Background Document

Reducing Emissions from Goods Movement via Maritime Transportation in North America

Evaluation of the Impacts of Ship Emissions over Mexico

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List of Abbreviations and Acronyms

BAU	Business As Usual
BC	black carbon
bcpw	born child per woman
BenMAP	Environmental Benefits Mapping and Analysis Program
CAE	Central American Emission estimates
CEC	Commission for Environmental Cooperation of North America
CHE	cargo handling equipment
CO	carbon monoxide
CO_2	carbon dioxide
Conapo	National Population Council of Mexico
CPW	concentration population-weighted
DGGCARETC	General Directorate for Air Quality Management and the Pollutant Release and Transfer Register
ECA	Emission Control Area
EDGAR	Emissions Database for Global Atmospheric Research
EERA	Energy and Environmental Research Associates
EF	emission factor
EPA	United State Enviromental Protection Agency
ERG	Eastern Research Group, Inc.
GDAS	Global Data Assimilation System
GHG	greenhouse gases
g/kWh	grams per killowat hours
GIS	Geographical Information System
GRT	Gross Register tonnage
HC	hydrocarbons
HC3	alkanes with HO rate constant (298 K, 1 atm) between 2.7×10^{-13} and 3.4×10^{-12}
HE	health effects
HEP	health endpoints
IMO	International Maritime Organization
INEB	*Inventario Nacional de Emisiones de Buques* (Mexico's National Ship Emissions Inventory)
INEM	National Emission Inventory of Mexico
INEP	*Inventario Nacional de Emisiones de Puertos* (Mexican Port Emissions Inventory)
IPCC	Intergovernmental Panel on Climate Change
IR	Incidence rate
kWh	kilowatt hours
MAE	mean absolute error
MSE	mean squared error
Marpol	International Convention for the Prevention of Pollution from Ships
MCE2	Molina Center for Energy and the Environment
NEI	US National Emissions Inventory
NCEP	National Centers for Environmental Prediction
NCO	*NetCDF Operators*
NetCDF	Network Common Data Form
NO_2	nitrogen dioxide
NOx	nitrogen oxide
O_3	ozone
PM	particulate matter
$PM_{2.5}$	particulate matter less than or equal to 2.5 microns (micrometers) in diameter

PM_{10}	particulate matter less than or equal to 10 microns (micrometers) in diameter
ppb	parts per billion
ppb_v	parts per billion by volume
ppm	part per million
RADM2	Second generation regional acid deposition model
RAMA	*Red Automática de Monitoreo Atmosférico* (Ambient Air Quality Monitoring Network, Mexico City)
RMSE	root-mean-squared error
RO-RO	Roll On-Roll Off
SCT	*Secretaría de Comunicaciones y Transportes* (Ministry of Communications and Transport, Mexico)
Semarnat	*Secretaría de Medio Ambiente y Recursos Naturales* (Ministry of the Environment and Natural Resources, Mexico)
SLCP	short-lived climate pollutants
SMOKE	Sparse Matrix Operator Kernel Emissions
SO_2	sulfur dioxide
SO_x	sulfur oxide
STEEM	Ship Traffic, Energy and Environment Model
UNAM	*Universidad Nacional Autónoma de México*
US-EPA	United States Environmental Protection Agency
VES	Economic value depending on HEP
VOC	volatile organic compounds
WHO	World Health Organization
WRF-Chem	Weather Research Forecast Chemistry model

Abstract

The influence of ship emissions on air quality in Mexico and the potential improvements resulting from the ratification of Annex VI of the International Convention for the Prevention of Pollution from Ships (Marpol Convention) and the establishment of a Mexican emission control area (ECA) have been evaluated using the WRF-Chem air quality model. The model's performance for the base year (2011) was evaluated against ambient air quality data from monitoring stations, as well as meteorological parameters. The modeling results for prospective scenarios in 2030 were used to feed the Environmental Benefits Mapping and Analysis Program (BenMAP). Two main pollutants (ozone and particulate matter less than or equal to 2.5 micrometers) were selected to evaluate the health and economic impacts of improvements in air quality resulting from reductions in the concentrations of these pollutants. Emissions from ships in the proposed Mexican ECA region contribute a significant number of cases of adverse health effects, especially in highly populated coastal areas. The implementation of an ECA for Mexico is expected to yield important health benefits for its inhabitants.

Executive Summary

Emissions from ships have an important influence on air quality in coastal areas and, in some cases, inland. The objectives of the modeling studies presented in this document were to a) evaluate the influence of emissions from large ships on air quality in Mexico; and b) identify potential improvements in air quality resulting from the ratification of Marpol Annex VI and the establishment of an emission control area for Mexico (Mex-ECA).

The objectives were accomplished through the following tasks:

- Compiling and preparing emission inventories for modeling.
- Configuring and validating the air quality model.
- Performing air quality modeling for base year and prospective emissions scenarios in 2030.
- Generating air quality maps showing ozone and fine particle concentrations, as well as sulfur dioxide deposition.
- Estimating health benefits resulting from reductions in ozone concentrations and fine particle emissions.

The air quality modeling studies were based on the latest available emissions inventories for Mexico. Land-based emissions data were taken from the 2011 National Emissions Inventory (*Inventario Nacional de Emisiones de México*, INEM 2011). Port and ship emissions inventory data were also for 2011, with emissions projected to 2030. The modeling study included three scenarios: a) a 2011 baseline scenario; b) scenario S1 (Marpol 2030), in which Mexico only ratifies Marpol Annex VI; and c) scenario S2 (Marpol + ECA 2030), in which Mexico ratifies Annex VI and also establishes an ECA. Emissions data were prepared as inputs to the Weather Research Forecast Chemistry (WRF-Chem) model. The modeling results were evaluated against available data from the ambient air quality monitoring stations. The modeling results were then used to feed the Environmental Benefits Mapping and Analysis Program (BenMAP). Two main pollutants, ozone (O_3) and particulate matter less than or equal to 2.5 microns (micrometers) in diameter ($PM_{2.5}$), were selected to evaluate the health and economic impacts of improvements in air quality. The BenMAP program was also configured through the selection of various parameters based on the most recent epidemiological studies in Mexico and other areas of the world.

The results of the benefits evaluation suggest that the establishment of an ECA in Mexico would prevent between 4,000 and 35,000 premature deaths and from 3.3 to 4.4 million other adverse health cases (hospital admissions, chronic bronchitis, restricted activity days, asthma, school absences). The associated monetized health benefits would be between $US18 and $US97 billion, mainly due to avoided premature deaths as a result of reductions in ship emissions and lower ambient concentrations of $PM_{2.5}$ and O_3.

This report is divided into two parts. Part I presents details of the air quality modeling undertaken and possible improvements in air quality following the ratification of Marpol Annex VI and the establishment of an ECA in Mexico. Part II presents the potential health benefits for the Mexican population resulting from the establishment of an ECA, and the associated cost savings.

Acknowledgments

The Commission for Environmental Cooperation (CEC) extends its sincere appreciation to the principal authors of this report, from the Molina Center for Energy and the Environment (MCE2), for their diligent work in conducting the air quality modeling and health benefits analyses: Luisa T. Molina, Agustín García, Sérgio Duarte, Marco Mora, Magdalena Armenta, Víctor Almanza, Miguel Zavala, Rodrigo González, Wenfang Lei and Gilberto Maldonado,The CEC also wishes to thank ERG, Inc. for coordinating the input of experts from the three North American countries.

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Finally, the CEC acknowledges the staff of the CEC Secretariat involved in bringing this project to fruition: Orlando Cabrera-Rivera, head of the Environmental Quality unit; and Danielle Vallée and Catherine Hallmich, project leads.

Background

The International Maritime Organization and the Marpol Convention

The International Maritime Organization (IMO) is the UN specialized agency responsible for creating a regulatory framework for the shipping industry that is fair and effective, universally adopted and implemented.[1] In response to growing international concern to protect the oceans from pollution by ships, tanker accidents, the enormous amount of discarded refuse which eventually makes its way to gyres at sea, and the chronic pollution of beaches and coastal waters, the International Convention for the Prevention of Pollution from Ships (Marpol Convention) was adopted in 1973 and amended by the Protocol in 1978. As of May 2013, 152 countries were signatories of the convention, representing about 99 per cent of the world's shipping tonnage. All ships flagged under countries that are signatories to Marpol are subject to its requirements, regardless of where they sail, and member nations are responsible for vessels registered under their respective nationalities.

The Marpol Convention has six annexes (Table 1), the objectives of which are to regulate discharges and spills from ships of all harmful substances that can cause risks to human health, flora and fauna, or marine ecosystems. Marpol establishes rules to prevent pollution by oil, noxious liquid substances carried in bulk, harmful substances carried by sea in packaged form, sewage from ships, and garbage from ships, along with rules for the prevention of air pollution from ships.

Table 1. Annexes of Marpol 73/78 and Current Status in Mexico

Annex	Regulation	Mexico Ratification	Year
I	Prevention of Pollution by Oil	Yes	1992
II	Control of Pollution by Noxious Liquid Substances in Bulk	Yes	1992
III	Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form	No	-
IV	Prevention of Pollution by Sewage from Ships	No	-
V	Prevention of Pollution by Garbage from Ships	Yes	1998
VI	Prevention of Air Pollution from Ships	Under development	

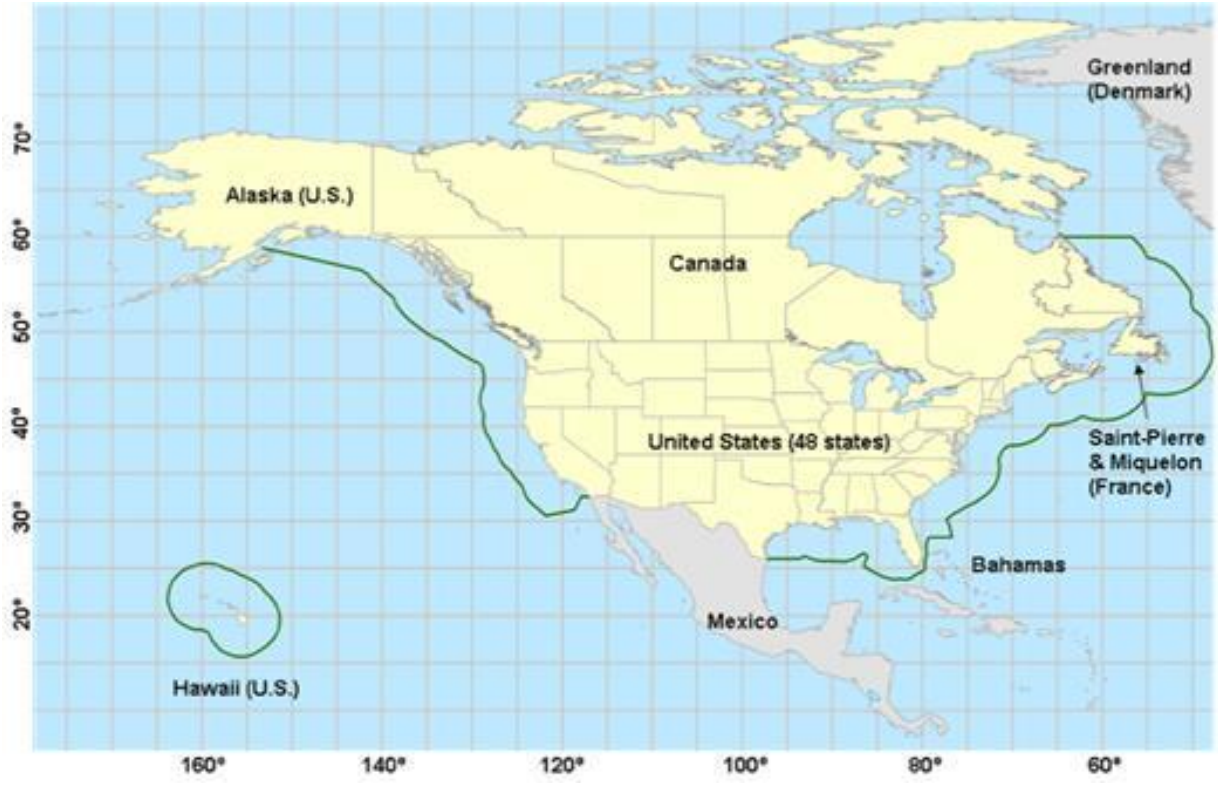
Marpol Annex VI and Emission Control Areas

Annex VI of the Marpol Convention addresses air pollution from ocean-going ships and includes requirements applicable to the manufacture, certification, and operation of vessels and engines, as well as fuel quality used in vessels operating in waters that are subject to the Convention. The international air pollution requirements of Annex VI establish limits on nitrogen oxide (NO_x) emissions and require the use of fuel with lower sulfur content, reducing the formation of ozone pollution and thereby protecting people's health and the environment. NOx can cause smog and aggravate asthma, respiratory symptoms, as well as increase mortality and hospital admissions.

[1] See : www.imo.org/.

According to the statutes of the IMO, countries that have ratified Marpol Annex VI may optionally further establish an emission control area (ECA) with more stringent standards for NO_x, sulfur oxides (SO_x), and particulate matter (PM). In this context, the United States and Canada proposed to the IMO Committee the establishment of an ECA, which applies to vessels operating in US and Canadian waters, as well as ships operating within 200 nautical miles off the coast of North America (shown in green contour in Figure 1). The North America ECA entered into force in August 2011 and its requirements became applicable one year later. From that date, all vessels operating within that ECA must use only fuel with a sulfur content not exceeding 1% by weight (10,000 ppm). After January 2015, the sulfur content should not exceed 0.1% (1,000 ppm).

Figure 1. The Existing North American ECA



Source: US Environmental Protection Agency (EPA)

Impacts of Ship Emissions over Mexico and Mexico's efforts to address them

Emissions from ships have an important influence on air quality in coastal areas and in some cases, on inland air quality. The most important substances emitted by marine vessels are carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), hydrocarbons (HC), and particles. These species are harmful air pollutants that impact air quality, human health and climate at local, regional and global levels.

Currently, Mexico is Party to Marpol Annexes I, II, and V (Table 1). In October 2014, Mexican government representatives met with Koji Sekimizu, Secretary General of the IMO, and announced that the Mexican government will sign Annexes III, IV and VI of Marpol.

By means of an ongoing collaboration, through the Commission for Environmental Cooperation (CEC), with the US Environmental Protection Agency (EPA) and Transport Canada, the Mexican government has been actively exploring international actions to reduce the air pollution from ship emissions that impact coastal communities. This document, presenting an evaluation of the impacts of ship emissions over Mexico resulting from the ratification of Marpol Annex VI and establishment of a Mexican Emissions Control Area (ECA), is a product of this tri-national collaboration.

The report is divided into two parts, with supplementary materials provided in the appendices.

Part I presents details on the air quality modeling conducted, as well as improvements in air quality expected after Mexico's ratification of Marpol Annex VI and its establishment of an ECA. The modeling study included three scenarios: a) baseline (2011); b) scenario Marpol (2030), in which Mexico only ratifies Annex VI; and c) scenario Marpol + ECA (2030), in which Mexico has ratified Marpol Annex VI and established an ECA. Each scenario was simulated using an air quality model for a one-year period, with the results then evaluated and analyzed.

Part II demonstrates the potential health benefits for the Mexican population and the potential savings associated with the implementation of an ECA. The impacts of the ratification of Marpol Annex VI and the establishment of an ECA were calculated based on: a) the results of air quality modeling for different scenarios, and b) information on the incidence rate of respiratory diseases at the national level and health costs. The potential economic benefits are related to changes in indicators such as premature deaths, hospital admissions, restricted activity days and their economic impacts resulting from changes in ambient concentrations of ozone and $PM_{2.5}$. Based on the above, it is possible to determine the benefit-cost ratio of the ECA regulation. For reference, the studies prepared for the North American ECA showed that this ratio is 90:1, which means that the cost of implementing an ECA is 90 times less expensive than the cost associated with inaction, mainly because of the effects on public health from exposure to air pollution from ships.

The results of the modeling exercises described in this document provide the necessary information for the Mexican government to meet the criteria required for the designation of an ECA, subsequent to ratification of Marpol Annex VI. It is important to note that in addition to the requirements of Annex VI, the IMO sets specific guidelines for proposing a new ECA, which enters into force one year after its adoption by the IMO.

PART 1. AIR QUALITY MODELING

1.1. Introduction

The objectives of the modeling studies were to: a) evaluate the influence, in magnitude and extent, of emissions from large ships on air quality in Mexico; and b) identify improvements in air quality resulting from the ratification of Marpol Annex VI and the establishment of an Emission Control Area (ECA) in Mexico. These objectives were accomplished through the following tasks:

- Compiling and preparing emission inventories for modeling.
- Configuring and validating the air quality model.
- Performing air quality modeling for prospective scenarios in 2030.
- Generating air quality maps showing ozone and fine particle concentrations, as well as sulfur dioxide deposition.
- Estimating health benefits resulting from reductions in ozone concentrations and fine particle emissions.

Mexico's National Ship Emissions Inventory (*Inventario Nacional de Emisiones de Buques,* INEB) of 2011 was developed by Dr. James Corbett with support from the United States Environmental Protection Agency (EPA), under the coordination of Semarnat's Air Quality and Pollutant Release and Transfer Register (PRTR) Directorate (DGGCARETC) (Corbett 2012). The INEB includes emissions data from marine vessels sailing in waters near Mexico, and categorizes them in three groups: INEB 2011 base data, and two emission projections (scenarios) for 2030. The first 2030 scenario (S1) considered the ratification of Marpol Annex VI, while the second scenario (S2) contemplated the ratification of Marpol Annex VI with the establishment of a Mexican ECA.

The emissions for these two scenarios were estimated based on the Ship Traffic, Energy and Environment Model (STEEM). The INEB includes data for greenhouse gases (GHGs), short-lived climate pollutants and other pollutants, including: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and black carbon (BC).

The Molina Center for Energy and the Environment's (MCE2) modeling team analyzed and processed data from the INEB and other emission inventories for air quality modeling; MCE2 subsequently identified potential air quality benefits and reductions in the deposition of reactive substances. The air quality modeling study was performed by the MCE2 modeling team in several stages, as follows:

- Selection of the spatial and temporal domains.
- Acquiring and processing inputs for modeling.
    - Emission inventories: collection of data and processing the emissions in order to build modeling scenarios.
    - Collection and processing of meteorological and air quality data.
- Set-up of the model parameterization according to the study area.
- Run the model for the base scenario in order to validate the data.
- Run the 2030 modeling scenarios i.e., S1 (without an ECA) and S2 (with anECA) .
- Generate air quality maps for $PM_{2.5}$ and O_3 concentrations and SO_2 dry deposition.

The differences between scenarios S1 and S2 in ambient concentrations of these pollutants, obtained from modeling results, were used as inputs for the cost-benefit evaluation (presented in Section 2 of the report).

The following sections present the technical details of each of the above activities.

1.2. Spatial Domain and Simulation Periods

In order to estimate emissions and fuel consumption within a potential Mexican ECA, a study area (or modeling domain) was defined as extending 200 nautical miles from the coastline, similar to the North American ECA. The spatial domain encompasses a wide area of sea and land, including the Mexican territory and parts of the United States and Central America. The study area refers to the region indicated by the blue box shown in Figure 2 and covers the entire Mexican territory and a portion of the southern United States and Central America, as well as a considerable marine extension. The proposed ECA spans territorial waters – that is, those that are under Mexico's jurisdiction.

The modeling includes a simulation for each year, the baseline scenario (2011) and the two possible scenarios in 2030. All scenarios were simulated using the WRF-Chem model (Grell et al. 2005).

Figure 2. Air Quality Modeling Domain

Note: The rectangle shows the spatial domain of emissions considered in this study (lat. 10° N to 35° N and lon. -130º to -80º) covering approximately 15 million km^2. The maritime dark green shaded area surrounding Mexico represents the possible Emission Control Area for Mexico.

1.3. Emission Inventories

Mexican National Ship Emissions Inventory (INEB) - 2011 and 2030

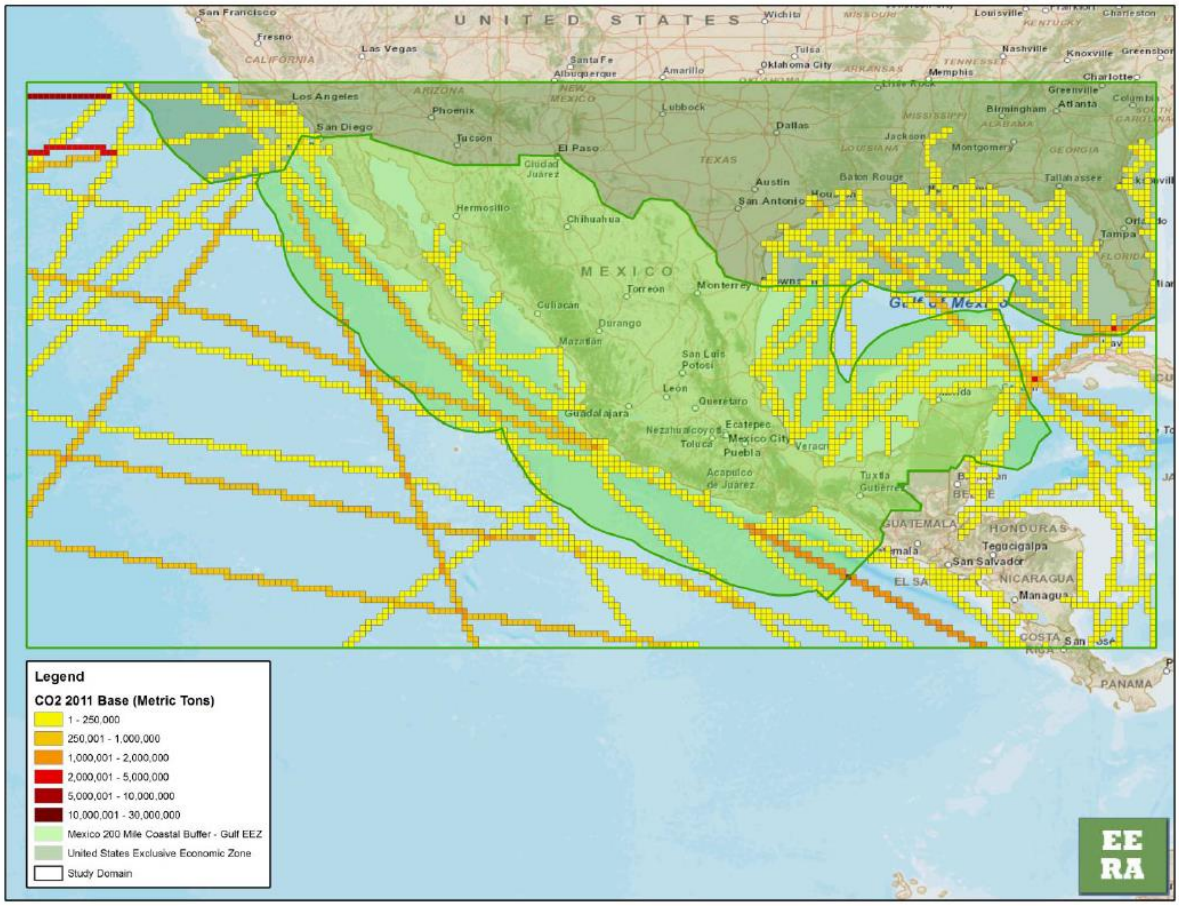
The Mexican National Ship Emissions Inventory (INEB) used in this project was provided by Semarnat and produced by Energy and Environmental Research Associates (EERA), based on the Waterway Network Ship Traffic, Energy, and Environmental Model (STEEM) (Wang, Corbett, and Firestone 2007, 2008).

EERA was contracted by the Battelle Memorial Institute to produce shipping emissions estimates within a Mexico domain for the years 2011 and 2030. The base year, 2011, represents estimates for a "current" year prior to potential Marpol Annex VI implementation. The 2030 future year shipping estimates enable Mexico to compare two scenarios: (S1) No Mex-ECA, where global IMO Marpol Annex VI global sulfur limits will apply; and (S2) Mex-ECA, where additional sulfur reductions would correspond to a Mexico Emission Control Area (EPA 2015).

The STEEM was developed to quantify and geographically represent interport vessel traffic and emissions. It applies advanced GIS technology and determines routes automatically at a global scale, following actual shipping routes. The model has been used to characterize energy use and emissions for interport ship movement in North America, including the United States, Canada, and Mexico (Corbett et. al. 2007, 2008; Corbett 2010). The STEEM uses a ship characteristic dataset including unique ship identification, ship type, gross register tonnage (GRT), installed power, and cruise speed. For this study, the ships were grouped into nine major ship types: container ships, bulk carriers, tankers, general cargo ships, roll-on/roll-off (RO-RO) ships, passenger vessels, refrigerated cargo ships (reefers), fishing vessels, and other types of vessels. Pollutant emissions and fuel use were estimated by multiplying the power in kilowatt-hours (kWh) by the emissions rates or fuel consumption rates in grams per kilowatt-hour (g/kWh).

The INEB includes emissions of CO_2, NO_x, SO_x, PM, HC, CO and BC for vessels near Mexico (spatial domain) and vessels operating within the proposed emission control area. Figure 3 shows CO_2 ship emissions for the baseline scenario.

Figure 3. Ship Traffic Density in the Proposed ECA—CO_2 Emissions, 2011

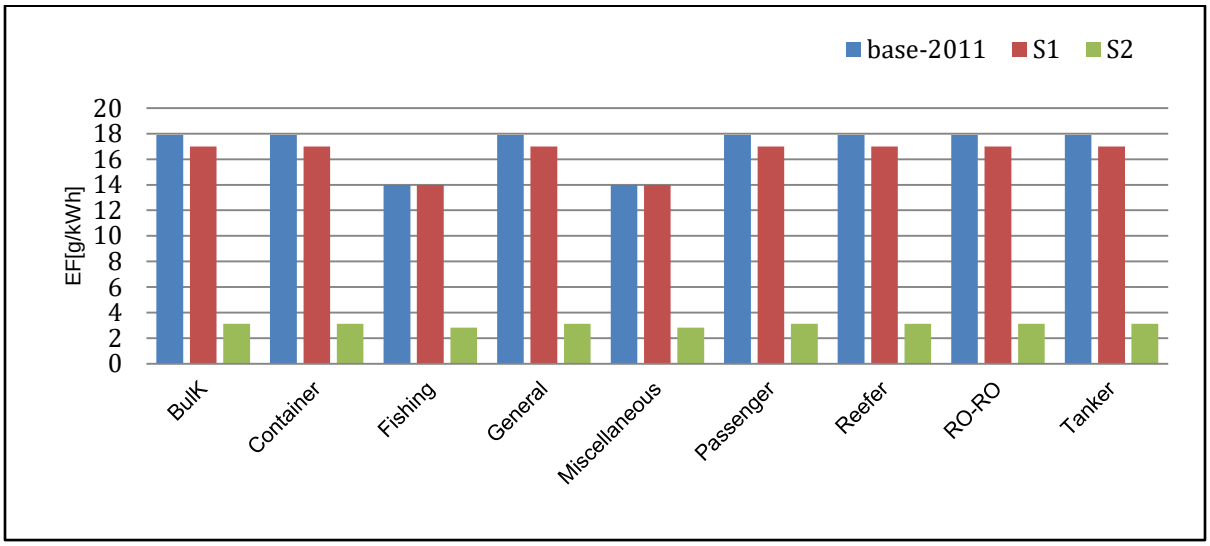


Source: STEEM 2011

The STEEM was used previously in the technical analyses underlying the US-Canada proposal to designate the North American ECA and also by the State of California to support the development of marine emissions control standards for ships operating in the waters off of California. The information obtained from the previous work was used by EERA as a starting point in producing the Mexico region-specific inventory. Emissions rates in 2011 were taken directly from the previous analysis for the North American ECA application and applied to estimate the 2011 inventory for Mexico. Black Carbon emissions rates are proportional to total PM rates. For vessels that are currently uncontrolled for PM, a BC:PM ratio of approximately 3% was used (EPA 2012). With regard to fuel consumption, vessel-specific assumptions about fuel type and consumption were taken from the prior STEEM work for the North American ECA, as updated in 2010 (Corbett 2010). No changes were made to these fundamental STEEM inputs to describe shipping energy demand characteristics. Emissions in 2030, under baseline conditions, were adjusted to represent the global sulfur emissions cap of 0.5%. Emissions in 2030, under potential ECA conditions, were adjusted to represent the sulfur limits of 0.1%.

