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An air quality emission inventory of offshore operations for the exploration and production of petroleum by the Mexican oil industry

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Abstract

An air quality screening study was performed to assess the impacts of emissions from the offshore operations of the oil and gas exploration and production by Mexican industry in the Campeche Sound, which includes the states of Tabasco and Campeche in southeast Mexico. The major goal of this study was the compilation of an emission inventory (EI) for elevated, boom and ground level flares, processes, internal combustion engines and fugitive emissions. This inventory is so far the most comprehensive emission register that has ever been developed for the Mexican petroleum industry in this area. The EI considered 174 offshore platforms, the compression station at Atasta, and the Maritime Ports at Dos Bocas and Cayo Arcas. The offshore facilities identified as potential emitters in the area were the following: (1) trans-shipment stations, (2) a maritime floating port terminal, (3) drilling platforms, (4) crude oil recovering platforms, (5) crude oil production platforms, (6) linking platforms, (7) water injection platforms, (8) pumping platforms, (9) shelter platforms, (10) telecommunication platforms, (11) crude oil measurement platforms, and (12) flaring platforms. Crude oil storage tanks, helicopters and marine ship tankers were also considered to have an EI accurate enough for air quality regulations and mesoscale modeling of atmospheric pollutants. Historical ambient data measure at two onshore petroleum facilities were analyzed to measure air quality impacts on nearby inhabited coastal areas, and a source–receptor relationship for flares at the Ixtoc marine complex was performed to investigate health-based standards for offshore workers. A preliminary air quality model simulation was performed to observe the transport and dispersion patterns of SO_2, which is the main pollutant emitted from the offshore platforms. The meteorological wind and temperature fields were generated with CALMET, a diagnostic meteorological model that used surface observations and upper air soundings from a 4-day field campaign conducted in February of 1999. The CALMET meteorological output and the generated EI drove the transport and dispersion model, CALPUFF. Model results were compared with SO_2 measurements taken from the monitoring network at Dos Bocas.

Keywords: Emission inventory; Emission factors; Marine platforms; Gulf of Mexico; Air quality modeling

1. Introduction

The Campeche Sound in the southwest portion of the Gulf of Mexico (GOM), off the coast of the states of Tabasco and Campeche in Mexico, represents an

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important region of expanding economic development for Mexico. This region is an oceanographically complex and dynamic system characterized by its benthic shelf production (Soto and Escobar-Briones, 1995). Besides the fishery resources that it encompasses, it is a strategically crucial area for the Mexican oil industry, since approximately 80% of the national fossil fuel production is derived from offshore wells. The two major industries, shrimp fisheries and petroleum production, have coexisted since 1976, when major oil extraction operations began. There is a growing concern by local and federal authorities that the increased demand for fossil fuels in urban areas will intensify oil and gas production activities in this potentially sensitive area. These prospects may put at risk oceanic biological diversity and the local ecosystems, which include coastal lagoons and estuaries. The prospect of increased offshore petroleum production activity will surely provoke many future debates at both national and local levels. Therefore, identifying some of the direct impacts of oil industry operations, and predicting non-desirable effects for various sources is mandatory if environmental equilibrium among the ecosystems is to be maintained in the marine region (MR) of Tabasco and Campeche.

Ciudad del Carmen, the largest urban center in the area, is located along the strand arm of the Laguna de Terminos where the lagoon connects to the GOM and is adjacent to the offshore marine platform area. Two important onshore petroleum facilities are the gas recompression station in Atasta, Campeche, and the Dos Bocas Marine Terminal located near Paraiso, Tabasco. The principal function of the Atasta facility, about 25 km east of Ciudad del Carmen, is gas recompression between the offshore platforms and four inland gas-processing centers. Dos Bocas, located approximately 100 km east of Ciudad del Carmen, is the primary storage and treatment facility for crude oil from the offshore area.

Among the most important emission sources from the oil industry are flares, discharges to water, cuttings from drilling activities and crude oil spills. An integrated study to characterize each of these sources in the Campeche Sound and the risk that these exert over the marine environment along with toxicology studies is definitely needed. Such a task demands a considerable amount of time as well as human and financial resources, and it is therefore outside the scope of this work. Nonetheless, the impacts of atmospheric emissions of current petroleum operations in the region can be assessed through a screening study using, for instance, records of flaring operations taken by the personnel at the gas and oil production sites, and by analyzing available meteorological and air quality data measured at stations located near anthropogenic sources.

Of the four aforementioned sources discussed above, flares release approximately 82% of all pollutants discharged into ambient air by the oil industry in this region. Chemical analysis of the flue gas emitted into the air by flares indicates that unburned hydrocarbons (HC), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), and particulate matter (PM) are the major constituents. According to a recent report on air pollutant emissions, SO_2 is the second largest pollutant emitted after hydrocarbons (PEMEX, 2001). The high relative humidity and the presence of chlorides from sea spray in the Campeche region together with industrial SO_2 emissions can promote corrosion and soil acidification. The screening study looks at emissions (SO_2 and NO_2) that can contribute to wet and dry deposition of chemicals that promote corrosion (SO_4^{2-} and NO_3^-) of common construction and agricultural materials in Tabasco and Campeche as a means of accounting for atmospheric impacts of the Mexican oil industry in the region.

Climatic data analysis of southeast Mexico (Magaña-Rueda et al., 1999) indicates three major scenarios, each involving a different mix of sources and occurring at different times of the year under different meteorological conditions. For the first period that runs from November to end of January, strong synoptic northerly winds enhanced atmospheric dispersion of pollutants leaving the Campeche Sound in compliance with ambient air quality standards. During the dry period at the end of winter sooty flames from elevated flares at offshore facilities are significant sources, and their impact continues until the beginning of June. High solar radiation and moderate to weak gradient winds mark the dry period between February and June. In the summer and fall, periodic thunderstorms and rainstorms maintain the area relatively clean of gaseous pollutants while wet and dry deposition exacerbates acidification of the region. From July through November moist weather conditions give rise to fogs, clouds, and rainstorms.

Determining whether potential effects from the oil and gas industry exist or not that merit further study is important for assessing the expected impacts of developing new offshore fields in deeper water that will exploit deeper petroleum reserves. As a first step towards the completion of this goal an estimate of ambient primary pollutants emissions was obtained with the application of emission factors reported in the literature. Thus, the major goal of this screening study was to provide an emission inventory (EI) accurate enough for both air quality policy makers and mesoscale modeling of atmospheric pollutants. The EI is the most comprehensive characterization of pollutant emissions ever attempted for the Campeche Sound. Another facet of this study addressed the question of whether SO_2 and NO_2 emissions met air quality standards or not. Finally, air quality modeling work was performed to observe degradation of ambient air downwind of the potential emission sources in the Bay of Campeche. Available concurrent meteorological and air quality data were used for conducting the atmospheric simulations. A scenario in February 1999 was chosen to simulate the transport and dispersion of precursors of acid deposition during the dry season since this is the time of the year when the plumes from offshore facilities are more prone to impinge upon the coastal communities during the diurnal cycle.

2. Approach

The project was divided into several tasks conducted in the following sequence. The first and major activity of this investigation was centered on the development of an EI for the oil and gas facilities of the Mexican Petroleum Industry in the Campeche Sound. The verification of whether air quality standards for SO_2 and NO_2 concentrations measured at Atasta and Dos Bocas were exceeded, and if so, how often and by how much was the second task. The selection of an episode for air quality modeling along with a regional meteorological simulation of the selected episode using a prognostic model for which surface and upper air soundings were available became next as the third task. This step was of utmost importance for delimiting the size of the dispersion modeling domain if the loss of pollutant mass at the edges of the computational grid boundary were to be avoided when applying the EPA transport/dispersion modeling system, CALMET/CALPUFF. The chosen event was decided upon air quality data becoming available that, conjointly with historic meteorological data, allowed us to study dispersion patterns of plumes from flaring operations in the bay of Campeche during the dry season. The last task focused on performing an analysis of the source–receptor relationship for flares at the Ixtoc marine complex to investigate health-based standards for offshore workers.

