Progress in Oceanography 129 (2014) 285–313

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Challenges in integrative approaches to modelling the marine ecosystems of the North Atlantic: Physics to fish and coasts to ocean

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ARTICLE INFO

Article history:
Available online 9 May 2014

ABSTRACT

It has long been recognised that there are strong interactions and feedbacks between climate, upper ocean biogeochemistry and marine food webs, and also that food web structure and phytoplankton community distribution are important determinants of variability in carbon production and export from the euphotic zone. Numerical models provide a vital tool to explore these interactions, given their capability to investigate multiple connected components of the system and the sensitivity to multiple drivers, including potential future conditions. A major driver for ecosystem model development is the demand for quantitative tools to support ecosystem-based management initiatives. The purpose of this paper is to review approaches to the modelling of marine ecosystems with a focus on the North Atlantic Ocean and its adjacent shelf seas, and to highlight the challenges they face and suggest ways forward. We consider the state of the art in simulating oceans and shelf sea physics, planktonic and higher trophic level ecosystems, and look towards building an integrative approach with these existing tools. We note how the different approaches have evolved historically and that many of the previous obstacles to harmonisation may no longer be present. We illustrate this with examples from the on-going and planned modelling effort in the Integrative Modelling Work Package of the EURO-BASIN programme.

Introduction

The North Atlantic Ocean and its contiguous shelf seas provide a diverse range of goods (e.g. food, renewable energy, transport) and services (e.g. carbon and nutrient cycling and biodiversity) to mankind. However, global climate change will lead to substantial changes in the physical conditions of the basin (e.g. circulation, stratification, temperature and light climate). At the same time, combinations of direct anthropogenic drivers (e.g. fishing and eutrophication) impact at both an organismal and population level, thereby influencing the biogeochemical cycles of carbon and nutrients on a regional and basin wide scale. The coupling between the climate, marine ecosystems and the human impacts on these ecosystems is a key facet of the Earth System, of which our understanding is only beginning to scratch the surface. This coupling relates to two overarching scientific issues of immense societal concern:

- the role of the oceans in mitigating the effects of anthropogenic CO_2 emissions,
- the impacts of climate (change and variability) and fishing pressure on ecosystem structure and function, and the consequences for biodiversity and fisheries production.

BASIN (Wiebe et al., 2009) is a joint EU/North American research initiative with the goal of elucidating the mechanisms underlying observed changes in North Atlantic ecosystems and their services, and EURO-BASIN is a programme to implement this, funded under the European Commission's 7th Framework

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http://dx.doi.org/10.1016/j.pocean.2014.04.024
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Programme. Much can be learned on these issues through an extensive observational and experimental effort, however, a crucial challenge for BASIN is to develop the predictive capability necessary to understand the space and time variation of broadly distributed and dominant members of the North Atlantic plankton and fish communities, the relevant biogeochemical processes, as well as feedbacks between and within these components and climate. It is only through the development and application of integrative modelling that these questions can be explored together and under possible future conditions, potentially far removed from any conditions in the observational base. In this paper, we explore the fundamental challenges of an integrative approach to modelling the marine ecosystem in the North Atlantic and its adjacent shelf seas, with a focus on these overarching issues. To illustrate this, we draw on examples from the Integrative Modelling Work Package in the EURO-BASIN programme, where state of the art models of physical, lower and higher trophic level processes are deployed. In the remainder of this introduction we set the scene by considering how these two overarching issues give rise to key science objectives in this region.

While the open-ocean (Sanders et al., 2014) and shelf seas (e.g. Chen and Borges, 2009) biological carbon pumps are well established, the dynamics of these processes and their vulnerability to future change are far from certain. This is particularly the case in the context of changing marine management strategies and physical, ecosystem and biogeochemical responses to climate change and variability. The recent identification of the 'non-steady-state' nature of the ocean carbon pump (e.g. in the North Atlantic: Schuster and Watson, 2007; Watson et al., 2009) and its response to climate raises concerns over its ability to continue to mitigate increasing atmospheric CO_2 levels (Le Quere et al., 2010).

