**Final Report**

# Shipping Lane Processing for EPS3 and TexAQS II Ship Emissions Rate Data Comparison to Enhance the Shipping Emissions Inventory for TCEQ Modeling

Work Order No. 582-07-84006-FY09-03

Prepared for

Texas Commission on Environmental Quality
12118 Park 35 Circle
Austin, Texas 78753

Prepared by

Uarporn Nopmongcol
Christian Lindhjem
Gary Wilson
Michele Jimenez
Tim Sturtz
Greg Yarwood

ENVIRON International Corporation
773 San Marin Drive, Suite 2115
Novato, CA 94998

August 2009

# TABLE OF CONTENTS

**Page**

**1. INTRODUCTION ..... 1-1**

**2. TASK 1: INVENTORY ADJUSTMENTS TO ENHANCE THE SHIPPING EMISSIONS INVENTORY FOR TCEQ MODELING ..... 2-1**

**3. TASK 2: NEW SHIPPING LANE PROCESSING CAPABILITY IN EPS3 ..... 3-1**

3.1. New EPS3 Modules for Shipping Inventories ..... 3-1
3.2. Testing the new EPS3 shipping emissions processor using two inventories near Texas Coast ..... 3-4
3.3. Conclusions and Recommendations ..... 3-16

**4. REFERENCES ..... 4-1**

## TABLES

Table 2-1 Fuel consumption from large marine engines ..... 2-2
Table 2-2 TexAQS Emission Factors (Table 4, Williams, 2009) ..... 2-2
Table 2-3 EPA Emission Factors. ..... 2-3
Table 2-4 Emission Factor Comparison based on EPA Fuel Use. ..... 2-3
Table 3-1 Data input into PRESHP model. ..... 3-2
Table 3-2 SCC/vessel type cross-reference file. ..... 3-4
Table 3-3 SCC/vessel type cross-reference file used with the TCEQ inventory. ..... 3-12
Table 3-4 12-km domain wide ship emissions distributed to each CAMx vertical layer ..... 3-13
Table 3-5 Shipping emissions of criteria pollutants by port within the 12-km domain. ..... 3-15

## FIGURES

Figure 3-1 PRESHP shipping lane parameters. ..... 3-1
Figure 3-2 Houston-Galveston shipping lanes (top); zoom-in (bottom); TCEQ shipping lanes are displayed as dots and EPA shipping lanes are displayed as line segments. ..... 3-6
Figure 3-3 STEEM relative (darkened to reflect higher) OGV NOx emissions near the Texas coast. ..... 3-7
Figure 3-4 Shipping NOx Emissions (a-c) at 500 m resolution and (d-f) at 2 km resolution. ..... 3-9
Figure 3-5 Shipping NOx Emissions at 12 km resolution from (a) TCEQ inventory, (b) EPA inventory, and (c) STEEM inventory. ..... 3-13

# 1. INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ) is responsible for air quality planning in Texas including the Texas Coast in the Gulf of Mexico. Ocean-going vessels (OGV) emissions are subject to International Maritime Organization (IMO) regulations and emission reductions for ocean-going ships are expected in the near future. Texas has several major ports along the Texas Gulf Coast and an intra-coastal waterway that contribute NOx emissions and influence air quality in Texas. The expansion of TCEQ's modeling domains to include a large portion of the Gulf of Mexico and the Atlantic Coast has also increased the importance of properly modeling ship emissions.

ENVIRON assisted TCEQ by performing two tasks. The first task was to use data from the Texas Air Quality Field Study II (TexAQS II) to evaluate emission factors for OGVs and provide TCEQ with recommendations for improving the existing shipping emissions inventory. The second task was to improve TCEQ's emission modeling tools to better handle OVG emissions in shipping lanes. These two tasks will help improve the shipping emission inventories used in future Texas SIP modeling.

During TexAQS II, a comprehensive research initiative to better understand the causes of air pollution, NOAA scientists intercepted ship plumes while cruising on the Ronald H. Brown (RHB) Research Vessel. These data were analyzed and average emission factors were developed by vessel type and engine speed (slow vs. medium speed diesel engines). The first task compared emission factors developed from the RHB collected data to the latest emission factors used in calculating ship emission inventories by the EPA as reported in EPA 420-D-07-007.

Emissions processing systems, such as EPS3 used by TCEQ, typically allocate emissions to grid cells by treating them as area sources, point sources, or mobile-source links. Shipping emissions are characterized by shipping lanes and because some ships have tall exhaust stacks shipping emissions may need to be released into aloft vertical layers. The area source modeling methodology distributes emissions spatially according to gridded surrogates and all area source emissions go into the surface layer of the air quality model. The gridded surrogates are usually created on a county level which is not applicable to open-water areas. The point source methodology places emissions in specific grid cells and allows emissions to be distributed to vertical layers. However, modeling shipping emissions as point sources requires pre-processing of emissions outside EPS3 to determine point source locations. This pre-processing is cumbersome and must be repeated if the modeling grid is revised. Modeling mobile sources as links allows emissions to be distributed along link segments and is useful for modeling roads and railways. Shipping lanes could also be treated as links, but the link-based methodology assumes that links have zero width and cannot distribute emissions to aloft layers. The objective of the second task was to build into EPS3 the ability to process shipping emissions that are defined by shipping lane locations and output emissions as surface or elevated sources, as prescribed by the user and plume height parameters. The shipping lane methodology has similarities to the EPS3 capability for processing link-based emissions (e.g., roads) but differs in that shipping lanes may be wider than a model grid-cell. This task will help increase the efficiency of providing timely and accurate modeling results for upcoming ozone SIPs.

The evaluation of inventory emissions factors using data from the TexAQSII study is described in Section 2 of this report. Section 3 presents the new EPS3 shipping lane processing capability, discusses modeling results and provides modeling recommendations.

# 2. TASK 1: INVENTORY ADJUSTMENTS TO ENHANCE THE SHIPPING EMISSIONS INVENTORY FOR TCEQ MODELING

During the Texas Air Quality Field Study II (TexAQS II), NOAA scientists intercepted ship plumes while cruising on board the NOAA research vessel Ronald H. Brown. These data were analyzed and average emission factors were developed by vessel type (Williams et al., 2009). The study area included the Gulf of Mexico, Galveston Bay, and the Houston Ship Channel, and measurements were taken from early August through mid-September, 2006. At least 274 plumes were associated with a known vessel and many more unidentified ship plumes were measured from vessels underway, anchored or docked. The measured data included:

- Total oxidized nitrogen (NOy)
- Sulfur dioxide ($SO_2$)
- Carbon monoxide (CO)
- Formaldehyde (HCHO)
- Ethylene ($C_2H_4$)
- Carbon dioxide ($CO_2$)

The plume measurements of CO, NOy and $SO_2$ were converted to emission factors for CO, NOx and $SO_2$ relative to fuel consumption by calculating fuel consumption from the measured plume $CO_2$.

The current Environmental Protection Agency (EPA) guidance on preparing emissions inventories for commercial marine sources as provided in the ICF (2009) includes emission factors for ocean-going vessels (OGV). This guidance forms the basis for OGV emission inventories used, for example, in EPA's proposed emissions control area (ECA).

This task compared real-world OGV emission factors from the TexAQSII study (Williams et al., 2009) and EPA best practices OGV emission factors.

### *Fuel Consumption*

Fuel consumption must be accounted for when comparing emission factors measured as grams of pollutant per kilogram of fuel by Williams et al.(2009) with the EPA best practices emission factors (ICF, 2009) expressed as grams of pollutant per kilowatt-hour. Fuel consumption rates were provided in both the EPA and the TexAQSII studies.

The TexAQSII study reported specific fuel consumption rates for Slow Speed Diesel (SSD) and Medium Speed Diesel (MSD) marine engines. The specific fuel consumption for SSD engines is based on an underway vessel with an engine rated at 11 MW operating at 75% load. The MSD engine fuel consumption is based upon a docked vessel operating a 2.6 MW engine at 50% load. The resulting fuel consumption rates of 0.17 kilograms of fuel per kilowatt-hour for both engine types were derived from engine manufacturer (MAN Diesel) reported efficiency as brake specific fuel consumption (BSFC). BSFC is a measure of the fuel consumed divided by the work performed by the engine.

The EPA best practices report provides specific fuel consumption estimates (Table 2-9 of ICF, 2009) when operating above 20% engine load. Table 2-1 compares the reported engine fuel

efficiency estimates. The manufacturers reported fuel efficiency used by the TexAQSII study is substantially better (9% to 25%) than the fuel efficiency used in the EPA best practices report.