An EI for exploration and production by Mexican oil company was not available at the time this work began. The EI of hydrocarbon-combustion processes in the Campeche sound was long required to assess the impact of atmospheric emissions on ambient air, and for decision making on future expansion of offshore petroleum production. In this work an EI was generated using published emission factors and other sources of information supplied by the oil company. Combustion sources were first allocated with the aid of geographic maps, and then classified by fuel-type emission and characteristics of the combustion system including fuel composition. Emission fluxes were estimated with published emission factors in conjunction with process charts, flow diagrams, layouts of pipelines, fittings and valves, and reported flow rates fed to flares, tanks, separators and other various types of industrial equipment. The compilation of the EI included mass fluxes of flares, pits, and stationary sources such as compressors, pumps and diesel generators. Incorporated in the EI are the emission sources of the offshore fields, the recompression station of Atasta and the crude-oil treatment terminal at Dos Bocas and the Cayo Arcas port.

Historical ambient measurements in the vicinity of Atasta and Dos Bocas for the period 1999–2000 were reviewed to measure the quality of the air in the coastal region of Campeche. The databases were provided by the Air Quality Division personnel of the Mexican oil company at Atasta and Dos Bocas. Time series of SO_2 and NO_x were analyzed to detect exceedances of these primary pollutants, and to determine if any violations to the national air quality standards were being made.

Concurrent meteorological and air quality data were only available in February 1999. Air quality modeling work was performed to simulate transport and dispersion of precursors of acid deposition in the Bay of Campeche for this month, which happened to take place during the dry season. The air quality model chosen for this task was the EPA approved CALMET/CALPUFF modeling system (Scire et al., 1997, 2000).

Upper air soundings were available from a 4-day field study carried out by IMP researchers in the state of Tabasco during early February in 1999. Two of the platform complexes continually collected hourly surface meteorological data during the entire year. The oversea database supplied by the Mexican oil company along with the measurements made at the Dos Bocas maritime terminal were used to produce the surface file for the diagnostic meteorological code. Wind observations treated with an objective analysis procedure yielded the three-dimensional wind and temperature field output needed by the diagnostic meteorological model CALMET. CALPUFF was then used to predict concentrations and depositions fluxes of SO_2. Model simulations were compared to air quality data reported from the monitoring site at the Dos Bocas network for SO_2 and NO_2. Meteorological and air quality measurements were unavailable during February 1999 for Atasta.

The size of the computational domain is an important key element for accurately predicting mass concentrations of pollutants by CALPUFF. CALPUFF has been traditionally used in US Environmental Protection Agency's (EPA) regulatory applications, where environmental impacts due to routine industrial releases or wild fires are modeled. The errors associated with the loss of pollutant mass at the edges of the computational grid boundary were recently evaluated for CALPUFF considering different modeling domain sizes (Venegas et al., 2002). The average percent error was found to increase with additional volume sources and as the computational domain size approached a

100 km × 60 km grid mesh. To avoid pollutant mass loss at the edges of the computational grid boundary due to the significantly large number of emission sources that were simulated the domain has to be sized without compromising computational efficiency. To do that the Regional Atmospheric Modeling System, RAMS (Pielke et al., 1992) was run to study the mesoscale flow patterns in the region. This approach allowed us to decide on the appropriate size of the CALMET/CALPUFF domain that will secure a maximum source-to-grid boundary distance thus reducing mass loss at the edges of the domain.

The RAMS model incorporated global NCEP data with four-dimensional data assimilation of surface and upper air wind observations made from 2 to 5 February 1999. To predict the local wind circulation near the shoreline RAMS was supplied with sea surface temperature (SST) on a 1° × 1° grid for February 1999 from a climatic data set obtained from NOAA. To identify average meteorological scenarios for February, the National Center for Environmental Prediction (NCEP) reanalysis database for sea level pressure and wind field data was downloaded from the Climate Diagnostics Center run by National Oceanic Atmospheric Administration (NOAA). The meteorological fields are global and have a horizontal resolution of 2.5° × 2.5°.

The outer domain of the RAMS prognostic model covered most of Mexico, Central America, and the GOM with a horizontal spatial resolution of 30 km × 30 km. The finer nested domain extended 336 km to the east, and 345 km to the north encompassing the Campeche Sound, and portions of the states of Tabasco and Campeche. The coarse-to-fine grid mesh ratio required that horizontal cells of 5 km × 5 km be used for the finer inner grid in RAMS. The CALMET domain was made equivalent to the RAMS inner domain. Wind patterns for the inner domain predicted by RAMS served as a benchmark for the wind fields calculated by CALMET for the same simulated episode. The vertical resolution of the cells in the fine and coarse grids that RAMS used varied from 100 m close to the ground to 1000 m above a height of 3 km. Topography of the area of interest was downloaded from the NOAA web-site (www.ngdc.noaa.gov) and land use data were obtained from the geographic facility at IMP. RAMS used a 2.5° × 2.5° spatial resolution, which is obviously too coarse for the domain of study but adequate to characterize the prevailing synoptic conditions.

The first component of the meteorological/transport dispersion system, CALMET used surface and upper air meteorological data to predict winds and turbulence parameters in each grid of the modeling domain for each

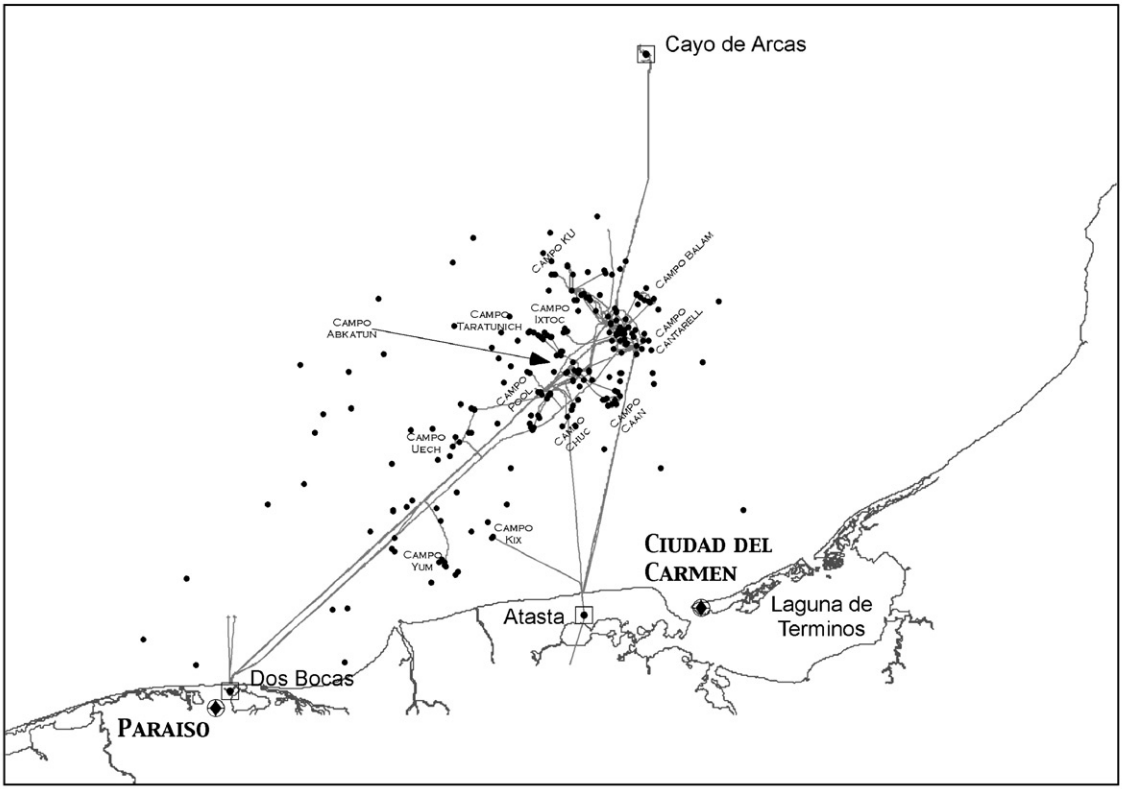

Fig. 1. Southeast portion of the GOM showing the physical domain used for the air quality screening study.

hour of a modeling period. Three surface meteorological stations were used for this work; the onshore station at Dos Bocas (18.585°N, 93.170°W), the offshore stations of Eco_1 (19.029°N, 92.047°W), and Ixtoc (19.406°N, 92.211°W). The origin of the computational domain was placed at (17.251°N, 94.250°W). The size of the inner grid that RAMS used turned out to be appropriate for the CALMET/CALPUFF simulations since the distance from the sources to the computational boundary ensured minimum mass loss, as seen in the contour maps of predicted concentrations shown in later sections, thus guaranteeing low error in the computations. The selected domain in this work is about 19 times larger than the domain of Venegas et al. (2002).

