Hidden Markov models identify regime shift from seabird at-sea-density in the Northern California Current

Caspian tern

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Ecological Indicators

Ecological indicators are widely used to synthesize information for scientists, managers, stakeholders and the public (Niemi and McDonald, 2004). Indicators can be used to detect and understand ecosystem changes, which can inform management decisions and allow for adaptive management. Past approaches for indicator development have often relied on expert opinion for the selection of indicators.

Selected indicators are then analyzed primarily using summary statistics to assess whether recent data diverge from long-term data—for example, if there is a trend in past 5-years (arrows) or whether the mean of the most recent 5-years differs from the long-term mean (+ and – symbols; **Figure 1**). Visual representations of indicators are also frequently used, such as "stoplight" charts which group indicator values into "good", "fair" and "poor" categories represented by a red/yellow/green color scheme (e.g. Harvey et al., 2020; Peterson et al., 2014).

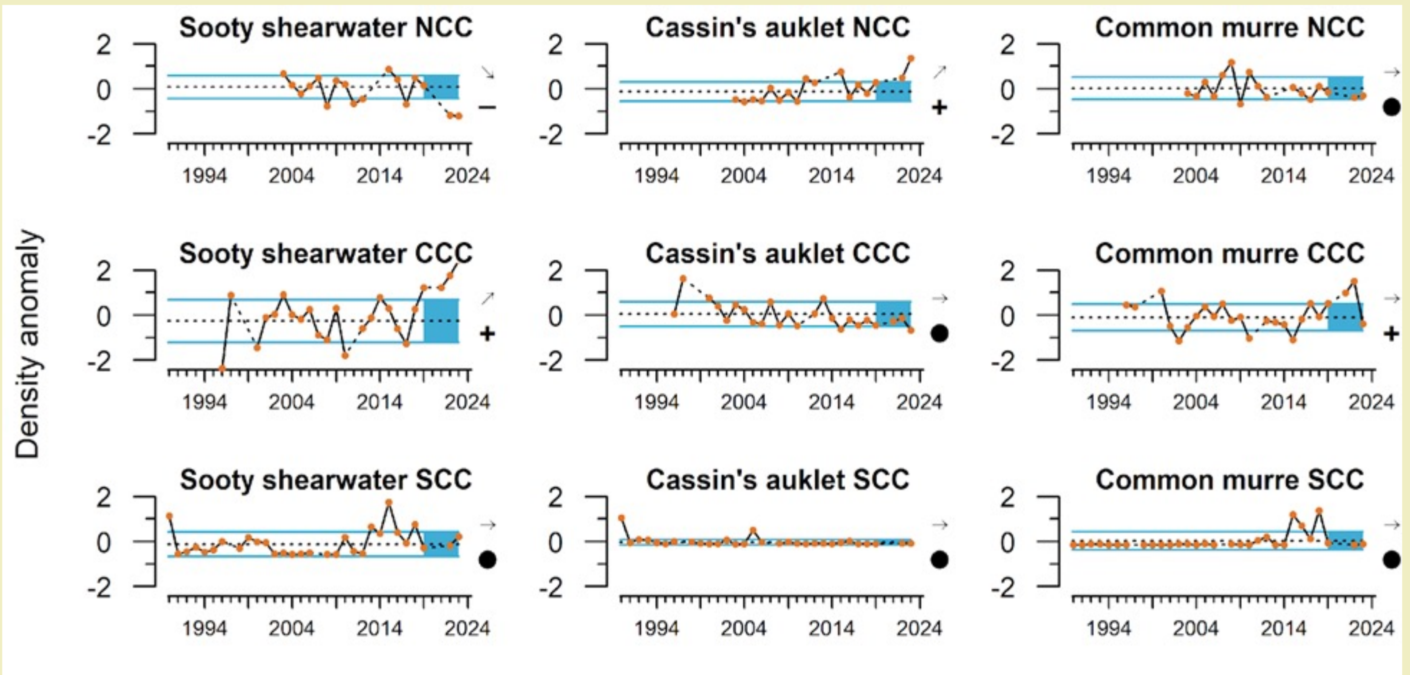

Figure 1. Time series of seabird density-anomaly ecological indicators used in the California Current Integrated Ecosystem Assessment. Arrows represent the most recent 5-year trend (↗ indicates increasing, → indicates no trend, and ↘ indicates decreasing) and symbols represent status of the 5-year mean relative to the long-term mean (+ indicates more than 1 s.d. above, • represents within 1 s.d. and – represents more than 1 s.d. below.)

Model-based approaches can advance the value of the ecosystem indicators. Models provide a more objective way to select indicators that represent a diverse range of responses to ecosystem processes, as well as to identify indicators that may be redundant due to providing similar information. Additionally, model-based approaches can account for non-stationarity, such as changes in the mean or variance over time.

