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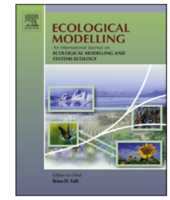

An Atlantis model of the southern Benguela upwelling system: Validation, sensitivity analysis and insights into ecosystem functioning

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ABSTRACT

Ecosystem models are valuable tools for evaluating the effects of different environmental stressors on an ecosystem and to increase system understanding. The Atlantis modelling framework is an end-to-end model that includes information and processes from the abiotic environment to the human component of a system. An application of Atlantis for the Benguela and Agulhas Currents was updated and validated against time series of biomass and catch (1990–2013). Five univariate skill metrics were used to evaluate model performance of biomass data of selected species. A sensitivity analysis, focused on the growth rate of small and large phytoplankton and large zooplankton, was conducted to evaluate the influence of these parameters on model outputs. A total of 26 alternative model parameterisations based on a variation of ±20% around the growth parameter of the selected groups were compared to the baseline model. Skill metrics suggest that the model captures the main emergent properties of the southern Benguela, the magnitude and trends in biomass and catch of most modelled groups. Large variations in biomass were observed among the sensitivity runs compared to the baseline. The most marked differences in relative biomass among runs seem to be attributed to changes in the growth rate of large zooplankton. The Atlantis model presented here has the capability to be used as a tool to provide strategic information for fisheries management purposes in the southern Benguela system.

1. Introduction

Classical fisheries management has focused on maintaining the sustainability of fishery target species but usually without taking into consideration the influence of environmental variability, species and habitat interactions, and impacts from other sectors. Because natural systems are inherently complex, there has been increasing recognition of the need for an integrated approach to management that considers the different components of a social-ecological system and not only the direct interactions between a fishery and its target species (Garcia et al., 2003). The ecosystem approach to fisheries (EAF) is such an holistic approach, which balances the ecological, environmental and human objectives of a fishery, aiming to achieve sustainable development (Garcia et al., 2003). Ecosystem models are a valuable tool in support of the implementation of an EAF (Hollowed et al., 2000; Plagányi, 2007). They offer a way to understand and consider the combined effects of different environmental stressors (e.g. climate, fishing, pollution) in a system, and account for direct and indirect interactions between species.

End-to-end (or whole of system) models include information and processes from the abiotic environment to the human component of a system, and are characterized by a two-way coupling between ecosystem components (Travers et al., 2007). End-to-end models are data intensive and require a large number of parameters for their initialization, making handling of uncertainty a challenging task (Fulton, 2010). Validation of end-to-end models consists of simultaneously fitting a model to available data sets, aiming to optimize the ability of the model to capture the most important processes in a system (Kramer-Schadt et al., 2007). Skill assessment is a means to determine model performance and consists of comparing model outputs to observations among different spatial and temporal scales. The use of quantitative skill assessment on end-to-end models has until recently been restricted to a few applications (e.g. Allen and Somerfield, 2009; Olsen et al., 2016; Stow et al., 2009).

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Ecosystem models are not generally suitable for tactical management (e.g. setting total allowable catches or effort) because of their complexity and associated uncertainty but have a role to play in strategic evaluation (e.g. "what if" scenarios) and are being increasingly used for this purpose in management of natural resources (Fulton, 2010). The Atlantis modelling framework is a biogeochemical end-to-end model designed for management strategy evaluation. It includes sub-models that represent the biophysical, human and socio-economic components of an ecosystem, as well as monitoring, assessment and management processes (Fulton et al., 2004). Applications of Atlantis models range from increasing system understanding to evaluation of fishery management options (Fulton, 2010).

An application of the Atlantis modelling framework on the Benguela and Agulhas currents (ABACuS) was developed to explore the impact of several fisheries on the southern Benguela in the context of an ecosystem approach to fisheries management (Smith, 2013). ABACuS was built to represent the conditions observed in the Southern Benguela during 1990–1999 because of the higher data availability for that decade and to allow comparisons with other modelling efforts for the system (Shannon et al., 2003; Shin et al., 2004).

The southern Benguela upwelling system supports several fisheries of considerable importance to South Africa, as well as many fishing communities that depend on fish and invertebrate resources for their livelihoods. The system has been identified as a hotspot of climate and social change because (1) it has been determined to be in the top 10% of marine areas in the world in terms of the rate of warming and (2) because it is also experiencing social tension and change, in part as a result of the environmental changes (Hobday and Pecl, 2014). As with other upwelling systems in the world, the southern Benguela is characterized by high inter-annual and decadal scale variability, including the abundance of anchovy and sardine, and is subject to regime fluctuations or shifts (Lluch-Belda et al., 1992).

