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Correlating Whale Strandings with Navy Exercises in Southern California

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Background and tasking

Marine mammals routinely strand along U.S. shorelines and in many other parts of the world. In most cases, the cause of strandings is unknown. Some identified causes include disease; parasite infestation; harmful algal blooms; injuries from ship strikes or fishery entanglements; and exposure to pollution, trauma, and starvation. A handful of mass strandings[1] of marine mammals coincided in time and location with Navy sonar operations at sea. Although a conclusive "cause and effect" relationship has not been established, there is evidence that military sonars could cause marine mammals, particularly beaked whales, to strand [2 - 10].

The Navy continues to face challenges to its use of active sonar in fleet exercises. A National Defense Exemption signed in January 2007 provided some relief to the Navy, but it also set forth various mitigation measures that the Navy must apply to prevent the harming of whales by active sonars from warships. More recently, a lawsuit brought by the Natural Resources Defense Council, an environmental advocacy group, threatens to severely curtail the Navy's ability to conduct anti-submarine warfare training off southern California [11].

Previous CNA studies compiled historical data on large-scale naval exercises and whale mass strandings [12, 13], and found mixed results. Significant correlations were seen in some cases but not in others. Fundamental questions remain: how, and under what conditions, do sonars affect marine mammals, and under what conditions might sonars lead whales to strand?

1. A mass stranding is defined as two or more animals, not a mother/calf pair [1].

To continue exploring possible links between sonar use and whale strandings, the Operational Environmental Readiness Division in the Office of the Chief of Naval Operations (CNO-N456) asked CNA to examine strandings and Navy operations in Southern California. For many years, the Navy has been conducting a great deal of fleet training in the areas around San Clemente Island, with no known mass strandings—an important fact in itself. However, N456 asked us to look even deeper for any potential link between sonar and strandings. Our tasking was to compile exercise information and any stranding data available to quantify the level of sonar activity taking place and see whether there is any indication of a link between sonar use and strandings—including single strandings—in this important area.

This analysis is similar to the previous studies (12, 13) in the sense that data on sonar use and whale strandings are combined and examined for correlations in time and location. Due to some additional information that is available in the stranding data for Southern California, however, this analysis employs a methodology that has not been used previously. For this study we had information of the state of decomposition of the observed stranded animals, so we were able to treat the age of the stranding (the time lag between the actual time of the stranding and the time it was observed) as a random variable. We then simulated the correlation between exercises and strandings with a Monte Carlo model. We will illustrate this procedure in the next chapter.

Summary of findings

We correlated stranding data for Southern California (latitudes below 34 North) with times of Navy exercises for the period March 1982 to April 2007. We removed from the data set those strandings for which the observation report indicated a known cause that was clearly unrelated to sonar (for example, "vessel strike" or "fishery interaction")[2]. Because of the seasonality of gray whale presence in this area, we performed separate analyses for gray whales (for the months of January through April only) and other species.

2. Our overall results do not change if we include these events.

For gray whales, the expected (average) *P*-value from 1,000 iterations with our model was 0.35, strongly consistent with the null hypothesis of no difference in stranding rates between times of Navy exercises and other times. For other species, the expected *P*-value was 0.53, again strongly consistent with the null hypothesis.

Ultimately, our analysis found no correlation between Navy exercises and whale strandings in the Southern California area. Where does this result fit with our previous findings?

In our earlier findings of strandings that were coincident with Navy exercises in other areas, we noted that the location of Navy sonar use relative to bathymetry could be a potential factor. Specifically, if sonar use takes place offshore of steep bathymetry that is adjacent to a coast, whales that may attempt to avoid the sonars could possibly be driven on shore, as hypothesized by A. D'Amico of the Navy's SPAWAR Systems Center [10, 14, 15].

Most major Navy exercise activity in Southern California takes place on the range to the west of San Clemente Island, although large battle group exercises involve some sonar use throughout the entire area. The key feature of this pattern of sonar activity is that it is generally not adjacent to the coast, where whales located landward of the exercise would be likely to be driven ashore. Although some exercise activity takes place nearer shore, the majority is well to the west.

Data and Methodology

Data

We built timelines of Southern California Navy operations from the Navy's Employment Schedule Database (EMPSKED) [16], various fleet Internet and SIPRNET sites, exercise after-action reports, and scheduling data provided by the Southern California Offshore Range (SCORE) operations center.

