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End-to-end model of Icelandic waters using the Atlantis framework: Exploring system dynamics and model reliability

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ABSTRACT

Icelandic waters are very productive and the fisheries are economically important for the Icelandic nation. The importance of the fisheries has led to progressive fisheries management and extensive monitoring of the ecosystem. However, fisheries management is mainly built on single species stock assessment models, and multispecies or ecological models are essential for building capacity around ecosystem-based fisheries management. This paper describes the first end-to-end model for the Icelandic waters using the Atlantis modeling framework. The modeled area is 1,600,000 km^2, and covers the area from Greenland through Icelandic waters to the Faroe Islands. The ocean area was divided into 51 spatial boxes, each with multiple vertical layers. There were 52 functional groups in the model: 20 fish groups (8 at a species level), 5 groups of mammals, 1 seabird group, 16 invertebrates, 5 primary producers, 2 bacteria and 3 detritus groups. The reliability of the model was evaluated using a skill assessment and a sensitivity analysis was conducted to understand the dynamics of the system. The sensitivity study revealed that saithe, redfish and tooth whales had the greatest effect on other groups in the system. The skill assessment showed that the model was able to replicate time-series of biomass and landings for the most important commercial groups and that modeling of the recruitment processes was important for some of the groups. This model now provides a solid basis for evaluating alternative ecosystem and fisheries management scenarios, and should produce reliable results for the most important commercial groups.

1. Introduction

Icelandic waters, where the relatively warm Atlantic water and the cold Arctic water meet, are very productive (Astthorsson et al., 2007). The annual harvest from these waters is around 1.3 million tones, which is 1.4% of the world´s harvest (Statistics Iceland, 2017). The fisheries are economically important for the Icelandic nation and they have, along with fish processing, accounted for 6–11% of the GDP and 37–63% of the exports since 2002 (Statistics Iceland, 2017). The highest catches are of capelin (*Mallotus villosus*), but cod (*Gadus morhua)* has the highest commercial value.

The importance of the fisheries has led to progressive fisheries management, and Iceland was one of the first nations to implement a quota system (Hilborn, 2007; Matthíasson, 2003). The ecosystem monitoring program is extensive and a bottom trawl survey is carried out twice annually (Anon., 2010) while acoustic surveys are conducted for pelagic species (Anon., 2016; Vilhjálmsson and Carscadden, 2002). The environmental conditions around Iceland are also monitored annually where nutrients, temperature, salinity and plankton is measured (Anon., 2015). In spite of extended datasets, including data on stomach contents, fisheries management advice is mainly built on single species stock assessment models for the most important commercial species (Anon., 2016). Nevertheless, there has been increased demand for ecosystem-based fisheries management (EBFM) in recent years. Single species models do not consider species interactions, which are an important factor in EBFM (Link, 2002). Multi-species and ecosystem models, where species interactions, and in some cases environmental factors, are considered are tools that can be used to support EBFM (Plagányi, 2007). Two preliminary food web models have been built for Icelandic waters (Buchary, 2001; Mendy, 1998), but have not been tested or used for fisheries management. A dynamic ecosystem model could support an EBFM and allow fisheries scenarios concerning the

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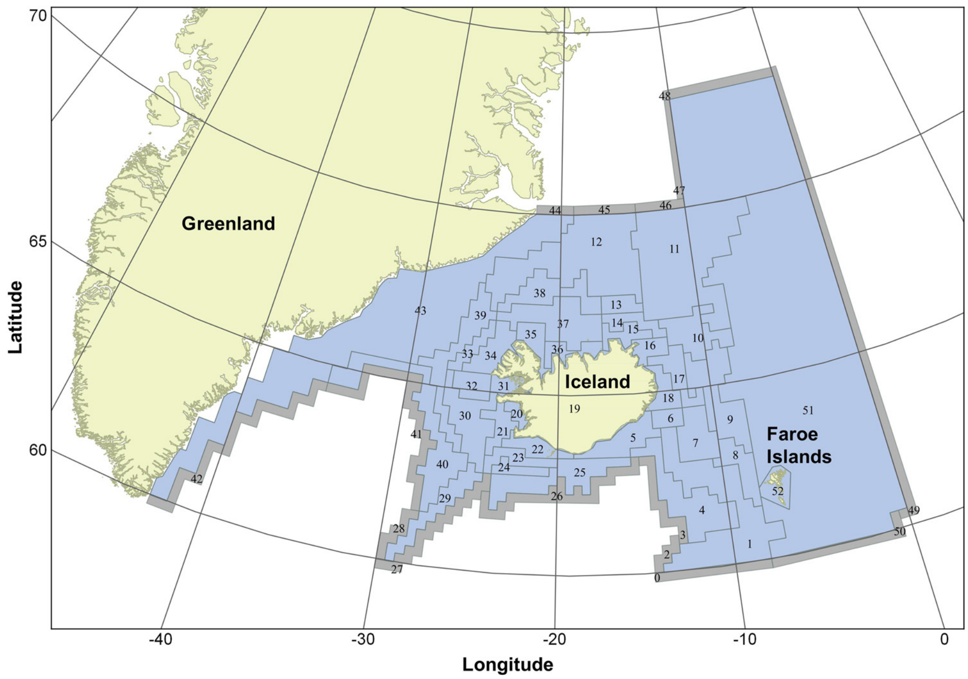

