DRAFT Progress report on the use of photographic capture histories of individually identified North Atlantic right whales in the Southeast United States to make inferences about whale occurrence in the mid-Atlantic region.

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Summary

This report describes analyses of photographic capture histories of individually identified North Atlantic right whales from the Early Warning System aerial surveys in the Southeast United States, and surveys in Cape Cod Bay to estimate the timing of whale migration between the two regions. There was a significant correlation between both median and modal departure times from the SEUS and the total number of calves born in a season. Our current best estimates are that for years with moderate to high number of calves observed in the Southeast area, the modal date of departure is in the third week of February, that few whales will leave more than 10 days before that date and that travel time to Cape Cod Bay is about 19 days. A travel time of 19 days suggests a mean speed of 1.8knots which is consistent with observations from satellite telemetry.

Introduction

North Atlantic right whales migrating between feeding areas in the Great South Channel, Bay of Fundy, and Gulf of Maine and calving areas in the Southeast United States have to cross shipping traffic bound for ports along the mid-Atlantic coast. It is believed that whales often travel close to the coast and hence measures taken to reduce collisions in areas of shipping concentration close to port entrances could potentially be more effective than measures where shipping is less concentrated off-shore. Knowlton *et al*. (2002) describe available data on right whale distribution in the mid-Atlantic region.

The aim of this additional analysis was to supplement the Knowlton *et al.* (2002) report by considering what inferences could be made from data collected from Early Warning System (EWS) aerial surveys in the Southeast US. These surveys, which have been flown systematically between 1st December and 31st March since 1994, record sightings of right whales and also photographs for identification of individuals. The basic premise is that whales migrate south into the study region, are resident for some period of time and then migrate north. The northward migration is of particular interest because this includes mothers with calves that have been born on the Southeast calving grounds

Methods and Results

The joint distribution of arrival and departure dates in each year.

Whales arrive in the Southeast, remain for some time and then start their migration northwards. Considering each year independently, we estimated the parameters defining the distributions of arrival date and residence time by considering the probability of the sighting sequence for each whale identified in that year's EWS flights. We assumed arrival date has a Normal distribution and residence time a Gamma distribution. The scale parameter of the gamma distribution was related to the whales' arrival time so that whales arriving "late" stay for a relatively short time. Environmental triggering of any sequence of seasonal events must generate some negative correlation between the intervals separating those events. In this case the residence time scale parameter was reduced as a sigmoid function of arrival date with three parameters giving the magnitude, timing and duration of the reduction. Let $b(a,d)$ represent the probability that a whale in the selected year arrives on day a and leaves on day d, as defined by these parameters.

Whales within the survey area are subject to detection and identification by aerial survey, with a probability that is proportional to the fraction of survey miles completed and varies from whale to whale. The proportionality constant P was assumed to have a Uniform distribution between limits $P_{\min}$ and $P_{\max}$.

Then the likelihood of the sighting history for each whale is given by

$$L = \sum_a \sum_d b(a,d) \int_{p\min}^{p\max} P^s (1-P)^{(n-s)} \big/ (P_{\max} - P_{\min}) \tag{1}$$

where s is the number of sightings of that whale, n the number of surveys between a and d and the summation with respect to a and d is over all pairs preceding the first and following the last sighting. The likelihood was made conditional on the whale having been re-sighted at least once in that season by dividing by one minus the probability of no sightings or exactly one sighting. Whales that are not re-sighted provide no information on residence time. The log likelihood was summed over all whales detected during the season and maximized with respect to the eight parameters. The corresponding joint distribution for a, d and P then yields their marginal distributions in each year. For example, the following figure plots the marginal distributions for the arrival and departure dates in 1996 (the year with maximum number of whales identified) and compares the corresponding distribution of the probability a whale is resident on a particular day with a running average of the number of whales seen per survey mile:

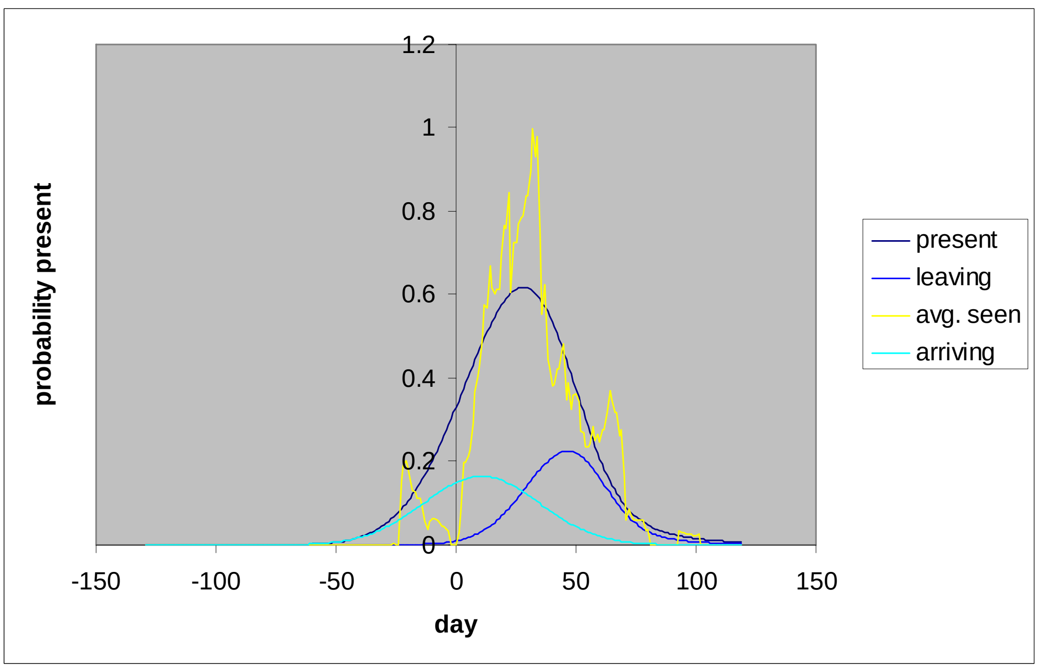

Figure 1

The next figure shows the change in the Gamma distribution of residence time over the 1996 season. The resulting marginal distribution of departure date is roughly symmetrical, which is atypical – in the other four years the number of sightings at the end of the season declined rapidly resulting in an estimated distribution of departure date with a sharp onset and a long tail to the right. The third figure shows the most extreme example, for 1998, but the rest of the years all show a similar pattern. It is possible that the initial pulse in departures is composed mainly of males. As more data becomes available we will repeat the analysis for males and females separately.