In previous CNA studies of sonar use and whale strandings, only mass strandings (defined as two or more stranded whales in a particular location) have been correlated with naval operations. Mass stranding data was preferred because individual strandings are far more common than mass strandings and thus produce "noisier" data. In addition, although mass strandings occur naturally for a variety of reasons (many of which remain unknown), a mass stranding is more likely to be indicative of some outside event (as opposed to a routine mortality) than an individual stranding would be.

There have been no previously known mass stranding events in southern California coincident with Navy operations—an interesting piece of information in itself. For this analysis, we use data on individual strandings[3] that occurred in southern California, despite the difficulty in determining the factors contributing to an individual stranding. One advantage of the stranding data we use is that it contains information not previously available in our data on whale strandings. Specifically, each stranding report includes information on the state of decomposition of the animal at the time of observation—informa-

3. Our data set does include one mass stranding event: three pygmy sperm whales on April 9, 2006. All other stranding events in our data are singles.

tion that can be used to estimate the time from the occurrence of the stranding to the observation of the stranded animal.

We visited the NOAA West Coast Stranding Network office, and obtained their database of California strandings, which covered the period 1982 to 2007. Because this data was hard-copy only (hand-written stranding report forms), we had to manually key it into computer files, and in many cases fill in latitude-longitudes based on descriptive location information. Through discussions with the NOAA stranding office, we determined the potential ages (given as a range of days from stranding event to observation) of the stranding events as a function of the state of decomposition noted at the time of observation.

Figure 1 shows all reported whale strandings in the state of California between 1982 and 2007[4]. On the map, each X marks the location of a whale stranding reported in the data. There are some obvious erroneous position reports (strandings over land), as well as several positions reported well at sea. The at-sea positions represent observations of dead whales floating. For this analysis, we are interested only in strandings that could have potentially been affected by sonar use off southern California, where the Navy performs most of its battle group training in the waters near San Clemente Island. Therefore, our correlation analyses include only strandings that occurred at latitude less than or equal to 34 N.

4. The data set contained many entries of "unknown species." These were generally reports of unidentifiable bones or organic matter on a shoreline, with no knowledge of how long they were there or what exactly they were. We excluded these reports from our analyses.