**Table 2-1.** Fuel consumption from large marine engines.

| EPA Fuel Use (kg Fuel/kWh) | |
|---|---|
| **Engine Speed** | **Fuel Use** |
| SSD – Residual Fuel | 0.195 |
| SSD – Distillate Fuel | 0.185 |
| MSD – Residual Fuel | 0.213 |
| MSD – Distillate Fuel | 0.203 |
| **TexAQS Fuel Use (kg Fuel/kWh)** | |
| **Engine Speed** | **Fuel Use** |
| SSD | 0.17 |
| MSD | 0.17 |

### *Emission Factors*

Williams et al. (2009) reported the mean and median emission factors for NOx, $SO_2$ and CO determined by the TexAQSII study as grams of pollutant per kilogram of fuel burned. The emission factors are shown in Table 2-2 along with uncertainty limits (except for HCHO). The fuel type for the SSD and MSD engines was classified as residual oil (RO) or Marine Gasoil (MGO) based on sulfur content (Williams et al., 2009).

**Table 2-2.** TexAQS Emission Factors (Table 4, Williams, 2009).

| TexAQS Emission Factors (g Pollutant/kg fuel) | | | | | |
|---|---|---|---|---|---|
| **Mean (uncertainty)** | | | | | |
| **Engine Speed** | **Fuel Type** | **NOx** | **SO2** | **CO** | ***HCHO*** |
| SSD | RO | 79.6 (27.4) | 27.8 (15.5) | 11.8 (11.7) | 0.15 |
| MSD | MGO | 61.5 (22.9) | 6.3 (9.5) | 11.0 (14.2) | 0.15 |
| **Median** | | | | | |
| **Engine Speed** | **Fuel Type** | **NOx** | **SO2** | **CO** | ***HCHO*** |
| SSD | RO | 63.7 | 27.3 | 6.3 | |
| MSD | MGO | 58.3 | 3.3 | 6.9 | |

The EPA best practices document (ICF, 2009) provided emission factors for NOx, SOx, CO and total hydrocarbons (THC) in grams per kilowatt-hour. HCHO emission factors were calculated from THC through the use of a THC to TOG conversion and HCHO speciation factors of 3.27% and 8.5%. The current EPA speciation for formaldehyde from marine vessel emissions is considered to be zero. However, the Western Regional Air Partnership (WRAP) previously used 3.27% formaldehyde by weight based upon data from light-duty diesel vehicles, and this speciation was also used for heavy-duty diesel vehicle emissions. EPA uses a different profile for non-marine offroad diesel engines of 8.5% formaldehyde by weight.

The EPA emission factors (ICF, 2009) were converted from grams of pollutant per kilowatt-hour to grams of pollutant per kilogram of fuel by dividing by the EPA fuel consumption (BSFC) as shown in Table 2-3.

**Table 2-3.** EPA Emission Factors.

| EPA Emission Factors (g Pollutant/kg fuel) except BSFC | | | | | | |
|---|---|---|---|---|---|---|
| **Engine Speed** | **Fuel Type** | **NOx** | **SOx** | **CO** | **HCHO (3.27%, 8.5%)*** | **BSFC (kg/kW-hr)** |
| SSD | RO | 92.8 | 52.8 | 7.2 | 0.108, 0.280 | 0.195 |
| MSD | MGO | 65.0 | 9.8 | 5.4 | 0.086, 0.224 | 0.203 |

* Converted from THC of 0.6 g/kg for SSD and 0.5 g/kg for MSD with formaldehyde speciation fractions of 3.27% and 8.5%.

In order to provide an accurate depiction of the TexAQS emissions a temperature and humidity correction factor should be calculated in accordance with the official emission factor measurement method. However the TexAQS report did not provide exact temperature and humidity data throughout the month of emission analysis thus corrections were not performed. Applying a single representative temperature and humidity correction would be uncertain due to the large range of climate conditions that exist between the Gulf of Mexico and the furthest inland ship plume samples. Typically, an increase in temperature would result in higher NOx emissions and an increase in humidity would result in lower NOx emissions. ENVIRON (2004) estimated the temperature and humidity corrections for the Houston area summer conditions and found a maximum NOx adjustment of 11% for average conditions in Galveston county during an ozone episode that represented summer conditions.

### *Results and Recommendations*

With emission factors converted to similar units, a comparison of the TexAQS study results and EPA best practices emission factors can be made. Ratios of the TexAQS II study emission factors to the EPA best practices emission factors are shown in Table 2-4.

**Table 2-4**. Emission Factor Comparison based on EPA Fuel Use.

| Comparison of Mean Emission Factors (TexAQS/EPA) | | | | | |
|---|---|---|---|---|---|
| **Engine Speed** | **Fuel Type** | **NOx** | **SOx** | **CO** | **HCHO (3.27%, 8.5%)** |
| SSD | RO | 86% | 53% | 164% | 139%, 54% |
| MSD | MGO | 95% | 64% | 204% | 174%, 67% |

The NOx emission factors appear to be slightly overestimated by EPA, but the uncertainty TexAQS II NOx emission factors (Table 2-3) is greater than the difference between the EPA and TexAQS II emission factors. In addition, applying a likely temperature and humidity adjustments to the EPA estimates (likely about an 11% downward adjustment, as discussed above) would make the adjusted EPA NOx emission factors nearly identical to the mean TexAQS results. Therefore, the TexAQS II study results provide no basis for modifying the EPA best practices NOx emission factors.

The SOx emission factors are highly dependant on fuel sulfur content suggesting that the vessels sampled during TexAQS II were using fuel with lower sulfur, on average, than assumed in the EPA best practices SOx emission factors. This suggests that the larger slow speed engines were primarily using fuel with sulfur levels of about 1.4% while the smaller medium speed engine fuel was about 0.3%. These findings seem surprising and the fuel sulfur levels should be investigated to determine whether the default 2.7% residual fuel sulfur levels should be adjusted downward.

The CO emission measurements are very uncertain with the uncertainty range equivalent to the mean values measured. While the mean values were substantially higher than EPA default, the measurement uncertainty is too high to recommend changing the emission factor.

The formaldehyde emission factors from EPA using formaldehyde speciation fractions of 3.27% and 8.5% results in an emission factor range that falls on either side of the measured emission factors. This suggests that the formaldehyde speciation profile of ocean going vessels lies somewhere between 3.27% and 8.5%. Further study is warranted to improve the speciation profiles for hydrocarbon emissions from OGV engines.

# 3. TASK 2: NEW SHIPPING LANE PROCESSING CAPABILITY IN EPS3

The objective of this task is to enhance the current version of EPS3 (v3.11) to include shipping lane processing capabilities. This section documents the emissions data sources, modeling methodology, testing, and results.

## 3.1 NEW EPS3 MODULES FOR SHIPPING INVENTORIES

Two new modules were created to enhance EPS3 the ability to process shipping emissions: 1) PRESHP (**PRE**processor for **SH**i**P**ping emissions) and 2) PSTSHP ((**P**o**ST** processor for **SH**i**P**ping source emissions). PRESHP must be run prior to PSTSHP.

PRESHP reads the shipping lane locations and criteria pollutant emissions, provides basic input data validation, distributes shipping lane emissions to grid cells, provides the standard EPS3 output reports, and writes the standard EPS3 formatted emission binary records (EMBR) that are compatible with the other EPS3 modules.

The shipping lane is defined by the end point coordinates of the lane center line and the lane width at the beginning and end points. The lane center in Figure 3-1 below is depicted by the line AB. The lane width is specified by the distance C at endpoint A, and distance D at endpoint B. PRESHP spatially allocates the shipping lane emissions by first allocating the emissions to the cells along the shipping lane center line AB, similar to LBASE. Then each center line cell estimate is further distributed to cells in the perpendicular direction from the center line to the lane boundaries. This ensures that higher emissions density occurs where shipping lanes are narrower e.g., near ports.

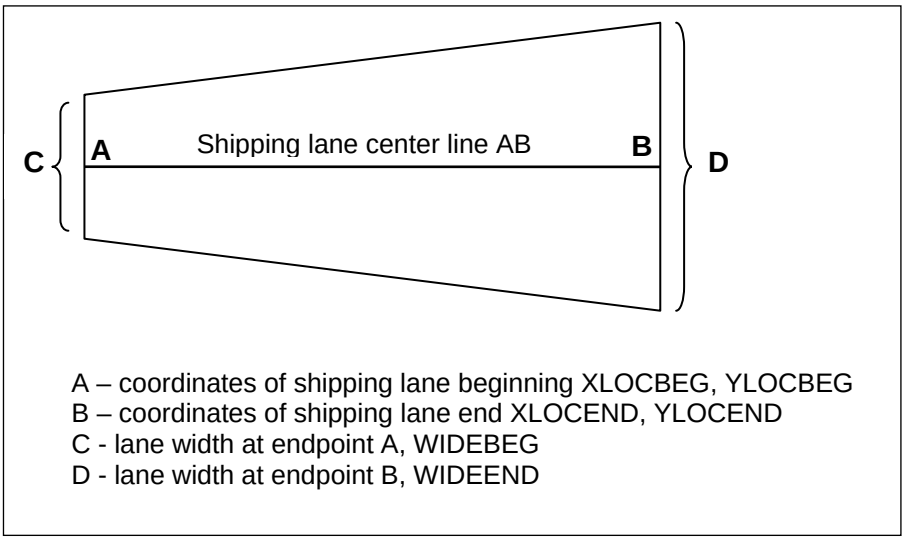



**Figure 3-1.** PRESHP shipping lane parameters.

Some existing shipping lane inventories have been pre-gridded in a GIS system and reported as 'point' sources. These data can be processed in PRESHP by defining the point A equal to the point B which will result in a zero length shipping lane. These point source shipping emissions will be gridded to a single grid cell.