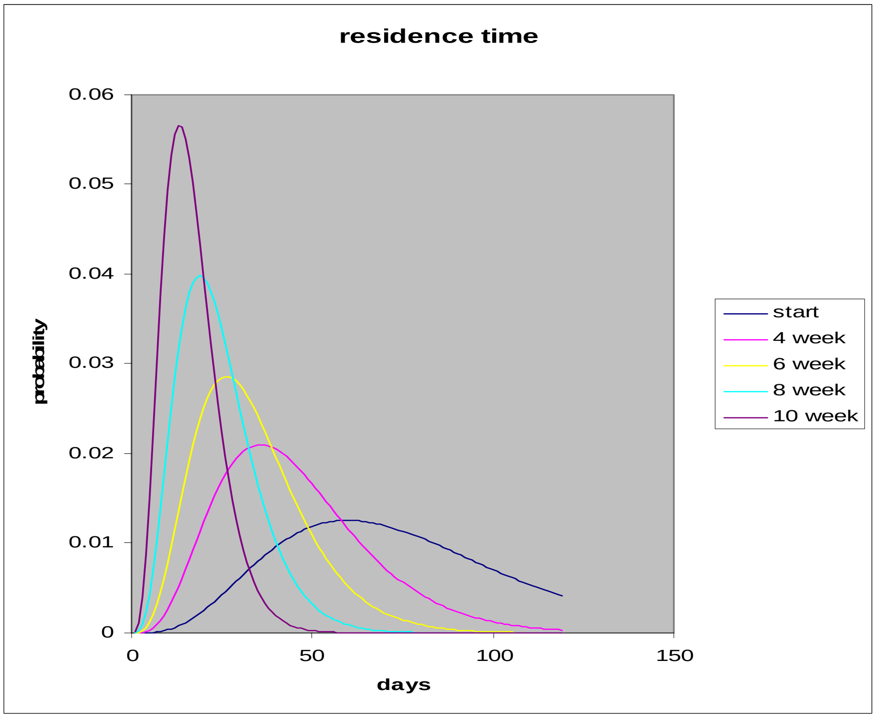

Figure 2

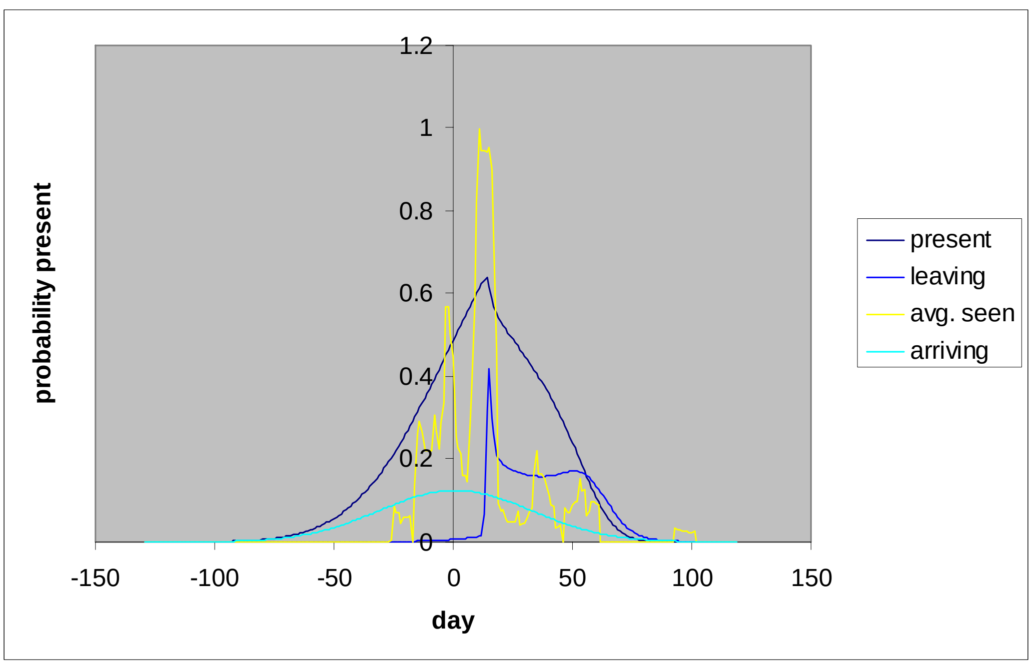

Figure 3

Departure date in relation to the numbers of calves

The following figure plots the modal and median values of the estimated departure date distribution against the number of calves seen during the surveys:

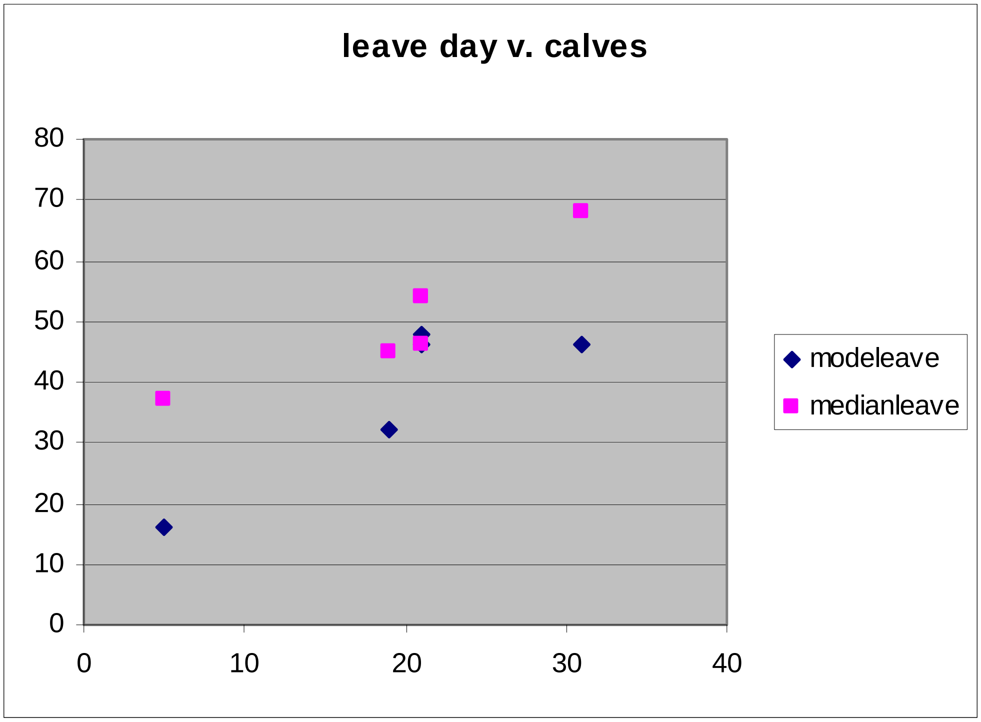

Figure 4

The plot shows an increase in both the modal and median departure dates with increasing number of calves seen and that the mode is generally well ahead of the mean, in accordance with the skewed distribution of departure date mentioned above. This relationship suggests that a prediction of the number of calves that will be seen in a future year could be used to predict, in turn, the distribution of departure date in that year. As the parameters defining the joint $b(a,d)$ distribution do not individually show a clear relationship with the number of calves, we regressed the individual $b(a,d)$ values on the number of calves to generate a "morphing" of the predicted departure date distribution as the predicted number of calves changes:

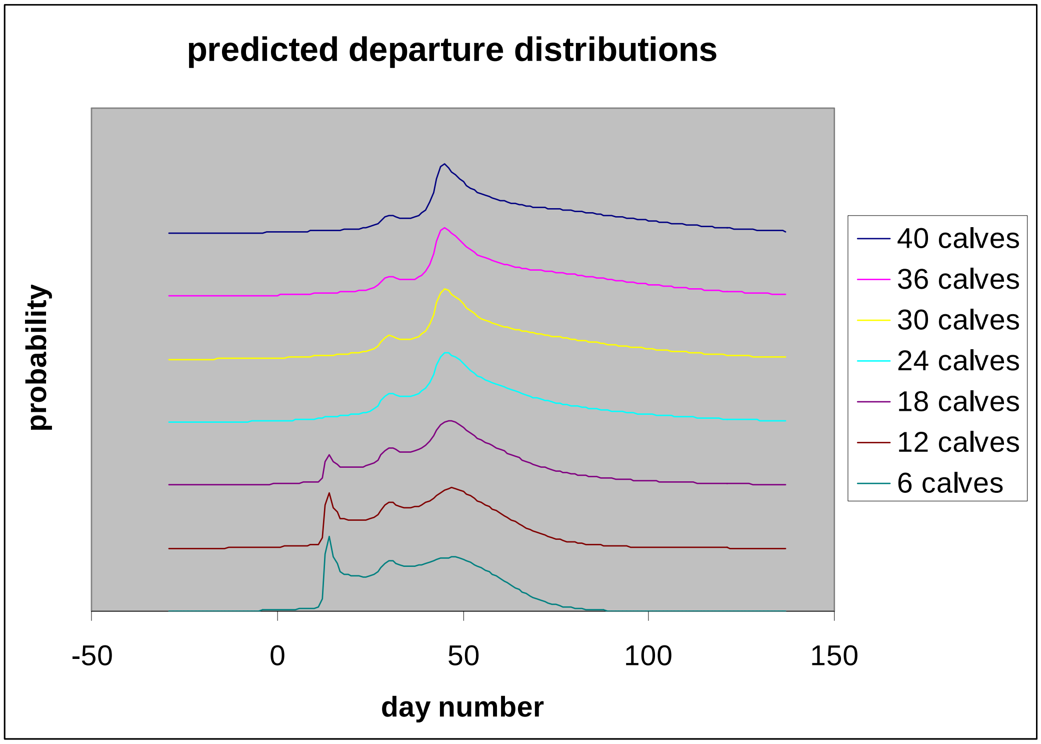

Figure 5

Conditional distribution of departure date

At the start of the survey sequence, before any whales have been seen, a predicted distribution of departure date might be based on a predicted number of calves, as in the above figure, or selected in some other way; for example, based on the $b(a,d)$ joint distribution estimated from the most recent survey sequence. Then, at any stage in the survey sequence, the departure date distribution for any whale identified by that stage could be conditioned on its sighting history up to that point. To derive the conditional distribution requires a prediction for the range of detection probabilities, in addition to a prediction for $b(a,d)$. Estimates for $P_{\min}$ and $P_{\max}$ from the five years of available data were reasonably consistent so their average values (0.09 and 0.41) could be used. The joint distribution for a, d and P, given the whale's sighting history, would then be proportional to $b(a,d)$ times the probability of that sighting history for a whale arriving and departing at a and d and with probability P of detection during a full survey. At any stage in the survey sequence the conditional probability would exist for all (a,d) pairs, but would equal zero for any pair that fails to bracket the survey dates on which that whale was seen. By summing the conditional distributions over all the whales detected and adding a contribution for whales undetected by that stage, we would obtain a departure distribution based on all available information up to that point. The section of that curve preceding the current date would give an estimate of the departure date distribution for a whale that had already left, the remainder of the curve a prediction for when a whale was due to leave.

The following figure compares such a summation of conditional distributions, derived by the completion of the survey sequence in 2002, with the departure date distribution corresponding to the ML estimates derived from the 2002 surveys. The conditional distributions provide an estimate of what actually happened over the survey period to a set of whales whose probability of departure on successive dates was given by the ML estimates.

