Ocean Sci. Discuss., 12, 1187–1217, 2015
www.ocean-sci-discuss.net/12/1187/2015/
doi:10.5194/osd-12-1187-2015

Ocean Science
Discussions
Open Access

Ocean modelling for aquaculture and fisheries in Irish waters

T. Dabrowski, K. Lyons, C. Cusack, G. Casal, A. Berry, and G. D. Nolan

Marine Institute, Rinville, Oranmore, Co. Galway, Ireland

Received: 21 May 2015 – Accepted: 29 May 2015 – Published: 25 June 2015

Correspondence to: T. Dabrowski (tomasz.dabrowski@marine.ie)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Marine Institute, Ireland, runs a suite of operational regional and coastal ocean models. Recent developments include several tailored products that focus on the key needs of the Irish aquaculture sector. In this article, an overview of the products and services derived from the models are presented. A shellfish model that includes growth and physiological interactions of mussels with the ecosystem and is fully embedded in the 3-D numerical modelling framework has been developed at the Marine Institute. This shellfish model has a microbial module designed to predict levels of coliform contamination in mussels. This model can also be used to estimate the carrying capacity of embayments, assess impacts of pollution on aquaculture grounds and help to classify shellfish waters. The physical coastal model of southwest Ireland provides a three day forecast of shelf water movement in the region. This is assimilated into a new harmful algal bloom alert system used to inform end-users of potential toxic shellfish events and high biomass blooms that include fish killing species. Further services include the use of models to identify potential sites for offshore aquaculture, to inform studies of potential cross-contamination in farms from the dispersal of planktonic sea lice larvae and other pathogens that can infect finfish and to provide modelled products that underpin the assessment and advisory services on the sustainable exploitation of the marine fisheries resources. This paper demonstrates that ocean models can provide an invaluable contribution to the sustainable blue growth of aquaculture and fisheries.

1 Introduction

According to the Food and Agriculture Organisation of the United Nations, aquaculture is the fastest growing food producing sector in the world (FAO, 2014). World capture fisheries production in marine waters remains at stable levels over the last c. 30 years following steady growth in the preceding decades. The same report stresses the importance of implementing an ecosystem approach to fisheries. The most recent report

OSD
12, 1187–1217, 2015

published in Ireland shows that the total shellfish production doubled in years 1990–2007 (Browne et al., 2008). Aquaculture is one of the five sectors targeted for further development under the European Union (EU) Blue Growth initiative (European Commission, 2012); the fisheries sector has also been identified as crucial for jobs and value under this agenda.

In this context, one of the key needs of the aquaculture and fisheries sectors is the implementation of effective analyses and management methods to ensure the sustainability, economic viability, minimization of negative impacts on the environment and risks to human health. Today, the above measures can be effectively supported by mathematical models. These models can vary in complexity from highly aggregated, low data requirements tools (e.g. ASSETS, Bricker et al., 2003), through to tools that address production and ecological sustainability at a finer spatial scale (e.g. Ferreira et al., 2007) to more detailed and complex research models. Examples of the latter include box models for analysis of mussel carrying capacity (Filgueira and Grant, 2009), ecosystem models to determine food depletion (Grant et al., 2008), and 2-D or 3-D biogeochemical models coupled with shellfish models (e.g. Dabrowski et al., 2013 and the references therein; Nunes et al., 2011). Numerical models used in aquaculture and fisheries studies can themselves vary in complexity, from general ocean circulation models to sophisticated coupled physical – biogeochemical – shellfish eco-physiological models, such as that presented in Dabrowski et al. (2013).

The Marine Institute, run a suite of operational forecasting regional and coastal ocean models. Developments in recent years have been tailored to address several key needs of the aquaculture and fisheries industries in the region. This paper presents an overview of these model-based products and services. In particular, those that relate to shellfish growth and carrying capacity, shellfish microbial contamination, harmful algae bloom warnings, offshore aquaculture site selection, cross-contamination of farms and, fisheries assessments. The overview is preceded by a brief description of the operational models set up.

OSD
12, 1187–1217, 2015

2 Description of the models

The 3-D operational models implemented by the Marine Institute are based on the Regional Ocean Modelling System (ROMS) which is a free-surface, hydrostatic, primitive equation ocean model described in Shchepetkin and McWilliams (2005). It uses orthogonal curvilinear coordinates on an Arakawa-C grid in the horizontal while utilizing a terrain-following (sigma) coordinate in the vertical. The prognostic variables of the hydrodynamic model are surface elevation, potential temperature, salinity and horizontal velocities.

The local model of southwest Ireland, hereafter called the Bantry Bay model, consists of 557×419 grid cells relating to a horizontal spacing of 200–250 m and 20 vertical levels. The model is nested offline in a regional North East Atlantic (NE_Atlantic model) model run operationally at the Marine Institute and is a refinement of the latter by a factor of five. Time series of water levels, 2-D and 3-D momentum, temperature and salinity are provided every 10 min. The Bantry Bay model was initialized in February 2010 from the parent model output interpolated onto a child grid. Surface forcing is taken from the half-degree Global Forecasting System (GFS) that is available at three-hourly intervals and the model interpolates data onto its current time step. Heat fluxes are calculated from the bulk formulae and surface freshwater fluxes are obtained from the prescribed rainfall rates and the evaporation rates calculated by the model. Freshwater discharges from five rivers are included in the model.

Some of the products and services presented in this paper concern another Irish coastal model that runs operationally and covers the mid-west Atlantic coast; called the Connemara model. The set-up is analogous to that of the Bantry Bay model.

The parent model domain (NE_Atlantic) covers a significant portion of the northwest European continental shelf and has a variable horizontal resolution, ranging from a value of 1.1–1.6 km in Irish coastal waters to 3.5 km in the south of the domain. There are 40 sigma levels in the vertical with a concentration of levels at the surface and the bottom. It is nested within the high resolution ($1/12^{\circ}$) Mercator Ocean PSY2V4R2

OSD
12, 1187–1217, 2015

operational model of the North Atlantic whereby daily values for potential, temperature, sea surface height and velocity are linearly interpolated from the parent model onto the NE_Atlantic model grid at the boundaries. Tide forcing is prescribed at the model boundaries by applying elevations and barotropic velocities for ten major tide constituents, which are taken from the TPXO7.2 global inverse barotropic tide model (Egbert and Erofeeva, 2002). The GFS atmospheric forcing is applied at the surface. The above model domains are presented in Fig. 1.

The authors also developed a wave model based on SWAN (Simulating Waves Nearshore) (Booij et al., 1999) to estimate wave climate on the west coast of Ireland for offshore aquaculture sites. The model domain encompasses Irish coastal waters from 12.000 to 7.500° W and 50.000 to 56.500° N at a horizontal resolution of 0.004°. The model is forced with winds from the GFS model and wave data at the boundaries from the Wave Watch 3 model developed by the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (Tolman, 2009).