Objectives

The purpose of this study is to develop model-based ecological indicators for non-stationary systems. We use seabird densities at-sea as a case study to demonstrate how hidden Markov models (HMMs) can be used to detect regime shifts when variance is changing over time, as well as to refine the list of indicator species.

Methods

Common murre

Hidden Markov models (HMMs) are a class of state-space model that provide a framework to distinguish underlying discrete states (regimes) from noisy time series data (McClintock et al., 2020). HMMs separate the observation process from an unobserved state process, assuming that each time series is an independent observation of the same latent state process (**Figure 2**).

For our case study, we used density-anomaly time series from 2003-2022 for nine taxa of seabirds collected on NOAA's Juvenile Salmon Ocean Ecosystem Survey (JSOES). Density-at-sea values were log-transformed (ln(x+1)) and expressed as anomalies by subtracting the long-term mean. We fit both two-state and three-state HMMs and chose the best-fitting model based on AIC. We assumed that all time series were normally distributed and had a constant mean (no time effect) and separate estimates of variance for each state. Models were fit using the package *hmmTMB* in R and the underlying state was calculated using the Viterbi algorithm.

Species used in model

Common name	Scientific name
Black-footed albatross	*Phoebastria nigripes*
Caspian tern	*Hydroprogne caspia*
Cassin's auklet	*Ptychoramphus aleuticus*
Common murre	*Uria aalge*
Northern fulmar	*Fulmarus glacialis*
Pink-footed shearwater	*Puffinus creatopus*
Sooty shearwater	*Ardenna grisea*
Western gull	*Larus occidentalis*
Western*Glaucous-winged hybrid gull	*Larus occidentalis x glaucescens*

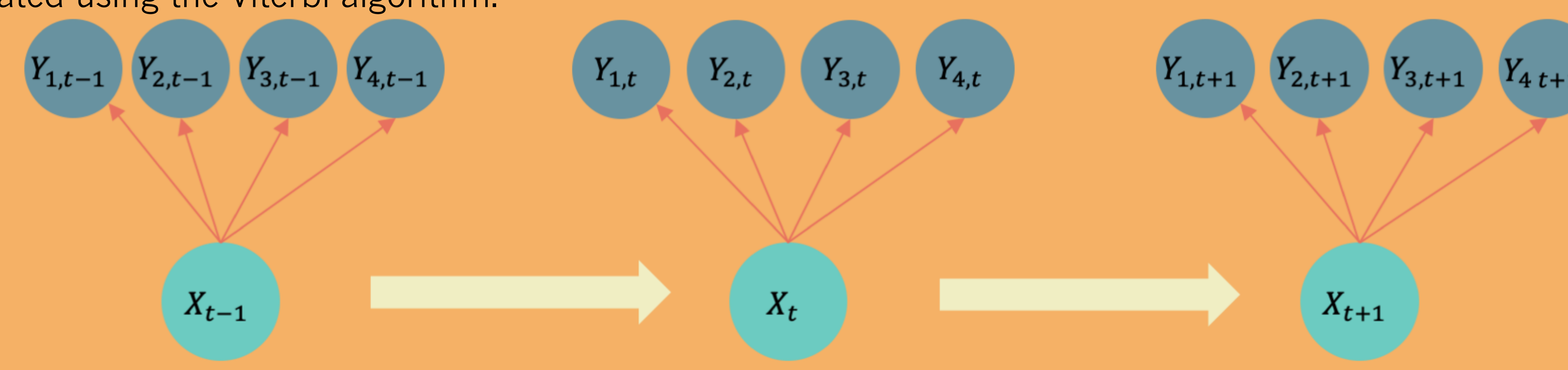

Figure 2. Diagram of multivariate hidden Markov model where X_t represents the underlying "hidden" state process and $Y_{i,t}$ the observations of a given indicator (i) at time t.

Regime Shift in Northern California Current

The best-fitting HMM was a two-state model with a shift between the first state and the second state occurring between 2010 and 2011. The difference between each state was primarily characterized by a difference in the estimated variance of density-anomalies (**Figure 3**). This is not something a traditional "stoplight" approach would have been able to easily detect.

This model highlighted taxa that respond differently to the regime shift. Common murres, Cassin's auklets, and sooty shearwaters are currently used as indicators in the California Current Integrated Ecosystem Assessment and were selected by expert opinion. Our model-based approach supports their inclusion as indicators because all three species responded differently to the regime shift in 2011.

