Northern Elephant Seals and Ocean Waves

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Introduction

Variability of physical parameters in ocean systems, such as temperature and salinity, can elicit responses from marine predators (Kuhn et al. 2009). One variable so far uninvestigated is sea state, which is the condition of the ocean surface as influenced by wind waves and swell. We are interested in investigating the effects storms have on the behavior and mortality of pelagic, air-breathing animals. Other marine species may have the luxury to remain below wave base as the intensity of sea state increases, however some species, such as the Northern Elephant Seal (*Mirounga angustirostris*), must return to the surface and cope with potentially challenging sea states.

The Northern Elephant Seal is a far migrating pinniped species, breeding in California and Northwest Mexico and foraging out to the Northeast Pacific for time periods lasting multiple months. During this migration, the seals dive continuously, spending roughly 90% of their time submerged (Le Boeuf et al. 1996). Juvenile females were found to spend an average of 15.2 minutes diving to an average depth of 373.0 m and spent an average of 2.0 minutes at the surface. Our study area covers Northern Elephant seals in the Northeast Pacific for a two month period, March-April 2011.

Few studies have sought to link behavioral data and environmental stimuli (Hakoyama et al. 1994, Crocker et al. 2006, Simmons et al. 2007), however none have addressed sea wave height. Though the effects on movement and mortality on various species have been observed after a storm's passing, effects on animal behavior during a storm is largely unknown (Miller et al. 2010). Experimental studies artificially increasing an elephant seal's drag have found that the post dive interval (PDI) at the surface is sensitive to an increased cost of transport (Maresh et al. 2014). Rough seas may have sublethal implications as well, by allocating energy and time away from foraging, leading to poorer body condition.

Storms are predicted to change in frequency and intensity as humans continue to influence Earth's climate (Nobuhito et al. 2010 and Young et al. 2011). If such storms are a stressor for these animals, understanding their impacts could be an important component in future management decisions under the Marine Mammal Protection Act (MMPA).

We plan to use sea state models and animal tag data to understand how these animals adapt to challenging ocean conditions. We expect the PDI will increase with increased wave height.

Methods

Elephant seal tracking data was obtained from the Costa Lab at University of California Santa Cruz. Elephant seals were instrumented in February 2011 at the Año Nuevo State Reserve, California, with satellite platform transmitter terminals (PTTs) and Time-Depth Recorders (TDR) or Sea Mammal Research Unit Conductivity-Temperature-Depth Satellite Relay Data Loggers (SMRU CTDSRDL) Sea Mammal Research Unit, St. Andrews, UK (Block et al. 2011). The data came preprocessed through a state-space model (SSM) that corrected for locational error in the Argos system and calculated dive statistics.

Each record represents a dive bout with a depth greater than 15 m. Coarse-scale behaviors were assigned to each record by dive type: transit, drift, forage, and benthic. The dataset was then processed to remove null values for location and dive statistics. For this analysis, we chose to only examine records classified as the 'transit' dive type from March and April 2011 (Fig 3). Dives with post dive intervals (PDI) greater than 10 min were removed from the dataset as defined in *Diving behavior of juvenile northern elephant seals* (LeBoeuf et al. 1996). With PDI values greater than 10 minutes removed, our dataset included 16,921 individual points. The next step was to remove data points that fell outside of our ocean wave dataset using ESRI's ArcMap 10.3. From that dataset we randomly sampled 1,000 individual point locations stratified by month.

We obtained Significant Wave Height (SWH) data from the European Centre for Medium-Range Weather Forecasts (ECMWF) European Reanalysis (ERA)-Interim dataset (Dee et al. 2011). ERA-Interim wave data is interpolated from ENVISAT and JASON satellite observations. The wave data was downloaded for our time frame (March-April 2011) in NetCDF form. Once obtained, we imported our NetCDF data into ArcMap using the "Make NetCDF raster layer" tool.

With our data as a single raster layer, the next step was to export each time slice from our raster layer into a single raster, which in our case was in 6-hour intervals. The Export NetCDF Time Slice tool was used, with only a slight script modification so our individual raster files could be used by the Marine Geospatial Ecology Tools (MGET) toolbox. We utilized the "interpolate time series of rasters at points" tool, which adds the SWH value to the seal point it is associated with.

The dataset was statistically tested in Geoda by performing Ordinary Least Squares (OLS) regressions and a spatial error regression. A weights matrix using a distance threshold of 150,000 m was used. A geographically weighted regression (GWR) was performed using GWR4. A fixed gaussian kernel type and the 'golden section search' bandwidth selection method was used to produce the GWR model.

