The following supplement accompanies the article

Bird mortality from the *Deepwater Horizon* oil spill. II. Carcass sampling and exposure probability in the coastal Gulf of Mexico

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Supplement. Bird carcass collection data, exposure probability model parameter selection methods, and carcass transportation probability methods, used to estimate total mortality

Table S1. Tallies of all bird species recorded as dead with visible signs of oiling (carcasses reported in US Fish & Wildlife Service, FWS *Deepwater Horizon* oil spill response, bird impact data, data by species, table for week of May 12, 2011 at www.fws.gov/home/dhoilspill/collectionreports.html, accessed 22 March 2013). Habitat affinity and body mass (in g) were taken from The Birds of North America online (http://bna.birds.cornell.edu/bna/) and Sibley (2000). The coastal designation included species likely to (1) migrate over the slick in the Gulf's open water during spring (when the spill began), (2) scavenge on beach carcasses of other birds, or (3) be exposed to oil on open shorelines but potentially transported elsewhere by tides. Body masses were then used to bin all retrieved carcasses into 1 of 3 mutually-exclusive body size categories: large (≥500 g), medium (300–499 g), and small (10–299 g)

Species		Carcasses retrieved	Habitat	Size cat.
Mallard	*Anas platyrhynchos*	5	Coastal	Large
Surf scoter	*Melanitta perspicillata*	1	Coastal	Large
Red-breasted merganser	*Mergus serrator*	1	Coastal	Large
Ruddy duck	*Oxyura jamaicensis*	1	Coastal	Large
Common loon	*Gavia immer*	33	Coastal	Large
Loon sp.	*Gavia* sp.	2	Coastal	Large
Pied-billed grebe	*Podilymbus podiceps*	18	Coastal	Medium
Grebe sp.	*Podilymbus* or *Podiceps*	2	Coastal	Medium
Great shearwater	*Puffinus gravis*	7	Coastal	Large
Manx shearwater	*Puffinus puffinus*	1	Coastal	Medium
Audubon's shearwater	*Puffinus lherminieri*	1	Coastal	Small
Leach's storm-petrel	*Oceanodroma leucorhoa*	1	Coastal	Small
Magnificent frigatebird	*Fregata magnificens*	3	Coastal	Large
Masked booby	*Sula dactylatra*	4	Coastal	Large
Northern gannet	*Morus bassanus*	225	Coastal	Large
Double-crested cormorant	*Phalacrocorax auritus*	2	Coastal	Large
Cormorant sp.	*Phalacrocorax* sp.	3	Coastal	Large
American white pelican	*Pelecanus erythrorhynchos*	5	Coastal	Large
Brown pelican	*Pelecanus occidentalis*	152	Coastal	Large
Pelican sp.	*Pelecanus* sp.	5	Coastal	Large
Great blue heron	*Ardea herodias*	5	Coastal	Large
Great egret	*Ardea alba*	6	Estuarine	Large
Snowy egret	*Egretta thula*	12	Estuarine	Medium
Egret sp.	*Ardea* or *Egretta*	2	Estuarine	Medium
Tricolored heron	*Egretta tricolor*	9	Estuarine	Medium

