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Gray whales strand more often on days with increased levels of atmospheric radio-frequency noise

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Relatively little is known about the cues whales use while migrating. Visual cues in the ocean are often limited, which may drive oceanic migrators to use other sensory modalities, such as the ubiquitous geomagnetic field [1]. While it is impractical to perform behavioral assays on whales, strandings have been recorded for decades, and may provide insight into whale migration. Many strandings document that the individual was neither ill nor injured and resumed normal activity following rescue [2–4]. It is therefore possible that a portion of these animals stranded due to navigational errors. Although many factors impact strandings (e.g. naval mid-frequency sonar, disease, etc.) [5], here we focus on whether strandings can be used to study the potential for magnetoreception in migratory whales. Previous studies have used spatial patterns in strandings to suggest the potential for magnetoreception in cetaceans [4,6]. We use 31 years of gray whale (*Eschrichtius robustus*) stranding data (n = 186) to build on earlier work that found a positive relationship between strandings and sunspot counts [2,3]. Sunspots are strongly correlated with solar storms — sudden releases of high-energy particles from the sun that modify the geomagnetic field and thus have the potential to disrupt magnetic orientation behavior [7]. We examined relationships between strandings and two aspects of Earth's magnetosphere altered by solar storms — radio frequency noise and displacements in the Earth's magnetic field. Our results suggest that the increase in strandings under high solar activity is best explained by an effect on the sensor, not on the magnetic field itself.

We acquired U.S. gray whale stranding data spanning 1985–2018 from the National Oceanic and Atmospheric Administration. We chose this species because it has one of the longest migrations of any mammal, an extensive history in the stranding database, and is a near-shore migrator — suggesting that small navigational errors increase the risk of stranding. Each stranding was examined, and only those that likely stranded alive with no signs of injury, illness, emaciation, or human interaction (e.g. entanglement, or boat strikes) were used (n = 186). While the multi-factorial nature of strandings adds variation to this data set, we hypothesize that isolating healthier whales is a more efficient method to study navigational effects.

We examined the frequency of live strandings in relation to sunspot count, and performed a permutation test that demonstrated strandings occurred more often on days with high solar activity (Figure 1A,D; $p < 0.0001$). A plausible explanation for this result is that solar magnetic storms are disrupting features of Earth's magnetosphere and, in turn, affect the whale's navigational system. Solar storms could have two impacts on magnetic orientation. They could alter the geomagnetic field, leading to false information, or disrupt the animal's receptor itself, leading to an inability to orient. To better understand how this phenomenon may be affecting the whales, we examined two effects of solar activity. The first, solar radio flux, is a globally averaged measure of radio frequency (RF) noise nominally measured at 10.7 cm wavelength (frequency: 2800 MHz). Solar storms cause an increase in broad-band RF noise. We use 10.7 cm RF noise because it has been reliably recorded for the longest time period. RF noise has been shown to affect magnetic orientation in several species [1,8], and thus acts as a proxy for disruption to the receptor itself. The second, Ap-index, is a measure of displacement in Earth's magnetic field, and thus acts as a proxy for the accuracy of magnetic information available.

We examined the frequency of live strandings in relation to RF noise and performed a permutation test that demonstrated strandings occurred more often on days with high RF noise (Figure 1B,E; $p < 0.0001$). In contrast, this test did not show that whales stranded more often on days with a higher Ap-index than random (Figure 1C,F; $p = 0.6$).

A logistic regression was used to determine whether these effects were due to multicollinearity between solar activity and climate or seasonal effects. We looked at the previously described solar variables (RF and Ap), along with season (measured as day-of-year), and a well-established parameter that encapsulates climate variability — the Pacific Decadal Oscillation (PDO). The PDO is a recurring pattern of ocean–atmospheric variability, similar to El Niño. It is known to impact tropical storm activity, rainfall patterns, marine ecosystem productivity, and global temperature patterns. Variance inflation factors show no multicollinearity between these variables (see Supplemental Information, published with this article online).

Finally, Akaike Information Criterion (AIC) model selection was used to determine which variables best fit these data (see Supplemental Information). The best model was Season+RF and adding PDO did not improve performance (ΔAIC = 1.2). Further analysis of the effects of PDO indicated it was not useful for predicting strandings (see Supplemental Information). In addition, RF alone performed significantly better than season alone, PDO alone, or season+PDO (ΔAIC = 11.9, 20.5, and 16.3, respectively). Logistic regressions gave an odds ratio of 1.006 for sunspots and 1.009 for RF. When comparing the largest to smallest bin of our data (Figure 1 A–C), this gave a 2.3-fold increase in the likelihood of a stranding on high sunspot days, and a 4.3-fold increase for high RF-noise days (see Supplemental Information).