This study aimed to update and expand the initial application of the Atlantis model for the southern Benguela (ABACuS) to examine potential fishing and climate scenarios on the southern Benguela with a view to assisting in the determination of management and adaptation options. This paper reports on the update and extension of the original model, the result of which is referred to as ABACuS v2. It also describes (1) calibration and validation of the model against time series of biomass and (2) a sensitivity analysis, focused on the growth parameters of primary producers and zooplankton groups, that was undertaken to provide insights into model behaviour and its potential application for climate change scenarios.

2. Materials and methods

2.1. Atlantis on the Benguela and Agulhas currents (ABACuS)

The first version of the Atlantis model for the Southern Benguela system was presented in Smith (2013). The area modelled by ABACuS extends from the Orange River mouth (29°S, South African—Namibian border) to the city of East London (28°E), to a maximum depth of 500 m offshore (Fig. 1). The model area (~220 000 km^2) includes the west and south coasts of South Africa, and the Agulhas Bank, an extensive area on the south coast that is an important spawning ground for several species (Shannon et al., 2003). Most fishing activity in South Africa is concentrated in the southern Benguela system (Pecquerie et al., 2004). The model area is divided into 18 regions (or polygons) representing the main hydrological, biological and management zones in the system. Each box has from one to four depth layers, with the number of layers increasing with the distance offshore.

A number of changes had been made to the Atlantis code since ABACuS was first built. These included a more robust handling of life history demography for species with long larval or gestation periods, refined handling of habitat and benthic processes and improved representation of geophysical processes and projection specific requirements. All of these changes meant that modifications to the initial ABACuS version were necessary to attain satisfactory calibration. The hydrodynamic forcing was also updated using more accurate hydrodynamic data that had become available since ABACuS was first built. We describe the steps involved in calibrating ABACuS v2 to fit time series of abundance of selected groups (1990–2013), while forcing the model with catch time series.

2.2. Hydrodynamic submodel

The initial version of ABACuS was forced with one year of hydrodynamic data (which was cycled repeatedly) and therefore did not account for inter-annual variability. In ABACuS v2, information on temperature, salinity, horizontal and vertical velocities from the Multi-tier Inter-regional Model of Southern Africa (MIMOSA) was used to represent the hydrodynamic fluxes (heat, salt and water) between boxes and depth layers. MIMOSA was built using the Regional Ocean Modelling Systems (ROMS), and captures shelf-scale and sub-mesoscale processes. The configuration "Tier 1" from MIMOSA was used to force the hydrodynamics of ABACuS v2. Tier 1 is based on a two-way AGRIF nested ROMS configuration (SAFR-AGRI, Debreu et al., 2012), which spans the entire South African coast (4.33°E to 34.42°E, 45.56°S to 16.99°S) and has a 1/12° resolution and 42 sigma layers vertically (Loveday, 2015). The model is forced with monthly data from the SODA (Simple Ocean Data Assimilation) version 2.2.4 hindcast (Carton et al., 2000; Carton and Giese, 2008).

2.3. Biology submodel

Initial biomass, species distributions and diets that were used as input data for ABACuS v2 represent the conditions in the southern Benguela system from 1990 to 1999. The initial biomasses for all modelled groups were derived from stock assessments and literature sources (see Smith, 2013 for details). ABACuS v2 includes the same 32 functional groups that were used in ABACuS, consisting of 15 fish groups, 2 mammal groups, 1 seabird group, 7 invertebrate and 3 phytoplankton/macroalgae groups (Table S1). Two detritus and bacterial groups are also modelled in both versions of ABACuS. For computational efficiency, the vertebrates are represented as age-structured groups with populations consisting of up to 10 age classes (the actual span of the age classes in each group is dependent on the maximum longevity of the group). The weight of a vertebrate in the model equals the sum of its structural and reserve weight. The size of an individual is represented by its structural weight (i.e. somatic growth) and its condition by the reserve weight (i.e. gonads, fatty tissue). Invertebrates are modelled as biomass pools, with cephalopods represented as juvenile and adult biomass pools. Nitrogen is the model currency in Atlantis.

In Atlantis models, calibration is achieved heuristically to obtain the best match between model forecasts and available time series. The process of calibration is constrained to adjusting a small number of parameters per group, related to feeding, reproduction and non-predation mortality. ABACuS v2 was calibrated against time series of abundance and catch for the period 1990–2013, thereby recreating observed biomass time series where available. For groups with no time series available, calibration aimed to ensure that the average biomass fell within the point estimates observed during the 1990–2013 period. Further requirements were that simulated vertebrate growth generates size at age within