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A simple short range model for the prediction of harmful algal events in the bays of southwestern Ireland

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ABSTRACT

A simple model is described which predicts harmful algal events in the bays of southwestern Ireland. Fundamental to the model is the physical forcing of circulation in these bays in summer. The predominant hydrographic feature at this time is a wind-driven two-layer oscillatory flow acting in a thermally stratified water column. This mechanism exchanges substantial proportions of the bays' volumes, and harmful algal events arise with the associated transport of harmful populations into them. The model is therefore based on the criterion that wind-driven water exchanges result in exchanges of phytoplankton, which, if the time of year is correct, result in toxic events. Utilising Bantry Bay as an example, hindcasting showed that the model has a high degree of success using a wind index based on the sequence of winds that results in water exchange. The model was implemented by estimating indices from the five-day weather forecast, and trialled in 2005. Results were published on the web in real time, during which a predicted water exchange event in mid-June was accompanied by an influx of *Dinophysis acuminata* into Bantry Bay with an associated contamination of shellfish with Diarrheic Shellfish Poisoning toxins.

1. Introduction

The considerable economic losses which can derive from harmful algal events, often referred to as Harmful Algal Blooms or HABs, makes their prediction desirable in order to develop or activate mitigation procedures. In the case of finfish culture in cages, primary mitigation actions include aeration, translocation of the cages or the physical prevention of bloom encroachment. Practical options include the use of skirts around the cage perimeter, airlift pumping or removal of the bloom through flocculation resulting from the spreading of clay, activities which are summarised and described in detail in Anderson et al. (2001). Mitigation procedures for the contamination of farmed shellfish with algal biotoxins are, however, not so direct. This is probably because, unlike finfish, the effects of HABs on shellfish do not usually involve mortalities of stock and the producer is only aware of its contamination after the time required for toxin testing. The whole stock in a location is usually affected, and the common option to the shellfish producer involves simply waiting, sometimes for long periods (months), for the product to naturally depurate the toxin. A forewarning of HAB events would therefore be extremely beneficial to both finfish and shellfish producers, enabling the activation of possible mitigation measures. In the case of shellfish producers this would allow procedures such as carrying out a small harvest for shellfish processing if markets for fresh stock are not available at that time, or moving marketable stock to clean tanks on shore.

The southwest of Ireland is one of the most important national regions for shellfish culture. Approximately 80% of national rope mussel (*Mytilus edulis*) and 50% of Pacific oyster (*Crassostrea gigas*) is produced here annually (Parsons, 2005). The industry is located in the large bays of Bantry, Dunmanus and Long Island (Fig. 1) which give Ireland its characteristic coastal outline in the southwest. These bays are drowned river valleys, or rias. They exhibit limited estuarine characteristics and thermally stratify in summer (Raine et al., 1990a). Tidal currents are weak (<5 cm s^{-1}) in these bays and the circulation is essentially driven by the wind due to the geometry of the bays: they are axially aligned to the predominant wind direction which comes from the southwest quarter (Edwards et al., 1996). When the bays are thermally stratified, variations in the axial wind vector cause two-layer oscillatory flows which generally result in the import of water from the near coastal continental shelf together with the phytoplankton within it (Edwards et al., 1996). Substantial fractions of the bay volume are exchanged during these events, which discourage the development of indigenous phytoplankton populations within the bays (Raine et al., 1993).

It has long been suspected that toxic algal events in the bays of southwestern Ireland arise due to the transport of populations of harmful species from the near coastal shelf. Wind-forced water exchange in Bantry Bay has been shown to import potentially harmful

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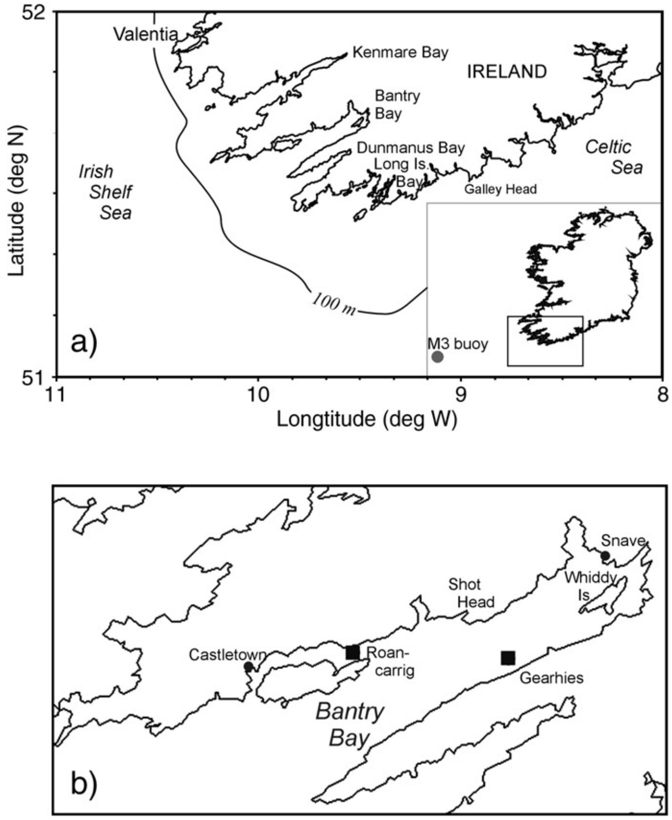

