# Modeled Air Pollution from *In Situ* Burning and Flaring of Oil and Gas Released Following the *Deepwater Horizon* Disaster

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## Abstract

The GuLF STUDY, initiated by the National Institute of Environmental Health Sciences, is investigating the health effects among workers involved in the oil spill response and clean-up (OSRC) after the *Deepwater Horizon* (*DWH*) explosion in April 2010 in the Gulf of Mexico. Clean-up included *in situ* burning of oil on the water surface and flaring of gas and oil captured near the seabed and brought to the surface. We estimated emissions of $PM_{2.5}$ and related pollutants resulting from these activities, as well as from engines of vessels working on the OSRC. $PM_{2.5}$ emissions ranged from 30 to 1.33e$^6$ kg per day and were generally uniform over time for the flares but highly episodic for the *in situ* burns. Hourly emissions from each source on every burn/flare day were used as inputs to the AERMOD model to develop average and maximum concentrations for 1-, 12-, and 24-h time periods. The highest predicted 24-h average concentrations sometimes exceeded 5000 μg m$^{-3}$ in the first 500 m downwind of flaring and reached 71 μg m$^{-3}$ within a kilometer of some *in situ* burns. Beyond 40 km from the *DWH* site, plumes appeared to be well mixed, and the predicted 24-h average concentrations from the flares and *in situ* burns were similar, usually below 10 μg m$^{-3}$. Structured averaging

of model output gave potential $PM_{2.5}$ exposure estimates for OSRC workers located in various areas across the Gulf. Workers located nearest the wellhead (hot zone/source workers) were estimated to have a potential maximum 12-h exposure of 97 μg $m^{-3}$ over the 2-month flaring period. The potential maximum 12-h exposure for workers who participated in *in situ* burns was estimated at 10 μg $m^{-3}$ over the ~3-month burn period. The results suggest that burning of oil and gas during the *DWH* clean-up may have resulted in $PM_{2.5}$ concentrations substantially above the U.S. National Ambient Air Quality Standard for $PM_{2.5}$ (24-h average = 35 μg $m^{-3}$). These results are being used to investigate possible adverse health effects in the GuLF STUDY epidemiologic analysis of $PM_{2.5}$ exposures.

**Keywords:** *Deepwater Horizon*; oil spill; $PM_{2.5}$ concentrations; $PM_{2.5}$ exposure; worker exposure

## Introduction

On 20 April 2010, high-pressure methane rose into the *Deepwater Horizon* (*DWH*) oil drilling rig, caught fire, and exploded in the Gulf of Mexico. The rig sank 2 days later. United States government agencies estimated that approximately 4.9 million barrels (780 000 $m^3$ ± 10%) of oil were released from the well before the spill was contained (Lehr *et al.*, 2010). After multiple efforts, on 15 July, a cap was successfully placed over the damaged wellhead, ending the large-scale release. About 25% of the released oil was collected or removed, while about 75% remained in the environment in one form or another (Kerr, 2010). Two burning removal methods were used: (i) *in situ* burns of oil on the water surface and (ii) capture of oil and gas near the seabed and transfer to the surface to be flared.

A few measurements and model estimates were made of air pollution released from the burning activities. Perring *et al.* (2011) measured black carbon and other combustion products during a flight through an *in situ* burn plume on 8 June 2010, finding that black carbon dominated mass and number concentrations of accumulation-mode aerosol and that the plume lofted above the marine boundary layer. Aurell and Gullett (2010) measured polychlorinated dibenzodioxins and dibenzofurans in the plumes of 27 surface oil fires using a tethered aerostat. Middlebrook *et al.* (2012) reported on a suite of in-flight (8 and 10 June) and ship-based (22–27 June) air quality measurements, finding that ~4% of the oil burned on the surface was emitted as soot particles. However, they found that most of the air emissions were hydrocarbons evaporating from oil at the surface, contributing to secondary organic aerosol (SOA) formation downwind. They also found that the high temperatures in some *in situ* burns resulted in lofting plumes above the marine boundary layer. Schaum *et al.* (2010) estimated dioxin emissions from *in situ* burns and used the AERMOD and HYSPLIT models to conduct a screening assessment of risks. Nance *et al.* (2016) reported that extensive onshore measurements showed elevated concentrations of $PM_{2.5}$ during the response period. However, the measurement methods varied, and most of the measurements did not meet U.S. Federal reporting guidelines. In addition, no attempt was made to relate elevated concentrations with air flow trajectories. Jelsema *et al.* (2019) further analyzed these data using a threshold knot selection method that may offer an improved statistical treatment for such data sets. Four measurements of the benzene soluble total particulate fraction were taken on workers involved in *in situ* burns (Gibbins *et al.*, 2010). No personal measurements or estimates of $PM_{2.5}$ concentrations from flaring were found. Air monitoring readings for particulates, toxic gases, and volatile organic compounds by OSHA/NIOSH teams found few detections and no readings above workplace standards except for a few measurements of CO related to boat engines (Allen *et al.*, 2011).

A second source of $PM_{2.5}$ came from operation of the thousands of mostly diesel-powered vessel engines working on oil spill response and clean-up (OSRC) activities in the Gulf waters and of the substantial numbers of material moving equipment on land. The number of vessels varied over time and space, primarily between 20 April and 30 September 2010. No detailed inventory of land equipment was available.

Approximately 55 000 workers were rostered during the OSRC [The National Institute for Occupational Safety and Health (NIOSH, 2011)]. The GuLF STUDY (Kwok *et al.*, 2017), initiated by the National Institute of Environmental Health Sciences, was designed to investigate potential health impacts for these workers. Estimates of worker inhalation exposures to total hydrocarbons and some of its volatile components were developed using data collected with passive organic vapor dosimeters worn by the workers and analyzed by Bayesian statistical methods (Huynh *et al.*, 2016, 2021a,b,c; Groth *et al.*, 2017; Arnold *et al.*, 2021; Ramachandran *et al.*, 2021; Stenzel, Arnold *et al.*, 2021; Stewart, Groth *et al.*, 2021). Dispersants and oil mist were also evaluated (Arnold *et al.*, 2021; Stenzel, Arnold *et al.*, 2021; Stewart, Groth *et al.*, 2021). Dermal exposure estimates (Ng *et al.*, 2021; Stewart, Gorman Ng *et al.*, 2021) have also been described.

Our goal was to estimate potential exposures to emissions from *in situ* burns, flaring, and vessel engines for OSRC workers, particularly GuLF STUDY workers. We first estimated emissions from the 3 source categories and then used those data along with meteorological data and source characterizations as inputs to an air dispersion model that estimated air concentrations of primary particles (as $PM_{2.5}$) and related pollutants at each of 3432 model receptor points across the Gulf region. We used the modeled concentrations to develop exposure estimates for GuLF STUDY workers in areas across the Gulf of Mexico and on land. We describe (i) estimation of primary $PM_{2.5}$ *emissions* from the *in situ* burns, flaring, and engine emissions; (ii) modeling of $PM_{2.5}$ *air concentrations* across the Gulf using AERMOD; and (iii) $PM_{2.5}$ *exposure estimates* of workers in areas of interest across the Gulf and on land for use in job–exposure matrices (JEMs) for the GuLF STUDY.