Figure 1. California strandings, 1982-2007

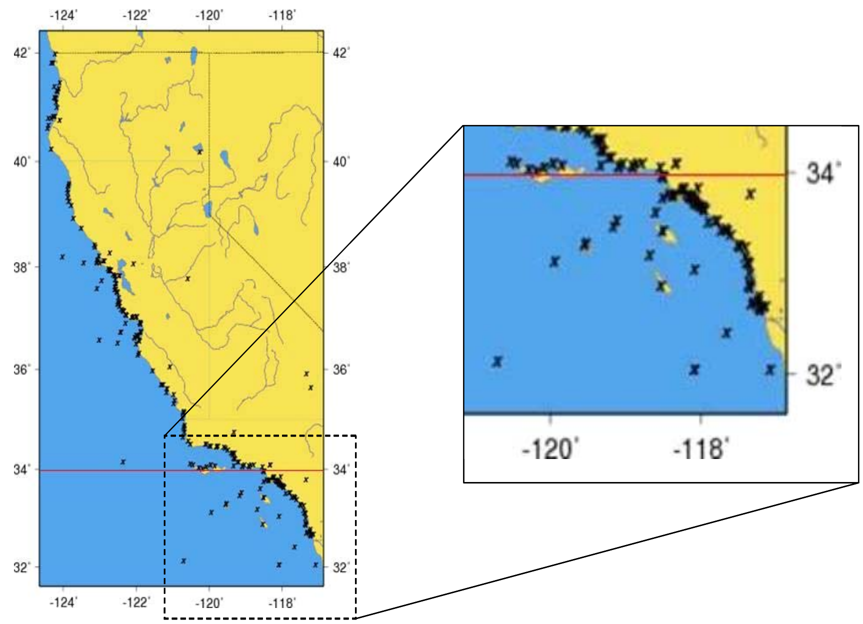
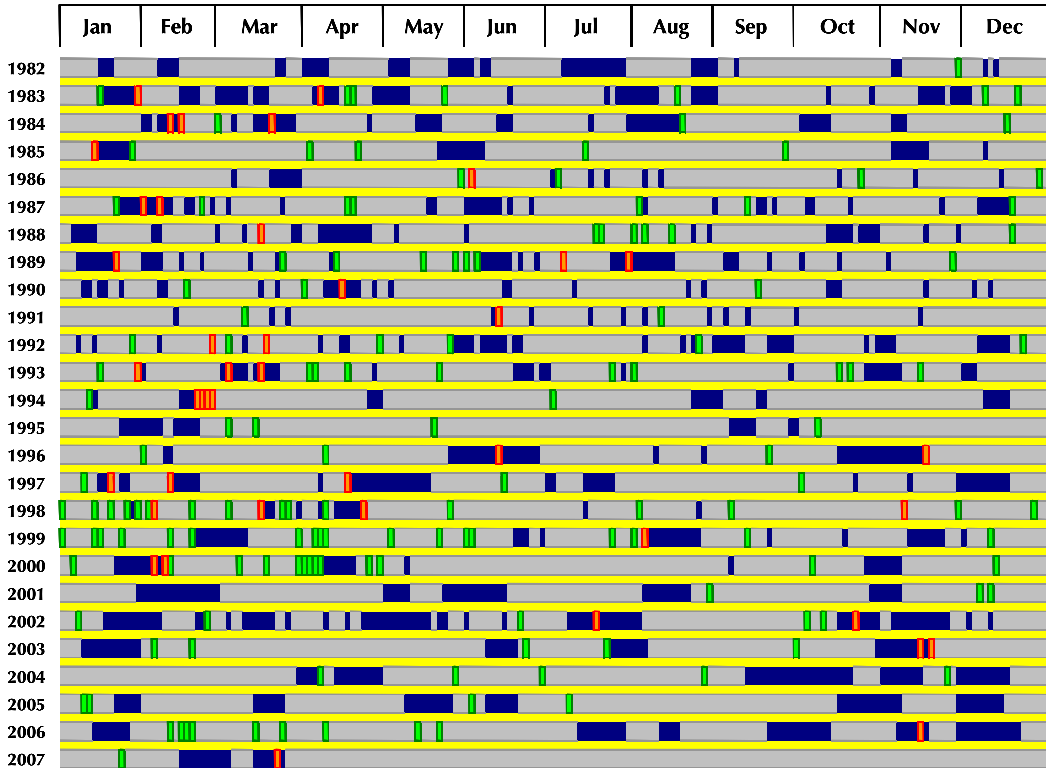


Figure 2 shows a timeline of strandings for all species at latitudes 34 North and below, along with Navy operations. The blue bars indicate the times of Navy exercises, and the tick marks indicate stranding events. For display purposes, we color the tick-marks green if they do not overlay a Navy exercise, and red if they do. The question we seek to address is: does this pattern of strandings and Navy exercises indicate a correlation between Navy exercises and strandings?

The stranding tick-marks shown on this slide represent the time the stranding was observed—not necessarily the time the stranding occurred. In the next section we discuss our methodology to account for this time discrepancy in the stranding data and address the above question in an objective manner.

Figure 2. Timeline of strandings and Navy exercises in Southern California



Analysis procedure

Our analysis of strandings vs. Navy exercises consisted of timeline analysis similar to that described in [12 and 13]. However, for this study we determined the correlation between exercises and strandings by treating the age of the stranding (the time lag between the actual time of the stranding and the time it was observed) as a random variable and calculating the correlation between exercises and strandings with a Monte Carlo approach.

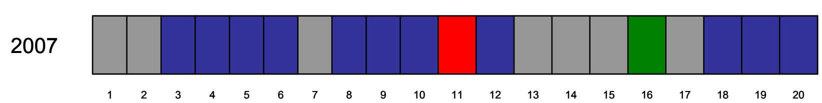
The most interesting feature of the whale stranding data is that we have some information on the state of decomposition for the whale carcass. For each reported stranding, the level of decomposition is assigned to one of five categories: (1) alive, (2) sick / injured, (3) fresh dead, (4) long dead / moderate decomposition, and (5) advanced decomposition. When a stranding report is filed, the individual filling out the report selects the category that in his/her judgment best describes the condition of the carcass. Because this classification mechanism is subjective, it is certainly not a precise measure of how long a particular whale carcass has been ashore. Nevertheless, the classification does provide us with additional information that can be useful for our analysis. Obviously there are a number of other factors that influence the rate of decomposition that we are not accounting for, such as the ambient temperature. Accounting for additional complications would be difficult and is beyond the scope of this study. NOAA Stranding Center personnel provided the following guidance concerning the likely age of stranding observations:

- Alive or sick / injured: no adjustment
- Fresh dead: adjust by 2-3 days
- Long dead / moderate decomposition: adjust by 4 days to 2 weeks
- Advanced decomposition: adjust by 2 weeks to a month or more

Given the available information on the state of the whale carcass, we would like to adjust the date of the whale stranding to reflect the fact that some strandings likely occurred earlier than the reported stranding date. If a stranding is observed on some given date but the carcass is classified as being long dead, we are fairly certain that the stranding did not in fact occur on that date. However, even though we have some guidance for how the decomposition classification corresponds to the length of time the carcass has likely been ashore, it isn't clear how to use that information to adjust the date of the stranding. One alternative would be to simply choose a particular adjustment factor for all strandings within a decomposition category and apply that adjustment factor to all reported strandings in that category. For example, since we believe that carcasses classified as long dead / moderate decomposition occurred 4 days to 2 weeks before the date they are reported, we could simply assume that all strandings in this classification actually occurred 9 days earlier than we observe in the data. But this approach is problematic for our analysis, as we illustrate below.

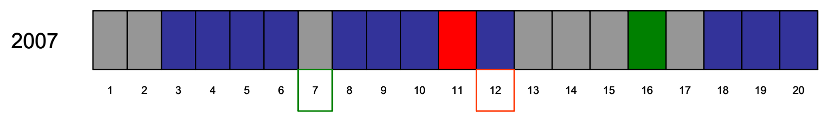
To see why making the same adjustment to all reported strands with the same decomposition classification could cause problems, consider the following simple example. Suppose we have 20 days of data on ship operations and whale strandings. In figure 3, each box represents a day. The boxes colored blue represent days on which sonar was used, the red box marks a day of both sonar use and a whale stranding, and the green box marks a day with a reported whale stranding but no sonar use. Also, assume that both whale carcasses were classified as moderately decomposed when reported. According to our earlier guidance, carcasses classified as moderately decomposed likely stranded anywhere from 4 days to 14 days before the reporting date.

Figure 3. Simple adjustment example: sonar and stranding days



Suppose we decide to adjust the date of all strandings classified as moderately decomposed by 4 days, the minimum of the adjustment range we defined for that category of decomposition. In figure 4, the boxes around days 7 and 12 show the adjusted stranding dates using this rule. The box around day 7 is green because the stranding that is reported on day 11 would now be assumed to have occurred on day 7, which does not correspond to a day of sonar use. On the other hand, the box around day 12 is red because the stranding originally reported on day 15 and not associated with a sonar day now occurs on day 12, a sonar day.

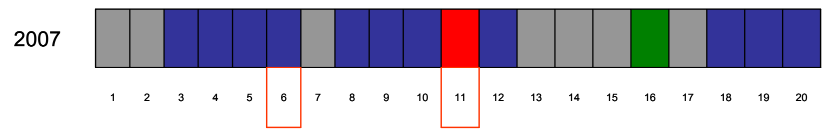
Figure 4. Effects of 4-day adjustment



In this case, our analysis using the adjusted stranding dates will produce the same results as an analysis using the unadjusted dates. This is because both before and after adjusting the stranding dates, we end up with one stranding on a sonar day and one stranding on a non-sonar day.

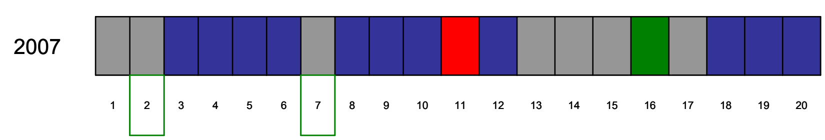
Now suppose we instead decide to adjust the date of all strandings classified as moderately decomposed by 5 days. In figure 5, the boxes around days 6 and 11 show the adjusted stranding dates using this rule. Both the box around day 6 and the box around day 11 are red because both reported strandings would now be assumed to have occurred on sonar days. Although our 4-day adjustment would not have altered our findings as compared to using unadjusted stranding dates, using a 5-day adjustment does. Because we would now assume that we have two strandings on sonar days, our analysis using adjusted dates would indicate a higher probability that sonar use and whale strandings are correlated than our unadjusted analysis.