PRESHP requires two input files. The first input file is the USERIN file, from which PRESHP reads the following packets:

/CRITERIA POLLUTANT/
/DATE/
/REGION/
/COUNTY/
/CRITERIA TABLES/

The second input file is the shipping emission estimates specified by shipping lane (Table 3-1).

**Table 3-1** Data input into PRESHP model.

| Line | Variable | Columns | Type | Description |
|---|---|---|---|---|
| 1+ | INFIPS | 1-5 | C | FIPS state/county/shipping lane code |
| | INSBRG | 7-11 | C | Subregion code (port ID) (optional) |
| | INSCC | 13-22 | C | Standard Industrial Classification (SCC) |
| | INVESL | 24-33 | C | Vessel Type (optional) |
| | IPEROD | 35-36 | C | Period Type<br>Blank = annual<br>PO = Peak O3 typical weekday<br>PC = Peak CO typical weekday<br>AD = Average Day<br>S = Specified interval |
| | IBEGDT | 38-45 | I | Begin Period (YYMMDDHH) |
| | IENDDT | 47-54 | I | End Period (YYMMDDHH) |
| | XLOCBEG | 56-65 | R | X coordinate of beginning of channel link (km) |
| | YLOCBEG | 67-76 | R | Y coordinate of beginning of channel link (km) |
| | WIDEBEG | 78-87 | R | Channel width at beginning of channel (km) |
| | XLOCEND | 89-98 | R | X coordinate of end of channel link (km) |
| | YLOCEND | 100-109 | R | Y coordinate of end of channel link (km) |
| | WIDEEND | 111-120 | R | Channel width at end of channel (km) |
| | INZONE | 122-123 | I | UTM Zone (or zero) |
| | INPOL | 125-129 | I | Pollutant Code |
| | EMISSHIP | 131-140 | R | Emissions of specified pollutant<br>Units depend on the Period Type<br>Annual = tons/year<br>PO/PC = tons/typical weekday<br>AD = tons/average day<br>S = tons/period (the period is specified using the beginning and ending time fields) |

PSTSHP determines the distribution of shipping emissions to vertical layers. Emissions distributed to the lowest layer are written to the CAMx surface emissions file. All other shipping emissions are written to the elevated files, the stack list and corresponding elevated emission file. Plume heights for elevated ship emissions are specified as a physical height (e.g., 60 m) which PSTSHP converts to CAMx layers using user input data for the layer heights. The PSTSHP module reads an EMBR file and is executed after all other processing of the shipping source data, prior to PIGEMS and MRGUAM.

PSTSHP requires three user input files: USERIN, an EMBR shipping source emissions file, and the vessel/stack cross reference file. PSTSHP reads the following packets from USERIN:

/LAYERS/
/DATE/
/REGION/
/COUNTY/
/SPECIES LIST/
/CRITERIA TABLES/
/SPECIE TABLES/

The /LAYERS/ packet provides the vertical layer structure for generating the layer specific elevated shipping source emissions. The layers must be specified in increasing heights where the specified height indicates the top of the layer above ground level. No default is assumed. For example,

```
/LAYERS/
Ht AGL (m) Layer 1 : 33.9
Ht AGL (m) Layer 2 : 84.9
Ht AGL (m) Layer 3 : 170.5
Ht AGL (m) Layer 4 : 256.8
Ht AGL (m) Layer 5 : 343.9
Ht AGL (m) Layer 6 : 431.7
Ht AGL (m) Layer 7 : 520.2
Ht AGL (m) Layer 8 : 609.5
Ht AGL (m) Layer 9 : 699.6
Ht AGL (m) Layer 10 : 790.5
Ht AGL (m) Layer 11 : 928.3
Ht AGL (m) Layer 12 : 1068
Ht AGL (m) Layer 13 : 1209.6
Ht AGL (m) Layer 14 : 1353.2
Ht AGL (m) Layer 15 : 1597.1
Ht AGL (m) Layer 16 : 1847
Ht AGL (m) Layer 17 : 2103.2
Ht AGL (m) Layer 18 : 2366
Ht AGL (m) Layer 19 : 2690.3
Ht AGL (m) Layer 20 : 3026.2
Ht AGL (m) Layer 21 : 3373.4
Ht AGL (m) Layer 22 : 4106.4
Ht AGL (m) Layer 23 : 4898
Ht AGL (m) Layer 24 : 5835.9
Ht AGL (m) Layer 25 : 6960.9
Ht AGL (m) Layer 26 : 9166.6
Ht AGL (m) Layer 27 : 12096.6
Ht AGL (m) Layer 28 : 15179.1
 /END/
```

The third input file, the SCC/vessel cross reference file, specifies the plume bottom and plume top heights by SCC and vessel type. This file is essentially a lookup table that assigns an appropriate plume height for each SCC and vessel Type. Currently most inventories do not have

vessel type details; however, as this information becomes available it can be used in the lookup to more accurately represent the vertical distribution of emissions. Similar to other EPS3 lookup packets, the best match hierarchy is supported. Table 3-2 indicates the file format of the SCC/vessel cross reference file.

**Table 3-2** SCC/vessel type cross-reference file.

| Line | Variable | Columns | Type | Description |
|---|---|---|---|---|
| 1+ | ASCMAP | 1-10 | C | Standard Industrial Classification (SCC) |
| | VSLMAP | 12-21 | C | Vessel Type (optional) |
| | PLUMEBOT | 23-32 | R | Minimum Stack Height (m.) |
| | PLUMETOP | 34-43 | R | Maximum Stack Height (m.) |

One example of a cross reference:

All vessels for commercial marine have stack heights between 34 and 58 meters.

```
2280000000                34   58 ! Com.Marine All
```

Another example with far more detail, should it be available, may assemble:

```
2280000000                34   58 ! Com.Marine All
2280001000                34   58 ! Total, Coal
2280001010                40   60 ! Coal Ocean
2280001010   LCruise      50   60 ! Coal Ocean
2280001010   Tanker       55   60 ! Coal Ocean
2280001020   Tug           8   10 ! Coal Harbor
2280001040   CARRIER      40   55 ! Coal Military
2280002000                34   58 ! Total, Diesel
2280002010                40   60 ! Diesel Ocean
2280001010   LCruise      50   60 ! Diesel Ocean
2280001010   Tanker       55   60 ! Diesel Ocean
2280002020                 4   10 ! Diesel Harbor
2280001020   Tug           8   10 ! Diesel Harbor
2280002040                34   58 ! Diesel Military
2280001040   CARRIER      40   55 ! Diesel Military
2280003000                34   58 ! Total, Residual
2280004000                34   58 ! Total, Gasoline
```

The PIGEMS module combines elevated point source outputs from PSTSHP with other EPS3 modules and generates a CAMx-ready binary point source file. PIGEMS prevents elevated shipping emissions from being PiGged or regrouped as co-located points.

## 3.2 TESTING THE NEW EPS3 SHIPPING EMISSIONS PROCESSOR USING TWO INVENTORIES NEAR TEXAS COAST

Two inventories were processed through the new shipping emissions processor to test and demonstrate the shipping processing capabilities of EPS3. One inventory was compiled by TCEQ; the other was based on EPA's inventory prepared for evaluating a potential emissions control area (ECA). The shipping inputs were processed through EPS3 to produce CAMx-ready shipping emissions, with both surface and elevated sources for the TCEQ's 12-km East Texas modeling domain. Also, 2 km and 500 meter grid resolutions were used to examine the results at high resolution.

### *Data Sources*

The marine shipping emissions can be broadly classified into near-port and inter-port. For near-port, two marine shipping emissions inventories are available for modeling the port of Houston-Galveston-Freeport; 1) TCEQ's SIP modeling inventory and 2) EPA's inventory prepared for evaluating a potential ECA.

1. TCEQ inventory: Shipping emissions in TCEQ's 2005 inventory are represented by a set of point sources (with stack parameters) along shipping lanes (shown as "dots" in Figure 3-2). Points are spaced about 1-km apart. Portions of the intra-coastal waterway are also included.