Figure 4 shows the emission factor (EF) for NO_x by vessel type and for each scenario. Possible reductions in NO_x could be achieved with the implementation of new technologies, but such measures are considered long-term strategies. Therefore, the NO_x emission factors do not show a significant change between the base (2011) scenario and the S1 2030 scenario. However, significant NO_x emissions are shown within the ECA (S2) scenario.

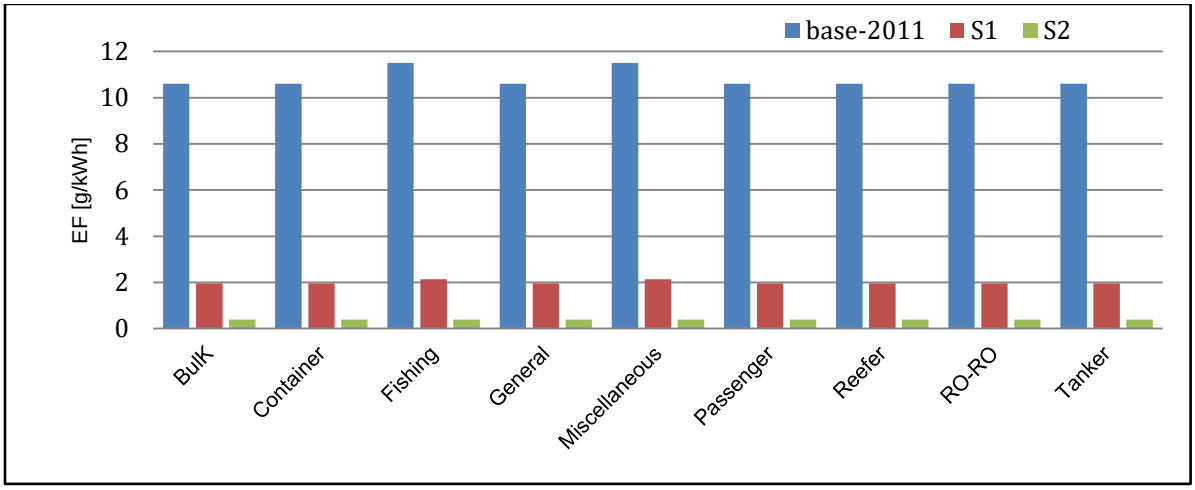
Figure 4. NO_x Emission Factors (EF) by Marine Vessel Type, for Each Scenario



Source: Corbett 2012.

In the case of SO_x emissions, reductions depend on improvements in fuel quality. Figure 5 clearly shows a significant reduction in SO_x emission factors from base-2011 to scenarios S1 and S2.

Figure 5. SO_x Emission Factors (EF) by Marine Vessel Type, for Each Scenario



Source: Corbett 2012.

The difference between continuing the worldwide trend (Marpol Annex VI) and adopting stricter regulations (Marpol + ECA) in 2030 relates to reductions in SO_2, NO_x, PM and BC emissions. Table 2 shows total estimated emissions for the INEB pollutants in the modeling domain for each scenario.

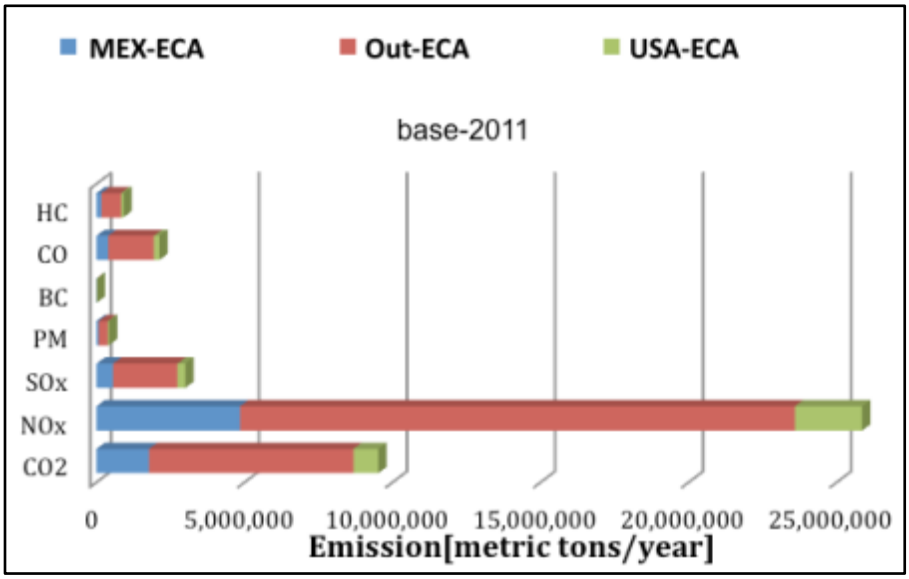
Table 2. Total Ship Emissions, by Pollutant

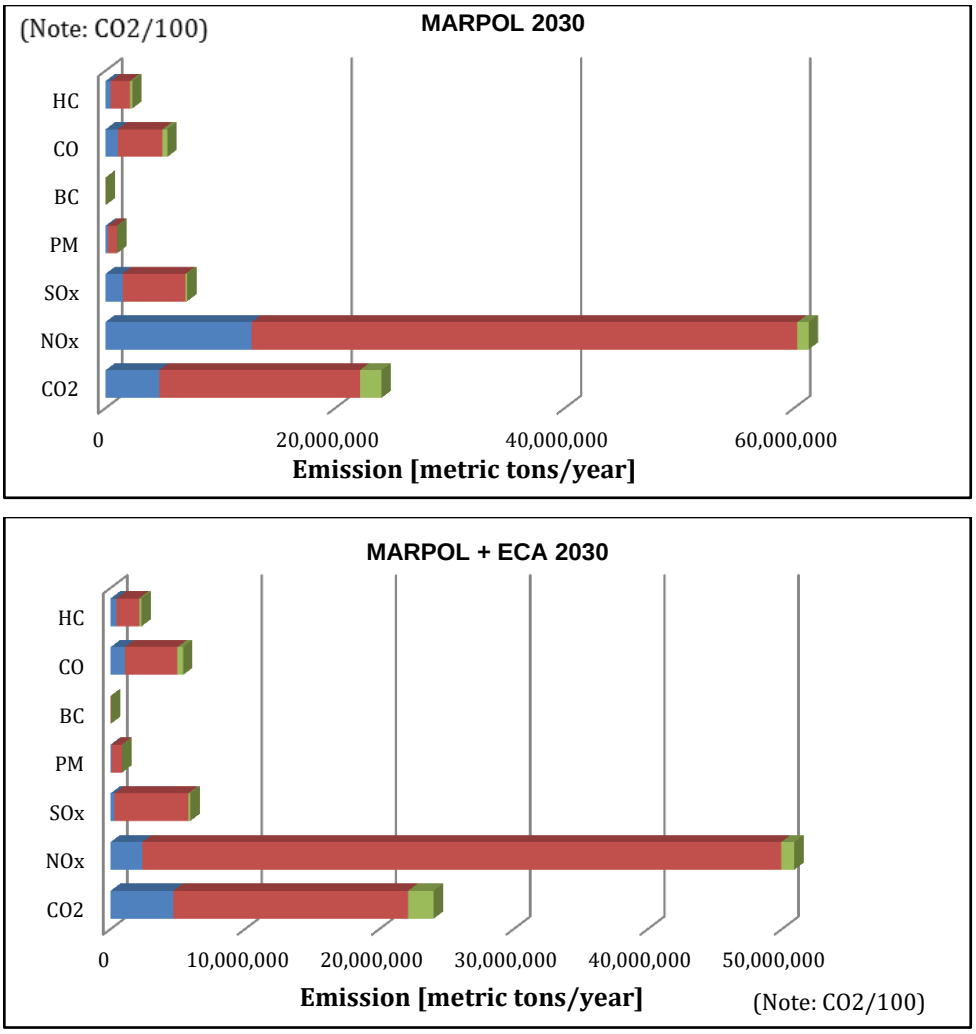
Pollutant	Emissions (Metric tons/year)		
	Base-2011	Marpol (S1)	Marpol + ECA (S2)
CO_2	952,170,000	2,404,353,000	2,404,353,000
NOx	25,865,000	61,273,000	50,907,000
SOx	3,000,000	7,095,000	5,911,000
PM	424,000	1,011,000	863,000
BC	13,000	30,000	26,000
CO	2,129,000	5,392,000	5,392,000
HC	913,000	2,312,000	2,312,000

Source: Corbett 2012.

The three graphs in Figure 6 show emissions within different areas (Mex-ECA, Outside-ECA, USA-ECA) of the spatial domain for each scenario.

Figure 6. Pollutant Emissions for Each Scenario





Source: Corbett 2012.

There are several points to highlight with regards to the INEB:

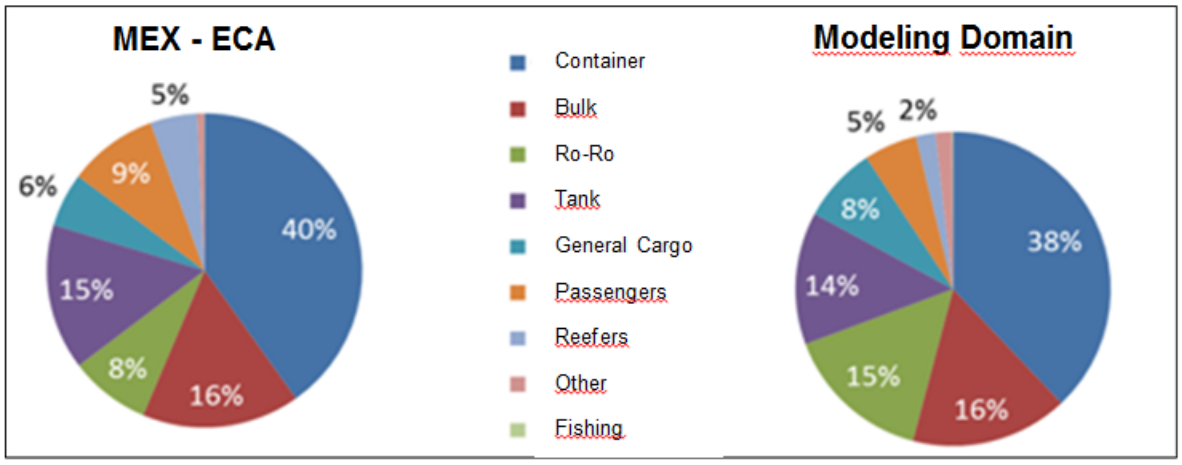
- The reductions of pollutants within the Mex-ECA range from 70 to 80%, when comparing scenarios S1 and S2 (Table 3).
- International flag vessels generate about 95% of emissions across the modeling domain.
- SO_x emissions by Mexican flag vessels are less than 1% in the modeling domain, and about 28% within the ECA for Mexico.
- Emissions from ships in the Mex-ECA are equivalent to 17% of black carbon emissions from mobile sources on land (INEM 2011).
- Highest emissions are associated with container ships, bulk carriers, RO-RO and tanker ships (Figure 7).

Table 2. Emissions Inside the Mex-ECA

Scenario	Year	CO_2	NO_x	SO_x	PM	BC	CO	HC
Base 2011	2011	178,229,000	4,855,000	562,000	79,000	2,000	400,000	171,000
Marpol 2030 (S1)	2030	467,106,000	12,738,000	1,472,000	208,000	6,200	1,049,000	450,000
Marpol +ECA 2030 (S2)	2030	467,106,000	2,372,000	289,000	60,000	1,800	1,049,000	450,000
Reduction (S1-S2)		-	81%	80%	71%	71%	-	-

Note: metric tonnes/year

Figure 7. Pollutant Emissions by Vessel Type



Mexico National Emissions Inventory (INEM), 2011

The 2011 National Emissions Inventory (INEM) was provided for this study by Semarnat, and presents the emissions generated in the 32 states across the country. It is based on projections for the year 2011, using 2008 data, the last official published version.[2] Since the INEM 2011 was built *ad hoc* for this project, an official version has not been released.

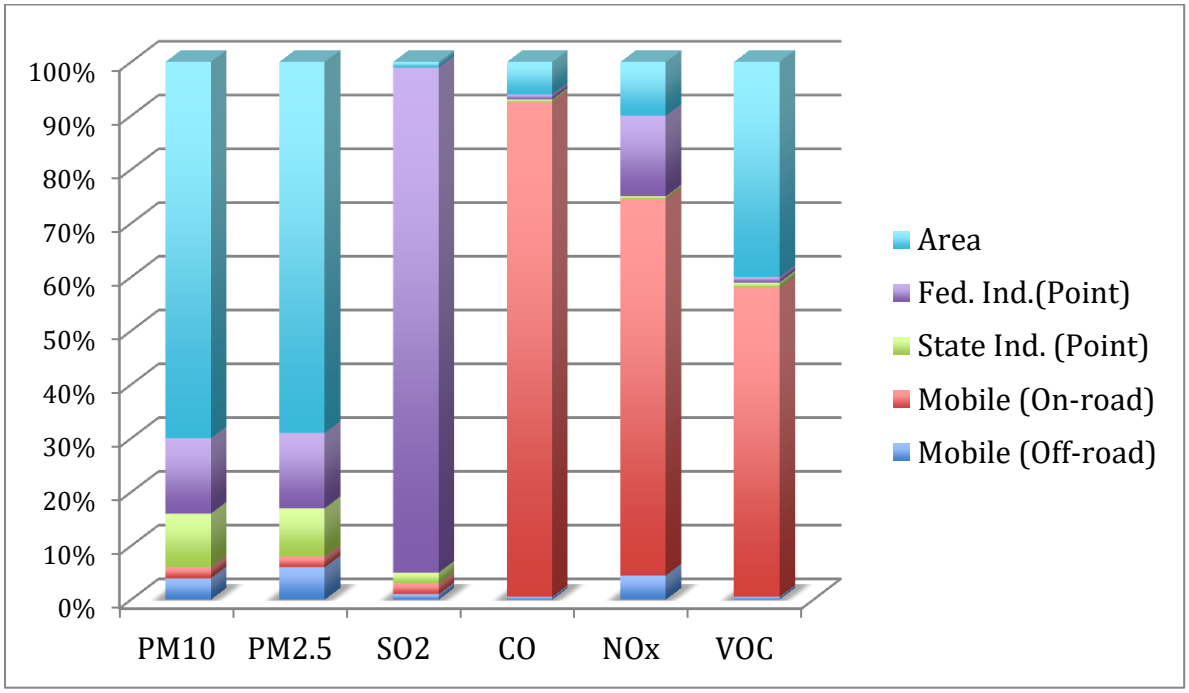
Emissions sources are classified into the following categories in the 2011 INEM:

- Point or stationary sources (industrial facilities),
- Mobile sources (vehicles, both on-road and off-road),
- Area sources (dry cleaners, residential combustion), and
- Biogenic sources (natural sources, such as soils and vegetation).

[2] Semarnat <http://sinea.semarnat.gob.mx>.

Point sources were disaggregated into 17 sectors; area sources in 7 sectors and 31 subcategories; and mobile sources into two groups (on-road and non-road) – with these, in turn, split into 15 subcategories. The INEM 2011 includes data from biogenic sources only for VOC and NO_x; however, the MCE2 modeling team subsequently included SO_2 emissions from the Popocatépetl volcano and other important sources. Figure 8 shows the percentage of pollutant emissions grouped by source category. For example – as is to be expected – particulate matter comes primarily from area sources, while emissions of sulfur dioxide are predominantly generated by the industrial point sources under federal jusrisdiction. The totals for each category are provided in Table 4.

Figure 8. Percentage of Emissions by Source Category in INEM 2011



Note: Source category emission projections re-grouped by CEC, based on INEM 2011 data.

Table 3. Total Emissions by Source Category, INEM 2011

	PM_{10}	$PM_{2.5}$	SO_2	CO	NO_x	COV	NH_3	BC
Point	221,125	139,580	2,516,007	1,045,559	550,389	297,592	23,794	13,905
Area	683,044	481,874	31,140	3,613,412	331,982	3,301,921	1,049,201	51,902
Mobile	57,206	48,541	73,017	54,765,437	2,982,866	4,949,249	40,009	11,863
Total	**961,376**	**669,997**	**2,620,165**	**59,424,408**	**3,865,238**	**8,548,763**	**1,113,006**	**77,671**

Note: metric tonnes/year

Mexico Port Emissions Inventory (INEP), 2011

The INEB did not include data for Mexican port emissions. The MCE2 modeling team used the Mexican Port Emissions Inventory (INEP) for the year 2011 and provided by ERG in July 2014 (ERG 2014). This inventory is based on port emissions and activity data from the unpublished CEC report entitled, *Inventario Nacional de Emisiones de Fuentes de Area 2008 (National Emissions Inventory for Area Sources)*, which was developed for a CEC project supporting the update of the Mexican National Emissions Inventory for the data year 2008 (CEC 2011). ERG also identified more recent marine engine and cargo handling equipment (CHE) emissions data which were applied to local Mexican CHE and vessel data provided by Semarnat to generate a more up-to-date and comprehensive port emissions inventory. A revised Mexican port emissions inventory was developed for 2011. The sources of emissions were classified as:

- Emissions of ground equipment (motors, platforms, etc.) for cargo handling.
- Emissions of ships approaching the port: Auxiliary engines, trawlers, etc.
- Port emissions generated during ship reparation, loading and unloading.

Port emissions generated by ship loading and unloading activities are the most important in this inventory. The largest Mexican ports were assigned to the T1 category, which means they have similar activity to equivalent US ports and, therefore, were assigned equipment and emission factors according to this classification (IPCC 2006). There are other ports in the inventory that are considered less active, and these were assigned to the T2 category; their emissions were calculated based on equipment inventories and emission factors provided by the Ministry of Communications and Transport (SCT). These details are summarized in Table 5.

Table 4. Type of Equipment and Sources Considered in each of the Mexican Ports included in the INEP

Port	Class	Category	Equipment	Vessel Dockside	Cargo Handling
Cayo Arcas, Camp.	High port	T1	x		
Manzanillo, Col.	High port	T1	x	X	X
Veracruz, Ver.	High port	T1	x	X	X
Altamira, Tamps.	High port	T1	x	X	X
Isla Cedros, B.C.	High port	T1	x		
Salina Cruz, Oax.	High port	T1	x	X	X
Tuxpan, Ver.	High port	T1	x		
Dos Bocas, Tab.	High port	T1	x	X	X
Lázaro Cárdenas, Mich.	High port	T1	x	X	X
Guerrero Negro, B.C.S.	High port	T1	x		
Guaymas, Son.	High port	T1	x		
Topolobampo, Sin.	High port	T1	x	X	X
Ensenada, B.C.	High port	T1	x	X	X
Coatzacoalcos, Ver.	High port	T1	x	X	X
Progreso, Yuc.	High port	T1	x		
Tampico, Tamps.	High port	T1	x	X	X
La Paz, B.C.S.	High port	T1	x		
Mazatlán, Sin.	High port	T1	x	X	X
Rosarito, B.C.	High port	T1	x		
Isla San Marcos, B.C.S.	High and cabotage port	T2	x		
Cozumel, Q. Roo	High and cabotage port	T2	x		

Acapulco, Gro.	High and cabotage port	T2	x		
Puerto Libertad, Son.	High and cabotage port	T2	x		
El Sauzal, B.C.	High and cabotage port	T2	x	X	X
San Carlos, B.C.S.	High and cabotage port	T2	x		
Puerto Morelos, Q. Roo	High and cabotage port	T2	x		
Puerto Chiapas, Chis.	High and cabotage port	T2	x		X
Santa Rosalía, B.C.S.	High and cabotage port	T2	x		
Ciudad del Carmen, Camp.	High and cabotage port	T2	x		
Frontera, Tab.	Cabotage	T2	x		
Punta Santa María, B.C.S.	Cabotage	T2	x		
Puerto Vallarta, Jalisco	Cabotage	T2		X	X
Puerto Morelos, Q. Roo	High port	T2	x		

Note: T1, Equipment suggested by ERG, T2. Equipment suggested by SCT

Pollutant emissions for each port are shown in Table 6.

Table 5. Annual Emissions, per Pollutant, in Each Port

Port	COV	CO	NO_x	SO_x	PM_{10}	$PM_{2.5}$
Cayo Arcas, Camp.	114.4	2,573.0	736.1	75.4	61.0	6.8
Manzanillo, Col.	252.3	1,665.0	6,342.6	3,445.7	499.1	437.3
Veracruz, Ver.	2,538.0	6,822.8	75,501.0	42,788.9	5,924.5	5,446.3
Altamira, Tamps.	114.1	854.9	2,749.1	1,475.3	216.5	187.1
Isla Cedros, B.C.	28.7	645.6	184.7	18.9	15.3	1.7
Salina Cruz, Oax.	131.6	989.3	3,167.1	1,699.1	249.4	215.5
Tuxpan, Ver.	34.3	772.0	220.8	22.6	18.3	2.0
Dos Bocas, Tab.	493.4	1,439.9	14,543.0	8,224.9	1,141.3	1,046.7
Lázaro Cárdenas, Mich.	63.0	1,406.7	415.6	48.9	34.4	4.7
Guerrero Negro, B.C.S.	15.2	342.2	97.9	10.0	8.1	0.9
Guaymas, Son.	14.0	314.4	90.0	9.2	7.5	0.8
Topolobampo, Sin.	135.8	542.3	3,830.9	2,144.4	300.9	272.7
Ensenada, B.C.	301.3	766.9	9,013.2	5,114.6	707.2	651.0
Coatzacoalcos, Ver.	139.9	1,614.5	2,702.7	1,344.9	213.8	169.6
Progreso, Yuc.	8.4	189.4	54.2	5.6	4.5	0.5
Tampico, Tamps.	451.6	1,440.1	13,168.7	7,429.1	1,033.7	945.3
La Paz, B.C.S.	4.3	96.6	27.6	2.8	2.3	0.3
Mazatlán, Sin.	57.6	256.5	1,592.7	887.3	125.1	112.8
Rosarito, B.C.	4.1	93.2	26.6	2.7	2.2	0.2
Isla San Marcos, B.C.S.	1.8	40.3	11.4	1.2	0.9	0.1
Cozumel, Q. Roo	0.6	3.4	7.8	1.0	0.8	0.1
Acapulco, Gro.	0.5	2.8	6.5	0.8	0.7	0.1
Puerto Libertad, Son.	0.9	4.7	10.8	1.4	1.1	0.1
El Sauzal, B.C.	448.8	1,049.6	13,537.2	7,695.7	1,062.0	979.7
San Carlos, B.C.S.	0.2	5.4	1.6	0.2	0.1	0.0
Puerto Morelos, Q. Roo	0.0	1.1	0.3	0.0	0.0	0.0
Puerto Chiapas, Chis.	18.5	44.1	558.1	317.2	43.8	40.4
Santa Rosalía, B.C.S.	0.0	0.5	0.1	0.0	0.0	0.0

Ciudad del Carmen, Camp.	0.0	0.0	0.0	0.0	0.0	0.0
Frontera, Tab.	0.0	0.0	0.0	0.0	0.0	0.0
Punta Santa María, B.C.S.	2.4	53.9	15.3	1.6	1.3	0.1
Puerto Vallarta, Jalisco	8.5	19.9	256.6	145.9	20.1	18.6
TOTAL:	**5,384.3**	**24,051.0**	**148,870.6**	**82,915.2**	**11,696.1**	**10,541.6**

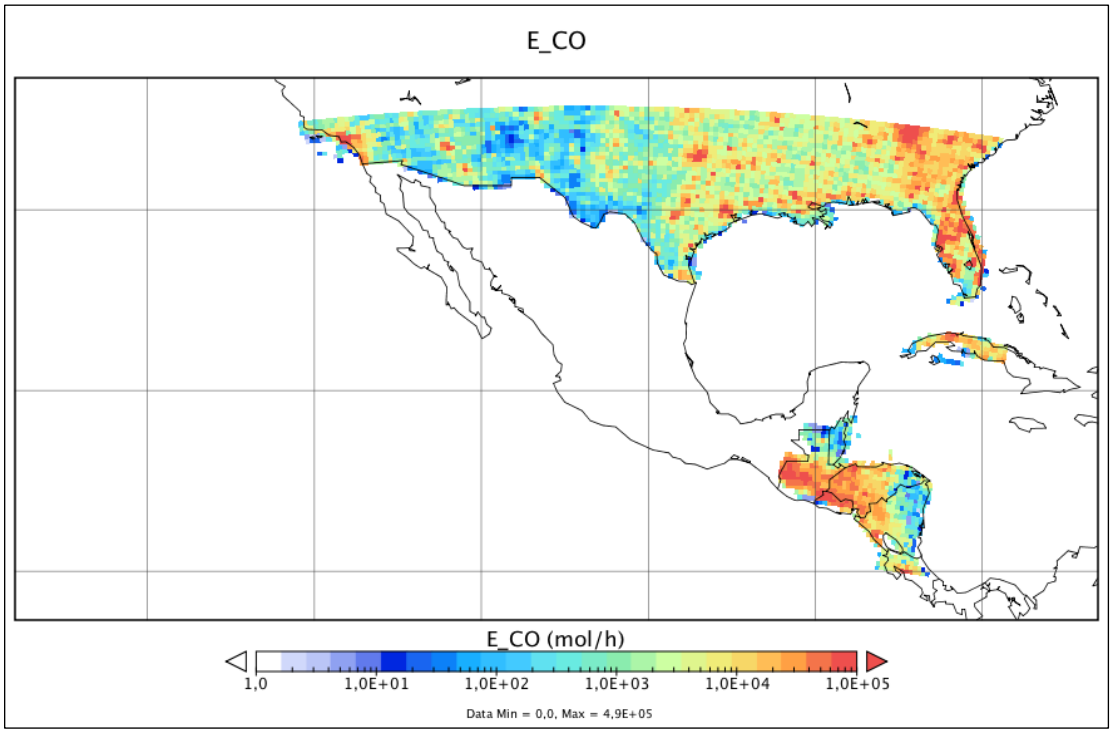
Note: metric tonnes/year

It should be noted that ERG updated the port data (ERG 2014); however, the revised data were not used in the present air quality modeling study due to time constraints. A sensitivity analysis run with the revised port data is included in Appendix III.

