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Assessing beaked whale behavioral response to naval sonar using a hierarchical hidden Markov model

Recent advancements in biologging technology (SMRT and Lander II tags) have made it possible to record marine mammal posture, movement, and depth at sub-second resolution over periods of days to weeks, often in conjunction with surface geolocations and acoustic recordings. The resulting large, complex datasets promise rich insights into whale behavior and behavioral responses to acoustic disturbance, but also present new challenges in data processing and statistical analysis. First, development of standard tools to calibrate, process, archive, and document data from the new tags was necessary. Analysis then required integration of information at vastly different time-scales: for example, animal surface positions were collected no more than once per 10 minutes, while accelerometer data was sampled at up to 200 Hz. Biology also dictates characterization of behavioral responses at both fine and coarse temporal resolution, since some key metrics are best observed at high temporal resolution (e.g., fluke-stroke rate, specific acceleration), others much lower (e.g., inter-foraging bout interval, dive duration), and a few at both scales (step length, turning angle). To glean information from many varying-resolution data-streams and assess behavior at both time-scales within a single framework, we formulated a hierarchical hidden Markov model (HHMM) to model beaked whale behavioral responses to sonar simultaneously at coarse (foraging-dive-cycle) and fine (5-minute-interval) time scales. In the model, acoustic exposure covariates modulate probability of transition into a “response” state at the coarse scale, with distinct state-dependent distributions during response. At the fine scale, baseline and response states share the same state-dependent distributions, but rates of transition between states can vary. Preliminary results from the HHMM fitted to 10 tags deployed on Cuvier’s beaked whales (Ziphius cavirostris) identify behavioral responses to sonar including longer inter-foraging dive intervals, shorter bouts of echolocation at the coarse time-scale, and greater occupancy of the highest- and lowest-activity non-foraging states at the fine time-scale. Response probability was dependent on received sound level, but modulated by source-whale distance or sonar source type. Areas of ongoing work include incorporation of individual differences in responsiveness and a Bayesian formulation to better incorporate measurement uncertainty.