2. EPA inventory: The EPA report "Emission Inventories for Ocean-Going Vessels Using Category 3 Propulsion Engines In or Near the United States" (Draft Technical Support Document EPA 420-D-07-007, Dec 2007) led to the development of emission inventories for ocean-going vessels in or near the U.S. for large ships for years 2002, 2020, and 2030. The inventories include emissions from both propulsion and auxiliary engines on vessels using Category 3 propulsion. 2002 EPA near-port shipping emissions are classified into three zones: 1) in-port zone, 2) reduced speed zone (RSZ), and 3) cruising zone which extend 25 nautical miles from the terminus of the RSZ for deep sea ports. In-port is represented as a single point location. Reduced speed zone and cruising zone are represented by shipping lanes as shown in Figure 3-2 (green and yellow line, respectively). The intra-coastal waterway is not included.

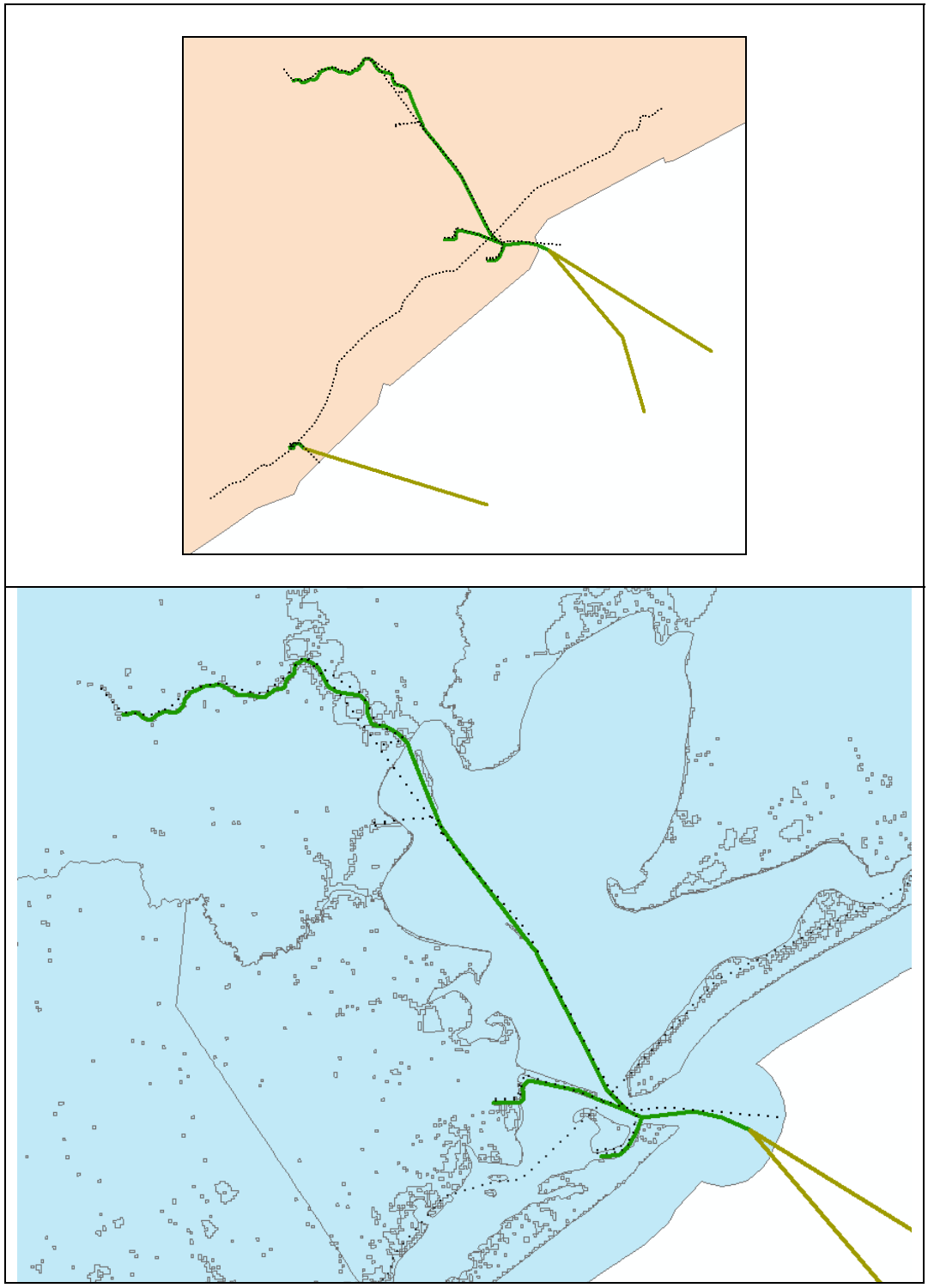


**Figure 3-2.** Houston-Galveston shipping lanes (top); zoom-in (bottom); TCEQ shipping lanes are displayed as dots and EPA shipping lanes are displayed as line segments.

Near-port emissions need to be combined with the inter-port emissions to produce a comprehensive regional shipping emissions inventory. Inter-port emissions were based on the Waterway Network Ship Traffic, Energy, and Environmental Model (STEEM) developed by the University of Delaware as a comprehensive approach to quantify and geographically represent ship traffic, emissions, and energy consumption from ocean-going vessels. The model estimates emissions using historical shipping activity, ship attributes, and activity-based emission factor information. These inputs were assembled using a GIS platform that also contains an empirically derived network of shipping lanes from global ship reporting databases. These data were used to spatially define the direction and width of each shipping lane in the waterway network. STEEM internally represents emissions using shipping lanes which would be compatible with the new PRESHP capability of EPS3. However, we were unable to obtain the STEEM emissions in shipping lane format and instead used a gridded format.

ENVIRON contributed to the EPA report for ocean-going vessels by combining emissions from STEEM with local, port-specific emission inventories resulting in a comprehensive national emissions inventory on a 4 km grid. That task involved removing any overlapping near-port emissions in the STEEM inventory, leaving only inter-port emissions in the STEEM inventory. This work used only the inter-port portion of the STEEM inventory. Figure 3-3 shows the EPA and STEEM estimates of ocean going vessel NOx emissions in the Gulf off the coast of Texas.

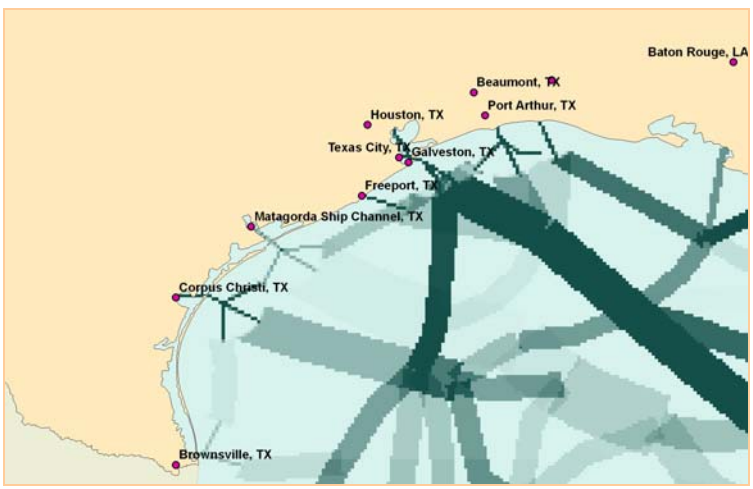



**Figure 3-3.** STEEM relative (darkened to reflect higher) OGV NOx emissions near the Texas coast.

### *Modeling Approach*

New EPS3 modules were developed to improve the spatial and vertical distribution of shipping sources. The EPS3 processing stream executed the following modules:

PRESHP → SPCEMS → TMPRL → PSTSHP → PIGEMS

For testing application and demonstration purpose, after PRESHP was run the standard area source EPS3 processing stream was also applied to allocate all shipping emissions to layer 1.