Fig. 1. Maps showing a) the bays of southwest Ireland with locations mentioned in the text and (inset) the position of the M3 meteorological buoy; b) location of sampling sites in Bantry Bay. Filled squares denote the positions of temperature sensors.

species such as *Karenia mikimotoi* (Raine et al., 1993), as well as other non-toxic phytoplankton populations (Goward and Savidge, 1993). Contamination of shellfish with algal toxins which cause Diarrheic Shellfish Poisoning (DSP) is one of the biggest problems caused by HABs in the region (Silke et al., 2005a). This paper demonstrates wind-driven import of *Dinophysis* spp. and consequent contamination of shellfish with DSP toxins and investigates the use of the short range weather forecast to predict harmful events. The prediction model is based on water and plankton exchanges resulting from variations in wind speed and direction, coupled with a simple probabilistic approach based on the time of year when harmful blooms are most likely to occur.

2. Methods

Field measurements were carried out in Bantry Bay (Fig. 1). Water temperature was monitored through the deployment of a string of four temperature sensors (TidbiT, Mass.) sited off the southern coast at Gearhies where the water column is approximately 27 m deep (Fig. 1b). The temperature sensors were deployed at 1 m below the surface, 1 m off the seabed, and two distributed evenly along the mooring line over a depth range of 1–25 m. A second thermistor chain was subsequently deployed off Roancarrig (Fig. 1b). Meteorological data (wind speed and direction) were routinely derived from measurements made by the national meteorological service (Met Éireann) at the Valentia weather station, a coastal station sited approximately 30 km north of the study region (Fig. 1). Wind measurements made within the bay have shown a high correlation with those measured at Valentia (Raine et al., 1993). Data were also obtained from the M3 weather buoy subsequent to its deployment in 2004 at 51° 13′ N 10° 33′ W (Fig.1a).

Near surface (0–1 m) water samples for phytoplankton analysis were taken weekly through the summer at Roancarrig, near Castletown and at Gearhies (Fig. 1) as part of the National Phytoplankton Monitoring Programme (NMP) (Silke et al., 2005a). In 2001, the data set was supplemented by additional weekly samples from 1 and 10 m taken at Gearhies using 5 l Van Dorn water sampling bottles (Hydrobios, Kiel). All phytoplankton samples were preserved in Lugol's Iodine, and counted using Utermohl's method (Raine et al., 1990b). The NMP data archive was also analysed for the period 1993–2003 for which only data derived from discrete water bottle samples were used. It should be noted that from 2003 increasing amounts of data in the archive were derived from integrated water samples using 10 m length tubes (Lindahl, 1986). Data on the presence of DSP biotoxins in mussel flesh from rope cultured mussel samples from sites around Bantry Bay were taken from the national biotoxin monitoring programme archive.

3. Model development

The circulation in Bantry Bay is one of weak tides, limited estuarine characteristics and in the thermally stratified summer season is dominated by a two-layer, wind-driven oscillatory flow (Edwards et al., 1996). This physical model for the bays of southwestern Ireland is sketched in Fig. 2a and originates from studies carried out in the early 1990s (Raine et al., 1993; Edwards et al., 1996). The predominant situation is portrayed in the upper diagram, as approximately 80% of the wind is from the southwest quarter. It is fluctuations in the axial (60° T compass direction) component which promote water exchange in Bantry Bay. Exchange events can therefore be deduced if there is a particular sequence in the axial wind vector.

The prediction model was developed on the simple hypothesis that in the first instance harmful algal events in Bantry Bay primarily arise in summer, a time of year when the water column is thermally stratified. Implicit in this statement is that dinoflagellates are the group of organisms that are the primary cause of HAB events, due to their observed correlation with high stratification (Margalef, 1978), which has its seasonal maximum in summer in temperate regions such as Ireland (Jones and Gowen, 1990). Of course this is by no means true in the global sense, and ignores the occasional contamination of shellfish with, for example, amnesic shellfish poisoning toxins derived from the diatom genus *Pseudo-nitzschia*. Nevertheless, the biggest HAB problems around southwestern Ireland arise from contamination with DSP toxins derived principally from populations of the dinoflagellates *Dinophysis acuta* and *D. acuminata* (see e.g. Parsons, 2005). Analysis of the data archive for the region derived from the national phytoplankton monitoring programme shows quite clearly that these *Dinophysis* species occur principally between June and mid-September (Fig. 2b), a period during which >97% of samples containing *Dinophysis* at cell densities >100 cells l^{-1} occur, a level close to that considered high enough to contaminate shellfish (Botana et al., 1996).

An oscillation in wind direction from axially negative (blowing seaward out of the bay) followed by axially positive (blowing into the bay), will cause an exchange event in the bays of southwestern Ireland in summer. The converse is also true, but as the typical situation is one of southwesterly winds, then the occurrence of winds with a northeast or east component is more important in the promotion of exchange events. East winds also cause a marked increase in the speed of the coastal current which flows clockwise around southwest Ireland, bringing a change in plankton population to the mouth of Bantry Bay (Raine and McMahon, 1998). The model therefore focused on the east wind component, and subsequent resumption of winds from the southwest quarter. Relating this sequence in wind direction to time of year allows an empirical approach to the prediction of harmful events. This is depicted in Fig. 2c, which couples the relatively high probability of HABs occurring within the summer temporal

