Chapter 25
Evaluating Impacts of Deep Oil Spills on Oceanic Marine Mammals

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Abstract The *Deepwater Horizon* (DWH) oil spill may be indicative of future large, deep spills that may occur in the coming decades. Given that future deepwater spills are possible, critical considerations include (1) establishing baselines for oceanic marine mammal and populations in at-risk areas, (2) understanding the implications of response choices for oceanic marine mammals, (3) designing studies with adequate coverage for post-spill monitoring, and (4) identifying effective strategies for oceanic marine mammal restoration. In this chapter, we consider these four stages in the context of a series of hypothetical oil spill scenarios, identifying ways that lessons learned from the DWH oil spill and prior events can be applied to future disasters.

Keywords Marine mammal · Sperm whale · Beaked whale · Dolphin · Passive acoustic monitoring (PAM) · Megafauna · Mammal · Odontocete · Bryde's whale · Spotted dolphin · *Stenella* · *Kogia* · Echolocation · Visual survey · Ship strike · Noise · Air gun · HARP · Mississippi Canyon · Green Canyon · Risso's dolphin · Pilot whale · Tag · Aerial survey · Habitat model · Loop Current · AUV · Satellite · Genetic · Monitoring · Dispersant · Hazing · Deterrent · NRDA · Cetacean · Disturbance · NOAA · Stock · Restoration · Mexico · Seismic

25.1 Introduction

The *Deepwater Horizon* (DWH) event differed from previous spills in that it occurred in deep water at an offshore location (1525 m deep, 66 km from the nearest shoreline). As a result it affected offshore marine megafauna in oceanic (>200 m bottom depth) habitats where prior study and monitoring efforts were sparse and infrequent. To characterize the effect of the event on marine mammals, the focus

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turned to coastal impacts and tractable nearshore surrogate species (Trustees 2016), because it was determined to be "unrealistic" to quantify offshore impacts directly. However, bay, sound, and estuary (BSE) bottlenose dolphins (the oceanic marine mammal surrogate) are weak proxies for the diverse, wide-ranging, and deep-diving oceanic species affected by the event. The true impacts of the DWH event on oceanic marine mammals and their offshore habitats may never be fully quantified.

As oil extraction operations deepen and extend into increasingly inaccessible locations, the difficulties of measuring spill impacts will likely increase. Future deep spills may affect deep waters of the Northern Gulf of Mexico (GOM) and Northeastern Atlantic, as well as Arctic waters (Huntington 2009; Cordes et al. 2016). As in the case of the DWH spill, effects of these events on marine mammal populations will likely be challenging to observe. Nonetheless, the ability to characterize the nature and magnitude of the impacts of these events is necessary for response, damage assessment, and restoration activities.

We discuss preparation strategies for future spills in at-risk regions. Based on the lessons from the DWH event, we ask what measures could be taken before, during, and after an offshore spill to characterize oceanic marine mammal populations, incorporate potential effects on marine mammals as a consideration in disaster response decisions, quantitatively evaluate population-level impacts of oil spills, and support population recovery.

25.2 Before a Spill: Establishing Baselines

The lack of precise pre-spill estimates of GOM marine mammal distributions and abundances severely limited efforts to evaluate the impacts of the DWH spill on oceanic megafauna. Measuring baseline marine mammal population sizes and distributions in at-risk areas is clearly a critical part of preparing for future oil spills; however it is rare to have this type of data prior to an event (Bonebrake et al. 2010). Monitoring an area the size of the GOM is expensive and logistically challenging, particularly with the level of readiness required to quantify impacts at an unknown time and location. Furthermore, standard survey methods are unlikely to achieve adequately precise density and abundance estimates or provide the level of spatiotemporal resolution needed to quantify exposure (Taylor et al. 2007). Practical approaches for long-term monitoring of large oceanic marine ecosystems with enough spatiotemporal resolution to quantify impacts of future spills at unknown times and locations on marine mammals have not been demonstrated.

Marine mammals are wide-ranging and capable of transiting long distances over large time scales (e.g., Jochens et al. 2008); therefore any monitoring strategy must account for population mobility and migration within and beyond the study region. Many GOM marine mammal species appear to migrate or shift their distributions seasonally, while others appear to be year-round residents (Hildebrand et al. 2015; Frasier 2015). Tropical and subtropical species may seek different habitat conditions. In the GOM, transient Loop Current features including cold- and warm-core eddies, as well as the loop itself, have a strong influence on regional oceanographic conditions and likely affect GOM marine mammal distributions (Davis et al. 2002). Interpreting these distributions is further complicated by the fact that surveys are typically limited to the US EEZ, which accounts for only 35% of the GOM ecosystem. Distinguishing between population declines and population shifts is challenging because it is unclear how some species move throughout the GOM.

A combination of in situ monitoring and modeling is likely the most realistic approach for establishing abundance and distribution baselines in large regions of concern. In situ monitoring data can be used to develop habitat models used to interpolate marine mammal distributions between measurements across space and time. In the case of a disaster, models can use observed historical relationships between seasonal and oceanographic drivers and marine mammal encounters (Redfern et al. 2006; Roberts et al. 2016) to estimate exposure at the event location. However, developing robust models requires extensive monitoring effort for species of concern across seasons, habitats, and regional oceanographic variability (Kaschner et al. 2012) and may require integration of multiple observation methods to achieve sufficient predictive power.

