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Absolute probability estimates of lethal vessel strikes to North Atlantic right whales in Roseway Basin, Scotian Shelf

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Abstract. Vessel strikes are the primary source of known mortality for the endangered North Atlantic right whale (*Eubalaena glacialis*). Multi-institutional efforts to reduce mortality associated with vessel strikes include vessel-routing amendments such as the International Maritime Organization voluntary “area to be avoided” (ATBA) in the Roseway Basin right whale feeding habitat on the southwestern Scotian Shelf. Though relative probabilities of lethal vessel strikes have been estimated and published, absolute probabilities remain unknown. We used a modeling approach to determine the regional effect of the ATBA, by estimating reductions in the expected number of lethal vessel strikes. This analysis differs from others in that it explicitly includes a spatiotemporal analysis of real-time transits of vessels through a population of simulated, swimming right whales. Combining automatic identification system (AIS) vessel navigation data and an observationally based whale movement model allowed us to determine the spatial and temporal intersection of vessels and whales, from which various probability estimates of lethal vessel strikes are derived. We estimate one lethal vessel strike every 0.775–2.07 years prior to ATBA implementation, consistent with and more constrained than previous estimates of every 2–16 years. Following implementation, a lethal vessel strike is expected every 41 years. When whale abundance is held constant across years, we estimate that voluntary vessel compliance with the ATBA results in an 82% reduction in the per capita rate of lethal strikes; very similar to a previously published estimate of 82% reduction in the relative risk of a lethal vessel strike. The models we developed can inform decision-making and policy design, based on their ability to provide absolute, population-corrected, time-varying estimates of lethal vessel strikes, and they are easily transported to other regions and situations.

Key words: absolute probability estimates; endangered whales; *Eubalaena glacialis*; marine area closure; mortality reduction; North Atlantic right whale; Roseway Basin, Scotian Shelf; vessel routing; vessel strike.

INTRODUCTION

The North Atlantic right whale (*Eubalaena glacialis*; hereafter right whale) remains one of the most endangered large whale species (Kraus et al. 2005). Despite international protection since 1935, the estimated right whale population has remained low, ranging from 300–350 individuals during 1988–1997 (IWC 2001) to approximately 415 in 2007 (Pettis 2009). The limited population recovery of the North Atlantic species, including negative or near-replacement population growth rates, is most easily explained by high mortality or low reproductive output or both (Kraus et al. 2005) and is likely related to its distribution along a heavily industrialized coastal margin.

Right whales seasonally inhabit coastal waters along the eastern seaboard of Canada and the United States

and exhibit annual north–south migrations between summer feeding grounds and winter calving grounds, and vice versa. Despite the designation of five “critical habitat” areas along their migratory corridor (southeastern United States, Cape Cod Bay, Great South Channel, Bay of Fundy, and Roseway Basin), the degree of spatial and temporal coincidence of whales and extensive fishing and shipping industries remains high (Kraus and Rolland 2007). Approximately 66% of documented right whale deaths are attributed to fishing gear entanglements and vessel strikes, compared to natural (e.g., calf mortality) or undetermined causes. Vessel strikes account for 53% of all deaths among necropsied right whales over the period 1970–2006 (Moore et al. 2007, Campbell-Malone et al. 2008). The remainder are attributed to undetermined or unknown causes and natural (e.g., neonatal) mortality (J. M. van der Hoop et al., unpublished manuscript).

The number of vessels in the world shipping fleet has more than tripled since 1950, and the number of vessels visiting ports along the eastern seaboard of the United States is predicted to double from 2000 to 2020, i.e., 4%

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per year (Corbett 2004). The increase in the number of vessels in the world fleet provides the simplest explanation for recent increases in whale mortality (Firestone 2009, Vanderlaan et al. 2009). Of those documented, 75% of vessel strike deaths among right whales since 1970 have occurred in the most recent ~15 years (Brown et al. 2009).

Though vessel traffic is a threat to many large whale species from an historical perspective (Laist et al. 2001), the North Atlantic right whale is two orders of magnitude more prone to vessel strike when the number of species-specific strikes are normalized by population size (Vanderlaan and Taggart 2007). Female right whales appear to be struck more often than males (Moore et al. 2007), leading to a reduced female life expectancy that has substantial implications for species recovery. Preventing two female right whale mortalities per year has a measureable influence on population growth rate (Fujiwara and Caswell 2001).

Various agencies in Canada and the United States have stressed the immediate need to reduce vessel strike mortality to right whales (Kraus et al. 2005, NMFS 2005, Brown et al. 2009). In response, multi-institutional efforts have led to the implementation of vessel speed restrictions and vessel navigation regulations, and policies explicitly designed to help achieve the goal of a sustained, positive population growth rate (IMO 2003, 2006, 2007, 2008, NOAA 2008, Vanderlaan et al. 2008, Vanderlaan and Taggart 2009, Lagueux et al. 2011, Wiley et al. 2011). One recent policy was the adoption by the International Maritime Organization (IMO) of a precedent-setting voluntary "area to be avoided" (ATBA) by vessels in the Roseway Basin feeding habitat on the eastern Scotian Shelf (Fig. 1).

Implemented by Canada on 1 May 2008, the Roseway ATBA is seasonally in effect each year from 1 June through 31 December, and it marks the first ATBA adopted by the IMO to specifically decrease vessel strike risk to an endangered species. Voluntary compliance with the ATBA is estimated to have reduced the relative risk of lethal vessel strikes by 82% (Vanderlaan and Taggart 2009). The same authors coarsely estimated that vessel compliance with the ATBA should decrease the number of lethal strikes from one every 2–6 years to one every 11–89 years. The large uncertainties in these estimates are related to limited data, the low estimated rate (17%) of a right whale mortality being observed (Kraus et al. 2005), and the application of various correction factors that nonetheless render the estimates extremely conservative (Vanderlaan et al. 2008, Vanderlaan and Taggart 2009).

Here we provide improved estimates of lethal vessel strikes in the Roseway Basin region by estimating absolute strike probabilities using information derived from mandatory, shipboard, automatic identification system (AIS) data in combination with an observationally based whale movement model. The AIS is an automated ship-to-ship and ship-to-shore VHF radio

broadcasting system designed to improve maritime safety. Adopted in 2002, the IMO requires AIS transponders on all commercial vessels ≥ 300 gross tonnage and on all passenger vessels. The system allows vessels carrying a transponder to be automatically identified and located (Harre 2000) in near-real time with a resolution of ± 10 m and speeds of ± 1 knot. (The knot [0.514 m/s] is used for vessel speed as it is the nautical convention.) The whales and their movements are simulated using an autocorrelated random walk governed by parameters derived from the literature and are restricted to a domain based on the known distribution of right whales in Roseway Basin. The combination of the vessel and the whale elements in the model determines their spatial and temporal intersection from which various probability estimates of lethal vessel strikes are derived. Correction factors have previously been formulated to estimate the true number of lethal vessel strikes, given that the majority of whale mortalities are undetected, and when detected, cause of death is often not determined. Comparison to model results determines the reliability of specific correction factors, confirming their appropriate use to estimate numbers of undetected and undetermined vessel strike mortalities.