PRESHP → SPCEMS → TMPRL → GRDEM

**PRESHP**

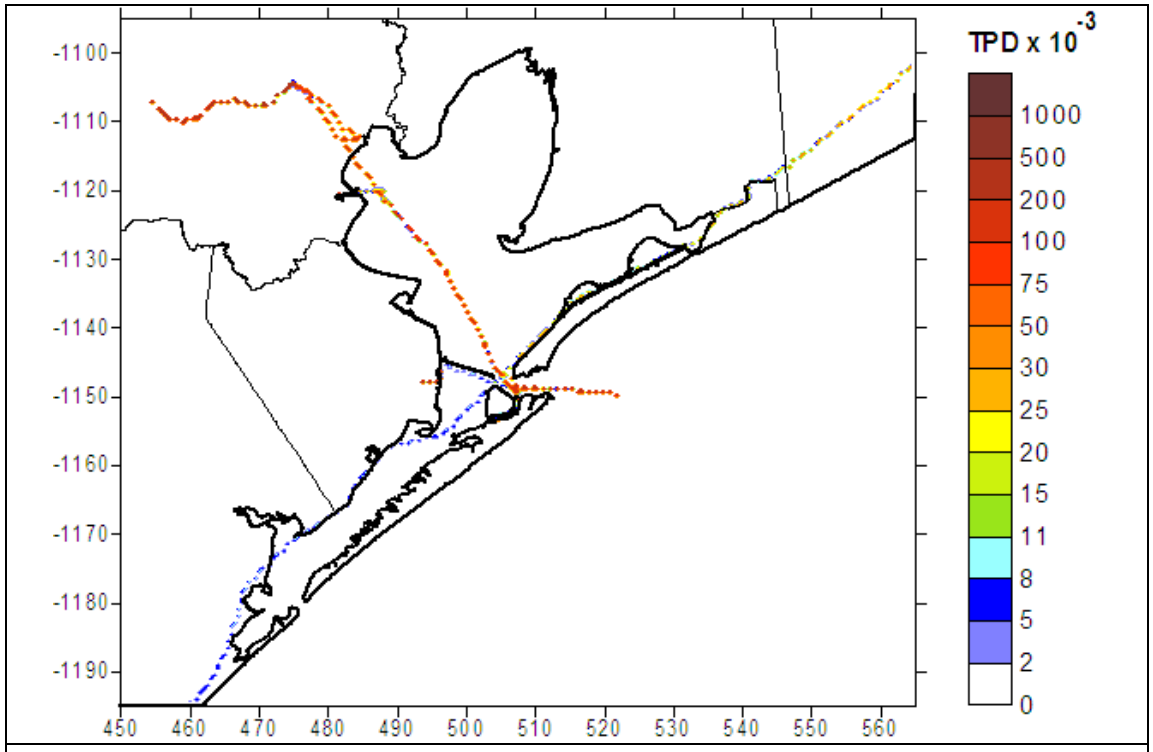
The new PRESHP module reads in shipping emissions in the PRESHP input format described in Table 3-1 and outputs data in the EMBR format. The PRESHP inputs were prepared as follow:

- Convert TCEQ Shipping points in AFS format to PRESHP format with zero length shipping lanes

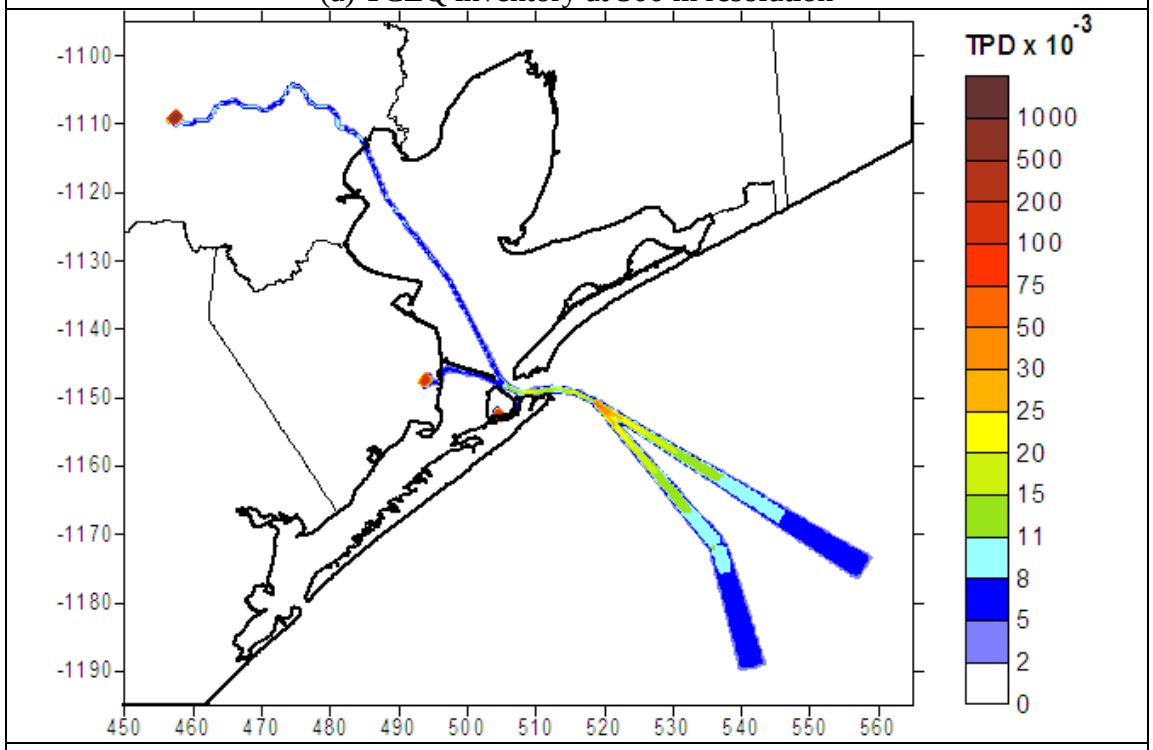
- Convert EPA shipping lanes to straight line segments with different width depending on distance from the Gulf. Width assignment are 100 m inland, 500 m through Galveston Bay, and 500 m expanding to 4000 m where lanes leave the bay and go into the Gulf. Since no detailed SCC is available in the EPA inventory, the default SCC 2280000000 was assigned to all records.

- Convert the STEEM gridded inventory to 4 km x 4 km shipping lane segments. The gridded STEEM emissions are in a different grid projection from the TCEQ's grid projection. Prior to developing the new shipping module, changing grid projection required pre-processing the STEEM emissions outside EPS3 (i.e. using Arc-GIS) which is time-consuming and must be repeated if the emissions or modeling grid are revised. For use with PRESHP, each STEEM grid centroid was assigned latitude/longitude coordinates which can be easily converted to other projections, such as LCP coordinates, later. Each STEEM grid was assigned length and width of 4km to preserve the original STEEM grid resolution. PRESHP can then spatially allocate the STEEM data to any modeling grid. Since no detailed SCC is available in the EPA inventory, the default SCC 2280000000 was assigned to all records.

Figure 3-4 displays emissions density maps of shipping NOx emissions from the TCEQ and EPA inventory at 500 m and 2 km resolution. For demonstration purpose, all emissions were assigned to layer 1 using the GRDEM module. Emissions from each shipping point in the TCEQ inventory were gridded to a single grid cell as shown in Figure 3-4(a, c); whereas emissions from each shipping lane in the EPA and STEEM inventory were allocated to the cells covered by the shipping lane. EPA shipping lanes vary in width resulting in higher emissions density near ports and lower density where lanes leave Galveston Bay and go into the Gulf. As described earlier, PREHSP spatially allocates shipping lane emissions by first allocating the emissions to the cells along the shipping lane center line and then further distributing the emissions to the cells in the perpendicular direction from the center line to the lane boundaries. Figure 3-4 (b) demonstrates that PRESHP appropriately distributed emissions of shipping lanes with varied widths as higher density emissions occur in cells at the narrow mouth of Galveston Bay.