A 3 km × 3 km horizontal grid cell was chosen for CALMET, to give adequate model resolution, while yielding an acceptable execution time. The orthogonal axes extend to the north (115 nodes) and east (112 nodes) creating a uniform grid system on the 15-UTM zone projection. The maximum acceptable divergence in the divergence minimization procedure was taken as $5.0 \times 10^{-6}\,\mathrm{s}^{-1}$. Sounding data were obtained every 6 h starting at 06:00 local time from 2 to 5 February 1999. The last sounding was released at 18:00 local time. The modeling domain encompassing the coastal oil and gas facilities and the marine platforms is shown in Fig. 1.

The modeling system was complemented with the EI produced in this work. The SO_2/NO_x emissions were treated as time-invariant point sources. In this work, the SO_2/NO_x emissions undergo chemical reaction according to the RIVAD (Scire et al., 2000) pseudo-first-order chemical scheme, which considers their conversion into SO_4^{2-} and NO_3^-. The RIVAD reduced mechanism treats only six species (SO_2, SO_4^{2-}, NO, NO_2, HNO_3, and NO_3^-) in the acid formation process. The nighttime conversion rates for $SO_2/NO_x/HNO_3$ used in RIVAD were taken from the CALPUFF database and are as follows 0.2%/2%/2/%/h. The RIVAD chemical mechanism assumes a background concentration for O_3 as a substitute of the OH radical concentration. The O_3 background concentration was assumed to be 30 ppb, while the NH_3 concentration was taken to be 1 ppb.

3. Emission inventory

Emission factors specific to the petroleum operations in the Campeche Sound do not exist. Thus an EI had to be constructed from international emission factors reported in the literature for the regulated air pollutants in Mexico: sulfur oxides, nitrogen oxides, carbon monoxide, and particulate matter. Other air pollutants like total hydrocarbons and hydrogen sulfide were included because of their toxic characteristics.

Offshore operations consist of platforms, oil wells, repumping/compression stations, pipelines, and trans-shipment stations (Cayo Arcas and Dos Bocas) where oil is loaded onto tankers. Fig. 1 shows the actual layout of wells and pipelines. Also, in Fig. 1 a schematic layout of the offshore platforms, pipelines, and trans-shipment stations is depicted. The offshore fields, northeastern and southwestern fields collectively called MR, produce two kinds of crude oil, the Maya and Istmo, respectively.

The wells in the northeastern field produce the Maya crude from wells that are approximately 6 km deep. Most of the Maya crude oil is pumped to Cayo Arcas for direct shipment from Cayo Arcas onto Tankers, and does not reach Dos Bocas. Four platforms comprise the primary pumping stations for the Maya crude oil. On the other hand, the wells in the southwestern field, which are about 4.5 km deep, produce a lighter crude oil. Three main pumping platforms deliver the Istmo crude oil to a repumping station, which in turn distributes the crude oil to four lines that divert the load for nearly 80 km to Dos Bocas. The heavy Maya crude is very low in produced water (1%) and gas, whereas the Istmo crude, produced mainly from the southwestern wells, contains more produced water (5%) and gas than the Maya crude. Because produced water contains a number of components of crude oil in solution as well as heavy metals, the produced mixture of crude and water is piped to the Dos Bocas Marine Terminal where water is separated and treated.

The facilities considered in the EI consider the main offshore platform complexes at the southwestern and northeastern petroleum fields including Cantarell, Ek, Balam, Ixtoc, Ku, Abkatum, Cayo Arcas and Pool, and the onshore installations of the Atasta Gas Compression Station and the Marine Terminal of Dos Bocas. To undertake the task of compiling a brand new EI from scratch, five types of platforms were characterized: extraction, production, compression, pumping, and flaring. Crude oil and gas from the extraction platforms are pumped through pipelines undersea to the production platforms. Other offshore facilities include lodging, linking, and treatment and services platforms.

The associated gas from wells in the southwestern and northwestern oil fields is sent out to compression platforms; thereafter the gas is transported through gasoducts to the Compression Station in Atasta, Campeche. The gas undergoes recompression in Atasta (see Fig. 1) including separation and pumping of condensates before being delivered to the four major gas processing complexes scattered about in the State of Tabasco and northern Chiapas. Excess gas is burned on the flaring platforms that are the main sulfur dioxide emitters in the area.

In addition, the Atasta station recompresses residual gas coming from the gas-processing center of Ciudad PEMEX for use on the platforms in the MR. Major equipment installed at Centro Atasta consists of turbocompressors for sour gas, separation batteries, residual gas turbocompressors, condensate pumps, electric power turbogenerators, and a sour water treatment plant. Natural gas fired turbines provide power for compressors, pumps and electrical generators at Atasta. These gas turbines are major sources of NO_x and volatile organic compounds. The separation batteries are major sources of volatile organic compounds and H_2S. Atasta has five elevated flares, of which four are operational, each consuming on average $14 \times 10^3\,m^3$/day. One ground flare, 100 by 40 m, burns pig waste along with approximately $28 \times 10^3\,m^3$/day of condensate.

The crude oil that is not transferred to the Cayo Arcas offshore facility for export is pumped in via oleoducts to the port of Dos Bocas. The Dos Bocas Marine Terminal is located near Paraiso, Tabasco (see Fig. 1). This facility is the primary storage and treatment facility for crude oil from the offshore area. Part of the crude oil in Dos Bocas is sent to refineries for processing and final domestic consumption. Water and gas separations are conducted at this facility, along with storage and mixing of crude oils from offshore and the inland centers for trans-shipment to tankers. This facility also comprises the principal port for exploration, drilling, and production activities, including supplying drilling muds to the platforms and receiving spent muds, sanitary wastes, and hazardous wastes from the platforms for treatment and disposal/recycling. Excess gases released during the separations and dewatering operations are burned at two active elevated flares. Pumping and compression stations within the Dos Bocas facility include diesel-powered compression stations, diesel-powered pumps. The engines are sources of volatile organic compounds, SO_2, and NO_x.

The three types of offshore flaring operations used either elevated, boom or ground level flares. Each of the seven major oil and gas producing platform complexes mentioned above may have one or more elevated flares. Some vertically pointing flares operate at either high flow ($4.2 \times 10^6\,m^3$/day) or low flow (9.1–$24 \times 10^5\,m^3$/day). Several platforms have "boom" flares rated at $2.3 \times 10^5\,m^3$/day. The designed flows to boom flaring are generally much higher than the average flows (0.85–$25 \times 10^5\,m^3$/day). In addition to flares, other air pollutant sources include diesel-powered pumps, compressors and generators, which contribute to emissions of volatile organic compounds, NO_x and SO_2 into the air at offshore platforms (Hansell and England, 1998). No data were available on the fuel consumption rates of these diesel engines. Internal combustion devices on onshore and offshore facilities run with either natural gas, diesel or sweetened gas, whereas oil tankers are powered by diesel and heavy fuel oil. Crude oil storage tanks, and pollutants emitted from vessels (mainly oil ship tankers) in the MR of Campeche are considered in the EI.

The tasks that summarize the procedure for generating the EI are discussed next. The first task in achieving this major goal was to geographically allocate the emission sources distributed over the southwestern and northeastern oil fields. The Universal Traverse Mercator (UTM) System of coordinates was selected for that purpose. The use of geographical maps, technical reports and census of the facilities were valuable aids to obtaining the UTM coordinates of each emission source. Geographical maps were the most useful materials for this job since they provided the location in UTM coordinates of equipment, plants, devices and emission sources, and in some cases detailed zooms of petroleum platforms. A big effort was done to ensure that every potential air pollution source was inventoried in order to generate the most thorough EI ever attempted for the MR. The EI that was undertaken in this work considered 174 offshore platforms, the compression station at Atasta, and the Maritime Port at Dos Bocas.

The second step in preparing the EI had as the main objective identifying the emission sources and their pollutants emitted from the allocated facilities in the previous step. To accomplish this, several sources of information were consulted among which the most indispensable were the following: (1) *Detailed layout plans* showing an aerial view of the facilities on each level of the platforms, the main pieces of equipment, tags, their physical location and some design specifications as name of the equipment, internal key, and operating capacities; (2) *Process flow diagrams* depicting the main stages of the process, principal equipment, product streams with chemical composition, mass balance of processes, flow and physical properties like density, pressure and temperature; and (3) *Piping and instrumentation diagrams* presenting the equipment-valves, piping and instruments used in the facilities including some design specifications for pipes (construction material, diameter, length, transported product), the main equipment (name, design capacity) and instruments controlling the process.

