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Estimates of Inhalation Exposures to Oil-Related Components on the Supporting Vessels During the *Deepwater Horizon* Oil Spill

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Abstract

The *Deepwater Horizon* oil spill response and clean-up (OSRC) involved over 9000 large and small vessels deployed in waters of the Gulf of Mexico across four states (Alabama, Florida, Louisiana, and Mississippi). For the GuLF STUDY, we developed exposure estimates of oil-related components for many work groups to capture a wide range of OSRC operations on these vessels, such as supporting the four rig vessels charged with stopping the spill at the wellhead; skimming oil; *in situ* burning of oil; absorbing and containing oil by boom; and environmental monitoring. Work groups were developed by: (i) vessel activity; (ii) location (area of the Gulf or state); and (iii) time period. Using Bayesian methods, we computed exposure estimates for these groups for: total hydrocarbons measured as total petroleum hydrocarbons (THC), benzene, toluene, ethylbenzene, xylene, and *n*-hexane (BTEX-H). Estimates of the arithmetic means for THC ranged from 0.10 ppm [95% credible interval (CI) 0.04, 0.38 ppm] in time periods 2 and 3 (16 July–30 September 2010) to 15.06 ppm (95% CI 10.74, 22.41 ppm) in time period 1a (22 April–15 May 2010). BTEX-H estimates were substantially lower (in the parts per billion range). Exposure levels generally fell over time and differed statistically by activity, location, and time for some groups. These exposure estimates have been used to develop job–exposure matrices for the GuLF STUDY.

Keywords: Bayesian methods; *Deepwater Horizon* oil spill; exposure assessment; job exposure matrix; occupational exposures

Introduction

The GuLF STUDY is a prospective cohort study of 32 608 individuals involved in the *Deepwater Horizon* oil spill response and clean-up (OSRC) that occurred between 22 April 2010 and 30 June 2011 in the Gulf of Mexico (Kwok *et al.*, 2017). To support the inquiry of the potential association of chemical exposures and short- and long-term adverse health outcomes, our exposure assessment team was tasked with developing quantitative exposure estimates for job–exposure matrices (JEMs) for the study. Unlike previous oil spill studies, we had access to a large database of personal inhalation exposure measurements of selected crude oil components that were collected by the federally designated Responsible Party (RP) for the oil spill. Access to these measurements and to the data recalculated to reflect the analytic limits of detection (LODs) (Stenzel, Groth, Banerjee *et al.*, 2021) enabled us to develop a comprehensive, quantitative exposure assessment strategy (Stewart, Groth *et al.*, 2021) for the ongoing epidemiological investigation to a level of detail (e.g. activity, location, and time) generally not possible in previous epidemiological studies of oil spills.

This paper presents estimates of exposure for total hydrocarbons (THC, as total petroleum hydrocarbons), benzene, toluene, ethylbenzene, xylene (combined *o*-, *m*-, and *p*- isomers), and *n*-hexane (BTEX-H) for workers on support vessels used in the OSRC that became the basis for exposure groups in the study JEMs. This manuscript is part of a larger effort to develop quantitative exposure estimates for all workers involved in the OSRC. Exposure estimates for these six substances on the four rig vessels responding to the oil release can be found in Huynh *et al.* (2021a); on the marine vessels piloting remotely operated vehicles (ROVs) and other marine vessels on which volatile organic compounds direct-reading area measurements were taken in Ramachandran *et al.* (2021); and on land operations in Huynh *et al.* (2021b). The development of exposure estimates for dispersants (Arnold *et al.*, 2021; Stenzel, Arnold *et al.*, 2021), $PM_{2.5}$ (Pratt *et al.*, 2021), oil mist (Stewart, Groth *et al.*, 2021), and dermal exposures (Gorman Ng *et al.*, 2021; Stewart, Gorman Ng *et al.*, 2021) are described elsewhere.

Background

Over 9000 large and small vessels such as marine ships, barges and cargo ships, skimmers, tug and crew boats, fishing and shrimpers, charter, recreational and small draft, air or jon boats participated in the OSRC effort. Many of the larger vessels supported the response effort by the four rig vessels engaged in stopping the release of the oil, flaring of oil and gas, and drilling of relief wells. Smaller vessels, in contrast, performed various activities related to the spill clean-up effort. These vessels were deployed primarily from one of four Gulf states: Alabama (AL), Florida (FL), Louisiana (LA), or Mississippi (MS).

In this section, we briefly describe the major OSRC activities that were performed on the water. Near the wellhead and the large four rig vessels, there were 14 large marine vessels that piloted ROVs, as well as many other large marine vessels (Groth, Banerjee *et al.*, 2021; Ramachandran *et al.*, 2021). Of the remaining vessels, four vessels sprayed dispersants onto the surface waters in the wellhead area to reduce vapors from the oil arising from the release. Smaller support vessels included transport vessels and crew boats that carried food, water, supplies, passengers, and other essential items between the shore and areas throughout the Gulf. Workers on a variety of vessel types scouted throughout the Gulf to identify oiled waters for skimming or burning and to capture oiled wildlife. Vessels conducted oil containment activities that consisted of laying out and inspecting booms and moving and collecting oily booms throughout the Gulf (but primarily near shore). Vessels skimming oil used various mechanical devices to collect oil from the water surface. Offshore, large skimmers, such as Navy salvage vessels, typically worked with boom-handling fishing vessels and shrimpers. These vessels laid boom on the water surface and then pulled it on both ends to contain the oil into a small area that allowed the skimming devices on the larger vessels to collect the oil and oily water. These vessels similarly laid and pulled boom to contain oil, after which an igniter was used to light a flame to burn the oil (called *in situ* burning). Barges (often moved by tug boats) and cargo ships carried skimmed oil/oily water back to shore. Barges and other vessels also transported clean boom from, and oiled boom and other hazardous waste to the shore. Gross decontamination (decon) of vessels (primarily the hull) was performed by vessels or barges prior to reaching port to prevent contamination of the waters as the vessels moved to shore. Research vessels operated by the National Oceanic and Atmospheric Administration (NOAA) and other organizations and specified fishing boats took samples of the air, water, sediments, subsurface oil, fish, and dispersants throughout the Gulf. Near shore, smaller boats (charter, recreational, draft, jon and air boats) patrolled the coastline looking for oil and oiled wildlife and performed transport activities such as delivering and retrieving workers, equipment, supplies, and decontamination materials. Some collected small patches of oil using manual tools such as hoses, nets, and absorbents.

