A novel application of Bayesian hierarchical models and recurrent event survival analysis to cetacean behavioural response studies

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Abstract: Measuring and quantifying the behavioural response of marine mammals to dis-

turbance is required for effective management and conservation. Field research to measure responses to acoustic disturbance is ongoing, but analysis and synthesis of the data remains a challenge. We consider data generated from Behavioral Response Studies (BRS) in the Bahamas (BRS07-08), California (SOCAL-BRS) and Norway (3S/3S2), during which simulated military sonar has been used to investigate behavioral responses of multiple cetacean species. We focus here on two analysis methods that have allowed us quantitatively to investigate exposure-behavioural response and exposure-response intensity relationships. Firstly, we have developed a Bayesian hierarchical model to relate expert-scored behavioural responses of multiple cetacean species to sound exposure level. The model allows for variation between species, between whales and between individual sound exposure sessions within the same whale. This model relies on choosing one response per exposure per individual, and we have focused on avoidance responses. The resulting exposure-response function contrasts sharply with current management approaches, predicting a substantial response probability at levels lower than previously assumed. Secondly, we have fitted a stratified Cox proportional hazards (PH) model to the same dataset. This survival analysis approach is well suited to the data: it accounts for the right-censoring in the data, but more importantly, it allows modelling of several types of recurring events associated with different doses of sound. The Cox PH model thus allows assessment of exposure-response relationships for responses of different intensities in one framework, and has also allowed us to investigate the relationship between social and environmental covariates and response severity.