associated with the case study, almost all of the maximum concentrations originated close to the center of the domain of study. Because Salalah is a coastal city, the wind gusts moving toward the land from the sea significantly affect the dispersion of CO, NO_x, and CO_2. Based on that geographical feature, the three pollutants accumulated close to the center of the study street.

The trend of vehicle-emitted pollutants indicates that their concentrations may even exceed the concentrations associated with this study and disperse close to the defined street. During the day, in places where concentrations of CO, NO_x, and CO_2 are extremely high, citizens of Salalah who are working or people who are engaging in tourist activities close to the street might experience serious adverse CO, NO_x, and CO_2 effects. Due to the side effects that might occur from the emission of high concentrations of CO, NO_x, and CO_2, it is recommended to construct flyovers instead of roundabouts in order to decrease traffic jams.


May 26, 2004
05:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Sep 27, 2005
03:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Aug 03, 2006
20:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Aug 22, 2008
22:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Jun 21, 2009
05:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Sep 05, 2012
05:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Nov 07, 2013
19:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
Jan 22, 2014
03:00 LST(UTC+0400)
Wind, Conc (ug/m**3)
LCC Origin: 17.023466N, 54.101037E
Matching Parallels: 5N, 45N
53.5E
54.0E
54.5E
55.0E
17.5N
17.0N
16.5N
LCC North (km)
LCC East (km)
CO2
Conc
10
1
0.1
0.01
0.001
0.0001
1E-005
1E-006
1E-007

◀**Fig. 11** Plume trajectories of the highest 1-h CO_2 concentration levels for the selected simulation periods

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