Species		Carcasses retrieved	Habitat	Size cat.
Reddish egret	*Egretta rufescens*	1	Coastal	Large
Cattle egret	*Bubulcus ibis*	4	Coastal	Medium
Green heron	*Butorides virescens*	2	Estuarine	Small
Black-crowned night heron	*Nycticorax nycticorax*	6	Coastal	Large
Yellow-crowned night heron	*Nyctanassa violacea*	1	Estuarine	Large
Heron sp.	n/a	5	Coastal	Large
White ibis	*Eudocimus albus*	1	Estuarine	Large
Glossy ibis	*Plegadis falcinellus*	1	Estuarine	Large
Roseate spoonbill	*Platalea ajaja*	7	Estuarine	Large
Osprey	*Pandion haliaetus*	2	Estuarine	Large
Clapper rail	*Rallus longirostris*	27	Estuarine	Medium
Sora	*Porzana carolina*	2	Estuarine	Small
Rail sp.	n/a	1	Estuarine	Medium
American coot	*Fulica americana*	2	Coastal	Large
Common moorhen	*Gallinula galeata*	1	Estuarine	Medium
Semipalmated plover	*Charadrius semipalmatus*	2	Coastal	Small
American oystercatcher	*Haematopus palliatus*	7	Coastal	Large
Willet	*Tringa semipalmata*	2	Coastal	Small
Ruddy turnstone	*Arenaria interpres*	1	Coastal	Small
Sanderling	*Calidris alba*	4	Coastal	Small
Dowitcher sp.	*Limnodromus* sp.	1	Estuarine	Small
Shorebird sp.	n/a	2	Coastal	Small
Laughing gull	*Leucophaeus atricilla*	1025	Coastal	Medium
Herring gull	*Larus argentatus*	10	Coastal	Large
Lesser black-backed gull	*Larus fuscus*	1	Coastal	Large
Gull sp.	n/a	79	Coastal	Medium
Least tern	*Sternula antillarum*	46	Coastal	Small
Caspian tern	*Hydroprogne caspia*	7	Coastal	Large
Black tern	*Chlidonias niger*	1	Coastal	Small
Common tern	*Sterna hirundo*	15	Coastal	Small
Forster's tern	*Sterna forsteri*	17	Coastal	Small
Royal tern	*Thalasseus maximus*	116	Coastal	Medium
Sandwich tern	*Thalasseus sandvicensis*	28	Coastal	Small
Tern sp.	n/a	38[a]	Coastal	Small
Black skimmer	*Rynchops niger*	51	Coastal	Medium
Rock pigeon	*Columba livia*	2	Estuarine	Medium
Pigeon sp.	*Columba* sp.	2	Estuarine	Medium
Mourning dove	*Zenaida macroura*	3	Estuarine	Small
Yellow-billed cuckoo	*Coccyzus americanus*	2	Estuarine	Small
Eastern kingbird	*Tyrannus tyrannus*	1	Estuarine	Small
Flycatcher sp.	n/a	1	Estuarine	Small
Purple martin	*Progne subis*	1	Estuarine	Small
Barn swallow	*Hirundo rustica*	1	Estuarine	Small
Seaside sparrow	*Ammodramus maritimus*	4	Estuarine	Small
Other	n/a	31	Coastal	Medium
Unknown	n/a	51	Coastal	Medium
Total carcasses		2121[b]		

[a] Unidentified tern carcasses assigned as follows: 30 to the medium- and 8 to the small-bodied size category

[b] This total consists of 92 and 2029 carcasses assigned to estuarine and coastal habitats, respectively. 25 birds retrieved offshore were allocated to but subtracted from an initial medium-bodied bird carcass total of 1408. A total of 2004 carcasses then remained for the carcass sampling model, consisting of 128 small-, 1383 medium- and 493 large-bodied bird carcasses.

Parameter selection for exposure probability model

Daily oil slick size, A_i, was calculated from shape files that were synthesized in the Experimental Marine Pollution Surveillance Daily Composite Products (www.ssd.noaa.gov/PS/MPS/deepwater.html; accessed 11 August 2013). Spatial depictions of the *Deepwater Horizon* oil slick in these products were based primarily on satellite sensors augmented with oil spill trajectory models and other ancillary data (see Haney et al. 2014). The average slick size $\bar{A}$ was computed by averaging the estimated slick sizes over 95 consecutive days from 28 April to 31 July 2010, when observed daily slick size (A_i) varied from 117 km^2 to 11000 km^2.

Parameter P was set to 1 d based in part on the fact that around 19% of the cumulative slick in the coastal zone consisted of locations where the oil persisted only 1 d. Coastal oil patches were more transient (less fixed in location) than in the offshore, posing new and recurring exposure hazards to birds in different locations. The coastal slick also included patches of oil that recurred on non-consecutive days, with the smaller cumulative slick often fragmented into many separate oil patches. Thus, regional-scale replacement of birds through daily offshore commuting flights of breeders, alongshore migrations of departing wintering species, and funneling by cross-Gulf migrants into coastal stop-over sites all acted to increase the turnover of birds over the coastal oil slick.

