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A high resolution hydrodynamic model system suitable for novel harmful algal bloom modelling in areas of complex coastline and topography

Dmitry Aleynik [1,*], Andrew C. Dale [1], Marie Porter [1], Keith Davidson [1]

Scottish Association for Marine Science, Scottish Marine Institute, Oban, Argyll PA37 1QA, United Kingdom

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ABSTRACT

Fjordic coastlines provide sheltered locations for finfish and shellfish aquaculture, and are often subject to harmful algal blooms (HABs) some of which develop offshore and are then advected to impact nearshore aquaculture. Numerical models are a potentially important tool for providing early warning of such HAB events. However, the complex topography of fjordic shelf regions is a significant challenge to modelling. This is frequently compounded by complex bathymetry and local weather patterns. Existing structured grid models do not provide the resolution needed to represent these coastlines in their wider shelf context. In a number of locations advectively transported blooms of the ichthyotoxic dinoflagellate *Karenia mikimotoi* are of particular concern for the finfish industry. Here were present a novel hydrodynamic model of the coastal waters to the west of Scotland that is based on unstructured finite volume methodology, providing a sufficiently high resolution hydrodynamical structure to realistically simulate the transport of particles (such as *K. mikimotoi* cells) within nearshore waters where aquaculture sites are sited. Model–observation comparisons reveal close correspondence of tidal elevations for major semidiurnal and diurnal tidal constituents. The thermohaline structure of the model and its current fields are also in good agreement with a number of existing observational datasets. Simulations of the transport of Lagrangian drifting buoys, along with the incorporation of an individual-based biological model, based on a bloom of *K. mikimotoi*, demonstrate that unstructured grid models have considerable potential for HAB prediction in Scotland and in complex topographical regions elsewhere.

1. Introduction

Early warning and prediction is a key requirement of the science that surrounds harmful algal blooms (HABs). For advective HAB genera, numerical modelling offers the potential to predict the development and track of a bloom from offshore waters, potentially allowing an early warning of its likely timing, position and magnitude when (if) it reaches coastal waters where most aquaculture facilities are located (Davidson et al., 2016).

The Scottish west coast and islands suffer from regular HAB events, primarily related to the shellfish biotoxin producing genera *Alexandrium*, *Pseudo-nitzschia* and *Dinophysis* with the ichthyotoxic species *Karenia mikimotoi* increasingly being prevalent in elevated densities (Davidson et al., 2009, 2011; Touzet et al., 2010). Of the shellfish biotoxin producing genera *Pseudo-nitzschia* (Fehling et al., 2012) and *Dinophysis* (Farrell et al., 2012) are thought to develop offshore and be advected towards the coast. While densities of *Pseudo-nitzschia* in Scottish waters have been recorded to reach 670,000 cells L^{-1} such densities are exceptional (Fehling et al., 2006), with shellfish toxicity related to both genera potentially occurring at much lower cell densities. As the regulatory thresholds for *Pseudo-nitzschia* and *Dinophysis* are 50,000 cells L^{-1} and 100 cells L^{-1}, respectively, any model-based early warning system

Abbreviations: ASIMUTH, Applied Simulations and Integrated Modelling for the Understanding of Toxic and Harmful Algal Blooms; BADC, British Atmospheric Data Centre; FASTNEt, Fluxes Across Sloping Topography in the northeast Atlantic; FVCOM, Finite Volume Coastal Ocean Model; HAB, Harmful algal bloom; MUR SST, Multi-scale Ultra-high Resolution Sea Surface Temperature; NCEP, National Centre for Environmental Prediction; RDA, Research Data Archive; SAMS, Scottish Association for Marine Science; UR, Uncertainty Radius; VP, Virtual Particle(s); WRF, Weather Research Forecast Model.

* Corresponding author. Tel.: +44 01631 559 251..
E-mail addresses: dmitry.aleynik@sams.ac.uk (D. Aleynik), andrew.dale@sams.ac.uk (A.C. Dale), marie.porter.@sams.ac.uk (M. Porter), keith.davidson@sams.ac.uk (K. Davidson).
[1] These authors contributed equally to this work.

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would require the capacity to detect offshore seed populations below these concentrations, something that is not yet routinely possible.

The fish-killing dinoflagellate *Karenia mikimotoi* is a common member of the dinoflagellate community of the NE Atlantic. In Scottish waters, blooms of *K. mikimotoi* that have reached potentially harmful densities in 1980, 1999, 2003, 2006 (Davidson et al., 2009), and also in the autumns of 2011 and 2013. In contrast to the shellfish biotoxin genera above, harmful *K. mikimotoi* events are characterised by a dramatic increase in cell abundance that can reach concentrations in the range of millions of cells per litre. A signature pigment gyroxanthin-diester has been identified in the related species *Karenia brevis* (Kirkpatrick et al., 2000) and multi-parameter methods have been developed by (Shutler et al., 2011) for its identification by satellite remote sensing. The potential therefore exists to remotely detect developing offshore *K. mikimotoi* blooms and to predict their transport pathways numerically, providing early warning for aquaculture.