Emissions Estimates for the United States (2011) and Central America (2008)

To supplement the data for land emissions in the modeling domain the MCE2 team, in agreement with Semarnat, took into consideration emissions from the southern United States and Central America. Data for emissions from the United States correspond to the official EPA National Emissions Inventory for 2011 and were processed using the Sparse Matrix Operator Kernel Emissions (SMOKE) model. Likewise, estimates of Central American emissions (CAE 2008) were obtained using the Emissions Database for Global Atmospheric Research (EDGAR) v4.2 model, for 2008 (Janssens-Maenhout et al. 2012). These emissions were distributed using population density maps for the region (see CO emissions, Figure 9). Subsequently, these emissions were processed in order to be used within the Air Quality Model WRF-Chem (Grell et al. 2005), for this project the RADM2 (Stockwell et al. 1990) chemical mechanism was applied.

Figure 9. CO Emissions for Central America and the southern United States



1.4. Modeling Scenarios

The inventories described in the previous sections were used to build three scenarios. The **baseline-2011 scenario** includes:

- Mexico's National Ship Emissions Inventory (INEB 2011),
- Mexico's National Emissions Inventory (INEM 2011),
- Mexico's Port Emissions Inventory (INEP 2011),
- US National Emissions Inventory (NEI 2011) and
- Central American Emissions estimates (CAE 2008).

As mentioned, the base year 2011 represents the "current" year, prior to Mexico's ratification of Marpol Annex VI. For the 2030 projections, Scenario S1 represents a situation in which IMO Marpol Annex VI (global) sulfur limits apply; and Scenario S2 represents a "Marpol + ECA" situation – i.e., where in addition to the first scenario (S1), Mexico has adopted an ECA, where stricter sulfur reductions apply. Table 7 lists a summary of the sources of information and data considered in each scenario.

Table 6. Emission Scenarios for this Project

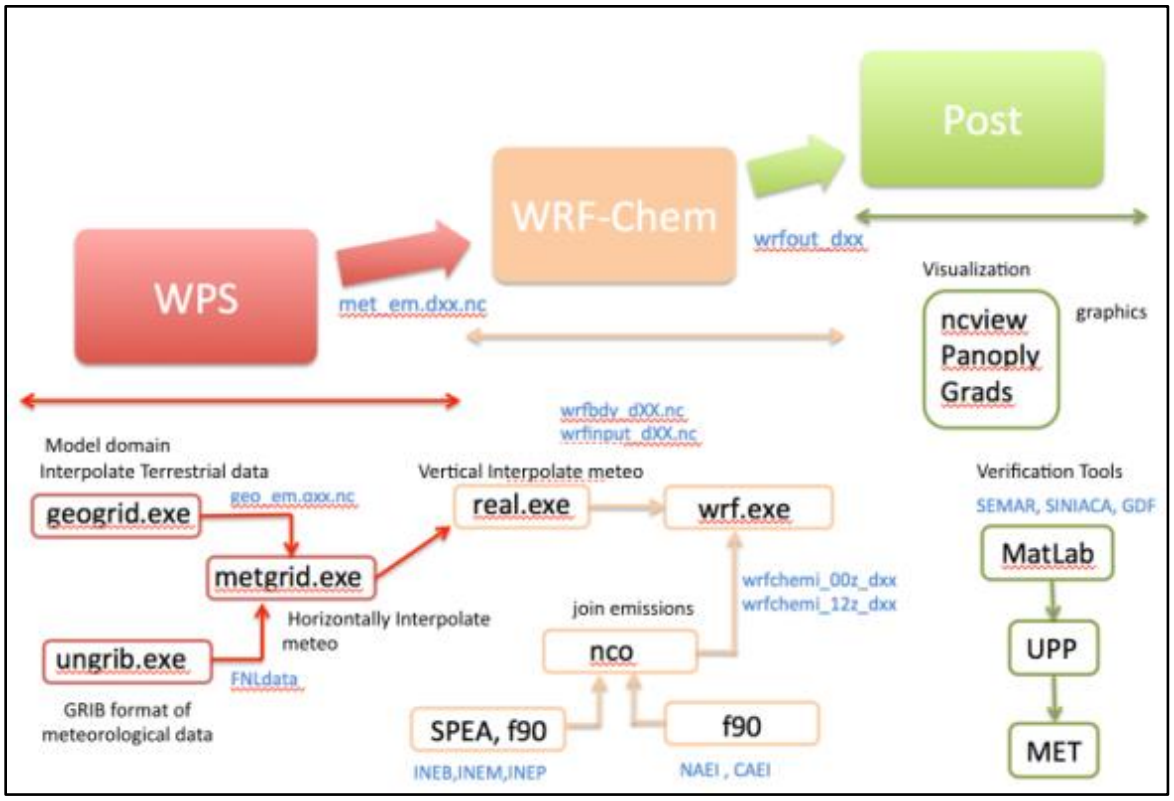
Scenario	Inventory	Source
Base-2011	INEB 2011	Semarnat & EERA
	INEM 2011	Semarnat
	NEI 2011	MCE2 & EPA
	CAE 2008	MCE2 & EDGAR
	INEP 2011	ERG, Semarnat & MCE2
S1	INEB 2030 (Marpol) + emissions on land*	Semarnat & EERA
S2	INEB 2030 (Marpol + ECA) + emissions on land*	Semarnat & EERA

*Note: Land emissions in both prospective 2030 scenarios come from INEM-2011, NEI-2011, CAE-2008 and INEP-2011.

1.5. Model Configuration

The air quality modeling for this project used the Weather Research and Forecasting (WRF) model, in chemical analysis mode (WRF-Chem) (Grell et al. 2005). The modeling process was divided into three stages: preprocessing (WPS), running/processing/execution (WRF-Chem) and post processing (Post), as shown in Figure 10. The following sections describe each step in more detail.

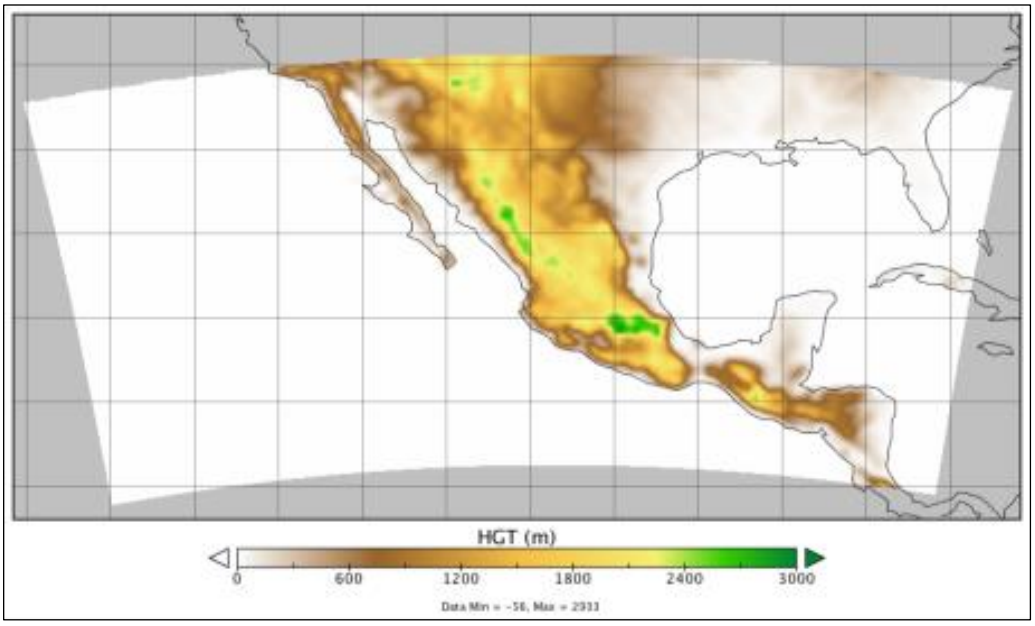
Figure 10. Schematic of Air Quality Modeling Using WRF-Chem



Notes: (1) WPS: spatial and temporal domain, data pre-processing for topography, land use and global meteorology. (2) WRF-Chem: process emissions, generates initial and boundary conditions, generating air quality data results. (3) Post: results visualization, model results evaluation.

The modeling domain is defined on a Lambert Conformal projection centered at a latitude and longitude of 22.25N–105.12W. Spatial resolution of 0.25 x 0.25 degrees (approximately 28x28 km) was considered. The domain shown in Figure 11 contains 20,000 cells covering an area of approximately 15 million of km^2 spanning Mexico, parts of Central America and the southern United States, as well as an extensive international maritime area. The model used 35 vertical levels; the land use data come from the US Geological Survey (www.usgs.gov), and 24 categories were taken into consideration.

Figure 7. Terrain Elevation in the Modeling Domain



Source: WRF input file.

Point source emissions were allocated in the levels or layers corresponding to their effective stack heights. Figure 12 shows the CO emissions in the modeling domainfor the first vertical layer, near the surface. Emissions from ships were considered at around 16 meters above sea level; therefore, those emissions appear in the second modeling layer.

Figure 8. CO Emissions in the Modeling Domain, Allocated to the First Vertical Layer

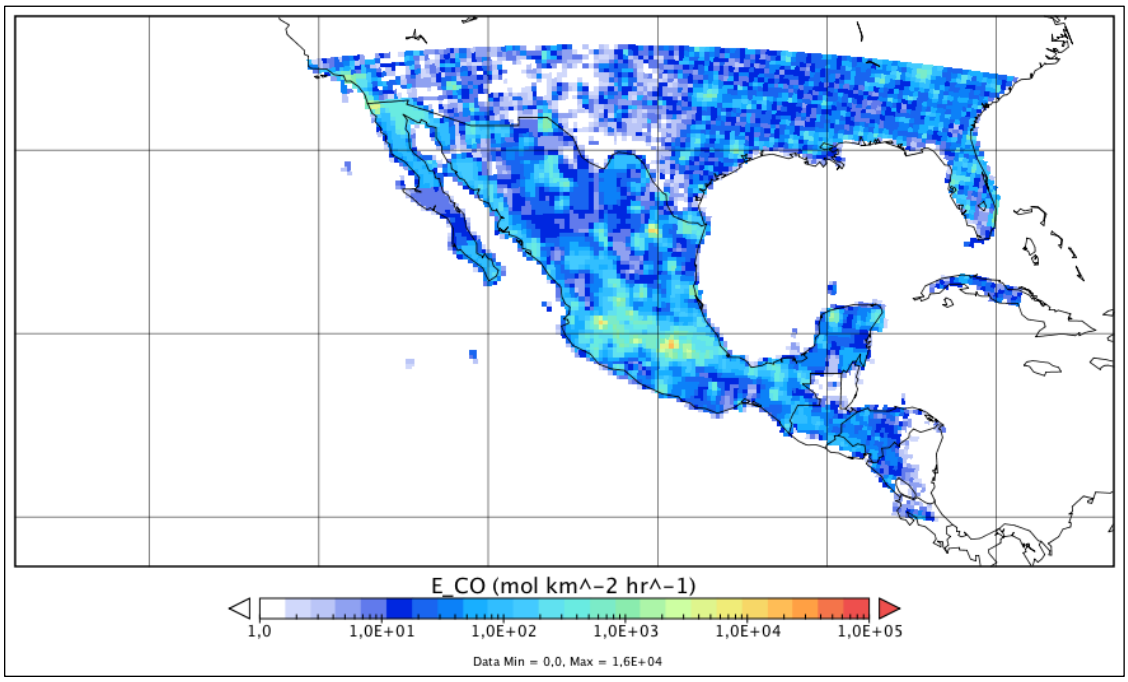
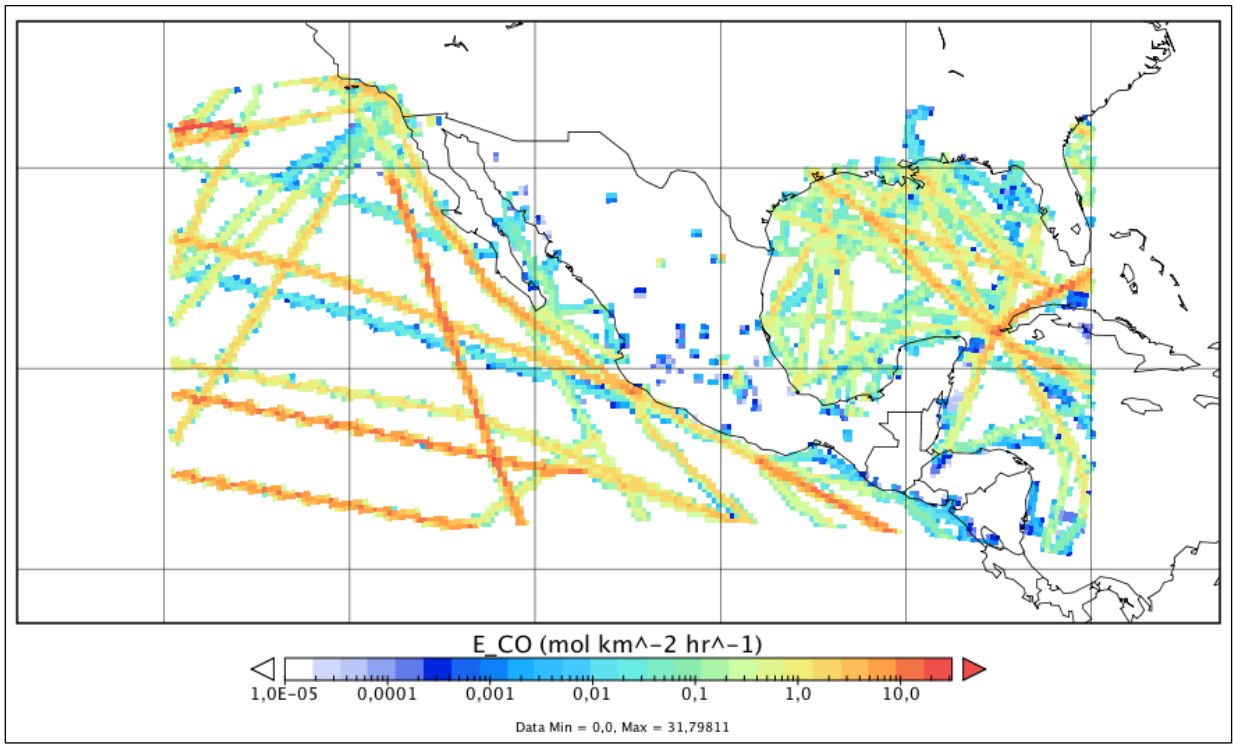


Figure 13 shows the CO emissions in the modeling domain and in the second layer, from 16 to 22 m above the sea level. In addition, some emissions from point sources appear in the second layer. It is noteworthy that all US and Central American emissions were allocated (as per original files) in the first vertical layer.

Figure 13. CO Emissions in the Modeling Domain, in the Second Vertical Layer



Note: Ship emissions and some point sources in Mexico are displayed.

Figures 14 (a, b, and c) display the distribution of HC_3, NO and SO_2 emissions in the first and second layers. They show emissions from the major cities in Mexico, as well as the shipping routes.

Figure 9a). Emissions of HC3 in the First Vertical Layer (left*) and Second Vertical Layer (right) of the Modeling Domain

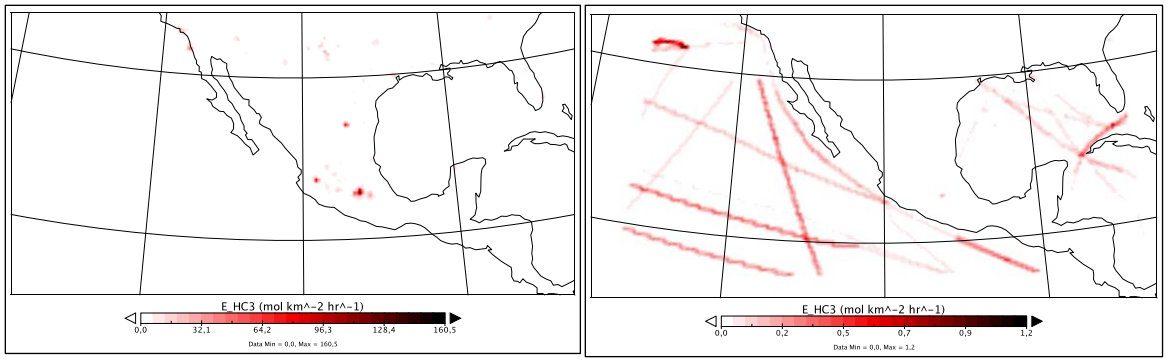
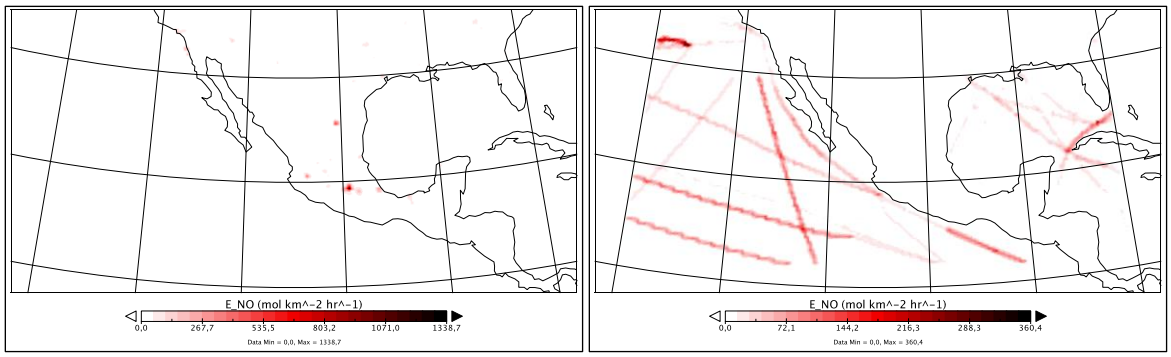
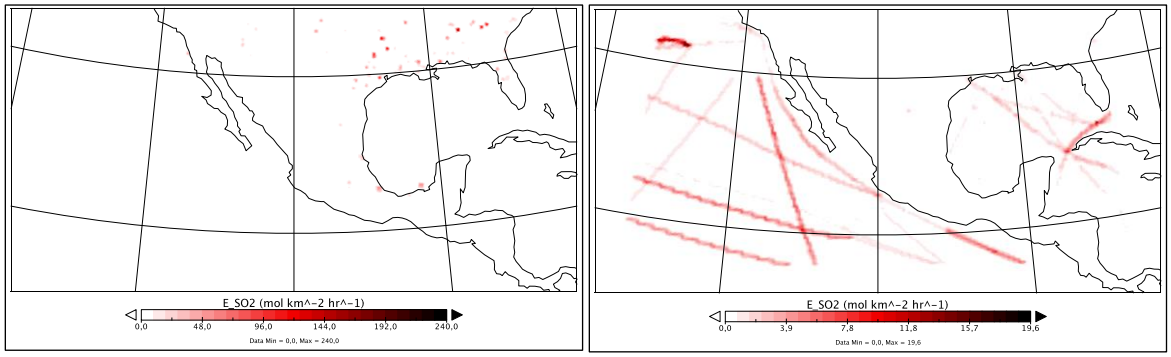


Figure 14b). Emissions of NO in the First Vertical Layer (left*) and Second Vertical Layer (right) of the Modeling Domain



* The left-hand figures show ship emissions as well as some point sources in Mexico.
Note: Emissions in mol/km^2/h.

Figure 10c). SO_2 Emissions in the First (left) and Second (right) Vertical Layers of the Modeling Domain



Note: Emissions in mol/km^2/h.

1.6. Results

In this section the modeling results are compared with the data from monitoring stations. The aim is to evaluate the WRF-Chem model in simulating meteorological variables, as well as the main chemical species of this project. Statistical indices were used to measure the correlation between predictions and measurements. Additionally, concentration maps for the main chemical species (O_3 and $PM_{2.5}$) and SO_2 dry deposition for each of the prospective scenarios are shown.

Model Evaluation

The modeling performance was evaluated using land-based monitoring station data, as well as assimilation data from the Global Data Assimilation System (GDAS), as shown in table 8.

Table 7. Meteorological and Air Quality Data Used to Validate Modeling

Number of Stations	Alias	Source	Variables	Coverage
32	SEMAR	Secretaría de Marina	Meteorological (coastal)	Coastal
44	RAMA	SMAGDF	Meteorological and Air Quality data	Central Zone of Mexico
132	GDAS	NOAA	Meteorological	Global

Data from land-based monitoring stations were processed, and later were analyzed with the Unified Post Processor (UPP) software and the Model Evaluation Tools (DTC 2014; Mora-Ramírez et al. 2012), which allow a systematic comparison of the modeling results (meteorological and air quality) against data from monitoring stations. Based on previous studies (Conagua 2011; Sesma 2012), four periods were selected for the baseline year 2011, with sufficient data to validate the model outputs (Table 9).

Table 9. Periods used for the 2011 baseline scenario

Period	Month	Days
1	February	10–16
2	May	16–22
3	Aug-Sep	31–06
4	Nov	21–27

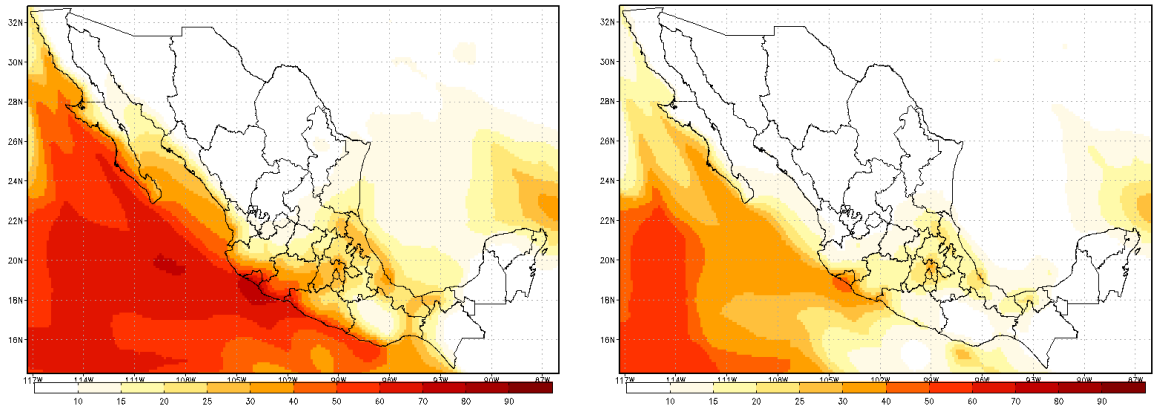
A good correlation between monitoring and modeling results was obtained. However, for air quality variables, the comparison was difficult since the data provided by the air quality monitoring stations were mainly from urban areas, and the grid used for modeling covered an area of 27.7 by 27.7 km. On the other hand, the concentrations of pollutants in the cities are higher than the surrounding areas; large grid cells covered urban and rural areas where the ambient concentration gradient was large and, therefore, the average concentration within the model grid was smaller than the measured values at the monitoring stations. Details of these results are presented in Annex II of the present document.

Following the modeling evaluation, $PM_{2.5}$ and O_3 concentration maps and SO_2 dry deposition maps were generated.

Particulate Matter $PM_{2.5}$

Figure 15 shows $PM_{2.5}$ concentration maps for scenarios S1 and S2. It reveals significant reductions in $PM_{2.5}$ concentrations after regulation, in S2 (Marpol+ECA 2030).

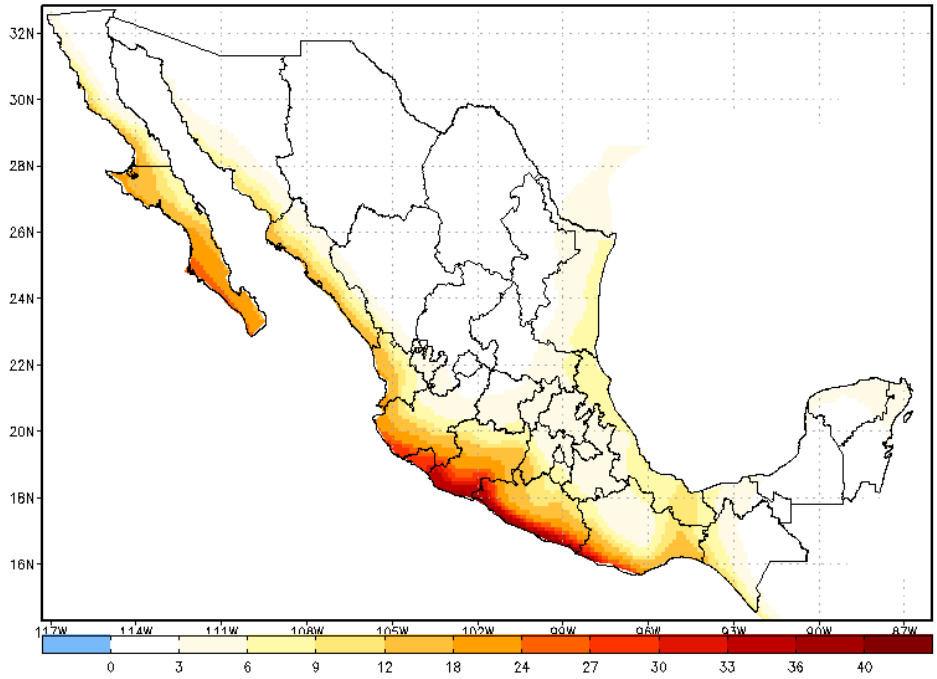
Figure 11. $PM_{2.5}$ Concentration, 24-hr Annual Average for Scenarios S1 and S2



Note: Interval from 0 to 100 μg/m^3. S1 (left) and S2 (right).

