A short range prediction model for forecasting HAB events in the bays of southwestern Ireland.

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Abstract

A simple model is presented which predicts harmful algal events in the bays of southwestern Ireland during summer. Fundamental to the model is the physical forcing of circulation in these bays, principally 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 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 which would generate water exchange. The model was implemented by estimating indices from the five-day weather forecast, and was trialed in the summer of 2005 during which a predicted water exchange events were accompanied by influxes of harmful algal blooms into the bay.

Introduction

The southwest of Ireland is a shellfish production region of particular importance to national aquaculture production (Raine *et al*., 2010a). There is, however, a history of harmful algal events here, notably contamination of shellfish with diarrheic shellfish toxins (McMahon *et al*., 1996) or exceptional blooms of *Karenia mikimotoi* (Roden *et al*., 1980; Roden *et al*., 1981; Raine *et al*., 1993; Raine *et al*., 2001; Silke *et al*., 2005a).

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 species such as *Karenia mikimotoi* (Raine et al., 1993)**,** as well as other non-toxic phytoplankton populations (Goward & 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*., 2005b).

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.

Methods

Field measurements were carried out in Bantry Bay (Figure 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 (Figure 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 (Figure 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 (Figure 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 (Figure1a).

Near surface (0-1m) water samples for phytoplankton analysis were taken weekly through the summer at Roancarrig, near Castletown and at Gearhies (Figure 1) as part of the National Phytoplankton Monitoring Programme (NMP) (Silke et al., 2005b). 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 (McDermott and Raine, 2010). 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.