The combustion equipment catalog prepared by personnel that operates the facilities was another source of information that proved helpful. The entries recorded in this register included equipment name, location, tag, brand, model, kind of service, design capacity, type and consumption of fuel. Technical documents dealing with quantities of hazardous wastes along with Environmental Assessment reports were also consulted to obtain valuable information regarding the design and operating conditions of air pollution sources. Internet web pages of the Mexican petroleum industry were also checked for additional information concerning the location, purpose and installed capacities of the petroleum facilities in the MR. The emissions of marine traffic were estimated from detailed reports of the Port Authority of Ciudad del Carmen showing the kind of ships, commercial license, capacity, size, fuel used, trajectories source–destination, and itinerary. For the quantification of the emissions from helicopters, reports of the oil company schedules, trajectories, brand and model of the aircraft were used.

Once the information was sorted out and classified, the name and type of the facility were recorded identifying in each case: (1) trans-shipment stations (Cayo Arcas and Dos Bocas), (2) maritime floating port terminal (Ta'kuntah Ship), (3) drilling (extraction) platforms, (4) crude oil recovering platforms, (5) crude oil production platforms, (6) linking platforms, (7) water injection platforms, (8) Pumping platforms, (9) shelter platforms, (10) telecommunication platforms, (11) crude oil measurement platforms, and (12) flaring platforms. In the Campeche Sound the oil fields are denoted as: Cantarell, Ek-Balam-Ixtoc, Ku-Mallopb-Zaap, Abkatum, Tabasco's Littoral, and Pool Chuc. The list of pieces of equipment that each facility comprises was also incorporated in to the database.

The compacted database that was finally compiled consider the entries given next. (1) Name and UTM location of the facility, (2) name of equipment, (3) equipment's tag, (4) brand and model, (5) name of the unitary operation or process, (6) type of emission (i.e. fugitive, evaporative, combustion), (7) design capacity of equipment, (8) type of fuel: diesel, natural gas, and process-gas, (9) consumption of fuel, and (10) emitted mass for each of the following air pollutants: SO_2, NO_x, CO, H_2S, CH_4, Total Hydrocarbons, and particulate matter.

The emission factors for flares, stationary equipment and internal combustion engines used to calculate the emissions were obtained from two sources: (1) AP-42: Compilation of Air Pollutant Emission Factors (USEPA, 2001), and (2) Guidelines for Atmospheric Emissions Inventory Methodologies in the Petroleum Industry (ARPEL, 1998). The Mexico EI program manuals, volume V: Area Sources Inventory Development (WGA & RI, 1997) provided emission factors for helicopters and marine traffic. Fugitive emission factors came from the handbook of control techniques for fugitive VOC emissions in chemical processes facilities (USEPA, 1993). When estimating fugitive emissions of each facility, detailed piping and instrumentation diagrams and information on number and type of compressors, pumps, flanges, valves and accessories were used. Table 1 shows the emission factors for flares, stationary equipment and internal combustion engines. Tables 2–4 list the emission factors for helicopters, marine traffic and fugitive emissions. Table 5 summarizes total pollutant emissions for each contaminant in thousands of ton per year inventoried for the two MR of the Campeche Sound.

Table 1
Emission factors for flares, stationary equipment and internal combustion engines used for the air quality screening study

Equipment	Fuel	Air pollutant						
		CO	CO_2	NO_x	SO_x	H_2S	CH_4	NMHC	PM_{10}
		Units: grams of pollutants per cubic meter of burned gas (standard conditions)							
Turbine-operated pumps, power generators and compressors	Sweet gas	24.50	By mass balance	1.70	By mass balance	Trace	0.20	2.00	2.30
Process heaters <10.4 GJ/h	Sweet gas	24.50	By mass balance	1.60	By mass balance	Trace	Trace	0.30	2.30
Process heaters 10.4–104 GJ/h	Sweet gas	24.50	By mass balance	2.20	By mass balance	Trace	Trace	0.30	2.30
Process heaters >104 GJ/h	Sweet gas	24.50	By mass balance	8.80	By mass balance	Trace	Trace	0.30	2.30
Internal combustion engines	Sweet gas	24.50	By mass balance	15.00	By mass balance	Trace	9.30	115.00	2.30
Flares	Sour gas	21.60	By mass balance	1.60	By mass balance	0.28	9.90	67.30	2.10
		Units: grams of pollutants per liter burned diesel (standard conditions)							
Internal combustion engines	Diesel	13.97	By mass balance	52.57	By mass balance	NA	NA	1.48	1.64
Cranes	Diesel	15.61	By mass balance	72.76	By mass balance	NA	NA	5.92	5.09

Table 2
Emission factors for helicopter emissions used for the air quality screening study

Operation	Fuel consumption (kg/min)	Air pollutant[a]					
		CO	CO_2	NO_x	SO_x	NMHC	PM_{10}
Taxi/idle-out	0.87	64.00	820.00	2.43	0.85	50.17	NA
Takeoff	3.21	1.01	820.00	7.81	0.85	0.00	NA
Climbout	3.03	1.20	820.00	7.00	0.85	0.00	NA
Route flight	3.21	1.01	820.00	7.81	0.85	0.00	NA
Approach	1.62	23.02	790.00	8.37	0.85	2.19	NA
Taxi/idle-in	0.87	64.00	765.00	2.43	0.85	50.17	NA

[a] Units: grams of pollutant per kg of burned fuel (standard conditions).

Table 3
Emission factors for marine traffic emissions used for the air quality screening study

Type and size of ship	Fuel consumption (l/h)	Air pollutant[a]					
		CO	CO_2	NO_x	SO_x	NMHC	PM_{10}
Port emissions							
Motor ships							
<2 m	104.00	5.27	By mass Balance	43.62	By mass Balance	7.27	Trace
2–4 m	104.00	5.27	By mass Balance	43.62	By mass Balance	7.27	Trace
4–6 m	104.00	5.27	By mass Balance	43.62	By mass Balance	7.27	Trace
$\geqslant 6$ m	104.00	5.27	By mass Balance	43.62	By mass Balance	7.27	Trace
Vapor ships							
$\geqslant 6$ m	Trace	4.36	By mass Balance	4.36	By mass Balance	0.46	1.20
Route emissions							
Motor ships							
<2 m	19.00	5.67	By mass Balance	46.65	By mass Balance	6.30	NA
2–4 m	38.00	11.95	By mass Balance	40.57	By mass Balance	5.48	NA
4–6 m	167.00	7.45	By mass Balance	20.03	By mass Balance	2.07	NA
$\geqslant 6$ m	484.00	13.18	By mass Balance	32.35	By mass Balance	6.16	NA
Vapor ships							
$\geqslant 6$ m	606	0.420	Mass balance	6.690	Mass balance	0.100	2.400

[a] Units: grams of pollutant per liter of burned fuel (standard conditions).