METHODS

Overview

The model domain was delineated by a rectangular area of 8236 km² defined by 42.6° and 43.3° N latitude and 66.1° and 64.8° W longitude that encompasses the Roseway Basin ATBA on the southwestern Scotian Shelf (Fig. 1). The model domain is larger than the ATBA to facilitate geometry. Within this domain a time-stepping model was used to track the real-time transit of vessels through the region and to determine the number of vessels striking simulated right whales. Vessels transit throughout the model domain, both inside and outside the ATBA. Whales are restricted to the bounds of the ATBA. The model was run sequentially on a daily (24-h) basis over the period 15 June through 31 October among various years using the highly resolved vessel transit data. At the start of each day, model whales were initialized in space and then moved by means of an autocorrelated random walk. The expected number of lethal strikes was calculated as the number of vessel-whale intersections multiplied by the average lethal probability of those intersections and by the probability of a whale being at the surface. We used the model to determine (1) any change in the expected number of lethal vessel strikes following ATBA implementation, by comparing model results from simulations of varying intra- and interannual populations of whales and vessel data from before and after ATBA implementation; (2) any change in the per capita expected number of lethal vessel strikes, by normalizing for the annual population size; and (3) whether changes in vessel distribution are the result of changes in navigation (i.e., not whale abundance), by comparing

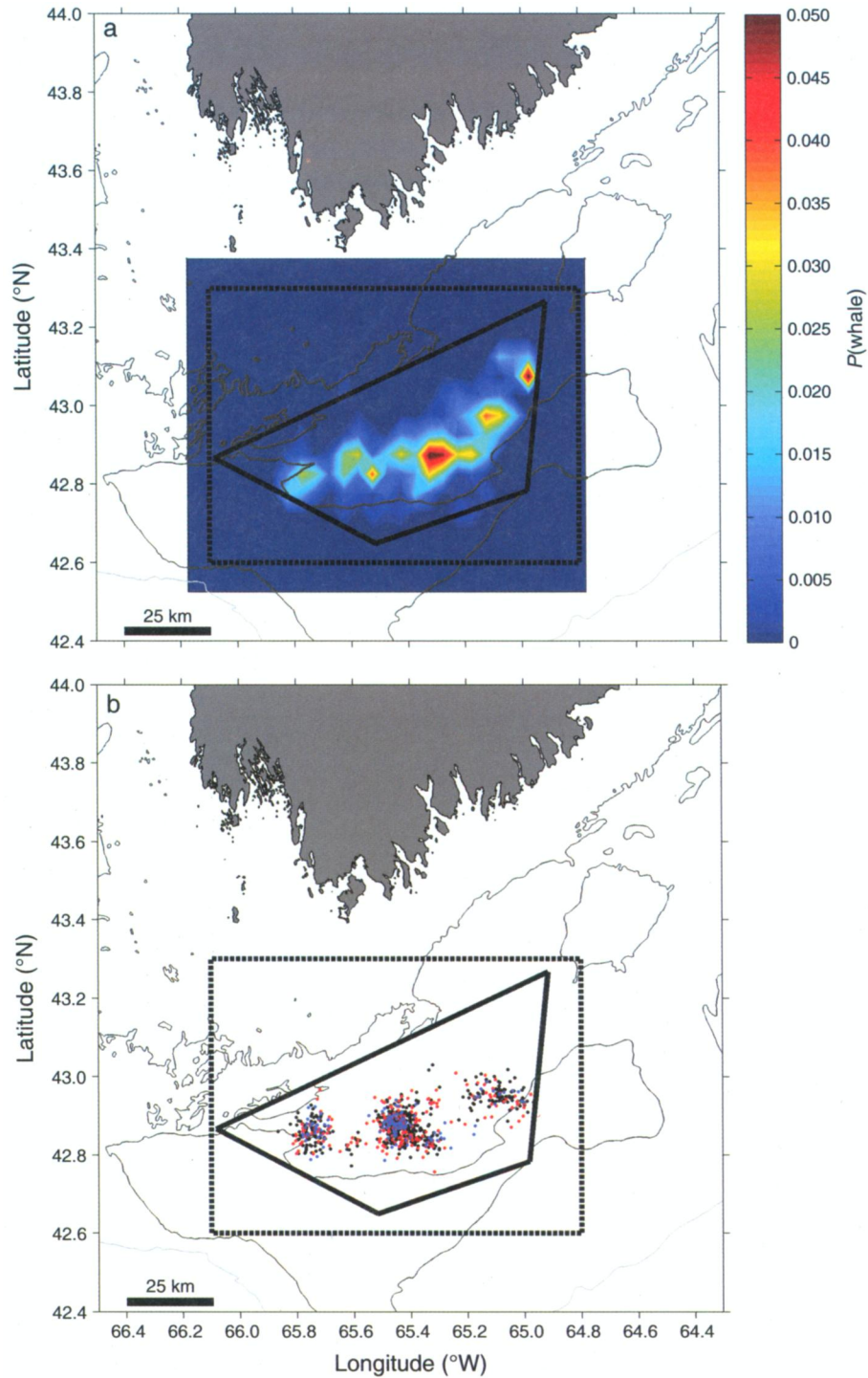


FIG. 1. The Roseway Basin region on the southwestern Scotian Shelf illustrating the model domain (black dashed line) enveloping the International Maritime Organization (IMO) “area to be avoided” (ATBA; black polygon) encompassing (a) the relative probability of observing a North Atlantic right whale (*Eubalaena glacialis*), $P(\text{whale})$, based on historical sightings per unit effort (SPUE) and (b) 1-h locations of five replicates of each 41 (black), 20 (red), and 10 (blue) whales as simulated over 24 h. Contours represent 100-m (dark gray) and 200-m (light gray) isobaths.

results from pre- and post-ATBA vessel data while holding the (minimum and maximum) population of whales constant.

Vessel data and navigation in the study domain

A network of dual-channel AIS receivers described by Vanderlaan and Taggart (2009) were used to capture transmissions from vessels navigating the Roseway Basin region. We used the AIS data collected over the period 15 June through 31 October for 2007 (prior to ATBA implementation), 2008, and 2009 (post-implementation). This study period envelopes the annual period of known right whale occupancy of the Roseway Basin feeding habitat (Winn et al. 1986, Vanderlaan 2010). Further, it includes the period of greatest reception range for AIS transmissions that decreases with changes in atmospheric refraction, air temperature and density. The AIS data were divided into 24-h periods and include date, time, vessel identification (Maritime Mobile Service Identity, [MMSI] and IMO number), speed (± 0.1 knot), and location ($\pm 1 \times 10^{-5}$ degrees latitude and longitude corresponding to approximately ± 1 m) logged at 1-minute intervals (dynamic data), and associated vessel specifications (name and length and beam, in meters) logged at six-minute intervals (static data). For some vessels, typographic error in the on-board transponder field entries associated with static data resulted in null or inappropriate data (e.g., beam > length). In such cases (41% of the unique transiting vessels), median values of length (99.5 ± 25.4 m) and beam (23.5 ± 3.67 m) of the remainder of the fleet were used.

