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## Accounting for correlated observations in an age-based state-space stock assessment model.

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### Summary

Fish stock assessment models often rely on size- or age-specific observations that are assumed to be statistically independent of each other. A state-space assessment model that allow for correlations between age groups within years in the observation equation as well as in the process equation is presented and applied to data on four North Sea fish stocks using various correlation structures. In all cases the independence assumption is rejected, and the consequences of ignoring correlations is found to be quite severe - specifically for reported confidence bounds.

### Materials and Methods

The data used in this study consist of total catches and survey indices by age for haddock, herring, turbot, and whiting in the North Sea. Data were obtained from ICES assessment reports, except survey indices for herring and whiting, which were calculated using the methodology described in Berg *et al.* 2014 .

The stock assessment model used here is an extension of the SAM state-space assessment model (Nielsen and Berg 2014), but the observation equations differ in that they do not assume independence between age groups within a year:

$$\log C_y = (\text{catch equation}) + \varepsilon_y^{(C)} \quad , \quad \log I_y^{(s)} = q^* N_y + \varepsilon_y^{(s)}$$

Where  $C_y$  and  $I_y$  are vectors of catches and survey indices by age,  $q^*$  denotes catchability,  $\varepsilon_y^{(C)} \sim N(\mathbf{0}, \mathbf{\Sigma}^{(C)})$  and  $\varepsilon_y^{(s)} \sim N(\mathbf{0}, \mathbf{\Sigma}^{(s)})$  , and multiplication and division are element-wise. The covariance matrices  $\mathbf{\Sigma}$  are constructed via the vector of observation variances and the correlation matrix  $\mathbf{\Sigma} = \text{diag}(\boldsymbol{\sigma})\mathbf{R}\text{diag}(\boldsymbol{\sigma})$ . The following parametrization is used  $\mathbf{R}_{ij} = 0.5^{|d_i - d_j|}$  ,  $1 < i, j < N(f)$ , where  $N(f)$  is the number of age groups for fleet  $f$  ,  $d_1 \equiv 0$ , and  $d_2 \dots d_{N(f)}$  are parameters to be estimated with the constraint that  $d_i \leq d_j$  for all  $i < j$ . This corresponds to an AR(1) structure on an irregular lattice, where the lattice is defined by the  $d$ 's. If all  $d$ 's can be assumed equal the regular AR(1) structure is obtained. Finally we consider free unconstrained parametrization of  $\mathbf{R}$  (via its Choleski factor,  $\mathbf{R} = \mathbf{L}\mathbf{L}^T$  ). Model selection is carried out using AIC and the five following models are investigated:

1. All observations are independent ( $\mathbf{R} = \mathbf{I}$ )
2. Regular lattice AR(1) observation correlation structure for all fleets
3. Irregular lattice AR(1) observation correlation structure for all fleets
4. Unconstrained observation correlation structure for commercial catches and irregular lattice AR(1) observation correlation structure for all surveys.
5. Unconstrained observation correlation structure for all fleets

### Results and Discussion

For haddock and whiting the unconstrained covariance model (Model 5) has the best AIC, whereas the correlation structure for the surveys for herring and turbot could be reduced to the irregular lattice AR(1) covariance structure (Model 4). With the exception of haddock, the point estimate of the stock status from the best model is not changed much compared to Model 1. However, the confidence bounds are substantially wider in the last data year when accounting for correlations between observations. In contrast, for all stocks the total uncertainty on the on the stock status after a

3-year projection (as measured by the area of the joint confidence ellipses) is substantially smaller indicating more accurate predictions from this model. In conclusion, the usual assumption of independent observations is clearly rejected for all four stocks, and should be dropped as the default assumption.

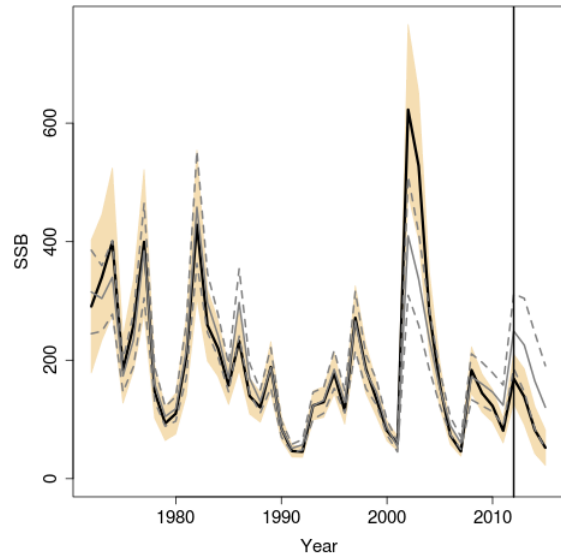


Figure 1: Haddock: estimated spawning stock biomass (SSB) from models 1 (grey/dashed) and 5 (black/shaded).

### References

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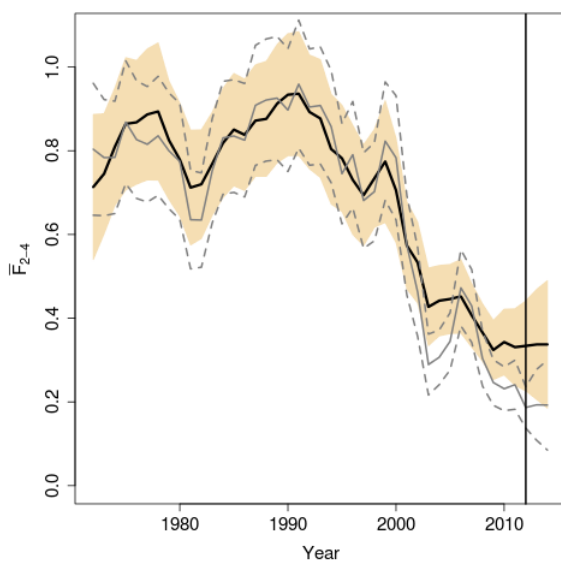


Figure 2: Haddock: estimated average fishing mortality over time from models 1 (grey/dashed) and 5 (black/shaded).

Table 1: Haddock: Akaike Information Criterion (AIC) and areas of the 95% joint confidence ellipsis for  $(\log \bar{F}, \log \text{SSB})$  in 2014 and 2017 relative to Model 1 in 2014.

Model	AIC	Var 2014	Var 2017
1	1014.71	1.00	6.98
2	981.25	1.43	7.41
3	944.85	1.48	5.22
4	925.00	1.30	4.16
5	<b>918.94</b>	1.40	4.34