The following supplement accompanies the article

Movements and foraging habitats of great shearwaters *Puffinus gravis* in the Gulf of Maine

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Evaluation of time-step in fitting Argos locations with a switching state-space model

A total of 66 great shearwaters *Puffinus gravis* were tagged with solar or battery powered platform terminal transmitters (PTTs) in the Gulf of Maine. We fitted the Bayesian switching state-space model (SSSM) described by Jonsen et al. (2005) to all observed Argos location data to estimate spatial locations and behavior at fixed intervals of time using R package bsam v0.43-1. Details of the PTT information are provided in Table 1 in the main article.

A key component to the modeling function is specifying the time-step argument, which determines the number of estimated spatial locations and the behavior associated with these locations. When selecting this time-step, researchers must balance a desire for highly-temporally resolved location estimates (i.e., a greater number of estimated locations per day), with the resolution of the observed Argos data used to estimate these locations. As an extreme example, estimating 4 locations a day when the tags only recorded one position a week would likely be a misuse of the tagging data.

In our study, the majority (45/66 or 68%) of the PTTs in this study used a duty cycle of 8-h:on and 16-h:off. Thus, with a 3-h time-step, approximately 67% of the estimated locations from these PTTs on a daily basis were estimated during the off-cycle. In order to assure the validity of our estimated locations we separately evaluated tracks from 6 birds that used the 8-h:on and 16-h:off duty cycle across 4 different time-steps (t=0.5 or 12-h, t=0.375 or 9-h, t=0.25 or 6-h and t=0.125 or 3-h). These 6 birds showed a wide range of movement and differing sequences of behavior while they were in the Gulf of Maine. For comparison we also provide fitted tracks using only the 3-h time-step for 4 birds outfitted with PTTs that used a continuous duty cycle (i.e., 24-h:on). The continuous duty cycle was used on the other 32% (21/66) of the PTTs.

Without a formal metric for track evaluation, we visually inspected plots to assess how well the fitted tracks for each time-step compared with the observed Argos locations. We also conferred with Dr. Greg A. Breed (U-Alaska) to understand if there could be issues with using a 3-h time-step with a PTT that was disabled for 16-h per day. In our visual assessment, we looked primarily for track overruns (i.e., where tracks continue in a spurious linear direction outside of the observed data during a continuous "off" period) and differences in fitted track sequences between estimated locations relative to the observed Argos locations. To minimize any implications in the determination of state behavior we adopted a confidence interval around the parameter *b* obtained from the SSSM model where we delineated two behavioral modes using cut-offs at 1.25 and 1.75 (Jonsen et al. 2007). The SSSM analysis from 66 PTTs provided 17,816 estimated locations within the study area using a 3-hr time-step, of which 2,479 (14%) locations were eliminated from the behavioral analysis as uncertain behavior. The removal of such locations with uncertain behavior has an undetermined effect on any conclusions drawn from this analysis. However, if we compare behavior for duty-cycled tags to continuous-cycle tags, 22% (1637/7547) of locations for the duty-cycled tags yielded uncertain behavior vs. only 8% (860/10,269) for the continuous-cycled tags.

Thus, the confidence interval placed on the *b*-value removed a higher proportion of behavioral locations from the duty-cycled estimated locations.

The results of our plotted track comparisons for birds with an 8-h:on and 16-h:off duty cycle for 4 time-steps are shown in Figure S 1 to Figure S 6. Overall modeled locations with a 3-h time-step provided a better fit to observed Argos locations. Fitted tracks with this time-step also showed the least number of track overruns than longer time-step projections. Examples of track overruns are noted in the 12-h panel in Figure S 1 where there are no observed data to support the modeled locations and fitted track. Overall poorest fits were noted most often with the longest time-step (12-h) due to track overruns. That is, the resolution between estimated locations was often insufficient to correct for observed changes in the birds movement. The lack of observed locations during the PTT off cycle can be most problematic as shown in Figure S 2 where all time-steps modeled provided fitted tracks that incorrectly crossed Nova Scotia or were unable to show a movement path around this land mass. All points over land were filtered out of final analyses. But there would be no way for the model to correctly project a track south of Nova Scotia in the absence of critical data when the tag was disabled. In this case, we simply lost usable estimated locations. Conversely, a similar set of locations is noted in Figure S 3, but in this case we had observed locations south and east of Nova Scotia and the fitted track projects a more meaningful movement path.