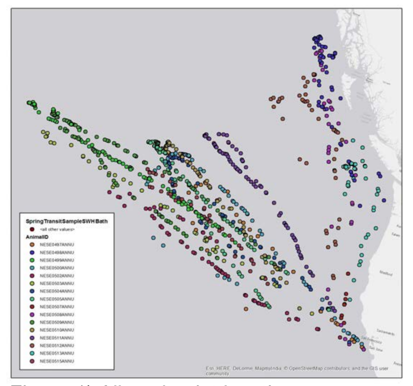
Figure 1) All seal point locations

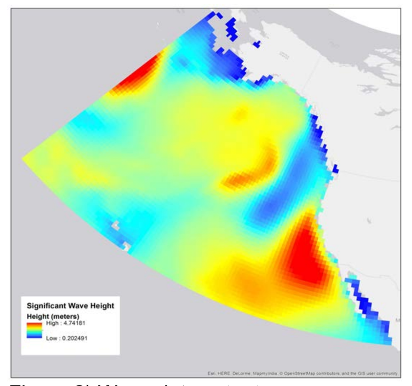
Figure 2) Wave data extent

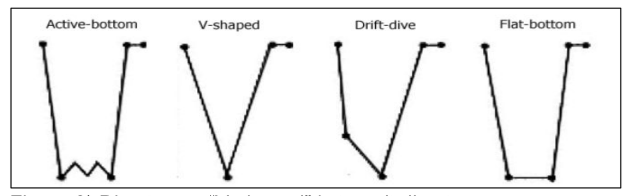

Figure 3) Dive types, "V-shaped" is transit dive type

Data

Model	R-Squared	AIC	Significant Predictors
OLS 1	0.071138	9532.53	Dive Duration, Water Depth, Ascent Rate, Temperature At Surface
OLS 2	0.061401	9534.96	Dive Duration, Water Depth, Ascent Rate
Spatial Error	0.098291	9504.28	Dive Duration, Water Depth, Ascent Rate

Figure 4) Each model, the R-squared value, the Akaike information criterion value, and the independent variables used in each respective model

	Multicollinearity Condition Number	Jarque-Bera		Breusch-Pagan		Likelihood Ratio	
Model	Value	Value	Prob	Value	Prob	Value	Prob
OLS 1	89.049527	17492.0559	0.00000	169.1617	0.00000	N/A	N/A
OLS 2	28.33087	17882.5905	0.00000	548.4122	0.00000	N/A	N/A
Spatial Error	N/A	N/A	N/A	174.0393	0.00000	30.6755	0.00000

Figure 5) Each model, the multicollinearity condition number, Jarque-Bera (value, probability), Breusch-Pagan (value, probability), Likelihood Ratio (value, probability)

	OLS 1		OLS 2		Spatial Error	
Variable	Coefficient	Probability	Coefficient	Probability	Coefficient	Probability
CONSTANT	38.18088	0.07529	70.74096	0.00000	68.08867	0.00000
Dive Duration (s)	0.02176471	0.02844	0.01221669	0.00025	0.01210535	0.00027
Ascent Rate (m/s)	13.51865	0.04040	15.13901	0.00040	14.12944	0.00093
Water Depth (m)	0.005274843	0.00001	0.00585494	0.00000	0.00540284	0.00086
Temperature At Surface (°C)	-1.656401	0.01996	-1.039696	0.08569	-0.4652614	0.59902
Significant Wave Height (m)	-0.8746712	0.31274	-0.6545657	0.44702	-0.3947258	0.64635
Max Dive Depth (m)	0.01824272	0.22745	N/A	N/A	N/A	N/A
Bottom Time (s)	-0.01688741	0.07353	N/A	N/A	N/A	N/A
Descent Rate (s)	5.021862	0.31913	N/A	N/A	N/A	N/A
Temperature At Bottom (°C)	4.275083	0.05387	N/A	N/A	N/A	N/A
LAMBDA	N/A	N/A	N/A	N/A	0.4423573	0.00000

Figure 6) Variables used, the Ordinary Least Squares 1 (coefficient, probability), the Ordinary Least Squares 2 (coefficient, probability), Spatial Error (coefficient, probability)