The limiting temporal resolution of the model time-step, Δt , was determined to be 3.5 seconds according to

$$\Delta t = \frac{V_{l_{\min}} + Wl}{V_{s_{\max}}} \quad (1)$$

where $V_{l_{\min}}$ is the lower 95% CI (26.2 m) of the length distribution of the entire transiting fleet, $V_{s_{\max}}$ is the upper 95% CI (22.4 knots; 11.5 m/s) of the speed distribution of the same fleet, and Wl is the length of a typical adult right whale (16 m; Kenney 2002). This time-stepping resolution ensured that vessel and whale intersections were not missed by a fast-moving vessel that “jumped over” a slow-moving whale in a single time step.

Vessels entered the model domain at the time that their first AIS transmission was located within the domain and from this point they continued on their same heading until they exited the domain. This simplification is well-justified as constant-heading navigation is characteristic of traffic in the Roseway Basin region (see Fig. 2) and elsewhere (Statheros et al. 2008). Such navigation describes a habitual traffic pattern (HTP), defined as a path, lane, or course frequently navigated by vessels traveling between geographic locations (Vanderlaan et al. 2009). Two HTPs were apparent in the model domain (Fig. 2). Relative to the

ATBA, one HTP was oriented west-southwest–east-northeast (WSW-ENE) just north of the ATBA, and one was oriented southeast–northwest (SE-NW) through (Fig. 2a) or around the ATBA (Fig. 2b, c). Though few vessels did not navigate with a constant heading, modeling them as such served to simplify the navigational geometry of model formulation.

While in the model domain, each vessel maintained its average speed that was calculated over the duration of its transit. This assumption is valid given that the average of the standard deviation among unique-vessel speeds across all transits was 0.524 knot (± 0.696 SD; 0.270 ± 0.358 m/s). A proportion of the fleet transited the domain at or above a critical speed of 15 knots (7.72 m/s; Table 1). Above this speed the probability of lethal injury resulting from a vessel strike asymptotically approaches 1 (Vanderlaan and Taggart 2007). The average speed over the entire fleet and their transits decreased over the three-year study period (Table 1); vessel speeds were significantly lower in 2009 relative to 2007 (Bonferroni-corrected T ; $P = 0.0413$). Seemingly minor increases in vessel speed have significant impact on the lethality of a collision: an increase in vessel speed by 1 knot increases the odds of a lethal injury 1.5-fold (95% CI: 1.2–2.0) regardless of initial speed (Vanderlaan and Taggart 2007).

Vessels exited the model domain when they navigated beyond its bounds. If any part of a vessel transit was interrupted by loss of data reception, the model vessel continued at the calculated average speed and on the same heading as determined above. Interrupted AIS reception occurred for 17, 10, and 4 vessel transits in 2007, 2008, and 2009, respectively.

Whale data and movement in the model domain

The whale movement model was initialized daily using the sighting locations of 41 right whales located in the Roseway Basin region during a six-day, 639-km track line survey conducted over the period 26 August through 3 September 2009 (Brown et al. 2010). Locations were randomly chosen with replacement drawn from a suite of 41 possible (observed) locations where n whales ranged from as few as 1 or 2 to 6 (2009) and as many as 9 to 40 to 129 in 2006 (Table 2). The spatial distribution of the observed whales and the dispersion of simulated whales via modeled trajectories approximated the known probability distribution of right whales in the region (Fig. 1) and did not differ from the historical (1979 through 2007) spatial distribution of right whale sightings per unit effort (SPUE) data (generalized two-sample Gramér-von Mises test, $P = 0.1550$; Syrjala 1996).

The number of whales initialized in the model domain from year to year was varied based on the annual sightings data and interannual population size indices. Large interannual variability in right whale occupancy of the Roseway Basin feeding habitat is reflected in SPUE estimates of right whales in the region and in the