3 Products and services

3.1 Shellfish growth and carrying capacity

The Bantry Bay model contains the biogeochemical module, which is based on the nutrient-phytoplankton-zooplankton-detritus model developed by Fennel et al. (2006). All biogeochemical model state variables are provided every 3 h at the open boundaries and are interpolated from the "parent" North-East Atlantic biogeochemical model, which is a coarser resolution version (~ 5 km) of the NE_Atlantic model described in Sect. 2.

This biogeochemical module is further coupled to the shellfish eco-physiological model developed and implemented by Dabrowski et al. (2013). This shellfish model has been written for the species of *Mytilus edulis* (blue mussel) and *Crassostrea gigas* (Pacific oyster) and comprises of two modules, namely the shellfish growth and

OSD
12, 1187–1217, 2015

the shellfish-ecosystem interactions. In Bantry Bay it has been implemented for the rope cultures of *M. edulis*. The growth model is a Fortran 90 implementation the Dynamic Energy Budget (DEB) algorithm (Kooijman, 2010) and the shellfish-ecosystem coupler is a new model developed by the authors and presented in detail in Dabrowski et al. (2013). The following processes are included: food uptake and assimilation of nitrogen and carbon in bivalve, egestion of faeces, NH_4 excretion, oxygen utilization and CO_2 production. The food comprises of phytoplankton and small detritus and the model dynamically adjusts food preferences through the inclusion of the food selection factor, and the egestion of faeces adds to the large detritus pool in the model.

The shell length, L, and dry weight, DW, are derived from the model, as these are important parameters from the farm operations and management perspectives and they have an impact on the price. Figure 2 presents the distribution of predicted L after c. 1 year simulation carried out for the period 2010–2011. Results were validated and compare well with data collected in the bay over the same time period. The areas offering good growth potential (i.e. greater L) can be distinguished from poorer growth areas (i.e. lower L) using this model.

The presented model can thus answer two overarching questions: what is the spatial distribution of growth rates in the bay and what impacts on the ecosystem are exerted by the farms (e.g. depletion of phytoplankton, dissolved inorganic nitrogen enrichment). Furthermore, the model can assist with issues of production and ecological carrying capacities by running the experiments with alterations to standing stocks and with relocation and addition of new farms.

3.2 Shellfish microbial contamination

The model described in Sect. 3.1 has been further extended to include a microbial module developed by and presented in Dabrowski et al. (2014). In the above paper the authors present a new method to simulate an uptake of *E. coli* from seawater and subsequent depuration by *M. edulis* that dynamically predicts *E. coli* concentration in the mussel tissue. Concentration of *E. coli* in water is determined by its die-off rate (de-

OSD
12, 1187–1217, 2015

pendent on light, temperature and salinity), the rate of uptake by mussels and the rate of input from the point sources in Bantry Bay. Depuration in the mussel tissue follows a first-order decay and assumes a constant T_{90} of 3 h, which yields a decay rate of 18.4 day^{-1}. Dabrowski et al. (2014) derived an equation for the filtration rate using the energy ingestion rate predicted by the DEB model for *M. edulis*. This energy ingestion rate is converted to carbon ingestion rate and its uptake in food is subsequently calculated. Phytoplankton is one of the food sources in the model; therefore the filtration rate can be expressed in terms of the ratio of phytoplankton carbon ingestion rate to phytoplankton carbon concentration.

The above approach proved to be successful in the modelling study of the rope mussel coliform contamination in Bantry Bay as presented in Dabrowski et al. (2014). Shellfish water classes defined in the EC directive (European Commission, 2006) and based on coliform concentration in shellfish flesh were derived from the model. Figure 3 presents the distribution of these water classes in Bantry Bay; these compare well with the classes established based on the national monitoring programme.

Some overarching questions that can be addressed by the presented model include:

- How does new/existing outfall impact on shellfish waters?
- Is it a safe location for a new farm?
- What is the best time for harvesting (based on short term forecasts if implemented operationally)?

3.3 HAB warning

A number of customised products are generated from the Bantry Bay model and are intended to improve the knowledge on driving forces behind harmful algae bloom (HAB) events off southwest Ireland. The products include Bantry Bay cross-sections at the mouth of the bay and midway between the mouth and the head showing three-day averaged volumetric flows and their vertical structures as well as the temperature, salinity and density profiles. The magnitudes of the current inflows are also compared to their long term means in order to identify pronounced events. These products along with other (e.g. satellite data: sea surface temperature and chlorophyll, data from the national harmful algal bloom and shellfish biotoxin monitoring programme) constitute part of a weekly HAB bulletin published online.

Another operational product is based on the predicted tracks of the particles released at the surface layer, at 20 m depth and at the bottom layer across the mouth of Bantry Bay and a transect perpendicular to the coast, through offshore waters, southeast of Bantry Bay at Mizen Head. The particles are released at the above transects over the first 12 h and at 30 min intervals upon the execution of each simulated three-day forecast. The particles are passive, that is they do not have any behaviour attached to them and so are advected freely by the model-predicted currents. The end product are maps (one per transect and release depth) presenting the total time spent by all particles at each model computational cell over the duration of the forecast, so called the particle-hours, and the maps are available online (http://vis.marine.ie/particles). An example map is presented in Fig. 4. The maps aim to quantify the strength of shelf water inflow into Bantry Bay, highlight upwelling/downwelling events and depict the strength of the Irish Coastal Current. Furthermore, a set of Matlab scripts has been developed allowing the execution of the particle transport model upon notification of suspected toxic bloom locations from the observational platforms and from institutions in other countries that provide forecasts of harmful algae trajectories based on particle tracking, which allows for inter-regional forecasts. The data exchange is facilitated by KML format and e-mail alerts are issued when particles cross the respective model boundaries.

The southwest coast of Ireland is particularly exposed to toxic events and site closures due to phycotoxins produced by HABs occur frequently. For example, in 2013, one or more shellfish farms in southwest Ireland were closed for 35 weeks due to HAB events (Cusack et al., 2015). In Ireland, the main toxins that cause shellfish production closures are okadaic acid and equivalents (OA and equiv.), and azaspiracids (AZAs).

OSD
12, 1187–1217, 2015

The main symptoms displayed by humans who consume contaminated shellfish at toxic levels, i.e. above EU regulations, include gastrointestinal discomfort with diarrhoea, nausea and vomiting. The associated syndromes are called diarrhoeic shellfish poisoning (DSP) and azaspiracid shellfish poisoning (AZP). Another economic threat to the Irish shellfish industry is a syndrome called amnesic shellfish poisoning (ASP); a more serious human illness that can induce, in extreme cases, symptoms of memory loss and even death. However, the rate domoic acid (DA, the ASP water soluble toxin) is excreted from shellfish is species specific e.g. the blue mussel (*Mytilus edulis*) quickly clears DA (Novaczek et al., 1991, 1992 Wohlgeschaffen et al., 1992). This is evident in the rapid increase and decline of a small *Pseudo-nitzschia* bloom and DA in long-line mussel cultures after an upwelling event (offshore-onshore wind driven bottom water advected into the bay) in Bantry Bay, April 2013 (Fig. 5a). Lipophilic toxins (dissolve in fats), related to DSP and AZP, depurate from blue mussels at different rates. In Ireland, this can take many months, especially in winter. The depuration times are highly variable and are likely to be related to food source (microalgal composition) availability among other things such as the metabolic rate of the bivalves (Marcaillou et al., 2010; Jauffrais et al., 2012). In 2013, shellfish farms in SW Ireland experienced a DSP event in July that lasted ~ 9 weeks, while an AZP event in October lasted ~ 11 weeks (Fig. 5b and c). Biotoxin levels in blue mussels increased quickly after the two dinoflagellate blooms (DSP toxin producers, Dinophysis and AZA potential producers, *Azadinium*-like species) occurred in July and October 2013. As presented in Fig. 5, both events were linked to downwelling (offshore-onshore wind driven surface water advection into the bay). Because depuration time of some phycotoxins is variable, there is a need to have an early warning system in place so farmers can remove product before long closures are experienced.