Our work indicates that the relationships found by previous researchers between strandings and sunspots are robust to additional statistical methods that account for the underlying distribution of the data, collinearity with seasonal or climate variability, and autocorrelation between the time of strandings (see Supplemental Information) [2,3]. There is a history of research on correlations between solar activity and migratory behavior [9,10]; however, our study is the first to examine potential mechanisms mediating this correlation by examining geophysical parameters that are affected by solar

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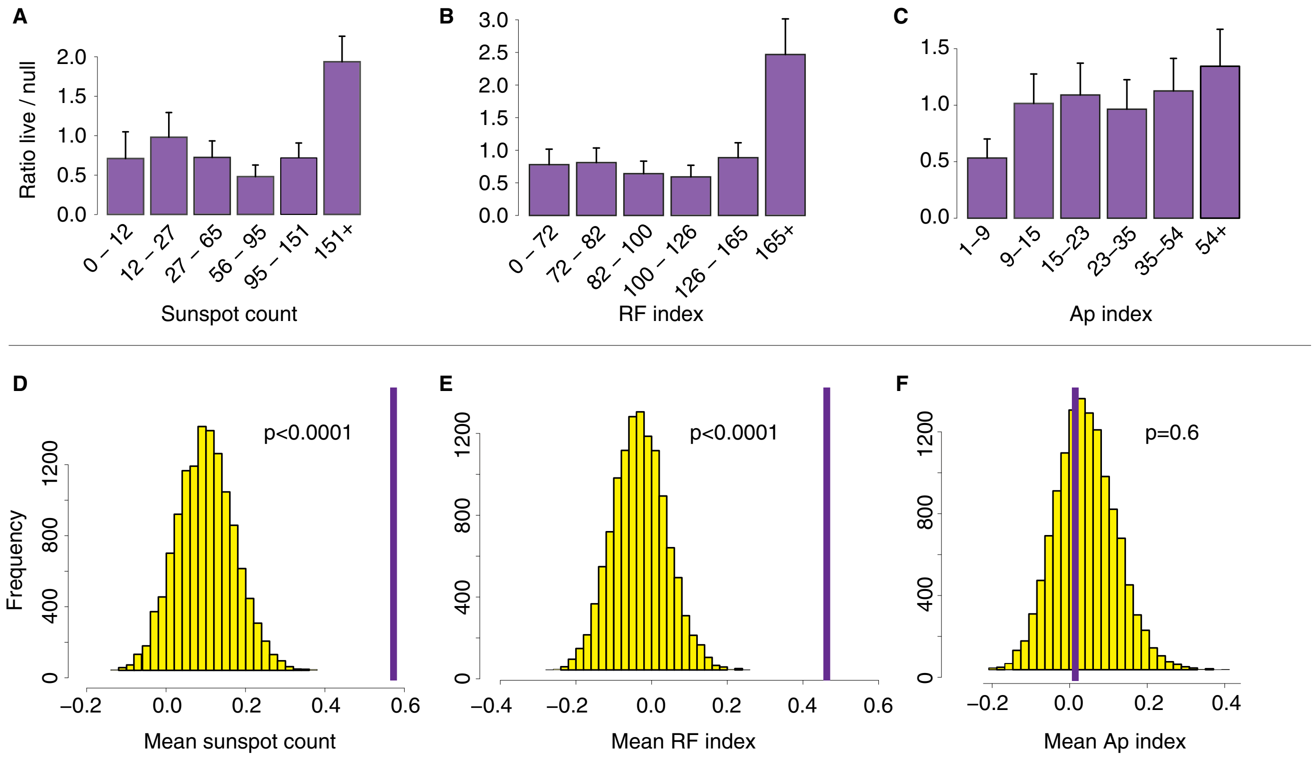

Figure 1. Visualization and statistical analysis of strandings versus solar activity.
(A–C) Data were divided into six bins comprising equal numbers of observations. 600 samples were randomly drawn, with replacement, from the stranding data and from all calendar days between 1985–2018 (see Supplemental Information). For each bin, we divided the number of days with strandings by the number of randomly selected days (see Supplemental Information). (D–F) The yellow null distribution was generated by randomly sampling 186 days from all calendar days between 1985–2018, during the months in which whales are typically migrating. From that sample, we calculated the mean of each variable of interest, and repeated 10,000 times. This represents the underlying probability distribution for each variable of interest. The purple, vertical line is the mean of our stranding data. The farther the mean of our stranding data is from the underlying distribution, the less likely we would have achieved this value by chance. We then calculate the probability of achieving this value or larger given the underlying distribution (see Supplemental Information).

storms. Specifically, we found that this relationship was best explained by increases in RF noise rather than alterations to the magnetic field. These results are consistent with the hypothesis of magnetoreception in this species, and tentatively suggest that the mechanism for the relationship between solar activity and live strandings is a disruption of the magnetoreception sense, rather than distortion of the geomagnetic field itself. While these results are consistent with the radical-pair hypothesis of magnetoreception, which is predicted to be disrupted by RF noise [1,8], they do not preclude other possible receptors, such as one based on magnetite. This research is not conclusive evidence for magnetoreception in this species, and further research is still necessary to determine the mechanism for the increase in strandings under high RF-noise. Finally, while this paper examines only a few aspects that contribute to strandings, many other variables are known to influence live-strandings [5]. This paper develops a procedure that will allow future researchers to analyze other interactions that affect stranding rates.

SUPPLEMENTAL INFORMATION

Supplemental Information contains one figure, one table, experimental procedures, acknowledgments, and author contributions, all of which can be found with this article online at https://doi.org/10.1016/j.cub.2020.01.028.

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