Although on the larger vessels, there often was a distinction between the crew who operated the vessel and workers who performed the activity of the vessel (as described above), oftentimes, particularly on the smaller vessels, the crew was involved in both the vessel operation and activity. In addition, several hundred industrial hygienists, safety professionals, and medics were located on vessels to conduct personal monitoring and ensure the safety of the workers on these vessels. Some of these were stationed on the larger vessels, but generally these workers moved around on the various vessels.

Methods

Data collection and processing

A detailed description of how the measurement data were collected, processed, and recalculated from the originally reported LODs (based on calibration curves accounting for occupational exposure limits) to the analytic method's true LOD can be found in Stenzel, Groth, Banerjee *et al.* (2021). Briefly, the RP contracted industrial hygiene personnel to monitor workers by collecting air samples that were to represent typical exposures of those activities with the highest potential for exposure (near the wellhead and offshore) or collecting sufficient samples to assess representative exposures (near shore). Samples were collected on organic vapor badges (3M 3500 or 3520, or Assay Technology 521) generally for 4–18 h, and each sample was analyzed for 5–11 analytes. Here, we included only measurements taken outdoors on vessels, as most of the workers on the water performed their tasks on deck. After these and other exclusions (Stenzel, Groth, Banerjee *et al.*, 2021), we used 6562 personal samples taken on the support vessels in this paper. Table 1 reports the number of measurements taken on the water and the percent censoring after the recalculation to the analytic methods' LODs. Of these 6562 samples THC had the least number of measurements below the LOD (% <LOD = 15.4) and benzene the most (% <LOD = 67.6).

Development of work groups

The goal of the exposure assessment effort in the GuLF STUDY was to estimate study participants' exposures. Much of the OSRC work was fluid and done on an *ad hoc* basis. Many oil field research and support service contractors were hired with their own trained staff to perform a particular activity (such as skimming) that was needed to be done for a short period of time (e.g. months) and then dismissed. Many were fishermen or shrimpers who were banned from fishing due to the contaminated waters. Other workers were hired from the general population when the need for a task arose (such as patrolling the near shore for oil). The RP hired these workers through multiple subcontractors to perform various clean-up activities on a temporary basis, as such it was not possible to contact employers for work histories. Furthermore, many participants in the measurement documentation were identified with very general job titles (e.g. deck hand, responder). We therefore collected work history information via a telephone questionnaire administered to the study participants. After asking about whether the participant worked on the water, we asked about the activity of the vessel the participant worked on.

The development of the exposure groups can be found in Stenzel, Groth, Huynh *et al.* (2021). We considered activity as one of the primary exposure determinants in the JEM used to link the study participants to the exposure estimates derived from the measurement data (*Statistical Analyses*) (Stewart, Groth *et al.*, 2021). We also developed several other groups under the activity determinant. For example, when the participant indicated that s/he worked on a boat but said 'no' to all questions on vessel activities, we used a broad group called 'Worked on a boat or ship' to capture people on these unspecified vessels. Specific research vessels were identified, as well as an 'All research vessels'. We also

Table 1. Number of measurements taken on the water and percent censoring by work group type and analyte.

Job group type[a]	Total *N*	THC	Benzene	Ethylbenzene	Toluene	Xylene	*n*-Hexane	
		% <LOD	% <LOD	% <LOD	% <LOD	% <LOD	*N*	% <LOD[b]
Research vessels	227	15.4	92.1	81.9	34.8	54.6	127	51.2
Combined water tasks	6204	6.9	67.6	73.1	41.1	36.2	680	59.9
Total	6562	10.0	81.2	66.8	30.9	38.3	938	50.8

N = number of measurements. The *N* imputed hexane values from THC and % <LOD were: research vessels, *N* = 100, % = 34.0; and combined water tasks, *N* = 5524; % = 57.7.

[a]For details on the work groups, see text.

[b]The values in the table represent the % <LOD for the actual measurements. The LODs, based on a sample of 12 h in duration, for THC, benzene, toluene, ethylbenzene, xylene, and *n*-hexane are 0.11, 0.003, 0.003, 0.0027, 0.0057, and 0.0027 ppm, respectively. If the actual sample duration was different than 12 h, the LOD used to calculate percent censoring was adjusted to reflect the measurement duration. For example, for a specific benzene measurement, if the sample duration was 8 h rather than 12 h, the measurement LOD used to determine censoring would be 12/8 h times the benzene LOD of 0.003 or 0.0045 ppm (Stenzel, Groth, Banerjee *et al.*, 2021).

included under the determinant of activity 'Industrial hygienist/safety' as this job was held by many people and was unique from the crew or clean-up workers. Finally, because the same task was sometimes performed on vessels with different activities we included two tasks under this determinant 'Cleaned oil pools' and 'Maintained pumps/tanks or dis/connected anything (inc oil)/Water'. More detailed description on activity groups can be found in Table 2 and Supplementary Material (available at *Annals of Work Exposures and Health* online).