25.2.1 In Situ Monitoring Strategies

Visual Surveys

Shipboard line transect surveys with visual observers are the standard method for estimating baseline abundance and describing the distributions of oceanic cetaceans (Davis et al. 1998; Mullin and Hoggard 2000; Fulling et al. 2003; Mullin and Fulling 2003, 2004; Barlow and Forney 2007). This method relies on animal sightings at the sea surface. Visual surveys provide broad spatial coverage of a region at brief snapshots in time (roughly 0.5 hours/10 km transect segment). Some temporal coverage can be obtained if surveys are repeated on a regular schedule; however visual methods are resource intensive, requiring extensive vessel and personnel time; therefore they may not be conducted often enough to provide precise estimates. Visual surveys also rely on fair weather conditions; therefore in the GOM, most visual survey effort has occurred in summer months (Maze-Foley and Mullin 2007; Mullin 2007).

To provide adequate data for training habitat models with broad spatial and temporal predictive capabilities, visual survey methods must cover a large surface area, survey across a variety of oceanographic features, occur in multiple seasons, and develop species-specific sighting rate estimates (Buckland et al. 2007). Given that marine mammals only spend a fraction of their time at the sea surface, visual survey data tend to be sparse (~1 sighting per 50 km of NOAA shipboard pelagic visual survey effort in the GOM, 2002–2014), requiring extensive survey effort to produce robust models. Double-blind visual surveys with two independent visual teams are typically used to accurately estimate sighting probabilities for different species (Palka 2006), as each species has a different probability of seen by observers: The tall blows of sperm whales or large groups of dolphins are more likely to be sighted than cryptic species such as beaked whales and *Kogia* species. Sighting rates are further influenced by survey platform height; therefore survey vessels are not interchangeable and must be calibrated (e.g., Palka 2006). Recent field studies have also found evidence of vessel avoidance by marine mammals (Cholewiak et al. 2017) which may lead to underestimates of marine mammal densities if not accounted for. In general, the low precision of abundance estimates from large-scale visual surveys prevents estimation of long-term population trends and precludes detection of all but the most catastrophic population-level impacts (Williams et al. 2011; Taylor et al. 2007).

Shipboard visual surveys for oceanic marine mammals were conducted in the GOM prior to the DWH spill (Waring et al. 2009), but due to the expense and limitations of the method, the population size estimates were too imprecise to allow damages to be quantified by comparison with post-spill survey results. Unless Gulf-wide surveys could be conducted frequently across a range of seasons, visual surveys alone would likely remain insufficient for determining the effects of a future spill (Jewell et al. 2012; Taylor et al. 2007). Aerial visual surveys in the GOM typically focus on the expansive continental shelf region (Fulling et al. 2003) and are not used to survey oceanic populations. Unmanned aerial vehicles (UAVs) may become a viable low-cost solution for coastal surveys (Bevan et al. 2016); however the current range and battery life limitations of commercial AUVs limit their use for pelagic monitoring.

Passive Acoustic Monitoring

Static passive acoustic monitoring (PAM) provides an alternative modality for cetacean monitoring; this approach employs acoustic sensors at fixed sites but can provide a nearly continuous record of animal presence at monitored locations (Wiggins and Hildebrand 2007) regardless of time of day or weather. This method relies on underwater detection of species-specific vocalizations; therefore monitored species must be classifiable based on features of their acoustic signals. Passive acoustic monitoring data have been collected in the GOM nearly continuously using fixed seafloor sensors since 2010 (Hildebrand et al. 2015; Hildebrand et al. 2019). The time series from acoustic monitoring sites provides high-resolution temporal coverage; however spatial coverage is limited because sensor locations are fixed, and detection ranges are restricted by the acoustic characteristics of the vocalizations monitored (Frasier et al. 2016; Hildebrand et al. 2015).

PAM tends to result in higher detection rates than visual surveys because they rely on sounds produced during foraging and social behaviors rather than surface sightings. This type of data can provide strong support for habitat modeling efforts (Soldevilla et al. 2011). Because the sensors are generally stationary, they must monitor over long periods (months to years) in order to capture the full range of environmental conditions and variability that visual surveys achieve in part by surveying along transect lines. Despite their stationarity, fixed PAM can monitor across a remarkably wide range of oceanographic conditions due to the dynamic nature of the marine environment (Fig. 25.1).