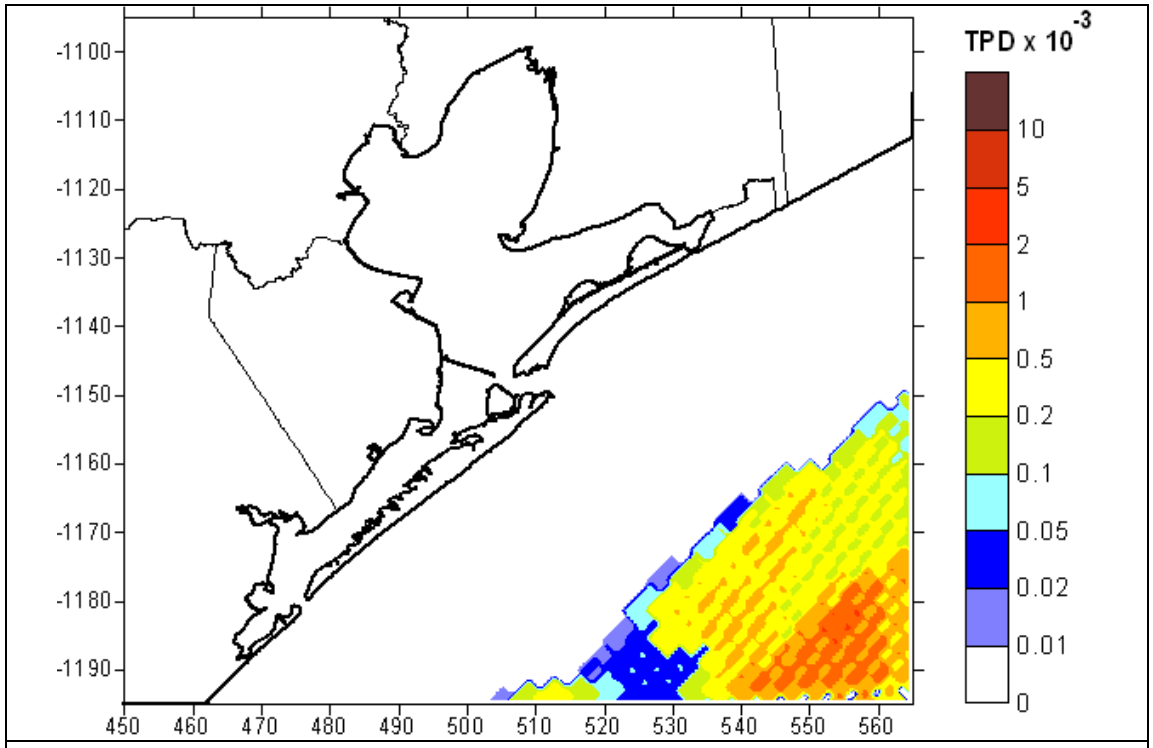



(a) TCEQ inventory at 500 m resolution

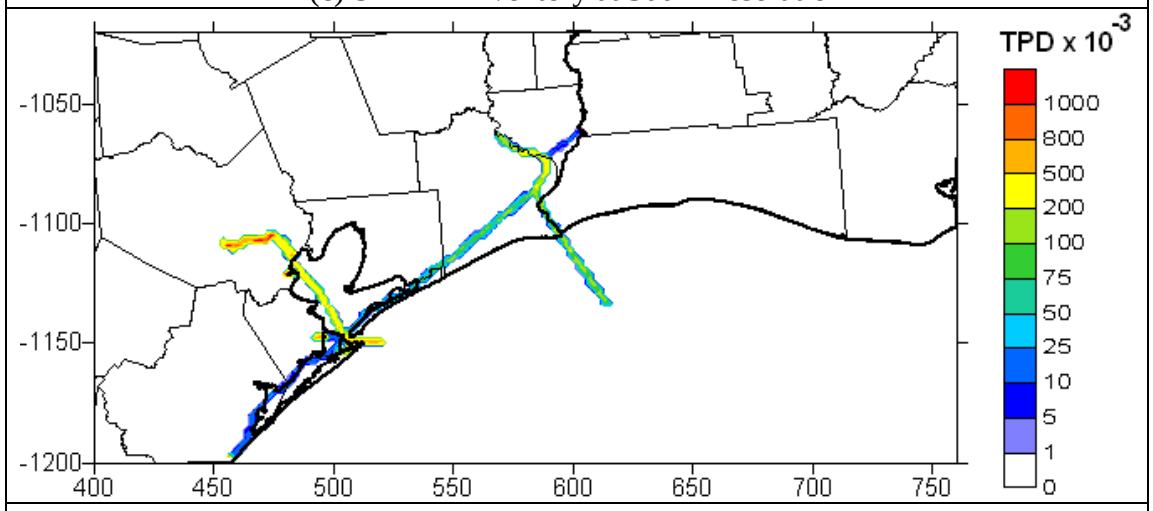



(b) EPA inventory at 500 m resolution

**Figure 3-4** Shipping NOx Emissions (a-c) at 500 m resolution and (d-f) at 2 km resolution.

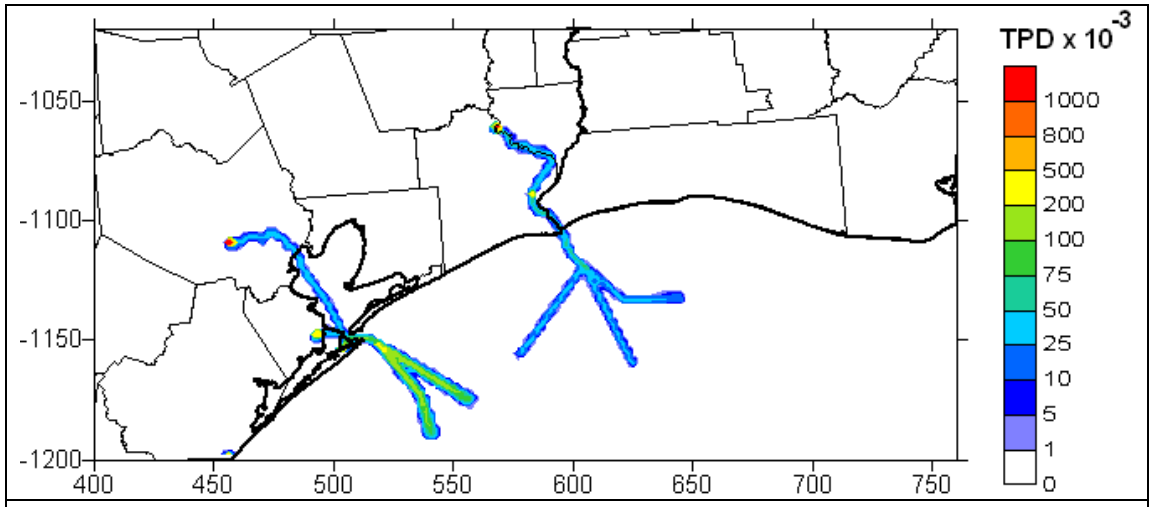



(c) STEEM inventory at 500 m resolution

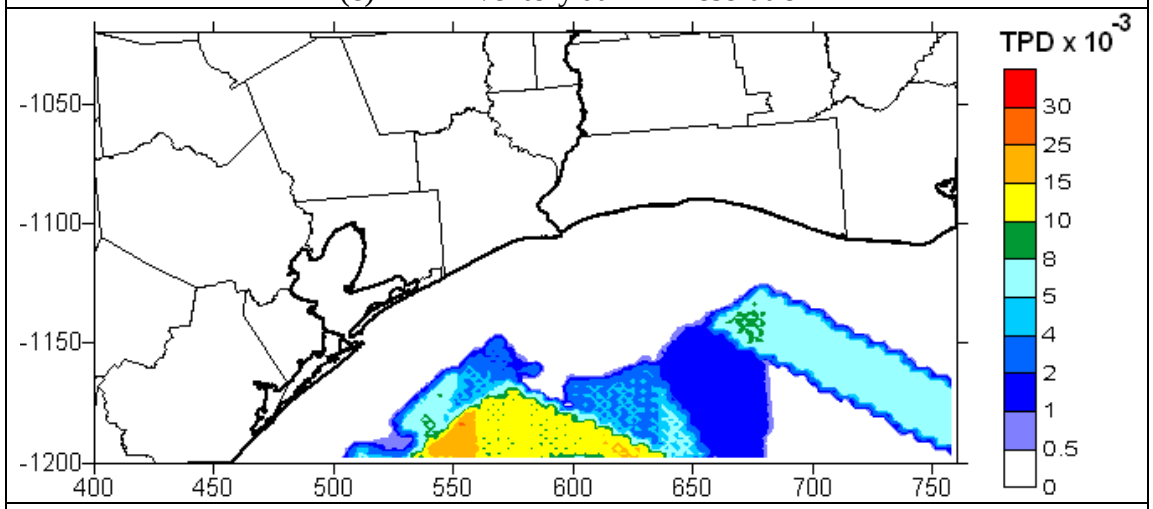



(d) TCEQ inventory at 2 km resolution

**Figure 3-4** Shipping NOx Emissions (a-c) at 500 m resolution and (d-f) at 2 km resolution (continued).




(e) EPA inventory at 2 km resolution




(f) EPA inventory at 2 km resolution

**Figure 3-4** Shipping NOx Emissions (a-c) at 500 m resolution and (d-f) at 2 km resolution (concluded).

**PSTSHP**

The new PSTSHP module vertically distributes shipping emissions based on the specified plume bottom and plume top heights by SCC and vessel type. In this test application, with limited information, the SCC/vessel cross reference (shown in Table 3-3) was created for all SCCs available in the TCEQ shipping inventory. SCC information is not available in the STEEM inventory, thus all of the vessels were assumed stack heights between 34 and 58 meters (default for SCC 2280000000). The EPA inventory also lacks SCC information. Since there was insufficient information to distinguish EPA's near-port marine vessel emissions by vessel type, these emissions were assigned 75% to the second CAMx layers and 25% to the first CAMx layer. The vertical layer structure is the 28-layer vertical structure for the TCEQ 4-km domain.