Estimates of coastal bird density, D, were derived from surveys on the upper Texas coast near but outside the spill zone during the same time of year and based on an X-band 9410 MHz radar system having a detection range ≥120 km (McFarlane & Lester 2005).

No direct measurements of the proportionate mortality for oiled birds were available for *Deepwater Horizon*. However, of the birds collected during the *Deepwater Horizon* incident, 2121 of these consisted of oiled dead birds out of 7258 birds alive and dead regardless of oiling status (compiled in the official DOI-ERDC NRDA database www.fws.gov/home/dhoilspill/collectionreports.html, accessed 22 February 2013). This gives a ratio of 0.292. However, this value did not reflect oiled birds alive when captured but subsequently dying after rehabilitation and release, nor birds that died at sea but could not be retrieved. Our choice for M of 0.40 thus lay within the lower half of the interval reported from this and other oil spills, after due consideration of the fact that the Gulf of Mexico's predominant coastal seabird taxa (sulids, terns, gulls) spend a high proportion of time in the air.

Estimating probability of seabird carcass transport to Gulf of Mexico shorelines

Shoreline deposition of seabirds killed offshore depends on the probability that carcasses will remain buoyant during transport. This probability can be computed from the transport time and the rate of buoyancy loss. Transport time depends on the initial position of a carcass at sea, and the subsequent speed and direction of the carcass en route to shore. We determine the transport probability, r, as the result of initial carcass position, time to reach a shoreline from that position, and probability of remaining buoyant during that time, as follows:

Computation of initial offshore carcass distribution

We assumed the initial distribution of seabird carcasses offshore to be the product of the relative area densities of seabirds and oil as functions of distance from Gulf shorelines. Because abundance of breeding seabirds declines rapidly with increasing distance from coastal roosts and breeding colonies (e.g. Mills 1998, Amorim et al. 2008, Zakkak et al.

2013), we assumed that the relative density of coastal seabirds declines linearly from a maximum at the shoreline to a negligibly low value at 40 km offshore. This dependence can be expressed as a simple function for relative seabird density, s_d, as $s_d = 1 - z/40$, where z is the distance from shoreline in km. The proportion of birds, $p_{z1,z2}$, occupying an interval of distance from z_1 to z_2 from the coast can be computed under these assumptions as

$$p_{z1,z2} = \frac{\int_{z_1}^{z_2}\left(1-\frac{z}{40}\right)dz}{\int_{0}^{40}\left(1-\frac{z}{40}\right)dz} = \frac{1}{20}\int_{z_1}^{z_2}\left(1-\frac{z}{40}\right)dz \qquad \text{(S1)}$$

We computed oil density as a function of distance from shoreline on the basis of GIS analyses of satellite surveillance of the oiled area within 40 km of the shoreline. The cumulative oiled area within each of 8 adjacent 5 km bands from the shoreline was evaluated for each day of the spill, and summed over all the days when oil was detected. The relative density of oiled area within each band was computed as the ratio of total area within a band and the overall total oiled area, both summed across days when oil was detected. The initial carcass distribution of seabirds killed by exposure to oil was computed as the product of the relative proportion of seabirds (from Eq S1) and relative proportion of the cumulative oil from the coast to adjacent 5 km distance intervals (Table S2).

Table S2. Computation of initial carcass distribution from estimated oiled area and the assumed variation of coastal seabird population density within 5 km intervals from the northern Gulf of Mexico coastline. Oil proportion (column 3) is the ratio of cumulative oil area from the coast to adjacent 5 km distance interval (column 2) and the sum of these cumulative oil areas from the coast to 40 km seaward

(1) Distance from shoreline (km)	(2) Oil area (km^2)	(3) Oil area proportion	(4) Seabird proportion (Eq S1)	(3) × (4)	Initial carcass distribution [(3) × (4)] / ∑ [(3) × (4)]
0–5	25000	0.019	0.234	0.0044	0.056
5–10	52000	0.040	0.203	0.0081	0.102
10–15	87000	0.066	0.172	0.0114	0.143
15–20	130000	0.099	0.141	0.0139	0.175
20–25	174000	0.132	0.109	0.0145	0.182
25–30	224000	0.171	0.078	0.0134	0.167
30–35	279000	0.212	0.047	0.0100	0.125
35–40	341000	0.260	0.016	0.0041	0.051
Total	1312000	1.000	1.000	0.0797	1.000