## Methods

### Model

AERMOD is a recommended U.S. Environmental Protection Agency guideline model that considers the turbulent structure of the mixed layer of the atmosphere nearest the earth's surface in the development of air concentrations. It is a steady-state Lagrangian plume dispersion model that uses a file of surface boundary layer parameters and a file of profile variables including wind speed, wind direction, and turbulence parameters to simulate dispersion in the planetary boundary layer (PBL) (Cimorelli *et al.*, 2004, 2005; Perry *et al.*, 2005). The PBL is the turbulent air layer next to the earth's surface that is affected by surface heating, friction, and overlying stratification, and it typically ranges in height from a few hundred meters at night to a few kilometers during the day. When the PBL is stable (stable boundary layer), AERMOD assumes a Gaussian concentration distribution in both the vertical and horizontal. However, under convective conditions (convective boundary layer, CBL) while horizontal dispersion is assumed to be Gaussian, the vertical distribution is described with a bi-Gaussian probability density function. AERMOD requires input of emissions, meteorological data, surface land use data, and source characterization.

### Emissions

#### *In situ* burns

From 28 April to 19 July 2010, 354 *in situ* burns resulted in the combustion of approximately 6% of the released oil, amounting to approximately 299 336 barrels (41 877 036 kg). See Fig. 1 for burn locations. The oil composition was not uniform. Over time, higher vapor pressure components volatilized so that the molecular weight of the remaining material increased. In addition, the oil was mixed with variable amounts of water. The result of these factors was considerable heterogeneity in the fuel of the *in situ* burns.

Air pollution emissions from combustion of oil on water have been measured in test burns and field studies (Fingas *et al.*, 1995; Ross *et al.*, 1996; McGrattan *et al.*, 1997; Park and Holliday, 1999; Aurell and Gullett, 2010). Selected results, including some during the *DWH* OSRC effort, are compiled in Table 1. These studies show that emissions vary with fuel source, water content, fuel and air temperature, physical form of the fuel, and depth of the fuel on the water surface.

From 1 to 26 *in situ* burns per day were conducted over the 30 days of burns and were limited to light wind conditions (generally <10 km $h^{-1}$) when combustion could be better managed. The burns were highly episodic and ranged in duration from 4 min to 23 h. Data on the times, durations, locations, and minimal and maximal estimates of fuel combusted were available for each of 354 burns. Total emissions for each burn were calculated using the average of the minimal and maximal estimates and the emissions factors for combustion of oil (Table 1) and apportioned evenly throughout the duration of the burn. Unsuccessful ignitions and burns of 10 min or less were eliminated from the documentation of total oil volume burned.

#### Flaring emissions

The wellhead oil release rate was estimated to be approximately 56 000 barrels (352 229 $m^3$) per day (Lehr *et al.*, 2010). A subsea oil recovery system became operational on 17 May 2010, capturing gas and oil that otherwise would have been released into the Gulf. Two rig vessels (the *Discoverer Enterprise* and the *Helix Q4000*) and a production/offloading vessel (the *Helix Producer 1*) flared the oil/gas from the subsea recovery system via a riser pipe and manifolds. Approximately 5% of the released oil total was flared.

The *Enterprise* was roughly 275 m by 38 m, with the main deck ~30 m above the water surface. It separated, stored, and transferred the captured oil to a second vessel while flaring the separated gas from a 38 m boom located 90 m from the stern on the port side and angled upwards at approximately 45°. The vessel processed about 18 000 barrels (113 217 $m^3$) of oil per day 17–24 May and 4 June–11 July 2010. The *Helix Q4000* was a 137 m square vessel sitting atop large pontoons, with a main deck 30 m above sea level. It flared 10 000 barrels (62 898 $m^3$) of combined oil and gas per day 17 June–16 July 2010

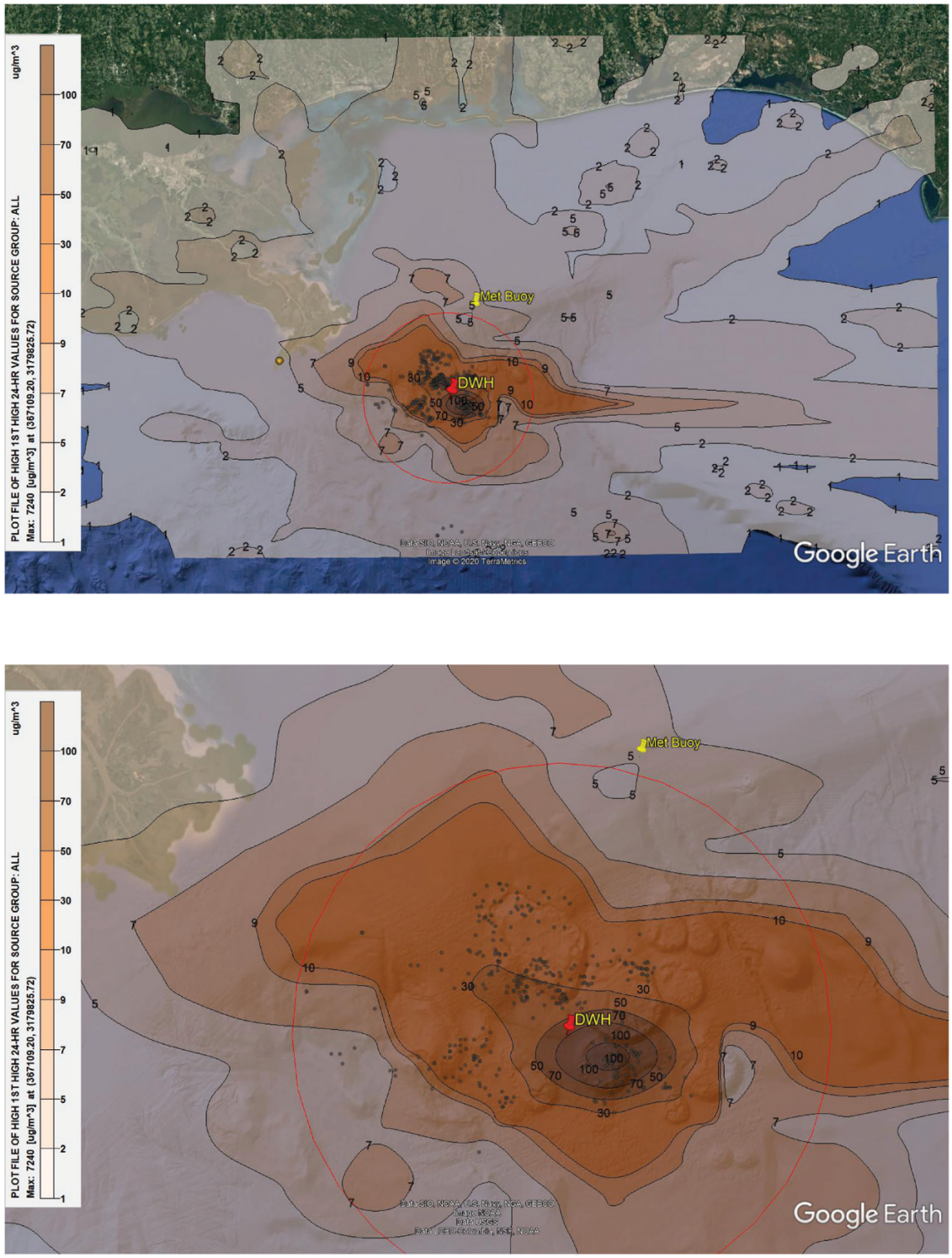


**Figure 1.** Modeled maximum 24-h $PM_{2.5}$ concentrations from all sources over the entire study period (28 April–19 July 2010). Top Overview. Bottom Closeup of *DWH* vicinity. Isopleth lines are labeled with the concentration in μg $m^{-3}$. The *DWH* was located at the center shown by the marker. The 42040 buoy meteorological station is shown by the marker to the north-northeast of the *DWH*. The small dark points are the locations of the *in situ* burns. The circle shows the 50 km polar coordinate grid. The coarse grid extends to the edges of the overview map where the isopleths are cut off. The axes are in UTM (Universal Transverse Mercator) coordinates.