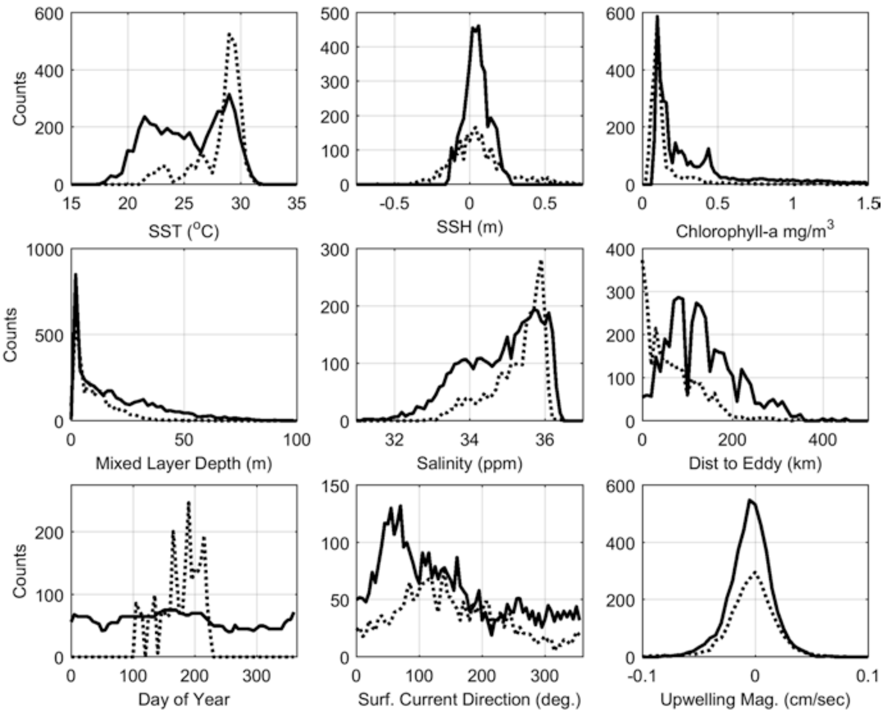

Fig. 25.1 A comparison of environmental parameter distributions observed at static PAM sites (black line) and those traversed by a NOAA visual survey vessel (dashed line). PAM data represents five static sites monitored continuously for 3 years as part of the GOM HARP project. Visual survey data represents five shipboard surveys conducted by NOAA in spring or summer of 2002, 2003, 2009, 2012, and 2014

Mobile passive acoustic sensors can combine some of the advantages of visual surveys (spatial coverage) with the autonomous advantage of PAM (Klinck et al. 2012; Moore et al. 2007; Mellinger et al. 2007). However these sensors come with their own set of challenges that may complicate their use for quantitative density and abundance estimation, including signal distortion and surface noise for near-surface sensor types, variable signal detection probabilities for profiling sensors, self-noise (e.g., electrical noise, onboard pumps, and flow noise), and limited navigational ability in regions with significant currents (Hildebrand et al. 2013). At the time of the DWH event, these systems were not a reliable option for large-scale monitoring, but mobile autonomous PAM may become a viable tool for future monitoring of at-risk regions.

Tagging

Marine mammal tag technology is a rapidly advancing field capable of providing insights to individual animal behaviors, home ranges, and migratory patterns (Jochens et al. 2008). However, insights gained individual animal tracks, and behaviors can be difficult to generalize to a population or species level and can require significant effort for even a limited sample size. Various tag designs exist, each with different strengths. Long-term implanted tags typically have GPS sensors and remain affixed to the animal for many months (Mate et al. 2007). Most long-term tags are not designed to be recovered; therefore data collection is typically limited to what can be transmitted via satellite, such as location of surface intervals. Satellite tagging studies may be particularly useful for understanding the degree to which populations flow in and out of an area of concern, as in the GOM. For instance, tag data showing seasonal migrations could fill in knowledge gaps related to large-scale distribution shifts, seasonal patterns, and migratory corridors (Costa et al. 2010; Baird et al. 2010). Shorter-term tags designed to be retrieved once they separate from the animal can store more information, such as underwater movement (body rotation, foraging lunges, acoustic recordings, and video footage), but must be recovered to acquire the data (Johnson et al. 2009; Calambokidis et al. 2007). Short-term archival tags are useful for obtaining information on behavior (Soldevilla et al. 2017). Low Impact Minimally Percutaneous Electronic Transmitter (LIMPET) tags are medium-duration option capable of supporting a range of sensors (Baird et al. 2010). Suction cups are another common short-term mounting method, typically remaining attached for a few hours to a few days. Beaked whales and dolphins have been successfully tagged with suction cup and LIMPET tags; however tags are most readily applied to large whales.

Other Methods

Satellite imagery has been proposed as a possible tool for marine mammal population monitoring (Fretwell et al. 2014). This strategy may be a viable option for large whales under favorable conditions (low glare, low Beaufort scale); however the resolution of publicly available satellite imagery is currently too low to detect or identify most marine mammal species. Satellite imagery might be a viable option in the future for studying distributions of large whales (Fretwell et al. 2014), depending on image resolution and the development of methods to account for poor detection conditions and other factors influencing detectability.

Genetic studies can also provide estimates of population sizes (Frankham 1996) and identify possible periods of population expansion or contraction (De Bruyn et al. 2009). These methods use biological samples such as tissue or skin to look at genetic diversity and drift. Genetic approaches have been used to estimate past and current population sizes and to quantify the impacts of historic events such as whaling; however sources of uncertainty including mutation rates, reproductive success, and effects of selection at individual loci can lead to low precision in population size estimates when used in isolation (Harris and Allendorf 1989; Alter et al. 2007). This method is most appropriate for studies over longer time scales but may be used to evaluate long-term effects of historic events when earlier data are not available. Genetic information has been used to identify distinct bottlenose dolphin stocks in the GOM (Sellas et al. 2005), allowing impact assessments to be limited to affected stocks. Similar efforts to delineate stocks for oceanic species could help narrow the focus of future damage assessments.

25.2.2 Complementary Monitoring Data Sources

Given the size of the survey areas, and unknown locations of future disasters, it is unlikely that any of these individual monitoring methods alone can cover space and time well enough to produce the data needed for baseline population size estimates or provide the spatiotemporal resolution required for large-scale disaster preparedness. Habitat models capable of predicting marine mammal density distributions as a function of environmental drivers (Redfern et al. 2006) may provide a mechanism for estimating marine mammal exposure to future events. Habitat models have been developed for the GOM based on visual survey data following the DWH oil spill (Roberts et al. 2016) however they do not currently cover all seasons or achieve high enough confidence to fulfill future damage assessment needs. Since no individual method seems capable of fully censusing mobile and migratory populations, the best approach may involve integrating multiple data sources (Fujioka et al. 2014). In particular, visual surveys and passive acoustics may be able to accomplish the task in combination by leveraging the spatial coverage of one and the temporal coverage of the other.