Fig. 1. The modeled area and the locations of the 53 spatial boxes. Active boxes are in blue and boundary boxes in grey. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

most important commercial groups, e.g. the effects of stop fishing capelin, an important prey species in the system, to be evaluated.

Modeling of marine ecosystems has increased in recent years, with developments in computational power, along with a growing understanding of ecosystem functioning and increased data sampling (Fulton, 2010). End-to-end models have become possible, where ecosystem and human components are integrated. They are not appropriate for tactical management advice (e.g., quota setting), unlike the single species models, but are useful to evaluate system-level trade-offs of alternative management strategies. Ecopath with Ecosim (EwE), a trophically-focused ecosystem model, has become widely used (Christensen and Walters, 2004; Fulton, 2010), but more complex models such as Atlantis are becoming more widely used (Fulton, 2010; Fulton et al., 2011; Nyamweya et al., 2016; Ortega-Cisneros et al., 2017).

Atlantis (Audzijonyte et al., 2017a, 2017b; Fulton et al., 2011) is a spatially resolved deterministic end-to-end model designed for exploited marine ecosystems. The modeling framework consists of four sub-models: biophysical, fisheries, management and socio-economic. It has been used to explore major processes and responses in systems (Kaplan et al., 2014; Nyamweya et al., 2016) and it has been used for management strategy evaluations (MSE, Fulton et al., 2007).

Different ecosystem models (e.g. Atlantis vs. EwE) for the same areas are not always consistent and have shown contradicting predictions (Forrest et al., 2015; Pope et al., 2018). Such an ensemble modeling approach can provide major insights into uncertainty around system structure and function. This is important as the modeling process for these models is subjective, as formal parameter estimation is prohibited by the complexity of the models. Instead, they are currently typically manually calibrated to historical data. This source of potential uncertainty means that even when not being used in an ensemble, a model skill assessment is an important means of determining how reliable models are, i.e. how well they fit to existing data and how well they predict (Olsen et al., 2016). The prediction ability of models is however usually not assessed because all existing data are used to calibrate the model (with subsequent use focused on relative projections rather than focusing on absolute predictions). Olsen et al. (2016) however performed a skill assessment on the predictive capacity of the Atlantis model for the northeast US, ten years after the calibration, when new data had been acquired. They recommend using a several metrics to assess the different aspects of the skill of the model, e.g. one that measures correlation and another that measures scale mismatch. They concluded that the forecasting skill of the model for the northeast US was comparable with the hindcasting skill, and did not degenerate for a medium-term forecasting.

Finding means of assessing uncertainties and performance for large ecosystem models is important, as they have both inherent structural and parametric uncertainty. Unfortunately, their size has meant traditional approaches to assessing parametric uncertainty (let alone structural uncertainty) have been impractical due to the curse of dimensionality, rapid growth of complexity in multi-parametric analyses and sensitivity to experimental design due to the feedback influences on time dependence of parametric sensitivity results (Fulton, 2010; Fulton et al., 2011). A sensitivity analysis can give insight into which parameters contribute the most towards uncertainty in the output (Pantus, 2007; Saltelli et al., 2006). However, a complete sensitivity analysis is not feasible for Atlantis because it has thousands of parameters and numerous possible interactions. Therefore, sensitivity analysis of Atlantis models have been carried out for each parameter one-at-time (Murray and Parslow, 1997) or for interactions between a selection of parameters, which are already known to have a strong influence on model performance or are particularly pertinent to that system type (Ortega-Cisneros et al., 2017).

This paper describes the first end-to-end model for Icelandic waters using the Atlantis modeling framework. The aim with this work is to describe the model, compare its output to available data and evaluate its reliability using a skill assessment. The aim is also to investigate how sensitive the output is to changes in parameters and to use a partial sensitivity analysis to understand the dynamics of the system.

2. Material and methods

2.1. Study area

The study area, the Icelandic waters, extends from 60° to 73°N and from 43° to 0°W (Fig. 1). Two water masses meet in this area, the relatively warm and saline Atlantic water and cold Arctic water with low