Figure 5. Effects of 5-day adjustment



Lastly, suppose we decide to adjust the date of all strandings classified as moderately decomposed by 9 days. In this case, in figure 6 the boxes around days 2 and 7 show the adjusted stranding dates using this rule. Both boxes are green because both reported strandings would now be assumed to have occurred on non-sonar days. Using this adjustment, our findings would indicate a lower probability that sonar use and whale strandings are correlated than an analysis using the unadjusted dates.

Figure 6. Effect of 9-day adjustment



The point of these three examples is to show if we select a single adjustment for each category of decomposition, our results will likely be sensitive to the particular adjustment we choose. Since we do not have any information to inform our choice of a single adjustment, any choice we might make would be completely arbitrary. As a result, we instead use statistical methods that account for our uncertainty with respect to the correct adjustment factor.

In our analysis, we want to use the information contained in the decomposition classification to adjust the data on stranding dates, but we need to account for our uncertainty with respect to the "correct" adjustment. That is, we do not want to choose the same adjustment to apply to all strandings within a category because our choice of the adjustment factor would be arbitrary and could have a serious impact on our results.

Instead, suppose we are willing to make two assumptions regarding the relationship between the reported stranding dates and the actual stranding dates. First, we assume that the actual stranding date is equal to the reported date minus an adjustment factor that falls in the range specified for the corresponding decomposition category. For instance, if we have a reported strand on 8/23 that is classified as fresh dead, our first assumption implies that the actual date of the strand was either 8/20 or 8/21. Second, we assume that within the specified adjustment range for a given decomposition category, each adjustment factor in that category is equally likely. In the context of our example, the second assumption means that there is a 50 percent chance that the true stranding date is 8/20 and a 50 percent chance that the true stranding date is 8/21.

Under these two assumptions, we can proceed by simulating adjustment factors for all strandings observed in the data. The simulation process we use explicitly incorporates our uncertainty about the true adjustment factor for each observed stranding.

The simulation procedure we use works as follows. From 29 November 1982 to 23 March 2007, 180 whale strandings were reported in the data. The first step in the simulation routine is to simulate adjustment factors for each of the 180 strandings. We do this by first generating random numbers for each strand from the appropriate interval given the decomposition classification of the carcass. For example, if a strand is categorized as being in an advanced state of decomposition, we draw a random number from the interval [14, 42] since we are assuming that the true date of the stranding is from two weeks to over one month earlier than reported. The upper bound of 42 on the interval corresponds to 6 weeks. Let u_r represent one set of adjustment factors for all 180 reported strandings.

After adjusting all of the stranding dates, we compute $S_1(u_r)$, which is equal to the number of date-adjusted strandings that occur on sonar days. In this expression, u_r is in parentheses to indicate that the quantity S_1 is dependent upon a particular set of adjustment factors u_r. Given $S_1(u_r)$, we next calculate the probability of observing at least that many strandings coincident with sonar use over the specific time period under consideration, under the null hypothesis that there is no relationship between sonar use and stranding.

For example, referring to the complete data set shown in figure 2, the overall stranding rate during this period is equal to 0.020 strands per day (total strands / total days = 180 / 8923 = 0.020) and there are 1,588 exercise days. If the stranding rate is unaffected by sonar, we would expect to observe about 32 whale strandings on sonar days (0.020 x 1,588 = 32.03). Thus, under our null hypothesis that Navy exercise activity does not affect the stranding rate, the number of strandings coincident with sonar use will follow a Poisson distribution with mean (μ) = 32.03. Letting P_r represent the probability of observing at least $S_1(u_r)$ strandings on sonar days under these assumptions,

$$P_r = Prob(X \geq S_1(u_r))$$

which is calculated by:

$$P_r = 1 - F(S_1(u_r)) = 1 - \sum_{x=0}^{S_1(u_r)-1} \frac{e^{-\mu} \cdot \mu^x}{x!}$$

where F( ) is the cumulative distribution function for the Poisson distribution.

The steps outlined above are then repeated a large number (R) of times, and the values of P_r for each of the R simulations are stored.

