Simulating the Atmospheric Fate and Transport of Dioxin Emitted from Oil Burning Activities Related to the Deepwater Horizon Oil Spill Using the NOAA ARL HYSPLIT Model

Screening Analysis and Potential Future Work

Draft, August 1, 2010

Mark Cohen and Richard Artz, NOAA Air Resources Laboratory (ARL), Silver Spring MD

As part of the response to the Deepwater Horizon (DWH) spill, controlled burns of oil on the ocean surface are being periodically carried out. Due to the presence of chlorine in the marine environment, there is a possibility that a non-negligible amount of polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/F) could be formed during these controlled burns. However, details regarding the magnitude and congener profile of PCDD/F emissions of from these burns are not known. As part of a preliminary screening analysis, simulations of hypothetical "unit emissions" of PCDD/F have been carried out with a specially configured version of the NOAA Air Resources Laboratory's HYSPLIT atmospheric fate and transport model. This screening analysis attempted to provide a preliminary answer to the question "If PCDD/F was being emitted, what would the local/regional impacts be?" These initial screening simulations will be briefly described here. Where relevant, we will note the types of additional work that could be carried out to refine these simulations.

The HYSPLIT modeling system (Draxler and Rolph, 2010) can be used to simulate the atmospheric fate and transport of emitted pollutants. It is primarily a Lagrangian model that considers the atmospheric behavior or puffs or discrete point "particles" of pollutants. HYSPLIT utilizes gridded meteorological data -- e.g., 3-dimensional values of wind direction, wind speed, temperature, relative humidity, etc. -- as an input to the simulation. The latest version of the HYSPLIT model is version 4.9, released in 2010. This new version has a number of enhancements including an integrated Eulerian simulation option. The base HYSPLIT model has been modified to provide a more advanced treatment of the atmospheric fate and transport of PCDD/F. A summary of these modifications can be found in Cohen et al. (2002) and include algorithms to simulate vapor/particle partitioning, reaction with hydroxyl radical, photolysis, particle size distributions, and deposition parameters for 2,3,7,8 TCDD and other PCDD/F congeners developed from empirical data. The modifications made to HYSPLIT for this earlier work have been incorporated into HYSPLIT 4.9, creating HYSPLIT-SV 4.9 (where the SV stands for *Semi-Volatile*).

As a preliminary screening analysis in mid-June 2010, HYSPLIT-SV 4.9 was used to simulate a continuous, "unit" emissions of 2,3,7,8-TCDD from the spill location (lat/long = 28.737,-88.387) at a height of 200 meters. It was recognized the controlled burns have taken place at various locations and times, but, for this preliminary analysis a continuous emission from the site of the spill was assumed. In future work, the actual locations and times of burns could be simulated. The time period from May 3 through June 14 2010 was modeled. EDAS 40km meteorological data were used as input to the HYSPLIT model (EDAS archive, 2010). An effective release height of 200 meters was chosen for the screening analysis. It is recognized that the plume rise (and hence, the effective release height) will vary significantly as a

function of meteorological and burn conditions. A more sophisticated treatment of plume rise could be included in future modeling analysis. This could be implemented using HYSPLIT's plume rise algorithms or via plume rise estimates developed in other modeling efforts (e.g., short-range AERMod modeling being carried out by EPA scientists). It is additionally noted that with additional work, derived meteorological parameters such as the Monin-Obukhov length could be provided for use in other modeling efforts (e.g., AERMod modeling).

The results of the screening analysis will be presented in more detail below, but as a summary, the key methodological details of the screening analysis are presented in the table below, along with extensions that could be carried out in potential future work.

Summary of Modeling: Methodology Used in Screening Analysis vs. Methodology that Could be Used in Future Analysis

Simulation Methodology	Screening Analysis	Potential Future Work
Emissions Rate	1 g/hr 2,3,7,8-TCDD assumed as hypothetical unit emission rate	Emissions rate based on estimated emissions factors [based, for example on measurements at the burn sites], scaled to rate of oil burned in each specific spill. Congener profile in emissions would also be factored into the simulation, with each of the 17 toxic PCDD/F congeners being simulated.
Plume Rise	constant effective height of 200 meters assumed	Plume rise explicitly included in the simulation, "in-line" using HYSPLIT's plume rise algorithms and/or "off-line" using results from very-local scale simulations carried out with other models (e.g., AERMod)
Emissions Location	burn location assumed to be at the spill site	Precise location and areal extent of each burn could be used. Presumably this information is available.
Periods of emissions	continuous emissions	Exact time period of each individual burn could be utilized
Spatial Resolution of Meteorological Data	40 km	12 km
Receptor Information	Fine and coarse grid, time series graphs for concentration at selected locations	In addition to information at left, congener-specific deposition could be estimated to critical ecosystems, e.g., agricultural areas linked to human food supply in which PCDD/F could bioaccumulate and lead to human exposure
Output of Derived Meteorological Parameters	not done	Could be implemented with additional effort in future work, e.g., estimates of the Monin Obukhov length could be made provided to other modeling efforts.

To provide order-of-magnitude estimates and to demonstrate the types of modeling that could be done if needed in the future, some illustrative examples of the results of the screening simulations will be presented here.

Figures 1 and 2 show one type of summary of the screening model results. The same modeling results are shown on two different grids:

- a *fine grid* extending 2.5 degrees in each direction from the site, with a resolution of 0.1 deg (~10 km) [Figure 1]; and
- a *coarse grid* extending 10 degrees in each direction from the site, with a resolution of 0.5 deg (~50 km) [Figure 2].

Note that these grid resolutions and extents were chosen for illustrative purposes only and could be changed as needed in future work. Maps are shown for each grid and for both the modeled near-surface air concentration *averaged* over the entire modeling period and the modeled deposition *summed* over the entire modeling period. The daily variations were also mapped (not shown here for brevity), and not surprisingly show significant "episodicity", i.e., the meteorological conditions change from day to day. For concentration the units shown are grams/m3, assuming a continuous 1 g/hr emissions rate of 2,3,7,8-TCDD. For deposition, the units shown are grams/m2 for the entire modeling period, again assuming a 1 g/hr emissions rate.

Model estimates for any other emissions rate can be obtained by simply adjusting these model estimates proportionally. For example, if the actual emissions rate were 1 pg/hr (one picogram per hour), one would simply multiply the results shown by a factor of 1.0E-12. Of course, all other assumptions would be assumed to hold, e.g., continuous emissions from 200 m, at the site of the spill, for the particular time period modeled. Figure 3 shows the extent of the fine and coarse grids (along with the coarse-grid concentration results), noting that for displays of model results on each grid, the model-estimated values are artificially truncated at the edge of the grid.

In Figure 4, the time series of hourly modeled concentrations in New Orleans is shown, for the simulation described above (1 g/hr, continuous emissions at 200 meters elevation from the spill site). It can be seen that the concentrations are highly episodic, as might be expected. There are only a few hours during the entire modeling period that the hypothetical plume appears to "hit" New Orleans.

In Figure 5, these same data for New Orleans are shown along with the modeled time series concentrations for 9 other locations in the Gulf of Mexico region -- New Orleans (LA), Pascagoula (MS), Houston (TX), Jackson (MS), Little Rock (AK), Montgomery (AL), Pensacola (FL), Tallahassee (FL), Tampa (FL), midpoint between Gulfport and Hattiesburg (MS) – and the NOAA Air Resources Laboratory's long-term atmospheric monitoring site at the Grand Bay NERR (MS). Note that the scale in Figure 4 is logarithmic (factors of "10"). As might be expected the concentration peaks occur at different times in different locations, and the magnitude of the peaks is highly variable. In Figure 6, the average concentration over the entire modeling period is shown for each of these same locations. Note that the choice of these locations was arbitrary and they were selected simply for illustrative purposes. In future work, results for different and/or additional locations could be presented in this way.