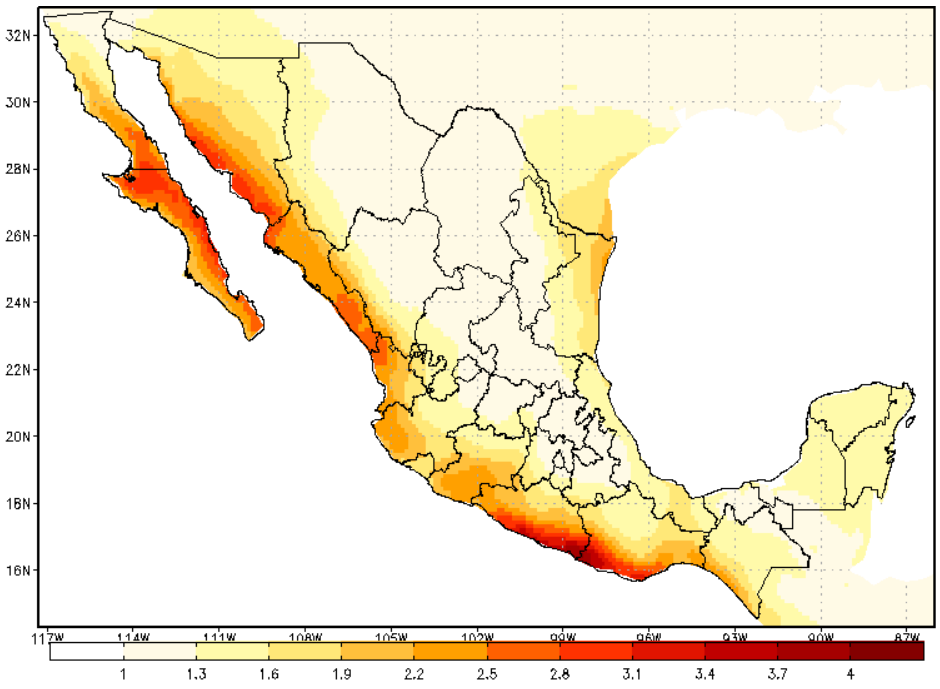
Details of these reductions can be seen in in Figure 16, which shows the difference between the prospective scenarios (S1-S2). The largest reductions (5–40 μg/m^3) occur in coastal areas. In other words, there would be up to 3 times lower $PM_{2.5}$ concentrations (in certain coastal areas, for certain periods) after regulation (see Figure 17). The resulting health benefits due to air quality improvements are analyzed and evaluated in Part II of the present document.

Figure 12. Estimated Reductions in $PM_{2.5}$ Concentrations due to Regulation: S1 (Marpol 2030) versus S2 (Marpol + ECA 2030)



Note: Concentrations in $\mu g/m^3$

Figure 13. Ratio (S1:S2) of $PM_{2.5}$ Concentrations: Comparison between Scenario S1 (Marpol 2030) and Scenario S2 (Marpol + ECA 2030)



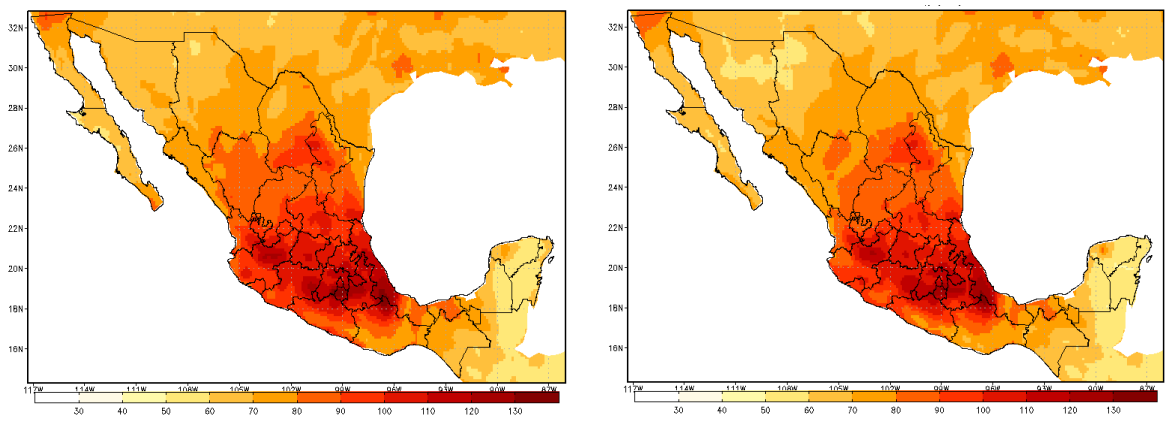
Note: larger ratio implies larger reduction.

Evaluation of Ozone Modeling

Modeling results for ozone were obtained hourly; subsequently 8,760 values representing the number of hours in a year were generated. The values were extracted to estimate the health benefits. Ozone is a secondary pollutant formed by photochemical reactions of precursor gases, such as volatile organic compounds (VOCs) and nitrogen oxides (NO_x). However, the production of ozone is a highly non-linear function of precursor concentrations; this has important implications for any ozone control strategy. For example, in the Mexico City metropolitan area, ozone formation was found to be VOC-limited in the urban area, but could be VOC-limited or NO_x-limited, depending on the meteorological conditions (Song et al. 2010).

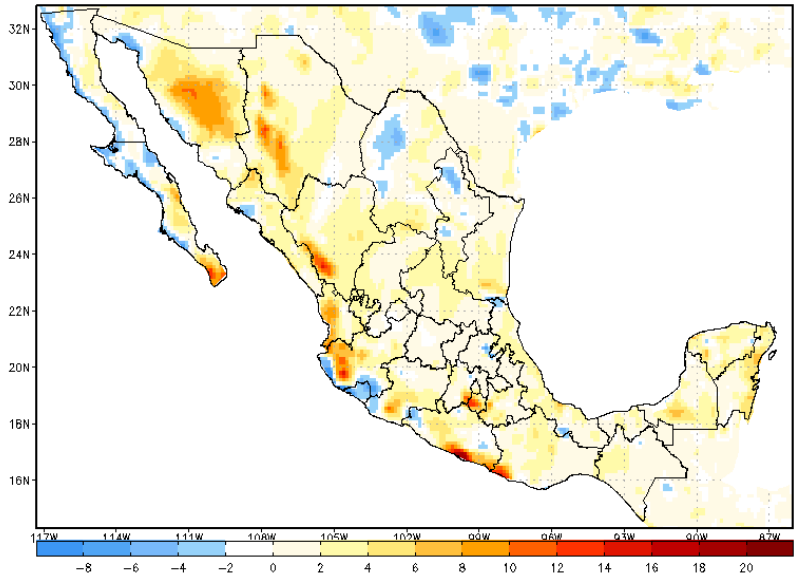
Ship emissions are major local sources of ozone precursors. Figure 18 shows the O_3 concentration maps for scenarios S1 and S2. Due to the non-linearity of the ozone formation process, ozone concentrations are predicted to decrease in some coastal areas but slightly increase in other areas after the Marpol Convention and the ECA are implemented. Figure 19 shows the difference in ozone concentrations between the S1 and S2 scenarios, with some regions of the modeling domain showing negative differences (-10 ppb_v). These regions represent increases in ozone concentrations after regulation. Likewise, there are other regions where the differences are positive, indicating reductions in ozone concentrations (0 to 22 ppb_v).

Figure 14. Average Annual O_3 Concentrations for Scenarios S1 (left) and S2 (right)



Note: Concentrations in ppb_v

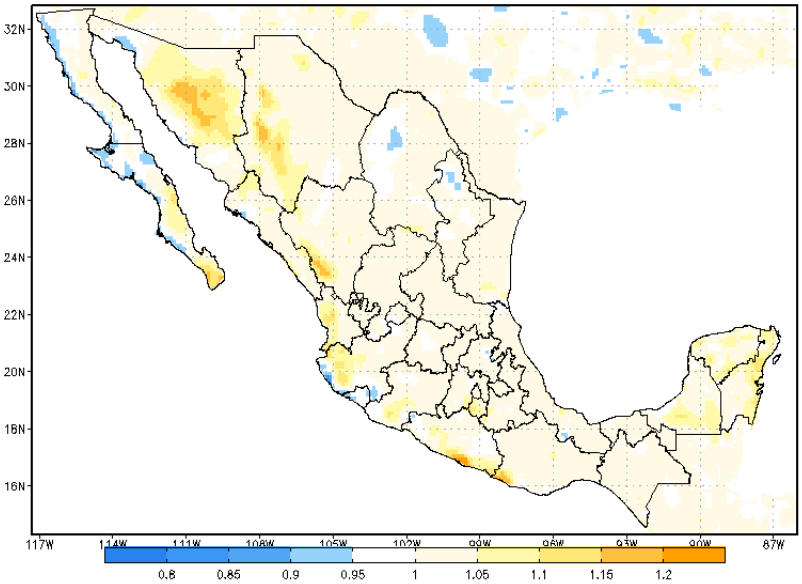
Figure 15. Projected Reductions in O_3 Concentrations as a Result of Establishing an ECA (S1 versus S2)



Note: Reductions in concentrations in ppb.

To more clearly assess the impacts on air quality, Figure 20 shows the ratio of scenarios S1 and S2. Improvements in air quality are up to 1.5 times lower under the ECA scenario, where additional regulations apply (S2), than under the Marpol Annex VI scenario (S1). Due to the non-linear relationship between emissions and ozone concentration, some areas will have an increase of 0.5 times in the ozone concentrations. It is worth noting that in the case of a deterioration in air quality, the increase in O_3 concentrations occurs mainly in coastal areas.

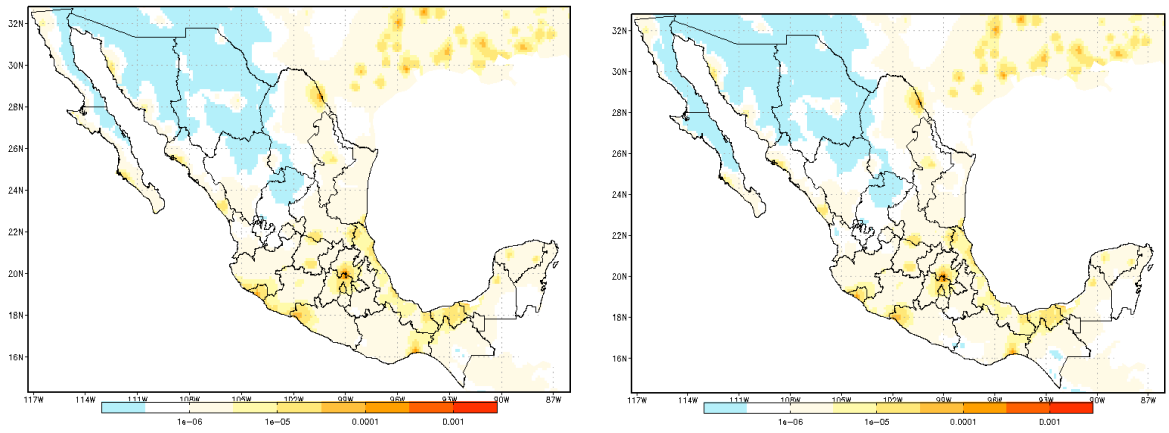
Figure 16. Ratio of O_3 Concentrations: Comparison between S1 and S2



Annual SO_2 Dry Deposition

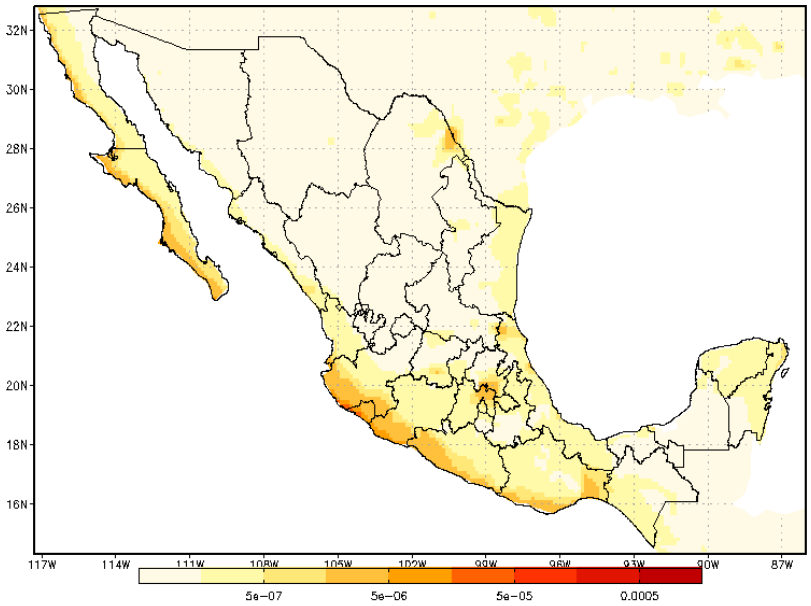
The WRF-Chem model was set up to calculate the SO_2 dry deposition. The model calculated deposition fluxes every hour (mol/m^2) and generated an hourly accumulative deposition value. In a monthly run, the last value represented the monthly accumulative dry deposition. In order to compute the total annual dry deposition, these monthly values were added and converted to kilograms per hectare (kg/ha). The annual dry deposition scenarios are shown in Figure 21. The results show that the implementation of regulation (Marpol + ECA) could reduce SO_2 dry deposition in coastal areas. Potential reductions were estimated by the difference of the S1 and S2 scenarios, with the results shown in Figure 22. The reductions are considerable: from 10 to 20 percent less SO_2 dry deposition in general in the Gulf Mexico territory (land), and from 10 to 450 percent less deposition in the Pacific coastal area, as shown in Figure 23.

Figure 17. Annual SO_2 Dry Deposition for Scenarios S1 (left) and S2 (right)



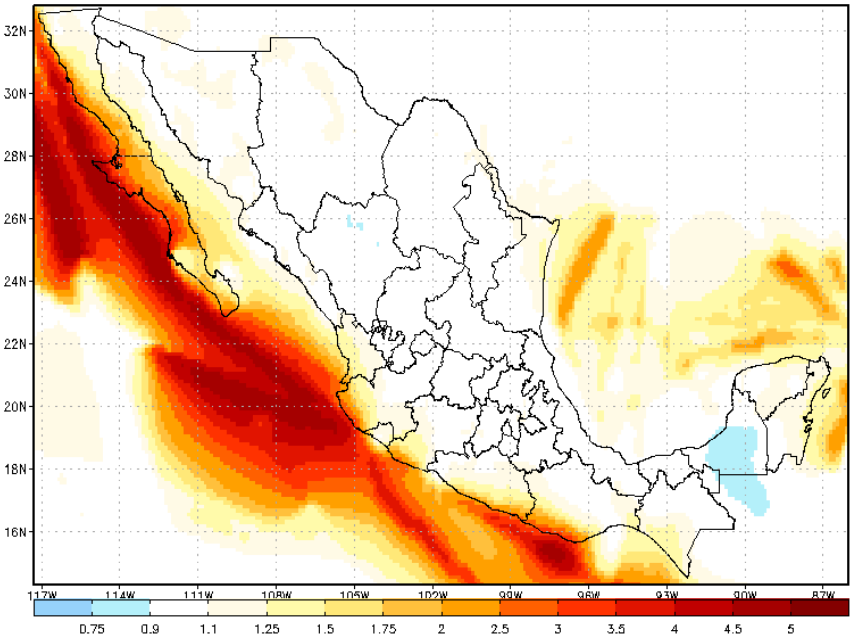
Note: Deposition in kg/ha.

Figure 18. Difference in Annual SO_2 Dry Deposition between scenarios S1 and S2



Note: Deposition in kg/ha

Figure 19. Ratio, S1:S2: Annual SO_2 Dry Deposition: Comparison between Scenarios S1 and S2



PART 2. EVALUATION OF HEALTH BENEFITS

2.1. Introduction

Marine vessels can be one of the most efficient means of transportation. Currently, commercial vessels transport approximately 75 to 90 percent of the world's cargo. Worldwide maritime transport is projected to grow by 150 to 300 percent by 2050 (Rothengatter et al. 2011; Grossmann et al. 2013), particularly due to container shipping activity, which is projected to grow by 425 to 800 percent by 2050 (Buhaug et al. 2008), and also from the expected growth in the world's population.

However, like all modes of transport based on fossil fuels, ocean-going vessels emit significant pollution that affect not only populations living near ports and coastlines, but also those living hundreds of miles inland (Bailey and Solomon 2004; Corbett 2007; Friedrich et al. 2007; IMO 2010; Winnes 2010).

The objective of Part 2 of this report is to estimate the health benefits that would accrue from Mexico's ratification of Annex VI of theMarpol Convention and the establishment of an Emission Control Area for Mexico (Mex-ECA); and specifically, to quantify the health effects associated with exposure of the population to ozone and fine particulates.

2.2. Overview of Pollutants and their Health Effects

Ground-level ozone and airborne particles are the two pollutants that pose the greatest threat to human health. They are two of the criteria pollutants for which acceptable concentration limits have been set to protect public health. The maximum permissible $PM_{2.5}$ and O_3 limits for Mexico, along with those established by the World Health Organization (WHO) and the standards applicable in the United States and Canada, are listed in Table 10.

Table 10. Maximum Permissible Exposure Levels for O_3 and $PM_{2.5}$

Pollutant	Period	WHO[a]	Mexico[b]	United States[c]	Canada[d]
O_3	1 h 8 h	– 0.0473 ppm	0.095 ppm 0.070 ppm	0.075 ppm	0.063 ppm
$PM_{2.5}$	Annual 24 h	10 µg/m^3 25 µg/m^3	12 µg/m^3 45 µg/m^3	12 µg/m^3 35 µg/m^3	10.0 µg/m^3 28 µg/m^3
PM_{10}	Annual 24 h	20 µg/m^3 50 µg/m^3	40 µg/m^3 75 µg/m^3	 150 µg/m^3	

Sources:
[a] World Health Organization Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Summary of risk assessment.
[b] Adapted from Mexican standards from http://www.cofepris.gob.mx/
Norma Oficial Mexicana NOM-025-SSA1-2014, Environmental Health. Permissible limits for the concentrations of PM_{10} and $PM_{2.5}$ in the environment and the evaluation criteria.
Norma Oficial Mexicana NOM-020-SSA1-2014, Environmental Health. Permissible limit for the concentration of ozone (O_3) in the environment and the evaluation criteria.
[c] http://www.epa.gov/air/criteria.html
[d] http://www.ccme.ca/en/current_priorities/air/caaqs.html

Particulate Matter (PM)

Particulate matter (PM) consists of a mixture of solid particles and liquid droplets present in the air, including elements (e.g., carbon and metal); compounds (e.g., organic chemicals, nitrates and sulfates) and complex mixtures (e.g., diesel exhaust, soil, dust). Some particles are emitted directly into the atmosphere from anthropogenic or natural sources, while others (secondary particles) result from gases that are transformed into particles through physical and chemical processes in the atmosphere. These solid and liquid particles come in a wide range of sizes, which are linked directly to their potential for causing health problems. Small particles less than 10 micrometers in diameter pose the greatest problems because they can get penetrate deep into the lungs and in some cases, may even get into the bloodstream.[3]

Particulates can be further subdivided into two categories: a) PM_{10} (inhalable coarse particles with an aerodynamic diameter of 10 micrometers or smaller); and b) $PM_{2.5}$ (fine particles with an aerodynamic diameter of 2.5 micrometers or smaller). PM_{10} is generated mainly by agriculture, mining and road traffic, while $PM_{2.5}$ results primarily from combustion or forms as a secondary pollutant from the atmospheric reaction of gases emitted from power plants, industrial activities and vehicle exhaust.

Fine particles ($PM_{2.5}$) are so small that they can get deep into the lungs and cause serious health problems, including premature death from heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function and increased respiratory symptoms such as coughing and difficulty breathing (Wong et al. 1999; Pope et al. 2002; Nel 2005; Kaiser 2005; Laden et al., 2006). Fine particles are also the main cause of reduced visibility (haze).

Most PM emissions from ships consist of the fine fraction of particles and contain substantial amounts of sulfate particles due to the high sulfur content of marine fuel. Secondary $PM_{2.5}$ can be formed from gas-phase emissions of SO_x and NO_x. Ships emit large amounts of these compounds, which form nitrate and sulfate particles in coastal regions, as well as inland areas. Therefore, controlling ship emissions will lead to improvements in air quality and will protect the health of the population.

Ozone (O_3)

Ground-level ozone (O_3) is a secondary pollutant formed from the reaction between NO_x and VOCs in the presence of sunlight. Ozone concentrations show clear diurnal and seasonal patterns. Ozone can be transported hundreds of kilometers and can be measured even in places with low emissions of NO_x and VOCs, as shown in a Mexico City study (Molina et al. 2010).

Ozone is a strong oxidant that affects health and causes serious damage to crops and other vegetation. Breathing ground-level ozone can result in a number of adverse health effects that have been observed in broad segments of the population, including induction of respiratory symptoms (coughing, throat irritation, chest tightness, wheezing, or shortness of breath), reduced lung function and inflammation of airways. In addition, evidence from empirical studies indicates that higher daily ozone concentrations are associated with increased asthma attacks, hospital admissions, daily mortality, and other morbidity indicators.

Ship emissions are major sources of VOCs and NO_x, which are harmful to human health, in addition to being ozone precursors. A reduction in emissions of these pollutants, therefore, would improve air quality and as a consequence, reduce the adverse effects on public health and the environment.

[3] EPA website (http://www.epa.gov/pm/health.html)

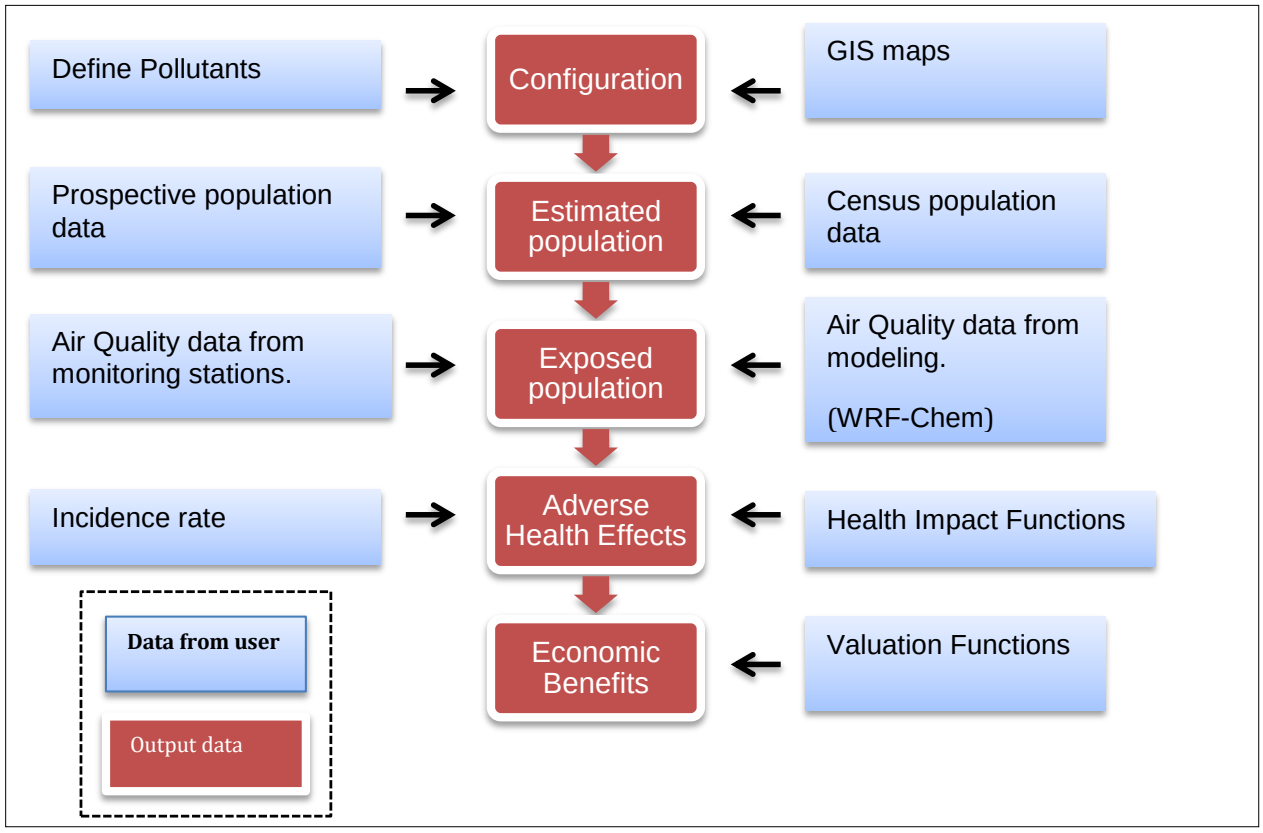
2.3. Evaluation of Costs and Health Benefits for Mexico

Model Description

In this study, the Environmental Benefits Mapping and Analysis Program (BenMAP-CE), v1.0.8,[4] was used to estimate the deaths and illnesses that would be avoided with the improved air quality resulting from the ratification of Marpol Annex VI and the establishment of an ECA in Mexico. This model includes a Geographic Information System (GIS) which allows calculations of health impacts at a very fine level of detail; it also facilitates the systematic processing of input and output datasets (Fann 2012).

The methodology for estimating health benefits is shown schematically in Figure 24. The first phase consisted of identifying the pollutants to be assessed and generating relevant maps (e.g., political division, municipalities) for use with BenMAP-CE.

Figure 20. BenMAP-CE v1.0.8 Workflow Scheme



[4] http://www2.epa.gov/benmap/benmap-community-edition

In the second stage, the fraction of the population that exists in every cell in the spatial domain (**Pop**) was calculated, which entailed collecting and processing population data in order to represent themin the spatial domain of the model. In order to determine the exposed population, it was necessary to calculate the improvements in air quality (**ΔC**); these were obtained by evaluating the difference between scenarios S1 and S2 in the concentration of a specific pollutant (O_3 or $PM_{2.5}$). The air quality data can be the result of numerical modeling, monitoring station data, or both. In the present case, **ΔC** values were the result of numerical modeling using the WRF-Chem model, as described in Part 1 of this document. The next step was to estimate the relationship between the pollutant emissions and adverse health effects (mortality, hospital admissions, lost workdays, etc.), also referred to as health endpoints (HEP). The health effects were calculated using health impact functions:

$$\mathbf{HE_{HEP} = Pop * IR\ [1 - exp(-\beta * \Delta C)]} \qquad \text{Eq. (1)}$$

Where:

HE_{HEP} = Health effects for each HEP [cases, visits, days],
ΔC = Air Quality improvements, [ppm or μg/m^3],
Pop = Exposed population, gender/age/race, [persons]
IR = Incidence rate [cases/person], and
β = Estimated rate of cases associated with changes in concentration, [cases/ppm or cases/ (μg/m^3)].

As previously mentioned, air quality (**ΔC**) and population data (**Pop**) were obtained for each grid cell of the model. As a result, the health effect (number of cases) for each cell was estimated for each HEP. Subsequently, BenMAP calculated the fraction of HE_{HEP} by geographical unit (town, state, delegation, etc.). To complete this task, geographic data based on GIS were processed using the geographic information previously defined in the configuration stage.

Finally, the estimated economic value (monetized benefits) resulting from a reduction in illness associated withimproved air quality was calculated using the following equation:

$$\mathbf{VE = HE_{HEP} * VES} \qquad \text{Eq. (2)}$$

Where:

VE= Economic value (dollars),
HE_{HEP} = Health effects for each HEP (cases, visits, days), and
VES= Economic value depending on HEP (dollars/cases, visits, days).