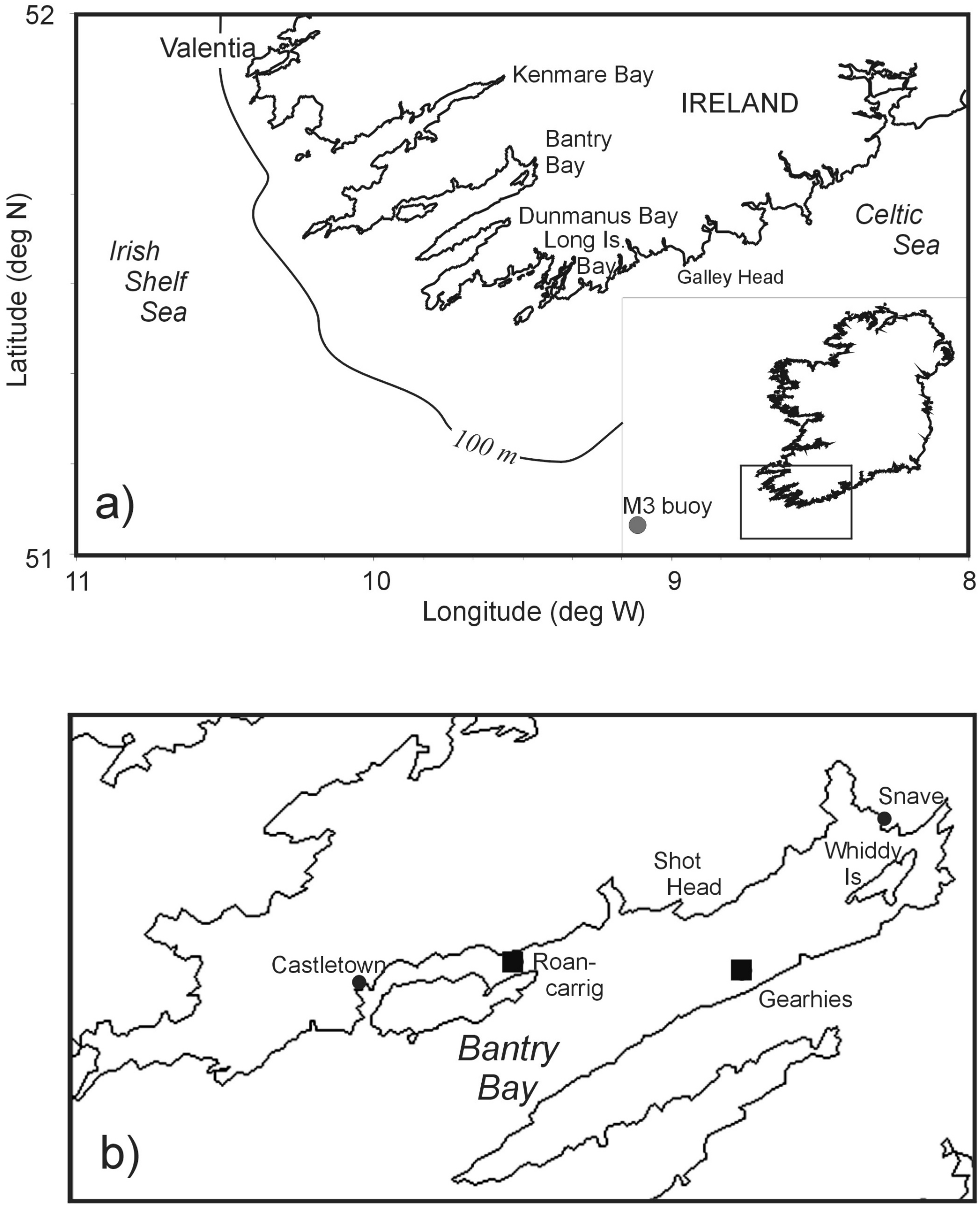

Figure 1. Maps showing a) the bays of southwest Ireland with locations mentioned in the text and (inset) the position of the M3 meteorological buoy; b) location of sampling sites in Bantry Bay. Filled squares denote the positions of temperature sensors.

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 Figure 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.

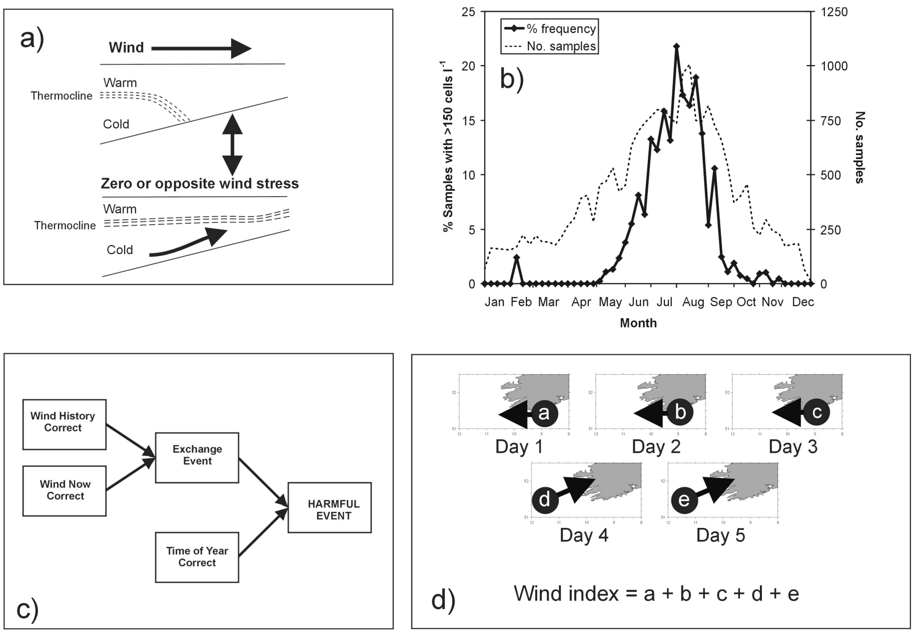

Figure 2. The basis of the predictive model described in the text. a) schematic of wind driven two layer oscillatory flows in Bantry Bay described in Edwards et al (1994); b) analysis of the *Dinophysis* record for Bantry Bay, 1993-2003, indicating the frequency of samples with cell densities considered potentially harmful (>150 cells litre^{-1}). The total number of samples analysed is also plotted; c) the fuzzy logic 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).

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 which has its seasonal maximum in summer in temperate regions such as Ireland. 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, 2004). 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 (Figure 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 & 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 Figure 2c, which couples the relatively high probability of HABs occurring within the summer temporal 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 (060º – 240º). First, the daily average westward (270 º) 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; 060º) 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 Figure 2d, and the value obtained is hereafter referred to as the wind index.

Results

Model hindcasting

The model was initially tested for 2001 when a suitably high resolution of phytoplankton data was available. Results are shown in Figure 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 Figure 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. 10m (Figure 3b). The timing of these influxes match the periods of negative axial winds.