**Table 3-3** SCC/vessel type cross-reference file used with the TCEQ inventory.

| SCC | Plume Bottom (m) | Plume Top (m) | Ship Description |
|---|---|---|---|
| 2280002021 | 7 | 10 | Assist Tugboats |
| 2280002022 | 9 | 12 | Ferries |
| 2280002023 | 7 | 10 | Towboats |
| 2280002031 | 5 | 10 | Dredge Sabine Pass |
| 2280002032 | 5 | 10 | Fishing Sabine Pass |
| 2280002033 | 7 | 10 | Towboats Port of Arthur |
| 2280002034 | 5 | 10 | Government Port of Arthur |
| 2280002035 | 7 | 10 | Assist Tug Port of Arthur |
| 2280003010 | 40 | 60 | Ocean-Going Vessels |
| 2280003011 | 40 | 60 | Bulk Cargo Vessel |
| 2280003012 | 40 | 60 | General Cargo Vessel |
| 2280003013 | 40 | 60 | Container Ships |
| 2280003014 | 50 | 60 | Liquefied Gas Carrier |
| 2280003015 | 55 | 60 | Oil/Chemical Tankers |
| 2280003016 | 40 | 60 | Other Ocean-going Vessel |
| 2280003017 | 50 | 60 | Cruse Ships |
| 2280003019 | 34 | 58 | Roro Sabine Pass |
| 2280003020 | 34 | 58 | Misc Sabine Pass |
| 2280003021 | 7 | 10 | Tug Sabine Pass |
| 2280003022 | 40 | 60 | Unknown Sabine Pass |
| 2280003023 | 40 | 55 | Military Sabine Pass |
| 2280002d25 | 5 | 10 | Dredging Emissions |
| 2280002d26 | 5 | 10 | Barge Pumps |
| 2280003b17 | 55 | 60 | Chemical Tankers |
| 2280003d10 | 40 | 60 | Ocean-going Vessel |
| 2280003d11 | 40 | 60 | Bulk Cargo Vessel |
| 2280003d12 | 40 | 60 | General Cargo Vessel |
| 2280003d13 | 40 | 60 | Contain Ships |
| 2280003d14 | 50 | 60 | LPG Carrier |
| 2280003d15 | 55 | 60 | Oil/Chem Tankers |
| 2280003d16 | 40 | 60 | Other Ocean Tankers |
| 2280003d17 | 50 | 60 | Cruise Ships |

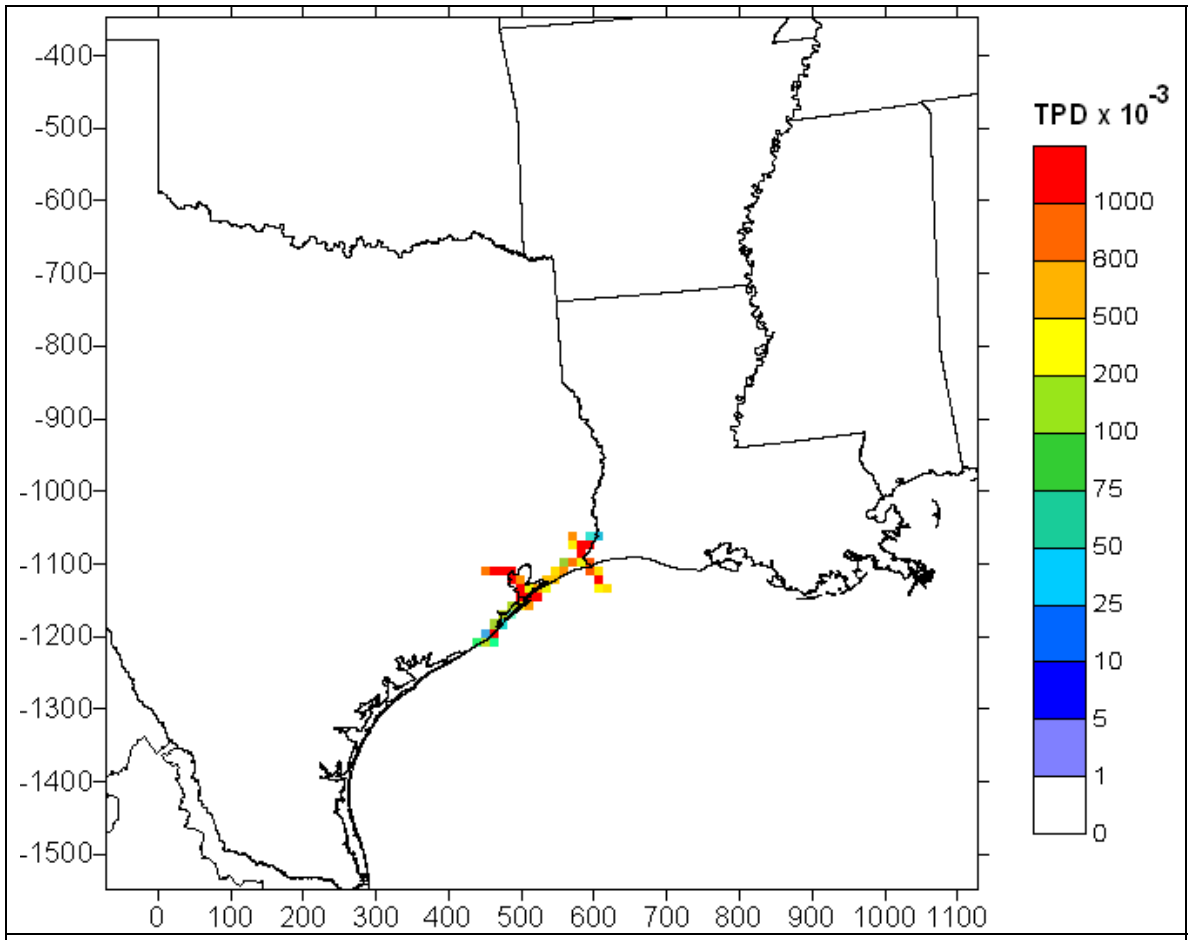
The shipping inputs were processed through EPS3 to produce CAMx-ready shipping emissions, with both surface and elevated sources for the 12 km East Texas modeling domain. The emissions were distributed vertical according to the assigned plume top and plume bottom heights. Table 3-4 shows the shipping emissions within the 12 km domain distributed to each CAMx layer. All of the STEEM emissions were distributed to layer 2 since the assigned bottom plume height is higher than the top of layer 1 and the top plume height is lower than the bottom of layer 3.

**Table 3-4** 12-km domain wide ship emissions distributed to each CAMx vertical layer.

| Data Source | Layer | Emissions (TPD) | | | % Emissions | | |
|---|---|---|---|---|---|---|---|
| | | NOX | CO | VOC | NOX | CO | VOC |
| TCEQ2005 | 1 | 19.4 | 3.4 | 0.4 | 36% | 42% | 29% |
| | 2 | 34.3 | 4.7 | 1.0 | 64% | 58% | 71% |
| EPA2002 | 1 | 9.2 | 0.9 | 0.3 | 25% | 25% | 25% |
| | 2 | 26.9 | 2.7 | 1.0 | 75% | 75% | 75% |
| STEEM | 1 | 0 | 0 | 0 | 0% | 0% | 0% |
| | 2 | 233 | 18 | 8 | 100% | 100% | 100% |