Given our assessment, we moved forward with our analysis and used the 3-h time-step. The fitted tracks using only a 3-h time-step for 4 birds with continuous duty cycles are shown in Figure S 7. In all cases the fitted track is contained within the observed locations and no cases of track overruns are noted. Breed et al. (2011) found that regular small-scaled observations are better suited to recover modeled locations and behavior. In this study the intermittent infrequence of observed locations caused by duty-cycled tags sometimes resulted in a loss of spatial and behavioral information. However, we were able to minimize those losses with use of a smaller time-step projection in the SSSM, which provided more meaningful changes in shearwater movement patterns, and with a confidence interval on the behavior values.

REFERENCES

Breed GA, Costa DP, Goebel ME, Robinson PW (2011) Electronic tracking tag programming is critical to data collection for behavioral time-series analysis. Ecosphere 2:1-12

Jonsen ID, Mills Flemming J, Myers RA (2005) Robust state-space modeling of animal movement data. Ecology 86: 2874-2880 [suppl]

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Petrie B, Drinkwater K, Gregory D, Pettipas R, Sandstrom A (1996) Temperature and Salinity Atlas for the Scotian Shelf and the Gulf of Maine. Canadian Technical Report of Hydrography and Ocean Sciences 171, Bedford Institute of Oceanography 398p

Figure S 1. Observed (Argos) vs. fitted (SSSM) great shearwater locations for PTT 96564a (duty cycle = 8-h:on and 16-h:off) are plotted using four separate modeled time-steps (12-h, 9-h, 6-h, 3-h). Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue. Dashed green circles denote examples of misplaced fitted locations in the track for the 12-h time-step panel only.