25.3 During a Spill: Megafauna and Response Efforts

There is no evidence that marine mammals avoid oil (Goodale et al. 1981; Geraci 1990; Vander Zanden et al. 2016; Wilkin et al. 2017); therefore it must be assumed that animals present during an oil spill are injured by the event and that response choices including dispersant use, noise, and vessel activity directly affect marine mammals.

25.3.1 Response Activities

Dispersants
Chemical dispersants have been applied at the sea surface in oil spill responses as early as 1967 (Torrey Canyon spill response; Southward and Southward 1978). The DWH response represented the first use of dispersants at depth, where they were applied directly to the oil outflow (Kujawinski et al. 2011). The use of deep dispersants as part of the DWH response has largely been viewed as a success: Approximately 50% of the spilled oil remained at depth (Joye 2015), never reaching the sea surface where it would have increased slick size, required further cleanup actions, and potentially reached coastlines. Managers have indicated that they would use deep dispersant applications in future response efforts (French-McCay

et al. 2018). However, the trade-offs of deep and surface applications of dispersant approach with respect to implications for pelagic marine organism health are largely unknown. The application of dispersants at depth is thought to increase oil residence times in the water column and increase the influence of subsurface currents on oil transport (Testa et al. 2016). In Frasier et al. (2020) we reviewed the sparse literature on dispersant effects on marine mammal health, which relies on surrogate species and cell cultures. There appears to be little consensus on whether dispersants or dispersed oil are more or less toxic to marine organisms than undispersed oil. Dispersing oil in a deep subsurface plume likely increases routes of exposure for many oceanic marine mammals. Indirect impacts of deep dispersant applications via deposition of large amounts of oil on the seafloor are also a concern (Fisher et al. 2016). Deposited oil has the potential to smother benthic communities and negatively affect pelagic food webs with long-term implications for marine mammal populations.

Although the use of dispersants has been considered a success so far, there is not enough data to conclude that dispersant use results in safer conditions for marine mammal populations. In a future spill scenario, the presence and density of deep-diving marine mammals may need to be considered as a risk factor when weighing the trade-offs of applications of dispersants at depth.

Vessels

Vessel activity was very high in the Mississippi Canyon region during the DWH oil spill response and oil slick cleanup effort. Elevated ship noise, echosounders, and underwater communication signals associated with response activities dominated the acoustic soundscape during the response period. Noise associated with seismic surveys and shipping is generally high in the GOM; therefore distinguishing between the response-associated noise and chronic noise impacts may be challenging. Increased ship traffic raises the risk of marine mammals being struck by vessels (Carrillo and Ritter 2010). Anthropogenic noise has been associated with a wide range of injuries to marine mammal species, ranging from disruption of foraging to possible death (Cox et al. 2006; Tyack 2008). Cleanup activities such as skimming and burning increase the potential for entanglement in deployed gear and reduce air quality and the sea surface for air-breathing marine mammals.

Deterrents

Deterrence or "hazing" strategies aimed at discouraging marine mammal presence in oiled areas do not appear to have been used during the DWH oil spill response but have since been proposed as strategies for future events (NOAA 2014). These strategies use sounds from underwater discharges ("seal bombs"), Oikami pipes, or helicopters to herd or move animals out of affected areas and have the potential to reduce direct exposure during a spill. However, these methods constitute illegal harassment outside of an emergency; therefore they should be viewed with extreme caution and require specific authorization (NMFS 2017).

25.4 After a Spill

25.4.1 Damage Assessment

NOAA's natural resource damage assessment (NRDA) process is the primary framework for estimating impacts on marine megafauna following an oil spill. In the DWH case, the injury assessment phase of the NRDA spanned from 2010 to 2015 (Trustees 2016). However the effects on these long-lived species likely play out over a much longer period (Schwacke et al. 2017; Ackleh et al. 2018; Matkin et al. 2008); therefore the full magnitude of the impacts may not be immediately measurable during an NRDA. This leads to a mismatch between the time frame in which damages are assessed (a few years) and the time frame over which the damage may appear (possibly decades).

Models may be necessary to predict the extent of future damage within the time frame of the NRDA. Following the DWH an effort was made to develop life history models to estimate the magnitude of the impacts in terms of "lost cetacean years" (Schwacke et al. 2017) for BSE bottlenose dolphins. These models rely on knowledge of life history traits such as average life span, typical mortality across different age classes, reproductive rates etc., which are difficult to establish for oceanic species (King et al. 2015). Targeted studies to establish these parameters for populations of concern would likely facilitate future damage assessment estimates. Population recovery models may not fully account for cumulative impacts when estimating recovery times (Williams et al. 2016). Even if pre-spill data do exist, some marine mammal populations may not be at their stable or optimal size at the time of an event (e.g., recovering from a prior event or declining due to other impacts), causing models to incorrectly estimate the time to full population recovery. Following the DWH event coordinated efforts began to develop models capable of estimating population-level effects of chronic disturbance (Pirotta et al. 2018) which may be incorporated into future recovery estimation efforts.

