Cetacean strandings in the US Pacific Northwest – changes in species and seasonal trends reveal potential linkages to climatic variability.

**Abstract**

**Introduction**

Over the past several decades, marine mammal stranding records have been used as an indicator of ocean and cetacean health (Gulland and Hall 2007; Bogomolni et al. 2010; Bossart 2011). Examining where, when, and how often marine mammals strand can provide insight into ecological behaviors, reproductive success, (Norman et al. 2004; Pikesley et al. 2011), the impacts of human activities (Warlick et al. 2018), and species distributions (Evans et al. 2005; MacLeod et al. 2005). Cetaceans are strongly influenced by changes in the marine environment via diverse and dynamic mechanisms, including changes in sea surface temperature, winds, or large-scale oceanographic oscillations that can shift the balance of nutrients and prey species abundance and distribution. These small changes are often amplified up through the food web or exacerbated by increased pollutants or algal blooms, ultimately having noticeable effects on top predators. Examining changes in strandings over time provides important information for monitoring cetacean populations, tracking distribution or abundance trends, and examining emerging health or disease conditions, particularly in light of recent documented changes in oceanographic conditions on both local and regional scales (Pierce et al. 2007; Truchon et al. 2013; Sprogis et al. 2017).

As top predators of their respective food webs, marine mammals may be especially sensitive to these changes (Moore 2008; Evans et al. 2010). Recent studies have found correlations between long-term stranding trends and several indices of climatic variability, demonstrating how strandings may be used as bio-indicators of prevailing environmental conditions. Evans et al. (2005) found that cetacean strandings in southeast Australia exhibited a periodicity coincident with regional wind patterns. Factors such as sea ice and the North Atlantic Oscillation have been found to correlate with strandings and mortality of certain pinniped and cetacean species in Gulf of St. Lawrence, Canada (Johnston et al. 2012; Soulen et al 2013; Truchon et al. 2013). Keledjian and Mesnick (2013) found that El Niño conditions corresponded with increased California sea lion (*Zalophus californianus*) strandings and fisheries interactions along the California coast. Berini et al. (2015) found that pygmy whale strandings in the southeast U.S. were correlated with sea surface temperatures, wind, and other oceanographic indicators. Gray whale mother-calf pair counts in their summer feeding grounds have been linked to sea ice conditions during the previous feeding season, while distribution of mother-calf pairs in some calving areas in Mexico are influenced by ENSO-related variability (Salvadeo et al. 2015). Increases in harbor porpoise (*Phocoena phocoena*) strandings over the last 12 years in the Pacific Northwest have been posited to be partially due to changes in their prey’s abundance and distribution (Greene et al. 2015; Jefferson et al. 2016). Because responses to environmental change are complex, variable, species-dependent, and often poorly understood, oceanographic features should be studied over varying scales (local and continental), ecotypes, and species (Laidre et al. 2008; Evans and Bjørge 2013; Truchon et al. 2013).

Environmental changes are acknowledged to be occurring on a global scale (IPCC 2014), though the local realization of these changes is patchy and difficult to predict due to varying degrees of ecosystem complexity and spatial heterogeneity (Moore 2008; Evans and Bjørge 2013; Jacox et al. 2016). The Pacific Northwest, or as it is sometimes referred to as Cascadia, is a loosely defined region region that includes coastal, inland, and estuarine waters extending from northern California through British Columbia, including the Salish Sea and the mouth of the Columbia River (Coates 2002). It is an ecosystem that contains important feeding and breeding habitat for numerous marine mammal species in the eastern north Pacific and beyond, including gray (*Eschrichtius robustus*) and humpback (*Megaptera novaeangliae*) whales, endangered southern resident killer whales (*Orcinus orca*), and numerous smaller delphinid and phocoenid species. In recent years, the California Current ecosystem experienced an “extreme marine heat wave” that became known as The Blob, where above average water temperatures persisted from 2014-2016, causing a wide range of changes, including shifts in primary production, fish spawning, larval abundance, and marine wildlife health (Bond et al. 2015; DiLorenzo and Mantua 2016; Auth et al. 2017). These conditions along the U.S. West Coast along with increasing ocean acidification and harmful algal blooms in the Pacific Northwest (Mote and Salathé 2010; Mauger et al. 2015) can negatively impact marine mammal population dynamics through changes in the abundance and distribution of their prey, among other effects.

We aimed to investigate the possible connection between oceanographic variability and the health and mortality of marine mammals throughout a large ecosystem by evaluating stranding records collected consistently and systematically from 2003-2017. Specifically, the goals of this study were to: compare recent cetacean stranding numbers and patterns in the Pacific Northwest to those previously reported for 1930-2002 (Norman et al. 2004); use strandings as a proxy to detect changing prevalence of cetacean species within certain geographic areas; and to investigate possible relationships between spatiotemporal variation in cetacean strandings and oceanographic conditions in the Pacific Northwest. This information is useful for both researchers and stranding responders studying the baseline and future health and status of these cetacean populations in a multi-use ecosystem subject to human impacts and exhibiting signs of degradation and environmental change.

It was expected that strandings of humpback whales and harbor porpoises, for example, might be higher than previously reported for the region (Norman et al. 2004) due to recent anomalous ocean conditions and/or changes in prey availability. We hypothesized that oceanographic variables such as sea surface temperature anomalies, upwelling, large-scale oceanographic processes (e.g., El Niño/Southern Oscillation [ENSO]/Pacific Decadal Oscillation [PDO]), harmful algal blooms as well as changes in prey availability, would be associated with alterations in strandings of specific species depending on how they use the Pacific Northwest marine ecosystem (year-round residents versus migratory and breeding versus feeding habitat) (*e.g.,* Truchon et al. 2013).