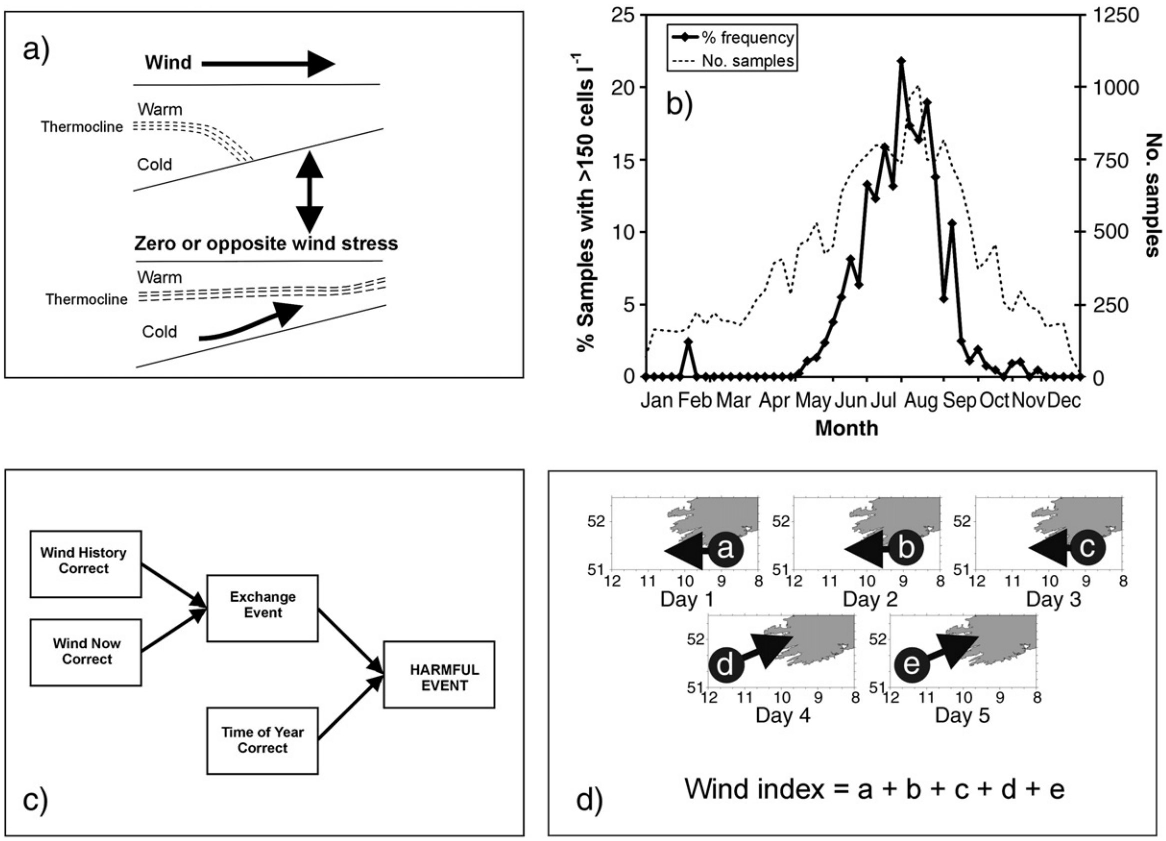

Fig. 2. The basis of the predictive model described in the text. a) schematic of wind-driven two-layer oscillatory flows in Bantry Bay described in Edwards et al. (1996); b) analysis of the *Dinophysis* record for Bantry Bay, 1993–2003, indicating the frequency of samples with cell densities considered potentially harmful (>150 cells l^{-1}). The total number of samples analysed is also plotted which do not include integrated tube samples which might bias the data. Note the substantial increase in the sample frequency between June and mid-September; c) the fuzzy logic style approach to prediction of harmful events in the bays of southwestern Ireland; d) generation of the wind index used to predict wind-driven exchange events. Values are the daily average westward vectors (days 1, 2 and 3) and vectors towards 060° (days 4 and 5).

window with the wind-driven hydrodynamic model of water exchange in the southwestern Irish bays. We established a numerical value, derived from the wind data, which signifies the likelihood of an exchange event.

The numerical value derived was essentially based on the magnitude and sign of the wind vector that is axially aligned to the bays (060°–240°). First, the daily average westward (270°) components of the wind for three consecutive days, in m s^{-1}, were added together. This value was then added to the daily average axial component blowing landwards (axially into the bay; 060°) for the subsequent two days. Emphasis is placed on the atypical condition when the southwesterly wind component is zero or negative through the choice of the initial three day period. This treatment is shown schematically in Fig. 2d, and the value obtained is hereafter referred to as the wind index.

4. Results

4.1. Model hindcasting

The model was initially tested for 2001 when a suitably high resolution of phytoplankton data was available. Results are shown in Fig. 3 for the time window 1 June–14 September, identified as high risk window for DSP contamination. The component of the wind axial to the bay during this period is shown in Fig. 3a. Winds blowing down the bay (seawards; negative) are associated with an efflux of surface water and influx of cool bottom water; currents reverse when the wind subsequently blows in the opposite direction (Edwards et al., 1996). Influx of cool water can be seen on 13–17 June, 4–8 July, and 16–20 July, during which water temperatures become cool (<12 °C) from the bottom of the water column up to a depth of ca. 10 m (Fig. 3b). The timing of these influxes matches the periods of negative axial winds. Cell densities of *Dinophysis* spp. increased on or before 26 July preceding a bloom event when maximum concentrations of over 3500 cells l^{-1} were observed on 7 August (Fig. 3c). This event coincided with an increase in water temperature over the depth range 1–20 m indicating an exchange of water had taken place (Fig. 3b). The observed increase in *Dinophysis* cell counts corresponded with the influx of warm surface layer water into the bay. The data set shown in Fig. 3 is in very good agreement with the hypothesis of Raine et al. (1993) that HAB events in the bays of southwestern Ireland are caused by the import of harmful populations.