A second determinant that was expected to affect exposures was oil weathering (Stenzel, Groth, Huynh *et al.*, 2021). As the oil was released from the well, some of the components were dissolved in the water as it rose to the water surface. Once the oil reached the surface, the oil changed composition due to contact with dispersants and due to various natural processes, such as wave action and evaporation. Because participants were not able to provide information on weathering, we used location (area of the Gulf or a Gulf of Mexico coastal state) and time period as proxies for degree of oil weathering.

The Gulf of Mexico areas we developed for the study to reflect oil weathering differences were: (i) the hot zone [within 1852 m (1 nautical mile (nm)) of the wellhead, which was approximately 92.6 km (50 nm) southeast of the Louisiana shore], (ii) the source [a 9.26 km (5 nm) radius around the wellhead, excluding the hot zone], (iii) offshore [outside of the source to within 5556 m (3 nm) of the four-state shore line], and (iv) near shore (within 5556 m of the four-state shore). The hot zone and source were combined due to the difficulty of participants describing their exact location. Areas were thought of as approximate, rather than precise, locations.

Seven time periods were developed over the STUDY period based on significant events that were expected to affect worker exposures and the oil weathering process. The defined time periods were time periods 1a (20 April–14 May 2010), 1b (15 May–15 July 2010), 2 (16 July–10 August 2010), 3 (11 August–30 September 2010), 4 (1 October–31 December 2010), 5 (1 January–31 March 2011), and 6 (1 April—30 June 2011) (Stenzel, Groth, Huynh *et al*, 2021). The description of these time periods may also be found in Supplementary Material (available at *Annals of Work Exposures and Health* online).

Another component of the location determinant was state. State was recorded in the sample documentation as the state with jurisdiction at that water location where the vessel was located at the time of the data collection. The further the state was from the wellhead, the more weathered the oil was likely to be. State also reflected differences in work practices and time spent on various tasks. A fifth state category 'All states' was used to combine all measurements. Hot zone, source, and some offshore activities were not designated by state as they were outside state waters.

We assigned each study participant to one or more activity, location, and time period based on the information reported in the questionnaire. As a result, there were a possible 675 unique activity/location/time period combinations, called here work groups (Stenzel, Groth, Huynh *et al.*, 2021). We also reviewed the accompanying documentation of every sample and assigned one or more activity, location, and time period where appropriate. The same 675 groups were assigned to the measurement data for of each of the six substances of interest (THC and BTEX-H).

Statistical analysis

We developed estimates of the statistical parameters [arithmetic means (AMs), geometric means (GMs), geometric standard deviations (GSDs), and 95th percentiles

Table 2. Description of activities on vessels that supported the oil spill clean-up operations.

Vessel activity (/water indicates the activity was on the water in contrast to a similar activity done on land)	Description[a]
Transport vessel	Vessel carried food, water, supplies, passengers, and other essential items throughout the Gulf of Mexico to and from shore.
Vessel burned oil	Vessels involved in burning oil on the water surface. The oil was ignited after being contained by fire boom pulled by fishing vessels. Primarily done offshore.
Vessel scouted for oil/wildlife on water	Vessel drove around the Gulf waters looking for oil to be burned or skimmed by other groups. Oiled wildlife (either alive or dead) were reported or captured and taken to shore.
Vessel put out, inspected, moved, or collected booms or absorbent	Boom and absorbents were used to contain the oil. These vessels put them out, inspected them to make sure they continued to be effective, moved them to increase effectiveness and collected them when the boom and absorbents was no longer needed. Could have been done offshore to support *in situ* burning or skimming or nearer to shore to protect shorelines.
Vessel handled oily booms and absorbents	A group developed for subjects in the GuLF STUDY questionnaire who indicated their vessel did not put out (clean) boom or absorbents (versus 'Vessel put out, inspected, moved, or collected booms or absorbent').
Vessel deconned other vessels/water	Gross decontamination of the vessel's (primarily) outside done to reduce the amount of oil dragged into the ports and docks. This was done primarily with pressure spraying with workers in boats off the side. Generally done near shore, although some stations were offshore.
Vessel patrolled beaches/marshes for oil/tar/animal	Vessel drove around looking for oil to be captured by other groups. Oiled wildlife (either alive or dead) were reported or captured and taken to shore. Near shore.
Worked on a boat or ship	A group developed for subjects who did not identify in the GuLF STUDY questionnaire any of the water activities. No information as to where these participants may have been.
Barge work	Barges carried recovered oil from the hot zone or oil/oily water skimmed from offshore and clean or decontaminated equipment from land to various locations in the Gulf and back.
Research vessels	Research vessels under the auspices of the NOAA, universities, or other research organizations tasked with collecting air, water, sediments, subsurface oil, and dispersants and fish samples. N = 33. These were larger vessels with greater resources than the fishing vessels assigned to 'Environmental sampling/water/non-NOAA'. These worked throughout the Gulf.
Vessel sprayed dispersant on surface	Vessel sprayed dispersant on the water surface to reduce the oil vapors. Only in the hot zone and source.
Environmental sampling/water/non-NOAA	Developed for study subjects who indicated in the GuLF STUDY questionnaire that they took collected samples but who appeared to have worked on a small, privately owned fishing vessel. No information on the location in the Gulf.
Handled hazardous waste/water	Vessel handled hazardous waste, including contaminated equipment, such as oiled boom. This may have been done throughout the Gulf waters, but primarily closer to shore.
Draft/air/jon boat	Small boats that traveled the coastline looking for oil or wildlife or transporting personnel to nearby islands. May have skimmed.
Vessel skimmed and personally skimmed	Large or small vessels using mechanical devices, nets, and absorbents to collect the oil. Includes the general crew and the specific workers who operated the skimming equipment.
Deconned all/water	A group developed for subjects who reported in the GuLF STUDY questionnaire deconning all equipment, i.e. vessels, boom, and any other equipment that needed cleaning. Cleaning was done primarily with pressure spraying but could have included absorbents. Most of the work would have been the hulls of vessels.
Vessel deconned and personally deconned/water	A group developed for subjects who reported in the GuLF STUDY questionnaire actually doing the deconning on a vessel that deconned other vessels/water. See 'Vessel deconned other vessels/water'.
Vessel carried oil/oily water	Vessels included barges and cargo ships that carried oil and oily water from the recovered oil in the hot zone and from skimming operations to shore.