Computation of transit time to shorelines

We computed the transport time for seabird carcasses to reach Gulf shorelines from measurements of wind velocity and direction, and assuming a 2% coupling of wind and seabird carcass drift speeds, Coriolis deflection 18° to the east, and 80% of shorelines facing south and 20% facing east (Tran et al. 2013). Seabird carcass drift speeds were computed as the respective northward and westward components of the drift velocity vector. The average values of these velocities $\bar{v}_N$ and $\bar{v}_W$ were used to compute the overall average carcass drift speed as $\bar{v} = 0.8\,\bar{v}_N + 0.2\,\bar{v}_W$, presented at the bottom of Table S3 below.

Table S3. Computation of northward, westward, and total transport velocities of seabird carcasses. Total transport velocity v was computed as the product of wind speed (m s^{-1}) and the assumed seabird carcass drift-coupling constant of 0.02, with the result converted to km d^{-1}. Letting v_t denote the measured wind velocity on day t, the northward and westward components of total seabird drift velocity were computed as $v_{\mathrm{N}} = v_t \cos(\theta + 18° + 180°)$ and $v_W = v_t\,[-\sin(\theta + 18° + 180°)]$, where θ is the compass bearing of wind origin, 18° accounts for Coriolis deflection, and 180° rotates θ to the direction of the carcass drift velocity. Average drift velocity weighted by shoreline aspect is 4.1 km d^{-1}

Date	Wind origin	Wind speed	Daily seabird drift (km d^{-1})		
	θ (°N)	(m s^{-1})	Total (v)	North (v_{N})	West (v_{W})
28-Apr	135	5.5	9.4	8.4	4.3
29-Apr	123	5.4	9.3	7.3	5.8
30-Apr	137	6.9	11.9	10.7	5.1
1-May	143	3.2	5.5	5.2	1.8
2-May	163	2.6	4.5	4.5	−0.1
3-May	166	5.7	9.9	9.9	−0.7
4-May	138	6.3	10.8	9.9	4.4
5-May	90	2.3	4.0	1.3	3.8
6-May	167	1.7	2.9	2.9	−0.2
7-May	189	4.4	7.7	6.9	−3.4
8-May	234	5.7	9.9	3.1	−9.4
9-May	54	6.9	11.9	−3.7	11.3
10-May	106	6.3	10.9	6.1	9.1
11-May	135	6.4	11.1	9.9	5.0
12-May	130	7.5	12.9	11.0	6.8
13-May	122	7.7	13.3	10.2	8.4
14-May	108	6.2	10.8	6.3	8.7
15-May	127	6.4	11.1	9.1	6.4
16-May	149	5.6	9.7	9.5	2.1
17-May	232	3.7	6.5	2.2	−6.1
18-May	239	3.7	6.4	1.4	−6.2
19-May	195	3.3	5.7	4.8	−3.1
20-May	163	5.4	9.3	9.3	−0.1
21-May	133	5.0	8.7	7.6	4.2
22-May	134	5.5	9.5	8.4	4.5
23-May	120	5.1	8.8	6.6	5.9
24-May	193	2.1	3.7	3.1	−1.9
25-May	248	2.7	4.6	0.3	−4.6
26-May	125	3.4	5.9	4.7	3.5
27-May	217	2.5	4.3	2.5	−3.5
28-May	305	4.5	7.8	−6.3	−4.7
29-May	240	4.8	8.2	1.8	−8.0
30-May	200	3.2	5.4	4.3	−3.4
31-May	185	3.8	6.5	6.0	−2.5
1-Jun	188	2.5	4.4	3.9	−1.9
2-Jun	175	4.2	7.3	7.1	−1.7
3-Jun	185	5.7	9.8	9.1	−3.8
4-Jun	198	5.9	10.2	8.2	−6.0
5-Jun	187	6.3	11.0	9.9	−4.6
6-Jun	196	4.9	8.5	7.0	−4.8
7-Jun	257	3.6	6.2	−0.5	−6.1
8-Jun	159	2.0	3.4	3.4	0.2
9-Jun	137	4.3	7.5	6.8	3.2
10-Jun	146	5.3	9.2	8.9	2.5
11-Jun	148	6.0	10.3	10.0	2.5
12-Jun	143	4.6	7.9	7.4	2.6
13-Jun	143	2.5	4.3	4.1	1.4
14-Jun	217	2.3	4.0	2.3	−3.3
15-Jun	188	2.8	4.9	4.4	−2.1