Table 4
Emission factors for fugitive emissions used for the air quality screening study

Source	Service	Emission factor	
		lb/(hour-source)	g/(hour-source)
Valves	Gas/vapor service	0.0123	5.5842
	Heavy liquid service	0.0156	7.0824
	Heavy liquid service	0.0005	0.227
Pumps	Light liquid service	0.1087	49.3498
	Heavy liquid service	0.0471	21.3834
Compressor seals	Gas/vapor	0.5016	227.7264
Pressure relief valves	Gas/vapor	0.2288	103.8752
Flanges and other connectors	All	0.0018	0.8172
Open-ended valves or lines	All	0.0037	1.6798

Table 5
Air pollutant emissions of the offshore and coastal installations of the extraction and production oil company in the Sound of Campeche

Region	Oil field	NO_x		SO_x		H_2S		CO		NMCH		PM_{10}		Total[a]	
		Thousands ton/year	%NO_x	Thousands ton/year	% SO_x	Thousands ton/year	% H_2S	Thousands ton/year	% CO	Thousands ton/year	% NMCH	Thousands ton/year	% PM_{10}	Thousands ton/year	% Total
Northeastern marine region	Cantarell	8.795	21.37	138.657	76.60	0.876	79.62	91.924	63.18	214.083	77.33	8.881	61.54	462.340	70.16
	Ku-Malloob-Zaap	1.371	3.33	25.655	14.17	0.142	12.94	12.858	8.84	34.660	12.52	1.351	9.36	75.896	11.52
	Ek-Balam	0.055	0.13	0.008	0.00	0.001	0.08	0.310	0.21	0.256	0.09	0.030	0.21	0.658	0.10
	Atasta	0.602	1.46	1.393	0.077	0.008	0.74	8.377	5.76	2.634	0.95	0.788	5.46	13.794	2.09
	Cayo Arcas & Repumping Station	8.286	20.13	0.132	0.07	0.000	0.00	2.201	1.51	0.246	0.09	0.260	1.80	11.126	1.69
	Total Nrtheastern Region	19.109	46.43	165.845	91.63	1.028	93.38	115.670	79.50	251.879	90.98	11.31	78.38	563.81	85.56
Southwestern marine region	Pool-Chuc	1.098	2.67	7.014	3.88	0.053	4.77	8.213	5.64	12.967	4.68	0.788	5.46	30.081	4.57
	Dos Bocas	12.326	29.95	0.799	0.44	0.004	0.41	4.365	3.00	6.086	2.20	0.485	3.36	24.060	3.65
	Abkatum	2.325	5.65	2.435	1.35	0.016	1.44	16.270	11.18	5.119	1.85	1.541	10.68	27.690	4.20
	Total Southwest Region	15.748	38.26	10.249	5.662	0.073	6.62	28.848	19.83	24.171	8.73	2814	19.50	81.831	12.42
All	Marine and aerial traffic	6.032	14.66	4.905	2.71	0.000	0.00	0.917	0.63	0.767	0.28	0.297	2.06	12.917	1.96
All	Perforation	0.268	0.65	0.004	0.00	0.000	0.00	0.070	0.05	0.020	0.01	0.009	0.06	0.373	0.06
Grand total		41.158	100.000	181.002	100.00	1.101	100.00	145.505	100.00	276.839	100.00	14.431	100.00	658.935	100.00

[a] Excludes H_2S since it is not a criteria air pollutant.

To perform mass balance calculations detailed knowledge of each of the streams going into the flares and internal combustion engines was needed. The method required the average composition of burned fuels and flow rates of internal combustion engines, such as compressors, pumps and power generators. Design data along with chromatographic composition including hydrocarbons and sulfur contents as well as monthly amounts of gas sent to the flares were used to calculate the emissions of sulfur oxides and carbon dioxide. To estimate carbon dioxide emissions, it was considered, following the recommendations of the International Panel on Climate Change (IPCC), that 99.5% of the carbon present in the gas streams was converted to CO_2 (IPCC, 1996) during combustion or flaring processes. For the sulfur oxides emissions, a 100% of conversion of total sulfur to sulfur dioxide was assumed. The average composition of natural gas with a molecular weight of 22.02 g/g-mol in percent mole was taken as follows: CH_4 74.22%, C_2H_6 14.87%, C_3 and higher 10.73%, CO_2 0.08%, and total sulfur 200 ppm. The average composition of diesel in percent weight along with physical properties is given as: carbon content 84.80–85.93%, total sulfur 0.05%, density at 1 atm and 15°C, 840–860 $kg\,m^{-3}$.

The gases for flaring have a time-varying composition. Many of the flares usually operate with more than one gas stream composition during flaring conditions. To overcome the difficulty of dealing with enormous quantities of data, an average composition for each flare was used. As a general guideline, the minimum and maximum composition in percent mole was adopted in this work. The low and high percent values turned out to be given by: H_2S (0.00–2.92%), CO_2 (0.07–3.05%), CH_4 (1.06–67.84%), C_2H_6 (1.05–19.54%), C_3H_8 (1.98–19.17%), i-C_4H_{10} (0.71–3.98%), n-C_4H_{10} (1.85–13.07%), i-C_5H_{12} (0.36–5.35%), n-C_5H_{12} (0.45–8.81%), n-C_6H_{14} (0.31–18.34%). The physical properties of flared gases are: (molecular weight from 23.35 to 129.50 g/g-mol), specific gravity (0.40–1.29), density at 1 atm and 15°C (0.09–0.54).

Table 4 shows the total emissions of the MR on the Campeche Sound. Annually, 658,935 tons of air pollutants are emitted to the atmosphere. Most of the air pollution sources are located in the northeastern region of the Campeche Sound. Platforms in the Cantarell field are responsible for most of the air pollution emissions: 79% of the sulfur oxides, 77% of the hydrocarbons, 63% of the carbon monoxide, 62% of the fraction of particulate matter less than 10 μm, and 21% of the nitrogen oxides. The Atasta Recompression station and Dos Bocas Terminal are the main contributors to nitrogen oxides emissions with 52% of the total. The marine and aerial traffic are also important contributors of nitrogen oxides with 15% of the total emissions.

4. Air quality data

A thorough evaluation of the contribution of various sources to the air quality at a particular location requires concurrent meteorological and air quality data spanning a period of at least 1 year. At present time, for the Campeche Sound, neither the air quality nor the meteorology data sets presently in hand are adequate for the task. None of the air quality monitoring sites (Atasta and Dos Bocas) reports concurrent meteorological conditions at the monitoring site, and air quality data from any of the offshore platforms are non-existent. The most complete data set corresponds to data collected at the Dos Bocas maritime terminal collected by a network of three monitoring sites. Of the 2 year period (1999–2000) when measurements were made, only seven months in 1999 have sufficient concurrent air quality (SO_2 and NO_2) and meteorological data. There were no meteorological data for Atasta, and ambient observations of SO_2 and NO_2 were available in May of 2001, and for a few months in 1999, which did not include February.

All of the quality-screened monitoring data reported to date for the Atasta monitoring network show the observed maximum 24-h average (hourly mean) concentrations of SO_2 to be significantly below the Mexican regulatory standard of 0.13 ppm. Maximum hourly NO_2 concentrations observed at the Atasta network are also well below the regulatory limit of 0.21 ppm. However, it should be stated here that these data represent only a brief glimpse of the range of SO_2 and NO_2 concentrations that could be experienced at the monitoring sites.

All of the quality-screened monitoring data reported to date for the Dos Bocas monitoring network shows the observed maximum 24-h average (hourly mean) concentrations of SO_2 to be significantly below the Mexican regulatory standard of 0.13 ppm. Maximum hourly NO_2 concentrations observed by the Dos Bocas are also well below the regulatory limit of 0.21 ppm.

While stringent procedures for screening SO_2 and NO_2 data for completeness and outliers have been used, average values include probable data outliers that are reported as maximum observed values. For example, at Station 3 in the Dos Bocas network, a 24-h SO_2 concentration of 0.227 ppm is reported. However, the data on which this average is based are clearly outliers, and may be due to an instrument or data transmission error rather than unusually high SO_2 concentrations. Excluding these outliers, the average value of the day is probably not much different than the prior and subsequent days, slightly less than 2 ppb. A similar situation exists for the peak hourly NO_2 concentration reported at Station 1 of the Dos Bocas network in November 1999. But, even when the outliers are included, the indicated maximum

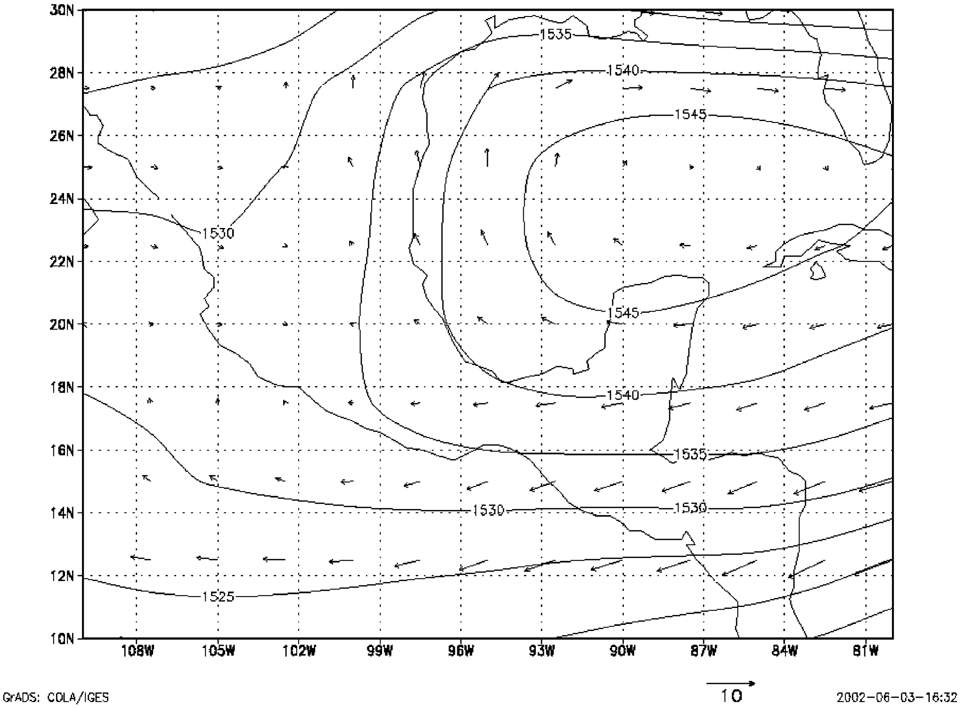

Fig. 2. February 1999 monthly mean for 850 mb geopotential height (m) and wind field.