As previously discussed, effective short-term damage assessment requires knowledge of the types and numbers of animals impacted by the disaster and a comparison of pre- and post-spill numbers to account for any loss. If habitat models (e.g., Roberts et al. 2016) exist for a region prior to a spill, these could be used to predict the magnitude of exposure based on the location, timing, and oceanographic conditions during the event (Gregr et al. 2013). Surveying or monitoring during the event could be conducted to validate the model predictions. In the case of the DWH, the GOM HARP project (a long-term passive acoustic monitoring effort; Hildebrand et al. 2015) began monitoring 19 days after the beginning of the spill, allowing for high temporal resolution monitoring of the wellhead region. NOAA shipboard oceanic marine mammal visual surveys were conducted during June through August and October through November 2010 (SEFSC 2018). Although these were relatively rapid responses, the initial exposure period was not recorded; therefore some immediate effects may have been missed. Preparedness plans for rapid deployment of monitoring tools following future oil spills could decrease the time lag between event and initial monitoring effort, which could in turn decrease uncertainty around short-term exposure.

25.4.2 Long-Term Monitoring

After a spill, long-term monitoring is necessary to establish trends and assess recovery progress at affected locations. Marine mammal presence varies on fine timescales as animals seek out prey and favorable conditions; follow mobile, ephemeral mesoscale features; and appear to respond to drivers ranging from lunar cycles to human activities (Davis et al. 2002; Simonis et al. 2017; Ellison et al. 2012). The mechanisms that drive oceanic marine mammal spatial distributions and variability are poorly understood, in part because many probable contributing factors such as prey availability and oceanographic conditions at depth are not readily measured on the broad spatial and temporal scales over which monitoring occurs. Indirect drivers such as sea surface conditions, primary productivity, and general ocean conditions, though widely available from satellite data and physical models, typically have only weak explanatory power with respect to oceanic marine mammal occurrence (Forney et al. 2012; Roberts et al. 2016). Unexplained variability in marine mammal distributions complicates interpretation of long-term trends from monitoring data, because short- and long-term population movements and true population size changes are convolved.

Targeted, carefully designed monitoring programs (Taylor et al. 2007; Jewell et al. 2012; Kaschner et al. 2012) are necessary to provide the spatial and temporal coverage required to achieve a level of precision high enough to confidently measure population-level changes on a reasonable time scale (years rather than decades or centuries). Considerations include coverage of the full range of habitats of interest, accounting for possible non-uniform species distributions across the monitored area, surveying across the full range of seasons, and taking measures to reduce inherent uncertainty in parameters such as animal availability for detection, method-specific probability of detection, avoidance or attraction effects, and multipliers used to convert detections into numbers of animals (e.g., cue rates, group size estimates) (Buckland et al. 2007). Although visual surveys are the most common oceanic marine mammal monitoring method, simply increasing the frequency of surveys may not result in more precise population estimates (Jewell et al. 2012). PAM is likely one of the more effective strategies for collecting enough data to resolve long-term trends despite short-term (weeks to months) and inter-annual variability at impacted sites. Where available, identification of impacted stocks can limit the spatial extent of survey effort needed (e.g., BSE bottlenose dolphin stocks in the GOM), but oceanic marine mammal stocks are typically large and poorly defined.

25.4.3 Restoration

Following the DWH oil spill, restoration of large, mobile marine megafauna appeared to be an intractable problem, given the scale of their habitat, the complexity, and length of their life cycles. Direct actions to increase marine mammal populations are not a viable option. However, there appears to be a growing consensus that indirect restoration actions aimed at mitigating the chronic impacts that weaken population resilience (Wright et al. 2011) may support population recovery and reduce harm from possible future events.

We suggest that a potential approach to restoration is addressing the chronic impacts that compromise marine mammal population resilience and reduce their ability to withstand and recover from disasters. Chronic impacts including sublethal stressors can have cumulative effects on survival, reducing reproduction rates, shortening life spans, and increasing sensitivity to disease or unfavorable environmental conditions (Wright et al. 2011). Chronic anthropogenic impacts to marine mammals in the GOM include noise, ship strikes, exposure to pollutants, entanglement, ingestion of debris, bycatch, and reduced prey quality and quantity (see Frasier et al. 2020). In the aftermath of an oil spill, restoration efforts could conceivably consist of identifying, quantifying, and mitigating these threats. For instance, if bycatch is considered a significant stressor in a region of concern, then a restoration strategy might include quantifying the extent of the bycatch issue across fisheries via an observer program, identifying high risk cases, and implementing mitigation strategies (equipment, regulation). Similarly if noise exposure was a concern, then areas of highest exposure could be identified by reviewing species distributions in relation to major shipping corridors and seismic surveys and taking actions to reduce vessel noise (via vessel quieting or speed limits) and move shipping lanes or timing seismic surveys to occur during windows of low expected densities in affected areas. Such efforts to reduce chronic impacts could increase population resilience and indirectly support recovery in the event of future oil spills.

25.5 Putting It into Practice: Alternate Spill Scenarios

Below, we step through three alternate oil spill scenarios to examine possible differences between the impacts of the hypothetical case and the DWH oil spill on oceanic marine mammals. Differences in species exposure are discussed, and implications of these differences for response and damage assessment processes are considered. Given the potential for GOM-wide population connectivity of oceanic marine mammal populations, coupled with how little is known regarding the processes that drive changes in GOM marine mammal densities and distributions, long-term monitoring needs would likely be comparable under all three scenarios, therefore recommendations are only detailed under Scenario 1. Restoration efforts would likely also be comparable; however, we highlight cases where certain species might benefit from targeted management actions.

25.5.1 Scenario 1

In this scenario, a hypothetical spill of similar origin, magnitude, and duration to the DWH event would have occurred during the fall of 2010 (beginning September 1), instead of during spring. Oil release from the well would have occurred over a 90-day period from September through November 2010.