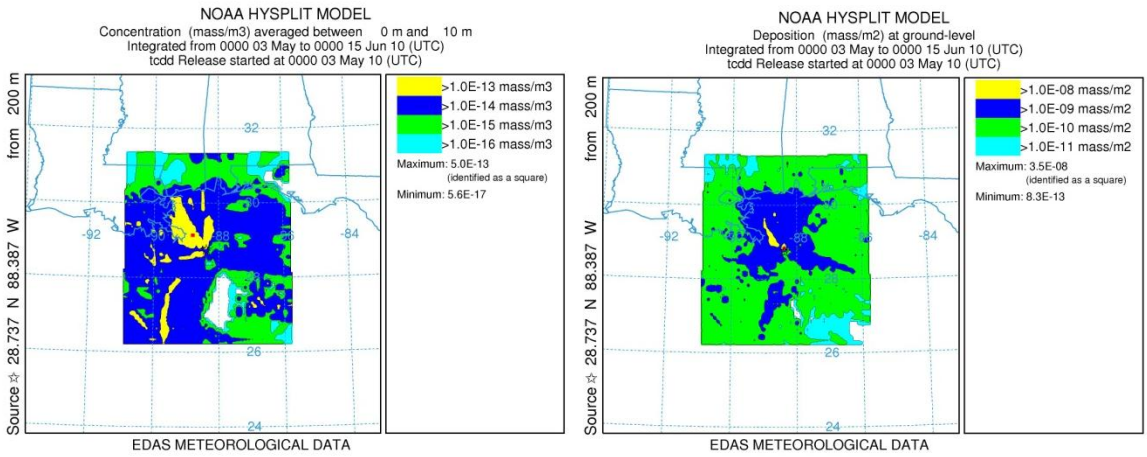

Figure 1. Preliminary modeling results displayed on a fine grid near the spill for air concentration averaged between 0-10 meters above the ground and deposition flux at the ground level arising from a hypothetical, continuous 1 gram/hour emission of 2,3,7,8-TCDD at an effective height of 200 meters from the DWH spill site (lat/long = 28.737,-88.387) from May 3 through June 14, 2010. The left panel shows the average concentration over the grid during the entire modeling period and the right panel shows the total deposition over the grid over the entire modeling period. It is important to note that the concentration and deposition distribution does not actually "end" at the boundary of the grid in the real world. The edges of the distribution in the figures above are simply the boundaries of the display grid being used to show the results (see additional explanation in Figure 3).

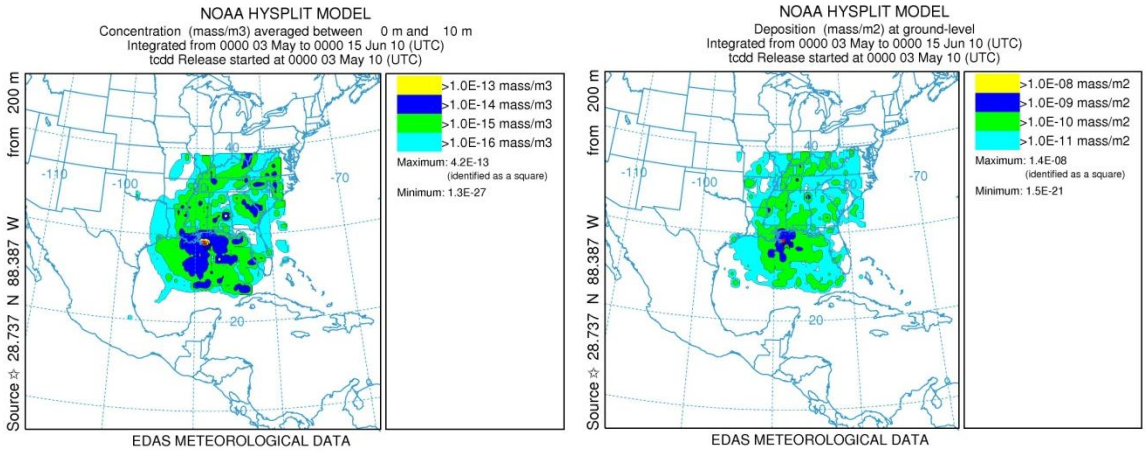

Figure 2. Preliminary modeling results – comparable to that shown in Figure 1 above -- displayed on a larger, coarser grid. The left panel shows the average concentration over the grid during the entire modeling period and the right panel shows the total deposition over the grid over the entire modeling period. As with Figure 1, it can be seen at the northern and eastern edges of the distribution that the display grid shown truncated the actual simulated distribution (see additional explanation in Figure 3).

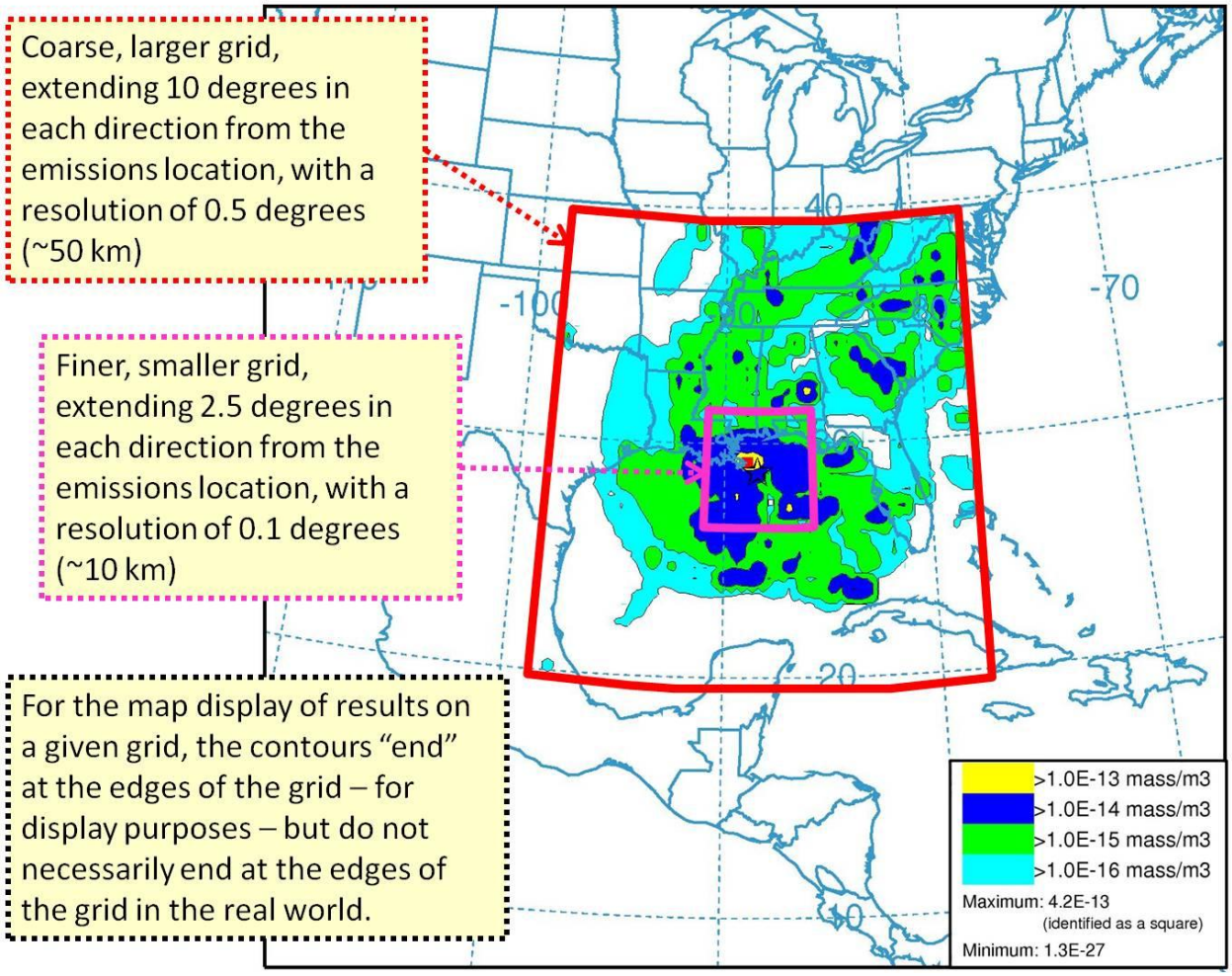

Figure 3. Extent of coarse and fine grids (along with the concentration results for the coarse grid), showing the artificial truncation of the mapped distribution at the "edges" of the coarse grid. A comparable situation exists with the display of results on the fine grid, as shown in Figure 1.

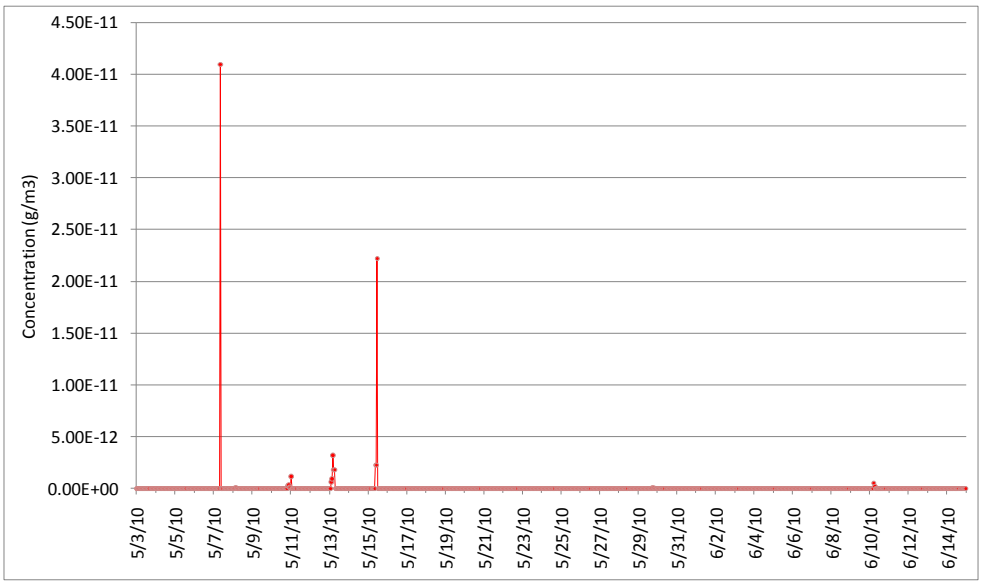

Figure 4. Time series of modeled, hourly 2,3,7,8-TCDD concentration estimates averaged between 0-10 meters in New Orleans (~city center), arising from HYPOTHETICAL unit emission of 1 gram per hour from location of DWH oil spill site. The average concentration over the entire modeled period was 7.6×10^{-14} g/m3 assuming a hypothetical 1 g/hr emission rate (see figure 6).