Overall, from April to October 2013, five downwelling events were evident in the volumetric flux simulations; three linked to harmful algal blooms and diarrhoeic shellfish poisoning (DSP) and azaspiracid shellfish poisoning (AZP) threats (Fig. 5b and c). Modelling results showed eleven upwelling events; two associated with potentially toxic

OSD
12, 1187–1217, 2015

diatom blooms, *Pseudo-nitzschia* and ASP threats, and one linked to the appearance in Bantry Bay of a fish killing dinoflagellate called *Karenia mikimotoi* (Fig. 5a). As can be seen in Fig. 5d and e, increased inflows into the bay relate well with identified strong upwelling and downwelling events. Cusack et al. (2015) showed that the model provides reliable estimates of water exchange events in Bantry Bay.

The model-derived products are not used in isolation, instead they are used as part of a "tool kit" to estimate the risk to inshore shellfish farms. The current HAB warning system for Ireland includes historical data (time of past toxic events) used to determine the seasonal temporal window for HABs, HAB and shellfish biotoxin maps for the most recent three weeks to show temporal and spatial changes at more than 100 stations around the Irish coast, and daily spatial remotely sensed sea surface temperature (SST) and chlorophyll, used to detect and monitor the surface appearance of high biomass nuisance HABs. As can be seen in Fig. 5, false positive alerts can, however, occur for Bantry Bay when a water exchange event is predicted by the model, but HABs are not transported inshore. It is therefore evident that a shelf ocean observing system is needed to provide the offshore HAB abundance data.

3.4 Offshore aquaculture

Offshore aquaculture development requires accurate knowledge of environmental conditions (e.g. weather and wave climate; characteristics of water currents, etc.) at proposed sites. Knowing the environmental conditions over a large area facilitates intelligent, targeted site selection for offshore aquaculture development. Site classification can be achieved by considering a number of factors such as exposure (e.g. wave, wind, currents), accessibility (which is related to exposure), and distance to shore/infrastructure.

The literature has a number of examples of attempts to classify sites, usually based on a combination of exposure (e.g. wave, wind, currents), accessibility (which is related to exposure), and distance to shore/infrastructure. There does not seem to be a strong

OSD
12, 1187–1217, 2015

consensus on the number of classes and the exact criteria to use, but Holmer (2010) describes 3 classes of sites and these are presented in Table 1.

A Geographical Information System (GIS) is the ideal platform for this type of decision support tool. A GIS-based model can incorporate and analyse large amounts of spatial data and produce simple visual displays of the results. The authors created a number of GIS raster layers for northwest coast of Ireland. The layers were (i) water depth, (ii) maximum tidal velocity (based on harmonics derived from a one year run of the NE_Atlantic model), (iii) 90 % percentile value of a significant wave height (Hs), Hs_P90 and (iv) maximum max_Hs. The wave parameters (Hs_P90 and max_Hs) were derived from a 13 month simulation of the wave model (January 2012–February 2013) described in Sect. 2. The layers were imported into Esri's ArcGIS to facilitate spatial analysis.

Simple raster analysis was used to apply rules to the individual layers to isolate areas where certain exposure criteria were met. Using the "Off-coast farming" classification of Holmer (2010) as a rough guide, the following simple model to highlight potential sites was enforced: water depth ≥ 15 m, maximum tidal velocity $< 1\,\mathrm{m\,s^{-1}}$, max_Hs < 4 m and Hs_P90 < 2 m. Figure 6 visually demonstrates the spatial extent resulting from the application of each rule separately for the northwest coast of Ireland. The superposition of the four layers shown in Fig. 6 was used to create a new raster. The resulting raster contains binary data: cell values of 1 where all the criteria are met and cell values of 0 where one or more of the criteria failed. Figure 7 shows the spatial extent of the cells with value of 1. These equate to the location of potential offshore aquaculture sites for this simple model.

With the addition of more geographical information (e.g. location of infrastructure) this type of GIS model can become a powerful decision support tool to aid in the selection and development of offshore aquaculture sites. The GIS model can be improved by including more raster layers, for example 50/100 return periods for wave height and wind speed, and environmental impact data such as location of Special Areas of

OSD
12, 1187–1217, 2015

Conservation, in which case the environmental impact of potential sites can also be included in the site selection process.

3.5 Cross-contamination of farms

The risk of infection to salmon stock by sea lice is recognised as a serious issue for the salmon farming industry. Infection of salmon within and between farms occurs during the planktonic copepodid stage of the louse life cycle. Since the dispersal of planktonic larval salmon lice is largely controlled by surface currents, it is possible to simulate their dispersal using hydrodynamic modelling. The results can be used to indicate infection pressure risk in bays where salmon farms are situated or proposed.

For this study, the Connemara model was run with Lagrangian particle tracking activated. This allows the introduction of model particles into the domain at a location of the user's choosing (e.g. a salmon farm) and the particles are advected around the domain by the model currents. The model particles behave as passive drifters with neutral buoyancy. The particles were released near the surface at the locations of the aquaculture farms in the region every three hours for 35 days and the location of each particle was recorded over the duration of 14 days (the particles were assumed to have a "lifespan" of 14 days, after which they were considered "dead", i.e. excluded from the analysis). The particle-hours, defined in Sect. 3.3, were then calculated for each model cell and from this the authors derived maps of relative infection risk for fish in each cell of the model domain. An example map for the infection risk from Daonish farm on the west coast of Ireland is presented in Fig. 8.

The results of the particle track analyses can also be used to create a cross-contamination matrix for a collection of salmon farms in a bay. In this study, each salmon farm was defined as a 500 m square centered on the particle release site used for the Lagrangian particle tracking. Then the cumulative particle-hour value for that salmon farm due to particles released from each of the other sites in the bay was calculated. The numbers derived from this analysis were placed in a matrix in order to quantify the relative risk of infection from one farm to another. Table 2 is an example

OSD
12, 1187–1217, 2015
Ocean modelling for aquaculture and fisheries in Irish waters
T. Dabrowski et al.

of a matrix developed from three release sites (locations visible in Fig. 8). Referring to the Daonish release site in Table 2, the high value (1359) for Casheen indicates that this farm has an elevated risk of sea lice infection from Daonish compared to the other farms in the vicinity. The cross-contamination matrix along with the risk maps are potentially useful tools in sea lice management strategies and in the selection process for new farms. More results from the presented study can be found in Jackson et al. (2012).