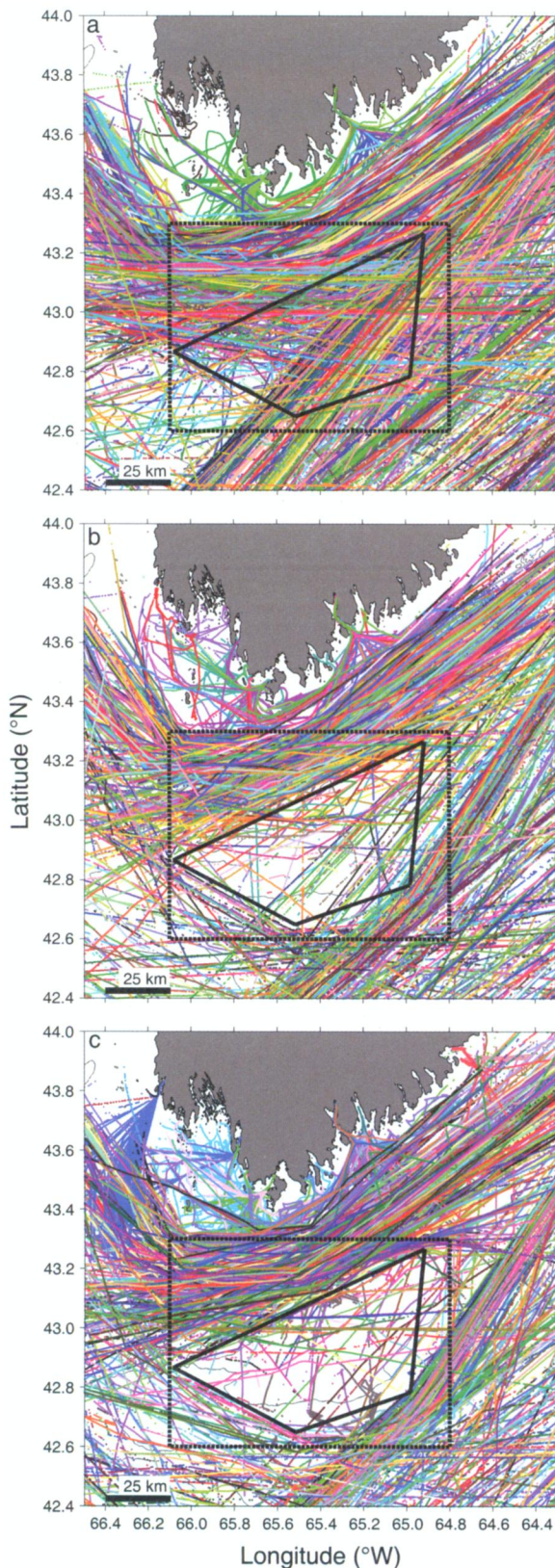


photo identification records of individual whales (Fig. 3). The interannual variability in the number of whales per year includes virtually complete abandonment in 1993, 1994, and 1996 through 1999 (Brown et al. 2001, Kenney et al. 2001), though survey effort was not constant across years. Although the SPUE estimates do not provide a population estimate, the number of photo-identified individuals per year in the region reasonably reflects fluctuations in the SPUE index (Fig. 3). Further, the number of catalogued individuals exceeds the current population estimate for the species, and a discovery curve of the number of catalogued individuals over time suggests that a very high proportion of the population has been identified (P. Hamilton, *personal communication*). Thus, the number of photo-identified individuals can be used as a minimum estimate of the number of whales occupying the area during a whale survey in a given year. Aggregate long-term average SPUE estimates (1979 through 2007) indicate that right whales occupy the region from June through October, with the highest abundance index occurring from late August through mid-September (Vanderlaan 2010), coincident with the time of the annual survey. Therefore, we assumed these minimum estimates above reflect the maximum population for the habitat.

We assumed that the number of uniquely identified right whales (Fig. 3) in each year represents their maximum abundance and used a smooth semimonthly interpolation to estimate, by proportion, the number of whales expected to be in the habitat on a semimonthly basis (Vanderlaan 2010: Fig. 7.2b). The 2009 sightings data had not been validated with NARWC abundance estimates, and the number of uniquely identified individuals in Roseway Basin for 2009 had yet to be determined. Therefore, we assumed no population change between 2008 and 2009 ($n=6$) but also simulated the maximum population ($n=129$) for these years

TABLE 1. Vessel identification information for 2007–2009.

Year	No. vessels	Speed (knots)	PVT ≥ 15 knots
2007	410	14.79 (3.64)	43
2008	347	14.69 (3.85)	38
2009	310	14.20 (4.02)	39

Note: Given are the number of vessels uniquely identified by the automatic identification system (AIS) that transited the model domain one or more times, the speed of all vessel transits through the model domain, and the percentage of vessels transiting the domain (PVT) at speeds ≥ 15 knots, for each year of the AIS data. Speed is given as mean with SD in parentheses.

←

FIG. 2. The Roseway Basin region on the southwestern Scotian Shelf illustrating the model domain (black dashed line) enveloping the International Maritime Organization (IMO) “area to be avoided” (ATBA; black polygon) and automatic identification system (AIS)-derived navigation tracks for each vessel and trip through the region from 15 June through 31 October (a) 2007, (b) 2008, and (c) 2009, where panels (b) and (c) follow the implementation of the ATBA.

TABLE 2. Vessel traffic data derived from the automatic identification system (AIS) and maximum and semi-monthly North Atlantic right whale (*Eubalaena glacialis*) population size used in all model runs over the years 2000 through 2009.

Year	Vessel traffic data	Maximum whale population	15–30 Jun	1–15 Jul	16–31 Jul	1–15 Aug	16–31 Aug	1–15 Sep	16–30 Sep	1–15 Oct	16–31 Oct
2000	2007	14	1	2	4	8	14	13	6	2	0
2001	2007	6	0	1	2	4	6	6	2	1	0
2002	2007	49	3	8	15	30	49	46	20	6	1
2003	2007	17	1	3	5	10	17	16	7	2	0
2004	2007	65	4	11	20	39	65	61	27	8	1
2005	2007	16	1	3	5	10	16	15	7	2	0
2006	2007	129	9	21	40	78	129	122	54	15	3
2007	2007	3	0	0	1	2	3	3	1	0	0
2008	2008	6	0	1	2	4	6	6	2	1	0
2009	2009	6	0	1	2	4	6	6	2	1	0

(Table 2) to cover the full possible range. Initial whale locations were varied for each 24-h period by “jittering” their observed coordinates by ± 200 m drawn from a uniform random distribution. Once initialized, subsequent whale movement occurred by means of an autocorrelated random walk, characteristic for animals with cephalo-caudal polarization (Fig. 4; Bovet and Benhamou 1988).

Autocorrelation was achieved by constraining the rate of change in direction of a swimming whale at each time step to a turning angle of no more than 22.1° per 10 m of swimming path derived as a weighted average of the upper 95% CI rate of change in direction estimated from observations of traveling, foraging, and socializing right whales (Mayo and Marx 1990). Swimming speed for each whale at each time step was chosen randomly from a uniform distribution of 0 to 1.23 m/s, where the maximum was based on the upper 95% CI of swimming speeds for satellite-tagged right whales (Baumgartner and Mate 2005).

All virtual whales were restricted to remain within the bounds of the ATBA that encompasses the known historical distribution of right whales in the Roseway Basin region. If a whale reached the border of the ATBA, it was replaced to its initial location, with “jittering,” where it then began to move again according to the defined algorithm. This restricts the possibility of whales immigrating or emigrating to or from the model domain and results in a “resident” population over the biweekly “statistical” periods used in the modeling. The length of the 139-d study period we used was based on the availability of AIS vessel data and was considered to represent a “year” as it is virtually identical to the long-term average residence time of 136.4 days (± 70.9 SE) estimated for right whales in the Roseway Basin region (Vanderlaan 2010) during the June through October period. Behavioral avoidance of vessels by whales was not included in the model as there is no evidence that right whales actively avoid vessels (Nowacek et al. 2004, Vanderlaan and Taggart 2007). The virtual whales were considered to be at the surface at all times, moving only

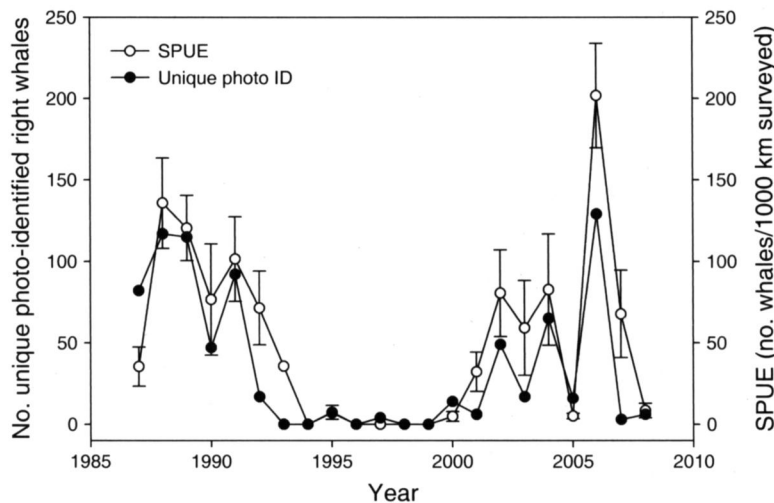


FIG. 3. Time series of annual right whale sightings per unit effort (SPUE, number of whales per 1000 km³ survey track; mean \pm SE) and number of individual photo-identified right whales in Roseway Basin over the period 1987 through 2008 (NARWC 2008).