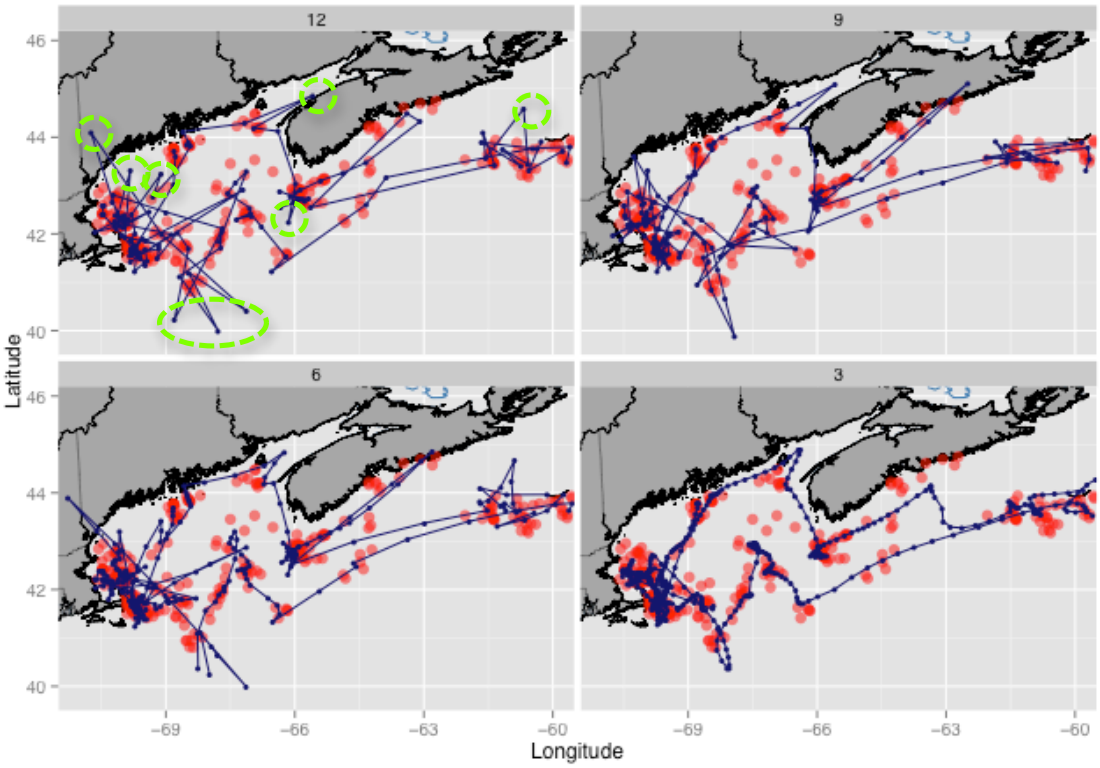

Figure S 2. Observed (Argos) vs. fitted (SSSM) great shearwater locations for PTT 67646a (duty cycle = 8-h:on and 16-h:off) are plotted using four separate modeled time-steps (12-h, 9-h, 6-h, 3-h). Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue. This bird should have tracked south and then north around Nova Scotia.

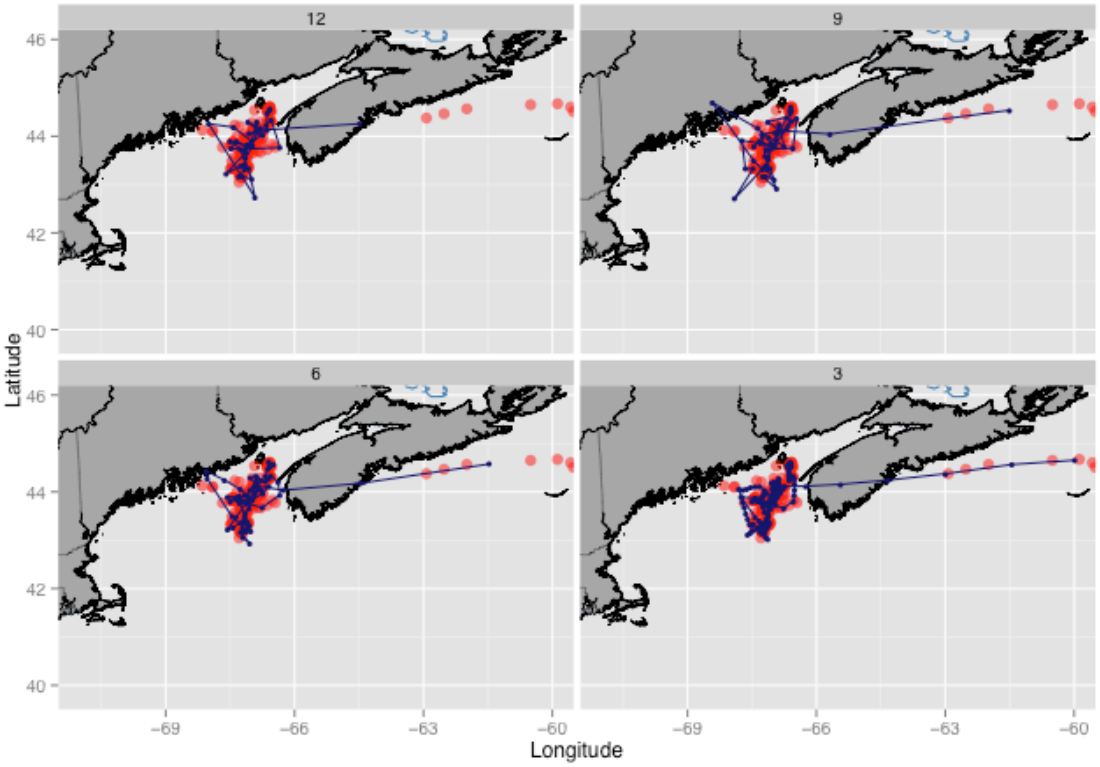

Figure S 3. Observed (Argos) vs. fitted (SSSM) great shearwater locations for PTT 84368a (duty cycle = 8-h:on and 16-h:off) are plotted using four separate modeled time-steps (12-h, 9-h, 6-h, 3-h). Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue.