**Table 1.** Emission factors ($Q$) for *in situ* burns (in units of g $kg^{-1}$ fuel burned, except for PCDD/PCDF, in units of ng TEQ $kg^{-1}$ fuel burned) and for flaring of gas (grams per million cubic meters, g $mmcm^{-1}$) and oil (grams per kg fuel). The PCDD/PCDF value from Aurell and Gullett, and the $CO_2$, CO, $SO_2$ and TSP values from NOBE were used in this study in addition to those noted for $PM_{2.5}$.

| Study | Source | Species | $Q$ | Fuel |
|---|---|---|---|---|
| Evans *et al.* (2001) | Burns | TSP (smoke) | 112 | Prudhoe crude |
| Evans *et al.* (2001) | Burns | PAHs | 1.44 | Alberta sweet crude |
| Perring *et al.* (2011) | Burns | Black carbon | 36 | *DWH* |
| Middlebrook *et al.* (2012) | Burns | Soot | 40 | *DWH* |
| Aurell and Gullett (2010) | Burns | PCDD/PCDF | 1.85 | *DWH* |
| Aurell and Gullett (2010) | Burns | TSP | 105 | *DWH* |
| NOBE (Fingas *et al.*, 1995) | Burns | $CO_2$ | 2800 | Crude oil |
| NOBE (Fingas *et al.*, 1995) | Burns | CO | 17.5 | Crude oil |
| NOBE (Fingas *et al.*, 1995) | Burns | $SO_2$ | 15 | Crude oil |
| NOBE (Fingas *et al.*, 1995) | Burns | TSP | 150 | Crude oil |
| NOBE (Fingas *et al.*, 1995) | Burns | $PM_{3.5}$ (smoke) | 113 | Crude oil |
| NOBE (Fingas *et al.*, 1995) | Burns | $PM_{3.5}$ (soot) | 55 | Crude oil |
| NOBE (Fingas *et al.*, 1995) | Burns | PAHs | 0.04 | Crude oil |
| Value used in this modeling analysis (from Fingas value for smoke) | Burns | $PM_{2.5}$ | 113 | *DWH* |
| EPA—non AP42 | Flares | $PM_{2.5}$-min | 0.24 | Natural gas |
| EPA—non AP42 | Flares | $PM_{2.5}$-max | 0.55 | Natural gas |
| EPA—for 2014 inventories | Flares | $PM_{2.5}$ | 0.14 | Natural gas |
| EPA AP-42 section 1.4—Table 3.4.1—1998 | Flares | PM, condensable | 7.28 | Natural gas |
| EPA AP-42 section 1.4—Table 3.4.1—1998 | Flares | PM, filterable | 2.43 | Natural gas |
| EPA AP-42—Table 1.4–2—current | Flares | $PM_{2.5}$ | 9.70 | Natural gas |
| EPA AP-42—Table 13.5-1 (lightly smoking flare) | Flares | Soot | 3.18 | Gas |
| EPA AP-42—Table 13.5-1 (moderately smoking flare) | Flares | Soot | 14.08 | Gas |
| EPA AP-42—Table 13.5-1 (heavily smoking flare) | Flares | Soot | 21.79 | Gas |
| McEwen and Johnson | Flares | Soot (max) | 13.80 | Natural gas |
| McEwen and Johnson (42 MJ $m^{-3}$) | Flares | Soot | 5.55 | Natural gas |
| Value used in this modeling analysis[a] | Flares | $PM_{2.5}$ | 25.53 | *DWH* gas |
| EPA AP-42 Table 1.11-1 | Flares | $PM_{10}$ | 7.01 | Waste oil |
| EPA AP-42 Table 1.11-1 | Flares | PM | 8.80 | Waste oil |
| EPA AP-42 Table 1.3-1 | Flares | PM-filterable | 1.26 | No 6 fuel oil |
| EPA AP-42 Table 1.3-1 | Flares | PM-condensible | 0.18 | No 6 fuel oil |
| EPA AP-42 Table 1.3-1 | Flares | PM-total | 0.27 | No 6 fuel oil |
| EPA AP-42 Table 1.3–15 | Flares | PM | 2.05 | No 6 fuel oil |
| EPA AP-42 Table 1.3–6 | Flares | $PM_{2.5}$ | 1.65 | No 6 fuel oil |
| Value used in this modeling analysis[b] | Flares | $PM_{2.5}$ | 20 | *DWH* oil |

CO, carbon monoxide; $CO_2$, carbon dioxide; PAHs, polycyclic aromatic hydrocarbons; PCDD/PCDF, polychlorinated dibenzo-*p*-dioxins/polychlorinated dibenzofurans; PM, particulate matter; $SO_2$, sulfur dioxide; TEQ, benzo-*a*-pyrene toxic equivalents; TSP, total suspended particulate. Units conversion assumptions: 139.9 kg fuel $barrel^{-1}$ and 117.27 kg carbon $barrel^{-1}$ (National Academies of Sciences, Engineering, and Medicine, 2016).

[a]25.53 g $mmcm^{-1}$ is equivalent to 20 lb $mmcf^{-1}$, which is rounded up to 1 significant digit from the originally reported heavily smoking flare value of 17.07 lb $mmcf^{-1}$.

[b]The value of 20 is taken as double the maximum value in the table to one significant digit. The reason for doubling is that the available values pertain to refined oil products that are assumed to be cleaner than the crude oil in the spill.

from a boom located at one corner. The *Helix Q4000* flare included air injection and 12 radially arranged nozzles. The *Helix Producer 1* was 162 m by 29 m, with the flare boom located at the stern. It flared a gas/oil mixture at a rate of about 25 000 barrels (157 245 $m^3$) of oil per day 13–16 July 2010. Total emissions from flaring of gas/oil were calculated using emissions factors for oil and gas combustion (Table 1) from the U.S. EPA AP-42 compilation of emissions factors (U.S. EPA, 2017a). Due to the poorly controlled conditions for both sources,

modeled emission rates were taken from the high end of reported values so as to avoid underestimating modeled concentrations.

### Vessel engine emissions

Vessel exhaust emissions were estimated from inventories of response vessels using emission factors from several sources (United Kingdom Department for Environment Food & Rural Affairs, 2010; Chen *et al.*, 2017, 2018; Nunes *et al.*, 2017; DieselNet, 2018) (Supplementary Information File 1, available at *Annals of Work Exposures and Health* online). The distribution of emission factors ranges widely depending on vessel type, vessel size, engine type, power rating, fuel type, age, and operating conditions. Although we had some information on type, size, fuel type, location, and mission of each vessel, the data were incomplete. Therefore, we broadly apportioned the number and type of vessels in time and space. First, based on some data on vessel length, we divided types of vessels into three size categories: large (e.g. marine, Coast Guard), small (e.g. fishing, recreational), and unknown (e.g. work boat), and then estimated the lengths of the two known vessel length categories [~>30 m (100 ft)] and [14 m (45 ft)], respectively. Then, we based our number of vessels on bi-weekly deployment reports between 1 May 2010 and 4 January 2011 (National Oceanic and Atmospheric Administration, 2011). Finally, we estimated the number of vessels in each of our study areas: the hot zone [≤1 nautical miles (nmi) (1.85 km) of the wellhead], the source (>1 and ≤5 nmi from the wellhead), offshore [≥3 nmi from shore to >5 nmi (9.26 km) from the wellhead], and near shore [<3 nmi (5.56 km) from shore]. Only 'large' vessels were allowed in the source and hot zones during the response and we assumed that they operated at 15% of maximum power while maneuvering slowly or being nearly stationary. We estimated that offshore and near shore areas ~60 to 99% of the vessels (depending on the date) were 'small' and assumed they operated at 60% of maximum power rating. Emissions from vessels were modeled separately from the burn and flare emissions for the hot zone, source, offshore, and near shore, as well as for the coastal counties of Louisiana, Mississippi, Alabama, and Florida. For convenience, only two cases were considered, corresponding to the highest and the lowest average number of vessels in our GuLF STUDY time periods (high average $n$ = 3706, 15 May–15 July 2010 and low average $n$ = 443, 22 April–14 May 2010) (see Stewart, Groth *et al.*, 2021 for the basis of these time periods).