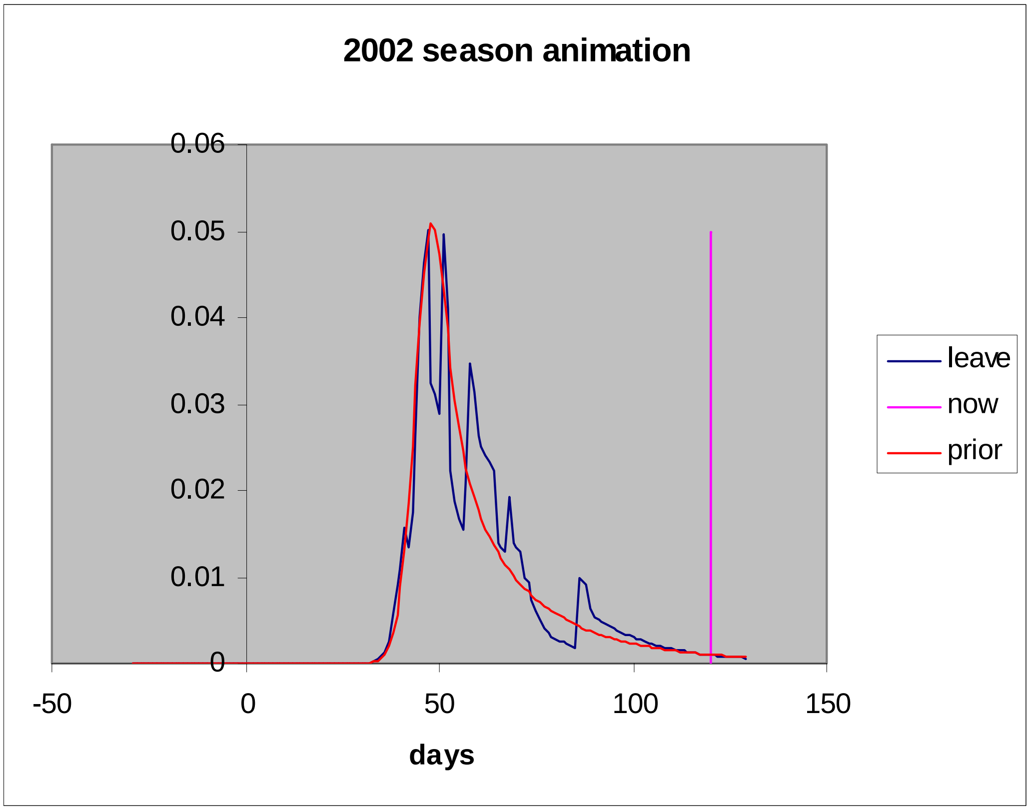

Figure 6

The conditional distributions provide the potential to enhance the prediction of future departure dates but unfortunately it takes about 30 days before the summed conditional distribution diverges significantly from the distribution given by the ML estimates. The vertical line in figure 6 shows the point at which the summation of conditional probabilities (the "leave" curve in the figure) was calculated. The figure can be generated as an animation, with the vertical line moving from left to right and the "leave" curve continually updated. The peaks and troughs in the curve then appear at a lag of about 30 days behind the position of the vertical line. The reason for the lag is that, despite the intensity of the EWS surveys, the detection probability is too low on average and its range too wide to provide strong evidence that a whale has left until well after its last detection. In comparison to probable travel times the lag of 30 days is too long to provide enhanced prediction of the dates over which the whales will be vulnerable to ship strikes.

Travel times

Survey data from Cape Cod were used to derive the conditional arrival date distribution, for each whale identified, in the same was as described above for departure from the Southeast. For those whales identified in both areas we then compared the conditional expectation of departure from the Southeast with the conditional expectation of arrival in Cape Cod in order to estimate the travel time between the two areas. On the assumption of a steady rate of progress between the two areas the travel time estimates would then provide a prediction for the period between departure from the Southeast and arrival at any intermediate position where the risk of ship strike is high.

The following figure shows the frequency distribution of travel times estimated from the three years in which whales were re-sighted in both areas: 1996, 1997 and 2001. Most of the travel times estimated from 1997 and 2001 are in the range two to three weeks. Those from 1996 cover a much wider range and are much larger on average. It is possible that whales in 1996 moved more slowly but more likely that travel times estimated from 1997 and 2001 represent migration from the Southeast to Cape Cod directly whereas in 1996 most whales moved to other areas before arriving in Cape Cod. The average travel time estimated from 1997 and 2001 was 19.2 days.