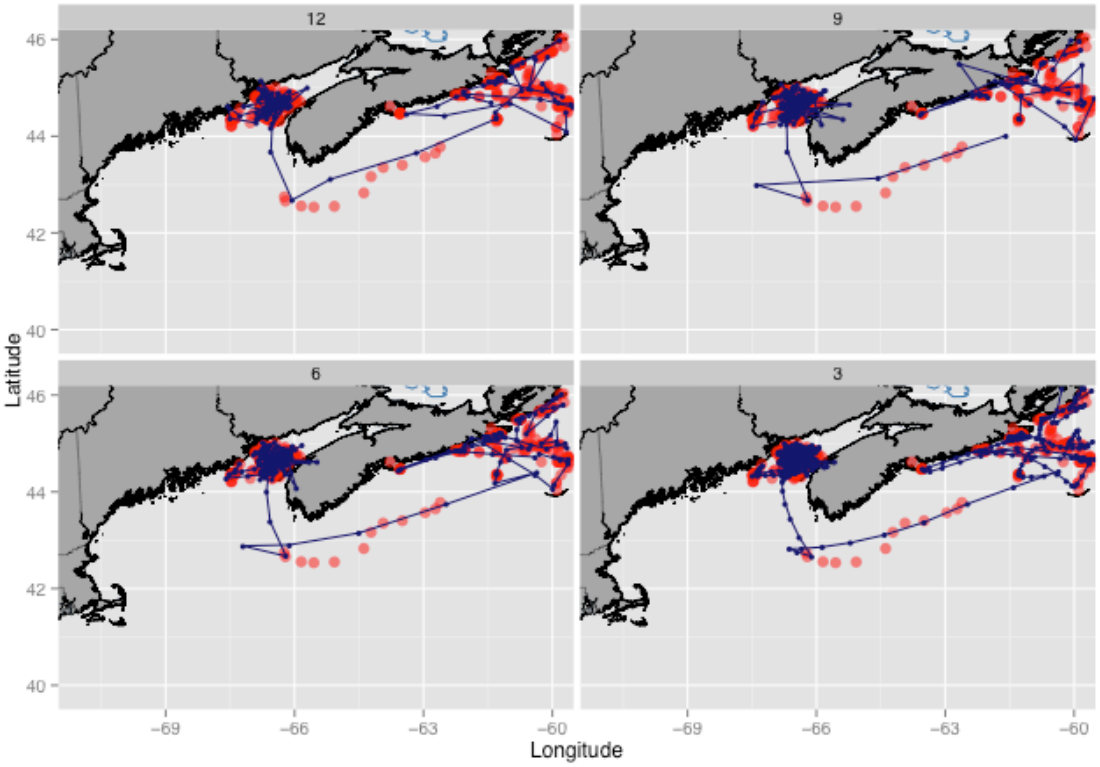

Figure S 4. Observed (Argos) vs. fitted (SSSM) great shearwater locations for PTT 95598a (duty cycle = 8-h:on and 16-h:off) are plotted using four separate modeled time-steps (12-h, 9-h, 6-h, 3-h). Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue.