2.4 Model Configuration

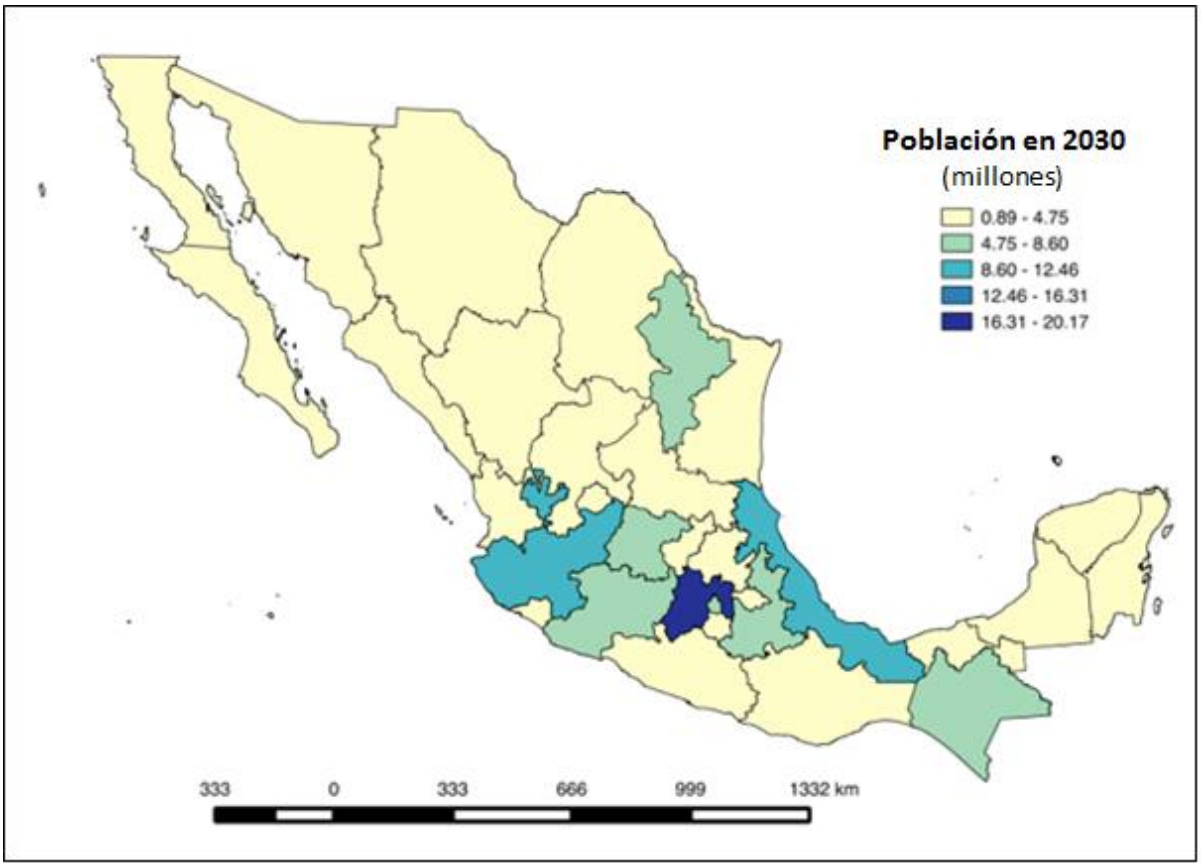
Spatial Domain

The model domain was derived from the domain used in the air quality modeling. It was defined based on a Lambert Conformal projection with a center at -105.12W longitude and 22.25N latitude, with a spatial resolution of 0.25 x 0.25 degrees (approximately 28 x 28 km). This domain contains 20,000 cells covering an area of approximately 15 million km^2 including the national boundaries and an extensive international maritime area. The ECA boundary was established at 200 nautical miles (370 km) from the coast, similar to the North American ECA.

Population Data

In this study the 2030 population was based on the 2010 population census and projections from the Consejo Nacional de Población (Conapo 2013). The compiled population data were disaggregated by county, state, municipality, gender and age. The demographic transition from 2012 to 2030 changed from high levels of mortality and fertility to minor levels, reflecting tendencies seens since the seventies, i.e.: from 6.1 birthsper woman (bcpw)in the seventies to 2.24 bcpw in 2012; with a projected 2.08 bcpw in 2030. The population projection to 2030 takes into consideration migration patterns. States with the largest expected populations in 2030 include the states of Mexico, Veracruz, Jalisco, Nuevo León, Puebla and Chiapas, as shown in Figure 25.

Figure 21. Prospective Population in 2030

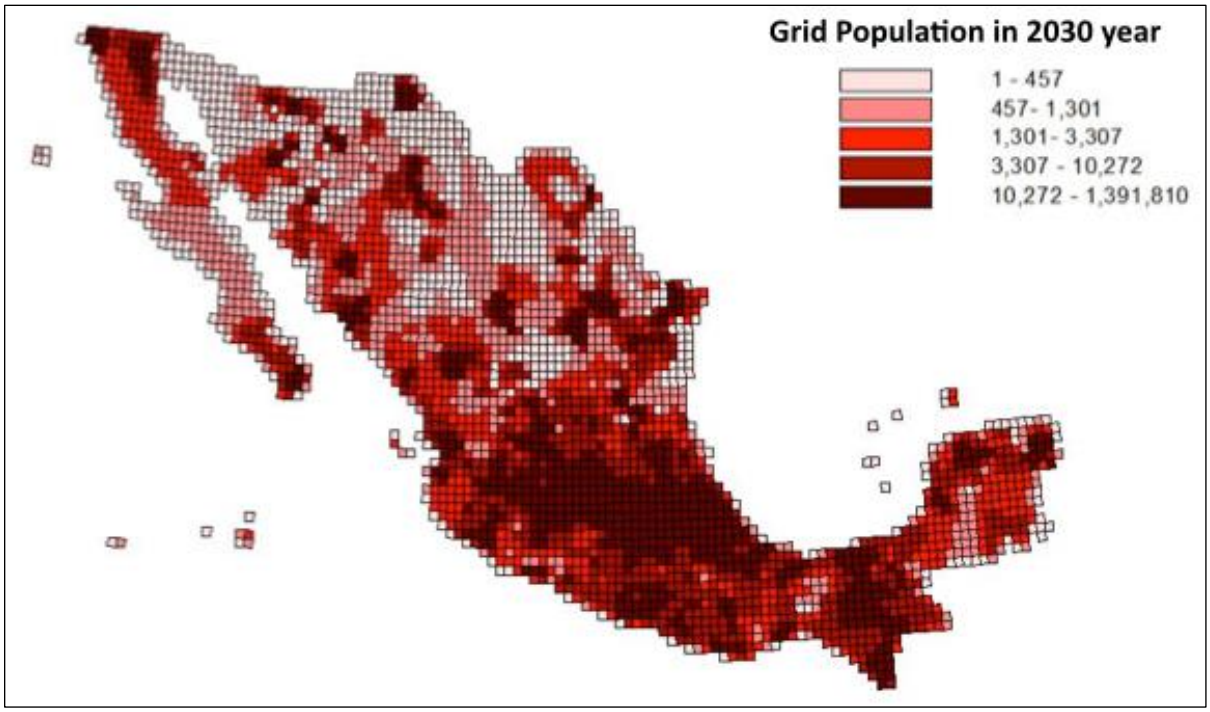


Source: www.conapo.gob.mx/es/CONAPO/proyecciones

Similarly, the relevant geographic files (* .shp, * .shx, * .prj, * .dbf) were processed to represent the country and the states in BenMAP. Population data were processed and separated by gender and age, for inclusion in the BenMAP model using geoprocessing tools (QGIS, www.qgis.org).

The fraction of population, for each category and for each cell in the study domain, was calculated. For example, Figure 26 shows the cell population for a vulnerable sector (children), corresponding to 0–14 years of age.

Figure 22. Projected Population of Children Aged 0-14 in 2030



Note: Data processed for the BenMAP model and considering the prospective population in 2030 (based on Conapo, 2013).

2.5. Air Quality Improvements

In this study two scenarios for 2030 were considered. The first scenario (S1) assumes that most countries, including Mexico, have ratified Marpol Annex VI in 2030; and the second scenario (S2) – the control scenario – assumes that Mexico has ratified Annex VI of Marpol and has also established an Emission Control Area (ECA).

S1	S2
Marpol 2030	Marpol + ECA 2030

The air quality model, run on a yearly basis, generated hourly values for $PM_{2.5}$ and ozone concentrations. The following metrics were used for the benefits evaluation:

a) For $PM_{2.5}$: Annual average, based on hourly values.
b) For ozone: Daily 1-hour maximum value.

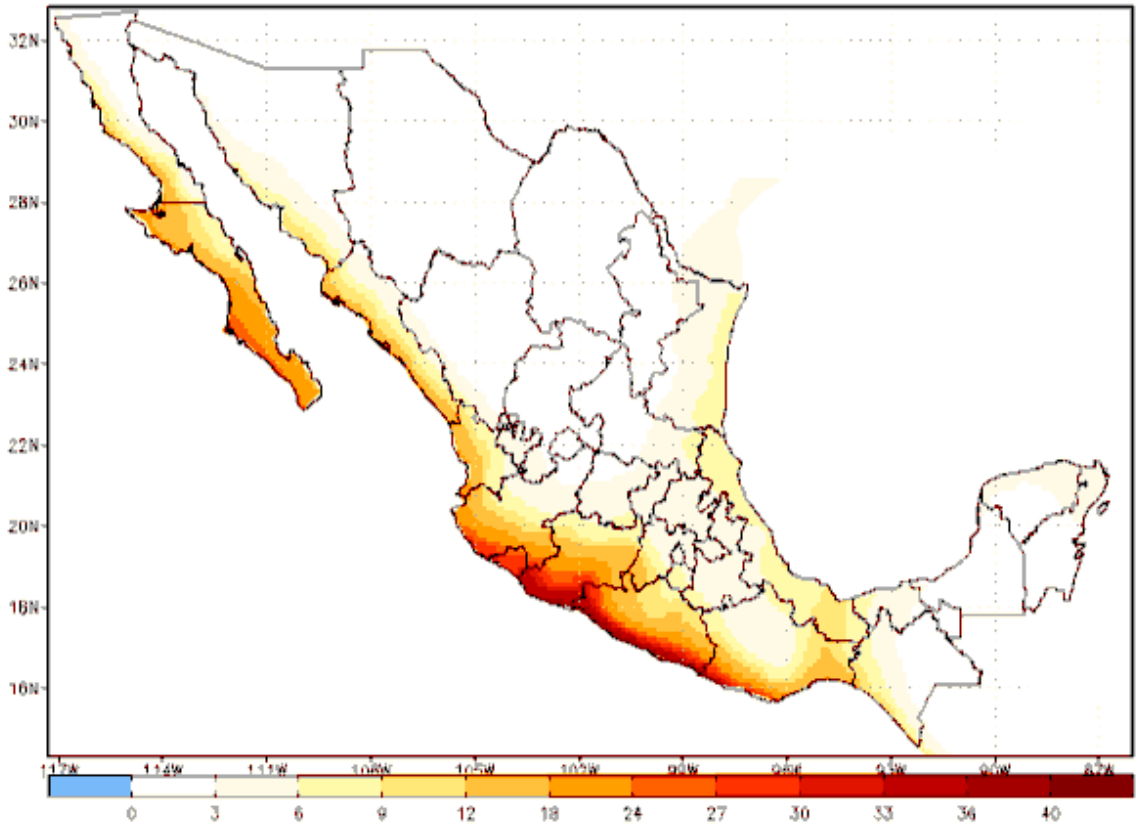
These data were processed for inclusion in the BenMAP model; and the potential reductions in pollutants were calculated for the establishment of an ECA in Mexico (S1-S2).

$PM_{2.5}$ Reductions

Figure 27 and Figure 28 show the improvements in $PM_{2.5}$ ambient concentrations annually, and for May and November, respectively, after the establishment of a Mexican ECA. Annual averages show that $PM_{2.5}$ ambient concentration reductions are largest in Pacific coastal areas. In particular, results

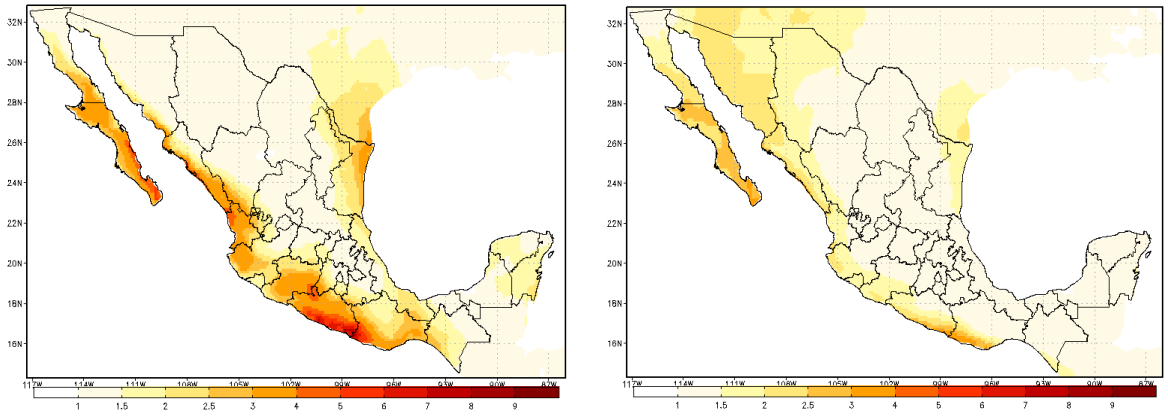
using the maximum monthly concentrations reveal a higher reduction in $PM_{2.5}$ concentrations attributed to emissions from ships occurred in May. Projections based on the annual average indicate that the establishment of an ECA would reduce the $PM_{2.5}$ concentrations in May by as much as 9 times in some coastal areas, and by 1.5 to 2.5 times in certain areas in the middle of the country. In contrast, the reduction in ambient $PM_{2.5}$ concenrations in the month of November is smaller. Nevertheless, reductions in the $PM_{2.5}$ concentrations still benefit many people, including vulnerable groups such as children, the elderly, and those with heart or lung disease – all of whom are highly susceptible to increased sickness due to exposure to high concentrations of $PM_{2.5}$ (Nel 2005).

Figure 23. Projected Reductions in Annual Average $PM_{2.5}$ Concentrations, S1 versus S2



Note: Concentrations in $\mu g/m^3$

Figure 24. Projected Reductions in $PM_{2.5}$ for May (left) and November (right), S1 versus S2 (with Mex-ECA)

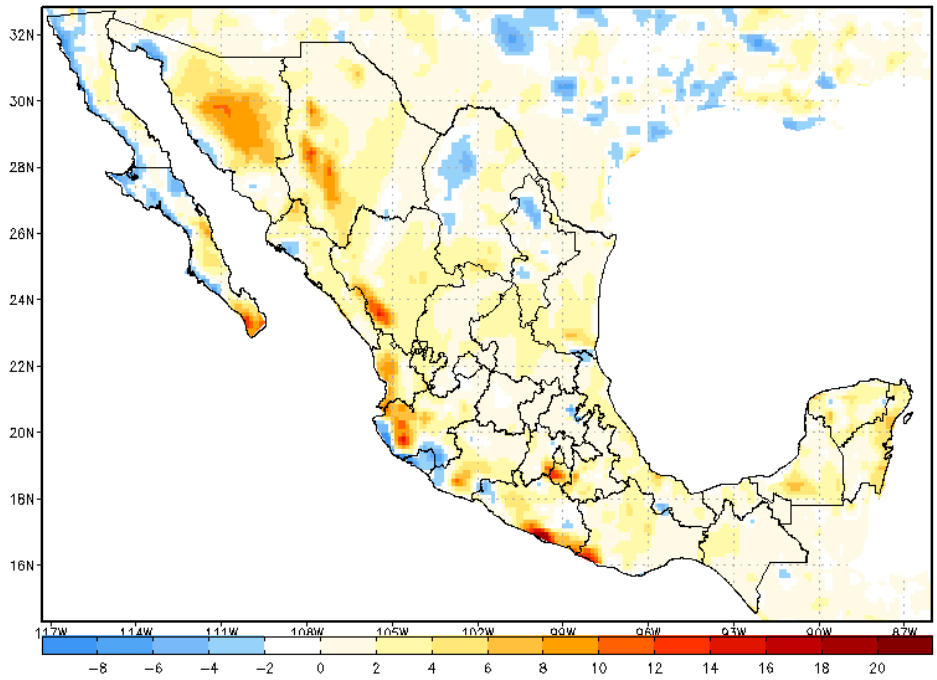


Note: Concentrations in $\mu g/m^3$

O_3 Reductions

The air quality modeling results suggested reductions of ozone concentration levels in various areas of the country with the implementation of the Mexico ECA. Figure 29 shows the reductions in ozone concentration using the 1-hr max; they are expected to have 20 ppb (20%) less ozone concentration with regulation.

Figure 25. Projected Reductions (S1-S2) in Ozone, S1 versus S2 (with the Mex-ECA)



Note: Concentrations in ppb.

Ozone modeling results showed locations with reductions in ambient ozone concentrations (positive values), such as in coastal areas and inland; while there were other areas with no reductions compared to the base case (scenario S1). This is due to the non-linear relationship between ozone and its precursors. Larger differences in densely populated areas could lead to larger changes in the benefits evaluation (with these being positive or negative).

2.6 Adverse Health Effects of Ozone and Particulate Matter

In this study, the following health endpoints (HEP) and specific diseases (EE) were taken into consideration:

- Premature deaths
    - Long-term mortality, all causes (LTMA)
    - Short-term mortality, all causes (STMA)
    - Child respiratory (IMR)
    - Sudden Infant Death Syndrome (MIDSC)
- Hospital admissions
    - Asthma (A)
    - Chronic bronchitis (CB)
    - All respiratory diseases (HARD)
    - Cardiovascular diseases (excepting myocardial infarctions) (HACD)
- Minor effects
    - Restricted activity days (RAD)
    - Lost work days (LWD).

Values were collected for each Beta parameter, and for $PM_{2.5}$ and O_3 incidence data and costs, based on available epidemiological studies and health studies (Pope et al. 2002; Woodruff et al. 1997; Moolgavkar 2000; Zanobetti and Franklin 2009; Abbey et al. 1995; Sheppard 2003; Ostro and Rothschild 1989; Ostro 1987; Levy et. al. 2005; Burnett et. al. 2001). Tables 11 and 12 show the health endpoints and the epidemiological studies used to quantify the health impacts in the core analysis, for $PM_{2.5}$ and O_3, respectively.

Table 8. Health Endpoints and Epidemiological Studies Used to Quantify Health Impacts in the Core Analysis – $PM_{2.55}$

End Point	Study	Age of the study population	Risk estimate (95th percentile confidence interval)
Mortality, All causes	Pope et al. (2002)	30-99	β= 0.005827 RR= 1.06 (1.02-1.11) per 10 μg/m^3
Mortality, Child respiratory	Woodruff et al. (1997)	<1	β = 0.006765865 OR= 1.04 (1.02-1.07) per 10 μg/m^3
Mortality, Sudden Infant Death Syndrome	Woodruff et al. (1997)	<1	β= 0.003922071 OR= 1.04 (1.02-1.07) per 10 μg/m^3
Hospital Admissions, All cardiovascular less myocardial infarctions	Moolgavkar (2000)	18-64	β= 0.0014 RR=1.020 (0.001980) per 10 μg/m^3
Hospital Admissions, All respiratory	Zanobetti and Franklin (2009)	65-99	β= 0.00207 RR=2.07 (1.20-2.95) per 10 μg/m^3
Chronic bronchitis	Abbey et al. (1995)	27-99	β= 0.013185 RR=1.81(0.98-3.25) per 10 μg/m^3
Hospital Admissions, Asthma	Sheppard (2003)	0-64	β= 0.003324 RR=1.04(1.01-1.06) per 10 μg/m^3
Minor effects, Restricted activity days	Ostro and Rothschild (1989)	18-64	β= 0.00741 std error=0.00036
Minor effects, Lost work-days	Ostro (1987)	18-68	β= 0.0046 std error=0.00036

Table 9. Health Endpoints and Epidemiological Studies Used to Quantify Health Impacts in the Core Analysis – Ozone

Endpoint	Study	Age of the study population	Risk estimate (95th percentile confidence interval)
Mortality Short-term all cause	Levy et al. (2005)	All ages	β= 0.000841 RR= 0.43 (0.29-0.56) per 10 ppb
Hospital Admissions respiratory	Burnett et al. (2001)	<1	β= 0.007301 std error= 0.002122
Minor effects, Restricted activity days	Ostro and Rothschild (1989)	18-64	β = 0.0022 std error= 0.000658
Minor effects, Lost school days	Chen et al. (2000)	5-17	β= 0.013247 std error= 0.004985

2.7. Results

In order to determine the health benefits, the annual average $PM_{2.5}$concentration and the daily 1-hr max for O_3 were used to evaluate the benefits, and the health effects (HE_{HEP}) were assessed for each the HEP.

Overall, the results obtained were consistent with the results of air quality modeling: a decrease in ambient pollutant concentrations resulted in an increase in avoided health effect cases. We have separated the health effects and economic benefits by pollutants. The results are presented in the following sections.

Health Benefits Resulting from $PM_{2.5}$ Reductions

The potential health benefits for Mexico, accruing from the establishment of an ECA and the resulting $PM_{2.5}$ reductions, were estimated using BenMAP and are shown in Table 13. It should be noted that the estimated health benefits depend on the health effect parameters selected; this is especially important in the case of "Mortality, all causes" (highlighted in the table). As illustrated in the table, the use of the Laden et al. (2006) study for "Mortality, all causes" results in an increase of approximately US$26 billion in the estimated monetized health benefits, compared to estimates based on the Pope et al. (2002) study. The total economic benefits will range from US$34 to $97 billion. Thus, with the establishment of a Mexican ECA, between 4,000 and 35,000 premature deaths and between 3.3 and 4.4 million other adverse health cases (e.g., hospital admissions, chronic bronchitis, restricted activity days, asthma and school loss days) could be avoided. The monetized health benefits for avoided adverse health cases range between US$18 and $97 billion.

Table 10. Projected Monetized Health Benefits from $PM_{2.5}$ Reductions under a Mexican ECA

Endpoint Group	Endpoint	Beta (cases/ µg/ m^3)	Age Range	Author	Exposed population (millions)	Benefit Population	Incidence Rate (cases/ pop)	Valuation (US$)	Economic Benefits (millions of US$)
Hospital Admissions	All cardiovascular less myocardial infarctions	0.000341	18 to 64	Moolgavkar (2000)	85	4,500	0.008807	11,882	54
						(2000–6000)			(32–74)
Hospital Admissions	All respiratory	0.0021	65 to 99	Zanobetti and Franklin (2009)	14	800	0.005966	2,669	2
						(490–1,000)			(1–3)
Hospital Admissions	Asthma	0.013185	27 to 99	Abbey et al. (1995)	123	120,000	0.1274	99,256	11,800
						(58,000–180,000)			(5,700–18,000)
Chronic	Chronic bronchitis	0.003324	0 to 64	Sheppard (2003)	80	25,000	0.007	443	11,200
						(3,900–44,000)			(5,400–17,000)
Mortality	Mortality all cause	0.005827	30 to 99	Pope et al. (2009)	73	10,400	0.0057	1,679,507	17,400
						(4,000–16,000)			(6,900–28,000)
Mortality	Mortality child respiratory	0.18	0 to 1	Woodruff et al. (1997)	4	300	0.00231	1,300,000	370
						(-237–767)			(-310–1,000)
Mortality	Mortality sudden infant death syndrome	0.11	0 to 1	Woodruff et al. (1997)	4	9	0.00012	1,300,000	11
						(4–13)			(5–17)
Minor effects	Restricted activity days	0.00741	18 to 64	Ostro and Rothschild (1989)	85	57,000	6.46	38	2
						(48,000–65,000)			(1–)
Minor effects	School loss days	0.0046	18 to 64	Ostro (1987)	85	3,600,000	2.17	15	54
						(3,200,000-4,100,000)			(47–60)
					Total	3,800,000		Total	41,000
						(3.3 M –4.4 M)			(18,000–64,000)

$PM_{2.5}$ results using "Mortality, all causes" parameters from Laden et al. study

Endpoint Group	Endpoint	Beta (cases / µg/m^3)	Age Range	Author	Exposed population (millions)	Benefit Population	Incidence Rate (cases/ pop)	Valuation (US$)	Economic Benefits (millions of US$)
Mortality	Mortality all cause	0.01484	25-99	Laden et al. (2006)	84	25,000	0.0057	1,679,507	43,000
						(14,000–36,000)			(23,000–61,000)
					Total	3,800,000		Total	67,000
						(3.3 M–4.4 M)			(34,000–97,000)

Note**:** Incidence rate values in Table 12 were taken from Semarnat, CEPAL, ONU, 2007, *Evaluación de externalidades ambientales del sector energía en las zonas críticas de Tula y Salamanca*. Economic values were provided by the *Instituto Nacional de Salud Pública* (INSP).

Health benefits Resulting from Ozone Reductions

In case of ozone, the daily 1-hour max was used to compute the benefits; the results are summarized in Table 14.

Table 11. Projected Monetized Health Benefits from O_3 Reductions Under a Mexican ECA

Endpoint Group	Endpoint	Beta (cases/ppb)	Age Range	Author	Exposed population (millions)	Benefit Population	Incidence Rate (cases/pop)	Valuation (US$)	Economic Benefits (US$)
Hospital Admissions	Respiratory	0.007301	0 to 1	Burnett et al. (2001)	4	0	0.0000063	2,669	1,200
						(0–1)			(610–1,800)
Minor effects	Restricted activity days	0.0022	18 to 64	Ostro and Rothschild 1989	85	5,800	0.01369863	38	220,000
						(2,900–8,600)			(110,000–330,000)
Minor effects	School loss days	0.013247	5 to 17	Chen et al. (2000)	28	11,000	0.01369863	15	170,000
						(4,300–18,000)			(62,000–270,000)
Mortality	Short term - all causes	0.000841	0 to 99	Levy et al. (2005)	137	6	0.000023	1,679,507	10 Million
						(4–8)			(7M–12M)
					Total	**17,000**		**Total**	**10.4 Million**
						(7,300–27,000)			(7.1M–12.6M)

Note: Incidence Rate values were taken from Stevens et al. 2005. Economic values were provided by the *Instituto Nacional de Salud Pública* (INSP). For the population benefits, a 90th percentile confidence interval was used, whereas the 95th percentile confidence interval was used for the economic benefits.

Conclusions

Emissions inventory data for 2011 and 2030 were integrated for this modeling study, taking into account land and marine emissions for Mexico, as well as parts of the United States and Central America. The WRF-Chem model was employed to analyze the possible impacts on air quality in two prospective scenarios for 2030. First, simulations for the 2011 baseline year were evaluated against ambient air quality monitoring station data. Measured meteorological variables on land and at sea (temperature, relative humidity, and wind) showed a good agreement with the modeling forecast. This is illustrated through the correlation coefficient and other parameters presented in Annex II. Validation of the forecast concentrations for chemical species (O_3, $PM_{2.5}$) was difficult, since data from available air quality monitoring stations showed many anomalies (a comparison was made only for RAMA stations in Mexico City). In general, when available, the results of the comparison showed good agreement.