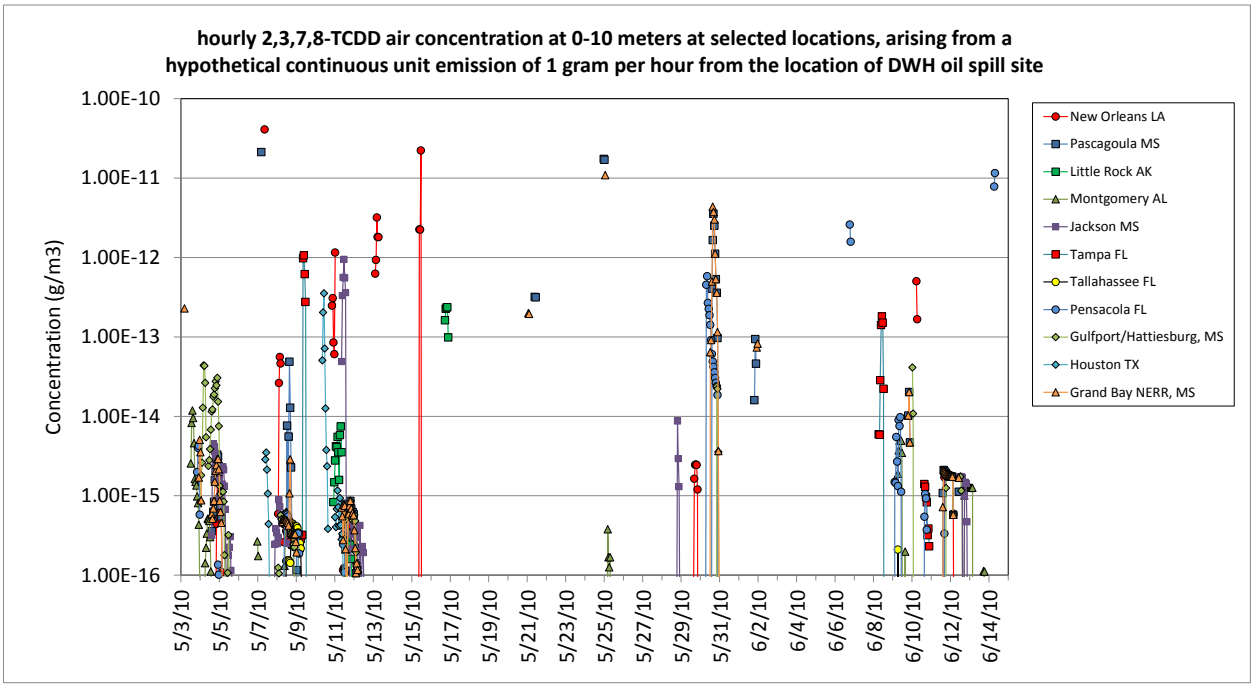

Figure 5. Time series of modeled concentrations at 11 selected locations in the Gulf of Mexico region, shown for illustrative purposes. Note the logarithmic scale and the episodicity of the results.

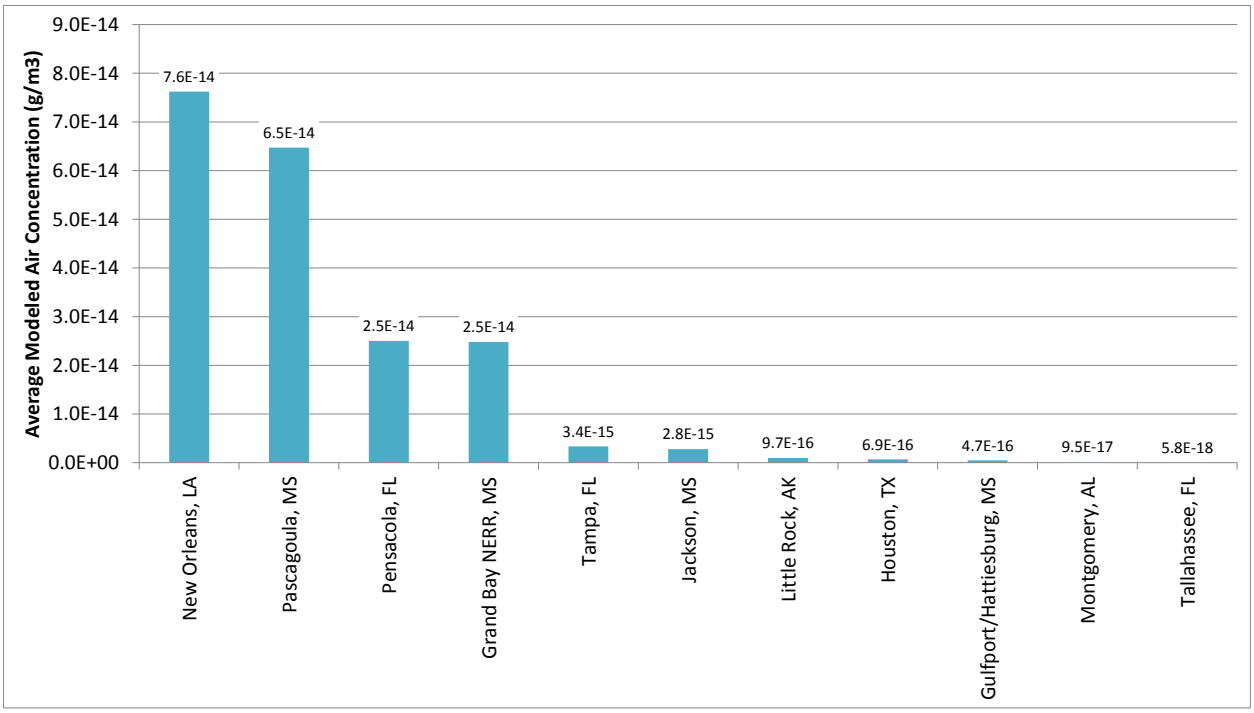

Figure 6. Average concentrations for the entire modeling period at 11 selected locations in the Gulf of Mexico region, shown for illustrative purposes, based on continuous 1 g/hr emissions of 2,3,7,8-TCDD at the spill site, at a height of 200 meters.

References:

Byun, D., Kim, H.C. (2010a). *Controlled Oil Burn Data for the Deep Water Horizon Gulf Oil Spill*. NOAA Air Resources Laboratory, Silver Spring, MD, July 29, 2010.

Byun, D., Kim, H.C. (2010b). *Burn Data Release 20100719_v1-b-ARL.csv*. Spreadsheet of Controlled Oil Burn Data for the Deep Water Horizon Gulf Oil Spill. NOAA Air Resources Laboratory, Silver Spring, MD, July 29, 2010.

Cohen, M., Draxler, R., Artz, R., et al. (2002). **Modeling the Atmospheric Transport and Deposition of PCDD/F to the Great Lakes**. *Environ. Sci. Technol.* **36**, 4831-4845. Available at: http://www.arl.noaa.gov/data/web/reports/cohen/13_cohen_et_al.pdf

Draxler, R.R. and Rolph, G.D. (2010). **HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model**. NOAA Air Resources Laboratory, Silver Spring, MD. Further information and documentation available at the NOAA ARL READY Website **:** http://ready.arl.noaa.gov/HYSPLIT.php

EDAS Archive (2010). **Eta Data Assimilation System (EDAS40) Archive**. NOAA Air Resources Laboratory, Silver Spring, MD. Available at: http://ready.arl.noaa.gov/edas40.php

USEPA (2010). Personal Communication from Shawn P. Ryan, Ph.D. Division Director, Decontamination and Consequence Management Division, National Homeland Security Research Center, U.S. Environmental Protection Agency (MD-E343-06), Office of Research and Development. Research Triangle Park, NC.