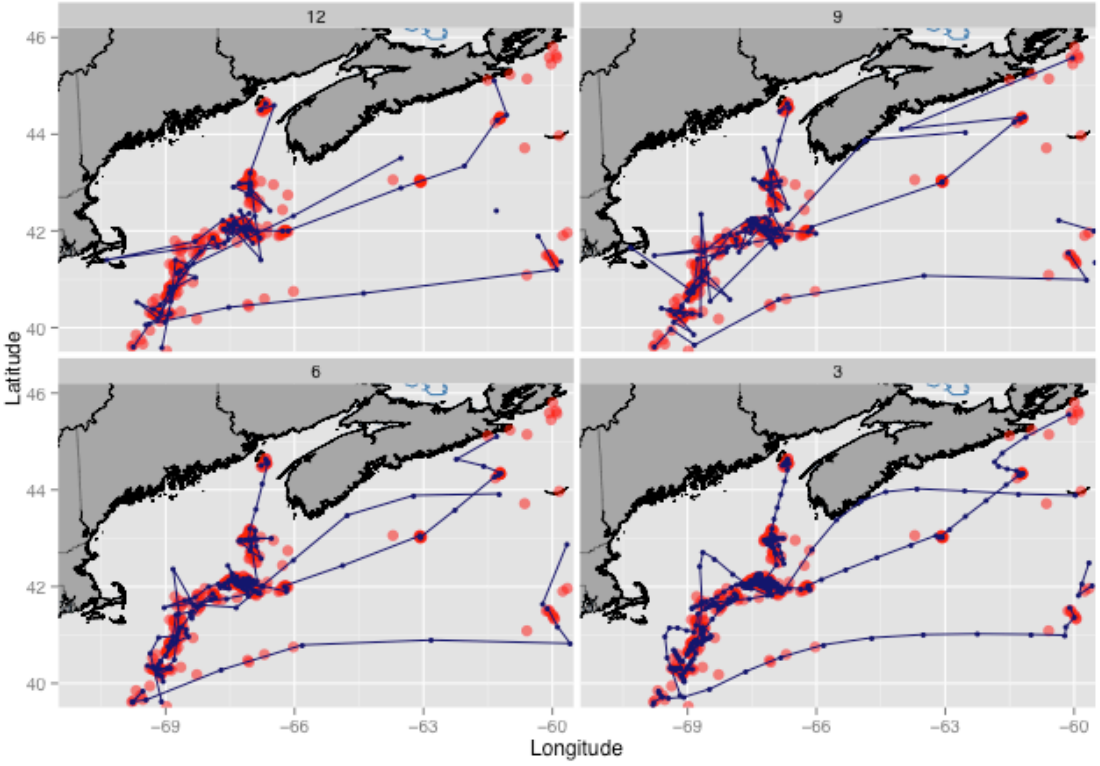

Figure S 5. Observed (Argos) vs. fitted (SSSM) great shearwater locations for PTT 106856 (duty cycle = 8-h:on and 16-h:off) are plotted using four separate modeled time-steps (12-h, 9-h, 6-h, 3-h). Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue.