The modeling results for the prospective scenarios indicated that emissions from ships sailing near the Mexican coastline have a substantial impact on the composition of the atmosphere. Ship emissions mainly affect the air quality in coastal areas; however, several central (inland) regions of Mexico are also affected.

Modeling results showed that:

- In a scenario in which Mexico ratifies Marpol Annex VI and establishes an ECA (S2), $PM_{2.5}$ concentrations would be reduced in general throughout the country (with reductions by up to 3 times in coastal areas).
- In this same scenario, increases and decreases were observed in O_3 concentrations, depending on the geographic area; this variation is attributed to the non-linear relationship between ozone and its precursors.

The air quality simulation results and monetized health benefits were integrated using the BenMAP model. Emissions from ships in the ECA region, as modeled, contributed to a significant number of cases of adverse health effects, especially in highly populated coastal areas. The Mexican ECA is expected to yield significant health benefits, including approximately 3.3 to 4.4 million averted premature deaths, hospital admissions and lost work days, among other cases. The monetized health benefits in 2030 resulting from the implementation of a Mexican ECA are projected to range from US$18 to $97 billion in the case of $PM_{2.5}$ reductions, and US$7 to $13 million in the case of ozone reductions.

By all indications, Mexican and international maritime trade is expected to grow and correspondingly, produce more air emissions. Updates to ship and port emissions inventories will be required, including data for port equipment, vehicles and engines.

Appendix I: Model Configuration

Table 15 summarizes the set of parameters used to configure the model according to the needs of the project. These parameters were selected based on the experience of the MCE2 modeling team. For example, SST_UPDATE = 1 was used to represent variations in sea temperature, given that the model domain considered a region just above the ocean surface and with simulations over long periods. The four- dimensional data assimilation GRID_FDDA = 1 was included to obtain a better representation of the meteorological variables, especially when modeling was applied to longer time periods (e.g., a week). This was important to ensure the representation of meteorological data, as well as their influence on the chemical transformations during the modeling and therefore, in the air quality forecasting.

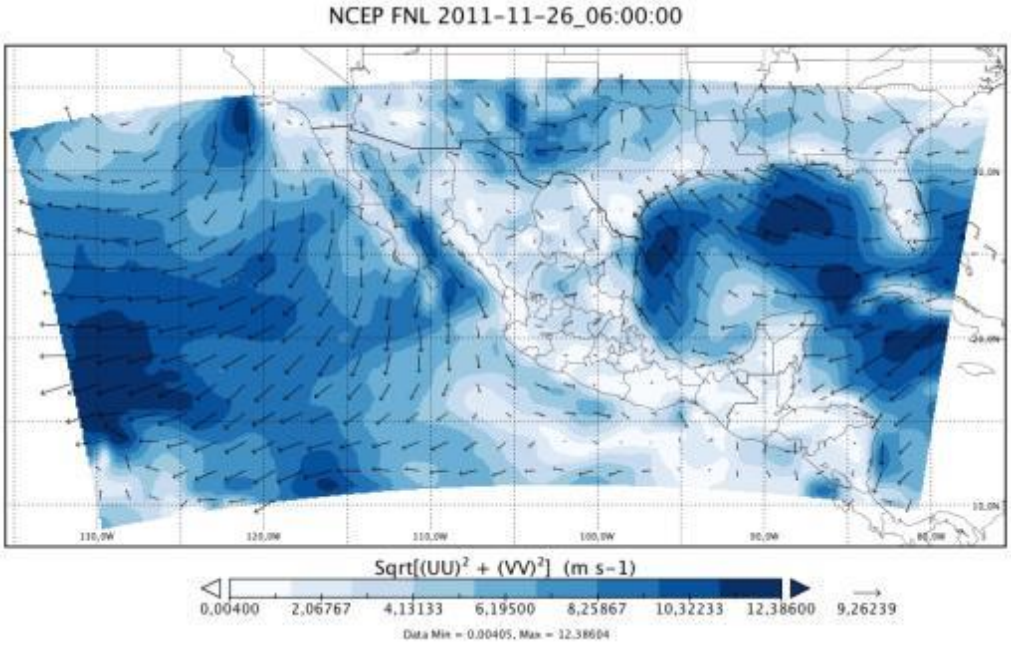
Table 12. Summary of Most Important Variables for the WRF-Chem Model Configuration

Variable/Value	Description
MP_PHYSICS = 4	WRF Single-Moment 5-class scheme: A slightly more sophisticated version of Single-Moment 3-class scheme that allows for mixed-phase processes and super-cooled water
RA_LW_PHYSICS = 1	Rapid Radiative Transfer Model. An accurate scheme using look-up tables for efficiency. Accounts for multiple bands, trace gases, and microphysics species
RA_SW_PHYSICS = 2	Goddard shortwave: Two-stream multi-band scheme with ozone from climatology and cloud effects
SF_SFCLAY_PHYSICS = 1	Based on Monin-Obukhov with Carslon-Boland viscous sublayer and standard similarity functions from look-up tables
SF_SURFACE_PHYSICS = 2	Noah Land Surface Model: Unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics.
BL_PBL_PHYSICS = 1	Yonsei University scheme: Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer
CU_PHYSICS = 5	Grell 3D is an improved version of the Grell-Devenyi (GD) ensemble scheme that may also be used on high resolution (in addition to coarser resolutions) if subsidence spreading (option cugd_avedx) is turned on.
SURFACE_INPUT_SOURCE = 1	Use and category of the soil data come from WPS/geogrid, but with dominant categories recomputed in REAL
SST_UPDATE = 1	Sea Surface Temperature variable in time, sea ice, the fraction of vegetation, and the albedo during a modeling simulation, recommended for a simulation time exceeding 5 days
GRID_FDDA = 1	Grid analysis nudging
HYPSOMETRIC_OPT = 2	Computes height in real.exe and the pressure in the model (ARW only) by using an alternative method (less biased when compared against input data)
SF_URBAN_PHYSICS = 0	The deactivated urban canopy model that serves to better represent the physical processes involved in the exchange of heat, momentum, and water vapor in urban environment. It is primarily intended for very high resolution simulations (DX < 3 km) over urban areas

To provide meteorological data to the model, NCEP FNL (Final) Operational Global Analysis data, with resolution of 1x1 degrees available every 6 hours, were considered. These data come from the

Global Data Assimilation System (GDAS) that nearly permanently collects data from the Global Telecommunications System (GTS) and other sources for various analyses. Figure 30 depicts an example of the wind field (from November 26, 2011) processed for modeling (obtained from NCEP FNL data).

Figure 26. Wind Field in the Domain Area for November 26, 2011



In the WRF-Chem model, the setting chem_opt_chem = 1 was selected for using the chemical mechanism Regional Acid Deposition Model (RADM2) (Stockwell et al. 1990). The Madronich photolysis option (Madronich 1987) and aerosol module MADE/SORGAM were also enabled. Emissions data for each scenario (Table 6) were processed based on these configurations, and taking into consideration the following:

- Spatial distribution (horizontal and vertical);
- Temporal distribution;
- Distribution of chemical species;
- Chemical speciation conducted according to the RADM2mechanism ;
- Generation of archives in an appropriate format for the NetCDF chemical mechanism.

This procedure was followed for the INEM, INEB and INEP inventories. The Air Emissions Processing System (*Sistema de Procesamiento de Emisiones Atmosféricas*, SPEA) program, v1.0.0 (Ortiz 2005), was used and the results were later processed in Fortran programs in order to generate two archives with data for hourly emissions , per pollutant, over 12 hours – with a diurnal and nocturnal period in each file.. As already noted, although the NEI and CAE inventories followed a similar procedure in their processing for modeling , the final emission modeling files were developed for use in a different model (CAMx) and different chemical mechanism (CBMZ); therefore,it was

necessary to convert these files to the WRF-Chem (RADM2) format. This conversion was performed by the MCE2 modeling team based on previous studies (Zaveri 1999), as shown in Table 16.

Table 13. Conversion of Original Chemical Species (NEI and CAE) for Use in the Regional Acid Deposition (RADM2) Model

RADM2 Species	CBMZ Species
HC3	= 0.4020 CH_3OH
HC3	= 1.198 C_2H_5OH
HC3	= 0.0804 PAR
HC5	= 0.05395 PAR
HC8	= 0.0384 PAR

Note: PAR species equivalents in CBMZ relative to HC3, HC5 y HC8 in RADM2

Finally, NetCDF Operators (NCO) tools (http://nco.sourceforge.net/) and several Fortran 90 programs were used to integrate the emissions inventories (processed for modeling), resulting in two NetCDF files (wrfchemi_00z_d01.nc; wrfchemi_12z_d01.nc). These contained hourly emissions data for daytime and night-time periods, respectively. The emissions data were distributed spatially, both horizontally and vertically.

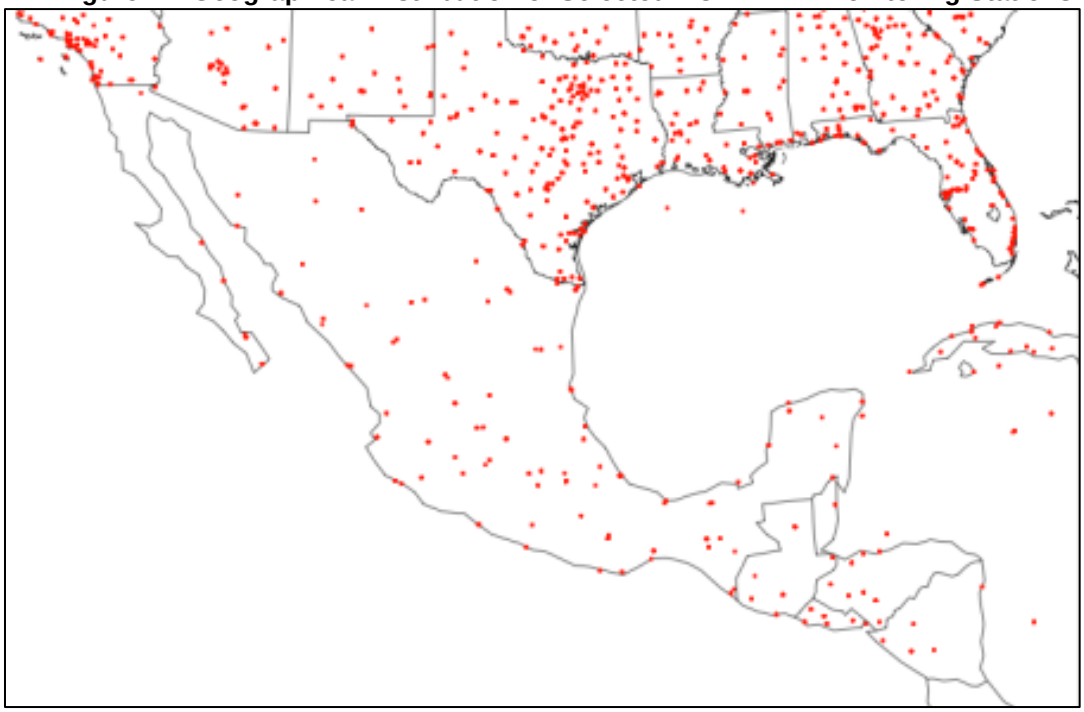
The WRF-Chem model was also modified to display the dry deposition of SO_2 (SO2_dry_dep). To achieve this, several lines were modified in the model's source code: Registry.chem, chem_driver.F, dry_dep_driver.F, and namelist.input, as described in the AQMEII-2 project website <http: // aqmeii-eu .wikidot.com/models:wrf-chem-here # toc1>.

Appendix II: Global Data Assimilation System (GDAS): Comparison of Results

Monitoring stations of the National Centers for Environmental Prediction (NCEP - ADP) are located throughout the modeling domain (see Figure 31); however, for the verification process, only the 132 land-based stations within Mexican territory were considered.

It is important to note that model output is for 27.7 x 27.7 km cells and that it contrasts with the output from the stations. In the case of variables such as humidity and wind intensity, it is possible to have larger differences between the model and the measurements, in comparison with temperature and wind direction in the monitoring stations, which measure synoptic variables. This will not be the case for stations located near cities; also, there will be larger differences between modeled and observed values.

Figure 27. Geographical Distribution of Selected NCEP-ADP Monitoring Stations



For the following tables, it was considered that the model performed well when the standard deviations of the model (FSTDEV) and the observations (OSTDEV) were similar; the Pearson coefficient of correlation (PR_corr) and the Spearman coefficient of correlation (SP_corr) can range between – 1 and 1 (a perfect correlation equals 1 and a value of – 1 indicates perfect negative correlation). Modeled values and observations were not correlated when a value of 0 was obtained. A perfect correlation between the model and observations occurred when the mean error (ME), mean absolute error (MAE), mean squared error (MSE) and root-mean-squared error (RMSE) were equal to 0.

Table 14. Summary of Baseline 2011 Scenario Evaluations

	Feb 9–16	May 15–22	Aug 30–Sep 06	Nov 20–27
Temperature				
FBAR	289.62	295.08	295.06	291.68
FSTDEV	6.18	5.05	6.49	5.26
OBAR	291.17	298.07	297.41	293.87
OSTDEV	7.53	6.60	6.38	6.46
PR_CORR	0.81	0.85	0.90	0.84
SP_CORR	0.80	0.84	0.89	0.85
ME	1.55	-3.00	-2.38	-2.18
ESTDEV	4.38	3.55	2.98	3.53
MAE	3.68	3.79	3.04	3.34
MSE	21.59	21.59	14.53	17.20
RMSE	4.65	4.64	3.77	4.15
Relative Humidity				
FBAR	55.68	55.62	75.14	66.86
FSTDEV	25.17	27.13	20.03	20.30
OBAR	57.73	59.75	77.91	68.71
OSTDEV	25.15	26.29	18.70	21.30
PR_CORR	0.72	0.81	0.66	0.67
SP_CORR	0.72	0.80	0.59	0.65
ME	-2.05	-4.13	-2.50	-1.78
ESTDEV	18.75	16.38	16.30	17.06
MAE	14.01	12.74	12.03	12.77
MSE	355.64	285.28	265.39	291.27
RMSE	18.86	16.89	16.29	17.07
Wind Direction				
FBAR	16.87	231.98	122.36	33.43
OBAR	7.38	166.37	115.26	92.92
ME	9.20	32.20	7.50	-6.33
MAE	21.22	52.34	48.73	54.91

Table 15. Description of Statistical Abbreviations

Variable	Description	Variable	Description
FBAR	Forecast mean	**ME**	Mean error
FSTDEV	Forecast standard deviation	**ESTDEV**	Error standard deviation
OBAR	Observation mean	**MAE**	Mean absolute error
OSTDEV	Observation standard deviation	**MSE**	Mean squared error
PR_CORR	Pearson correlation coefficient	**RMSE**	Root mean squared error
SP_CORR	Spearman correlation coefficient		

Graphs and Comparisons between Forecasts and Observations

The following histograms and scatterplots for temperature show an underestimation in the modeled values. Overall, however, the data were aggregated around the 1:1 line, indicating that the model can reproduce temperature values. For the *u* and *v* wind components, the model overestimated the observed values; however, the points obtained employing the observed and measured values group

around the 1:1 line, indicating that the model can have similar wind fields around the station sites. Relative humidity had a larger similar distribution between modeled forecasts and observed measurements and the values were located around the 1:1 line.

Week of 9 to 16 February 2011

The analyses of forecasts and observations for temperature, *u* and *v* wind components, and relative humidity for the week of 9 to 16 February 2011 are presented in the following figures.

Figure 28. Temperature for the Week of 9 to 16 February

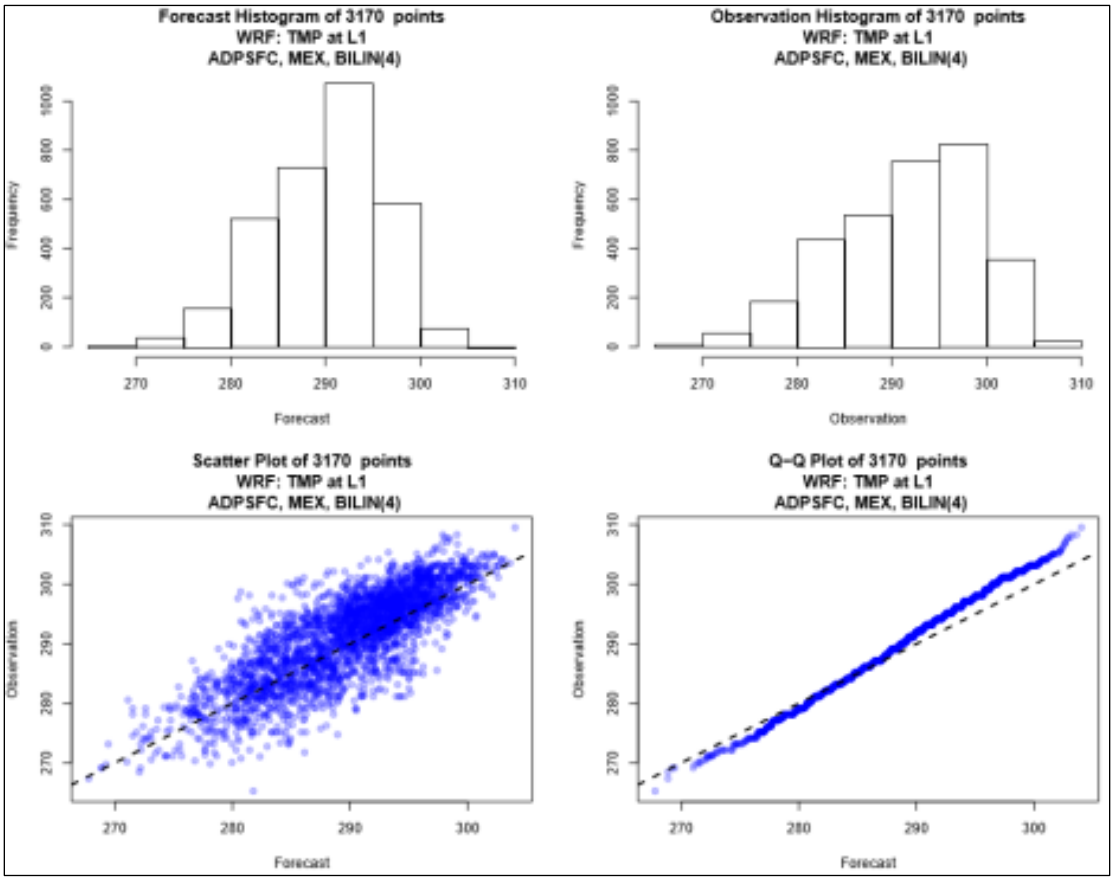


Figure 29. Wind Component (*u*) for the Week of 9 to 16 February

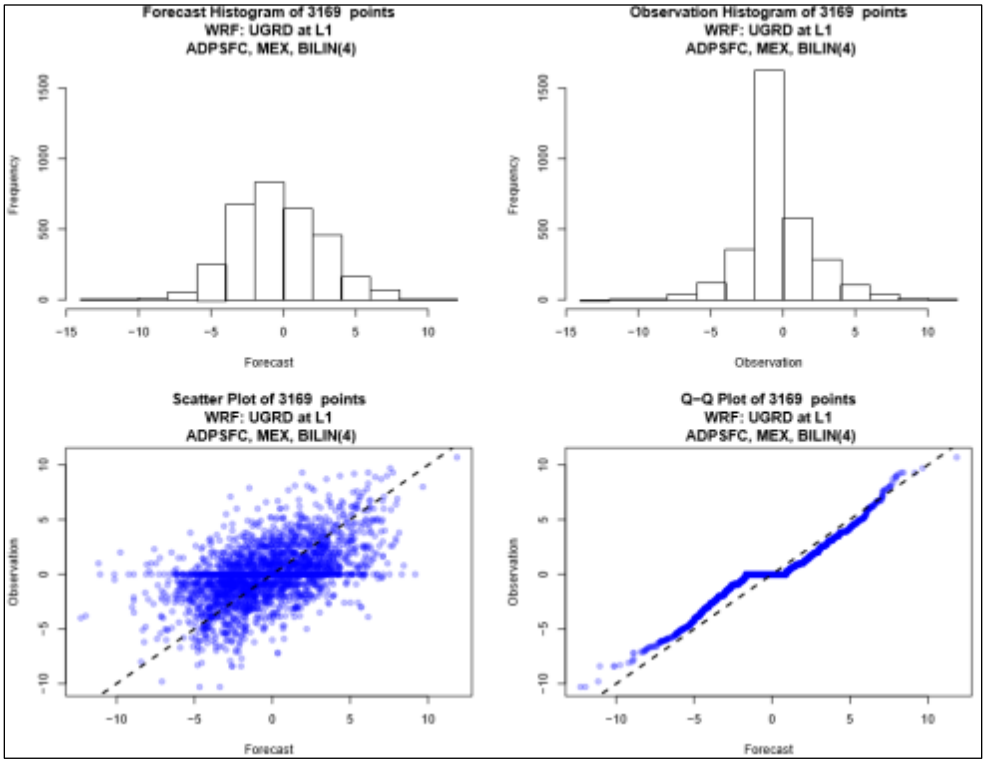


Figure 30. Wind Component (*v*) for the Week of 9 to 16 February

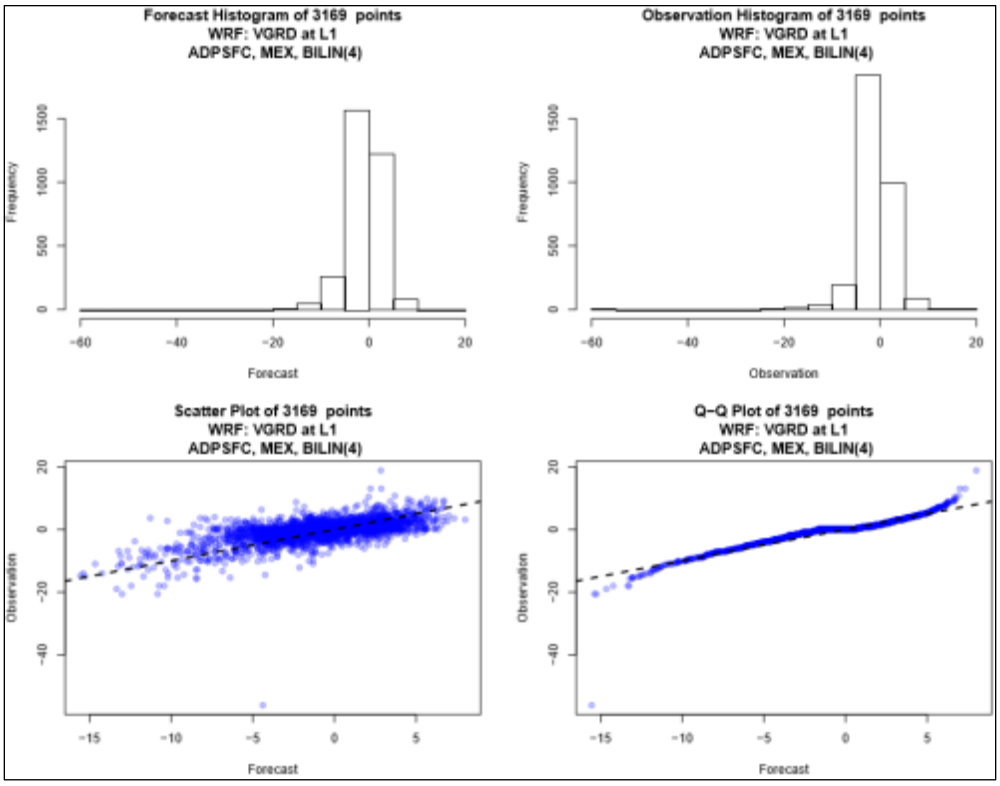
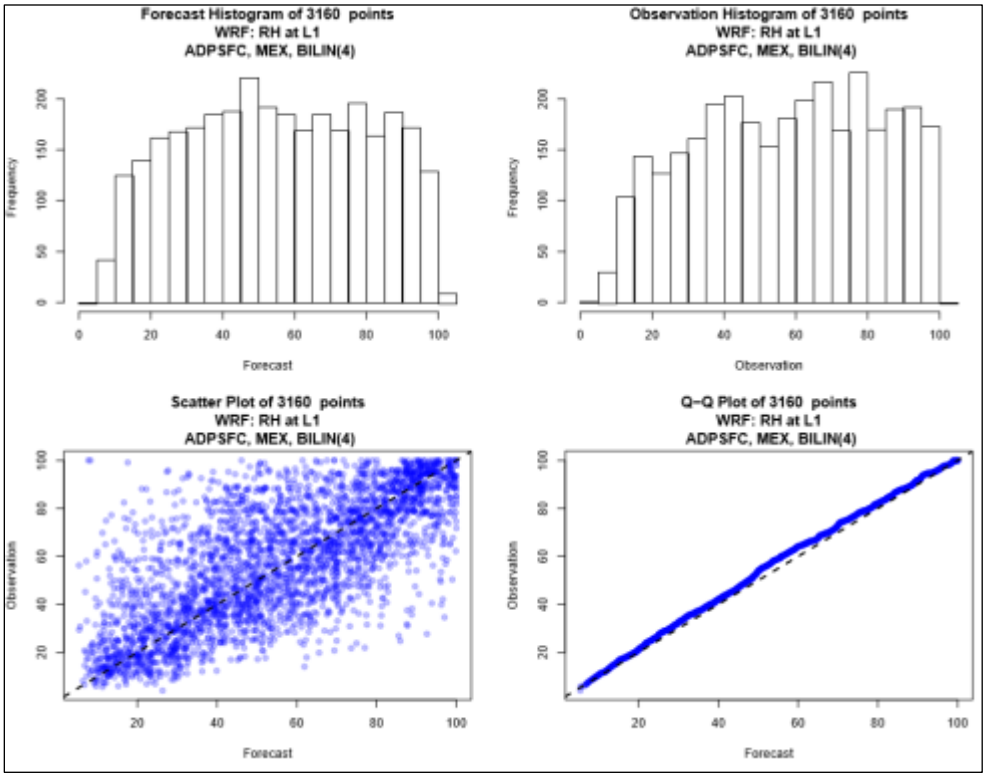


Figure 31. Relative Humidity for the Week of 9 to 16 February



Week of 15 to 22 May 2011

The analyses of forcasts and temperature observations, *u* and *v* wind components, and relative humidity for the week of 15 to 22 May 2011 are presented in the following figures.