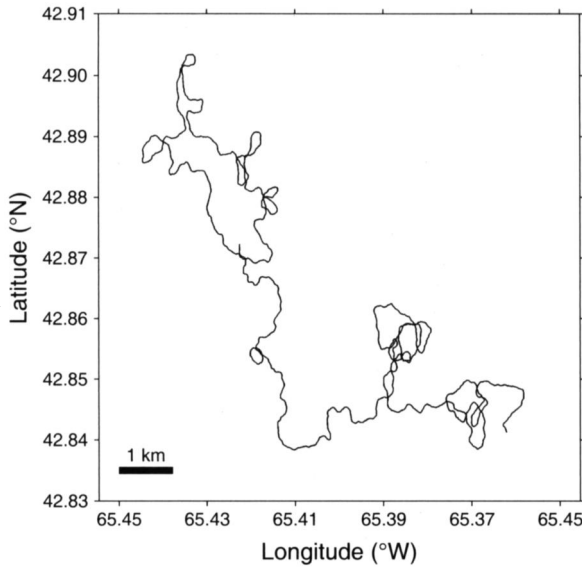


FIG. 4. Trajectory of an individual right whale modeled using an autocorrelated random walk over a 24-h period.

in two dimensions. This unrealistic behavior is addressed in *Probability of a lethal vessel strike*.

Modeling vessel and whale intersection

The time-stepping model was used to combine the real-time vessel navigation and virtual whale movements and to determine the number of times that a vessel and a whale intersected in time and space. The positions of each whale and vessel in the model domain, and the distance between all whales and all vessels, were calculated at every 3.5-s time step. The length and beam of each unique vessel was represented in the model by its rectangular element with its geographic position located within the center of the rectangle. The virtual whales (16 m length) were represented as a point within a circular element with an 8-m radius as a whale may be heading in any direction at the time it intersects a vessel. To simplify model calculations with the whale as a point on the geographic plane the rectangular domain of each vessel was expanded by 8 m on all sides to account for the radius of a whale (Fig. 5). Thus, an intersection occurs when a whale (point) intersects any part of the expanded rectangular domain of a vessel at any given time step. In the event of an intersection between a vessel and a whale, the whale was assessed for strike and lethal probabilities and removed from the model for the remainder of the model day (reinitialized on the subsequent day) and the vessel continued on its predetermined course.

Probability of a lethal vessel strike

If a vessel and whale intersect in the model, N_T , we then estimated the probability that the whale was at the surface, P_{surf} , and if so, the probability that the strike was lethal, P_{leth} . To do so, we used a constant $P_{surf} =$

0.20 based on the average submergence time across all whale behaviors exhibited by tagged right whales (Mate et al. 1992). Day/night differences in the probability of a whale being at the surface have not been sufficiently investigated for inclusion in the model. Following Vanderlaan and Taggart (2007), and the associated collision physics described therein, the lethality, P_{leth} , of a vessel strike was determined by the speed of the vessel and the aforementioned author's logistic function

$$P_{leth} = \frac{1}{1 + \exp^{-(-4.89+0.41speed)}} \quad (2)$$

where speed is the vessel-specific speed. Thus, P_{leth} is unique for each vessel and whale intersection, and P_{leth}^i represents the probability of a lethal strike for the i th vessel and whale intersection (N_T) within a given period T .

To estimate the probabilities of lethal vessel strikes, 30 replicate runs of the 139-d model were completed for each year from 2000 through 2009 (Table 2). Within each model run, the number of vessel and whale intersections (N_T) over a period of T years was determined.

Using the lethal probabilities that are unique for each intersection (Eq. 2), we calculated the average lethal probability (P_T) of all intersections (N_T) over time T as

$$P_T = \frac{P_{surf}}{N_T} \sum_{i=1}^{N_T} P_{leth}^i \quad (3)$$

We then calculated the expected number of lethal vessel strikes for each model run as follows:

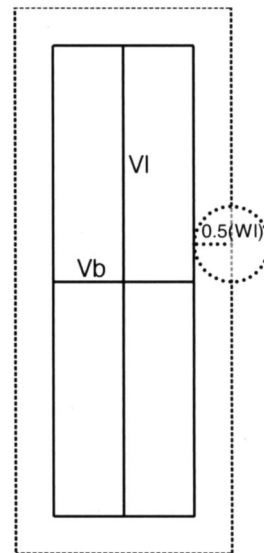


FIG. 5. Schematic of automatic identification system (AIS) vessel domain (solid black rectangle) defined by length (VI), beam (Vb), and the expanded dimensions (dashed black rectangle) that incorporate the circular dimension (dotted circle) of a point-position whale defined by half the length of a whale, 0.5 (WI).

TABLE 3. Model variables over 30 replicate model runs for years 2000 through 2009.

Year	No. whales	N_T	$E(X_T)$ (95% CI)	$P(x \geq 1)$
2000	14	3.83 (2.069)	0.590 (0.334–0.846)	0.441
2001	6	1.43 (0.935)	0.210 (0.144–0.271)	0.195
2002	49	11.6 (2.762)	1.76 (0.903–2.61)	0.836
2003	17	5.80 (2.007)	0.931 (0.558–1.30)	0.615
2004	65	12.1 (3.137)	1.89 (1.01–3.91)	0.855
2005	16	3.73 (1.981)	0.581 (0.272–0.891)	0.441
2006	129	29.6 (5.183)	4.29 (1.68–6.91)	0.987
2007	3	0.50 (0.634)	0.072 (0.060–0.084)	0.070
Pre-implementation mean (SD)		8.58 (9.53)	1.29 (1.38)	0.555 (0.327)
Median		4.82	0.761	0.528
2008	6	0.500 (0.777)	0.073 (0.054–0.092)	0.069
2009	6	0.367 (0.049)	0.059 (0.051–0.067)	0.060
Post-implementation mean (SD)		0.434 (0.094)	0.066 (0.010)	0.065 (0.006)
Median		0.434	0.066	0.065
2007	129	29.6 (5.18)	4.29 (4.02–4.56)	0.987
2008	129	5.73 (2.88)	0.757 (0.625–0.890)	0.525
2009	129	7.87 (2.35)	0.941 (0.818–1.06)	0.610