Date	Wind origin	Wind speed	Daily seabird drift (km d^{-1})		
	θ (°N)	(m s^{-1})	Total (v)	North (v_N)	West (v_W)
16-Jun	186	1.8	3.2	2.9	−1.3
17-Jun	240	2.2	3.8	0.8	−3.7
18-Jun	227	2.9	5.0	2.1	−4.5
19-Jun	247	2.8	4.9	0.5	−4.9
20-Jun	155	2.7	4.6	4.6	0.5
21-Jun	147	2.5	4.4	4.2	1.1
22-Jun	151	4.2	7.2	7.1	1.3
23-Jun	138	6.5	11.2	10.2	4.5
24-Jun	102	3.7	6.4	3.2	5.5
25-Jun	112	4.1	7.1	4.5	5.5
26-Jun	108	4.5	7.8	4.6	6.3
27-Jun	121	6.1	10.5	7.9	6.8
28-Jun	145	6.7	11.6	11.1	3.4
29-Jun	111	3.6	6.3	4.0	4.8
30-Jun	105	4.1	7.0	3.8	5.9
1-Jul	95	6.6	11.3	4.5	10.4
2-Jul	149	5.8	10.0	9.7	2.2
3-Jul	59	4.4	7.6	−1.7	7.4
4-Jul	99	4.8	8.4	3.8	7.4
5-Jul	148	7.1	12.2	11.9	3.0
6-Jul	123	4.6	7.9	6.1	5.0
7-Jul	121	4.6	7.9	5.9	5.2
8-Jul	106	6.4	11.0	6.2	9.1
9-Jul	148	2.2	3.8	3.7	0.9
10-Jul	262	4.1	7.0	−1.2	−6.9
11-Jul	256	5.1	8.8	−0.6	−8.8
12-Jul	252	6.4	11.1	−0.1	−11.1
13-Jul	244	5.8	10.1	1.4	−10.0
14-Jul	267	3.7	6.3	−1.7	−6.1
15-Jul	293	4.6	7.9	−5.2	−5.9
16-Jul	154	3.6	6.2	6.1	0.8
17-Jul	159	4.9	8.5	8.5	0.5
18-Jul	168	4.7	8.2	8.1	−0.9
19-Jul	117	4.2	7.2	5.1	5.1
20-Jul	115	6.1	10.5	7.1	7.7
21-Jul	106	7.5	13.0	7.3	10.8
22-Jul	110	7.1	12.3	7.6	9.7
23-Jul	105	4.7	8.1	4.5	6.8
24-Jul	106	4.3	7.4	4.1	6.2
25-Jul	151	6.5	11.3	11.1	2.1
26-Jul	155	5.9	10.1	10.0	1.3
27-Jul	189	4.4	7.7	6.8	−3.5
28-Jul	120	2.2	3.9	2.9	2.6
29-Jul	273	3.7	6.4	−2.3	−5.9
30-Jul	320	6.8	11.7	−10.8	−4.3
31-Jul	273	5.8	10.1	−3.6	−9.4
Average	166	4.6	8.0	4.9	0.88