Figure 32. Temperature for the Week of 15 to 22 May

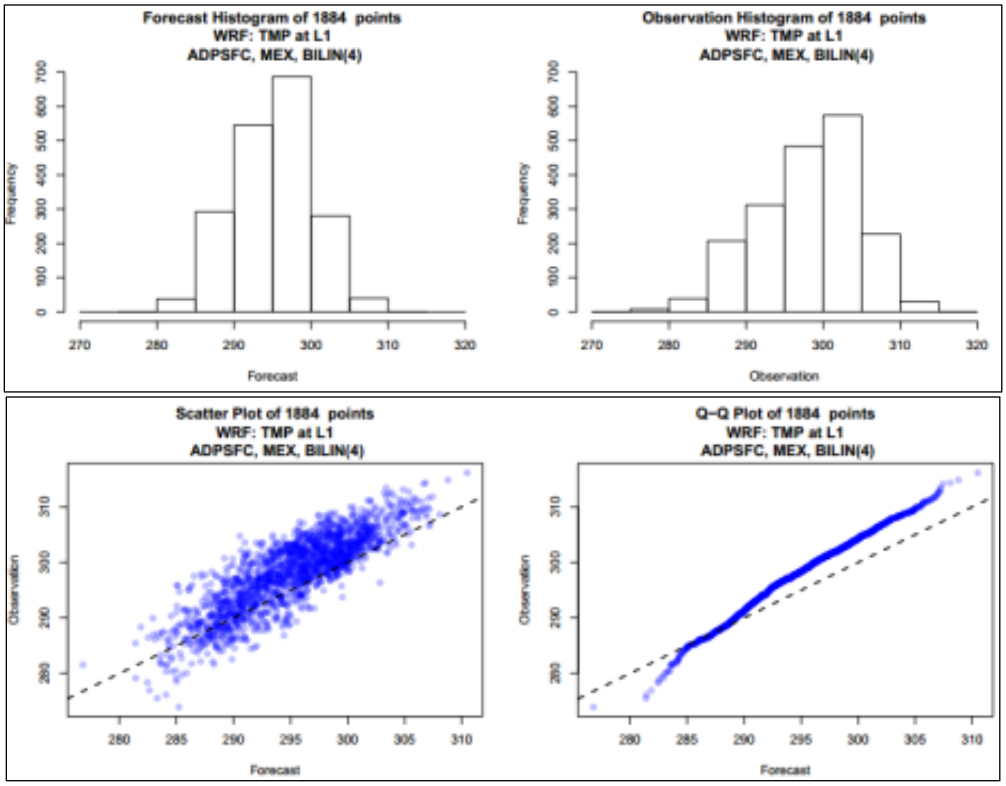


Figure 33. Wind Component (*u*) for the Week of 15 to 22 May

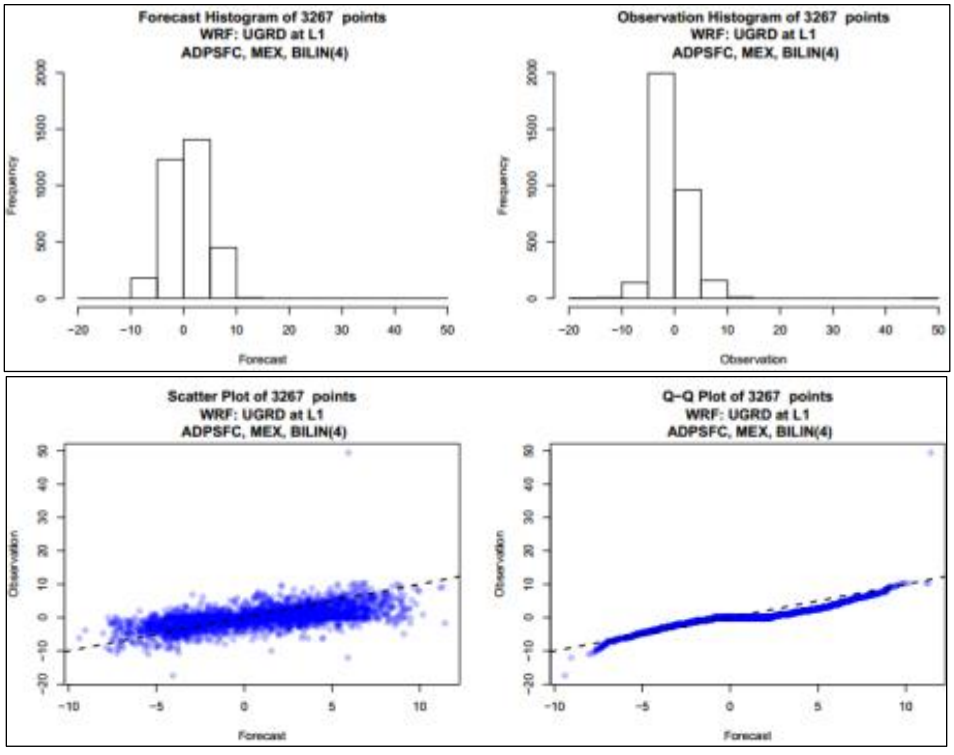


Figure 34. Wind Component (*v*) for the Week of 15 to 22 May

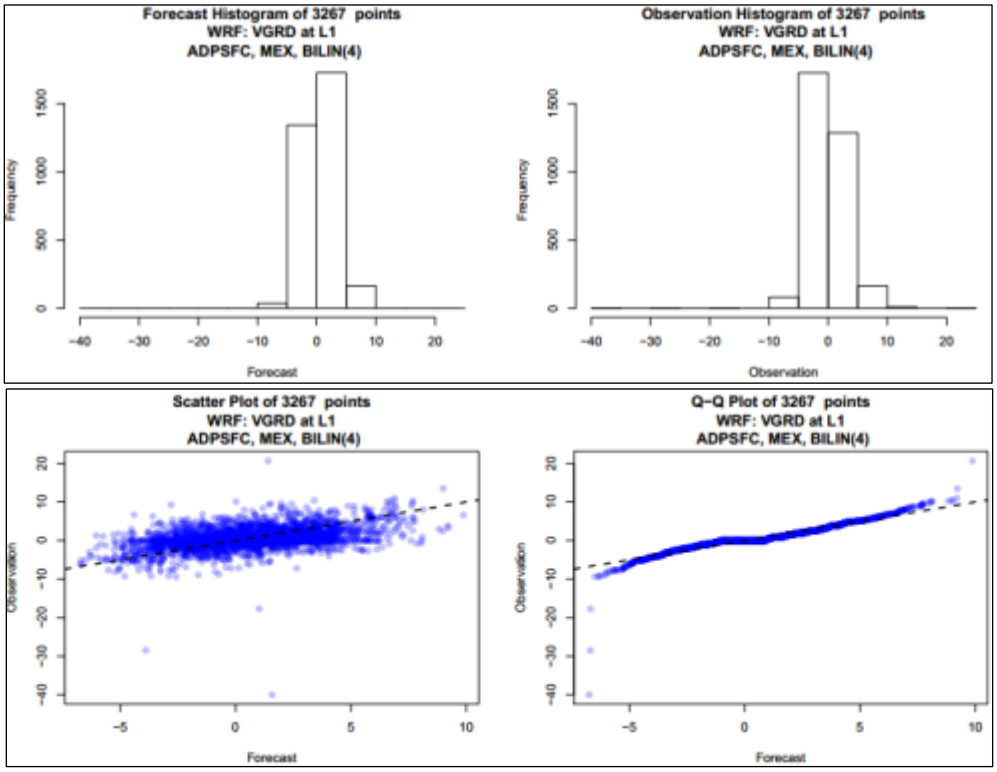
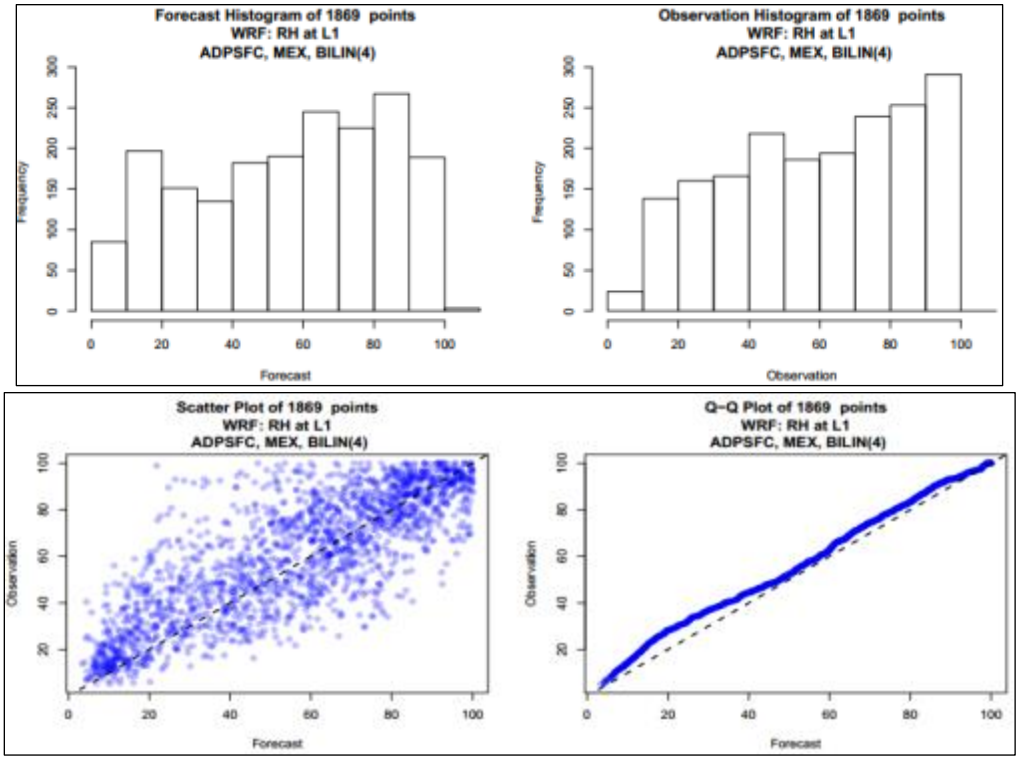


Figure 35. Relative Humidity for the Week of 15 to 22 May



Week of 30 August to 6 September 2011

The analyses of forecasts and observations for temperature, *u* and *v* wind components, and relative humidity for the week of 30 August to 6 September 2011 are presented in the following figures.

Figure 36. Temperature for the Week of 30 August to 6 September

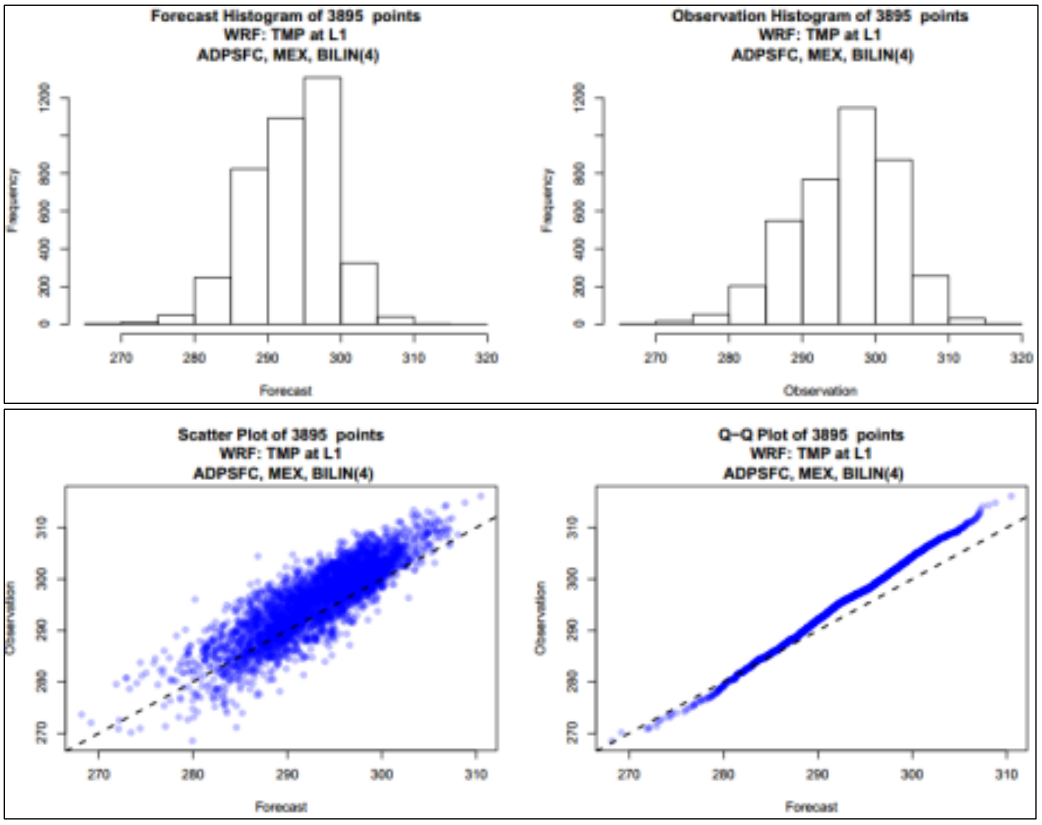


Figure 37. Wind Component (*u*) for the Week of 30 August to 6 September

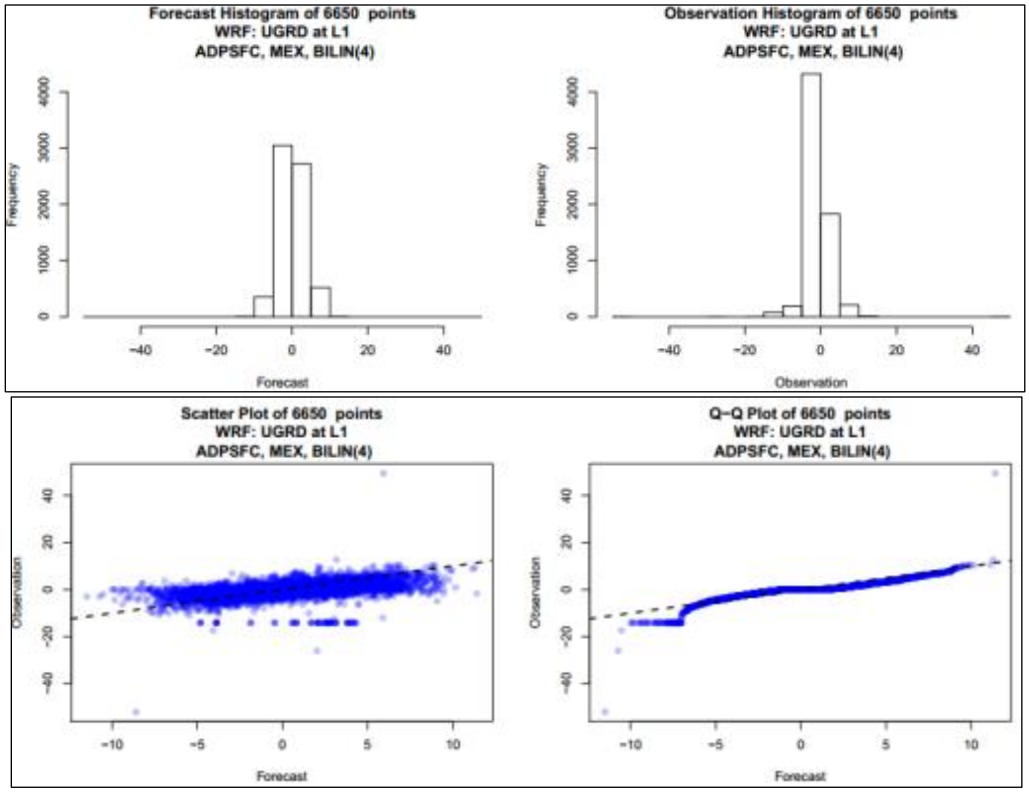


Figure 38. Wind Component (*v*) for the Week of 30 August to 6 September

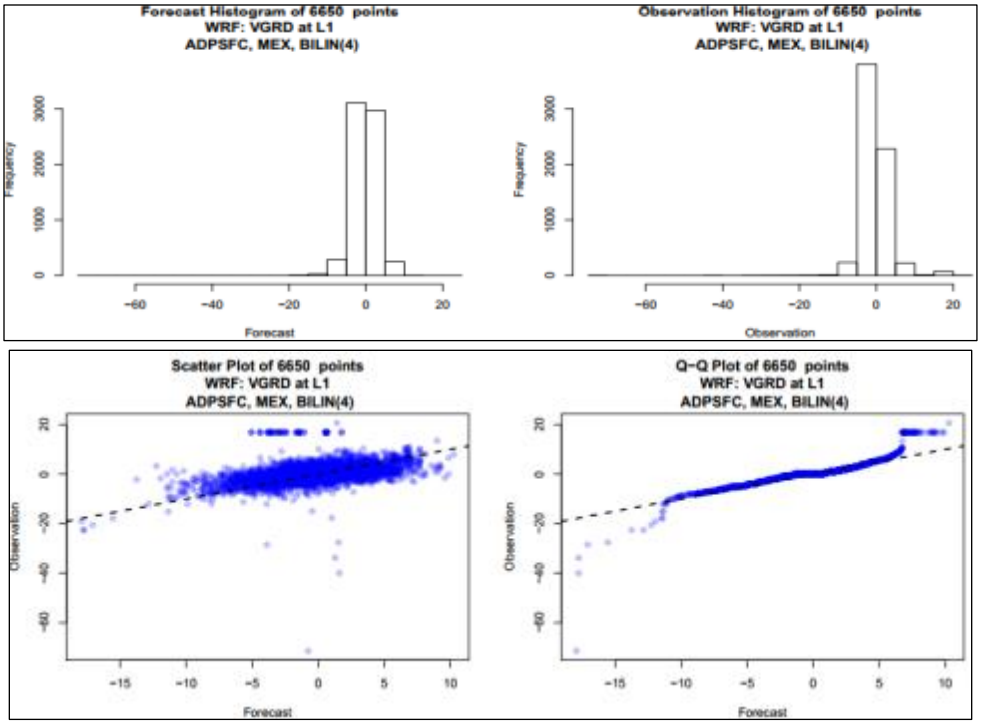
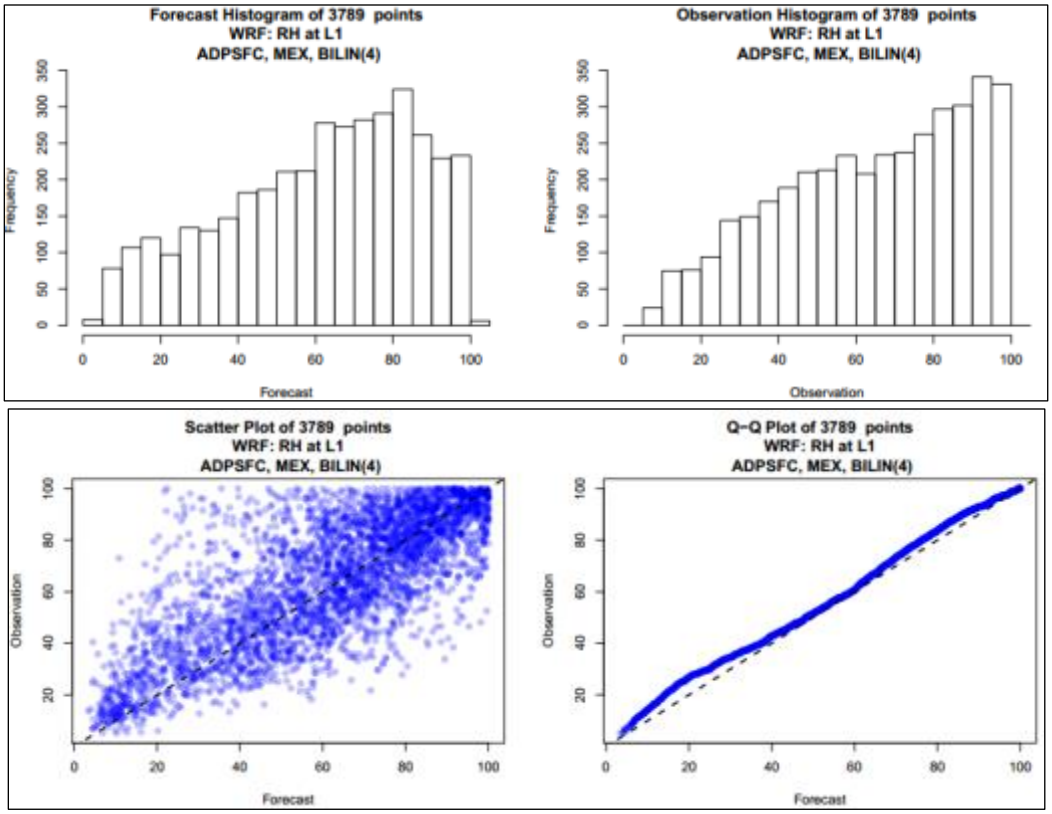


Figure 39. Relative Humidity for the Week of 30 August to 6 September



Week of 20 to 27 November 2011

The analyses of forecasts and observations for temperature, *u* and *v* wind components, and relative humidity for the week of 20 to 27 November 2011 are presented in the following figures. *Wind direction:* In this case, the forecast mean and observation mean were 33.4 and 92.9 degrees, respectively.