The timing of the *Dinophysis* bloom of 2001 correlated with a peak in the wind index when a value of 14.3 m s^{-1} was recorded for 21 July (Fig. 3d). Prior to this, smaller peaks of 5–8 m s^{-1} were observed, linking with periods of east winds, but these had not been followed by substantial inflows of water into the bay, as adjudged by the temperature record in Fig. 3b. The event following 21 July had a substantially larger inflow of warm water subsequent to it.

The same treatment of data derived from meteorological records and the NMP for 2002 gave similar results (Fig. 4). The first six months of the temperature record were, however lost and data start on 16 July at Roancarrig, towards the mouth of Bantry Bay (Fig. 1b) and on 24 July at Gearhies. A rapid increase in bottom (20 m) water temperature occurred from 12.1 °C on 20 July to 14.9 °C on 29 July, indicating that an exchange of water, and phytoplankton, had taken place in the bay (Fig. 4a). *Dinophysis acuminata* cell densities in water samples taken at Roancarrig rose from 40 cells l^{-1} taken on the 10 and 25 July up to 4600 cells l^{-1} on 1 August (Fig. 4b). Over the same period, levels of okadaic acid, the DSP toxin associated with *D. acuminata*, in mussel

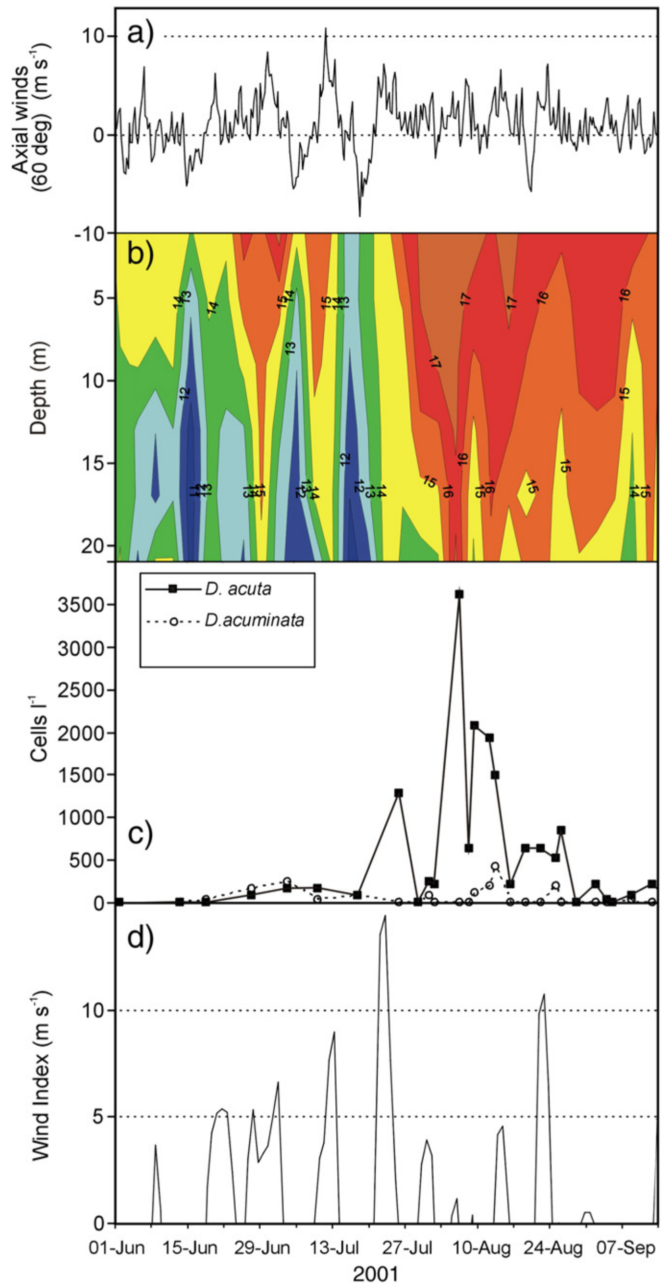

Fig. 3. Field data for 2001. a) axial (060°) wind vector from data recorded at Valentia b) contoured temperature data (°C) from a string of four temperature sensors located at Gearhies. Note the influx of warm surface water occurring between 26 July and 7 August; c) the *Dinophysis* record for Gearhies; d) the wind index derived from data recorded at Valentia. Locations are marked in Fig. 1.