concentrations are still well below regulatory limits for 24-h average SO_2 and for hourly NO_2 at the Dos Bocas sites. However, a longer-term monitoring data set is needed to determine if these outliers represent transient phenomena emanating from the Dos Bocas facility, or are instrumental or transcription errors.

5. Synoptic meteorological conditions

During the month of February, local winds near the surface and within the boundary layer are influenced by large scale wind conditions that are often associated with winter storms in the GOM (Schultz et al., 1998; Magaña-Rueda et al., 1999). This condition produces moderate to strong northeasterly winds near the surface favoring long range transport of pollutants inland and very efficient dispersion near the sources. February 1999 shows important departures from the long-term February climatology (not shown). Data extracted from the NCEP Reanalysis for February 1999 at 850 mb geopotential height show a high pressure center over the GOM that is shifted about 10° towards the east relative to the climatic high pressure center. As a consequence, a stronger easterly wind component over the Campeche Sound is observed (Fig. 2) during the month of February of 1999.

During the field experiment, departures from the above-mentioned climatic condition were observed. An average of days 2 and 3 of February (Fig. 3) shows easterly winds over much of south central and the southeastern portions of the country. A deep trough associated with a frontal zone is noted over the west part of Mexico at this period of time. This cold front traveled to the east causing the winds in the Campeche area change from easterly to southeasterly (not shown) during days 3 and 4. On 4 and 5 February the cold front weakened substantially as the high pressure center that previously remained stationary on days 2 and 3 of February at about 80°W moved 8° to the west. As a result, wind direction over the Campeche area shifted to the northeast during the last part of the campaign.

These results may suggest that if the dispersing plumes were able to penetrate into the upper air layers (~ 1500 m) by vertical mixing during midday, the trend would indicate that from days 2 to 4 of February pollutants at 850 mb will be transported out into the GOM. Contour maps for the 950-mb geopotential height and wind field (~ 600 m), the lowest level for which data were available, were produced in order to verify if there were notable changes in relation to the 850 mb charts. It was found that both maps displayed very little differences, thus the above scheme on the fate of pollutants would not be invalidated.

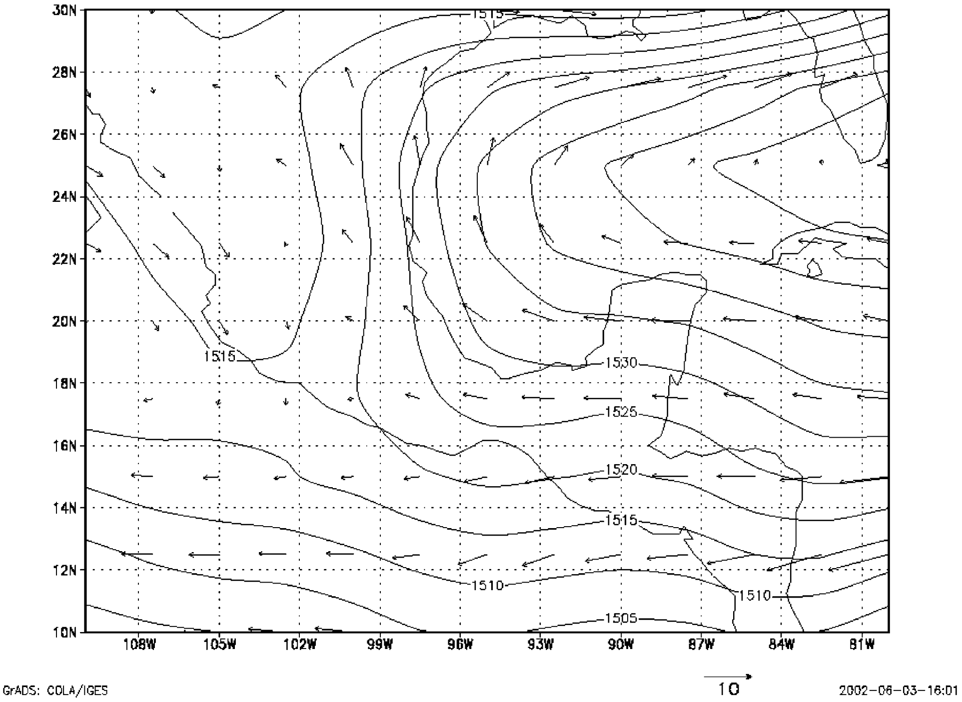

Fig. 3. Days 2 and 3 of February 1999 for 850 mb geopotential height (m) and wind field.

6. Model simulations

RAMS and CALMET models were initialized with the same rawinsonde and meteorological surface data. Figs. 4–6 show simulated surface wind fields predicted with the inner grid mesh with RAMS (left panel) and CALMET (right panel) for 3 February at three local times (03:00, 12:00, and 20:00 h). Surface concentrations of SO_2 are adjacently displayed to show plume dispersion patterns from the MR sources overlay with the diagnosed CALMET vector field. The start time for the CALMET/CALPUFF model simulations was 18:00 h local time on 1 February 1999, while the RAMS computation initiated at 00:00 h on 1 February 1999.

A direct comparison between these two models has to be exercised with caution as there is not a one-to-one correspondence since RAMS spatial resolution slightly differs from that of CALMET, despite their identical size domain. Figs. 4 and 6 can rightly be said to be similar but discrepancies between the RAMS and CALMET wind fields arise as observed in Fig. 5. The surface flow structure that RAMS shows at 12:00 h is not captured by CALMET along the seashore. The RAMS simulation shows a well-defined line of convergence along the western coast of Tabasco (see Fig. 5 left panel). A noteworthy feature when examining Figs. 4–6 outside the coastal line reveals an outstanding resemblance of predicted surface wind patterns between RAMS and CALMET simulations, particularly in areas where there are either clusters of observational stations, or where the effect of topography is not as abrupt as in the mountainous region.

The distinct behavior shown by the models is related to their design. Both RAMS and CALMET extrapolate sparse wind field and thermodynamic data within the domain of interest to their computational grids. While RAMS is a full fledged atmospheric model that solves for the governing equations as a boundary and initial value problem, CALMET works more as an interpolator, albeit, maintaining near-zero wind divergence, conserving energy, and allowing for topographic effects. Thus RAMS recognizes the sea–land temperature contrast that drives sea–land breeze development, while CALMET can only adjust the wind field to the available observations, while maintaining the above divergence and energy conservation conditions.