Notes: Variables include the maximum number of North Atlantic right whales (*Eubalaena glacialis*) (variable and held constant) inhabiting the model, the number of vessel and whale intersections (N_T ; mean with SD in parentheses), the expected number of lethal strikes [$E(X_T)$, with 95% CI in parentheses], and the probability of one or more lethal strikes [$P(x \geq 1)$]. On 1 May 2008, the “area to be avoided” (ATBA) in Roseway Basin was implemented by Canada and adopted by the International Maritime Organization (IMO). Pre-implementation thus refers to years before and including 2007, and post-implementation years after and including 2008.

$$E(X_T) = N_T \times P_T. \quad (4)$$

Given that P_T is a Bernoulli statistic (lethal or not), we assumed the probability distribution is approximated by the binomial, and the probability of exactly x lethal strikes occurring over T was estimated as $P_T(x)$ where

$$P_T(x) \equiv \binom{N_T}{x} \times P_T^x (1 - P_T)^{N_T - x}. \quad (5)$$

Thus, the probability of at least one lethal strike occurring over period T was estimated as

$$P_T(x \geq 1) = 1 - P_T(x = 0) = 1 - (1 - P_T)^{N_T}. \quad (6)$$

Eq. 6 was also solved to calculate the number of intersections (N_T) required for $P(x \geq 1)$ to exceed 0.95, given any specific value of P_T . The result was then divided by the average rate of intersection per year to determine the time period (T ; years) required for the probability of at least one lethal strike to exceed 0.95. This calculation allowed for the estimation of reduction in the rate of lethal strikes following ATBA implementation, as not enough time has so far elapsed to reach sufficiently high values of $P(x \geq 1)$.

Applying the known ratio of male (62.3%) and female (37.7%) right whale occupancy of the Roseway Basin feeding habitat (1980–2005; NARWC 2005, Vanderlaan 2010) allowed us to determine the number of gender-specific lethal strikes.

Statistical methodology

The Greenwood statistic (Stephens 1986) was used to determine whether the time elapsed between intersections was uniformly distributed. A chi-square test was

used to compare the number of periods (N_k) with exactly k intersections to the expected values, N_p , based on a Poisson distribution where

$$N_P(k, \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad (7)$$

and λ is calculated as the number of intersections, N_T , that occurred over a 139-d period.

A generalized two-sample Cramér-von Mises test (Syrjala 1996) was used to determine differences in the spatial distributions of (1) initial whale sightings data and the historical distribution of the population in the region, (2) intersection locations and the initialized daily whale locations, (3) intersection locations prior to and following the implementation of the ATBA. A Wilcoxon rank sum test was used to analyze changes in the number of absolute and per capita expected lethal strikes pre- and post-ATBA implementation. The relation between the maximum population of whales in a given year and the associated number of intersections in a given year was assessed with linear regression. All uncertainties are expressed as ± 1 SD of the mean, unless otherwise specified.

RESULTS

Given that a whale is found at the surface and that each strike is associated with a unique P_{leth} derived from the speed of the vessel, the expected number of lethal strikes, $E(X_T)$, ranged from 0.060 to 4.29 in a given year over the period 2000 through 2009, with a median of 0.586 per year (Table 3). Each year had independent estimates based on the number and time and space distributions of the resident whales and the number,

speed, and time and space distributions of the vessels involved in the intersections.

We estimated an average of 8.58 ± 9.53 (median 4.82) intersections (N_T), and 1.29 ± 0.202 (median 0.761) lethal strikes ($E(X_T)$) per year prior to implementation of the Roseway Basin ATBA, compared to an average of 0.43 ± 0.09 (median 0.434) intersections and 0.066 ± 0.021 (median 0.066) lethal strikes per year following ATBA implementation. The average probability of one or more lethal vessel strikes per year was reduced by almost an order of magnitude from 0.555 ± 0.327 (median 0.528) before ATBA implementation to 0.0645 ± 0.006 (median 0.065) following implementation (Table 3).

The variability in the number of intersections per year is most easily explained by the correlation between the number of whales inhabiting the model domain and the number of vessel and whale intersections ($r^2 = 0.91$). While the number of whales fluctuates over the study period (Table 2, Fig. 3), the number of vessels in the domain is more or less constant over time in the AIS data (Table 1). The annual per capita number of expected lethal strikes expressed as a proportion of the number of whales present significantly decreased from 0.036 ± 0.009 to 0.011 ± 0.002 following the implementation of the ATBA in the Roseway Basin in 2008 (Wilcoxon rank sum; $Z = -8.0734$, $P < 0.0001$; Fig. 6), a per capita reduction in lethal vessel strikes of 69%.

Aggregating the average data for all years yields the estimate of at least one lethal strike in 2.56 ± 0.154 years. However, when the time series is disaggregated into pre- and post-implementation periods, at least one lethal strike occurs every 2.07 ± 0.128 years for years 2000 through 2007, and average values for 2008 and 2009 indicate 41.0 ± 3.15 years must elapse for at least one lethal vessel strike to occur for a constant population of six whales and assuming consistent vessel compliance with the ATBA.

To validate the conclusion of reduced numbers of lethal vessel strikes following the implementation of the ATBA, we compared the model results from years with the same population size of whales ($n = 6$; 2001, 2008, 2009). While there is no significant difference (Wilcoxon rank sum; $Z = -0.1542$, $P = 0.878$) between the expected number of lethal strikes for all replicates in years 2008 and 2009, the expected number of lethal strikes is significantly greater (based on the number of whales observed in 2001) prior to the implementation of the ATBA (Wilcoxon rank sum; $Z = 4.7660$, $P < 0.0001$). We also ran the models using the maximum population size estimate of 129 whales and the vessel data from 2007, 2008, and 2009 (Fig. 6) to ensure that our results were not an artifact of the small number of whales in the model for the years 2001, 2008, and 2009 (Table 3). Again the expected number of lethal vessel strikes in 2007 was significantly higher when compared to 2008 and 2009 (Kruskal-Wallis; $\chi^2 = 59.52$, $P < 0.0001$).

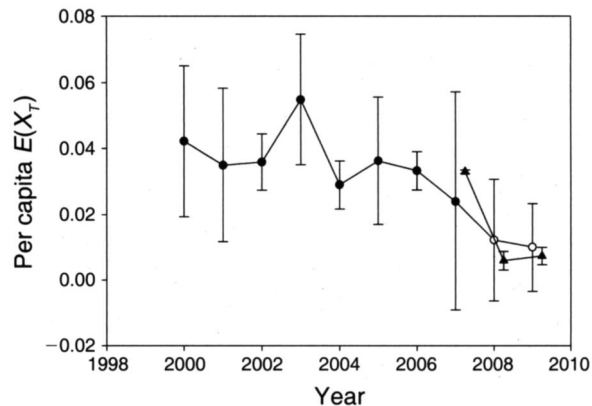


FIG. 6. Annual per capita number (mean \pm SD) of expected lethal vessel strikes [$E(X_T)$] over the period 2000–2009, where circles represent years prior to (2000–2007; solid circles) and following (2008–2009; open circles) “area to be avoided” (ATBA) implementation and for the years 2007, 2008, and 2009 with a constant population of 129 whales (solid triangles).