3.6 Products for fisheries

Output from the Marine Institute operational models also underpin the assessment and advisory services on the sustainable exploitation of the marine fisheries resources in the waters around Ireland and on the impacts of fisheries on the ecosystem. Monthly and annual averages of selected modelled state variable from the ocean circulation and wave models are produced routinely. These include surface and bottom temperatures, surface and bottom salinities, surface velocity, bottom shear stress, mixed layer depth, significant wave height, mean wave direction and mean wave period. Most of the above products are published on the centralised Marine Institute data portal at http://data.marine.ie/ and on the ERDDAP http://erddap.marine.ie/ and THREDDS servers allowing a data download in variety of formats to suit the end users' individual requirements. The authors also maintain an archive of 3 hourly model prognostic variables from a hindcast run for 3-D currents and temperatures in Irish waters from the NE_Atlantic model, which is used to force an offline particle tracking model LTRANS (Schlag et al., 2012) used to investigate fish larvae transport. Readers are referred to O'Sullivan et al. (2014) for details on the study of the potential dispersal fields of *Nephrops* larvae from individual fishing grounds and the assessment of stock connectivity using the output from the models.

The above model-derived outputs are supplemented by further products from the observational platforms, namely the satellites and the Marine Institute marine observation network, that are tailored to the fisheries research requirements. Daily optimum interpolation SST for the period 1982 to 2014 produced by the USA National Oceanic and Atmospheric Administration (Reynolds et al., 2007) were downloaded for processing. This dataset also uses the in situ data from ships and buoys and includes a large-scale adjustment of satellite biases with respect to the in situ data. Annual SST averages were derived by the authors and exported in the GeoTIFF and NetCDF formats. The annual averages were then spatially averaged for the International Council for the Exploration of the Sea (ICES) subareas and divisions in Irish waters. ICES divisions considered in this study are presented in Fig. 9a. Figure 9b also shows a timeseries of annual SST in ICES subareas West of Scotland (divisions VIa-b) and the Celtic Sea (divisions VIIa-k). The analyses revealed that there is a clear increasing SST trend in both zones. If the recent 10 years are taken into account, the SST in the Celtic Sea has undergone an annual increase of 0.33 °C (±0.02) while in the West of Scotland the average annual increase is 0.54 °C (±0.04). These results coincident with the global SST trend and with the general trend in other studies carried out in Irish waters (Cannaby and Hüsrevoglu, 2009; Nolan et al., 2010; Olbert et al., 2011, 2012). Annual anomalies referenced to the 1971–2000 climatologies along with the error standard deviations for every year were also produced. The authors also developed analogous datasets for chlorophyll *a* separately for various ocean colour sensors i.e. CZSC (1982–1986), SeaWIFS (1997–2010), MERIS (2002–2012) and MODIS-Aqua (2002–2014). Since chlorophyll *a* concentrations dervided from the many sensors vary, work is ongoing to produce a consistent longterm dataset for Irish waters taking also into account different algorithms for Case 1 and Case 2 waters. Further details of this work can be found in Casal et al. (2015).

Monthly SST observations and anomalies at Marine Institute fixed ocean observation stations are also of interest to the fisheries. The authors produce graphs of current monthly mean SST along with the standard deviations and minimum and maximum temperatures recorded in a given month since records began at the individual stations that are part of the Irish National Weather Buoy Network. These graphs are included in the Monthly Oceanographic Bulletin, currently an internal Marine Institute publication, and Fig. 10 shows the example of the product for the M3 (51.216° N, 10.550° W) and M4 (55.000° N, 10.000° W) buoys in 2014. The M3 station data has been included in the ICES Report on Ocean Climate 2012 (Beszczynska-Möller and Dye, 2013).

4 Summary and conclusions

The authors presented an overview of numerous products and services based on the operational ocean modelling system developed in recent years at the Marine Institute, Ireland, and which have been tailored to address several key needs of the aquaculture and fisheries sectors in Irish waters. These developments have been driven by the end users requirements and many are still evolving, e.g. weekly HAB bulletin has an increasing uptake by the aquaculture farmers, whose feedback is used to reformat the presentation of data and information, including model-based. The expansion of the database consisting of the observational and modelled data and products from the operational service also improves our understanding of the ecosystem functioning that in turn stimulates further development of these products and pinpoints current deficiencies that need to be addressed, e.g. need for HAB monitoring on the shelf to improve the forecast skill in coastal embayments. Presented products and services are relatively easily transferable to other geographical locations. Some will require a programming effort, e.g. coupling the shellfish ecophysiological and microbial contamination model to the ocean circulation and biogeochemical model of choice, whereas other will only need post-processing of standard ocean circulation models output and dissemination to stakeholders via user friendly data servers, such as ERDDAP.

There is an increased interest in using computer models as tools for sustainable management of coastal ecosystems, accounting for multiple uses, including aquaculture and fisheries. The numerical models remain an appropriate vehicle to further our understanding of the complex interactions between ecological processes in marine ecosystems and thus enable end-users to make more informed management decisions. The level of spatial and temporal detail offered by these models, their forecasting and hypothesis and scenario testing capabilities are virtually unachievable through the monitoring programmes alone. Cost effective solutions in social and economic dimensions and measures aimed at protection of marine environments can be then implemented. Risks such as losses in ecosystem services, greater incidence of diseases and increased occurrence of harmful algal blooms can be mitigated or reduced with the aid of modelling services. The contribution that ocean models can make to the sustainable blue growth of aquaculture and fisheries is thus invaluable.

Acknowledgements. The authors thank their colleagues at the Marine Institute for their continued support and feedback to help shape the ocean modelling and oceanographic services. Special thanks to Damian Smyth for developing the particle tracks visualisation portal. Work presented in Sects. 3.1 and 3.2 has been funded under the EU Interreg IVB EASYCO project and work presented in Sect. 3.3 under the EU FP7 ASIMUTH project, Space Theme project Agreement No.: 261860.

References

Beszczynska-Möller, A. and Dye, S. R. (Eds.): ICES Report on Ocean Climate 2012, ICES Cooperative Research Report, No.321 Special Issue, 2013.

Booij, N., Ris, R. C., and Holthuijsen, L. H.: A third generationwave model for coastal regions. 1. Model description and validation, J. Geophys. Res., 104, 7649–7666, 1999.

Bricker, S. B., Ferreira, J. G., and Simas, T.: An integrated methodology for assessment of estuarine trophic status, Ecol. Model., 169, 39–60, 2003.

Browne, R., Deegan, B., Watson, L., MacGiolla Bhríde, D., Norman, M., Ó'Cinnéide, M., Jackson, D., and O'Carroll, T.: Status of Irish Aquaculture 2007, Report by Marine Institute, Bord Iascaigh Mhara and Údarás na Gaeltachta, 142 pp., 2008.