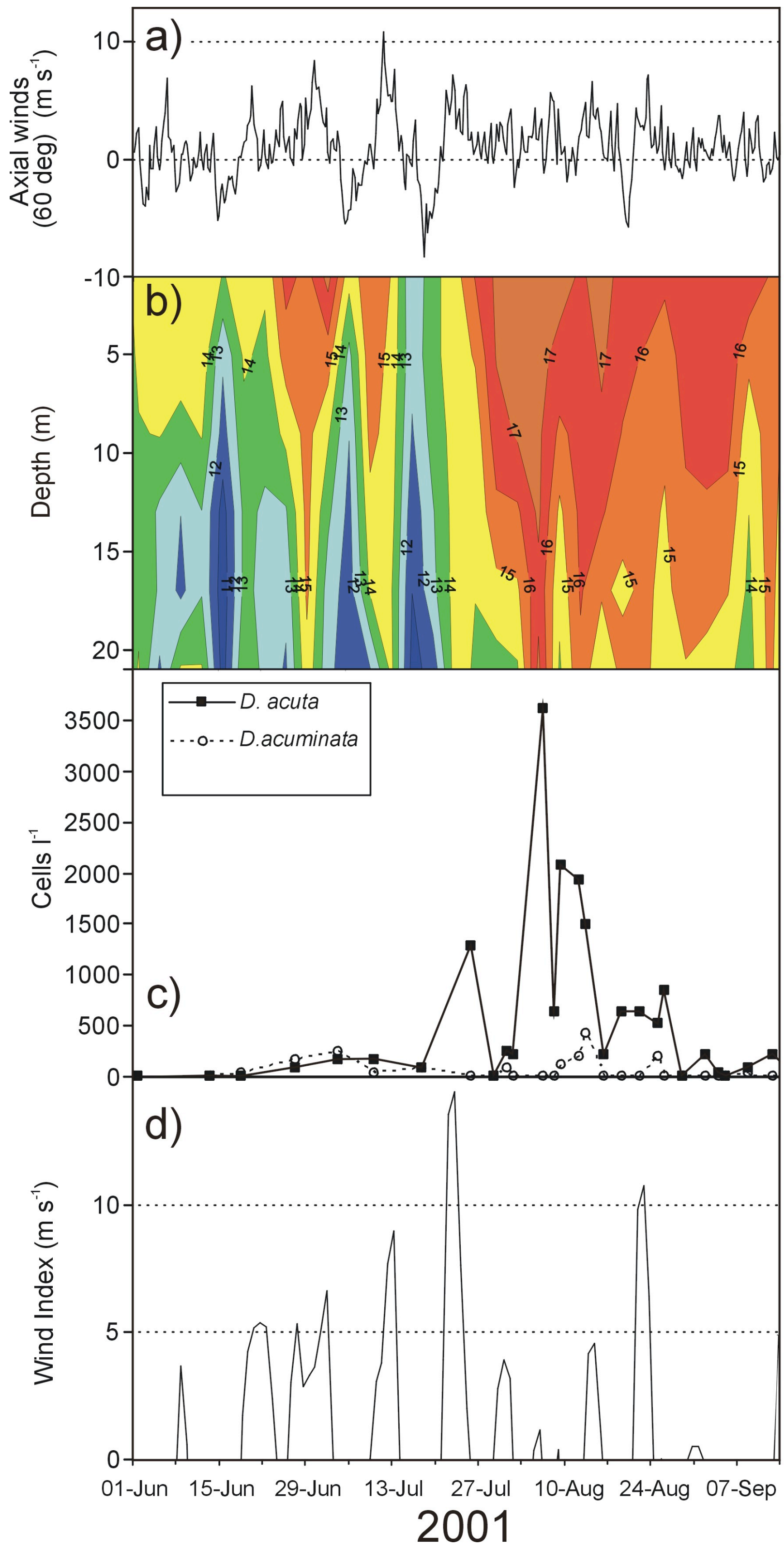

Figure 3. Field data for 2001. a) axial (060°) wind vector from data recorded at Valentia b) contoured temperature data (°C) from a string of four temperature sensors located at Gearhies. Note the influx of warm surface water occurring between 26 July and 7 August; c) the *Dinophysis* record for Gearhies;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

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 (Figure 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 (Figure 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 Figure 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 (Figure 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 Figure 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. 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 (Figure 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 (data not shown). *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. Over the same period, levels of okadaic acid, the DSP toxin associated with *D. acuminata,* 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.

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 Figure 4. A high wind index of 11.2 m s^{-1} was evident on 29 June, with no indication of an influx of *Dinophysis* spp. (Figure 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 (Figure 4b), corresponding with an influx of warm surface water as adjudged from the temperature record (Figure 4a). Again, these observations are consistent with wind-driven exchange of water causing an influx of *Dinophysis* into Bantry Bay.