Table 2. Continued

Vessel activity (/water indicates the activity was on the water in contrast to a similar activity done on land)	Description[a]
Vessel handled oily boom and absorbents and personally handled oily boom	A group developed for subjects who reported in the GuLF STUDY questionnaire actually handling boom or absorbents. See 'Vessel handled oily booms and absorbents'.
IH/safety-water	Industrial hygienists, safety professionals and medics monitored air concentrations and ensured the safety of the workers.
On vessel while being deconned/ water	A group developed for subjects who reported in the GuLF STUDY questionnaire staying on a vessel as it was being decontaminated on the water. See 'Vessel deconned other vessels/water'.
Cleaned oil pools	As an unintended consequence of many of the tasks, oil collected on the deck of the vessels. Clean-up was done by wiping it up with absorbents.
Maintained pumps/tanks or dis/ connected anything (inc oil)/water	Tasks performed on the barges, cargo ships, and skimming vessels generally in the transfer or oil or oily water. Could have occurred throughout the Gulf.
Areas on the Gulf: Developed because workers in the different Gulf areas were found to have statistically different AMs and a question was not asked of each subject where they performed each of their reported activities.	
Offshore	A group developed to reflect study subjects' higher exposure levels than levels near shore due to the proximity to the hot zone and source.
Vessel could see shoreline (near shore)	A group developed to reflect study subjects' lower exposure levels than offshore or the source/ hot zone areas due to the greater distance from the wellhead.
Could see wellhead from vessel	A group developed to reflect the highest exposures study subjects may have experienced due to their proximity to the wellhead.

[a]Each activity includes all workers on the vessel indoors or out of doors and whether the worker is a crew member or performing the actual work, unless specified (i.e. 'personally…'). See text for more details.

($X_{0.95}$s) and their 95% credible intervals (CI, similar to confidence levels)] using Bayesian methods for each work group with at least five measurements and ≤80% censoring. These criteria were selected because together they were shown to have an average relative bias of <15% and an average relative imprecision (root mean square error) of <65% in our simulation study (Huynh *et al.*, 2016). For THC, we used a univariate Bayesian model with uniform (Unif) priors for $\mu(\ln(GM))$ and $\sigma(\ln(GSD))$: $\mu \sim$ Unif(ln 0.025, ln 50) and $\sigma \sim$ Unif(ln 1.1, ln 12). These priors were the same as those used in estimating THC levels on the rig vessels; the basis for using these priors are described in Huynh *et al.* (2021a). We expected exposure levels on the vessels described here to be lower than those on the rig vessels so these priors are considered conservative. We used a bivariate Bayesian model to predict BTEX-H work group exposures (Groth *et al.*, 2017, 2018). The priors were derived from the correlations between the THC and each of the BTEX-H chemicals' measurements by area and time period (Groth, Huynh *et al.*, 2021). *n*-Hexane was not analyzed on all of the personal samples described here for THC and BTEX. We estimated missing *n*-hexane from a Bayesian bivariate analysis using the THC:*n*-hexane correlations for samples where both THC and *n*-hexane were present (Groth, Huynh *et al.*, 2021).

We used nonoverlapping 95% CIs of the AM estimates to identify notable differences (i.e. statistically credible differences) across activities, locations, and time periods. Statistical credible (at alpha = 0.05) refers to when the 95% CI do not overlap. All analyses were conducted in JAGS (Just Another Gibbs Sampler) (Plummer, 2003) and R (R Development Core Team, 2015).

Results

Supplementary Tables S1–S6 (available at *Annals of Work Exposures and Health* online) show the posterior medians of the AMs, GMs, GSDs, and the 95th percentiles and their 95% CI for THC and BTEX-H for all work groups that met our criteria of $N \geq 5$ and censoring ≤80%. THC estimates are in parts per million (ppm); the BTEX-H estimates are in parts per billion (ppb).

THC estimates

Relatively high THC AM exposure estimates were observed in TP1a and TP1b before the well was mechanically capped. The highest observed THC AM estimate was 15.06 ppm (95% CI 10.74, 22.41 ppm; *N* = 188; All states) during TP1a for 'Could see wellhead from the vessel' (i.e. the measurements collected in the hot zone or source area) (Supplementary Table S1, available at *Annals of Work Exposures and Health* online). We observed the lowest THC AM estimates in TP2 and 3 at 0.10 ppm (95% CI 0.02, 0.21 ppm; *N* = 22) for the *Ocean Veritas* (a research vessel) (TP2) and for 3 activities with overlapping measurements: 'Vessel deconned other vessels/water' (95% CI 0.04, 0.39 ppm; *N* = 13, FL); and 'Deconned all/water' and 'Vessel deconned & personally deconned/water' (95% CI 0.04, 0.38 ppm, *N* = 14, FL) (see Supplementary Material, available at *Annals of Work Exposures and Health* online for a description of these activities).