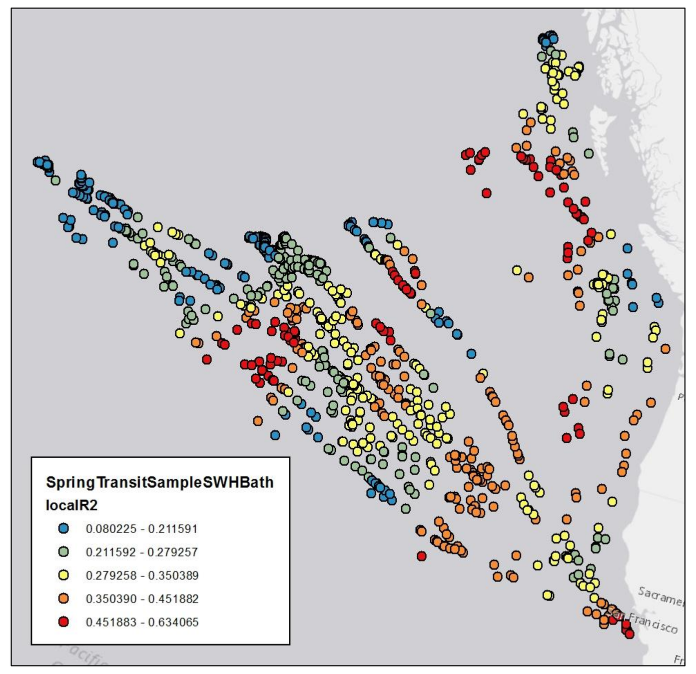

Figure 7) The Geographically Weighted Regression (GWR) showing local R-Squared values for each seal point

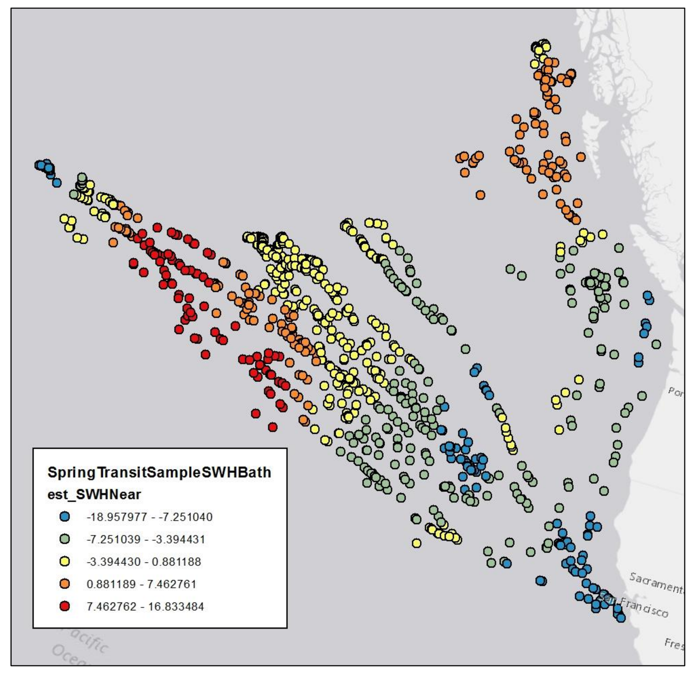

Figure 8) The GWR showing the coefficient values for each seal point

Results

- OLS 1 used all the chosen variables and produced an R-squared of 0.071138 (Figure 4). A multicollinearity condition number of 89.049527 indicated that collinear variables were influencing the result (Figure 5).
- OLS 2 produced an R-squared of 0.061401, with dive duration, depth, and ascent rate as significant predictors (Figure 4). The multicollinearity condition number was 28.33087 (Figure 5).
- The spatial error produced an R-squared of 0.098291 (Figure 4). Lambda significantly accounted for spatial autocorrelation, however the Likelihood Ratio Test was also significant (Figure 5).
- The Jarque-Bera test on the normality of errors was significant for both OLS models (Figure 5). The Breusch-Pagan test for Heteroskedasticity was significant for all three models.
- Significant wave height was not a significant predictor of the post dive interval time in any model (Figure 6).
- The GWR indicated spatial nonstationarity in the relationship between significant wave height and the post dive interval (Figure 7,8).

Discussion

- This analysis found no significant, global relationship between northern elephant seals' post dive interval and significant wave height.
- Nonstationarity in the relationship between wave height and the post dive interval indicates the strong influence of spatial effects.
- PDI may not be the correct dependent variable to assess the effect of wave height on elephant seals. Other behavioral statistics could demonstrate a significant response.
- There may be missing variables in our analysis, such as day/night time.
- We looked at transit type dives exclusively, further investigations could consider other dive types.
- Extended Surface Interval - is this a separate behavior?
- Elephant seals could already be biologically adapted and show no change in behavior during rough ocean conditions.
- This analysis looks at population level response. Variation among individuals may mask an individual's response to increased wave height.
- Prior studies have shown high variability among individual diving behavior (Robinson et al. 2012).
- The individual variation makes spatial analysis a challenge.
  - Seals are not randomly distributed throughout the study area, likely driving spatial autocorrelation of variables

Future Research:

- Look into other dependent physical variables (ascent rate, dive duration, etc.).
- Potential correlation between SWH and dive duration.

Spatial Error Model with Dive Duration as the dependent variable:

Model	R-Squared	AIC	Significant Predictors
Spatial Error	0.390019	13700.9	Significant Wave Height, Depth, Maximum Depth, Temperature at Surface

Figure 9) Spatial Error model, the R-Squared value, the Akaike Information criterion value, and the independent variables used

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