Average shoreward drift speed = (0.8 × 4.9) + (0.2 × 0.88) = 4.1 km d^{-1}

Computation of transport probability to shorelines

Our computation of the probability that seabirds killed offshore would remain afloat during transit towards shorelines is based primarily on experiments reported by Wiese (2003) and Ford et al. (1991). Wiese (2003) reported that 70% of frozen and then thawed murres (*Uria* spp.) sank after 5 d in experiments conducted during late fall in Newfoundland, Canada when water temperatures were about 5°C. Murres lost buoyancy approximately according to a negative exponential function (see Fig. 2 in Wiese 2003), implying an instantaneous rate of buoyancy loss of 24% (i.e. 0.24) d^{-1} (i.e. loss over 5 d was approximately $1 - e^{-0.24(5)}$). Ford et al. (1991) reported instantaneous loss rates of about 13% d^{-1} for murres tethered in Oregon seas, where the mean temperature was about 15°C. Averaging loss rates reported in these 2 studies leads to 18% d^{-1} at an average temperature of about 10°C. Applying this result to seabirds killed by oil exposure in the Gulf of Mexico requires accounting for the different environmental conditions there.

Three factors would cause seabird carcasses to sink faster in the northern Gulf of Mexico than in the experiments reported by Wiese (2003) or Ford et al. (1991). The northern Gulf of Mexico is substantially warmer, leading to faster body decomposition rates, and it has numerous predators that could damage or consume carcasses. Average sea surface water temperatures in the northern Gulf of Mexico during the spring and summer of the *Deepwater Horizon* incident were ca. 20° to >32°C (NOAA 2014), approx. 10–20°C above the temperatures in the Ford et al. (1991) or Wiese (2003) experiments. Based on the $Q_{10} = 2$ approximation for the variation of metabolic rates with temperature (Schmidt-Nielsen 1997), this implies decomposition rates that are faster by a factor of about $2^{1.5} = 2.8$, increasing the rates of buoyancy loss from decomposition alone for seabird carcasses to at least $2.8 \times 18\% = 50\%$ d^{-1}.

Carcass damage inflicted by scavengers nearly doubled the rate of buoyancy loss (Wiese 2003, their Fig. 2). Carcass removal by scavengers such as tiger sharks *Galeocerdo cuvier* (Kaufman 2012) would increase carcass disappearance rates from the sea surface still more, but we have no quantitative basis for assessing this contribution to total disappearance rates. We therefore presumed that the instantaneous carcass disappearance rate for the northern Gulf of Mexico during spring and summer is 100% (i.e. 1.00) d^{-1}, with the contribution attributable to consumption by scavengers partially offsetting possible overemphasis on the magnitude of the Q_{10} temperature effect or the faster sinking caused by carcass damage inflicted by scavengers.

Assuming an overall instantaneous disappearance rate of 100% d^{-1}, the proportion of carcasses initially killed z km offshore that remain afloat until reaching a shoreline may be computed as $\exp-(1.00t)$, where t is the time in days required for the carcass to reach the shore. We compute t as the ratio of the distance from shore z and the average shoreward velocity $v = 4.1$ km d^{-1} from Table S3, or $\exp-[(1.00)\, z/(4.1 \text{ km d}^{-1})]$.

Using the midpoint for each 5 km distance interval from shore to 40 km offshore as z, the product of this proportion and the frequency distribution of the initial location of seabird carcasses (Table S2) gives the relative probability for each 5 km distance interval, and summing these results across the distance intervals from the shoreline to 40 km offshore gives the overall transport probability = 0.057 presented in Table S4. Note that most of this transport probability arises from carcasses originating within 15 km of the shore, beyond which the average transport time of ~4 d or more leads to nearly complete removal of carcasses from the sea surface before reaching a shoreline.

Table S4. Computation of oiled seabird carcass transport probability to shorelines along the northern Gulf of Mexico during the *Deepwater Horizon* oil spill

(1) Distance from shoreline, z (km)	(2) $\exp-[(1.00\ z)/(4.1\ \text{km d}^{-1})]$	(3) Initial carcass distribution (from Table S1)	(4) Probability of shoreline deposition (2) × (3)
0–5	0.542	0.056	0.030
5–10	0.160	0.102	0.016
10–15	0.047	0.143	0.007
15–20	0.014	0.175	0.002
20–25	0.004	0.182	0.001
25–30	0.001	0.167	0.000
30–35	0.000	0.125	0.000
35–40	0.000	0.051	0.000
Total		1.000	0.057

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