We observed notable differences in THC exposure levels among some activities within a time period (Fig. 1a). Details on all estimates are found in Supplementary Material (available at *Annals of Work Exposures and Health* online). For instance, in TP1b the AM for 'Transport vessel' (2.1 ppm, 95% CI 1.55, 3.00 ppm; All states) was markedly greater than the AM for 'Vessels handled oily booms & absorbents' (0.67 ppm, 95% CI 0.53, 0.90 ppm; All states) and 'Vessel deconned other vessels/water' (0.49 ppm, 95% CI 0.27, 1.16 ppm; All states). Another example was the AM for 'IH/safetywater', which was much greater in TP1a than the AM for 'Vessel could see shoreline (near shore)' in the same period (4.19 ppm, 95% CI 2.40, 8.72 ppm, All states versus 0.57 ppm, 95% CI 0.43, 0.78 ppm, All states, respectively).

Differences in exposure levels were also observed by area and state. The hot zone/source area ('Could see the wellhead from vessel') AM was credibly higher than the AM for near shore ('Vessel could see the shoreline (near shore)') (15.06 ppm, 95% CI 10.74, 22.41 ppm versus 0.57 ppm, 95% CI 0.43, 0.78 ppm, respectively) in TP1a (there were no offshore measurements in this time period). Similarly, in TP1b the hot zone/source AM was 3.29 ppm (95% CI 2.90, 3.77 ppm); the offshore AM was 1.11 ppm (95% CI 0.91, 1.39 ppm); and the near shore AM was 0.65 ppm (95% CI 0.60, 0.71 ppm). In TP2, the hot zone/source and offshore AMs were not that different (0.73 ppm,

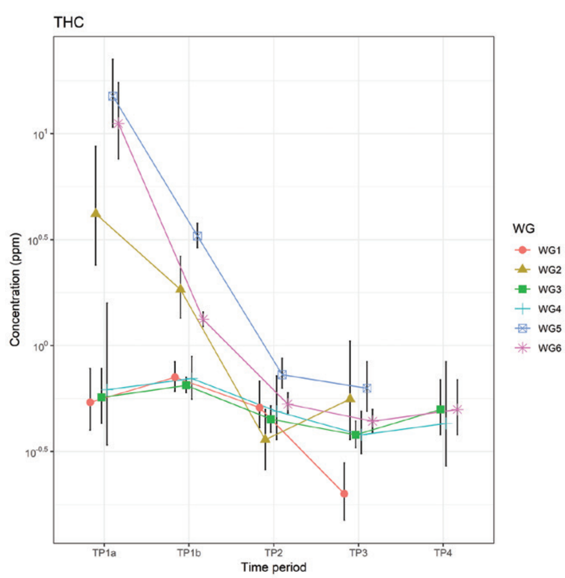

Figure 1. (a) Time trends of the AM estimates of selected work groups (WGs) for 'All states' for THC: WG1 ('Vessel put out, inspected, moved, or collected booms or absorbents'), WG2 ('IH/Safetywater'), WG3 ('Vessel could see shoreline (nearshore)'), WG4 ('Vessel handled oily boom and absorbents, and personally handled oily boom'), WG5 ('Could see wellhead from vessel'), and WG6 ('Worked on a boat or ship'). Note differences in the scale and measurement units of each graph. See Supplementary Material (available at *Annals of Work Exposures and Health* online) for definitions of time period. (b) Time trends of the AM estimates of selected WGs for 'All states' for toluene and xylene. (c) Time trends of the AM estimates of selected WGs for 'All states' for ethylbenzene and benzene. (d) Time trends of the AM estimates of selected WGs for 'All states' for hexane. The WGs are the same as THC.