25.5.1.1 Impacts and Damage Assessment

Based on seasonal trends observed in long-term monitoring data collected during the GOM HARP project, the expected presence of Risso's dolphins, mid-frequency (presumed *Stenella* species) dolphins, and *Kogia* spp. would have been lower in the fall scenario than during the spring (Fig. 25.2); therefore potential exposure of these species might have been lower. It is not known where these populations tend to go during winter months, only that occurrence appears to decrease at northern GOM HARP monitoring locations along the continental slope. Some populations may migrate into deeper waters or into the southern GOM during winter months. Sperm whale and low-frequency dolphin (presumed to be primarily short-finned pilot whale) presence are typically somewhat higher in the PAM record during fall at northern monitoring locations; therefore exposure might have been higher for these species. Gervais' beaked whale presence is not strongly seasonal at this site; therefore expected exposure under this scenario would be similar to the spring event. Cuvier's beaked whales are typically only detected in winter at this location; therefore expected exposure would be low but increasing at the very end of the oil spill period.

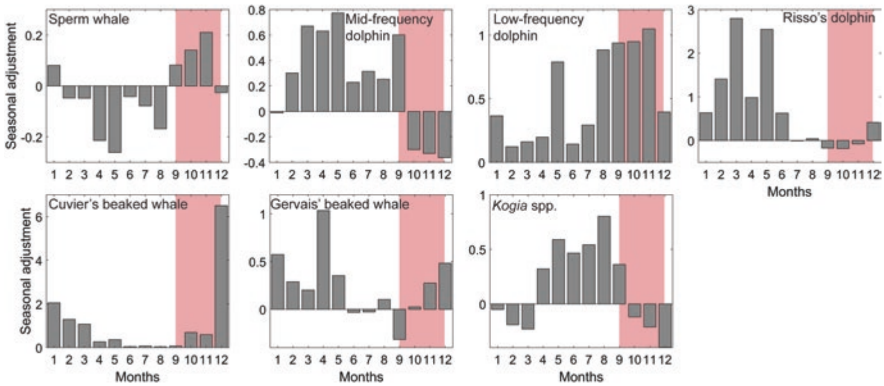

Fig. 25.2 Seasonal patterns in marine mammal presence at a passive acoustic monitoring site in Mississippi Canyon, located approximately 10 km from the DWH wellhead. The vertical axis indicates the factor by which seasonal presence varies relative to mean presence. Higher values indicate stronger seasonality. Pink shading indicates the months of the hypothetical oil spill examined in Scenario 1

Similarly to the DWH case, there would not have been enough survey data to estimate pre-spill population sizes or to develop models capable of estimating the magnitude of marine mammal exposure. Moreover, between 1992 and 2010, NOAA visual surveys were conducted no later than August; therefore there would have been no marine mammal observations for fall months in pre-spill data (Waring et al. 2009). *Stenella* dolphins, particularly pantropical spotted dolphins (*Stenella longirostris*), are the most abundant oceanic marine mammals in the northern GOM based on summer visual survey data (Waring et al. 2015). If *Stenella* dolphins do shift away from the Mississippi Canyon area in fall and winter as suggested by the PAM data, then the overall number of animals directly exposed to oil, dispersants, and response activities would have been significantly lower. The northern GOM appears to be a nursing ground for sperm whales (Jochens et al. 2008); therefore higher exposure might have had larger effects on the population as a whole. A focused effort on estimating sperm whale life history parameters to estimate lost sperm whale years would have been particularly useful under this scenario for quantifying impacts with potential long-lasting, population-level implications.

25.5.1.2 Long-Term Monitoring

Oceanic GOM marine mammal populations are typically classified by NOAA as single oceanic stocks, because no information exists to support more fine-scale structure. The degree to which populations flow between US waters in the north and Mexican waters in the south is unknown, but exchange between the northern and southern GOM is likely. A long-term monitoring strategy for oceanic GOM marine mammals likely needs to cover both US and Mexican waters, monitor year-round, and achieve high enough precision to detect impacts from large-scale events and/or restoration activities. A viable strategy involves the use of static PAM at a combination of permanent and temporary sites in the entire GOM. Temporary sites would be moved periodically across a grid of short-term (<1 year) monitoring locations to provide coverage of the full range of habitats and environmental conditions in the GOM, while long-term sites would be monitored continuously over many years as reference points. Using this type of dataset, habitat models could be produced to interpolate marine mammal density distributions across the entire region such that changes and effects could be evaluated on a gulf-wide scale. Further, impacts of future events could be inferred from modeled density surfaces. Model precision would be dictated by the number of sensors and monitoring locations occupied and the duration of the effort.

25.5.1.3 Restoration

Mississippi Canyon appears to be a hot spot of biological activity in the northern GOM; therefore restoration actions to support biodiversity might be particularly appropriate. The Mississippi River plays a dominant role in shaping offshore northern GOM ecosystems, by bringing in nutrients that fuel high productivity. Although these nutrients contribute to the creation of a seasonal hypoxic zone on the continental shelf, they also likely form the foundation of the rich food web that appears to sustain high marine mammal presence in the Mississippi Canyon region. One set of management actions to support marine recovery in the region might include minimizing upstream contaminant inputs from agricultural activities. Nitrate from fertilizers is the most abundant and problematic (Rabalais et al. 1996) contaminant found in these riverine inputs, along with pesticides and herbicides (Goolsby and Pereira 1996; Pereira and Hostettler 1993). Recent research also indicates an increase in Mississippi River salinity (Kaushal et al. 2018) which could have impacts on the offshore food web. Pollutants are also derived from oil and gas extraction in the region (Neff 1990; Neff et al. 2011a, b). A second avenue for restoration would include limiting and tightly regulating the activity of increasingly deep drilling rigs which may increase the risks of impacts of future incidents on recovering populations.