Male and female vessel strike mortality in the region was reduced from 0.804 ± 0.860 and 0.486 ± 0.52 individuals per year, respectively, to 0.041 ± 0.006 and 0.025 ± 0.004 individuals per year following ATBA implementation. Prior to implementation, one or more lethal strikes to males were estimated to occur, with 95% confidence, every 3.33 ± 0.206 years. For females we estimated one or more lethal strikes every 5.51 ± 0.341 years. The above estimates were reduced to every 65.8 ± 5.06 and 109 ± 8.36 years for males and females, respectively, following ATBA implementation, assuming a consistent gender ratio among the six resident whales and stable vessel compliance with the ATBA.

Analysis of intersections

Of the vessels involved in intersections, 49.1% were traveling at speeds ≥ 15 knots (7.72 m/s), the previously defined critically lethal speed. As a result, the average probability of a lethal strike, if the whale was at the surface, was 0.751 ± 0.202 .

The spatial distribution of intersections did not differ from the daily initialized points of right whales (Cramér-von Mises test, $P = 0.1930$; Syrjala 1996) and thus from the historical spatial distributions of right whales based on SPUE data. Similarly, there was no significant difference between the spatial distributions of intersections prior to and following the implementation of the ATBA (Cramér-von Mises test, $P = 0.2590$; Syrjala 1996).

Analysis of the temporal distribution of intersections indicates a highly irregular and nonuniform spacing of time intervals between intersections (Greenwood statistic, $G_{\text{obs}} \gg G_n$ for multiple replicates; Stephens 1986). Further, the observed number of intersections in a particular time interval were different from that expected from a Poisson distribution with $\lambda = 14.465$ (χ^2 test, $P < 0.001$).

DISCUSSION

The time-stepping model we used to combine the real-time transit of vessels through a population of simulated right whales, based on their known abundances and temporal and spatial distributions, allowed us to estimate that the probability of one or more lethal strikes occurring in the Roseway Basin region in a given year lies between 0.060 and 0.987. The potential for a lethal vessel strike to occur, at least once (>95% chance), was reduced significantly from every 2.07 years pre-ATBA implementation to 41.0 years post-implementation.

We estimated one lethal vessel strike every 0.775–2.07 years prior to ATBA implementation, consistent with previous relative probability estimates (Vanderlaan and Taggart 2009). The observed and historical lethal vessel strike rate in the region is one every 16 years (Vanderlaan et al. 2008), an extremely conservative estimate as Kraus et al. (2005) estimate that only 17% of right whale mortalities are observed and reported. Various correction factors have determined more reliable lethal vessel strike rates, resulting in estimates as high as one every two years in the Roseway Basin region prior to the implementation of the voluntary ATBA (Vanderlaan and Taggart 2009). The correction applied by Vanderlaan et al. (2009) was one of many variants, based on different assumptions that could be used to estimate the total number of whale mortalities attributable to vessel strikes. We present eight correction formulae (see Appendix) applicable to lethal strike estimation in the Roseway Basin region. Comparing the number of lethal vessel strikes expected by the modeled outcomes to those expected from previously established formulae can determine the reliability of specific correction equations. Eqs. A.1.0, A.2.1, A.2.2, and A.4.1 are likely unreliable as they provide estimates well outside the new estimate of one lethal strike within 0.775–2.07 years (excluding “forecast” estimates following ATBA implementation). Eqs. A.5.0 and A.6.1 reasonably approximate our modeled estimates and should not be rejected as reasonable estimators. Eqs. A.4.2 and A.6.2 appear to be most reliable as they provide estimates of one lethal vessel strike every 1.69 and 2.02 years, within the range predicted by modeling estimates. In the future, assuming lethal vessel strikes continue to be reported, use of the above equations could provide improved estimates of the “true” strike rate in regions where AIS data, or its equivalent, are unavailable for estimating lethal vessel strikes.

The implementation of the voluntary ATBA in the region as of 1 June 2008 resulted in a shift of the diagonal HTP to the southeast as vessels actively avoided the area. We estimated that voluntary vessel compliance with the ATBA, stabilizing at 71% in the first year of implementation, results in a 69% reduction in the per capita rate of lethal strike, an estimate that is considerably lower than 82% based on relative risk reduction provided by Vanderlaan and Taggart (2009),

who assumed constant whale probabilities pre- and post-ATBA implementation. However, we do estimate an 82% reduction in the expected number of lethal vessel strikes when comparing the 2007 model results to the 2008 results when using a constant and maximum population of whales. By assuming a constant number of whales among years, similar to the approach of Vanderlaan and Taggart (2009), the estimated reduction in the absolute expected number of lethal vessel strikes is equivalent to the estimated reduction in relative risk of a lethal strike for Roseway Basin.

The uneven proportions of male and female whales that occupy the Roseway Basin results in a predicted reduction in lethal vessel strikes occurring to a male and a female from every 3.33 and 5.51 years, respectively, pre-ATBA to every 65.8 and 109 years post-ATBA. This order of magnitude change has substantial and positive implications for the survival and population growth potential of the species. Though risk of lethal vessel strikes may be lower for females in this region, due to their limited occupancy, the potential remains, as evidenced by the lethal vessel strike of an adult female in the region in 2006 (see Plate 1). Recent estimates indicate right whale population growth has reached replacement levels; however, prevention of female right whale mortalities remains one of the most critical determinants of recovery potential for the species (Fujiwara and Caswell 2001).

The relative consistency and uniformity of vessel traffic in the model domain (Fig. 2), either pre- or post-ATBA implementation, but not when comparing pre- and post-implementation, implies that lethal vessel strike rate estimates are primarily a function of the number of whales present for this region. As the number of whales in the region approaches zero, so will the number of lethal strikes (Vanderlaan et al. 2008). Estimating the number of expected lethal vessel strikes per capita per year attempts to address the issue when making temporal comparisons and forecasting in systems where whale abundance varies. When making comparisons among different periods, and holding the number of individual whales constant, we demonstrate that the changes in vessel distribution as a result of new navigation policies can significantly decrease the expected number of lethal strikes to right whales, i.e., a direct measure of the effectiveness of a conservation initiative.