Using the R values of P_r that are generated from our simulation process, we then take the average of those values as our estimate of the probability that the number of whale strandings coincident with sonar use is greater than or equal to the number indicated by our data.

$$\hat{P} = \frac{1}{R} \cdot \sum_{r=1}^{R} P_r$$

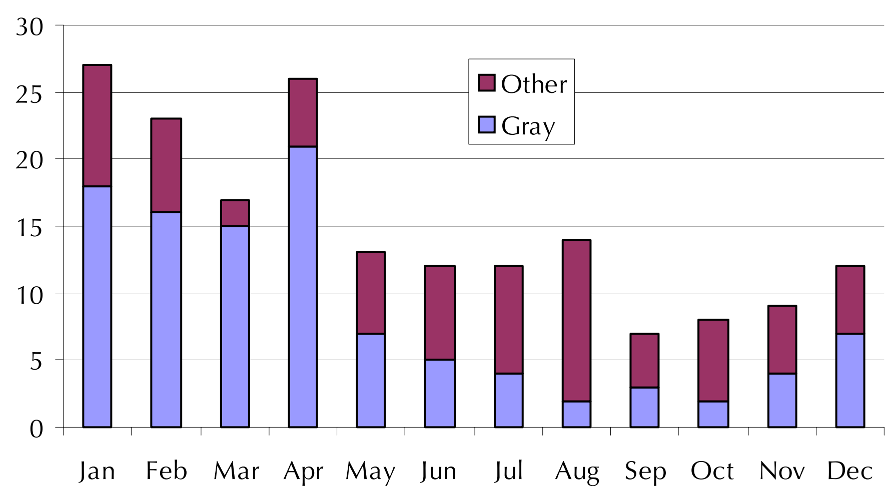
As R becomes large, our estimate will converge in distribution to the true value of P. In technical terms, our estimator is said to be consistent. For our analysis, we set R = 1000.

Results

Seasonality of strandings

Before performing any correlation calculations, we had to check for seasonality of the strandings, primarily for gray whales, which make their seasonal migration past Southern California in the winter months. Figure 7 shows the number of Southern California strandings per month with gray whales broken out. Gray whale strandings are seen throughout the year, but dominate the stranding data from January through April.

Figure 7. Strandings by month, SOCAL, gray whales and all others



We tested the months January through April for departures from the monthly mean of 8.67 gray whale strandings per month. Under the null hypothesis of a constant stranding rate throughout the year, we calculate the probability of an observed number K or greater gray whale strandings as follows, for the months January through April:

$$P(n \geq K) = 1 - \sum_{x=0}^{k-1} \frac{e^{-\mu} \cdot \mu^{x}}{x!}$$

where $\mu = 8.67$

Table 1 shows the results; all four months showed a significant departure (at the .95-level) from the assumption of constant stranding rate throughout the year. Therefore, to account for the seasonality introduced by the gray whale winter presence, we separately performed two correlation analyses: gray whales during the period January through April and all other whales for the entire year.

Table 1. Test for seasonality in non-gray strandings

month	P(k)
Jan	0.0037
Feb	0.0163
Mar	0.0317
Apr	0.0003

Correlation results

We first removed those strandings for which the original observation report indicated a known cause that was clearly unrelated to sonar (for example, “vessel strike” or “fishery interaction”).

Non-gray

We correlated strandings with exercises by removing gray whales from the stranding data. For this calculation, there were 76 strandings over the 8,923 day period, for an overall (null-hypothesis) expected value $\mu = 13.53$ strandings during the 1,588 days of Navy exercises.

Figures 8 and 9 show the correlation results from 1,000 iterations with our model; figure 8 shows the distribution of the number of coincident strandings, and figure 9 shows the distribution of the P-values from each iteration. Details of this calculation are shown in table 2. The average (expected value) of the P-values is 0.53, strongly coincident with the null hypothesis of no correlation between Navy exercises and strandings.