25.5.2 Scenario 2

In this scenario the origin of the hypothetical spill would have been at a location along the west Florida shelf (27.0° N, 85.168° W) with oil escaping over a period of 90 days beginning April 20, 2010, and ending July 19, 2010.

25.5.2.1 Impacts and Damage Assessment

This scenario would likely have had greater impacts on beaked whales, which have been recorded at very high densities at a west Florida shelf site relative to other GOM monitoring locations (Hildebrand et al. 2015). However, the PAM site nearest this hypothetical spill location for the GOM HARP project was located further south along the west Florida shelf, and the degree of generalizability of beaked whale habitat preferences based on these observations remains unclear. A PAM study focused on the Mississippi Canyon region (Sidorovskaia et al. 2016) suggested that neighboring sites (50 nm apart) could have quite different beaked whale species compositions. Patchiness in beaked whale distributions may be related to their deep-dive capabilities which could enable them to interact with and take advantage of seafloor features which are not available to shallow-diving species. Applications of deep dispersants might have an outsized impact on beaked whales at this location by increasing oil deposition in their benthic foraging grounds. Beaked whales are also sensitive to anthropogenic noise (particularly echosounders) and might have been repelled or stranded in response to high-frequency anthropogenic noise (communications and echosounders) associated with the response (Weilgart 2007). Densities of Risso's dolphin are also higher in the region but tend to peak in the fall; therefore Risso's might avoid the majority of direct exposure under this scenario.

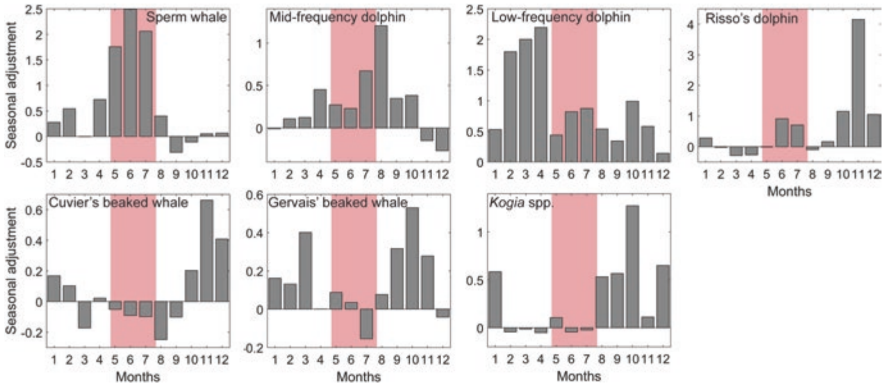

Fig. 25.3 Seasonal patterns in marine mammal presence at a passive acoustic monitoring site on the west Florida shelf. The vertical axis indicates the factor by which seasonal presence varies relative to mean presence. Higher values indicate stronger seasonality. Pink shading indicates the months of the hypothetical oil spill examined in Scenario 2

Direct impacts on female and juvenile GOM sperm whales might also have been reduced because overall sperm whale densities are likely to be lower in this region relative to Mississippi Canyon; however migratory males moving through the area in summer months might have been more strongly affected (Fig. 25.3).

One population of particular concern under this spill scenario is the very small GOM Bryde's whale population (proposed to be listed as endangered; NMFS 2015). GOM Bryde's whale core habitat is located just north of the origin of this hypothetical oil spill. This population appears to be an endemic GOM subspecies and consists of an estimated 33 animals (Hayes et al. 2018). Although the reasons behind its current small population size are largely unknown, Soldevilla et al. (2017) proposed based on a tagged animal that this species may be particularly vulnerable to ship strikes. The tagged individual showed a repetitive behavior of resting at night at the sea surface and foraging near or at the seafloor during the day. These two behaviors, if they are characteristic of the population (subsequent unpublished data suggests that they are), might put the species at high risk of exposure to surface and deposited oil, as well as increased risk being struck by response vessels (Soldevilla et al. 2017). Given the small size of this population, the potential impacts from an oil spill overlapping its core habitat could threaten the long-term survival of GOM Bryde's whales.

As in other scenarios, there would have been limited pre-spill visual survey data for this region of the GOM. Entrainment of oil into the Loop Current and possibly the Gulf Stream would open up the possibility of oil exposure to an even greater number of marine mammal species in the Western Atlantic where marine mammal diversity and densities are fairly high. Marine mammal survey effort in the NE Atlantic (US EEZ) has been more extensive than in the GOM, but habitat models were not available at the time. They have been published since using pre-spill data (Roberts et al. 2016) but lack certainty for many species. Given that beaked whales might have been particularly affected under this scenario, the ability to quantify impacts to beaked whales in terms of “lost beaked whale years” would be an important tool in estimating the extent of the damage in this scenario. These are particularly cryptic, difficult animals to study; therefore it would be very difficult to establish accurate life history parameters for damage assessment purposes.

25.5.2.2 Restoration

Key restoration actions for Bryde’s whales would likely involve vessel restrictions in their core habitat. Restricting vessel speeds and prohibiting nighttime transits through the area would likely be an effective restoration strategy (Carrillo and Ritter 2010). Beaked whale-oriented restoration efforts might include taking action to minimize acoustic disturbance from echosounders, fish-finders, and sonar. Preliminary research suggests that male sperm whales may transit through this region, but it is unclear where they are coming from. Undertaking tagging efforts to better understand the connectivity between the apparently resident northern GOM population of sperm whales (primarily females and juveniles) with mature males observed in the broader Atlantic might help inform management actions to support recovery of this population. Sperm whales, particularly large males, were highly targeted by the whaling industry; therefore it cannot be assumed that the pre-spill GOM sperm whale numbers reflected a healthy or stable population size.