Appendix A: Some considerations in using these preliminary model simulation results in an initial screening analysis

Summary of Screening Level Estimates of Concentration and Deposition Discussed in the Following Section	
Exposure Pathway	Screening Level Estimate (fg = femtogram = 1.0E-15 gram)
Short term, air concentration for shoreline exposure, 1-hour average	150 fg TEQ/m3
Short term, air concentration for shoreline exposure, 3-hour average	50 fg TEQ/m3
Short term, air concentration for shoreline exposure, 8-hour average	20 fg TEQ/m3
Short term, air concentration for shoreline exposure, 24-hour average	6 fg TEQ/m3
Long term, air concentration for shoreline exposure, 82-day average	0.16 fg TEQ/m3
Approximate range of total atmospheric deposition flux to impacted, continental shelf marine environments over the 82-day burning period	300-3000 fg TEQ/m2

1. Estimation of Short-Term and Long-Term Concentrations at Shore-line Locations

The assumption of continuous emissions, used in the initial simulations, was made only because more detailed information was not available at the time this modeling was done. In reality, of course, the oil burning was not continuous. More details have become available and the modeling could be done again using actual times, durations, and amounts burned in each deliberate burning event (Byun and Kim, NOAA ARL, 2010ab). In addition, details are now available regarding a preliminary emissions factor estimate for PCDD/F emissions from the surface oil burning activities (USEPA, 2010). A summary of some of this new information is presented in Appendix B (see below).

Based the data described in Appendix B, some initial estimates of PCDD/F emissions rates can be made, and with these estimates, the earlier HYSPLIT-SV-based modeling results can be utilized. These estimates are summarized in Table A-1 below. This table presents overall PCDD/F emissions rates estimated in six different ways.

Table A-1. Estimates of PCDD/F emissions rates from deliberate oil burning at sea

Rate Description	Estimated Emissions Rate (grams TEQ/hr)			Notes
	Low	Medium	High	
	Low estimate of amount of oil burned; emissions factor calculated assuming ND=0	Average estimate of amount of oil burned; emissions factor calculated assuming ND=0.5*DL	High estimate of amount of oil burned; emissions factor calculated assuming ND=DL	
Emission rate during burn periods	2.03E-04	3.35E-04	4.98E-04	Estimated Rate during actual burn periods. Adding up the estimated durations of each burn, and removing the overlap periods in which more than one burn took place (don't double count any particular time), the total time in which one or more burns were taking place is approximately ~250 hours.
Equivalent "continuous" emissions rate over entire calendar period of burns (April 28 – July 19, 2010)	2.57E-05	4.24E-05	6.31E-05	These rates were calculated by assuming the same total amount of PCDD/F emitted, but assuming a continuous emissions source for the entire period from April 28 through July 19

For the estimation of the maximum short term "worst case" exposure – at least insofar as this simulation is able to represent – it is perhaps appropriate to use the highest hourly burn rate in the table above, i.e., about 5.0E-04 g TEQ/hr (0.0005 g TEQ/hr). This essentially assumes that:

- the emissions factor is based on all non-detected congeners being present in the emissions test at the detection limit;

- the meteorological conditions were such that emissions during the actual burning periods were ultimately transported – at least to a certain extent – to the U.S. Gulf of Mexico shore line. The modeling shows that during some periods, the emitted material would be expected to be transported away from the U.S. coast, and if the burning took place during one of those times, then the impact on the U.S. coast would be negligible for that particular period.

In this discussion, it must be noted that the 0.0005 g TEQ/hr rate would not actually be the maximum hourly rate during the burn period. The actual hourly emissions rate – even during hours in which burning was taking place – no doubt was highly variable. The 0.0005 g TEQ/hr rate simply represents an estimate of the high end of the "average" emissions rate during these burning hours.

For the continuous, unit-emissions simulation carried out earlier, hourly concentrations were not saved everywhere in the modeling domain. For the general modeling domain, only daily average concentrations were output by the model. However, hourly concentrations at 11 locations in the Gulf Coast region were chosen to be output by the model. These were chosen simply for illustrative purposes. For these initial screening calculations using the earlier HYSPLIT-SV modeling results, the only data available with temporal resolution less than one day are for these 11 locations. Table A-2 shows the maximum surface-level concentrations (0-10 meters) over averaging periods of 1, 3, 8, and 24 hours for these 11 locations, assuming an emissions rate of 0.0005 g TEQ/hr. The units shown in this table are femtograms TEQ/m3 in which a femtogram represents 1.0E-15 grams.

Table A-2. Maximum short term concentrations for different averaging periods found in preliminary modeling simulation for 11 selected locations – selected for illustrative purposes only – for the modeling period of May 3 through June 14, assuming an emissions rate of 5 g TEQ/hr

[note: concentration units are femtograms TEQ/m3, in which a femtogram represents 1.0E-15 grams]

	max hourly average concentration	max 3-hour average concentration	max 8-hr average concentration	max 24-hr average concentration
	fg TEQ/m3	fg TEQ/m3	fg TEQ/m3	fg TEQ/m3
New Orleans, LA	20.39	6.80	2.55	0.85
Pascagoula, MS	10.57	5.71	2.14	0.71
Pensacola, FL	5.75	3.21	1.20	0.40
Grand Bay NERR, MS	5.41	1.84	0.85	0.29
Tampa, FL	0.53	0.44	0.18	0.06
Jackson, MS	0.47	0.34	0.17	0.06
Little Rock, AK	0.12	0.12	0.060	0.020
Houston, TX	0.18	0.10	0.043	0.015
midway between Hattiesburg and Gulfport, MS	0.022	0.019	0.011	0.007
Montgomery, AL	0.0059	0.0049	0.0026	0.00095
Tallahassee, FL	0.00022	0.00021	0.00021	0.00012

An important question to ask is: How do the results for other locations in the Gulf of Mexico coastal regions compare with the results for these 11 locations? Are there locations that may have experienced higher potential concentrations? In future work, hourly results will be saved for each grid point, but in the earlier modeling, hourly results are not available for locations other than the 11 illustrative sites. However, daily results were saved for the entire fine and coarse grids.

To provide an initial answer to the above question, these *daily* average concentration results for each grid point in the fine (0.1^o x 0.1^o) grid around the spill site were analyzed. The results are presented below in Figure A-1, for the average concentration over the entire modeling period, and Figure A-2,

showing the maximum daily concentration at any time during the modeling period. Both Figure A-1 and A-2 show that none of the limited number of illustrative sites appears to be representative of the highest potential coast-line impacts.

The highest coastal concentration impact found in the earlier screening-level modeling was at a location southwest of New Orleans [latitude =29.437, longitude =-90.487]. At this grid point, the average concentration over the entire modeling period was 317 fg/m3, for a 1 g/hr continuous emissions rate, and the highest daily average concentration was 12,600 fg/m3. If an emissions rate of 0.0005 g TEQ/hr is assumed to have occurred at the emissions time contributing to this peak daily concentration, then the average daily concentration at this grid point would be on the order of 6.3 fg TEQ/m3.). This is approximately 7.4 times higher the highest 24-hr concentration observed at any of the 11 illustrative locations chosen [0.85 fg/m3 at New Orleans].