**Methods**

Stranding data and characterization

We compiled all available records of cetacean strandings (2003-2017) that are maintained by the National Oceanic and Atmospheric Administration’s (NOAA’s) National Marine Fisheries Service (NMFS) and its stranding response network members in Oregon and Washington. Completed stranding reports are typically submitted to NMFS’ national stranding database by network members each year and include data such as field identification number, observation date, stranding location, and when determinable, age class, sex, status (dead or alive), species, evidence of injury or human interaction, and postmortem condition. Some reports, including photos, are received from the public through various media outlets (phone calls, texts, or emails). Reports containing ambiguous species identification, regardless of source, were included in one of several ‘Unknown’ categories based on the level of information known. Entangled live cetaceans or strandings attributed directly to human activity such as ship strikes were excluded.

Records were aggregated by year, season, sex, and stranding location. Seasons were defined as Spring: March-May; Summer: June-August; Fall: September-November; Winter: December-February. Similar to Warlick et al. (20018), three stranding location regions were analyzed because stranding response, logistics, and species’ presence differ among these areas – Oregon, outer Washington coast, and inland Washington waters (inland of the mouth of the Strait of Juan de Fuca).

Environmental data

Environmental data were obtained from various NOAA monitoring programs in partnership with other agencies and organizations that are aggregated under the California section of the Integrated Ecosystem Assessment (IEA) project (https://www.integratedecosystemassessment.noaa.gov/regions/california-current-region/indicators/climate-and-ocean-drivers.html), unless otherwise noted. Parameters such as sea surface temperature anomalies, harmful algal blooms, upwelling indices, zooplankton biomass, and oceanographic oscillations (Murase et al. 2002; Cotté and Simard 2003; Flewelling et al. 2005; Hemery et al. 2008; Evans et al. 2010; Fire et al. 2010; Truchon et al. 2013) were extracted from the California Current Integrated Ecosystem Assessment project website. The variable for large-scale oceanographic events such as NOI represented the index of the previous winter (NOIwt-1). We selected the final predictors (HAB, SST, UI, MW, MEI, and MEIw–1).

*Local environmental conditions*

~~Annual HAB events are recorded with the Harmful Algae Information System, a HAB database established within the "International Oceanographic Data and Information Exchange" (IODE) of the "Intergovernmental Oceanographic Commission" (IOC) of UNESCO, and in cooperation with several scientific global organizations, including the North Pacific Marine Science Organization (PICES) and others (http://haedat.iode.org/index.php).~~ Sea surface temperature (SST) anomalies were calculated by subtracting a given month SST value (39ºN) from a long-term (since 1981) mean SST in that month (*e.g.*, mean of all Januaries 1981-2017 minus January 2005). Monthly upwelling (from buoy at 39 ºN and 125 ºW) was included as a model covariate because seasonal upwelling in the California Current greatly impacts primary production and fishery production. Meridional winds (MW) at 39ºN, those occurring along the local meridian (i.e., northerly-southerly direction) were also included as an environmental covariate. The annual number of HAB events (as documented by the Harmful Algae Information System) were documented and compared to the number of annual strandings that occurred in the region where the HAB occurred.

*Large-scale oceanographic oscillations*

Parameters used to assess the effect of large-scale, climatic factors on strandings included: (1) Multivariate ENSO index (MEI) index of the current year, (2) Northern Oscillation Index (NOI), and (3) Pacific Decadal Oscillation (PDO), all of which were obtained from the California Current IEA at the monthly level. The MEI is a point index that best describes ENSO events since it couples six meteorological parameters that are measured over tropical portions of the Pacific Ocean (Wolter and Timlin 1993, 1998). Large positive MEI values indicate the occurrence of El Niño conditions, while large negative MEI values indicate La Niña conditions. The NOI is an index of mid-latitude climate fluctuations that exhibits a relationship with marine ecosystems and is dominated by interannual variations associated with El Niño and La Niña events (Schwing et al. 2002). The PDO represents a recurring, long-lived El Niño-like pattern of climate variability (Mantua and Hare 2002) with historical records strongly suggesting an association with salmon production (Beamish et al. 1999; Hare et al. 1999) and zooplankton production in the eastern North Pacific (Francis et al. 1998). Oceanographic indices were examined in real-time and with one, three, and six-month lags.

Statistical analysis

To determine whether the number of cetacean strandings was significantly different across categorical variables such as sex, species, season, or location, we used pairwise Kruskal-Wallis Nemenyi tests (`posthoc.kruskal.nemenyi.test` function in R) (R Development Core Team 2009) sex, and species as independent variables and the number of stranding reports as the dependent variable. We used the same approach to ascertain whether mean annual strandings in the current study were different from those previously reported (Norman et al. 2004). The species with the highest number of strandings over the study period (harbor porpoise) was analyzed separately. Differences were considered statistically significant at p<0.05. Stranding hotspot maps were generated with a kernel density estimation (Gatrell et al., 1996) with three bins (`geom\_density2d` function in the ggplot2 R package).

To examine the relationship between the number of strandings and environmental parameters, we again used negative binomial GLM regressions. Because many of the oceanographic variables are inter-related, we tested for collinearity between variables using a Pearson’s correlation coefficient. Due to having numerous covariates, we used two automated model selection functions (`regsubsets` and `stepAIC` in the leaps and MASS R packages, respectively) and then selected the final, most parsimonious model by minimizing the Akaike’s Information Criterion (AIC) in conjunction with biological relevance and the absence of collinearity. Deviance goodness-of-fit tests were conducted to examine overall model significance using the `pchisq` function. We used negative binomial general linear model (GLM) regressions for total annual stranding reports against year (`glm.nb` function in the MASS R package). Negative binomial GLM regressions were used to account for overdispersion. Regression coefficients reported using this technique were back transformed.

**Results**

**Discussion**

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