25.5.3 Scenario 3

In this scenario, an oil spill of similar magnitude, depth, and duration to the DWH event would have occurred in the northwestern GOM (26.66° N, 93.19° W), from April 20 to July 19, 2010.

25.5.3.1 Impacts and Damage Assessment

The oceanography of the northwestern GOM differs significantly from the eastern GOM. Instead of the clearly defined continental slope regions typical of the northeastern GOM, the seafloor in the northwestern GOM gradually deepens from 40 to 2000 meters deep over hundreds of kilometers across a complex network of salt domes and other geological features. Oil and gas infrastructure is more prevalent in the western half of the northern GOM (BOEM 2018), and the Port of Houston, one of the busiest ports in the USA, is associated with high vessel traffic through the region (BOEM 2015). Visual survey and PAM data indicate that overall marine mammal occurrence may be lower in this region, but marine mammal survey effort has also been lower.

The relative influence of differences in habitat, infrastructure, human activity, and marine mammal survey effort on perceived lower marine mammal occurrence

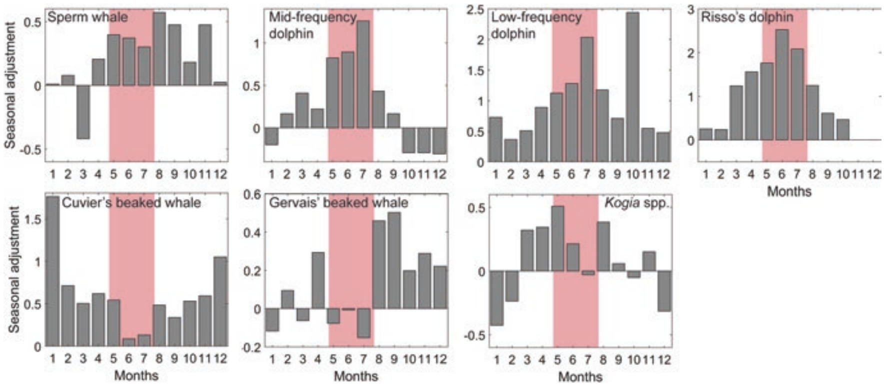

Fig. 25.4 Seasonal patterns in marine mammal presence at a passive acoustic monitoring site in Green Canyon, the western-most year-round monitoring location for toothed whales in the GOM. The vertical axis indicates the factor by which seasonal presence varies relative to mean presence. Higher values indicate stronger seasonality. Pink shading indicates the months of the hypothetical oil spill examined in Scenario 3

in the western GOM is unknown. The westernmost sensor deployed by the GOM HARP project was located near Green Canyon (27.56° N, 91.17° W); however this location was selected as an un-oiled comparison with Mississippi Canyon and does not necessarily represent average western GOM conditions. PAM data from that location indicated somewhat lower occurrence of marine mammals relative to the Mississippi Canyon site. Sperm whales, *Stenella* dolphins, pilot whales, *Kogia* spp., and Risso's dolphins would likely have been directly exposed to oil and response activities (Fig. 25.4). Insufficient monitoring data are available to estimate the extent of the potential exposure. Oil spills of various sizes are not uncommon in the western GOM; therefore it might be particularly difficult to distinguish the effect of one event from impacts from other sources.

25.5.3.2 Restoration

Given the comparatively high risk of future oil spills in the western GOM and the challenges of measuring new impacts in a highly exploited context, a proportional increase in marine mammal monitoring effort relative to the western GOM may be appropriate to establish robust baselines and fill in extensive knowledge gaps. However current marine mammal population sizes and distributions in the western GOM are unlikely to represent historic extents given the clear human footprint on the region. For example, data suggest that the GOM Bryde's whale population's home range, now restricted to the eastern GOM, may have previously extended into the western GOM (Soldevilla et al. 2017).

A particularly common source of disturbance in the western GOM are seismic surveys, in which explosive releases of air are used to produce high amplitude sounds waves to map the seafloor and search for oil deposits. Noise generated by these surveys dominates the low-frequency soundscape in the GOM. Research into the effects of seismic surveys on marine mammals is ongoing; however studies have reported a range of effects including no perceived response, decreased foraging, and displacement (Mate et al. 1994; Miller et al. 2009; Stone and Tasker 2006). Determining seasonal trends in marine mammal abundance and distributions in the GOM might reveal strategies for minimizing spatiotemporal overlap between seismic surveys and critical habitat. Measures taken to quiet container ships could also significantly reduce noise-related stressors on GOM marine mammals (Malakoff 2010).

25.6 Conclusions

Direct measurement of impacts will become more difficult as spills get deeper, further offshore, and in less accessible locations. Robust baselines are needed to measure impacts to oceanic megafauna. A multi-pronged approach to monitoring utilizing visual surveys and passive acoustic monitoring is likely the best method for quantifying injury to and measuring recovery of oceanic marine mammal populations. Marine mammal species are wide-ranging, with long, complex, poorly understood life cycles. Direct restoration of marine mammal populations is unlikely; however management actions aimed at limiting chronic stressors such as ship strikes, pollution, noise, bycatch, entanglement, or actions taken to restore and protect oceanic food webs would likely increase marine mammal population resilience and improve long-term outcomes.

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