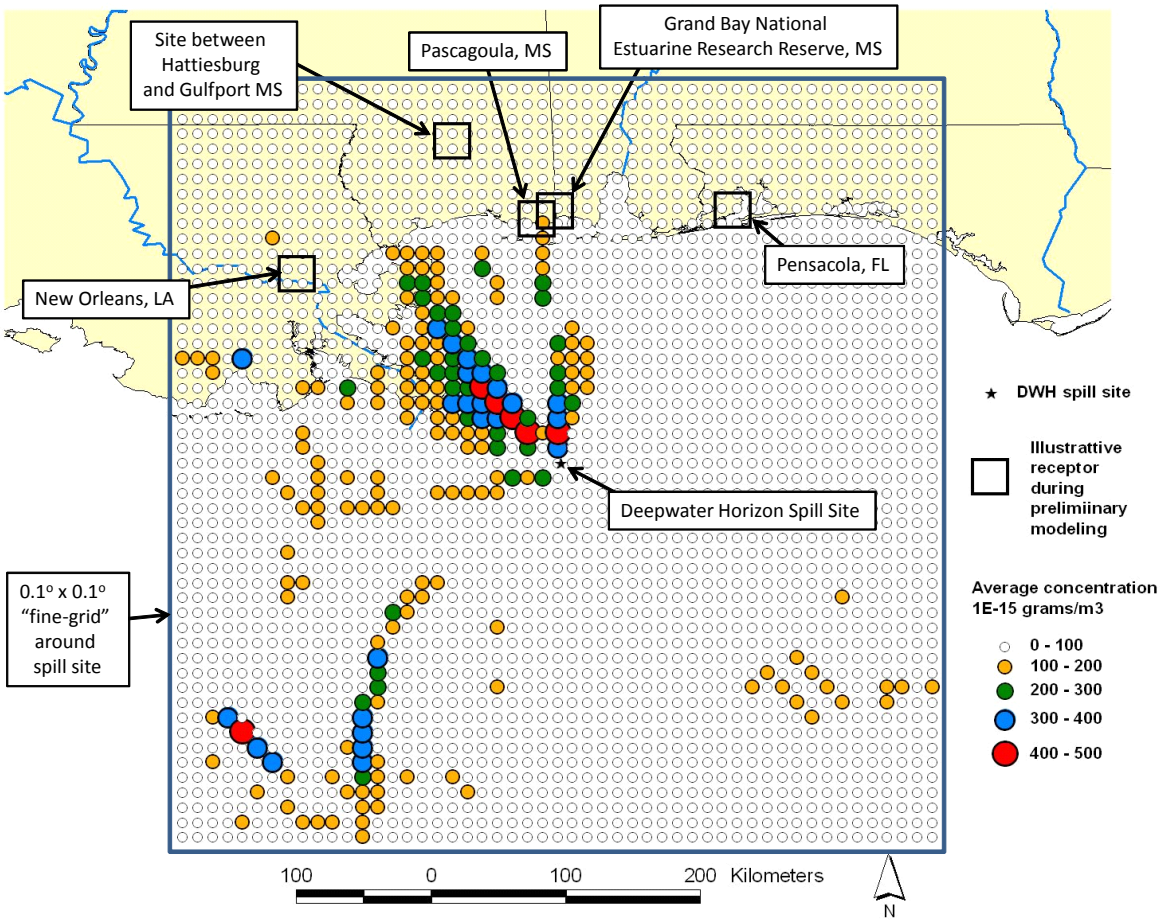

Figure A-1. Average concentrations for each grid point in the "fine grid" over the entire modeling period May 3 – June 14, 2010, arising from a hypothetical, continuous emissions rate of 1 gram/hr of 2,3,7,8-TCDD from a height of 200 meters above the Deepwater Horizon oil spill site.

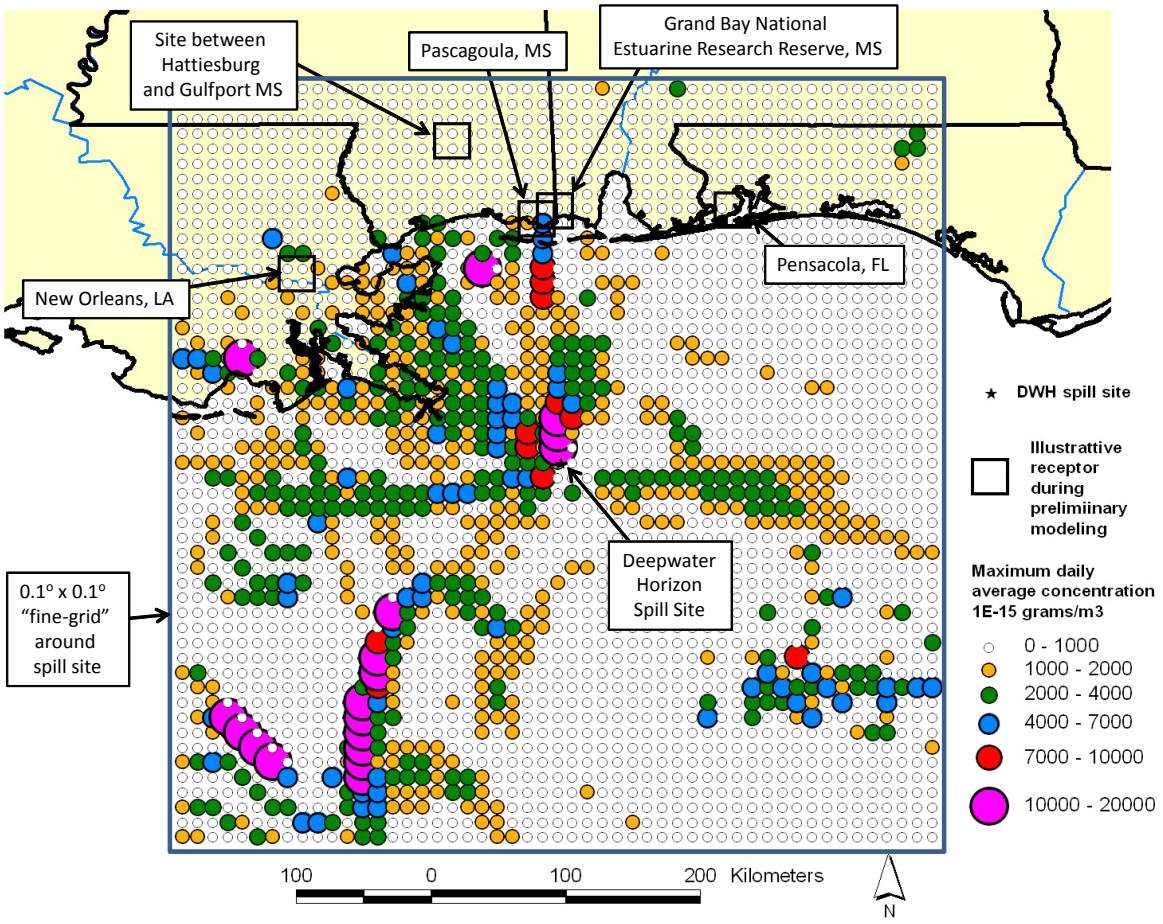

Figure A-2. Maximum daily average concentrations for each grid point in the "fine grid" over the entire modeling period May 3 – June 14, 2010, arising from a hypothetical, continuous emissions rate of 1 g/hr of 2,3,7,8-TCDD from a height of 200 meters above the Deepwater Horizon oil spill site. If an emissions rate of 0.0005 g TEQ/hr is assumed to have been occurring at the time associated the maximum for any given gridpoint, then the values shown above would be multiplied by this emissions factor. The resulting legend ranges would be: 0–0.5, 0.5-1, 1-2, 2-3.5, 3.5-5, and 5-10 fg TEQ/m3 for maximum daily average concentrations.

If it is assumed that the highest 1, 3, and 8 hour averages for this location are proportionately higher than the peak values for New Orleans, then the peak 1, 3, and 8 hour average concentrations would be on the order of 150, 50, and 20 fg TEQ/m3. It is important to point out that in addition to all of the uncertainties inherent in these simulations, for these peak values to have actually occurred at this location, emissions of 0.0005 g TEQ/hr would have had to have been occurring at the time that the modeled emissions contributed to the maximum concentrations at this location. At the same time, however, as discussed above, the 0.0005 g TEQ/hr rate is only the high end of the *average rate* estimated to have occurred during the burning hours. *The rate during "peak" burning hours may have been significantly greater than this.*

To summarize the above considerations, for the purposes of an initial, preliminary screening analysis for coastal, airborne, short-term exposures to PCDD/F concentrations that may have occurred as a result of the deliberate burning of oil from the Deepwater Horizon oil spill, peak ground-level concentrations could be assumed to be on the order of 150, 50, 20, and 6 fg TEQ/m3 for averaging periods of 1, 3, 8, and 24 hours, respectively. If the screening analysis suggests that these levels are a cause for concern – or are reasonable close to levels which might be a cause for concern – then the preliminary simulations described here could be repeated using the estimates of burn times, locations, and amounts that are now available.

To estimate the approximate peak coastal value of the average concentration over the entire modeling period, based on the above considerations, a "continuous" emissions rate of 6.3E-05 g TEQ/hr could be assumed. As described in Table A-1 above, this emissions rate, if continuous, would result in approximately the same total PCDD/F emissions over the entire calendar burning period as the 0.0005 g TEQ/hr rate represents for the specific times at which burning occurred. Using this emissions value in conjunction with the modeling results being considered here, the peak, average ground-level airborne PCDD/F concentration for coastal locations for the overall period of April 28 through July 19, 2010 would be on the order of 0.16 fg TEQ/m3. This value was estimated by taking the highest coastal modeled average concentration – 317 fg/m3 – estimated in the 1 g/hr continuous emissions simulation, and multiplying this by the 6.3E-05 g TEQ/hr "continuous" emission rate discussed above.

2. Estimation of Atmospheric Deposition to the Marine Ecosystem

To assess potential ecosystem-related exposure risk, an estimate of total atmospheric deposition to a given ecosystem is needed. Following the reasoning outlined in the previous discussion, to use the present simulation results, the "continuous-equivalent" emissions rate might be used, i.e., the emissions rate of 6.3E-05 g TEQ/hr. In addition, the calendar burn period was ~82 days, while the modeling period was only 42 days. Therefore, the unit-emission results can also be scaled – proportionately -- due to the longer-duration of the calendar burning period. Should this screening analysis indicate potential concern worthy of more detailed investigation, a more realistic simulation would be carried out for the entire period of the burning, and also take into the account the episodic nature of the burns. Nevertheless, for the present screening purposes, the earlier modeling results can be used to make an order-of-magnitude estimate of PCDD/F deposition to the marine ecosystem.