The waters off western Scotland principally consist of contributions from the Irish Sea and Atlantic (Ellett, 1979; McKay et al., 1986) supplemented by local freshwater runoff and Irish shelf waters (Fernand et al., 2006), Fig. 1. To the east, water tends to be Irish Sea-dominated, whereas the outer shelf to the west is Atlantic-dominated. This west–east gradient is distinct in the south, as the Islay Front (Hill and Simpson, 1989), but becomes less distinct further north (Ellett, 1979). The fresher Irish Sea water is associated with an ill-defined, northward flow, the Scottish Coastal Current (Simpson and Hill, 1986), which has a south–north advective timescale of months to a year (McKay et al., 1986). For an offshore HAB to reach coastal waters it must therefore cross this west–east gradient. In addition, the tidal complexity of the region is expected to play a role in this, with locally intense tidal flows making this a highly dispersive environment. There is also a net overturning within fjordic systems in which relatively fresh surface water moves offshore and draws in denser water at depth.

HAB modelling therefore requires a coupled biophysical approach. Development of the physical framework for such models in fjordic regions such as the Scottish west coast is, however, far from straightforward. Scotland has, behind the similarly fjordic Norway, the second longest coastline in Europe with a geometric length (incorporating the 790 major islands) of 18,588 km (Darkes and Spence, 2008). Hence, despite a long history of local observations, hydrodynamic modelling of Scottish waters has remained challenging for medium and low resolution models that use a structured (i.e. evenly-spaced) computational grid. This is partly because some important features (islands, fjords) and interconnections (straits) are not resolved, but also

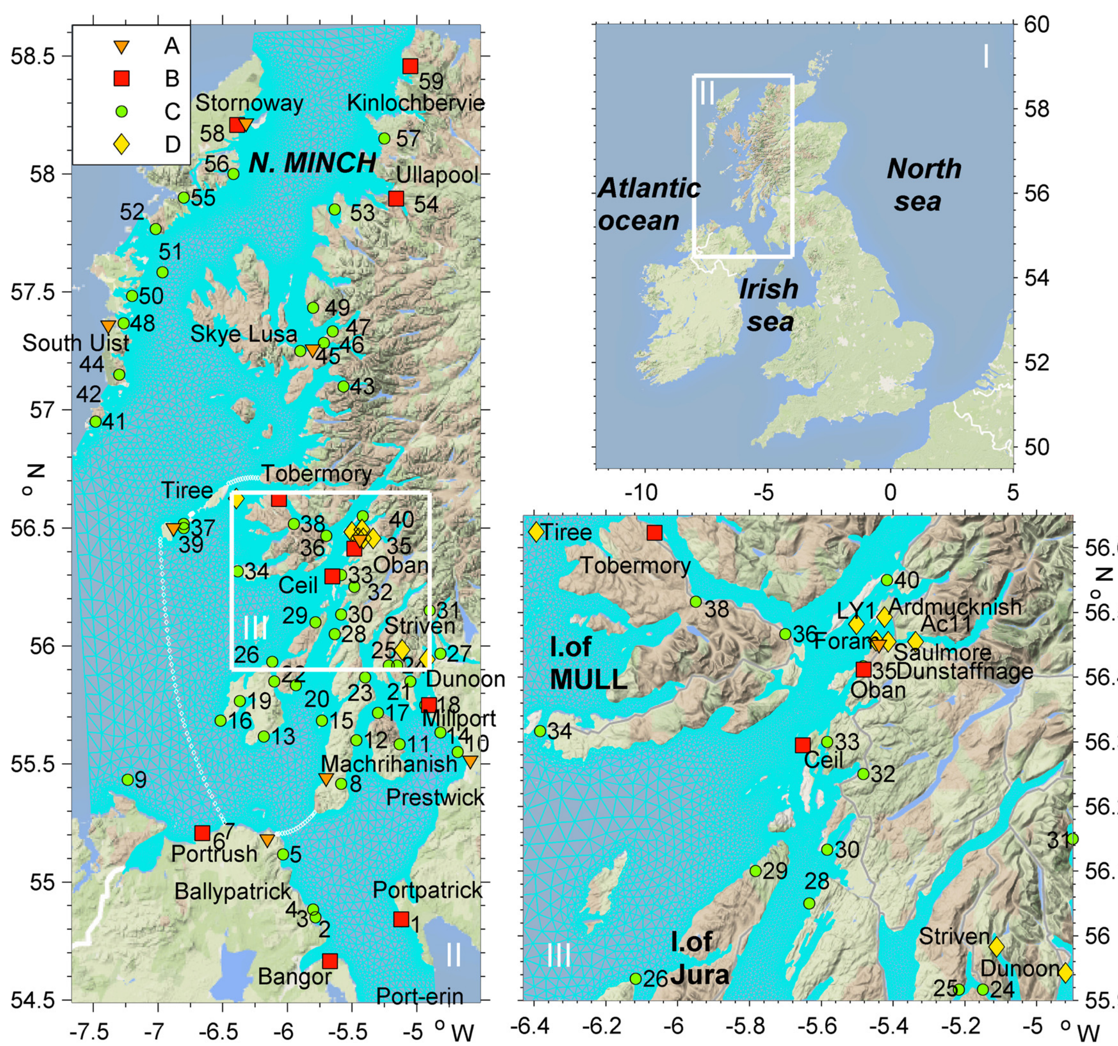

Fig. 1. The West Coast of Scotland FVCOM model mesh and observation/validation locations. Symbols A (△) indicate UK MetOffice–MIDAS weather stations, B (□)–pressure gauge sites from BODC, C (○)–International Hydrographic Office (IHO) port sites, D(◇)–moorings (CTD or temperature loggers). White rectangles indicate the parts of the domain that are shown in detail in II and III panels. The ASIMUTH–FVCOM domain boundaries are shown with white dashed line.