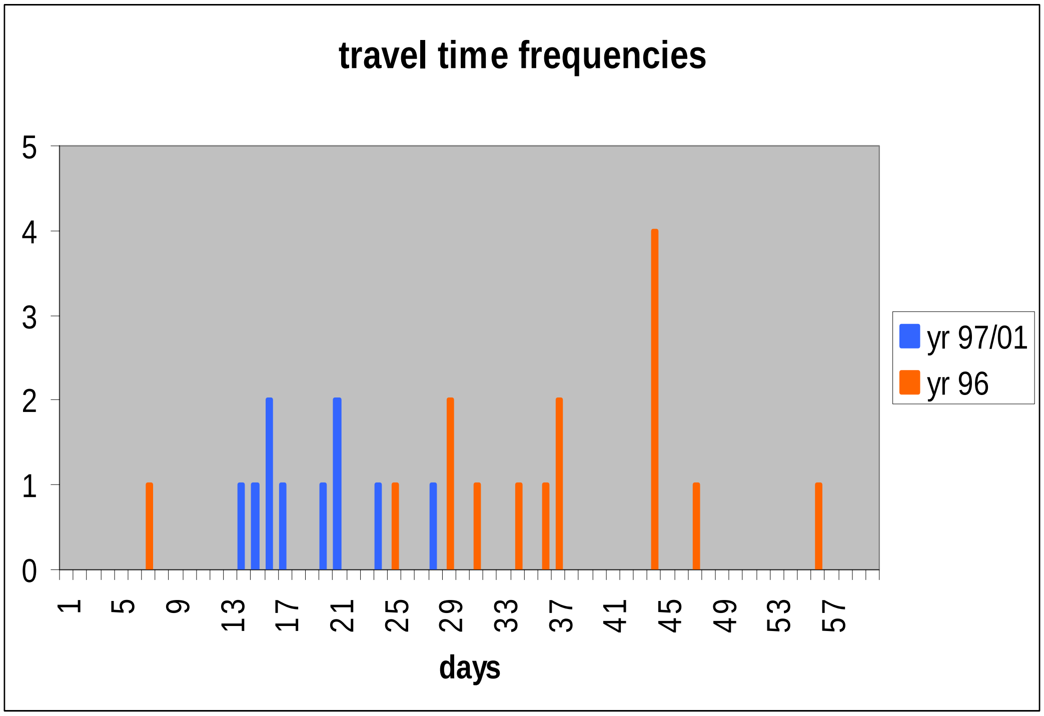

Figure 7

Discussion

We derived estimates for the probability distribution of date of departure from the Southeast by proposing a stochastic model for the arrival/departure process and combining that with a model for detection and identification of whales by the ESW surveys to calculate the probability of observed re-sighting histories. Maximising that probability with respect to the model parameters provided maximum likelihood estimates and the corresponding joint distribution for arrival and departure date was then summed over arrival dates to give the marginal distribution for departure date. Two aspects of those marginal distributions are relevant to the objective of predicting when whales on their northwards migration are at maximum risk of ship strikes. One is that the modal and median dates of departure increase with an increase in the number of calves counted during the surveys. A prediction of that number in a future year could thus be used to predict, in turn, the modal and median departure dates. The other is that the onset of the departure phase is rapid whereas its decline is slow, so that the start of a high-risk period at an intermediate latitude may be easier to predict than the end.

Estimates of departure dates from the Southeast were compared to estimates of arrival dates in Cape Cod to estimate travel times between the two areas. An average travel time of 19.2 days was estimated from the two years in which most whales appeared to move directly between the two areas. In the three years in which the highest numbers of calves were counted the estimated modal departure date was day 46 (in 1996 and 2001) and day 48 in (2002). So for a year with moderate to high numbers of calves counted in the Southeast (say 20+ calves) our current best estimate is that most whales will leave the Southeast during the third week in February and their expected arrival time at an intermediate latitude a fraction F of the way from the Southeast to the feeding grounds is 19F days later. The estimates suggest that few whales will leave more than 10 days before the peak time and as travel time is unlikely to be much less than 19 days, few whales should reach the intermediate latitude more than 10 days before the predicted peak date. We have no current estimate for the date at which the number of whales at an intermediate latitude is expected to decrease because the estimates suggest a much slower decline in the rate of departures and, whereas travel times can not be much less than 19 days, they could easily be more than 19 days if whales move very slowly or pause at other intermediate locations. However, estimates of the arrival date distribution for Cape Cod suggest that almost all whales identified there arrive before day 100 so that day 100 should provide an upper bound to the date by which whales will have passed any intermediate latitude. In addition, a travel time of 19 days for the approximately 900 nautical miles between the SEUS and Cape Cod Bay relies on a mean travel speed of 2.0 knots. This is very similar to the mean speeds observed from satellite telemetry studies. Mate et al. (1997) observed a mean swim speed of 1.9 knots for whales tagged in the Bay of Fundy that then left and a maximum mean of 2.5 knots for one individual over a distance of 416 n. miles. Mate and Baumgartner (2001) reported one tagged whale that travelled 1041nm in 23 days (mean = 1.9knots) from Brown's Bank to Georgia. Average speeds of tagged whales over the Scotian Shelf and Gulf of Maine were around 1knot. Thus the assumption of a steady rate of progress between the SEUS and Cape Cod Bay is consistent with telemetry studies

Our attempts to use sightings early in the survey sequence to enhance predictions for later in that same year were not successful because of the time delay required before those sightings modify the distribution of departure dates significantly. It may be possible to exploit detection probabilities estimated for individual whales and/or incorporate sightings within the same year in northern areas to improve the predictions later. However our next stage in the analysis will be to compare any sightings of identified whales at intermediate latitudes with our current predictions.