Figure 8. Model results, non-gray whales, SOCAL: number of strandings coincident with Navy exercises, 1,000 iterations

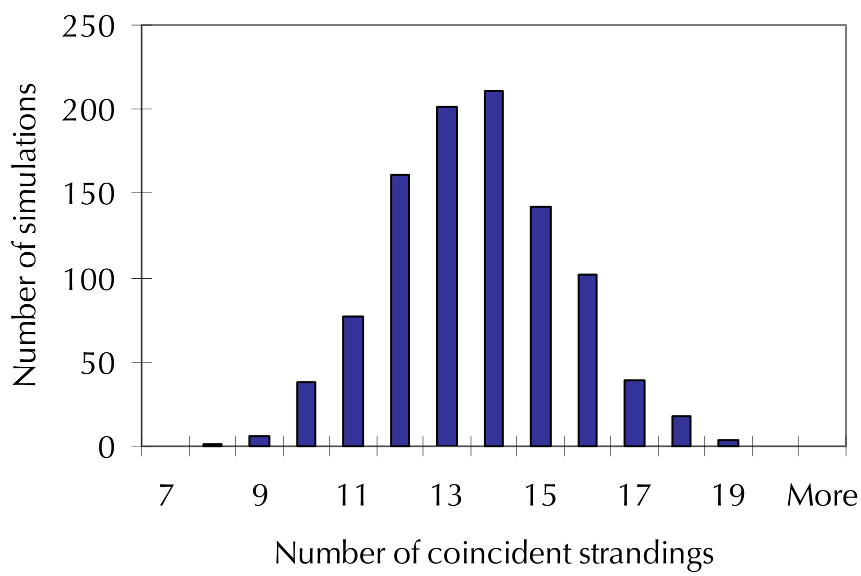


Figure 9. Model results, non-gray whales, SOCAL: P-values, 1,000 iterations

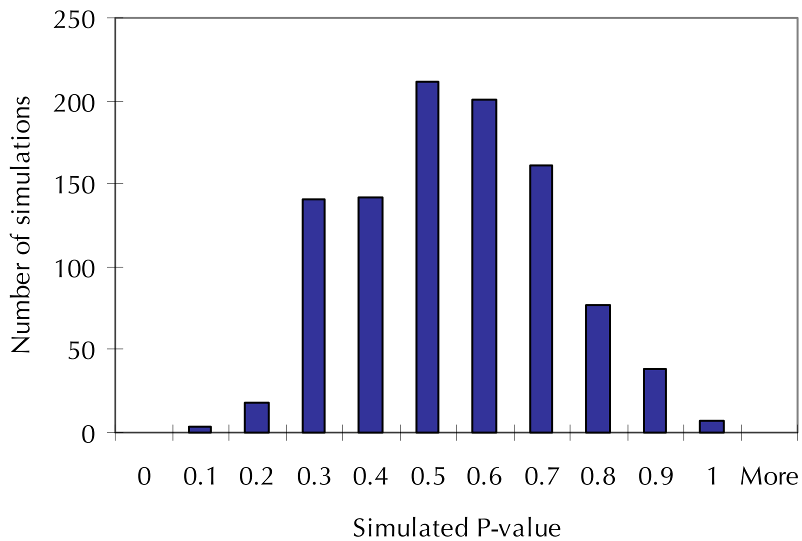


Table 2. Correlation details, non-gray whales

Parameter	Value
Total duration (days)	8,923
Exercise days	1,558
Strandings	76
Overall stranding rate	76/8,923 = .0085 strandings per day
Expected number of strandings during exercises (μ)	.0085 * 1,588 = 13.53
Average *P*-value	0.53

Gray whales

We performed a similar correlation analysis for gray whales only. In this case we looked only at the months January through April.

Figures 10 and 11 show the correlation results from 1,000 iterations with our model; figure 10 shows the distribution of the number of coincident strandings, and figure 11 shows the distribution of the P-values from each iteration. Details are given in table 3. The average (expected value) of the P-values is 0.35, again strongly coincident with the null hypothesis of no correlation between Navy exercises and strandings.

Figure 10. Model results, gray whales, SOCAL: number of strandings coincident with Navy exercises, 1,000 iterations