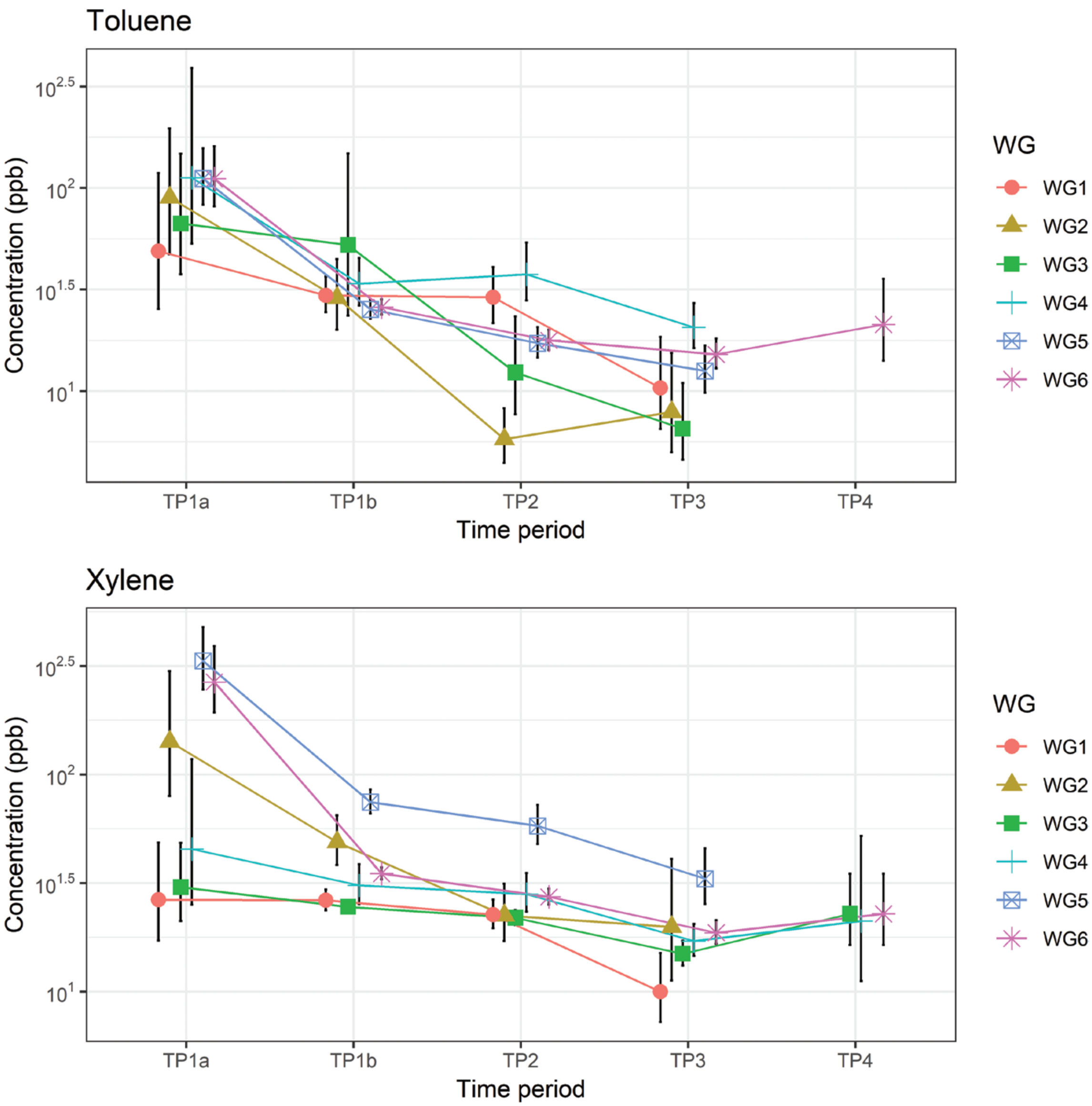

Figure 1. Continued.

95% CI 0.63, 0.87 ppm and 0.80 ppm, 95% CI 0.59, 1.14 ppm, respectively) but both were notably higher from the near shore AM (0.45 ppm, 95% CI 0.39, 0.52 ppm).

The state of LA was generally higher than the other 3 states. The AM estimate in TP1b for 'Vessel patrolled beaches/marshes for oil/tar/animal' in LA was 1.15 ppm (95% CI 0.77, 1.98 ppm) versus AL, 0.34 ppm (95% CI 0.24, 0.52 ppm); FL, 0.29 ppm (95% CI 0.24, 0.36 ppm); and MS, 0.35 ppm (95% CI 0.25, 0.5 ppm). Similarly, the AMs for 'Vessel skimmed' were LA, 0.64 ppm (95% CI 0.52, 0.82 ppm) versus AL, 0.26 ppm (95% CI 0.18, 0.42 ppm); FL, 0.30 ppm (95% CI 0.22, 0.44 ppm); and MS, 0.23 ppm (95% CI 0.13, 0.60 ppm). Exposure levels in other three states were more similar to one another than to LA.

Lastly, we observed an overall trend of decreasing exposure levels over time, with some noteworthy

