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Modelling *Pseudo-nitzschia* events off southwest Ireland

Caroline Cusack [a,*], Helena Mouriño [b], Maria Teresa Moita [c,d], Joe Silke [a]

[a] Marine Institute, Rinville, Oranmore, Co. Galway, Ireland
[b] Faculdade de Ciências, Universidade de Lisboa, Edifício C6, Campo Grande, 1749-016 Lisbon, Portugal
[c] Instituto Português do Mar e da Atmosfera, Av. Brasilia, 1449-006 Lisboa, Portugal
[d] CCMAR, Campus de Gambelas, 8005-339 Faro, Portugal

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ABSTRACT

Toxic and non-toxic *Pseudo-nitzschia* blooms are common in coastal waters worldwide including Ireland. Off southwest Ireland, the timing of blooms on a weekly scale is highly variable, while the seasonal pattern is more regular with a bimodal distribution. Upwelling conditions are closely linked to *Pseudo-nitzschia* blooms. The work presented here describes a mathematical model, a Zero-Inflated Negative Binomial Model, employed to forecast the onset, abundance and duration of *Pseudo-nitzschia* blooms in the bays of southwest Ireland. Variables used in the model included field observations of *Pseudo-nitzschia*, sea surface temperature and wind. The estimated model reveals that, on average, cell levels on a given day depend on sea surface temperature, the value of a wind index on the previous day and the number of *Pseudo-nitzschia* in the water the previous week. The model forecast performed well for the onset and duration of blooms. However, the magnitude of blooms was sometimes underestimated by the model.

1. Introduction

To date, 12 out of the 37 known *Pseudo-nitzschia* species produce a biotoxin called domoic acid (DA), harmful to humans if contaminated shellfish are consumed (Lelong et al., 2012). Domoic acid can accumulate in marine fauna (e.g. shellfish, fish, mammals, seabirds), cause mortalities (e.g. sea lions) and transfer through food webs with negative impacts most notable in eastern boundary upwelling systems (Trainer et al., 2012). The biotoxin depurates quickly from many shellfish species with the exception of bottom dwelling scallops (Trainer et al., 2012). Of the 10 species observed in Irish waters, 7 have the potential to produce DA (Cusack et al., 2004; Lelong et al., 2012). While all *Pseudo-nitzschia* blooms pose a risk, late February to May is a very high risk period for DA contamination of long-line cultured mussels off southwest Ireland with *Pseudo-nitzschia australis* confirmed as a species responsible for some toxic events (Marine Institute, unpublished molecular data). In Ireland, records of DA in shellfish include species of scallops (*Pecten maximus* Linnaeus), blue mussels (*Mytilus edulis*), oysters (*Crassostrea gigas* Thunberg and *Ostrea edulis* Linnaeus) and razor clams (*Ensis siliqua* Linnaeus) (Cusack et al., 2002). The toxin can be found throughout the year in some shellfish e.g. scallops; DA was first detected in king scallops (*P. maximus*) in 1999 (McMahon and Silke, 2000). The southwest coast of Ireland is important in terms of national aquaculture production volume; finfish and shellfish operations promote employment in rural coastal communities. Circa 67% of Irish rope cultivated blue mussel, *ca.* 74% native oyster and *ca.* 9% of pacific oyster are produced in the region (five year mean 2008–2012 supplied by BIM, Ireland's Sea Fisheries Board). Mussel production is suspended when toxic *Pseudo-nitzschia* blooms result in DA contamination of long-line cultures with the first recorded episode in 2005 (Moran et al., 2006).

Local hydrographic conditions that involve the upwelling of cold nutrient rich water play an important role in the distributional patterns of *Pseudo-nitzschia* (e.g. Buck et al., 1992; Kudela et al., 2005; Walz et al., 1994). In some regions, weak to moderate upwelling events can transport large populations of these potentially toxic diatoms shoreward (GEOHAB, 2005). For example, along the coast of Portugal, upwelling is seasonal from April to September and *Pseudo-nitzschia* spp. time and space distributions are associated with the main upwelling patterns (Abrantes and Moita, 1999; Fiúza et al., 1982). Similarly, off the Atlantic coast of Spain (Galician Rias) *Pseudo-nitzschia* spp. have a tendency to increase in cell numbers at times of post-upwelling events (González Vilas et al., 2014). While off northwest America, where the oceanography is complex, one mode of offshore to onshore transport of *Pseudo-nitzschia* blooms is that they develop and are retained in the Juan de Fuca Eddy, cells exit the eddy under upwelling favourable winds and travel in alongshore currents until they are dispersed shoreward under strong downwelling winds (Giddings et al., 2014).