The transport of SO_2 and dispersion trajectories in the Campeche Sound airshed was investigated with CALPUFF. The CALPUFF model uses the same grid system as CALMET, consisting of 9 layers over the 112×115 horizontal grid cells. The vertical layers were specified with variable spacing heights of 20, 80, 160, 300, 600, 1000, 1500, 2000, and 2130 m to ensure that the mixed

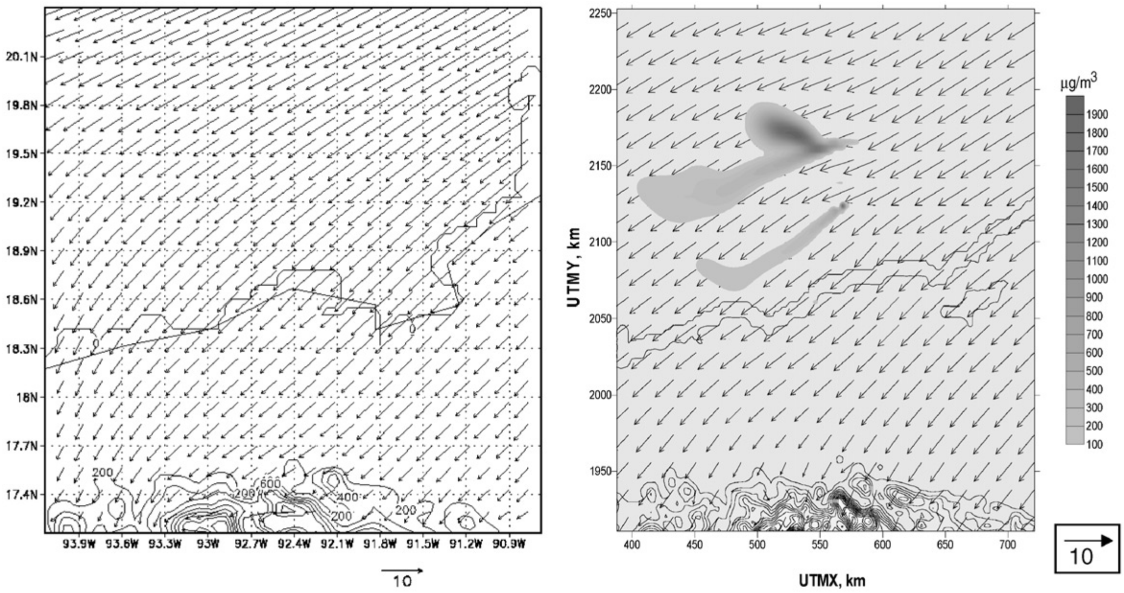

Fig. 4. Left panel: RAMS surface wind simulations. Right panel CALMET surface wind simulations and surface SO_2 concentration predicted with CALPUFF for 3 February 1999 at 03:00 LST.

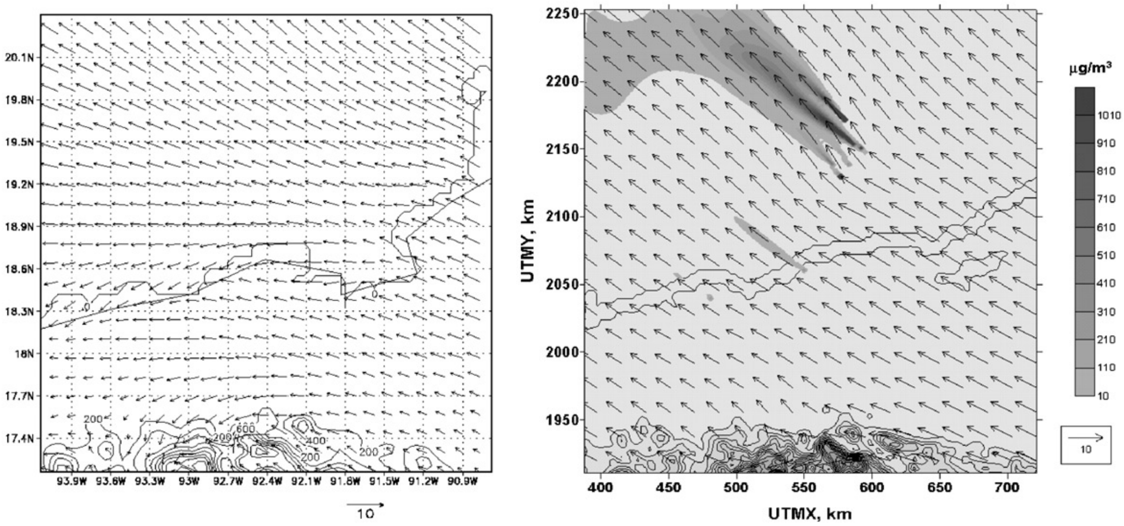

Fig. 5. Left panel: RAMS surface wind simulations. Right panel CALMET surface wind simulations and surface SO_2 concentration predicted with CALPUFF for 3 February 1999 at 12:00 LST.

layer height and the entrainment layer were well below the domain top. To increase computational efficiency the emission sources were grouped according to their elevation referred to sea level, taking into account the plume rise effect since all point sources had stack emission temperatures higher than ambient temperature. It was possible to estimate plume rise considering certain average parameters for stacks such as wind speed, stack height, stack exit velocity, gas temperature and stack diameter. The plume-rise Briggs formulas were applied for plumes dominated by buoyancy forces resulting in plume rise values ranging from 10 to 70 m for stable, neutral and unstable atmospheres (Seinfeld and Pandis, 1998). This means that the effective stack height for the emissions sources injected into the upper air layers lie within 50–110 m, and therefore the model layers that received flare emissions were the second and third from the bottom up.

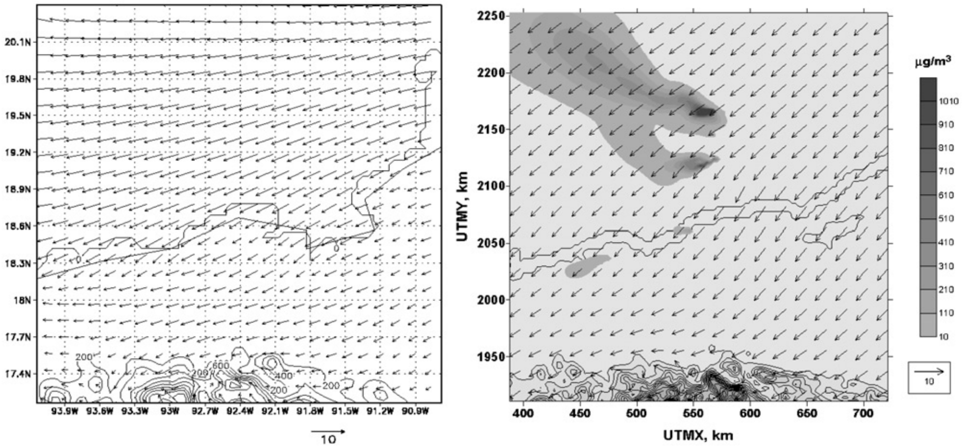

Fig. 6. Left panel: RAMS surface wind simulations. Right panel CALMET surface wind simulations and surface SO_2 concentration predicted with CALPUFF for 3 February 1999 at 20:00 LST.

It is seen in Figs. 4–6 that the most significant puffs issue from offshore operations where process or excess gas is continuously burned. Diesel-powered pumps, compressors and generators also contribute to emissions of SO_2/NO_x into ambient air at offshore platforms but these emissions represent only a small fraction when compared to flaring. Fugitive emissions are very marginal and if removed from the EI no noticeable change would be virtually observed. Mass fluxes of SO_2 issuing into atmospheric air from the re-compressing station of Atasta and the Dos Bocas crude-oil facility treatment plant do not seem to have a large radius of influence, hence their impact on neighboring communities is not as pronounced as one might have guessed. This is of course corroborated by looking at the air quality screening data on SO_2/NO_x that was mentioned in a preceding section.

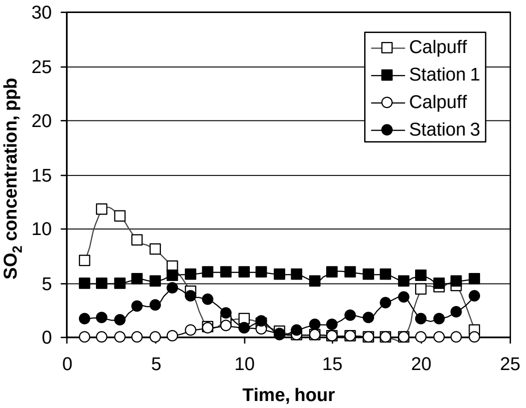

Fig. 7. A comparison of CALPUFF predictions with observations for SO_2 concentrations taken at the Dos Bocas air quality network for 3 February 1999.