The straight-line vessel navigation we assumed in the model to simplify geometry likely had limited effect on intersection estimates, as the rate of intersection is determined only for regions where whales and vessels overlap and in this case the whale distribution is limited to the ATBA, i.e., it was explicitly designed to encompass the long-term whale distribution. The AIS data show that vessels turning during their transit do so primarily outside the ATBA, yet within the bounds of the model domain. Furthermore, those vessels that do turn primarily navigate northward and away from the

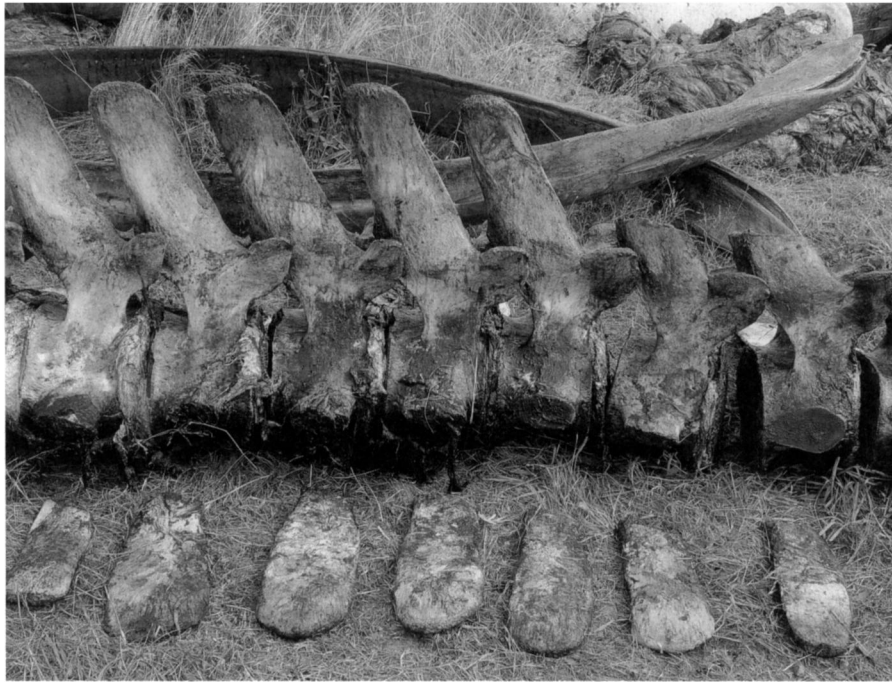


PLATE 1. Blunt-trauma associated fractures to the neural spines (two right-most) and transverse processes (all seven vertebrae shown) of a female right whale, MJM9406Eg, determined to have been struck by a vessel near Roseway Basin in 2006. In total, ten neural spines, 13 transverse processes, and two zygomatic processes were fractured. Note that the smooth cut surface (right-most vertebra) was sawed smooth for sampling purposes. Photo credit: Andrea Bogomolni, Woods Hole Oceanographic Institution.

ATBA, rather than southward to enter the region where they may coincide with whales.

Whale swimming was modeled using an autocorrelated random walk while employing a weighted average of turning angles across various behaviors, though activity budgets likely differ among whale habitats. Surface active groups (SAGs) are a behavior characteristic of right whales in the Roseway Basin region and are not explicitly included in the model, though sampling with replacement results in spatial patchiness and aggregation (Fig. 1). The existence of SAGs implies a greater proportion of time spent at the surface and thus greater risk of a lethal strike (Reeves and Kenney 2003). Applying a constant value of P_{surf} determines the presence or absence of whales at the surface and directly influenced the number of lethal strikes among the number of intersections. The model is sensitive to this parameter, though knowledge of diving and SAG behavior specific to the Roseway Basin region is limited. Nevertheless the model approximates the number of expected intersections between vessels and right whales and provides insights into the potential of lethal vessel strikes.

The estimate of lethal injury resulting from a vessel strike in the model incorporates vessel speed and not the closing velocity between the vessel and whale. Closing velocity could incorporate the angular velocity of the whale relative to the vessel (Silber et al. 2010), as a whale struck at the bow of a ship (i.e., a head-on strike) may

sustain a greater injury compared to a whale struck by the side of a ship (i.e., a glancing blow). We assume the angle of attack is inconsequential, as the average speed of vessels (14.56 ± 3.84 knots; 7.49 ± 1.98 m/s) greatly exceeds the maximum swimming speed attained by a modeled whale (1.23 m/s). Further, the probability of lethal injury resulting from a strike is calculated using the logistic function presented in Vanderlaan and Taggart (2007) in which the uncertainties around the model exceed the potential effect of a whale's maximum angular velocity.

We have presented a set of models to determine the regional effect of the implementation of a voluntary conservation initiative, the Roseway Basin ATBA, by means of calculating reductions in absolute vessel strike rates. All previous estimates of risk to marine mammals by the shipping industry, and the resulting policy considerations, have employed relative probabilities, primarily due to the nature of the data available for vessels and whales that do not provide absolute measures of their elements per unit area and per unit time (Vanderlaan et al. 2009). Increased knowledge of traffic systems through high-resolution AIS data can facilitate the formulation of routing amendments and allows compliance to be monitored (Fonnesbeck et al. 2008, Vanderlaan and Taggart 2009, Lagueux et al. 2011, Wiley et al. 2011). With improved whale abundance estimates, these models are capable of providing time-varying and population-corrected strike

rate reduction scenarios, transportable to any region where AIS data are available and for any species for which movement parameters have been defined.

The most recent vessel-related protection measures in the United States, “the ship strike rule” (NOAA 2008), includes a sunset clause that requires proof of conservation benefit before its expiry on 13 December 2013. Recent reports (Pace 2011) have indicated more elapsed time since implementation is required to determine the efficacy of the rule by using mortality frequencies and Bayesian change point analysis. However, AIS data are available for those areas where mandated speed restrictions apply. These data could be combined with a whale movement model as we provide here, and conditioned by observational data, to estimate lethal strike probabilities while simultaneously detecting areas of high and low compliance, thereby informing future rule-making considerations among regions.

The governments of Canada and the United States have acted in their responsibility to support and implement policies to reduce human-induced right whale mortalities in their respective waters (NMFS 2005, NOAA 2008, Brown et al. 2009). Designing vessel management strategies by means of re-routing or speed restrictions often poses a challenge to managers due to the perceived economic impacts (Knowlton and Brown 2007, Vanderlaan et al. 2009). Fortunately, governments and mariners alike show interest in cooperating to mitigate the vessel strike issue (Moore et al. 2007). Vessel-routing alterations and speed restrictions are generally applied on a case-by-case basis along the North American seaboard based on vessel traffic characteristics and economic concerns (Knowlton and Brown 2007, Elvin and Taggart 2008), though shifting vessel routes is preferable when feasible, compared to implementing speed reductions, as it minimizes the probability of a vessel-whale intersection rather than simply reducing the lethality of a strike should it occur (Vanderlaan and Taggart 2007). The ability to perform before-and-after calculations and to forecast the potential reductions of a given design facilitates planning and implementation of vessel routing amendments as a means to reach the goal of reduced negative human impact on large whales. We propose that the modeling approach provided here is one means of reaching the goal.

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SUPPLEMENTAL MATERIAL

Appendix

Estimation of right whale deaths by vessel strike (*Ecological Archives* A022-109-A1).