Following the simplified approach discussed above, the estimated deposition flux of PCDD/F as a result of the deliberate burning of Deepwater Horizon oil at the sea surface for the period of April 28-July 19 is shown in Figure A-3, below. It can be seen that there are large spatial gradients in the estimated deposition, as would be expected. Thus, an estimate of the average deposition flux will depend greatly on the area being considered. In Figure A-4 below, it can be seen that the continental shelf lies in the region north of the Deepwater Horizon spill site. In general, this is the region in which the model-estimated deposition appears to be the highest. Based on a visual inspection of Figures A-3 and A-4, a

screening level estimate of the deposition flux over the entire 82-day burn period to continental shelf ecosystem regions can be estimated to be on the order of 300-3000 fg TEQ/m2.

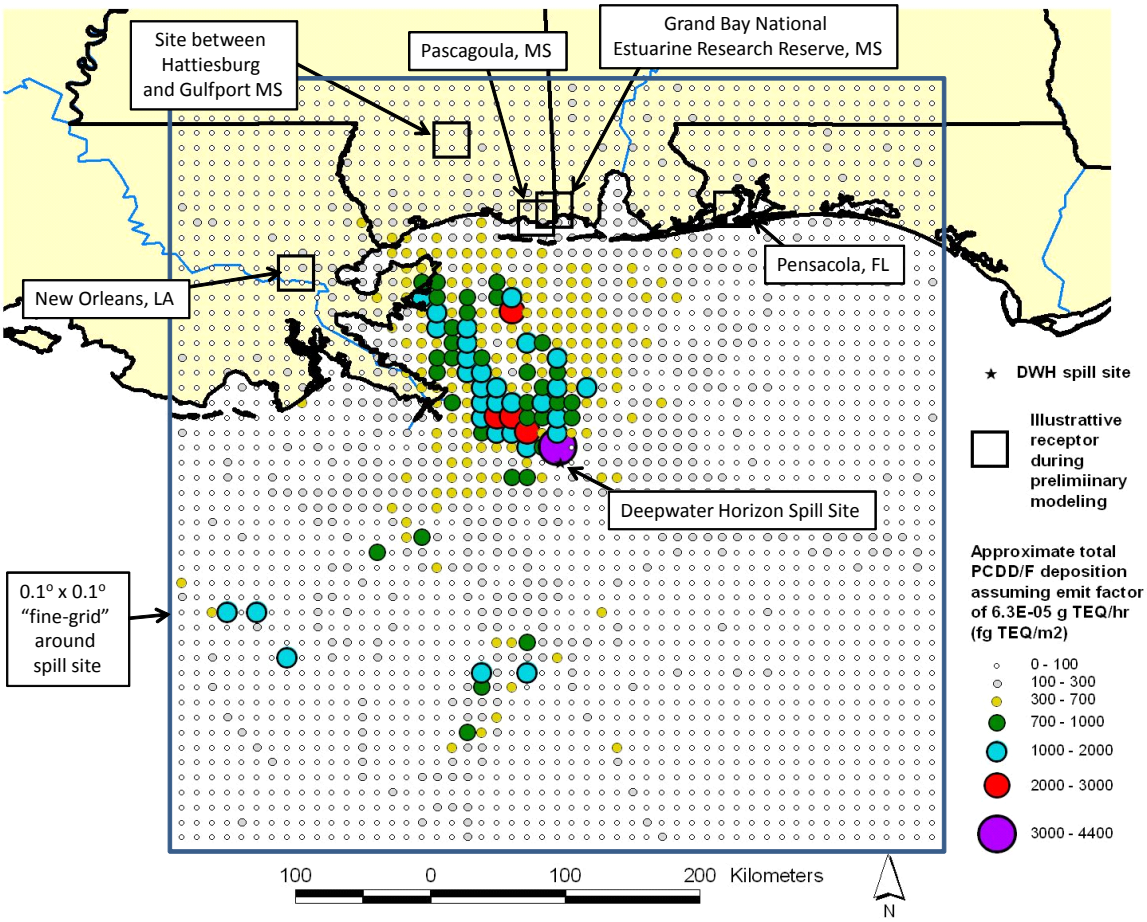

Figure A-3. Approximate total atmospheric deposition for each grid point in the "fine grid" over the entire calendar burning period from April 28 through July 19, arising from a hypothetical, continuous emissions rate of 6.3E-05 g TEQ/hr of 2,3,7,8-TCDD from a height of 200 meters above the Deepwater Horizon oil spill site. To get the values mapped above, the unit-emission simulation results were multiplied by 6.3E-05 to convert from 1 g/hr to 6.3E-05 g/hr, and by a factor of 82/42 = 1.95 to account for the fact that the modeling period was shorter than the calendar burn period.

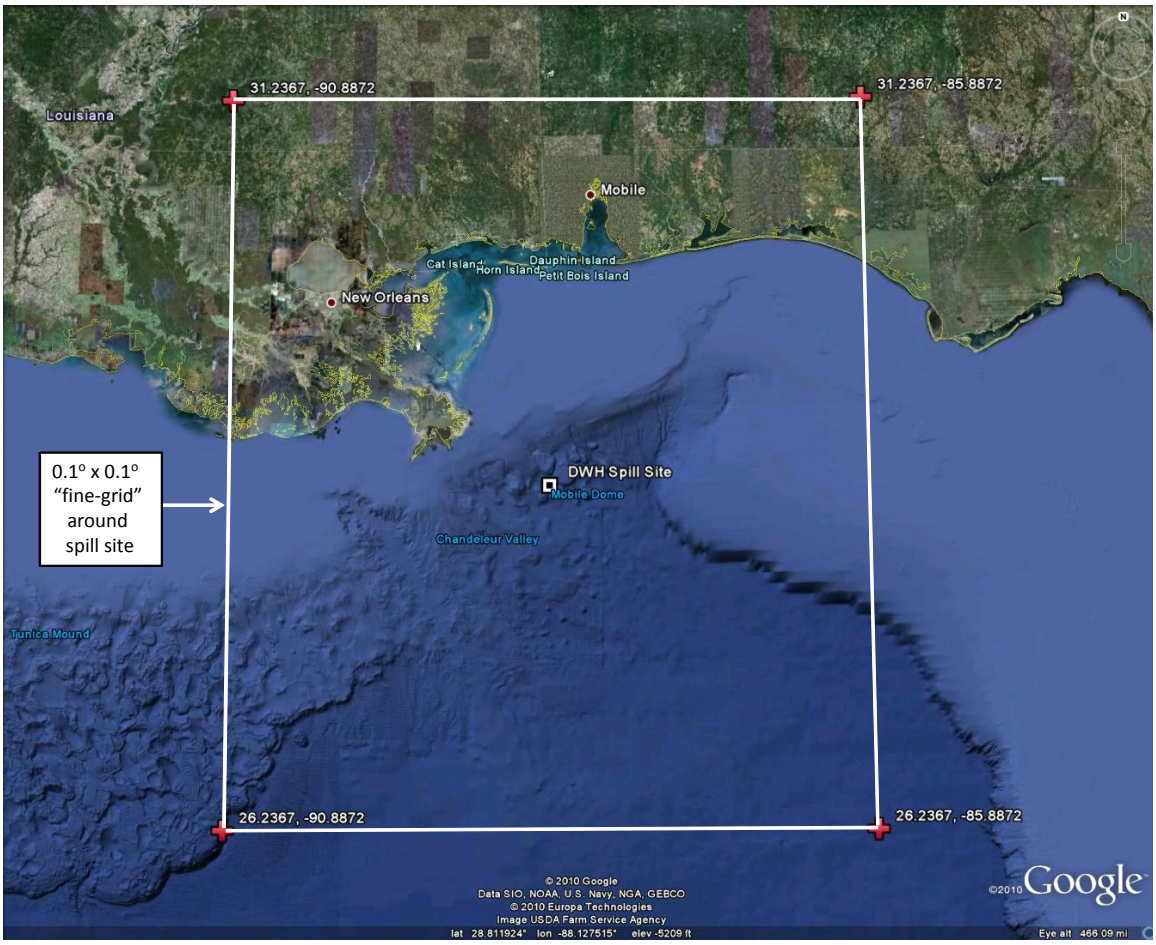

Figure A-4. Image from Google Earth, with region of fine grid added, to see the approximate relationship between the fine grid locations and the continental shelf, and other features of the marine ecosystem.

Appendix B: Summary of some preliminary estimates of dioxin emissions during deliberate oil burning at sea

based on emissions factor information provided by USEPA,
and on oil burning data provided by Daewon Byun and Hyun Cheol Kim
of NOAA's Air Resources Laboratory

In this Appendix, data regarding the estimated emissions rates of PCDD/F are briefly summarized, using the estimated emission factor estimated by EPA's measurements, and the estimated burn amounts and burn durations assembled by Daewon Byun and Hyun Cheol Kim of NOAA ARL (Byun and Kim, 2010ab).

The graphs presented here are from the following spreadsheet:
"Burn Data Release 20100719_v1-b-ARL_mdc_002.xlsx"
This spreadsheet is based on the original spreadsheet from Byun and Kim (2010b).