Cannaby, H. and Hüsrevoglu, S.: The influence of low-frequency variability and long-term trends in north Atlantic sea surface temperature on Irish waters, ICES J. Mar. Sci., 66, 1480–1489, 2009.

Casal, G., Furey, T., Dabrowski, T., and Nolan, G.: Generating a long-term series of SST and chlorophyll-a for the coast of Ireland, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W3, 2015, 36th International

OSD
12, 1187–1217, 2015

Symposium on Remote Sensing of Environment, Berlin, Germany, 11–15 May 2015, 933–940, 2015.
Cusack, C., Dabrowski, T., Lyons, K., Berry, A., Westbrook, G., Nolan, G., and Silke, J.: HAB warning system for Bantry Bay, Ireland. Part II: ASIMUTH-tailored model products, observations, Harmful Algae, accepted, 2015.
Dabrowski, T., Lyons, K., Curé, M., Berry, A., and Nolan, G. D.: Numerical modelling of spatio-temporal variability of growth of *Mytilus edulis* (L.) and influence of its cultivation on ecosystem functioning, J. Sea Res., 76, 5–21, 2013.
Dabrowski, T., Doré, W. J., Lyons, K., and Nolan, G. D.: Numerical modelling of blue mussel (*Mytilus edulis*) bacterial contamination, J. Sea Res., 89, 52–63, 2014.
Egbert, G. D. and Erofeeva, S. Y.: Efficient inverse modeling of barotropic ocean tides, J. Atmos. Ocean. Tech., 19, 183–204, 2002.
European Commission: Directive 2006/113/EC of the European Parliament and of the Council of 12 December 2006 on the quality required of shellfish waters, Official Journal of the European Union, L 376/14, 2006.
European Commission: Blue Growth – Opportunities for marine and maritime sustainable growth – Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Publications Office of the European Union, Luxembourg, 13 pp., 2012.
FAO: The State of World Fisheries and Aquaculture 2014, Rome, 223 pp., 2014.
Fennel, K., Wilkin, J., Levin, L., Moisan, J., O'Reilly, J., and Haidvogel, D.: Nitrogen cycling in the Middle Atlantic Bight: results from a three-dimensional model and implications for the North Atlantic nitrogen budget, Global Biogeochem. Cy., 20, GB3007, 2006.
Ferreira, J. G., Hawkins, A. J. S., and Bricker, S. B.: Management of productivity, environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) model, Aquaculture, 264, 160–174, 2007.
Filgueira, R. and Grant, J.: A box model for ecosystem-level management of mussel culture carrying capacity in a coastal Bay, Ecosystems, 12, 1222–1233, 2009.
Grant, J., Bacher, C., Cranford, P. J., Guyondet, T., and Carreau, M.: A spatially explicit ecosystem model of seston depletion in dense mussel culture, J. Marine Syst., 73, 155–168, 2008.
Holmer, M.: Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs, Aquaculture Environment Interactions, 1, 57–60, 2010.

OSD
12, 1187–1217, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Jackson, D., O'Donohoe, P., Kane, F., Kelly, S., Mc Dermott, T., Drumm, A., Lyons, K., and Nolan, G.: Result of an epidemiological study of sea lice infestation in South Connemara, West of Ireland, Aquaculture, 364–365, 118–123, 2012.

Jauffrais, T., Marcaillou, C., Herrenknecht, C., Truquet, P., Séchet, V., Nicolau, E., Tillmann, U., and Hess, P.: Azaspiracid accumulation, detoxification and biotransformation in blue mussels (*Mytilus edulis*) experimentally fed *Azadinium spinosum*, Toxicon, 60, 582–595, 2012.

Kooijman, S. A. L. M.: Dynamic Energy Budget Theory for Metabolic Organisation, 3rd edn., Cambridge University Press, Cambridge, 514 pp., 2010.

Marcaillou, C., Haure, J., Mondeguer, F., Courcoux, A., Dupuy, B., and Pénisson, C.: Effect of food supply on the detoxification in the blue mussel, *Mytilus edulis*, contaminated by diarrhetic shellfish toxins, Aquat. Living Resour., 23, 255–266, 2010.

Nolan, G., Gillooly, M., and Whelan, K. (Eds.): Irish Ocean Climate and Ecosystem Status Report Summary 2009, Marine Institute, 100 pp., 2010.

Novaczek, I., Madhyastha, M. S., Ablett, R. F., Johnson, G., Nijjar, M. S., and Sims, D. E.: Uptake, disposition of domoic acid by blue mussels (*Mytilus edulis*), Aquat. Toxicol., 21, 103–118, 1991.

Novaczek, I., Madhyastha, M. S., Ablett, R. F., Donald, A., Johnson, G., Nijjar, M. S., and Sims, D. E.: Depuration of domoic acid from live blue mussels (*Mytilus edulis*), Can. J. Fish. Aquat. Sci., 49, 312–318, 1992.

Nunes, J. P., Ferreira, J. G., Bricker, S. B., O'Loan, B., Dabrowski, T., Dallaghan, B., Hawkins, A., O'Connor, B., and O'Carroll, T.: Towards an ecosystem approach to aquaculture: assessment of sustainable shellfish cultivation at different scales of space, time and complexity, Aquaculture, 315, 369–383, 2011.

Olbert, A. I., Hartnett, M., Dabrowski, T., and Mikolajewicz, U.: Long-term inter-annual variability of a cyclonic gyre in the western Irish Sea, Cont. Shelf Res., 31, 1343–1356, 2011.

Olbert, A. I., Dabrowski, T., Nash, S., and Hartnett, M.: Regional modelling of the 21st century climate changes in the Irish Sea, Cont. Shelf Res., 41, 48–60, 2012.

O'Sullivan, D., Lordan, C., Doyle, J., Berry, A., and Lyons, K.: Sediment characteristics and local hydrodynamics and their influence on the population of *Nephrops* around Ireland, Irish Fisheries Investigations No. 26, Marine Institute, Ireland, 38 pp., 2014.

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., and Schlax, M. G.: Daily high-resolution-blended analyses for sea surface temperature, J. Climate, 20, 5473–5495, 2007.

Schlag, Z. R. and North, E. W.: Lagrangian TRANSport (LTRANS) v.2model User's Guide, Technical report of the University of Maryland Centre for Environmental Science Horn Point Laboratory, Cambridge, MD, 183 pp., 2012.
Shchepetkin, A. F. and McWilliams, J. C.: The regional oceanic modeling (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, Ocean Model., 9, 347–404, 2005.
Tolman, H. L.: User manual and system documentation of WAVEWATCH III version 3.14, NOAA/NWS/NCEP/MMAB Technical Note 276, 194 pp., 2009.
Wohlgeschaffen, G. D., Mann, K. H., Subba Rao, D. V., and Pocklington, R.: Dynamics of the phycotoxin domoic acid: accumulation and excretion in two commercially important bivalves, J. Appl. Phycol., 4, 297–310, 1992.