Based on empirical knowledge from the field studies referred to below, we surmise that *Pseudo-nitzschia* blooms off southwest Ireland

* Corresponding author.
E-mail address: ck.cusack@gmail.com (C. Cusack).

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are not limited to bays and that inshore blooms are linked to "upwelling" events (i.e. offshore water enters the bays at depth). Our assumption is that blooms develop in the Celtic Sea (off the south coast of Ireland; Fig. 1a), are transported westward in the coastal current and delivered into the bays off southwest Ireland under upwelling conditions. *Pseudo-nitzschia* spp. are frequent visitors in Irish coastal waters throughout the year and are found in both mixed and stratified waters. In the Celtic Sea, *Pseudo-nitzschia* blooms occur on the shelf, outside the mouth of bays and are recorded from spring (late February to early March) through to autumn (Cusack et al., 2004; Farrell et al., 2012; Pybus, 2007; Raine and McMahon, 1998). Similarly, to the north, *Pseudo-nitzschia* populations have been recorded in the shelf seas to the west of Scotland (Fehling et al., 2012). A fifty year time series shows a recent increase in the relative abundance of *Pseudo-nitzshia* spp. in surface shelf waters off southern Ireland; related to increases in sea surface temperature (SST) and summer wind speed (Hinder et al., 2012). Blooms are either dispersed throughout the surface mixed layer or are present at high cell concentration in subsurface thin layers (Cusack, 2002; Farrell et al., 2012). Populations are transported from the Celtic Sea to the southwest coast in the Irish coastal current (Raine and McMahon, 1998). Periodic upwelling and downwelling pulses in the coastal zone off southwest Ireland facilitate the cross shelf transport of phytoplankton (Raine, 2014). *Pseudo-nitzschia* can be very abundant off southwest Ireland with high biomass blooms evident at times of relaxed upwelling (Cusack, 2002; Raine and Joyce, 1996; Raine and McMahon, 1998; Raine et al., 1990, 1993; Roden et al., 1981). Raine and McMahon (1998) noted that the phytoplankton composition off the southwest coast changed in relation to the position of the Irish Shelf Front (ISF; separates Atlantic and coastal shelf waters) with *Pseudo-nitzschia* only evident on the coastal side of the front on the shelf. *Pseudo-nitzschia* cell densities along the axial transect of Bantry Bay showed highest abundances at the mouth of the bay. It is the front's position that determines if the Irish Coastal Current, the along shore shelf current, can flow freely from the Celtic Sea (see details in Raine and McMahon, 1998; Raine, 2014). Jet-like flows on the shelf, driven by the formation of seasonal subsurface bottom density fronts, increase the speed of the clockwise coastal current at depth and are an important transport pathway for *Pseudo-nitzschia* in summer (Farrell et al., 2012). Rates of transit can be in the order of 6–7 km/day (Raine et al., 2010a). Winds from the east are considered important in the westward directed transport system (Raine et al., 2010b). Raine et al. (2010b) also demonstrated that shifts in local wind forcing can cause large water exchanges between thermally stratified southwest bays and the adjacent shelf in summer. The link between the bays and offshore waters is strongly influenced by the bays axial wind strength i.e. SW and NE quarter winds (056°–236° compass true direction used to calculate a "wind index"). A reversal or cessation in the strength of prevailing southwesterly winds can result in the off-shore movement of the surface boundary layer in thermally stratified waters (Edwards et al., 1996; Raine et al., 2010b), referred to here as "upwelling".

In this paper, we explore if a statistical model can be developed to predict the appearance and flux of *Pseudo-nitzschia* cell densities in the bays off southwest Ireland (model objective). The model objective does not address the origin of blooms, although a regional knowledge of environmental factors related to bloom events and transport processes were considered important for the selection of parameters.