Alongside the carbon cycle context, the structure and function of the ecosystem itself and how this responds to changing external conditions such as climate and fishing pressure is of particular importance as it relates to the economic and food security aspects of the exploitation of living marine resources (Stock et al., 2011), and also the societal drive to ensure a healthy marine environment. In Europe this is encapsulated in the Marine Strategy Framework Directive (MSFD) and the descriptors of Good Environmental Status therein.[1]

Fig. 1a shows a schematic contrasting the shelf sea and open-ocean biological carbon pumps. In both cases the driver is the same, photosynthesis (P). However, the pathways of the fixed carbon to the point where it is isolated from atmospheric exchange on centennial time scales are very different. In the open ocean the respiration (R) that occurs as material sinks is a critical control, whereas in shelf seas the on/off-shelf transport is an important additional factor (Holt et al., 2009; Wakelin et al., 2012). In shelf seas much of the sinking carbon enters the benthos, but it is still largely respired and its long term fate largely depends on the relation between lateral transport (pathways and time scales) and the exposure to atmospheric exchange through vertical mixing. In both cases top-down control (grazing, G) has the potential to alter these pathways. This simple conceptual model belies the underlying complexity of the ecosystem (e.g. Fig. 1b), whereby individual organisms compete for resources at trophic levels from primary producers to top predators, leading to intricate ecological interactions. While this ecology has long been studied in the context of living marine resources (e.g. Hardy, 1924), its relationship to the carbon cycle is far from clear.

The North Atlantic is important and unique in several respects. It is a key component in the climate system due to the substantial poleward heat flux in its surface waters and the formation of intermediate/deep water masses in its northern regions that help drive the Thermohaline Circulation (Macdonald and Wunsch, 1996). This region accounts for 23% of the global marine sequestration of anthropogenic CO_2 despite having only 15% of the area (Sabine et al., 2004). This arises because of the deep winter mixing forming intermediate and mode water masses combined with a lower Revelle factor than other mid- to high latitude regions. There is exceptionally high primary production (for a large ocean basin area) in the sub-polar gyre region (e.g. Carr et al., 2006) owing, among other factors, to significantly deeper winter mixed layers than other ocean basins (de Boyer Montégut et al., 2004). The ocean basin is bounded by shelf and marginal seas that support substantial economic activity (e.g. fisheries) and are themselves bounded by populous countries of Europe and Africa on the eastern side and the Americas on the west. Hence, impacts of large coastal cities and resource exploitation are acutely felt in this region, potentially mitigated by recent legislative action (e.g. MSFD). In contrast, the less developed countries of West Africa rely on artisanal fisheries as an important protein source (FAO, 2012) and so are highly vulnerable to changes in fish production in this upwelling region.

The particular question within the BASIN programme we aim to make progress towards answering are:

- What defines the biogeographic regions of the North Atlantic, and how might these change, and in what way and on what time scales might the ecosystem respond to these changes?
- What is the impact of top down control on the carbon cycle and phytoplankton community structure, how does this vary temporally and spatially, and under future climate and fisheries management scenarios?
- What are the pathways and ultimate fate of carbon sequestered by biological production, and how might these change?
- How does climate change and variability impact the ecosystem productivity, structure and function?

This requires a truly integrated modelling approach that spans from fisheries to plankton, and from the shelf seas to the open ocean. However, to achieve this we must, not only make significant advances in modelling individual systems, but also break down barriers in traditional scientific approaches, for example between modelling biogeochemical systems and modelling ecological systems, and between modelling the open-ocean and coastal–ocean. There is of course sound scientific reasons why different approaches are taken for each of these so full harmonisation is neither possible nor desirable, but to move towards the goal of an integrative system we must find the common ground and exploit the potential linkages.

Modelling approaches are context dependant; at each stage (physics, biogeochemistry, ecosystem, etc.) there are several complimentary ways to explore the system differing in how the system is represented, in the time and space scales considered, and in the capability to address the particular questions at hand. Each will be a compromise in some sense, but also have particular advantages. Hence an integrative modelling approach needs to embrace this diversity and rather than providing a single mechanistic connection between drivers, impact and response, each component provides complimentary evidence towards our understanding of the system's behaviour. Practical considerations inevitably limit the approach to a few discrete choices.

Within EURO-BASIN, we consider three configurations of a common physical model (Nucleus of a European Model for the Ocean, NEMO; Madec, 2008); three biogeochemistry/lower trophic level (LTL) models (ERSEM, MEDUSA and PISCES, described below); a regional scale Individual Based Model for the zooplankton species *Calanus* spp. coupled to a small pelagic fish (herring) population model (Utne et al., 2012; Utne and Huse, 2012); a spatially explicit

[1] http://ec.europa.eu/environment/water/marine/ges.htm