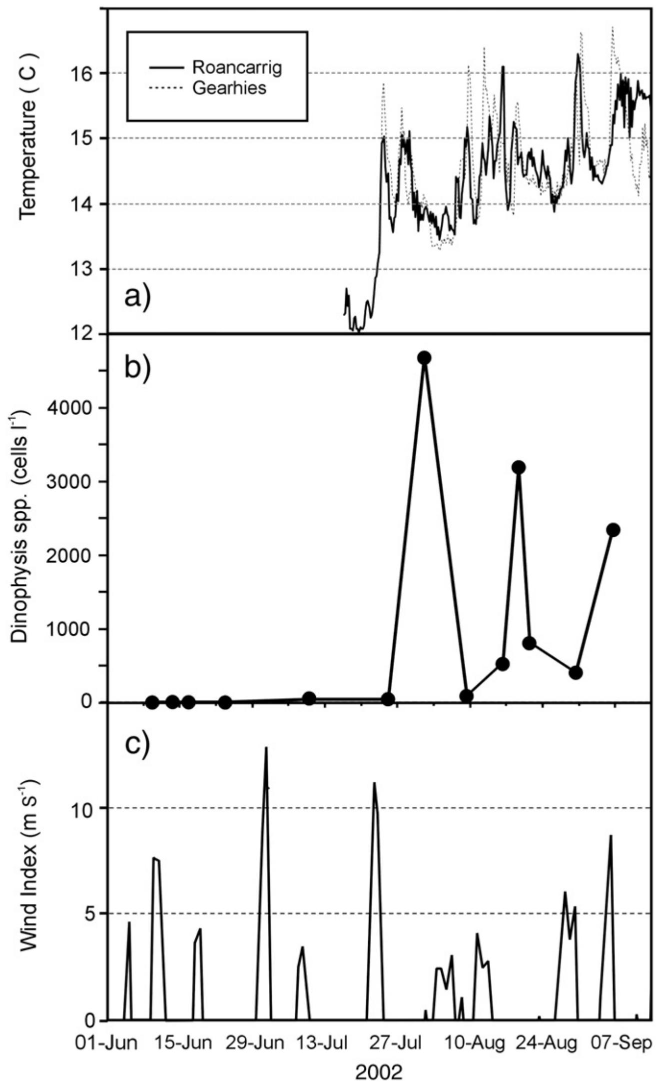

Fig. 4. Field data for 2002. a) near bottom (20 m) water temperature at Roancarrig and Gearhies; b) total *Dinophysis* spp. in water samples taken near Roancarrig; c) the wind index derived from data recorded at Valentia. Locations are marked in Fig. 1.

flesh rose from 0.03 and 0.05 μg g^{-1} on 15 and 22 July respectively, to 0.20 μg g^{-1} on 29 July. This increased concentration was above the action level of 0.16 μg g^{-1} when harvesting is prohibited. These events correlated with a high wind index of 12 m s^{-1} on 26 July (Fig. 4c).

No wind indices above 10 m s^{-1} were recorded through June–September 2003. The highest value of 9.0 m s^{-1} was observed on 29 August 2003, otherwise values were less than 6.5 m s^{-1} (data not shown). *Dinophysis* cell densities remained low in Bantry Bay through this period, never exceeding 650 cells l^{-1}, with only two samples exceeding 300 cells l^{-1}, on 14 and 29 July. In 2003 there were relatively few closures compared to other years (Cusack et al., 2003).

Field results for 2004 are shown in Fig. 5. A high wind index of 11.2 m s^{-1} was evident on 29 June, with no indication of an influx of *Dinophysis* spp. (Fig. 5). A subsequent value >10 m s^{-1} was noted on 14 August. High cell densities of over 9000 cells l^{-1} *Dinophysis* spp. were recorded in samples from near Roancarrig (and elsewhere in Bantry Bay) taken on 17 August 2004 (Fig. 5b), corresponding with an influx of warm surface water as adjudged from the temperature record (Fig. 5a). Again, these observations are consistent with wind-driven exchange of water causing an influx of *Dinophysis* into Bantry Bay.

Prior to 2001, the biological record is not as comprehensive. This is due to an inadequate regularity in both sampling and toxin testing, as well as a problem in interpretation of toxicity test results due to changes in methods of analysis. Nevertheless, between 1993 and 2000 shellfish closures can be related to wind-driven exchange events indicated by high wind indices (Blauw et al., 2006). In this period, there was a bloom event for which a plankton data set with suitable resolution exists for hindcasting. A DSP event caused by *Dinophysis acuta* and the toxin DTX-2 occurred in Bantry Bay in 1994 and is described in McMahon et al. (1998). *D. acuta* levels rose from <200 cells l^{-1} on 7 August to 4000 cells l^{-1} on 12 August (Fig. 6a). The influx of *D. acuta* can be clearly related to a high wind index of ~14 m s^{-1} for 12 August (Fig. 6b).

The data suggest quite strongly that a value of 10 m s^{-1} in the wind index is sufficient to cause an exchange event. With this criterion, however, the predictive model occasionally, in hindcast,