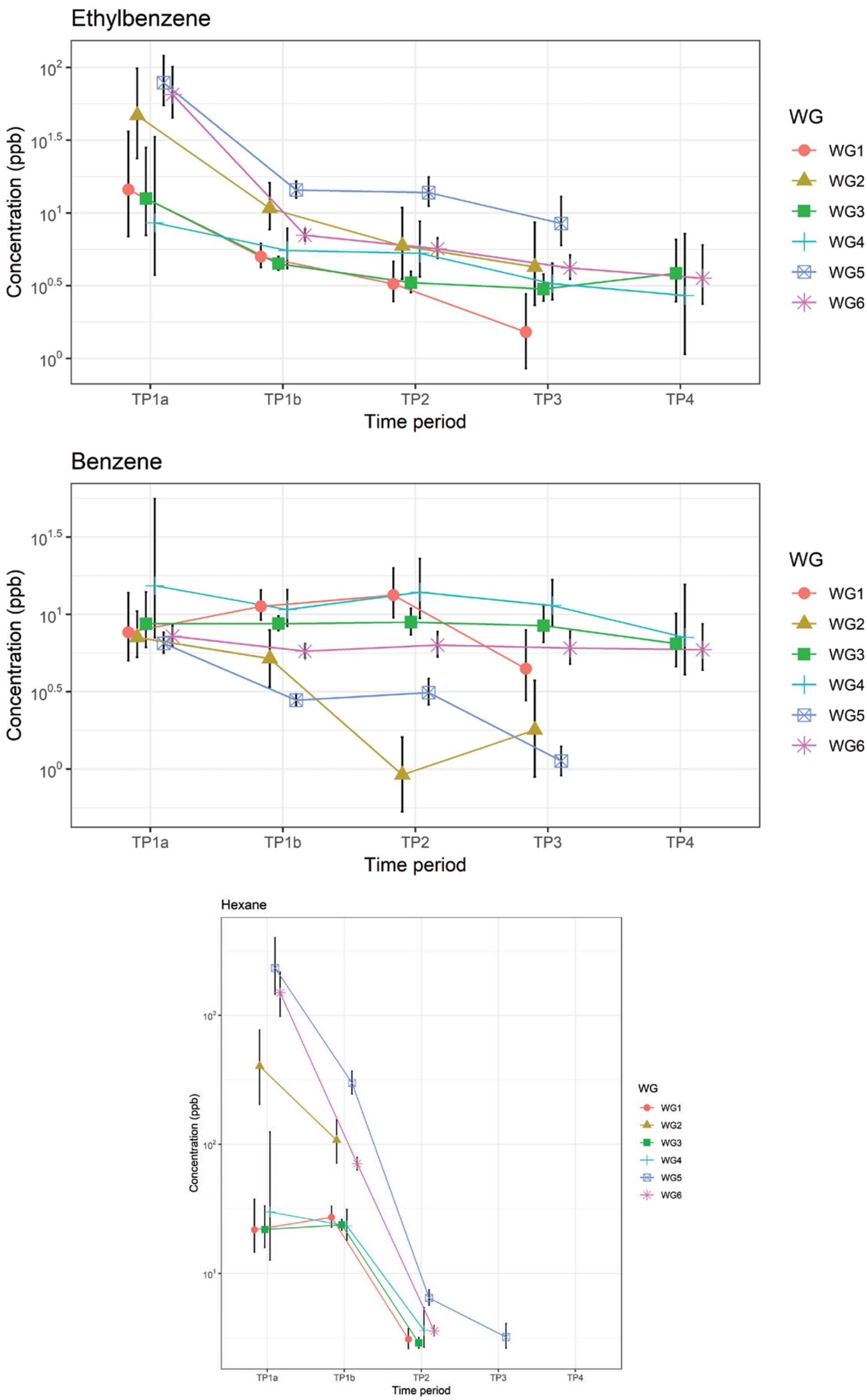

Figure 1. Continued.

differences. For instance, the general category of 'Worked on a boat or ship' for 'All states' had an AM of 11.18 ppm (95% CI 7.59, 17.37 ppm) for TP1a, which was greater than the AM for TP1b (1.33 ppm, 95% CI 1.23, 1.44 ppm); both were greater than the AMs for TP2, 3, and 4 (0.53 ppm, 95% CI 0.48, 0.60 ppm; 0.44 ppm, 95% CI 0.39, 0.50 ppm; and 0.50 ppm, 95% CI 0.38, 0.69, ppm, respectively). Similarly, the AM for 'IH/safety-water' in TP1a was 4.19 ppm (95% CI 2.40, 8.72 ppm) and for TP1b was 1.84 ppm (95% CI 1.35, 2.64 ppm) versus TP2 0.36 ppm (95% CI 0.26, 0.50 ppm) and TP3 0.56 ppm (95% CI 0.36, 1.05 ppm).

BTEX-H estimates

The BTEX-H exposures were substantially lower than THC and generally followed a similar pattern in trends across activities, states, and time periods (Supplementary Tables S2–S6, available at *Annals of Work Exposures and Health* online), however, the CIs for most groups overlapped with each other. Fig. 1b (toluene and xylene), 1c (benzene and ethylbenzene), and 1d (hexane) showed the time trend of the AM and their 95% CI of selected work groups. Benzene AMs ranged from 2.27 ppb (95% CI 0.32, 14.75 ppb; N = 8, FL, TP3) 'Barge work' to 33.94 ppb (95% CI 16.28, 86.35 ppb; N = 52, MS, TP2) 'Vessel handled oily booms & absorbents'. Toluene posterior medians for the AM ranged from 1.80 ppb (95% CI 0.81, 4.31 ppb; N = 30, All states, TP3) 'Vessels skimmed and personally skimmed' to 128.4 ppb (95% CI 62.07, 385.87 ppb; N = 13, MS, TP1b) 'Vessels deconned other vessels/water'; ethylbenzene from 1.58 ppb (95% CI 0.23, 9.99 ppb; N = 8, FL, TP3) 'Barge work' to 78.50 ppb (95% CI 55.05, 120.42 ppb; N = 188, TP1a) 'Could see wellhead'; xylene from 6.08 ppb (95% CI 4.76, 8.30 ppb; N = 195, MS, TP4) 'On vessel while being deconned/water' to 333.71 ppb (95% CI 246.67, 477.11 ppb; N = 188, TP1a) 'Could see wellhead', and *n*-hexane from 2.10 ppb (95% CI 0.25, 15.31 ppb; N = 6, AL, TP3) 'Barge work' to 2320.6 ppb (95% CI 1448.7, 3985.2 ppb; N = 188, All states, TP1a) 'Could see wellhead from the vessel'.

The variability of the estimates was generally high (Supplementary Tables S1–S6, available at *Annals of Work Exposures and Health* online). The percentages of the posterior medians for GSDs >6 were 10.8% for THC (GSDs ranged from 1.4 to 9.0); 41.7% for benzene (2.4–9.8); 32.6% for toluene (range 2.7–10.8); 43.2% for ethylbenzene (3.1–10.2); 6.6% for xylene (1.8–8.7); and 31.3% for *n*-hexane (2.9–11.1).

Discussion

This paper presents exposure estimates for work groups on the thousands of vessels that performed OSRC activities on water. These vessels were generally in the offshore and near shore areas and engaged in a variety of activities including supporting the response operations; transporting supplies and personnel; scouting; skimming oil; burning oil *in situ*; laying out and collecting booms; decontaminating vessels and equipment; and taking samples for research purposes. Determinants of THC and BTEX-H exposures for these workers included vessel activity; proxies for oil weathering, i.e. area of the Gulf water and state (both of which incorporated distance from the wellhead) and time period; and physical and chemical properties of the crude oil (Stenzel *et al.*, 2021c).

To our knowledge, very few studies have assessed exposures of workers on vessels performing the work described here. NIOSH industrial hygiene investigations during the *Deepwater Horizon* spill reported the range of THC between 0.0094 ppm (0.038 mg m^{-3}) (skimming operations) to 2.25 ppm (9.1 mg m^{-3}) (*in situ* burning) (NIOSH, 2010). Many of those investigations also found that BTEX-H personal measurements on water activities had high percentages of censoring, similar to ours and the measurements were within the ranges of our estimates. Avens *et al.* (2011) analyzed the RP's publicly available BTEX personal measurements and found similar levels to ours, despite different methodologies. Those authors attributed elevated BTEX levels to engine exhausts and found few differences in exposure before and after the top capping. This report and our other reports presenting the *Deepwater Horizon* measurements (Huynh *et al.*, 2021a,b; Ramachandran *et al.*, 2021) however, often found large and sometimes notable differences between vessels, vessel types, activities, areas across the Gulf (e.g. hot zone, source, etc.), states, and time periods, suggesting that a number of factors other than engine exhaust affected exposures.