Portions of the plumes from offshore platforms are well diluted by northeasterly winds when they reached coastal areas in the early hours of the day. However, the transport–dispersion pattern of SO_2 plumes along the seashore may not be completely accurate when simulated by CALPUFF from midday to late afternoon when sea breeze effect is triggered by sea–land temperature gradients. The smooth topography and lower surface friction over water give rise to large spreading rates of offshore plumes than what otherwise could be on land. At mid day when vertical mixing is strong the plumes will be more diluted and also subjected to directional wind shear. The turning of the mean wind with height and time and the vertical mixing by convective turbulence will also cause the plume to spread as seen in Figs. 4–6. From midnight to 06:00 h the surface winds gradually change from northeasterly to easterly winds, then from 07:00 to noon there is another steady shift in wind direction causing SO_2 puffs to be transported outside the shoreline out into the GOM. At 15:00 h there is a flow reversal in which surface winds veer from southeast to northeast winds deflecting the plumes accordingly to bring polluted air masses inland.

Model predictions for SO_2 were compared with observations taken at the Dos Bocas air quality network. Fig. 7 shows the hourly SO_2 concentrations measured at the Dos Bocas ambient monitoring stations 1 and 3 against the CALPUFF calculated profiles. From Fig. 7 it can be seen that CALPUFF predicts SO_2 concentrations that are below the measured values, except at a few hours in the morning in which model predictions are higher than observations at station 1. At station 1 the predicted profile decays at 06:00 h, then stays constant and it does not increase again until 20:00 h when the observed and predicted values reach approximately the same concentration. The CALPUFF hourly SO_2 mass concentrations are underpredicted at

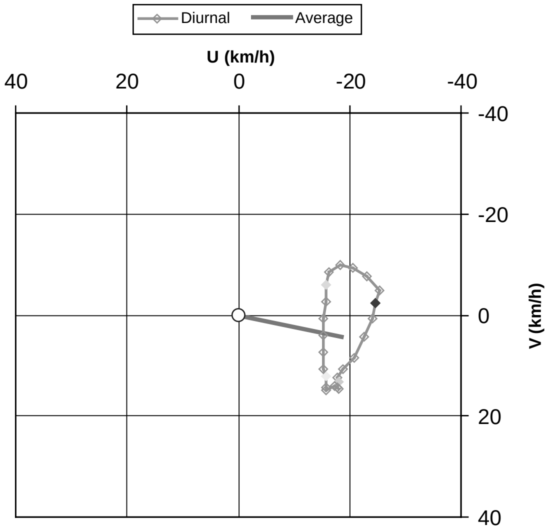

Fig. 8. Diurnal variation of both vector average wind speed and direction and average wind speed and direction over all data for the Ixtoc meteorological station of 1999 at the Ixtoc oil field complex.

station 2 (not shown). It is very likely that the lower concentration values predicted by CALPUFF for this episode may be partly due to emission sources not accounted for in the EI. In the state of Tabasco where Dos Bocas is found the Gas Processing Complexes (GPC) of La Venta, Ciudad PEMEX, Nuevo PEMEX and Cactus were not inventoried since mass fluxes of these emissions were not available at the time this work was undertaken. The GPCs are managed by a subsidiary other than the exploration and production industry. The GPC are within a radius of influence of 100 km or less toward the southwest, south, and southeast. It is precisely from 07:00 to 19:00 h when south winds blow into the coastal zone of the GOM where Dos Bocas lies, hence carrying with them contaminants from the GPC.

An analysis of the source–receptor relationship for flares at the Ixtoc marine complex was performed to investigate health-based standards for offshore workers. To bring emissions from the fares to the habitation platform, the wind must be aligned in the direction from the flare to the habitation. The distances between many of the elevated flares on offshore platforms and their distances (top) and direction (bottom) to various inhabited platforms located in the Campeche Sound were determined. The meteorological station at the Ixtoc complex is nearly centrally located with respect to many of the inhabited platforms. Wind data of 1999 for the Ixtoc meteorological station yielded the mean diurnal variation of both vector wind speed and direction, and the corresponding vector average speed (19 km/h) and direction (103° from N) are shown in Fig. 8. Throughout the morning hours (06:00–12:00) the wind direction is nearly constant from the SE (~130° from N). In the afternoon (12:00–18:00), wind directions shift gradually from SE to ENE (60–70° from N). After 18:00 h there is a gradual strengthening of the wind speed and a shift toward a more easterly direction. Then, after midnight, there is a steady shift toward winds out of the SE. A similar diurnal pattern is evident in every month. Spring and summer months show a larger diurnal range in direction (more southerly in the 06:00–12:00 h period) than the fall and winter months.

Based on the wind direction data for Ixtoc, pairs of flare and inhabited platforms were identified for which the habitation to flare direction was within the sector 60–135° from N and in the sector ±5° about the mean wind direction vector of 103° from N. For these inhabited platforms, the flares are located such that the downwind plume may pass over the platform at some time during the day. It is noteworthy that no nearest flare falls within either of these sectors. While this means that the nearest flare to inhabited platforms is unlikely to be upwind under the prevailing meteorological condition, it does not rule out the possibility that the plume from the nearest flare could affect air quality at the inhabited platform for brief periods during unusual weather conditions.

7. Summary and conclusions

An EI for the exploration and production activities of petroleum in the Campeche Sound was developed for the first time. Assembling emissions data of offshore and onshore petroleum sources in a spread sheet was among the most significant products of this work. No EI with this level of detail had ever been attempted before. The emission factors employed in calculating atmospheric emission rates are derived from the US Environmental Protection Agency document: AP-42: and from Guidelines for Atmospheric Emissions Inventory Methodologies in the Petroleum Industry from the Latin-American Association of Petroleum Companies.

The EI considered the installations of offshore gas and oil fields comprising 174 platform, the re-compression station at Atasta, the Dos Bocas marine terminal for storage and treatment of crude oil, and the transshipment station at Cayo Arcas. The total mass of air pollutants emitted into ambient air was calculated as nearly 660,000 tons per year. Of the two MRs, northeasterly and southwesterly, the former was found to be responsible for most of the sulfur oxides emitted in the area followed by hydrocarbons. Both the Atasta re-compression station and the Dos Bocas Marine Terminal were the main contributors to nitrogen oxides emissions with 52% of the total emissions. The marine and aerial traffic such as tankers and helicopters, respectively, were also important contributors of nitrogen oxides with 15% of the total emissions.

Quality-screened ambient air quality monitoring data from the Atasta and the Dos Bocas monitoring networks were used to measure the impact of SO_2 and NO_2 on ambient air. Air quality data in the vicinity of the Atasta re-compression station and the Dos Bocas maritime terminal for brief periods scattered over several years and during longer formal monitoring programs at three-site networks at each facility did not find any violations of the Mexican national air quality standards for 24-h average SO_2 and hourly NO_2 concentrations.

A preliminary air quality model simulation was performed for a single event during the dry season to observe trends on transport and dispersion of SO_2 emissions. Surface meteorological data and upper air soundings collected during a 4-day field campaign in February of 1999 were used for driving the meteorological model CALMET. The generated EI along with the wind field produced by CALMET was used to drive the transport and dispersion model CALPUFF. Predictions from CALPUFF were compared with ambient air quality data from the Dos Bocas network. CALPUFF predicted lower SO_2 concentrations than measurements taken at Dos Bocas. The underpredicted results during midday hours may suggest that emissions sources south of Dos Bocas (i.e. GPC) have to be considered in the EI.

Future work to further improve the accuracy of the EI is recommended. Measurements of the emission fluxes should be performed using remote sensors, thus reducing uncertainties in the EI and allowing for improving the confidence in the modeling simulations of atmospheric pollutants. Other classes of sources such as agricultural and commercial transportation, industrial and commercial activity, residential heat processes, agricultural burning, and natural sources that include marshes, swamps, and vegetation should be considered in the emissions inventory. This extraordinary task demands qualified personnel and sufficient funding for several field studies and long-term air quality and meteorological monitoring to amass the much-needed databases for refining and expanding the current EI and for running and verifying air quality models.

The air quality monitoring networks at Atasta and Dos Bocas should be continued with greater attention being paid to increasing data recovery and quality from these sites. Meteorological measurements should be added to the air quality monitoring sites so that dispersion modeling can be more confidently done at these locations. Offshore meteorological data acquisition and archiving should continue with greater attention given to increasing data recovery. At least an air quality monitoring station should be installed at one of the offshore platforms to confirm future model predictions for air quality simulations.

Although this work constitutes an essential advancement on developing basic tools for evaluating the effects of the petroleum industry in the GOM due to exploration and production operations, more work is still needed to fully assess the complete range of impacts in the different compartments in this undeveloped area (i.e. water discharges, spills on soil, toxicology, etc.).

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