Emissions were estimated hour by hour for each *in situ* burn and flaring source for the entire study period. In contrast, a single vessel exhaust emission value was estimated by area for each of the two time period indicated above. The hourly emissions input file contained the emissions from all three sources apportioned in time and space.

## Air concentrations

### Meteorological data and surface land use

Several potential meteorological data stations were located in the Gulf area near the *DWH* area in 2010. Data from site 42040 (Fig. 1) in the National Data Buoy Center were the closest station to the area of interest with a complete set of representative surface observations. Upper air sounding data were taken from the Lake Charles, Louisiana station. These meteorological data were processed using the U.S. EPA AERMET preprocessor and regulatory default options to produce surface and upper air profile files used by AERMOD.

The AERMET processor calculates several variables from the meteorological observations, including sensible heat flux, surface friction velocity, convective velocity scale, vertical potential temperature gradient above the PBL, height of CBL, height of the mechanically generated boundary layer, and Monin–Obukhov length. Station 42040 records only wind direction, wind speed, temperature, and pressure. Missing parameters, such as ceiling height, sky condition, dew point, and sky cover, were obtained from the Louis Armstrong Airport monitoring station in New Orleans, Louisiana. Surface land use was characterized as 'water'.

### Source characterization

Releases similar to *in situ* burns are often characterized in AERMOD as area or volume sources; however, these characterizations do not allow for thermal buoyancy. Instead, such sources are assigned a predetermined release height. Since thermal buoyancy is important in high-temperature combustion releases, we investigated alternative source characterizations.

Photographs (see, e.g. Gibbins *et al.*, 2010; Allen, 2011) and videos of the burns show plumes that often rose rapidly from the water surface to the top of the mixed layer, or in some cases, penetrated the top of the mixed layer. Other plumes rose more gradually, remaining near the water surface for some distance downwind. Temperatures in burns were measured in the range of 1100°C (Allen, 2011; Barnea, n.d.). Insufficient information was available to assign variable temperatures within and between burns. Furthermore, as fuel is depleted, burns typically become less intense, and the combustion temperature falls. Test model simulations were done on specific burns with available photographic and video evidence showing plume rise and initial transport. In these simulations, temperatures, initial vertical

velocities, and stack diameters were varied across ranges of reasonable values. The test simulation source characterizations giving the best approximation to the photographic evidence were chosen to represent all of the *in situ* burns. Thus, we characterized each burn as a point source stack release with a very large diameter (30 m), a very short (2 m) stack, an exit velocity of 2 m $s^{-1}$, and a temperature of 1100°C (1373 K).

The flares from the three ships were characterized as point sources using pseudo stack parameters as recommended by U.S. EPA (2017b). The flares were unconventional in terms of the configuration and direction of release, and the release parameters were not precisely known. Locations of the flaring vessels were available for most days during the flaring, and rig ships were considered oil or gas installations with safety zones around them. They usually maintained a distance of at least 500 m from other vessels, but if closer than 500 m specific safety requirements became operational. The *Discoverer Enterprise* locations centered around the *DWH* site, and it was assigned the *DWH* coordinates. The *Q4000* was most often located east of the *DWH* site and was assigned coordinates 500 m to the east. The *Helix Producer 1*, generally located north of the site, was assigned coordinates 500 m to the north. Vessel headings were variable and often realigned so that the flares would be downwind of the main body of the vessel but not necessarily downwind of other vessels in the area. The three vessels were treated as structures using the building profile input program to account for the increased turbulence due to their presence (Cimorelli *et al.*, 2005).

**Modeling methods**

A nested receptor grid (as distinguished from the exposure grid developed in Exposure Estimates) consisting of two polar (circular) coordinate grids and one Cartesian (rectangular) grid was established to cover the GuLF STUDY areas of interest. One polar coordinate grid was placed around the *DWH* wellhead (with receptors on 36 radials at distances of 500 and 1000 m, and then in 1000 m increments to 10 km, $n = 396$) at a height of 30 m to capture concentrations at heights relevant to the workers aboard the rigs and other large vessels at the *DWH* site. A second polar coordinate grid extended in 1000 m increments out to 50 km (~27 nmi) from the *DWH* site ($n = 1836$) and was assigned a height of 3 m above sea level to represent air concentrations at deck heights on fishing vessels involved in the *DWH* efforts. Finally, a coarse rectangular Cartesian grid consisted of receptors with 10 km (5.4 nmi) spacing ($n = 1200$) at a height of 3 m extending to and including the coastal counties of the four states (see Fig. 1a for an overview of the grid extent).

Individual AERMOD runs were done for each hour for each day when burning or flaring occurred between 28 April and 19 July and incorporated the cumulative contributions from both sources. Concentrations from vessel emissions were calculated from the average number of vessels in the time period. Every day at each of the 3432 receptors, three air concentrations were determined: the maximum 1-h concentration (to represent peak concentrations), the maximum of two 12-h concentrations (each averaged from on-the-hour concentrations at 1:00–12:00 or 13:00–24:00, for work shift concentrations), and the 24-h average concentration (for comparison to standards). The 2 12-h values are a standard feature of AERMOD and, as such, do not correspond with typical work shifts. Nevertheless, we report them as our best estimates of work shift concentrations.

Emissions of each pollutant other than $PM_{2.5}$ were taken to be proportional to $PM_{2.5}$, meaning that model results for $PM_{2.5}$ could be scaled to another pollutant without modeling each pollutant independently. Since emissions of pollutants other than PM were not available for flares, the same proportions of the fuel burnt to $PM_{2.5}$ used for the *in situ* burns were also applied to the flares. We report results on other pollutants for information purposes.

We used a graphical user interface for AERMOD and AERMET that was developed by Lakes Environmental Software, AERMOD View®.

## Exposure estimates

The exposure assessment component of the GuLF STUDY was based on work history information [job or activity, location (vessel, area of the Gulf, and/or US state), and dates] obtained from the study participants during a telephone interview (Kwok *et al.*, 2017). From this information we developed >3400 exposure groups (EGs), groups expected to have similar distributions of exposure based on unique combinations of the exposure determinants: job or activity, location (as above), and date (Stenzel, Groth *et al.*, 2021). The participants were linked to exposure estimates through EGs in a JEM (Stewart, Gorman Ng *et al.*, 2021).