OSD
12, 1187–1217, 2015

Table 1. Classification of aquaculture sites (after Holmer, 2010).

	Coastal farming	Off-coast farming	Offshore farming
Physical setting	< 500 m from shore < 10 m water depth Within sight of shore users	500 m to 3 km from shore 10 to 50 m water depth Usually within sight	> 3 km from shore > 50 m water depth On continental shelf Not visible from shore
Exposure	Waves < 1 m Local winds Local currents Strong tidal currents Sheltered 100 % accessibility	Waves < 3 to 4 m Localised winds Localised currents Weak tidal currents Somewhat sheltered > 90 % accessibility	Waves up to 5 m Ocean winds Ocean swell No tidal currents Exposed > 80 % accessibility
Legal definitions	Within coastal baseline National waters	Within coastal baseline National waters	Outside coastal baseline National/international waters
Examples of major producers	China Chile Norway	Chile Norway Mediterranean	USA (Hawaii) Spain (Canaries)

OSD
12, 1187–1217, 2015

Ocean modelling for aquaculture and fisheries in Irish waters

T. Dabrowski et al.

Table 2. Cross-contamination matrix for salmon aquaculture farms in the west of Ireland.

Release sites	Receiving sites				
	Casheen	Cnoc	Daonish	Golam	Red flag
Cnoc	129		202	111	525
Daonish	1359	129		73	439
Golam	155	37	206		237

OSD
12, 1187–1217, 2015

Ocean modelling for aquaculture and fisheries in Irish waters

T. Dabrowski et al.

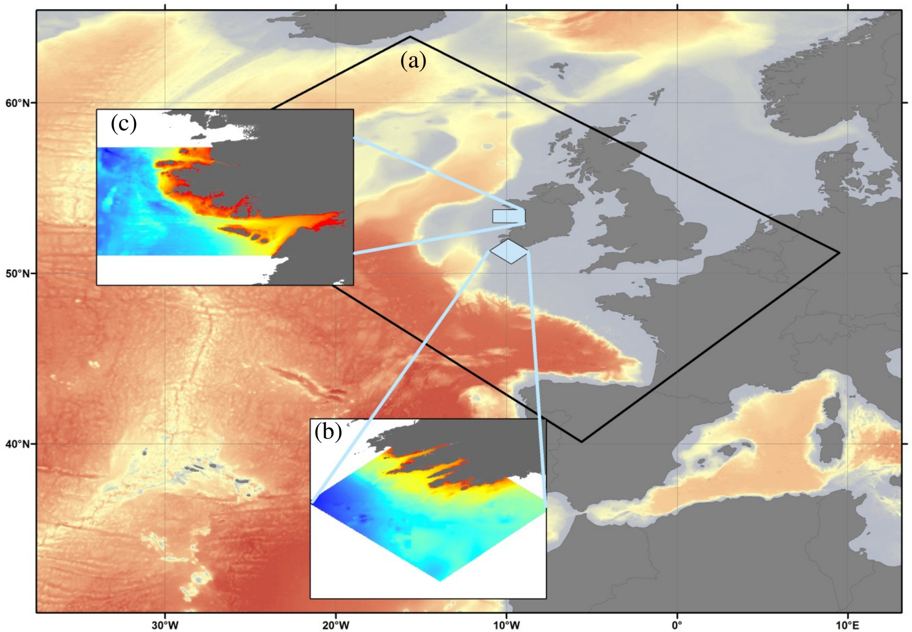

Figure 1. The Marine Institute operational general ocean circulation models domains: **(a)** NE_Atlantic, **(b)** Bantry Bay and **(c)** Connemara.

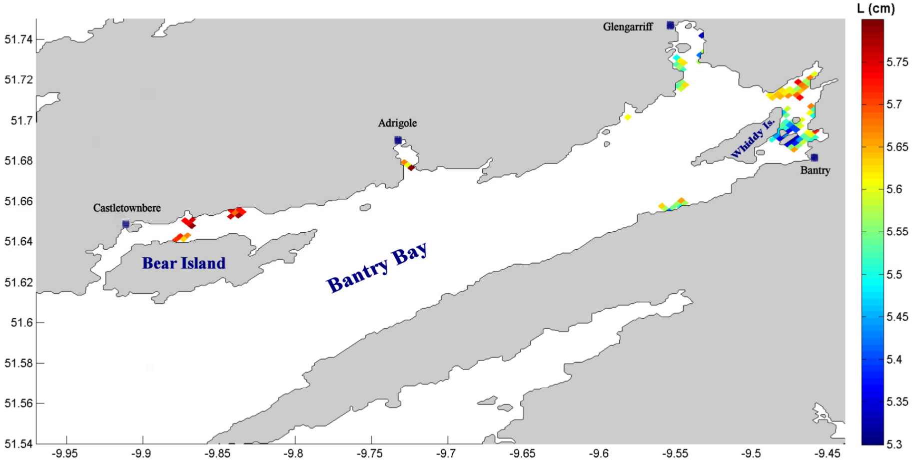

Figure 2. Predicted shell lengths at the end of June 2011 after c. 1 year simulation with initial shell lengths of c. 3.3 cm (after Dabrowski et al., 2013).

OSD
12, 1187–1217, 2015

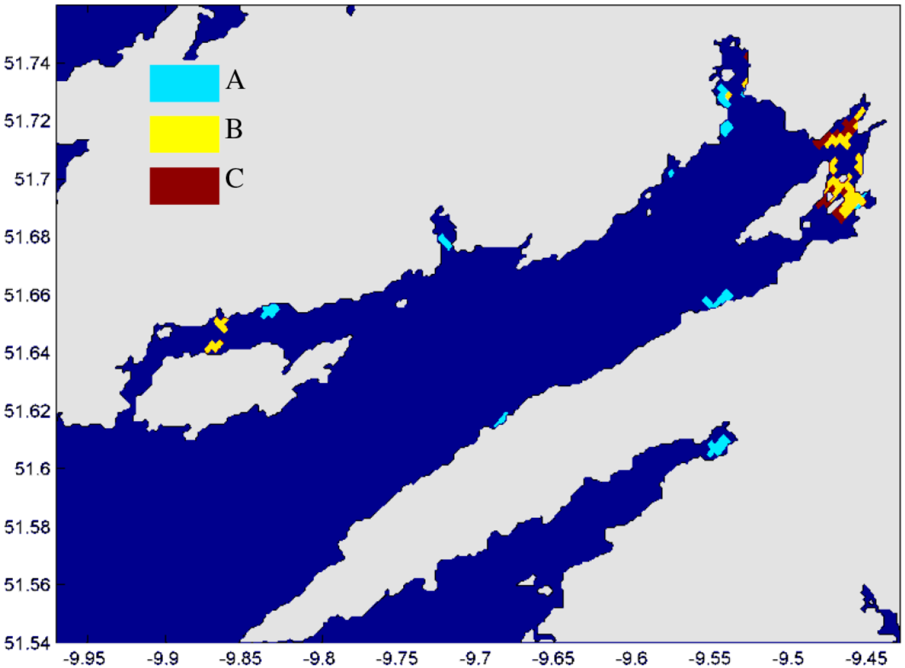

Figure 3. Shellfish waters classification in Bantry Bay predicted by the model (after Dabrowski et al., 2014).