In figures B-1 through B-5 below, estimated emissions amounts and rates for the 411 individual burns that have been characterized are shown as a function of burn duration and other parameters.

One potentially relevant aspect of the data is illustrated by Figures B-1. This plot shows the estimated emissions of dioxin in each burn as a function of the duration of the burn. The power-law regression shown in Figure B-1 appears to be relatively significant. The fitted exponential factor of ~1.5 suggests that the emissions amount is not necessarily directly proportional to the burn duration. Direct proportionality would result in an exponential factor of 1. The fact that the exponential factor is greater than 1 suggests that longer burns have a higher emissions rate than shorter burns.

However, when the same data are shown on a linear plot (Figure B-2), it is seen that most of the burns lie in a relatively linear part of the "curve". That is, based on Figure B-2, the assumption of a direct proportionality between emissions and duration may not be unreasonable.

In Figures B-3 through B-5, the estimated emissions rates for each burn are plotted against burn emission amounts. Higher rates of emission appear to be correlated to a certain extent with emissions amounts, but, the assumption of a linear relationship is seen to be somewhat reasonable. So again, there may be variations in emissions rate among the different burns, but the overall assumption of emissions amount being more or less proportional to burn duration seems somewhat reasonable, at least based on the highly simplified treatment of the data, and extremely limited basis for these estimates. The same emissions factor was used for all of the burn data shown here (1.7 ng TEQ/kg oil burned), and obviously, there may very likely be large variations in emissions rates between different burns but these differences have not yet been characterized.

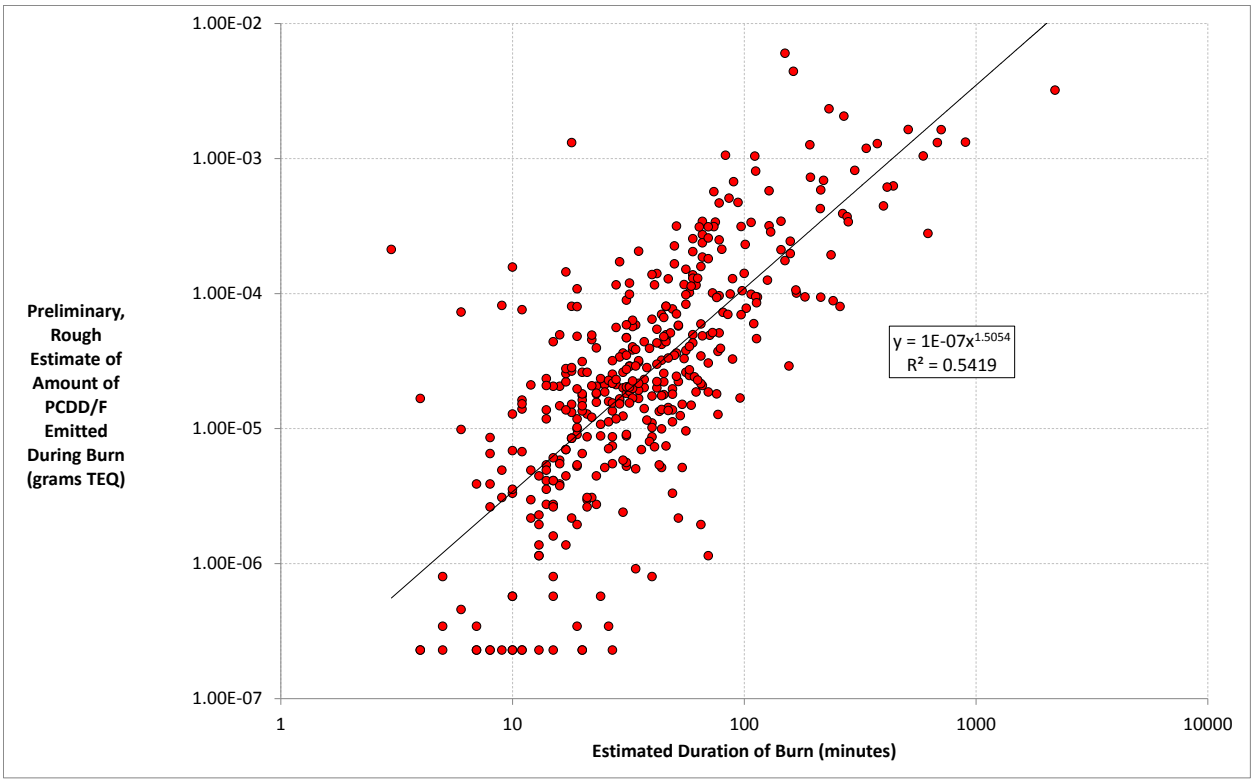

Figure B-1. Logarithmic plot of estimated dioxin emissions during individual burns as a function of the estimated duration of each burn. A fitted power-law regression is shown.

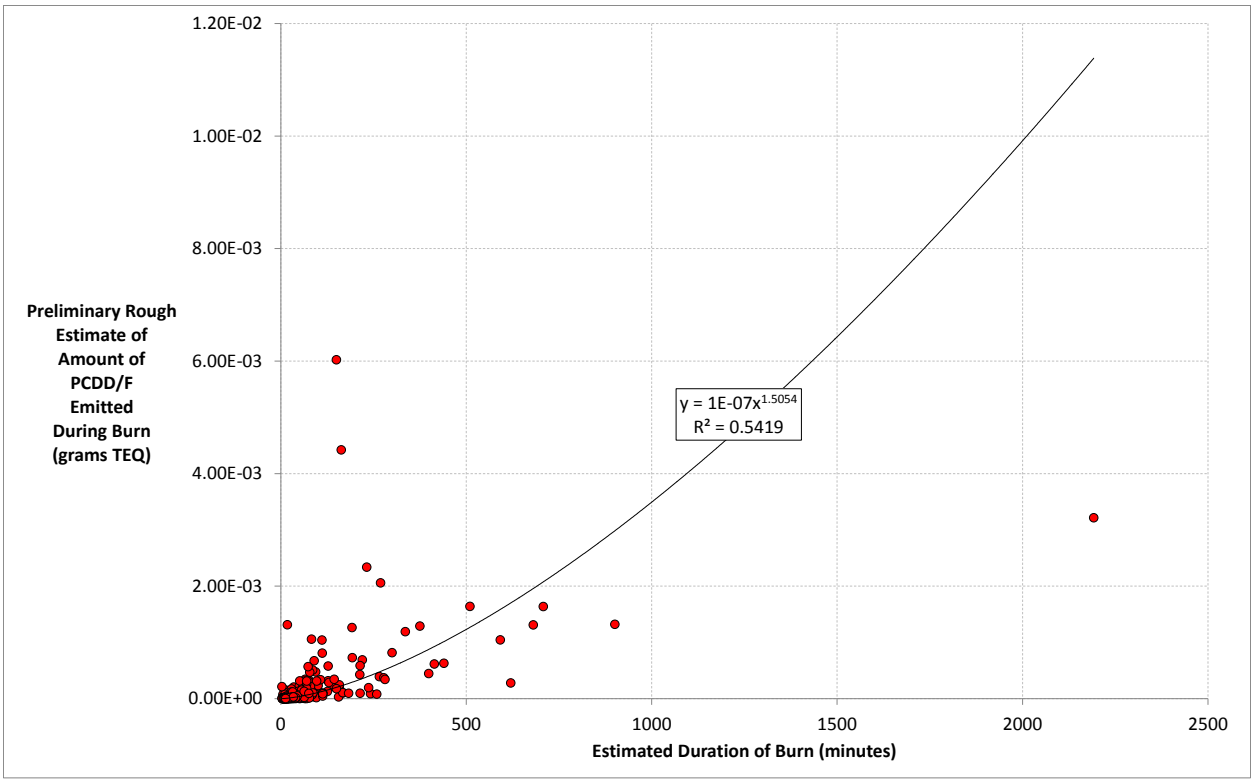

Figure B-2. Linear plot of dioxin emitted during individual burns as a function of the estimated duration of each burn. The fitted power-law regression displayed in Figure B-1 is shown for reference.