We followed the same procedure here, retaining the same EGs to link the participants to exposure estimates through a JEM. To link the ambient air concentrations estimated from the *in situ* burns, flaring, and vessels to study participants, we did not incorporate job or activity (except for the specific *in situ* burn workers) into JEM, since these were ambient concentrations. Second, as we

could not, generally, link participants or vessels to the specific latitude/longitude locations by date, we defaulted to identifying from the interview each participant's work location(s) to one or several large areas of the Gulf (areas defined above in Emissions, *Vessel Engine Emissions*) and/or if on land, as a state. We estimated number of vessels by area as well. Third, *in situ* burning and flaring primarily occurred in one time period (15 May–15 July 2010), so we estimated ambient exposure estimates from both sources combined, averaged over that time period. For vessels, we estimated possible exposures for only the time periods with the lowest and highest number of vessels, for information only. All other EGs were not assigned a $PM_{2.5}$ estimate. We employ the term JEM loosely here to indicate the common use of the term, i.e. that all study participants with the same exposure determinants are assigned the same exposure (in contrast to assigning each individual participant a unique exposure), even though, in this instance, most of the determinants were not the jobs themselves.

To estimate workers' exposures by area, we first overlaid on the emission grid used in AERMOD an exposure grid, a set of 10 by 10 nmi (18.5 × 18.5 km) grid squares centered at the wellhead and extended across the Gulf to each coastal county to define the study areas (Supplementary Information File 2, available at *Annals of Work Exposures and Health* online). The square containing the well site was subdivided into 1 by 1 nmi (1.9 × 1.9 km) squares for higher resolution in the hot zone and source. Each grid square was uniquely identified by number and area. Offshore, near shore and land were further identified by state. The maximum 1-h, maximum 12-h, and average 24-h air concentrations estimated by AERMOD were averaged across all receptors within each defined area on each day. All receptors in an area were given equal weight. We calculated arithmetic means (AMs), geometric means (GMs), geometric standard deviations (GSDs) and 95th %iles of these means over all 62 days during which burning and/or flaring occurred to characterize the exposure over the entire 90-day time period. The reported exposure values thus represent a spatial average of the maximum values estimated in an area over the study period. Grid development and averaging calculations were done using R (version 3.3.2) and WGS84 projection.

In contrast to the method for estimating exposures for most workers by area, $PM_{2.5}$ exposure estimates specifically for *in situ* burn workers were calculated assuming these workers were present in each grid cell where a burn occurred at the time of the burn. We averaged the 1-, and 12-h maxima and 24-h average concentrations separately at each receptor in each grid square in which a burn occurred on a particular day and then averaged those concentrations for each metric within each burn grid square on each day. Next, we averaged each of those three average air concentrations across all squares in which a burn occurred on that day. Finally, we calculated the AM, GM, and GSD estimates across all *in situ* burn days ($N = 30$).

From the AERMOD estimates from vessel exhaust we calculated ambient exposures by study area from vessel activity for the lowest and highest time periods: 20 April–14 May (lowest) and 15 May–15 July (highest). We then calculated the AM, GM, and GSD across all of the 24-h concentrations for each area during the period of burning and flaring. These estimates are less precise than the *in situ* burn/flare exposure estimates because the exact numbers, locations, and characteristics of the vessels are not precisely known and thus are provided for information purposes only.

## Results

### Emissions

$PM_{2.5}$ emission estimates ranged from 30 kg to $1.33e^6$ kg per day and were generally uniform over time for the flares but highly episodic for the *in situ* burns. (Estimated 24-h total emissions from the *in situ* burns and the flaring are separately shown in Fig. 2.) Initially, *in situ* burn emissions were greater than those from flaring, but starting about the middle of June, the emissions from flaring became similar to those from *in situ* burns. The approximately 299 336 barrels (41 877 036 kg) of oil burned *in situ* released approximately 4 732 105 kg of $PM_{2.5}$ (~11% of the carbon in the crude oil on the sea surface, the high percentage in keeping with the uncontrolled conditions of the *in situ* burns). Approximately 264 930 barrels (37 063 712 kg) of oil and 1867 mmcf (million cubic feet, equivalent to $53.12e^6$ $m^3$) of gas were flared, releasing about 741 274 and 47 665 kg $PM_{2.5}$, respectively (~2% of the carbon in the flared oil, due to the more controlled conditions of flaring).

### Air concentrations

Model predictions were made for each of 24 h in a day on 66 days at 3432 receptors for a total of 5 436 288 concentration estimates. At any given hour, the winds were blowing in a particular direction and most receptors were unaffected. Burns typically lasted less than 24 h, so for the other hours of the day the concentrations were basically zero (i.e. <0.001 μg $m^{-3}$). Of the almost 5.5 million estimates, nonzero concentrations were estimated for 736 560 (14%) day × hour × receptor

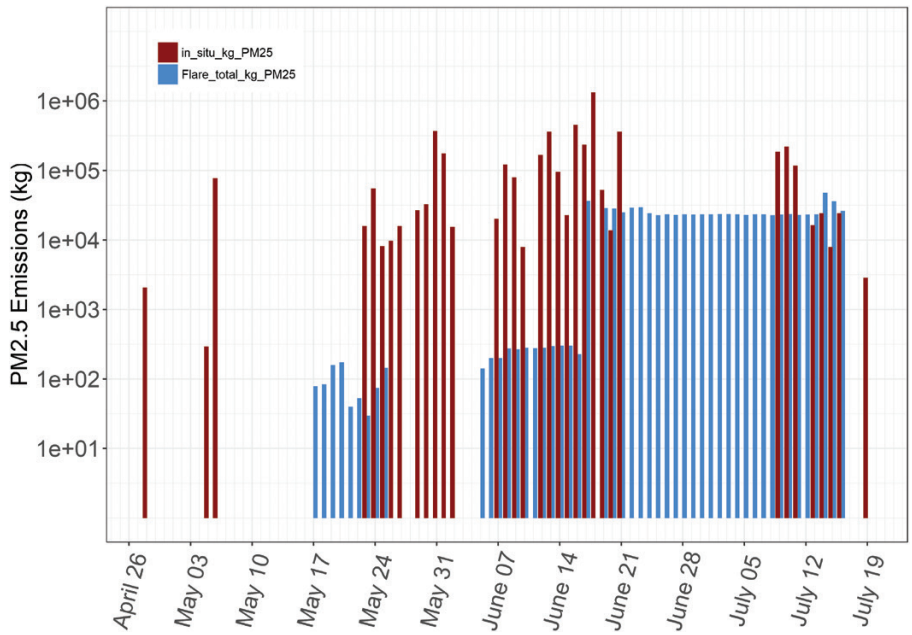


**Figure 2.** Estimated 24-h total emissions of $PM_{2.5}$ for each day of *in situ* burning and flaring (18 April–19 July 2010). Only values between 15 May and 15 July 2010 were used for air concentration estimates.

combinations. The frequency distributions of modeled concentrations at a given receptor and across the Gulf were highly skewed, with the vast majority of predictions at very low concentrations. Given the large number of zeroes, we include only nonzero estimates in the database provided in Supplementary Material, available at *Annals of Work Exposures and Health* online. [The impact of this decision on the smallest value in Table 3 (0.74 μg $m^{-3}$) changed that value to 0.7399 μg $m^{-3}$.] Thus, the results we report are averages over space and time for those places and times that were impacted by plumes from the sources. Fig. 3 is a box plot of modeled 24-h average $PM_{2.5}$ air concentrations ≥0.001 μg $m^{-3}$ on each day when burning and/or flaring occurred.

The predicted median and upper 75th percentile 24-h average air concentrations across all receptors and all burn/flare days, even after excluding values <0.001 μg $m^{-3}$, rarely exceeded 1 μg $m^{-3}$. However, very high concentrations were predicted on some days at some receptors. Flaring was done almost continuously over a 2-month period, sometimes under conditions of high wind speeds during which the relatively intact plume did not loft significantly but was transported to nearby model receptors at near the deck height of the large vessels. As a result, 24-h average concentrations sometimes exceeded 5000 μg $m^{-3}$ in the first 500 m downwind of the flaring at a height of 30 m above sea level.