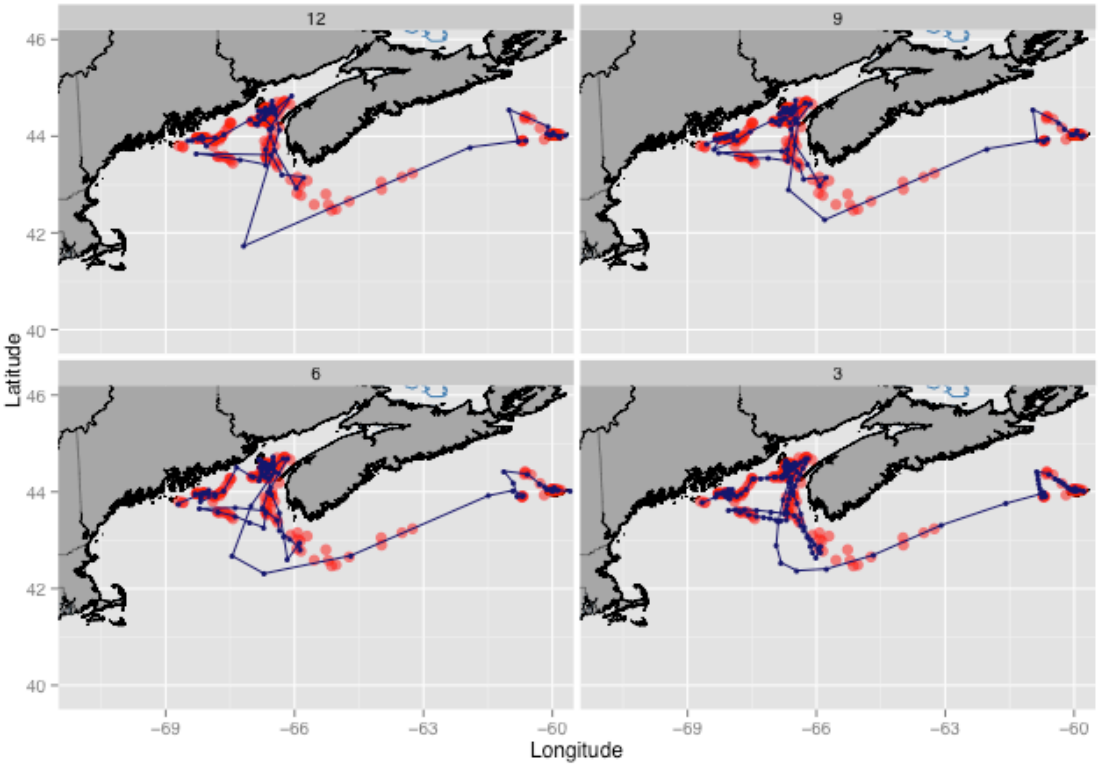

Figure S 6. Observed (Argos) vs. fitted (SSSM) great shearwater locations for PTT 106852 (duty cycle = 8-h:on and 16-h:off) are plotted using four separate modeled time-steps (12-h, 9-h, 6-h, 3-h). Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue.

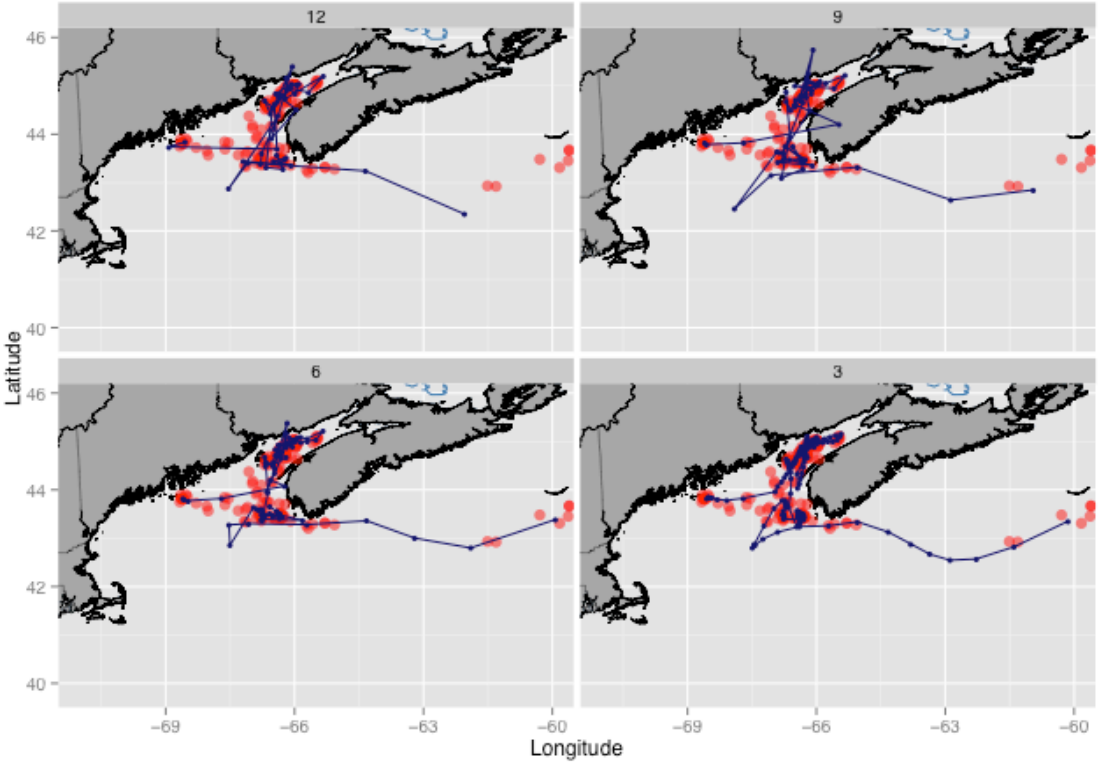

Figure S 7. Observed (Argos) vs. fitted (SSSM) great shearwater locations for 4 different birds (Plymouth, Wareham, Provincetown, Marblehead) with tags that used a continuous duty cycle are compared against a 3-h modeled time-step. Observed locations are noted in red. Sequential track line using fitted locations is shown in dark blue.