Sooty shearwater

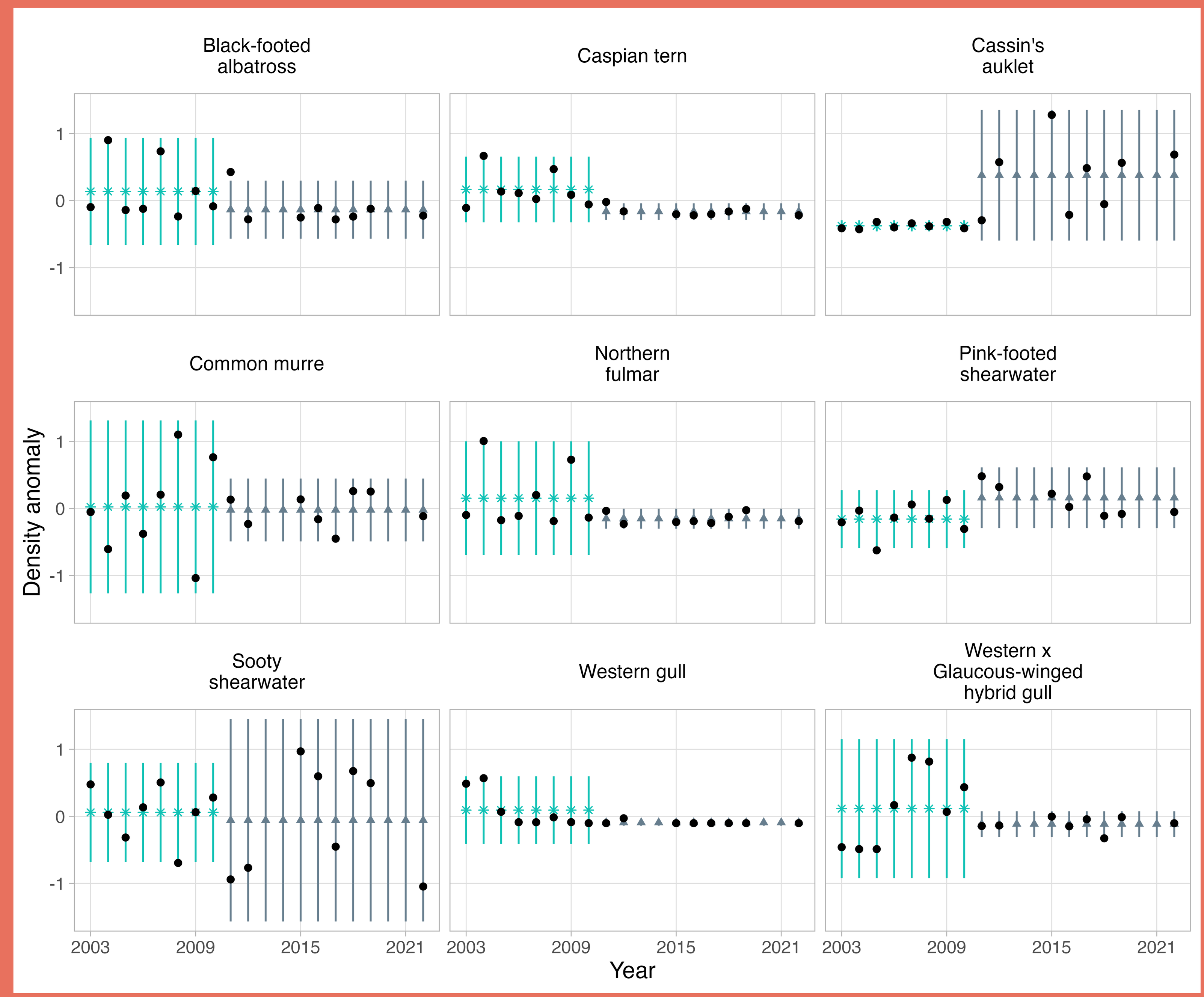

Figure 3. Model-estimated means (colored symbols) and 95 % prediction intervals (lines) for nine seabird taxa used in a two-state hidden Markov model. Logged density anomaly values for each taxon are indicated by black circles.

This model-based approach identified indicators which may provide redundant information. For instance, Caspian terns, northern fulmars, western gulls, and western and glaucous-winged hybrid gulls all responded similarly to our estimated regime shift, suggesting that adding all these species as indicators may not provide much additional information about ecosystem processes. However, because the estimated decrease in variance for these species was larger than for common murres, adding one of these species to the suite of indicators may provide useful information about ecosystem processes. Similarly, the density-anomaly of pink-footed shearwaters did not change significantly between the two states, suggesting that they may not be responding to the same ecosystem indicators as other species and could be another useful addition to the current suite of indicators.

Conclusions

- A model-based approach to developing ecosystem indicators can account for non-stationary time series, such as time series with changing variances, as well as highlight taxa that respond differently to estimated regime shifts.
- While HMMs validated the use of common murre, Cassin's auklet, and sooty shearwater as indicator species, other species could be added to the existing indicator portfolio because they provide additional information about ecosystem processes, especially if those species also represent unique life-history, foraging or migration traits; pink-footed shearwaters and norther fulmars could be potential additions.
- Hidden Markov models estimate the probability of transitioning between state and could be used to forecast the probability of moving from one state to another in a future year. These forecasts could be useful for earlier detection of regime shifts and therefore more effective responses from scientists, managers, and other stakeholders.

Western*glaucous winged hybrid gull

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Code and data used for this analysis can be found in our GitHub repository