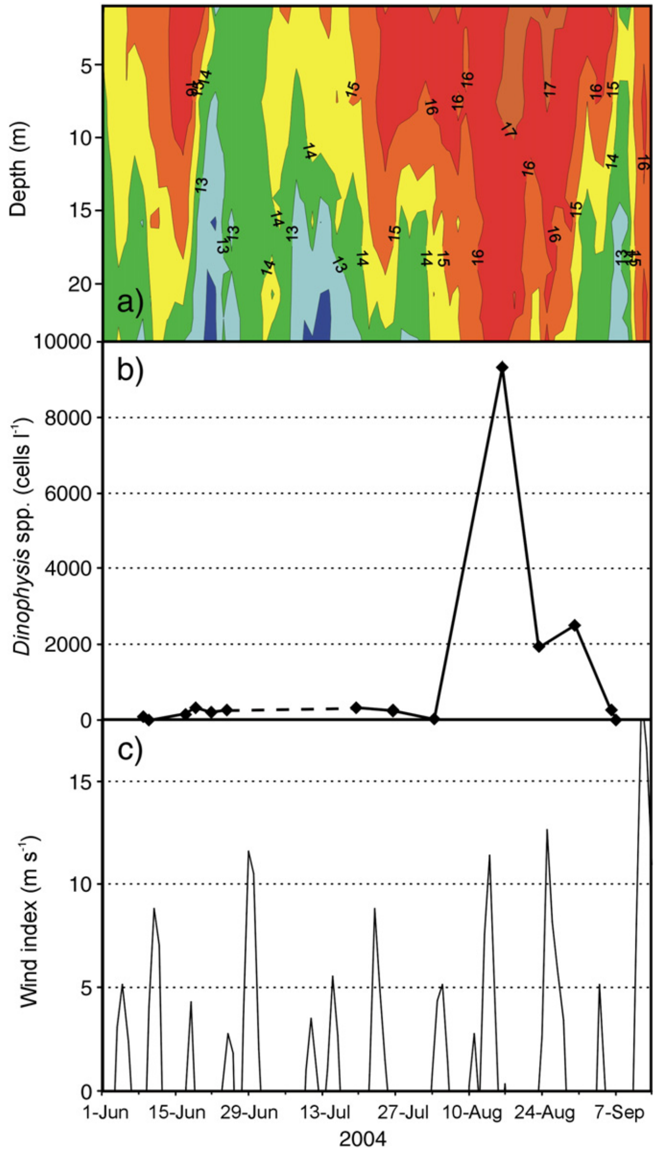

Fig. 5. Field data for 2004. a) contoured water temperature (°C) from a string of temperature sensors located at Gearhies; b) total *Dinophysis* cell densities in water samples taken near Roancarrig; c) the wind index derived from data recorded at Valentia. The maximum cell density observed on 17 August coincides with an influx of warm water. These observations were subsequent to the high wind index of 11.5 m s^{-1} recorded for 12 August. Locations are marked in Fig. 1.

resulted in positive indications of a toxic event but without a corresponding increase in *Dinophysis* levels or toxicity. Not every high wind index resulted in a toxic event during the critical season of June to mid-September. 'False positive' indications occurred on 1 July 2002 (Fig. 4c), when a high wind index of 13 m s^{-1} occurred, and again on 29 July 2004 (Fig. 5c). These events were not accompanied by an observed increase in *Dinophysis* or toxicity in shellfish tissue. The significance of false positives is discussed below.

4.2. Model implementation

The predictive model was implemented in 2005 by downloading a daily feed of a 5-day weather forecast for Bantry Bay (www.bbc.co.uk/weather) and calculating the wind index. Negative values for the predicted wind index were ignored and designated zero. Negative values imply prolonged southwesterly winds, a situation which would not produce water exchange. The wind index data were updated and published daily on the web (www.marine.ie). The accuracy of the

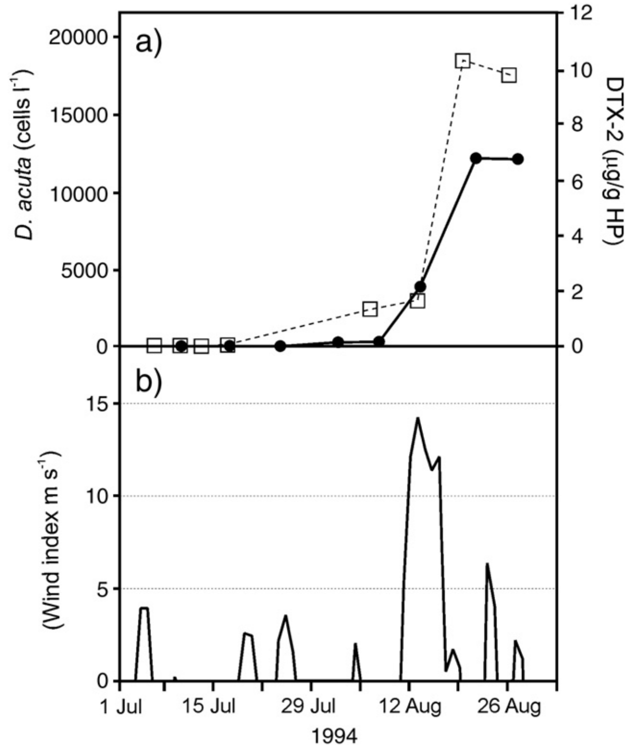

Fig. 6. Hindcasting the predictive model using data from 1994. a) Data record for *Dinophysis acuta* (open squares) and levels of associated toxin (DTX-2; filled circles) in mussel hepatopancreas (HP) in Bantry Bay. Maximum observed cell densities have been plotted for clarity (adapted from McMahon et al., 1998); b) wind indices measured over the toxic event in 1994 derived from observations at Valentia.

prediction was tested against weather data from both Valentia and the M3 Weather Buoy, which had been recently deployed in 2004. The comparison is shown in Fig. 7.