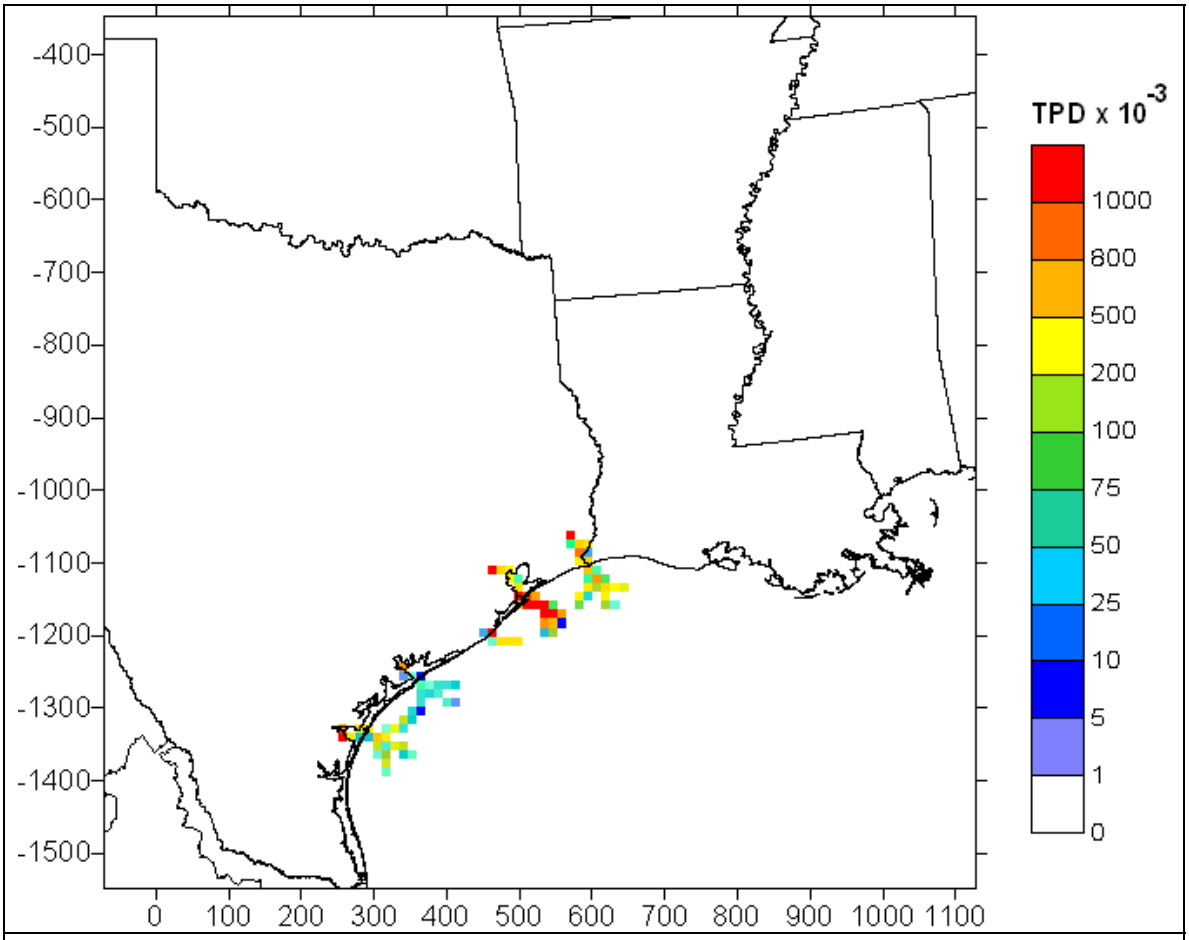
### *Modeling Results*

Spatial plots of shipping NOx emissions in the 12 km domain are shown in Figure 3-5. Emissions of criteria pollutants from the two inventories are compared in Table 3-5. Part of the difference for near-port emissions in the TCEQ and EPA inventories is because portions of the intra-coastal waterway are included in the TCEQ inventory but not the EPA inventory.



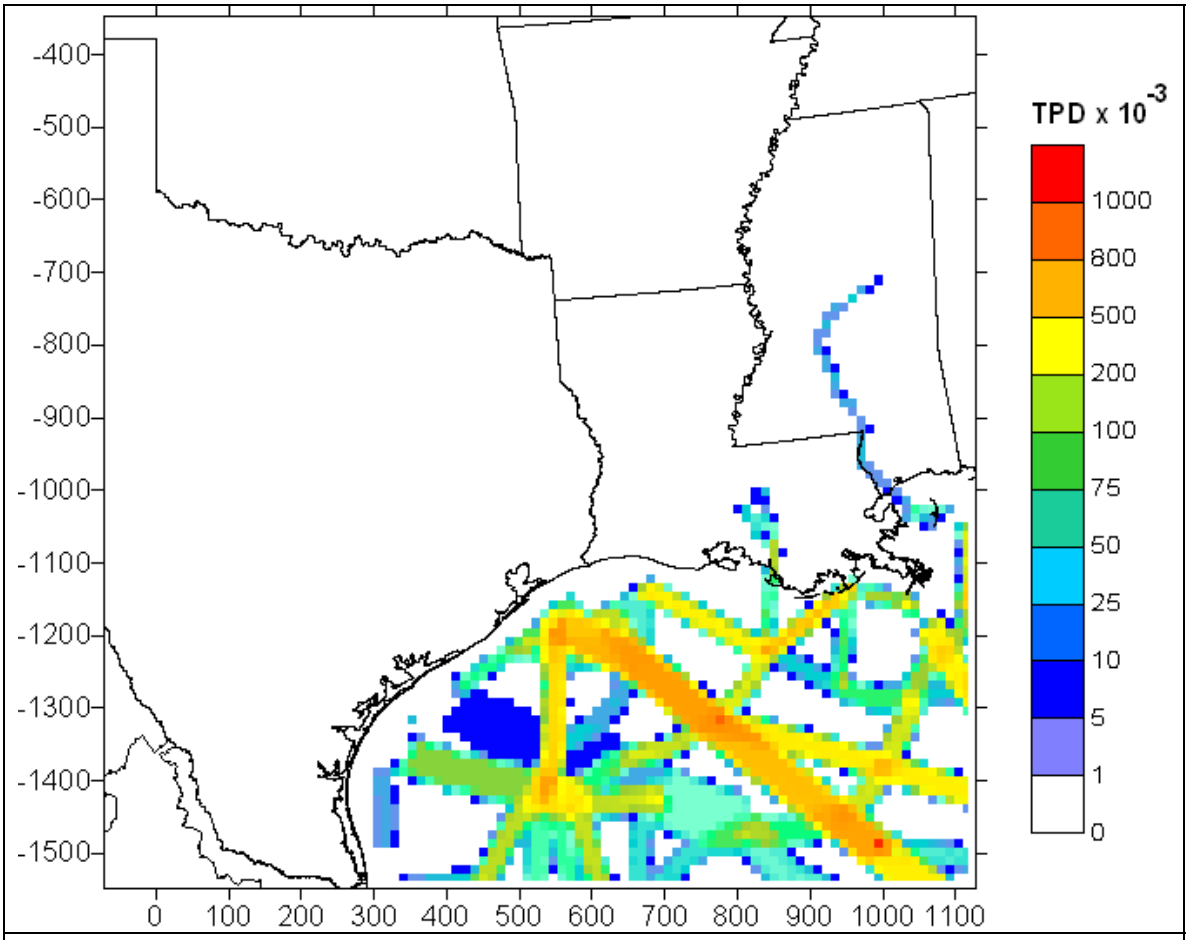

(a) TCEQ inventory at 12 km resolution

**Figure 3-5** Shipping NOx Emissions at 12 km resolution from (a) TCEQ inventory, (b) EPA inventory, and (c) STEEM inventory.




(b) EPA inventory at 12 km resolution

**Figure 3-5** Shipping NOx Emissions at 12 km resolution from (a) TCEQ inventory, (b) EPA inventory, and (c) STEEM inventory (continued).




(c) STEEM inventory at 12 km resolution

**Figure 3-5** Shipping NOx Emissions at 12 km resolution from (a) TCEQ inventory, (b) EPA inventory, and (c) STEEM inventory (concluded).

**Table 3-5** Shipping emissions of criteria pollutants by port within the 12-km domain.

| Data Source | Related Port | Emissions (TPD) NOX | CO | VOC |
|---|---|---|---|---|
| TCEQ2005 | Houston-Galveston | 41.2 | 41.2 | 6.5 |
| | Beaumont-Port Arthur | 12.5 | 12.5 | 1.6 |
| | Total | 53.7 | 53.7 | 8.1 |
| EPA2002 | Houston-Galveston | 16.9 | 1.3 | 0.6 |
| | Beaumont-Port Arthur | 7.7 | 0.7 | 0.3 |
| | Corpus Christi | 5.2 | 1.2 | 0.2 |
| | Texas City | 2.9 | 0.2 | 0.1 |
| | Freeport | 2.1 | 0.2 | 0.1 |
| | Matagorda Ship Channel | 1.2 | 0.1 | 0.0 |
| | Total | 36 | 4 | 1 |
| STEEM | Total | 233 | 18 | 8 |

## 3.3 CONCLUSIONS AND RECOMMENDATIONS

The new shipping emissions processors in EPS are proven to perform effectively. The new tools will increase the efficiency of providing timely and accurate modeling results especially near the Texas Coast. In order to take fullest advantage of the new tools, detailed spatial information will be required for shipping lanes (i.e., GIS shape files) including widths of the shipping lanes. When inter-port emissions (i.e. from STEEM inventory) are combined with the near-port emissions, caution is needed in removing overlapping sections of the inventories. SCC information specifying vessel types also is important for determining vertical distributions of shipping emissions. Nonetheless, the SCC information is only useful if the appropriate bottom and top plume heights by SCC/vessel type are available. Current emission inventories tend not to provide the detailed information that is required for accurate modeling, possibly because suitable modeling tools have not been available. Now that EPS3 has powerful tools for modeling shipping emissions, efforts should focus on improving the transfer of information between emission inventory developers and emissions modelers.

# 4. REFERENCES

ENVIRON. 2004. "Humidity and Temperature Effects on On-road and Off-road Emissions and Ozone Formation (HARC Project H8B)." ENVIRON International Corporation, Novato, CA. Prepared for Houston Advanced Research Center (HARC). November.

ICF, 2009. "Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories." Prepared for U.S. Environmental Protection Agency. April.

Williams, E.J., B. M. Lerner, P. C. Murphy, S. C. Herndon, and M. S. Zahniser, 2009. Emissions of $NO_x$, $SO_2$, CO, $H_2CO$ and $C_2H_4$ from commercial marine shipping during TexAQS 2006. *J. Geophysical Review*, to be published.