Figure 40. Temperature November for the Week of 20 to 27 November

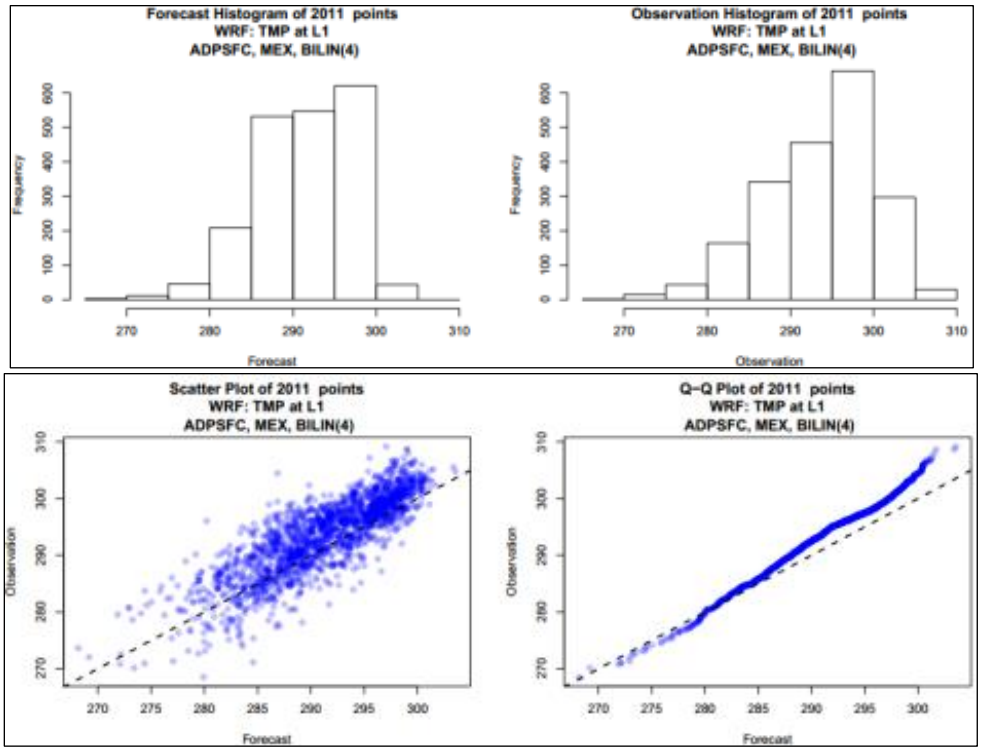


Figure 41. Wind Component (*u*) for the Week of 20 to 27 November

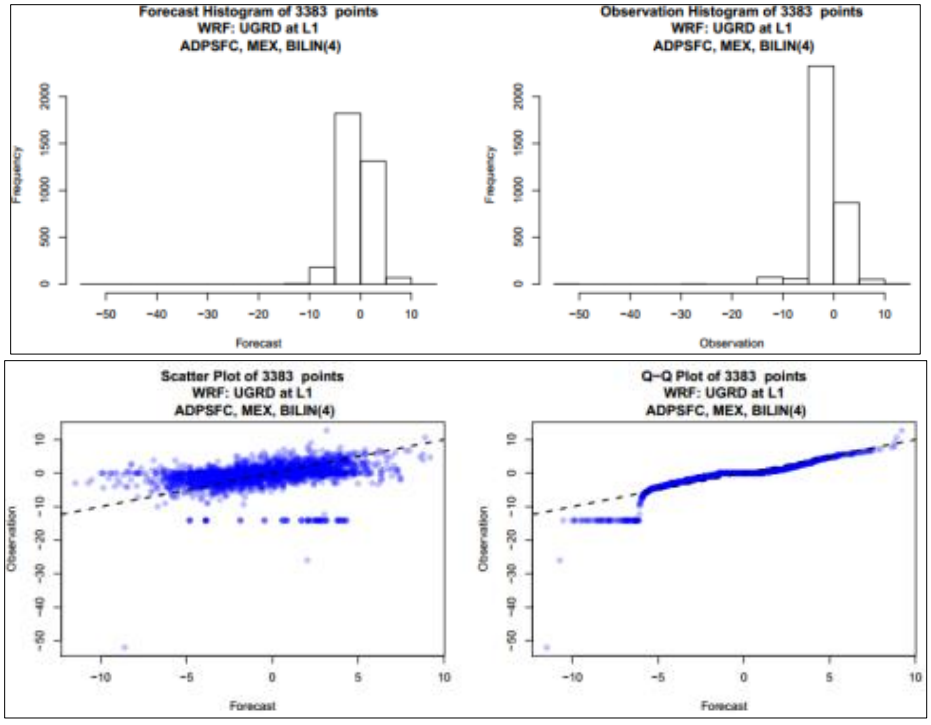


Figure 42. Wind Component (*v*) for the Week of 20 to 27 November

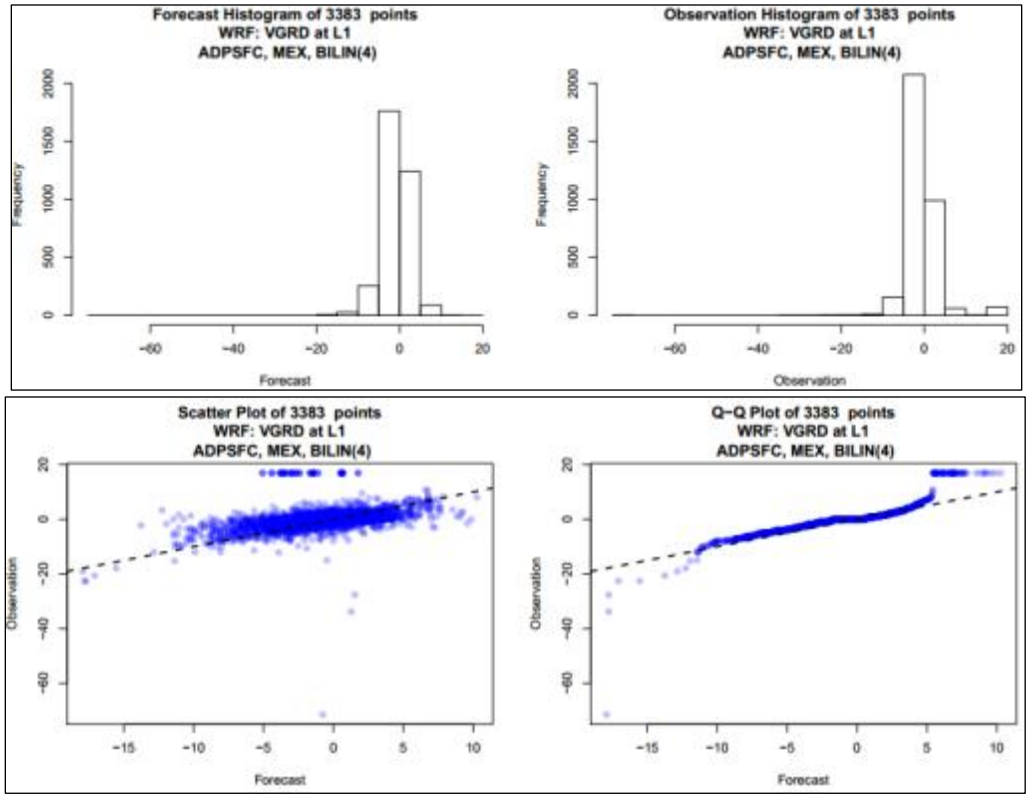
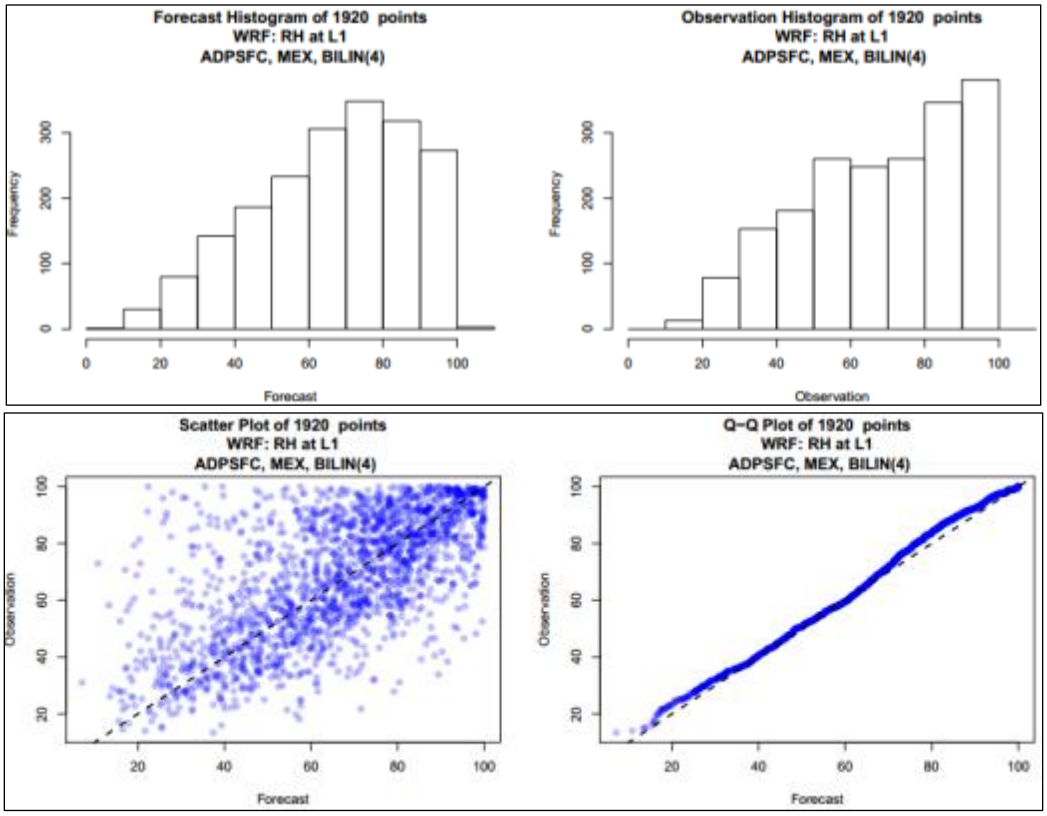
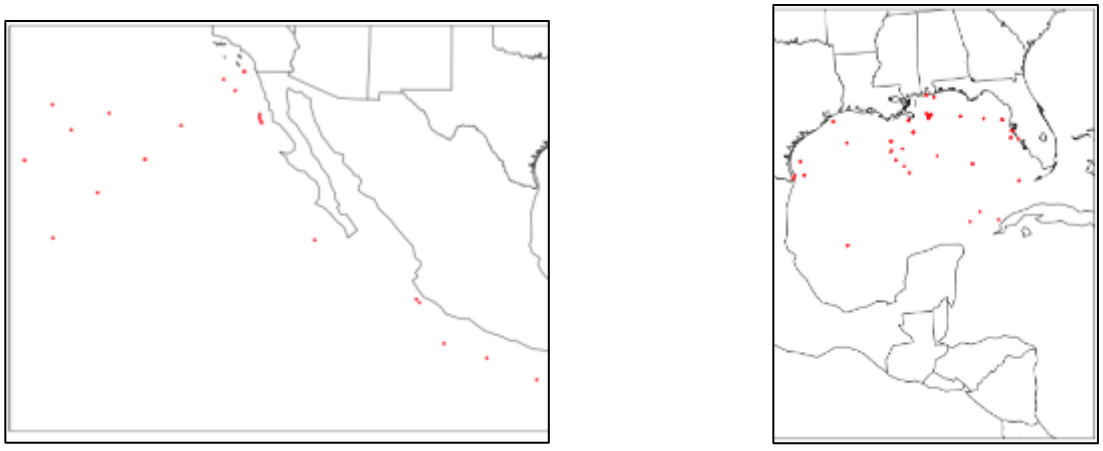


Figure 43. Relative Humidity for the Week of 20 to 27 November



A comparison between model results and buoys in the Gulf of Mexico showed a Pearson correlation coefficient larger than 0.66 for temperature and wind components, as presented in the following table. In the August-September period the agreement was lower, perhaps due to the hurricane season.



Pacific (left) and Gulf (right): buoys considered for the comparison between the model and measurements.

Table 16. Comparison of Model Results and Buoy Measurements in the Gulf of Mexico

	February 9–16	May 15–22	Aug 30–Sep 06	November 20–27
Temperature				
FBAR	289.59	297.16	302.31	296.23
FSTDEV	3.10	1.79	1.04	1.47
OBAR	287.98	297.01	301.78	296.36
OSTDEV	4.28	2.67	1.89	2.57
PR_CORR	0.90	0.80	0.41	0.80
RMSE	2.58	1.63	1.82	1.64
Relative humidity				
FBAR	74.90	76.05	80.93	82.90
FSTDEV	11.94	11.19	7.58	7.69
OBAR	69.29	71.53	77.34	78.61
OSTDEV	15.51	15.55	10.69	10.93
PR_CORR	0.77	0.74	0.38	0.66
RMSE	11.39	11.32	11.07	9.27
U wind component				
FBAR	-1.29	-1.64	-2.73	-3.56
FSTDEV	3.33	3.68	6.59	3.39
OBAR	-1.57	-2.30	-2.73	-3.50
OSTDEV	3.85	4.42	6.11	3.44
PR_CORR	0.70	0.85	0.66	0.78
RMSE	2.86	2.43	5.23	2.25
V wind component				
FBAR	-2.23	1.04	3.63	1.84
FSTDEV	5.20	5.03	8.70	4.81
OBAR	-1.98	0.88	2.43	1.54
OSTDEV	5.71	5.31	6.25	5.00
PR_CORR	0.77	0.78	0.61	0.81
RMSE	3.70	3.42	7.04	3.04

For the Pacific Ocean, the comparison between the model predictions and the buoy measurements also showed a Pearson correlation coefficient larger than 0.66 in February, May, and November.

Table 20. Comparison of Model Results and Buoys in the Pacific Ocean

	February 9–16	May 15–22	Aug 30–Sep 06	November 20–27
Temperature				
FBAR	291.42	294.46	296.79	294.80
FSTDEV	3.95	5.73	4.71	4.55
OBAR	291.54	294.95	296.85	294.82
OSTDEV	4.14	5.75	4.05	4.21
PR_CORR	0.90	0.94	0.91	0.94
RMSE	1.80	2.11	1.95	1.55
Relative humidity				
FBAR	78.23	80.50	86.06	78.46
FSTDEV	7.76	7.93	7.64	6.07
OBAR	77.21	77.19	80.47	78.63
OSTDEV	10.46	10.18	10.37	11.61
PR_CORR	0.25	0.28	0.01	0.22
RMSE	11.38	11.47	13.95	11.83
U wind component				
FBAR	-1.13	3.14	2.69	-1.33
FSTDEV	3.33	2.72	3.77	4.29
OBAR	-0.50	3.92	2.89	-0.26
OSTDEV	4.16	3.48	3.98	4.71
PR_CORR	0.73	0.63	0.48	0.73
RMSE	2.90	2.86	3.95	3.48
V wind component				
FBAR	-2.39	-2.82	-2.15	-2.92
FSTDEV	3.24	3.58	4.67	3.55
OBAR	-2.64	-3.19	-2.46	-3.62
OSTDEV	4.63	4.45	5.48	4.74
PR_CORR	0.76	0.71	0.64	0.75
RMSE	3.04	3.18	4.36	3.21

Statistical Analysis of Ozone and $PM_{2.5}$

A comparison between the model and data from the Mexico City Ambient Air Quality Monitoring Network (RAMA), was done by using observed data from RAMA for the four time periods under evaluation; for the month of May, only values for $PM_{2.5}$ were used for the sensitivity analysis.

In order to obtain the simulated ambient concentrations from the model, data from the model results were extractedby using NetCDF libraries.. Because of the size of the grid cells, only the value nearest to the station was used. The analysis is for the selected periods in 2011, and for the month of May (for the sensitivity analysis).

Table 17. Comparison of Model Results and Observations for $PM_{2.5}$

$PM_{2.5}$ (24h ave.)							
Period	Average Obs.	Average Model	Sdev Model	Sdev Obs.	RMSE	Max Obs.	Max Model
Feb 15–22	29.0	36.7	15.9	5.5	16.2	33.4	69.8
May 9–16	31.6	22.3	11.9	3.4	17.1	41.0	46.5
Aug 30–Sept 6	16.1	16.7	7.9	6.2	10.2	26.8	32.0
Nov	23.7	36.3	12.1	5.5	15.7	32.8	52.2

Table 18. Comparison of Model Results and Observations during May for $PM_{2.5}$

24-hour average for the complete month of May							
Average Obs.	Average Model	r	Sdev Model	Sdev Obs.	RMSE	Max Obs.	Max Model
33.58	33.10	0.08	11.51	7.35	12.95	50.63	55.34

Note: Concentrations in µg/m^3

Table 19. Comparison of Model Results and Observations for Ozone

Ozone (1hr Max value)							
Period	Average Obs.	Average Model	Sdev Model	Sdev Obs.	RMSE	Max Obs.	Max Model
Feb 15–22	70.7	68.1	9.8	12.3	13.0	89.2	83.3
May 9–16	99.9	87.6	15.4	12.0	20.0	116.7	106.7
Aug 30–Sept 6	56.1	55.0	14.1	20.4	24.4	95.2	74.5
Nov	62.4	65.7	13.0	20.7	28.8	89.0	88.4

Note: Observed and modeled values in ppb.

Appendix III: Sensitivity Analysis of Port and Ship Emissions

Sensitivity Analysis – Port Emissions

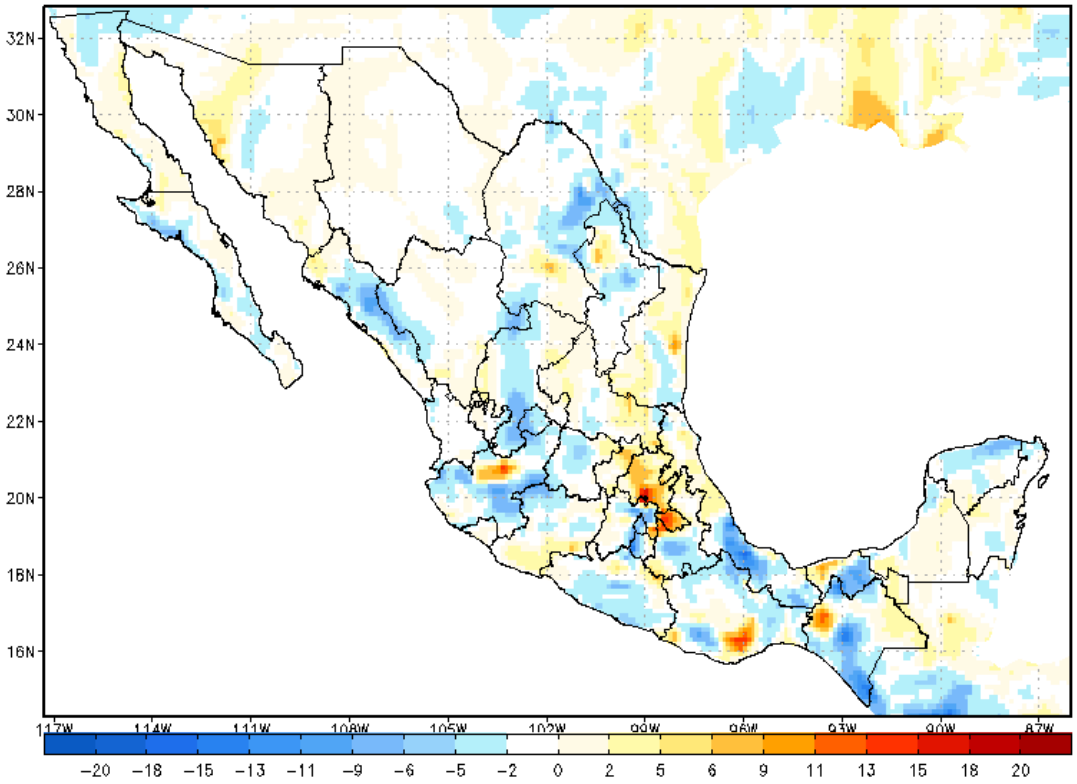
In order to evaluate the impact of port emissions on air quality, a set of simulations was performed for two emissions scenarios: the Marpol 2030 scenario (S1); and Marpol+ECA 2030 scenario (S2), using port emissions data obtained in July 2014 from Eastern Research Group, Inc. (ERG). The difference between ambient concentrations (Dif1) for $PM_{2.5}$ and O_3 in the two scenarios (S1-S2) was computed using the July 2014 data;and the same procedure was followed for estimating the difference for updated port emissions ("Dif2 (S1-S2)u").

Table 20. Sensitivity Scenarios

Scenario	Description
S1	Marpol emissions, 2030
S2	Marpol emissions + ECA, 2030
S1u	Marpol emission + Port emissions update
S2u	Marpol emissions + ECA + Port emissions update
(S1-S2)-(S1-S2)u	Difference between Scenarios with updated emissions.

Figure 48 shows the difference between scenarios "(Dif1 - Dif2)" for 24-hour average values of $PM_{2.5}$. From the results, it appears that port emissions can induce changes in concentrations of around (+/-) 20 $\mu g/m^3$. The change varies in different areas of the country; some places, such as Mexico City and Monterrey, saw a negative variation in $PM_{2.5}$ concentrations; however, other areas, such as Guadalajara, Querétaro, Tlaxcala and Pachuca (Central Mexico) saw a positive change. A negative value implies that Dif2 is larger than Dif1. The benefit was computed by the difference in ambient concentrations, using I =Tb (β) (ΔC) (Population). In this case, ΔC=Dif1 or Dif2. In principle, if there were greater differences, ΔCwould lead to greater benefits. A positive value implies the opposite.

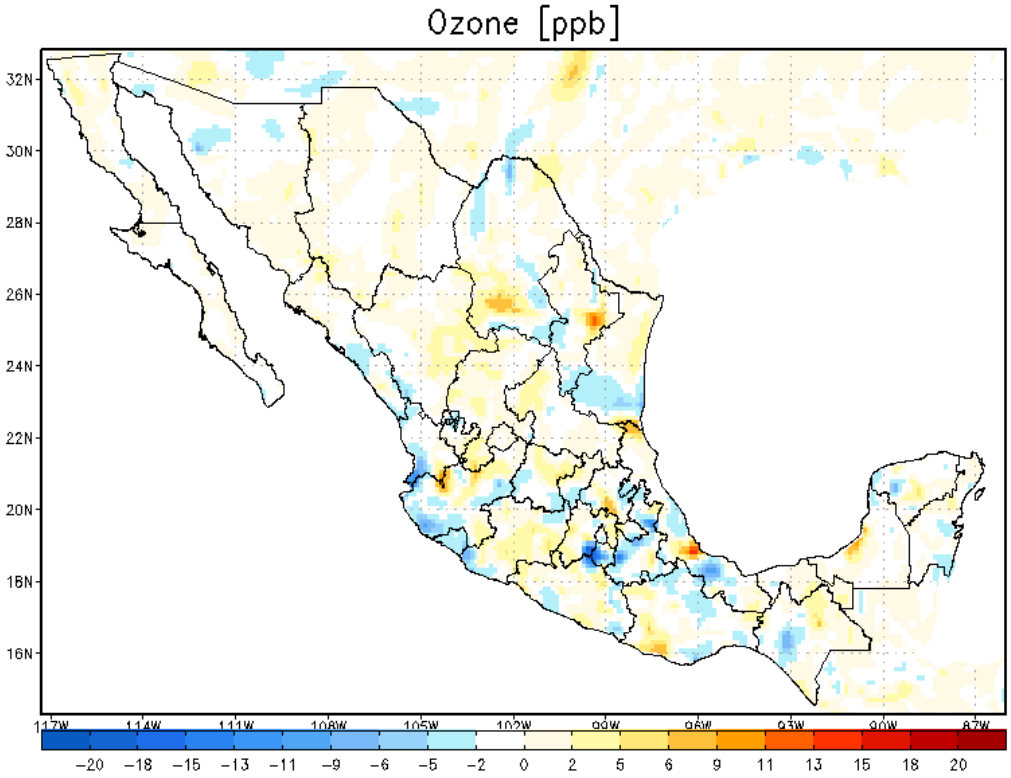
Figure 44. Difference in $PM_{2.5}$ Concentrations between (S1-S2)-(S1-S2)u



Note: Concentrations in µg/m^3

Figure 49 shows the difference between scenarios (Dif1 - Dif2) for the maximum concentration of ozone in one hour, with ozone concentrations varying by around +/- 10 ppb. The cities of Cuernavaca, Puebla, Tlaxcala and Querétaro had larger benefits in contrast with Guadalajara and Monterrey, where the benefits were less pronounced.

Figure 45. Difference in Ozone Concentrations between (S1-S2)-(S1-S2)u



Note: Concentrations in ppb

Conclusions:

- Updating the port emissions data results in certain regions in Mexico having a better air quality, withothers having a poorer air quality.
- The economic benefits calculated using updated port emissions data were lower than the economic benefits calculated using original port emissions data.
- Benefits were approximately 14% lower using updated port emissions for the month of May 2011, only. This difference falls within the confidence interval.

Sensitivity Analysis – Ship Emissions

In order to evaluate the impact of ship emissions on air quality, a set of simulations was conducted using the base-case, S1 (Marpol 2030) emissions scenario presented in Table 2. For these simulations, $PM_{2.5}$ and ozone concentrations were used, according tothe following scenarios:

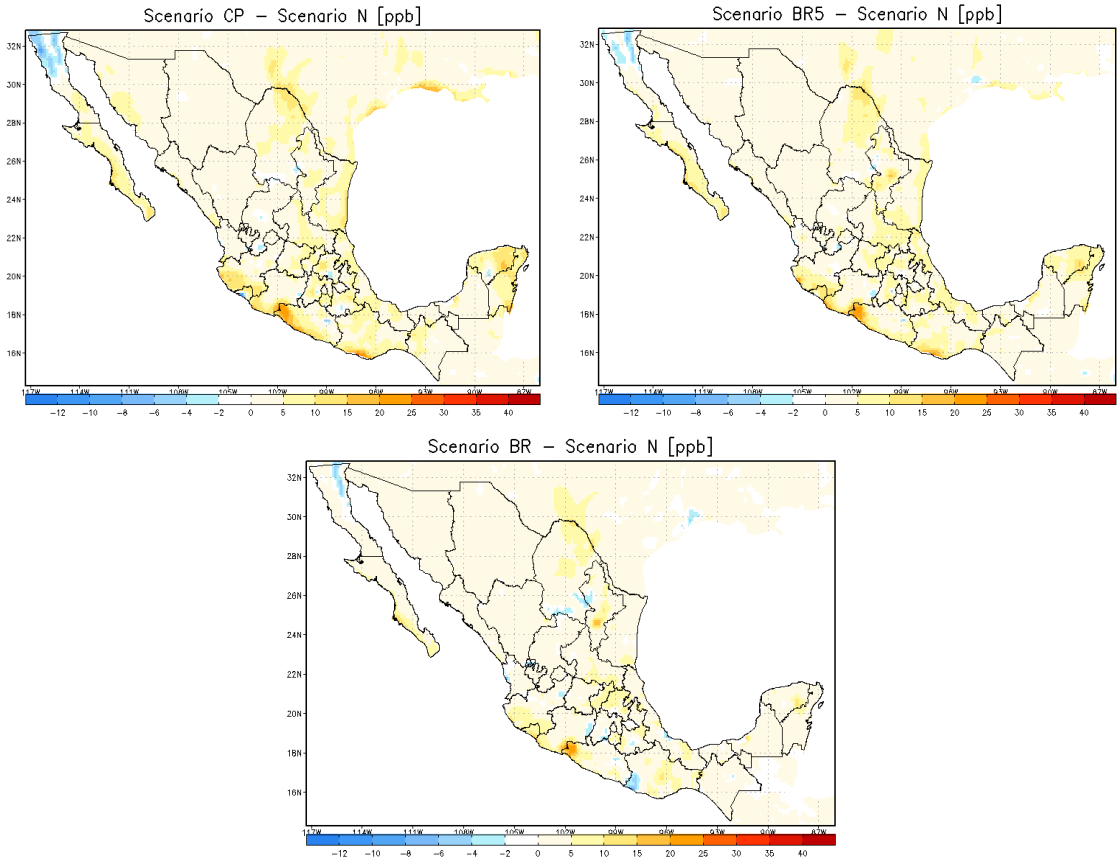
CP	Updated Port Emissions + 100% ship emissions
BR5	Updated Port Emissions + 50% ship emissions
BR	Updated Port Emissions + 10% ship emissions
N	Updated Port Emissions + 0% ship emissions

In order to compare these scenarios, the population-weighted concentration (CPW) was used, combining the air quality modeling results and the population data. A decrease of 50% in ship emissions drove a reduction of 25% in the CPW, while a reduction of 90% in ship emissions could result in a reduction in the CPW of up to 50%. There were certain areas where the reduction in ambient concentrations was larger, but because there was no population in those areas, they were not taken into account for the CPW.

It should be noted that an evaluation of marine, forest and agricultural ecosystems could result in an increase in benefits, due to a reduction in ambient pollutant concentrations; however, such an evaluation is outside the scope of this project.

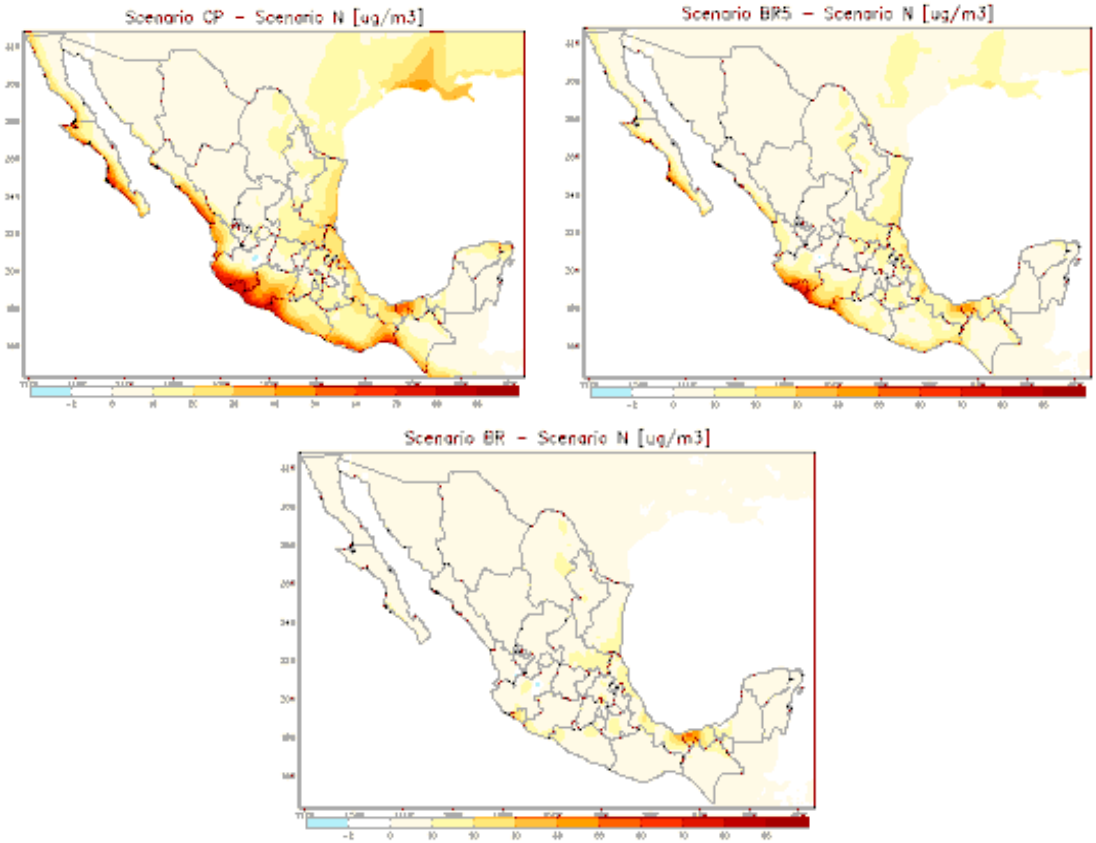
The results for ozone and $PM_{2.5}$ concentrations are shown in Figures 50 and 51, respectively. They indicate that reductions in ship emissions have an important impact on concentrations inland; hence the importance of reducing ship emissions.

Figure 46. Differences in Ambient Concentration of Ozone



Note: Larger reductions are observed in the top left (CP-N) and top right (BR5-N) panels; with smaller reductions in the bottom panel (BR-N). Concentraions in ppb.

Figure 47. Differences in Ambient Concentration of $PM_{2.5}$



Note: Larger reductions were observed on the top left (CP-N) and top right (BR5-N) panels; with smaller reductions in the bottom panel (BR-N). Concentrations in $\mu g/m^3$

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