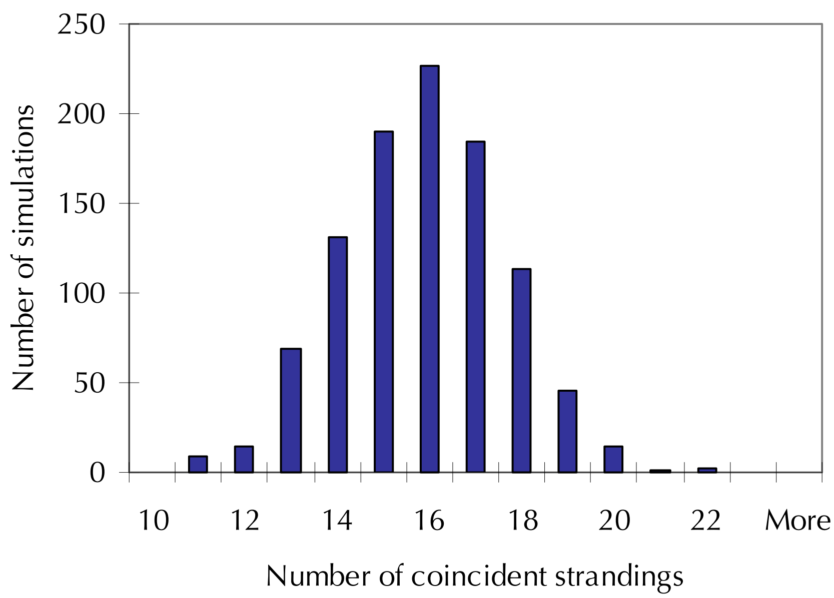


Figure 11. Model results, gray whales, SOCAL: P-values, 1,000 iterations

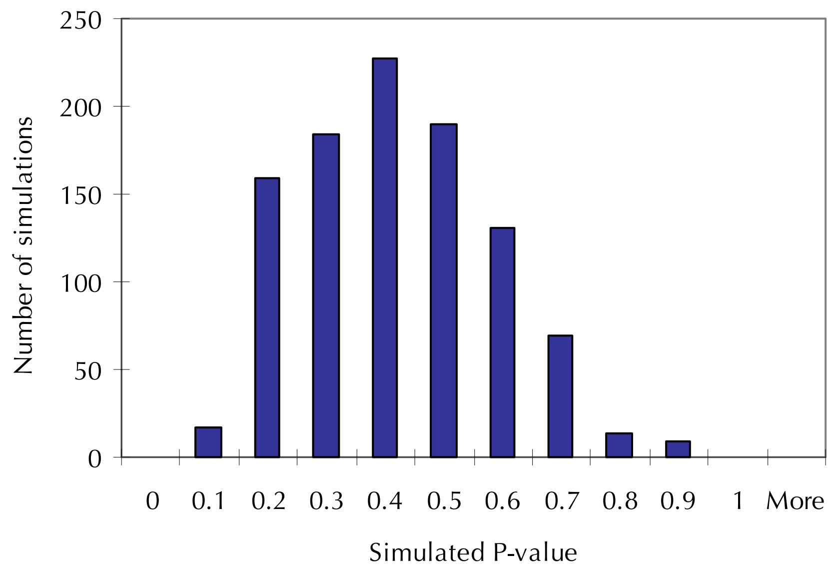


Table 3. Correlation details, gray whales

Parameter	Value
Total duration (days)	2,968
Exercise days	590
Strandings	70
Overall stranding rate	70/2,968 = .0236 strandings per day
Expected number of strandings during exercises (μ)	.0236 * 590 = 13.92
Average *P*-value	0.35

Summary

To summarize, we used data from November 1982 through March 2007 on whale strandings and naval operations to investigate whether there is a correlation between Navy exercise activity and whale strandings. Using information on the reported extent of decomposition of the whale carcass, we employ a simulation procedure to adjust the date of the stranding before computing the probability of observing the number of coincident strands implied by the data. Our analysis found no correlation between Navy exercises and whale strandings in the Southern California area.

Where does this result fit with our previous findings?

In our earlier findings of strandings that were coincident with Navy exercises in other areas, we noted that the location of Navy sonar use relative to bathymetry could be a potential factor. Specifically, if sonar use takes place offshore of steep bathymetry that is adjacent to a coast and if whales react by fleeing the area of sonar activity, the whales could be driven on shore. This idea was first put forth by A. D'Amico of the Navy's SPAWAR Systems Center [10, 14, 15].

Most major exercise activity in this area takes place on the range to the west of San Clemente Island, although large battle group exercises involve some sonar use throughout the entire area. The key feature of this pattern of sonar activity is that it is generally not adjacent to the coast, where whales located landward of the exercise would likely be driven ashore. Some pinging takes place nearer shore, but the majority of sonar use is well to the west.

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