Explanatory independent environmental variables included in the model are shifts in local wind forcing using a "wind index" (WI) and SST. Both are important parameters in the study of mesoscale oceanic processes. Wind data was chosen as measurements are collected at regular hourly intervals and changes in wind forcing (direction and speed) have already proven useful to predict the delivery of offshore phytoplankton into the bays off southwest Ireland (Raine, 2014). Sea surface temperature was selected as measurements are collected at regular hourly intervals and temperature is a fundamental water property that varies with season and local mesoscale processes (e.g. tidal changes, position of ISF). Phytoplankton growth rate is a function of temperature and more importantly nutrient resource and light availability are linked with temperature since water column thermal stratification influences the biological availability of nutrients; nutrients levels are correlated with the SST signal in spring and summer off southwest Ireland (van de Poll et al., 2013).

Pseudo-nitzschia is considered an important parameter (dependent variable) because cell count increases in previous weeks should give an indication of bloom development. Also, near real time cell densities of target phytoplankton have proven useful for predictive model development (for example, cell densities: Palma et al., 2010; abundance categories: González Vilas et al., 2014). Here, evolution of *Pseudo-nitzschia* abundances are predicted at the genus level since individual species cannot be identified with classic light microscopy, a technique applied

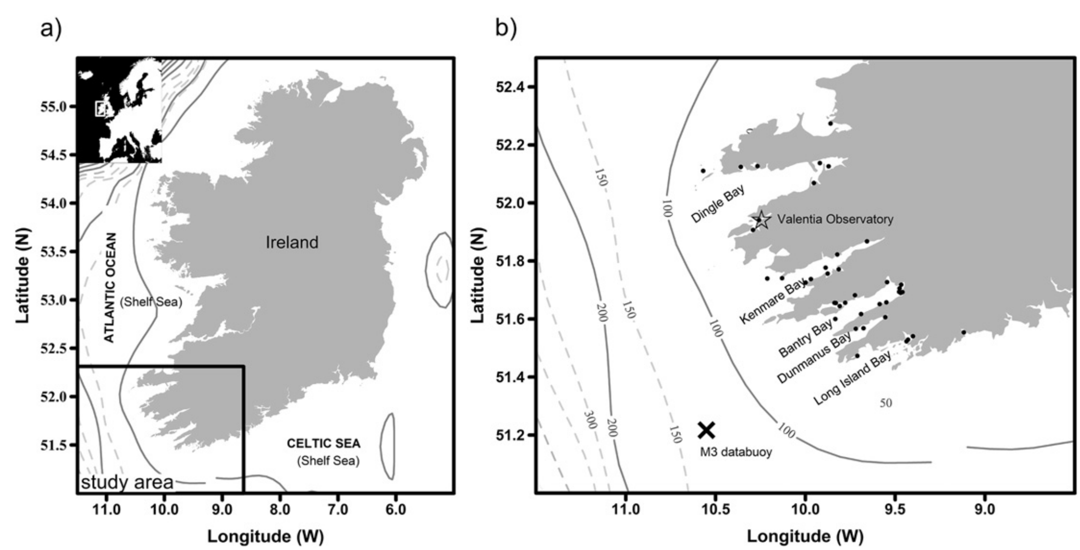

Fig. 1. Maps of the study area. Grey solid and dashed lines denote changes in bathymetry (metres). (a) The southwest coast of Ireland marks the boundary between the northeast Atlantic seaboard and the Celtic Sea. Study area is in the box on bottom left hand corner of map. Upper insert shows Ireland's geographic position in Europe. (b) Map of study area extends along the coastline to include the five main bays of Long Island Bay, Dunmanus Bay, Bantry Bay, Kenmare Bay and Dingle Bay, all with a NE–SW orientation. Black circles denote stations where the shellfish and finfish industries collect weekly water samples. The black X marks the position of the national weather data buoy, M3 (51° 13.02′ N; 10° 33.06′ W), ~80 km from Valentia (51° 56.38′ N; 10° 14.67′ W), the open star symbol, a national meteorological observation station, operated by Met Éireann.