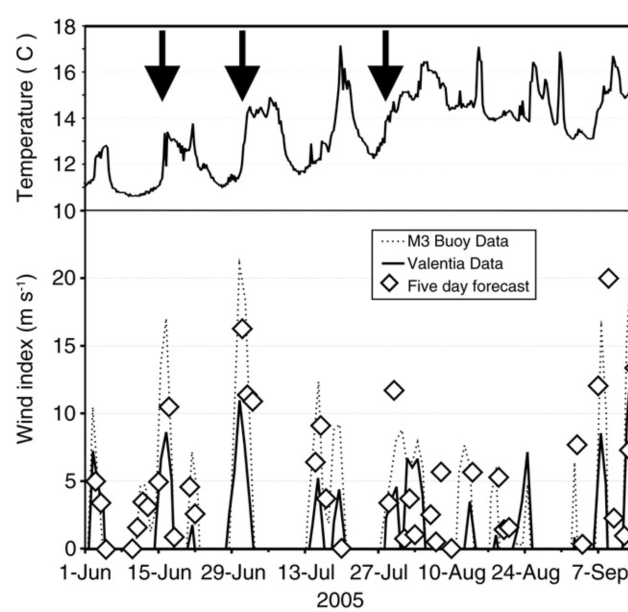

Fig. 7. The use of wind indices to predict harmful algal events in Bantry Bay. The wind index obtained from the 5-day weather forecast is plotted against actual values calculated from measurements at both Valentia and the M3 Weather Buoy (see Fig. 1 for respective locations). Exchange events are predicted for 16 and 30 June and 30 July when values of the wind index of over 10 m s^{-1} were forecast. On each occasion water exchange as indicated by sharp increases in the bottom temperature record (upper panel) were observed as indicated with the filled arrows. The temperature data suggest a fourth exchange may have taken place on 16 July, although here the forecast wind index did not achieve a value of 10 m s^{-1}. See text for details.

It can be seen that through the summer the prediction based on weather forecast indicated that within the high probability window June–mid-September exchange events should have occurred on 16 June, 2 and 30 July. The forecast exchange of 30 July did not yield a wind index above 10 m s^{-1} from the actual Valentia record. The M3 buoy consistently gave higher values for the index than Valentia due to its location out at sea.

The bottom water temperature data shows that exchange events occurred on each of these occasions, with a sudden increase following a drop in temperature. This is the signal for an influx of surface water associated with an exchange event. The temperature record also indicates an additional exchange occurring on 18 July when the forecast index was 9.2 m s^{-1}. Nevertheless the numerical threshold of 10 m s^{-1} for the (forecast) wind index appears to be satisfactory for operational purposes. Use of regression statistics on the forecast data is diminished, when applied to the practical success of the model, as the regression on actual data (between Valentia and M3 weather stations) gives an r^2 value of only 0.44 ($n=36$; positive values only). Of more practical relevance is that the model was capable of predicting exchange events during the trials (Fig. 7). On only the one occasion did the model produce a wind index >10 m s^{-1} which was not matched by the actual wind record from Valentia on 29 July.

4.3. Harmful algal events in 2005

In terms of potentially harmful phytoplankton, the year 2005 was marked by an extensive bloom of *K. mikimotoi* which extended along the entire western seaboard of Ireland (Silke et al., 2005b). Substantial increases in *Dinophysis* cell densities (in integrated water samples) were observed in samples taken at Roancarrig between 12 June (150 cells l^{-1}) and 21 June (900 cells l^{-1}). Significant concentrations of *Dinophysis* were not observed at Gearhies until later, where cell densities increased from virtually zero towards the end of June to 1000 cells l^{-1} on 11 July. A subsequent peak (800 cells l^{-1}) was observed at Gearhies on 2 August, when a sharp maximum in *Dinophysis spp.* densities lasting ~1 week was also observed in samples from Snave at the eastern most end of Bantry Bay (Fig. 1b), where high levels of toxins in shellfish were subsequently reported (Moran et al., 2006). All of these timings correspond to exchange events as forecast through the wind index, and substantiated in the water temperature data. Virtually all mussel harvesting sites in Bantry Bay were closed due to contamination with DSP toxins from 4 August (Clarke et al., 2007). These results are highly indicative that *Dinophysis* had been transported into Bantry Bay with exchange events forecast for the summer period.

5. Discussion and conclusions

The frequency and length of harvest closures of shellfish aquaculture around southwestern Ireland (see e.g. McMahon et al., 1996) demand some form of prediction. The use of relatively sophisticated biological and physical coupled predictive models requires an intimate knowledge of the behaviour of these species to enable the models to be successful. Although contamination with *Dinophysis*-derived DSP toxins is one of the principal causes of shellfish closures in the area, at present we know very little of the life cycle and behaviour of species within this genus, except that they are known to occur in thin sub-surface layers in very high density. We still know nothing of the maintenance and behaviour of the populations in these sub-surface layers (GEOHAB 2008). Recent advances in our ability to culture the organism may improve this situation (Park et al., 2006). However, the accurate prediction of these layers is still impossible, and their origin remains unknown.