In contrast to the flares, the estimated 24-h average air concentrations from *in situ* burns were typically lower due to the lower amount of fuel combusted and the release conditions. *In situ* burns were done under low wind speed, stable conditions during which the plume typically rose to the top of the mixed layer, and the emissions were transported downwind and dispersed before being mixed back to the surface. The highest predicted 24-h average $PM_{2.5}$ concentrations within a kilometer of some *in situ* burns reached 71 μg $m^{-3}$ at a height of 3 m above sea level, the approximate deck height of the smaller vessels. The closest burn to the wellhead was 2.1 km away, but most burns were more than 10 km distant. Wind directions were seldom such that the burns and flares were directly downwind from one another and as a result, the plumes typically did not combine to additively increase concentrations in the burning and flaring areas. Beyond 40 km from the *DWH* site the plumes appeared to be well mixed, and the predicted 24-h concentrations from both flares and *in situ* burns were similar and usually below 10 μg $m^{-3}$.

Fig. 1 shows the spatial distribution of the modeled highest 24-h average $PM_{2.5}$ air concentrations across the Gulf over the period of 28 April to 15 July 2010. The values shown may have occurred on different days for different receptors. As expected, the highest

**Table 2.** Summary statistics of model-predicted concentrations to various contaminants from the *in situ* burns and flaring for all receptors, *in situ* and flaring sources averaged over 15 May–15 July 2010, with zero values excluded. Units are micrograms per cubic meter (μg $m^{-3}$) with parts per million (ppm) values given in parentheses.

| Pollutant | Average time (h) | Mean | SD | Median | Max |
|---|---|---|---|---|---|
| $PM_{2.5}$ | 1 | 32.67 | 441 | 0.290 | 59 132 |
| CO | 1 | 5.06 (0.004) | 68 (0.06) | 0.045 (0.000) | 9165 (8.01) |
| $CO_2$ | 1 | 816.79 (0.45) | 11 036 (6.13) | 7.240 (0.004) | 1 478 305 (821.8) |
| PAH | 1 | 0.42 | 6 | 0.004 | 769 |
| PCDD_F[a] | 1 | 0.52 | 7 | 0.005 | 946 |
| $SO_2$ | 1 | 4.35 (0.002) | 59 (0.023) | 0.039 (0.000) | 7865 (3.00) |
| TSP | 1 | 49.01 | 662 | 0.434 | 88 698 |
| $PM_{2.5}$ | 12 | 5.42 | 79 | 0.072 | 8202 |
| CO | 12 | 0.84 (0.0007) | 12 (0.01) | 0.011 (0.000) | 1271 (1.11) |
| $CO_2$ | 12 | 135.39 (0.08) | 1983 (1.10) | 1.809 (0.001) | 205 038 (114.0) |
| PAH | 12 | 0.07 | 1 | 0.001 | 107 |
| PCDD_F[a] | 12 | 0.09 | 1 | 0.001 | 131 |
| $SO_2$ | 12 | 0.72 (0.0003) | 11 (0.004) | 0.010 (0.000) | 1091 (0.417) |
| TSP | 12 | 8.12 | 119 | 0.109 | 12 302 |
| $PM_{2.5}$ | 24 | 3.46 | 55 | 0.053 | 7240 |
| CO | 24 | 0.54 (0.0005) | 9 (0.008) | 0.008 (0.000) | 1122 (0.98) |
| $CO_2$ | 24 | 86.58 (0.05) | 1374 (0.76) | 1.314 (0.0007) | 181 006 (100.6) |
| PAH | 24 | 0.05 | 1 | 0.001 | 94 |
| PCDD_F[a] | 24 | 0.06 | 1 | 0.001 | 116 |
| $SO_2$ | 24 | 0.46 (0.0001) | 7 (0.003) | 0.007 (0.000) | 963 (0.368) |
| TSP | 24 | 5.20 | 82 | 0.079 | 10 860 |

PCDD_F, polychlorinated dibenzo-*p*-dioxins and dibenzofurans.
[a]Units for PCDD_F are femtograms TEQs per cubic meter (fg $m^{-3}$).

concentrations were predicted within 5 km of the *DWH* wellhead (up to 7240 μg $m^{-3}$), but concentrations >10 μg $m^{-3}$ were predicted over a large (~120 km by 80 km) area around the wellhead. At the shoreline from Louisiana to Florida, 24-h average $PM_{2.5}$ concentrations ranged from 1 μg $m^{-3}$ to as high as 6 μg $m^{-3}$ near Biloxi, Mississippi.

The highest modeled 1-h $PM_{2.5}$ air concentrations exceeded 500 μg $m^{-3}$ over an area of ~40 km by 20 km around the wellhead, with the highest value being ~59 000 μg $m^{-3}$. At the shoreline the highest predicted 1-h concentrations ranged from 5 μg $m^{-3}$ to as high as 100 μg $m^{-3}$ along Mobile Bay. Modeled 12-h concentrations were between the 1- and 24-h results, but closer to the 24-h averages. Summary statistics of $PM_{2.5}$ and for each 1-, 12-, and 24-h period are given in Table 2. Concentrations of each pollutant at each model receptor are available in the model output database available from the first author (an example of the database format is given in Supplemental Information File 3, available at *Annals of Work Exposures and Health* online).

The modeled lowest and highest 24-h average $PM_{2.5}$ concentrations from vessel exhaust emissions during periods of low vessel activity (22 April–14 May 2010) were 0.17 μg $m^{-3}$ (offshore) to 6.0 μg $m^{-3}$ (hot zone/source areas). During periods of high vessel numbers (15 May–15 July 2010), the 24-h $PM_{2.5}$ concentrations ranged from 1.81 (offshore) to 14.3 μg $m^{-3}$ (hot zone/source areas).

Estimated exposure values are presented as the average of the potential 1- and 12-h maximum exposures by area (Table 3). The highest values were estimated for workers in the hot zone (545.0 and 96.9 μg $m^{-3}$, respectively) who comprised the workers on the four major oil rigs responding to the oil release (two of which were the rigs doing the flaring) and workers on several other vessels (including the third vessel flaring and vessels with remotely operated vehicles supporting the oil rig operations). As distance from the flaring increased, potential exposures decreased. Workers directly involved in *in situ* burns were estimated to have potential maximum 1- and 12-h exposures of 71 and ~10 μg $m^{-3}$, respectively. Near shore and land workers had much lower potential exposures (<2.5 and <0.3 μg $m^{-3}$, respectively).