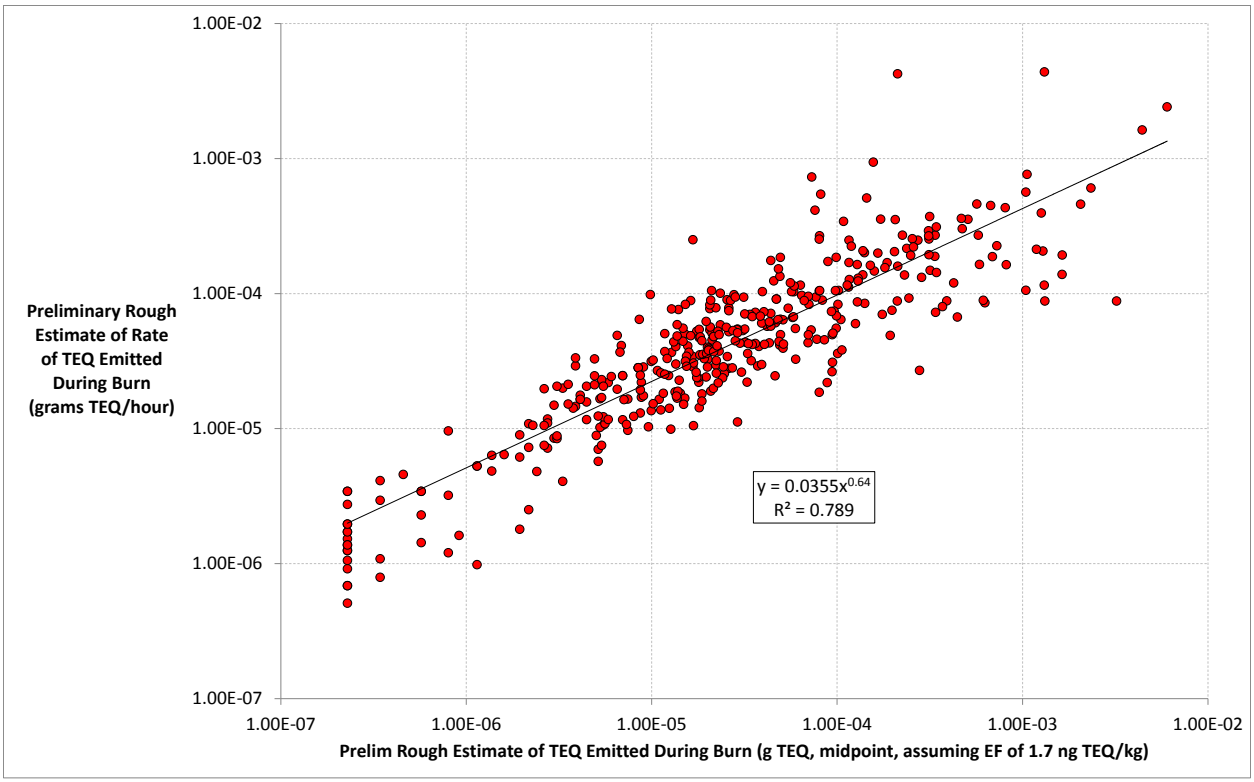

Figure B-3. Logarithmic plot of estimated emissions rate vs. emissions amount of dioxin, for each of the 411 individual burns. A best-fit power-law regression is shown.

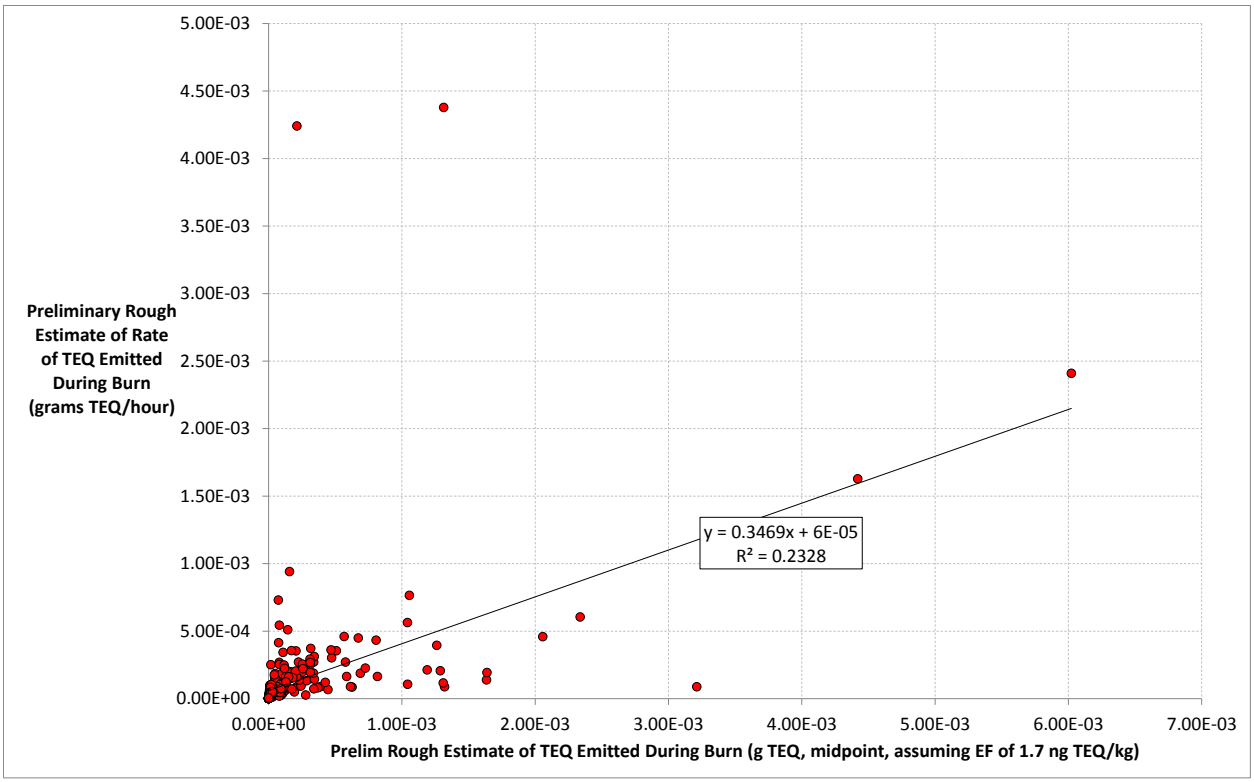

Figure B-4. Linear plot of estimated emissions rate vs. emissions amount of dioxin, for each of the 411 individual burns.

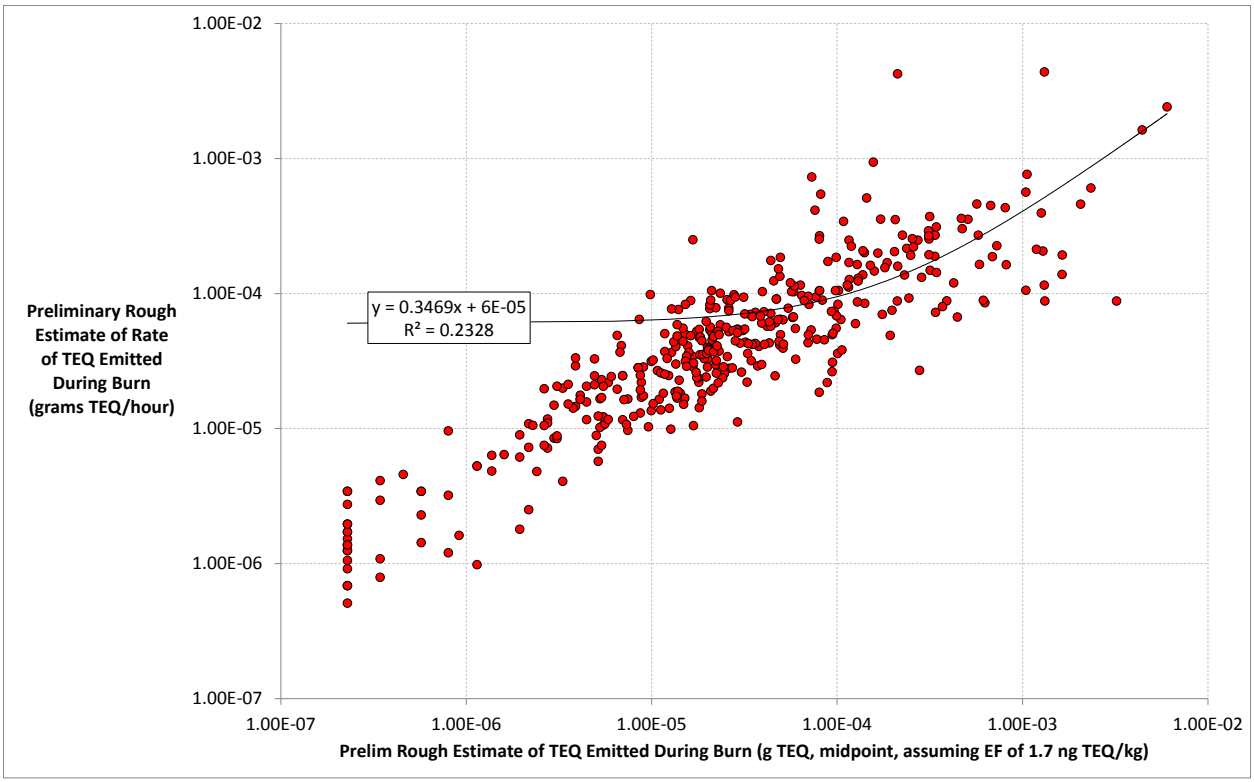

Figure B-5. Logarithmic plot of estimated emissions rate vs. emissions amount of dioxin, for each of the 411 individual burns. The “linear regression” from Figure B-4 is shown for reference.