OSD
12, 1187–1217, 2015

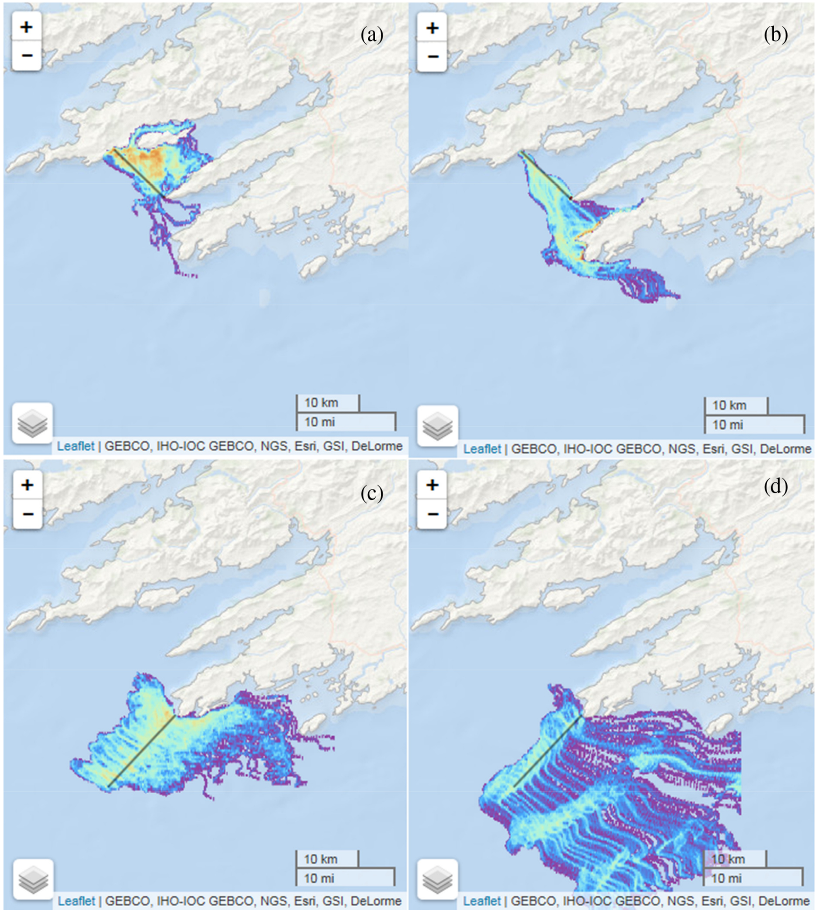

Figure 4. The particle-hours map from the 3 day forecast starting on 27 April 2015. Particles were released at the bottom layer along the transect shown. Colour scheme: purple – low values, orange – high values.

OSD
12, 1187–1217, 2015

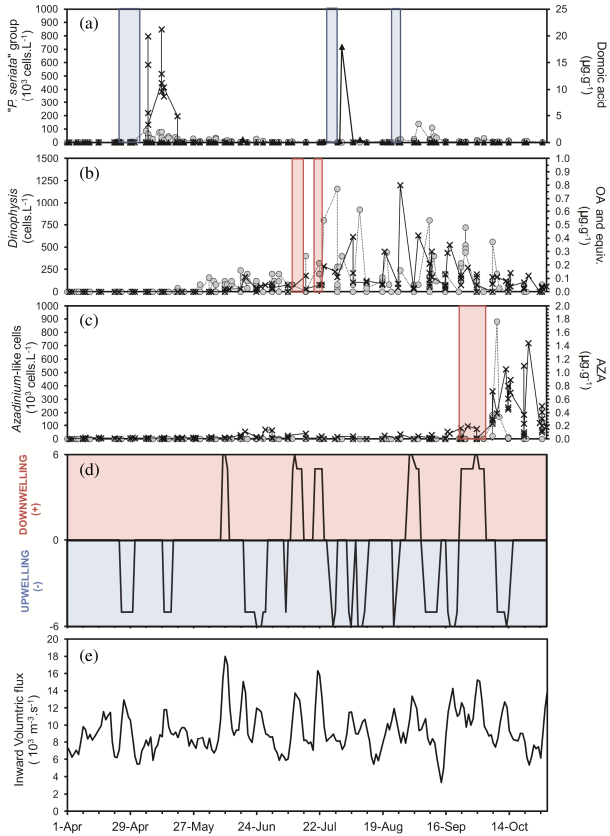

Figure 5. Harmful Algal Bloom events and model results, Bantry Bay, April to October 2013; concentrations of **(a)** *Pseudo-nitzschia* ("o"), *Karenia mikimotoi* ("▲") and DA ("x"), **(b)** *Dinophysis* ('o') and OA & equivalents ("x") and **(c)** *Azadinium*-like dinoflagellates ("o") and AZAs ("x"); **(d)** upwelling and downwelling events in the bay, **(e)** volumetric inflow to the bay; Blue and red boxes overlaid on plots (Fig. 6a–c) relate to upwelling and downwelling, respectively.

OSD
12, 1187–1217, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

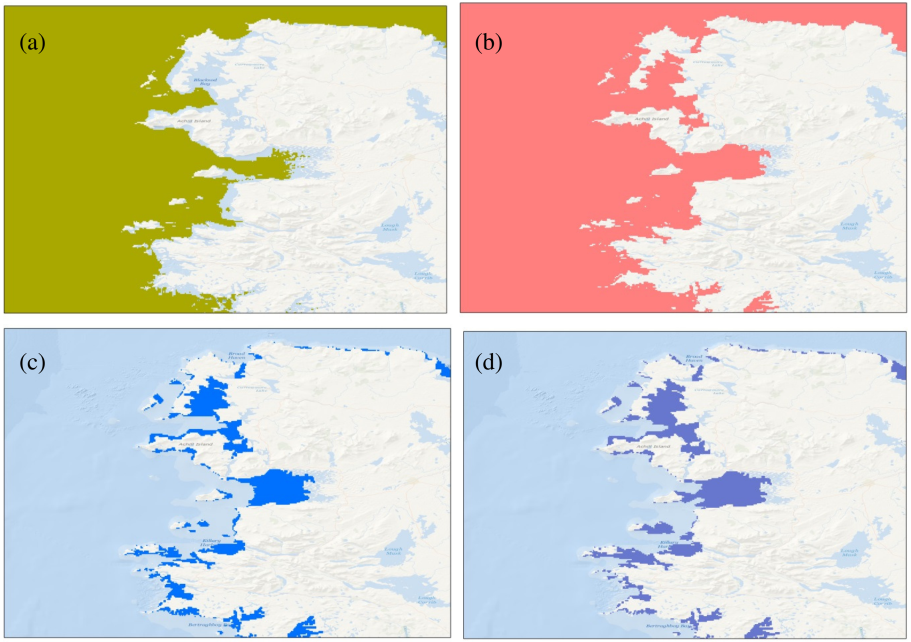

Figure 6. Spatial extents of **(a)** depth ≥ 15 m, **(b)** max tidal velocity < 1 m s^{-1}, max_Hs < 4 m and Hs_P90 < 2 m for the west coast of Ireland.