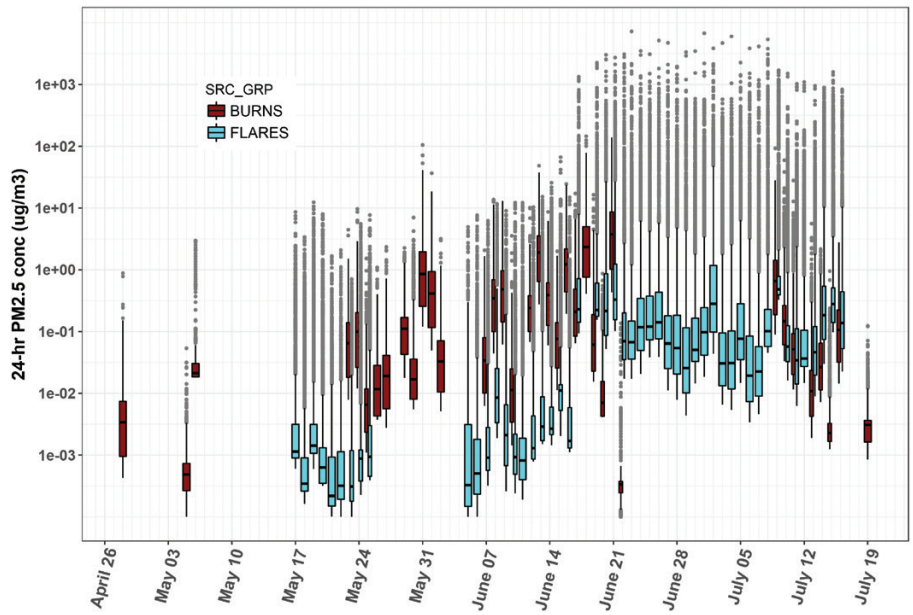


**Figure 3.** Box plot of modeled 24-h average air concentrations across all nonzero receptors on each day when burning and/or flaring occurred. The horizontal midpoint of each box is the median value for the day across all receptors in the model domain. The boxes extend from the 25th to the 75th percentile values, and the lines include all data not considered statistical outliers. The dots are statistical outliers that show the high values that occurred at some receptors.

## Discussion

This modeling analysis provides a basis for evaluating potential maximum exposures to airborne $PM_{2.5}$ particles and related pollutants to the workers of the *DWH* OSRC efforts. Using standard regulatory air dispersion modeling tools, we estimated air emissions and air concentrations of $PM_{2.5}$ and related pollutants near the *DWH* wellhead and across a portion of the Gulf of Mexico extending to the shores of Louisiana, Mississippi, Alabama, and Florida for each day of burning. From the $PM_{2.5}$ air concentrations, we estimated potential maximum worker exposures. This comprehensive picture of pollutant concentrations and potential exposures of those involved in OSRC activities is unique and provides a basis for epidemiologic analyses of the GuLF STUDY.

Potential maximum 12-h worker exposures (comparable to a full-shift for many of the OSRC workers) ranged up to 96.93 μg $m^{-3}$. There are no occupational standards. The U.S. EPA National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ for the general population are a 24-h average of 35 μg $m^{-3}$ and an annual average of 12 μg $m^{-3}$. Thus, exposures sometimes exceeded concentrations the NAAQS has associated with adverse health effects for the general population.

The available data were incomplete, and assumptions were needed to conduct the assessment. First, the predicted air concentrations represent only the burning/flaring contributions and do not include background concentrations from other sources, such as engine exhaust emissions from vessels or vehicular traffic or material handling equipment on land that may have contributed to total exposures. No $PM_{2.5}$ measurement data were available on the water. Concentrations from vessel exhaust therefore were estimated but not included in the assessment of study participants' exposure for the GuLF STUDY due to uncertainties about worker and vessel locations. The nearest land location with continuous $PM_{2.5}$ measurement data (using EPA Federal Equivalence Methods) during the OSRC effort was in Dothan, Alabama, approximately 400 km northeast of the *DWH* site and over 100 km inland. Daily 24-h average concentrations (using EPA Federal Reference Methods, FRM) were available for 11 stations in southern Louisiana, Mississippi, and Alabama, but most of the stations collected data only 1 or 2 days per week, so many of the days of interest are missing. The 24-h average $PM_{2.5}$ concentrations at the 11 monitoring sites during burning and flaring periods ranged from means of 9.5 to 10.2 μg $m^{-3}$, (medians 9.1–9.5 μg $m^{-3}$; maximums 19.4–33.8 μg $m^{-3}$). The contribution to these levels from sources other than the *DWH* burning cannot be determined. For comparison, the maximum modeled 24-h average $PM_{2.5}$

**Table 3.** $PM_{2.5}$ exposure estimates (μg $m^{-3}$) 15 May–15 July 2010 from flaring and *in situ* burns.

| Type of workers | Maximum $PM_{2.5}$ exposures (μg $m^{-3}$) (AM, GSD) | |
|---|---|---|
| | 12 h | 1 h |
| Hot zone | 96.93 (15.9) | 545.03 (15.2) |
| Workers in the source[a] | 28.70 (12.1) | 177.29 (11.9) |
| Workers who participated in *in situ* burns | 10.4 (4.8) | 67.01 (4.6) |
| Workers located on water offshore (all states combined)[b] | 1.25 (8.9) | 8.77 (8.7) |
| Louisiana offshore workers | 0.66 (11.4) | 5.00 (12.8) |
| Mississippi offshore workers | 0.26 (10.6) | 1.76 (11.5) |
| Alabama offshore workers | 0.24 (10.3) | 1.50 (11.0) |
| Florida offshore workers | 0.17 (9.7) | 0.99 (10.2) |
| Workers located near shore (all states combined)[c] | 0.27 (8.1) | 1.76 (7.9) |
| Louisiana near shore workers | 0.34 (10.4) | 2.35 (11.3) |
| Mississippi near shore workers | 0.23 (10.1) | 1.40 (10.4) |
| Alabama near shore workers | 0.20 (10.4) | 1.17 (11.3) |
| Florida near shore workers | 0.15 (9.6) | 0.74 (9.8) |
| Workers on land (all states combined)[d] | 0.23 (8.6) | 1.50 (8.5) |
| Louisiana land workers | 0.26 (11.0) | 1.81 (12.3) |
| Mississippi land workers | 0.20 (10.1) | 1.26 (10.5) |
| Alabama land workers | 0.19 (10.2) | 1.14 (10.6) |
| Florida land workers | 0.14 (9.7) | 0.79 (9.9) |

PM, particulate matter. $N = 57$ measurement days, except for the *in situ* workers who had 30 burn days. The source of the $PM_{2.5}$ for workers other than the *in situ* workers incorporated both the *in situ* burns and flaring.

[a]Study participants who responded yes to the question, 'Did you ever work in an area where you could see the individual ships or rigs that were working in the wellhead area?'

[b]Study participants who responded no to questions in footnotes a and c.

[c]Study participants who responded yes to the question 'For most of the time that you were on a vessel, could you see the shoreline?'

[d]Study participants who responded yes to the question 'Did you work on land?'

concentrations at receptors near the two FRM monitors located within the model domain (New Orleans, Louisiana and Gulfport, Mississippi) were 2 μg $m^{-3}$.

One other data source covering similar times and locations was available for comparison with our modeled concentrations. PCDD-F toxic equivalent (TEQ) concentrations estimated by Schaum *et al.* (2010) using a hybrid regional model over the study period ranged from 5.4e–07 to 0.05 femtograms per cubic meter (fg $m^{-3}$). These values, obtained with a different modeling approach, are similar to ours (0.06 fg $m^{-3}$), although the locations of the highest modeled PCDD-F TEQ concentrations of Schaum *et al.* (2010) were more than 10 km nearer shore than we found, most likely due to different methods of estimating plume rise, but also possibly due to vessels and vehicular/equipment traffic on land. They also found that at higher wind speeds the maximum concentrations were closer to the sources, while lower wind speeds resulted in lower overall concentrations and maximums further downwind. This result is in agreement with our finding of higher concentrations from the flares under higher wind conditions.

The limited data on background concentrations make the assessment of the total $PM_{2.5}$ exposures uncertain. What is often done in regulatory air dispersion modeling is to add a background level taken from available monitoring data to the model results to give a total concentration. The metric may be an average, a maximum, or a percentile, depending on the circumstances. Although we estimated the engine emissions from the water vessels, we did not add these values to the combustion exposures because of the high spatial and temporal uncertainty in the engine emissions.