It is now understood that virtually all harmful algal bloom events that occur in the bays of southwestern Ireland arise as a result of the transport of harmful phytoplankton populations from the continental shelf via wind-driven exchange. The Irish coastal current runs clockwise around the south and west coasts of Ireland (Raine and McMahon, 1998). The principal feature of this flow is a narrow (<10 km) density driven coastal jet which results from the increasing effect of tidal mixing on a stratified water column as one nears the coast (Fernand et al., 2006). These jets have been considered as important transport pathways for potentially harmful plankton populations (Brown et al., 2001; O'Boyle and Raine, 2007; Hill et al., 2008) and there is now direct evidence for this (Farrell et al., 2008). These jets are usually quite fast flows of up to 25 cm s^{-1} but prevailing southwest winds impinge on this flow at the southwest corner (Raine and McMahon, 1998; Brown et al., 2003). However, the critical point is that until physical models describing continental shelf dynamics attain a sufficiently high resolution to incorporate small scale processes such as these jets, use of complex biological physical coupled models to predict harmful events originating over the continental shelf off southern Ireland will likely remain unsatisfactory.

The simple model presented here is based on water exchange events caused by oscillations in the wind vector axial to the bays of southwest Ireland. Such an oscillation would arise, for example, from the passage of an atmospheric low pressure across the south of Ireland, or even a shift in the position of a high pressure region, usually located over Ireland and Britain at this time of year. The simplicity of the model masks more complex wind-dependent physical processes occurring on the continental shelf. Under southwest winds the anticyclonic (clockwise) currents around the southwest corner of Ireland are quite small, typically of the order 5 cm s^{-1}. The flow can increase substantially to 20–25 cm s^{-1} under easterly wind conditions when the wind has a negative component axial to the bays of the southwest (Raine and McMahon, 1998). It takes approximately 2–3 days under east wind conditions for water to flow from a region off Galley Head (Fig. 1) around to the mouth of Bantry Bay. This coastal shelf area off the south of Ireland is the area where high densities of *Dinophysis* have been found in summer. For example a population of 124,000 cells l^{-1} *D. acuminata* was observed here in 1992 (Raine and McMahon, 1998), and one of 55,000 cells l^{-1} of *D. acuta* in 2007 (Raine, 2008). On both occasions the populations were directly observed (in 2007) or inferred to exist (in 1992) in subsurface thin layers. The three day period of negative axial winds applied in the model not only starts an exchange event but would also allow alongshore transport of these harmful populations to the mouths of the bays, prior to them being advected in when the axial wind component returns positive.

The simplicity of the model is its main advantage and optimises its operational value. Certain aspects of physics have been ignored. For example, the effect of wind on surface currents has a quadratic dependance, although an effectively linear relationship has been applied in the model. This approach would also be readily applicable to other bays where wind-driven water exchanges occur. Certain modifications will be necessary for bays where freshwater input contributes to water exchange with the shelf through processes such as entrainment. The fact that the model is site specific, as opposed to species specific, is an advantage. Physical processes which affect the transport of *Dinophysis* will also affect other harmful species. This has been the case for *Karenia* in Bantry Bay. In 1991, a *Karenia* bloom associated with the pycnocline was advected into the bay with an ingress of cold bottom water under east wind conditions. Once inside the bay, the bloom was established in the surface resulting in visibly discoloured water (Raine et al., 1993). There is a subtle difference here in that *Karenia* was transported into the bays with cool bottom water, whereas *Dinophysis* populations are advected in with ingress of surface warm water.

The model has good accuracy. When still at the developmental stage using fuzzy logic, the onset of toxic events prior to 2001 could be interpreted in the context of high wind indices, and hence water exchanges (Blauw et al., 2006). However, the data record includes occasional closures not predicted by the model, but most often these were restricted to single sites: there are eight shellfish quality testing sites around the Bantry Bay. Uncertainty in the toxin contamination data series increases with the age of the record, whether this is due to false positive assays or the type of bioassay applied, and bioassays in general do not indicate the precise nature of the contamination.

Predictive models of the type described here have an in-built probability which will on occasion generate false positive results, the frequency of which will depend on the statistic used. In this case, the key criterion was the temporal window of June to mid-September, outside of which little or no *Dinophysis* was present. Within this risk period, false positives have occurred, for example in 2002 and 2004 as shown earlier and one is also documented for 2007. In the case of 2007, it is now known that a *Dinophysis* population was present in the northern Celtic Sea, but was not in the correct position to be transported into Bantry Bay when water exchange occurred (Farrell, 2010). By far the more important criterion of the quality of the model is if it generates false negatives, i.e. does not predict an exchange event yet *Dinophysis* blooms occur. This the model has not done.

A disadvantage of models forecasting the initiation of a harmful event is that they do not predict when the contamination of shellfish will dissipate, information highly desirable to the shellfish producer. Another disadvantage of the model presented here lies in its forecast range. This is restricted to that of the meteorological forecast, which at present is accurate for approximately five days. Obviously predictions which have a 30+ day range would be much more desirable and practical, allowing the activation of mitigation measures by shellfish producers. For systems such as the bays of southwest Ireland which are driven by wind speed and direction, this is at present unattainable. However, given recent observations confirming the transport of *Dinophysis* within the coastal jet off the south of Ireland (Farrell, 2010), one practical measure which could lead to an extended prediction would be the deployment of offshore plankton observatories. These would utilise modern, sophisticated *in situ* monitoring techniques, and are only now beginning to be developed (Greenfield et al., 2006). Their placement at key locations upstream in the known paths of harmful blooms would provide information which would improve the prediction capability of the model presented here, as well as those for other areas such as the Gulf of Maine (Keafer et al., 2005) where offshore harmful blooms impact onshore as a direct result of weather patterns.

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