Our estimates are below existing occupational exposure limits. The closest equivalent exposure limit to THC is petroleum distillates, which has a NIOSH Recommended Exposure Limit (REL) of 86 ppm (350 mg m^{-3}) (NIOSH, 2007). In Supplementary Table S1 (available at *Annals of Work Exposures and Health* online), the highest 95th percentile (the typical compliance metric used to assess compliance with occupational exposure limits) observed was 60.07 ppm in TP1a for the area 'Could see wellhead from the vessel'. Our BTEX-H estimates, however, were substantially below the current exposure limits. The respective ACGIH Threshold Limit Values™

for benzene, toluene, ethylbenzene, xylene, and *n*-hexane are 0.5, 20, 100, 100, and 50 ppm, respectively (ACGIH, 2018). The highest 95th percentiles observed for the work groups reported here were 0.14 ppm for benzene, 0.58 ppm for toluene, 0.57 ppm for ethylbenzene, 2.11 ppm for xylene, and 1.07 ppm for *n*-hexane (Supplementary Tables S2–S6, available at *Annals of Work Exposures and Health* online). Despite these low levels, it is important to develop these quantitative estimates so that researchers can investigate the exposure–disease relationships for these activities and exposure levels.

The RP worked with OSHA to develop personal protective equipment (PPE) matrices. The matrices covered some of the specific activities we describe here, but not others. Assessment and enforcement of PPE were the responsibility of the industrial hygienist/safety professional on site and no consistent documentation of PPE worn was made in the measurement database. For this reason, we did not account for respiratory protection in the exposure levels reported here.

The results of this report are likely impacted by the same limitations as the estimates developed for the rig and land workers (Huynh *et al.*, this issue, a,b). Briefly, one limitation may be the GSD values we found, which, in addition to being affected by the censored measurements and the samples having been taken outdoors, may also have resulted from combining measurements that represented different distributions of exposures (i.e. different vessel work groups) into a single distribution. Another source of misclassification may be from the limited documentation associated with some of the measurements. Due to our inability to visit the operations while they were occurring, we relied on data generated after the fact or on secondary reports, and some documented activities from the measurement data. To ensure completeness of the activities list, however, we reviewed the extensive literature generated after the *Deepwater Horizon* disaster on operations, vessels, and job tasks. Another limitation in our estimates may be the statistical assumptions that were made when applying the Bayesian models including: (i) the use of overarching priors of work groups [broad groupings of measurements, e.g. all water measurements in TP1a and TP1b to represent smaller work groups (e.g. skimming in TP1a)]; (ii) assuming *n*-hexane imputation developed estimates that were comparable in accuracy and imprecision to the BTEX chemicals; (iii) assuming the linear regression assumptions were valid and appropriate. Lastly, some of the data were collected by the RP with the purpose of monitoring those activities with the highest potential for exposure. Strictly interpreted this should mean that activities were selected for monitoring that were most likely to be exposed (based on various exposure characteristics) regardless of the level of exposure. This policy would result in a greater number of measurements for specific activities but would not necessarily have resulted in biased estimates for those activities. In contrast, if interpretation of the policy was that people with potentially the highest exposure should be monitored (e.g. among all people performing an activity), our estimates could reflect higher than average exposures for the activity. This is probably unlikely, however, since it has been shown that industrial hygienists do not do very well in estimating exposure levels without measurement data (Arnold *et al.*, 2017).

The strengths of this study are the large number of measurements (more than 6562 collected over 5 months) and comprehensive documentation on the disaster to allow development of quantitative estimates for the JEM in the epidemiological study. Another strength is the use of Bayesian methods to account for censored data and leveraging the correlation between THC and BTEX-H as priors to inform estimates, helping to minimize the overall error to the extent feasible. A fourth strength is the large number of activities performed to clean-up a major oil spill that have not, to our knowledge, been described in any other study. Finally, we used exposure determinants to develop our work groups, which should have reduced error in the estimates from that which would have occurred had we not used determinants. We found notable differences based on these determinants, which suggests that we were at least partially successful in developing unique work groups. The differences among the groups should enhance analyses of exposure–response relationships in the GuLF STUDY.

The information provided here should also be useful for professionals involved in disaster preparedness and response to oil spills. It suggests which water operations were more likely to be hazardous and which water operations less so. It provides information that can be used to assign PPE and dedicate resources, such as air sampling. It sets a framework on how to think about an OSRC effort with regard to determinants that is useful to developing sampling strategies for collecting measurements on workers and documenting exposures.

Conclusions

This paper describes estimates of exposures to THC and BTEX-H chemicals for workers on vessels that supported the OSRC effort. We developed work groups to characterize the clean-up operations on water based on reported vessel activities, locations, and time periods. We found that these were important determinants of exposures, resulting in notable differences among several of the subgroups. THC AM levels were below 16 ppm, whereas the levels for BTEX-H were in the ppb range. The exposure levels for these workers on the support vessels were generally lower than those of rig workers, but higher than those of land workers. As with the rig workers, levels varied by activity and generally decreased over time. In addition, exposures decreased as distance from the wellhead increased. These exposure estimates are being used to support the investigation of potential adverse health effects associated with these oil spill clean-up activities in the GuLF STUDY.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

The authors declare that there is no conflict of interest.

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