During the *DWH* event, de Gouw *et al.* (2011) observed significant formation of SOAs following the volatilization of lower molecular weight components from surface oil slicks. The formation was rapid and occurred by the time the air passing over the oil slick had reached the shoreline. SOA formation depends on meteorological conditions and precursor emissions. The timing

and magnitude of SOA formation could not be assessed and therefore, this added particulate loading also was not included in our analysis. As a result, we may have underestimated $PM_{2.5}$ concentrations due to our inability to account for background concentrations and SOA formation, although due to the small size (<0.1 μm) their contribution to $PM_{2.5}$ mass was likely to be small.

Another limitation in our analysis is that although we had data on time, duration, location, and amount of fuel combusted for the 354 *in situ* burns, another 57 were listed in the records with dates but no further information. Thus, exposure from this additional set of 'burns' is likely to be minimal. An additional limitation is that estimates of emissions from uncontrolled combustion sources and from flares are often highly uncertain. Past studies have shown that in many modeling analyses, emissions estimates are the largest source of uncertainty (Pratt *et al.*, 2012), and this is especially true for uncontrolled combustion. Finally, the estimates of emissions of substances other than PM were based on two studies. The studies, however, covered crude oil burns similar to (and for two substances under) the *DWH* combustion conditions. We assumed proportionality to $PM_{2.5}$ emissions, but applicability of this assumption undoubtedly varies over time, fuel composition, and by pollutant, and therefore the emissions estimates for these additional pollutants are more uncertain than for $PM_{2.5}$.

Another significant limitation in our analysis is that we applied the steady-state AERMOD model at distances up to 300 km. This approach assumes that the plume moved downwind and dispersed according to the conditions at the time of release. It does not account for within-day changes in meteorological conditions that may have affected the dispersion of the plume or the direction of its movement. Over time and distance the steady-state assumption becomes less valid, and as a result, AERMOD is typically not recommended for distances greater than 50 km. In this study, most of the receptors of interest, i.e. those on the water, were within the 50 km radius; however, concentrations at more distant locations were also of interest, including the near shore and onshore coastline of Louisiana, Mississippi, Alabama, and Florida, which were more than 50 km from the sources.

The meteorological conditions during the *in situ* burns were typically light and steady winds, almost calm at times, with minimal turbulence over a uniform (water) surface. Under these conditions, we deemed the assumption of steady state over distances that exceeded the 50 km recommendation to be reasonable. The flares operated continuously under all meteorological conditions, and the steady-state assumption may be less appropriate for those sources. Despite these limitations, AERMOD was used to estimate the concentrations within the recommended 50 km of the *DWH site* as well as outside of the recommended 50 km (i.e. near shore and land). The effect of this assumption, however, is that these shoreline estimates are more uncertain than the estimates closer to the wellhead. An alternative would have been to use a more intensive approach such as a puff-based Lagrangian model like CALPUFF or an Eulerian plume-in-grid model. Given the large uncertainties in the model input information, we decided that the additional resources required for more precise modeling would not have appreciably increased the reliability of our model results.

Another limitation is that, in the calculation of exposure estimates by area, we averaged all nonzero receptor concentration estimates on a single day in each grid cell. This method underestimates the variability of the concentrations. Descriptive statistics were performed by day to evaluate how much variability was reduced (not shown). GSDs of the 12-h maximum exposures generally averaged less than 3 μg $m^{-3}$ in areas away from the wellhead, but increased considerably near the wellhead (see Supplementary Information File 2, available at *Annals of Work Exposures and Health* online). Variability in the 1-h maximum exposure levels was similar but slightly higher. We had expected larger variability in the 1-h maximum exposures than those of the 12-h exposures because of the greater range in modeled concentrations. Elimination of variability due to spatial averaging is likely to have little effect on our epidemiologic results, due to the limitations of the information available on the study participants. A participant's assigned area (and therefore exposure) generally was based on responses to the questions about whether an individual could generally see ships in the wellhead/source area (hot zone/source), could generally see the shoreline (near shore), or whether they worked on land. If the participant indicated s/he worked on water and responded 'no' to both the wellhead and shoreline questions, the default was assignment to the offshore area.

Given the potential issues with emissions estimates and limitations in the modeling approach (i.e. uncontrolled combustion, lack of information on the condensable fraction of emissions, omission of SOA formation) and lack of background air concentrations, we chose emissions factors at and sometimes above the range of published values. In addition, we developed potential 1- and 12-h maximum exposures. Maximum values were selected due to the large number of extremely low values throughout most of the Gulf outside the plume area while burning/flaring occurred, meaning that averages or medians would have resulted in essentially zero exposure. These values do not represent the exposure

level experienced every day by any given worker in a particular area nor do they represent the exposure of all workers in an area on any single day. Thus, these modeled exposure levels overall are likely to be overestimates for most of the workers performing OSRC in a particular area. However, given the underestimation due to lack of information on engine emissions and SOA formation, it is not clear whether our exposure levels are over- or underestimated for the study population.

This study has several strengths. It is the first study to estimate $PM_{2.5}$ air concentrations and worker exposures from the *in situ* burning and flaring operations. We used a well-established model to estimate air concentrations. The inputs and assumptions needed for the model were taken from measurements in comparable studies and from values estimated from videos and photographs of the burns. The model results and exposure estimates are compiled into databases available for further analyses of exposure and potential health effects from the first author. A previous analysis (Gam *et al.*, 2018) using less refined methods found an association between estimated exposure and reduced pulmonary function. These new modeled estimates have the potential to improve the precision of those estimates and new analyses. The model predictions in the database can be systematically changed if assumptions different from those we used are deemed of interest. Another strength is that we present potential exposure levels across large areas of the Gulf from burning and flaring as well as from the combined effect of both sources.

We also developed ranges of potential exposures due to engine emissions from vessels involved in the *DWH* clean-up activities. The estimated air concentrations from vessels were substantially lower than the concentrations from burning and flaring around the well site. Near shore and on-land, however, the vessel contribution was proportionately higher than the burning/flaring contribution, although these results may be misleading due to insufficient information about vessel and worker locations. Due to the higher uncertainty in the near shore and land estimates, particularly due to the lack of information on vessels and on equipment and traffic on land, and the lack of specific information about participants, we recommend considering only the *in situ* burn, hot zone, and source workers in an epidemiologic analysis and taking into account the potential confounding from these other sources of emissions.

Our goal in presenting these estimates is to raise awareness of potential $PM_{2.5}$ exposures from these three sources of combustion. The exposure estimates were developed to describe $PM_{2.5}$ exposures from *in situ* burns and flaring, not total for $PM_{2.5}$. Nonetheless, the estimates developed here should provide useful information for protection of workers in future OSRC efforts. The model-predicted concentrations, especially very near the *DWH* site, appear to be significant with respect to 24-h NAAQS and known health endpoint effects. Despite the large uncertainties, our estimates indicate that workers near both the *in situ* burning and the flaring operations may be at risk of experiencing $PM_{2.5}$ exposures that could have an adverse impact on health. Future analyses in the GuLF STUDY will explore this potential.

## Conclusions

Modeled $PM_{2.5}$ air concentrations (1- and 12-h maximum and 24-h average concentrations) in some instances were very high near the combustion sources of the *in situ* burns and flares that were conducted as part of the OSRC effort following the *DWH* disaster. Twenty-four-hour concentrations, as well as concentrations at distant locations, were lower than the concentrations of shorter duration closer to the combustion sources. Potential worker exposures may have exceeded the federal standards for the general population. These data suggest that the individuals working near combustion operations could be at risk of adverse health effects due to $PM_{2.5}$. The GuLF STUDY will provide a better understanding of the risks to these workers.

## 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 they have no competing interests.

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