OSD

12, 1187–1217, 2015

Ocean modelling for aquaculture and fisheries in Irish waters

T. Dabrowski et al.

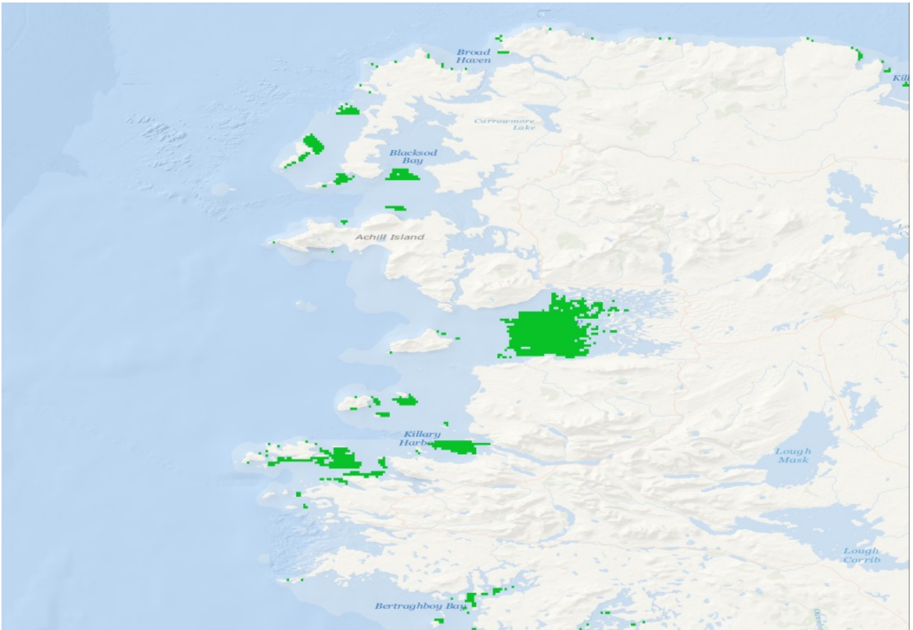

Figure 7. Potential offshore aquaculture sites (green) off the west coast of Ireland.

OSD
12, 1187–1217, 2015

Ocean modelling for aquaculture and fisheries in Irish waters

T. Dabrowski et al.

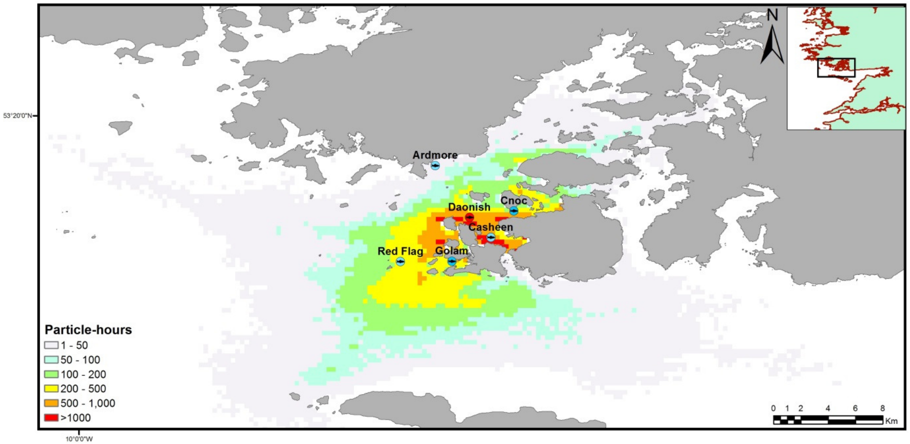

Figure 8. Sea lice infection risk map from Daonish farm located in the west of Ireland (after Jackson et al., 2012).

OSD
12, 1187–1217, 2015

Ocean modelling for aquaculture and fisheries in Irish waters

T. Dabrowski et al.

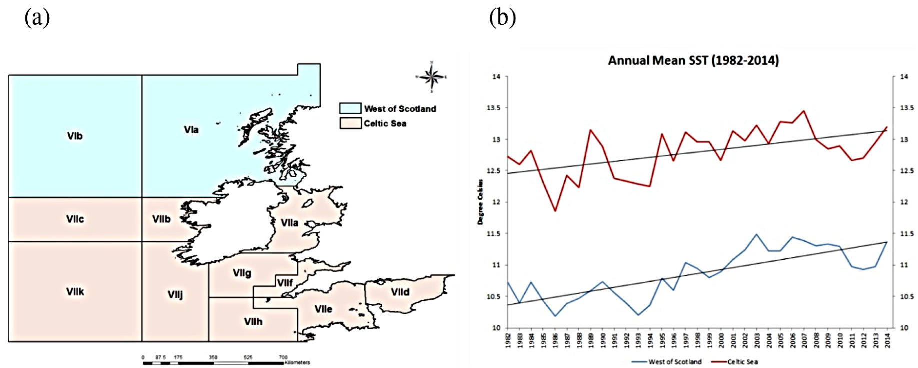

Figure 9. (a) ICES divisions around Ireland and **(b)** timeseries of annual SST for the West of Scotland (divisions VIa-b) and the Celtic Sea (divisions VIIa-k) subareas (after Casal et al., 2015).

OSD
12, 1187–1217, 2015

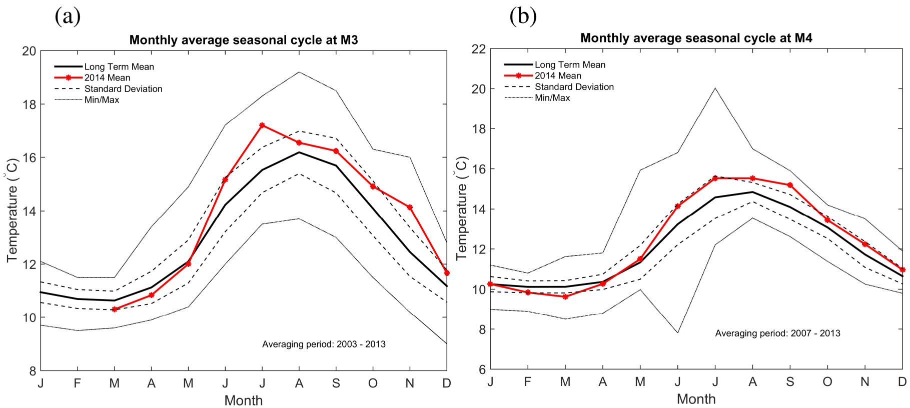

Figure 10. Monthly average seasonal cycles with 2014 monthly temperatures at the **(a)** M3 (51.2166° N, 10.55° W) and **(b)** M4 (55° N, 10° W) weather buoys west of Ireland.