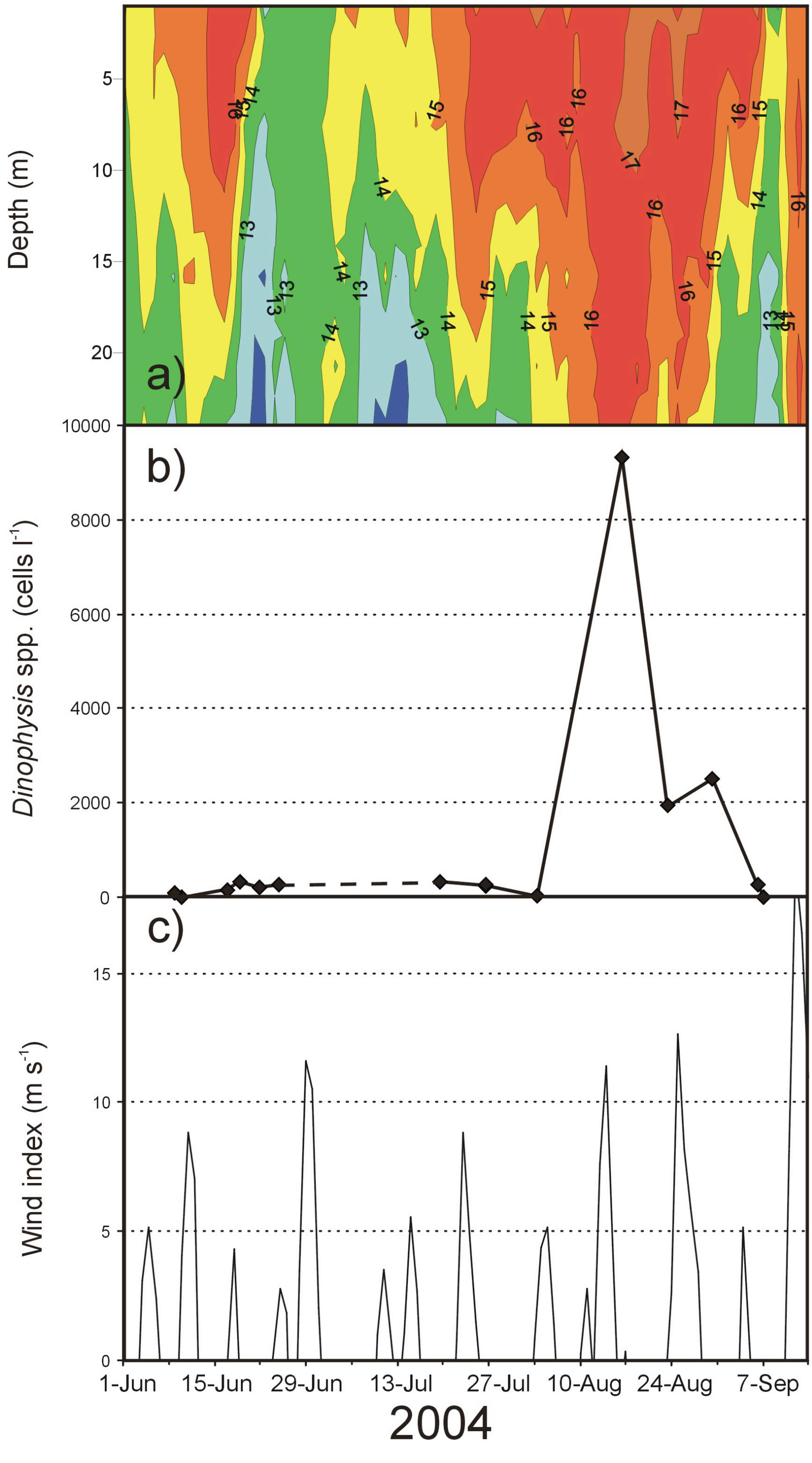

Figure 4. Field data for 2004. a) contoured water temperature (°C) from a string of temperature sensors located at Gearhies; b) total *Dinophysis* cell densities in water samples taken near Roancarrig; c) the wind index derived from data recorded at Valentia. The maximum cell density observed on 17 August 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 Figure 1.

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, the model is successful in describing the initiation of harmful events in 1991 and 1994 for which there are suitably detailed environmental data (Raine et al., 2010b).

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 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 Figure 5.

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 (Figure 5). 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.

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., 2005a). 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 (Figure 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. These results are highly indicative that *Dinophysis* had been transported into Bantry Bay with exchange events forecast for the summer period.

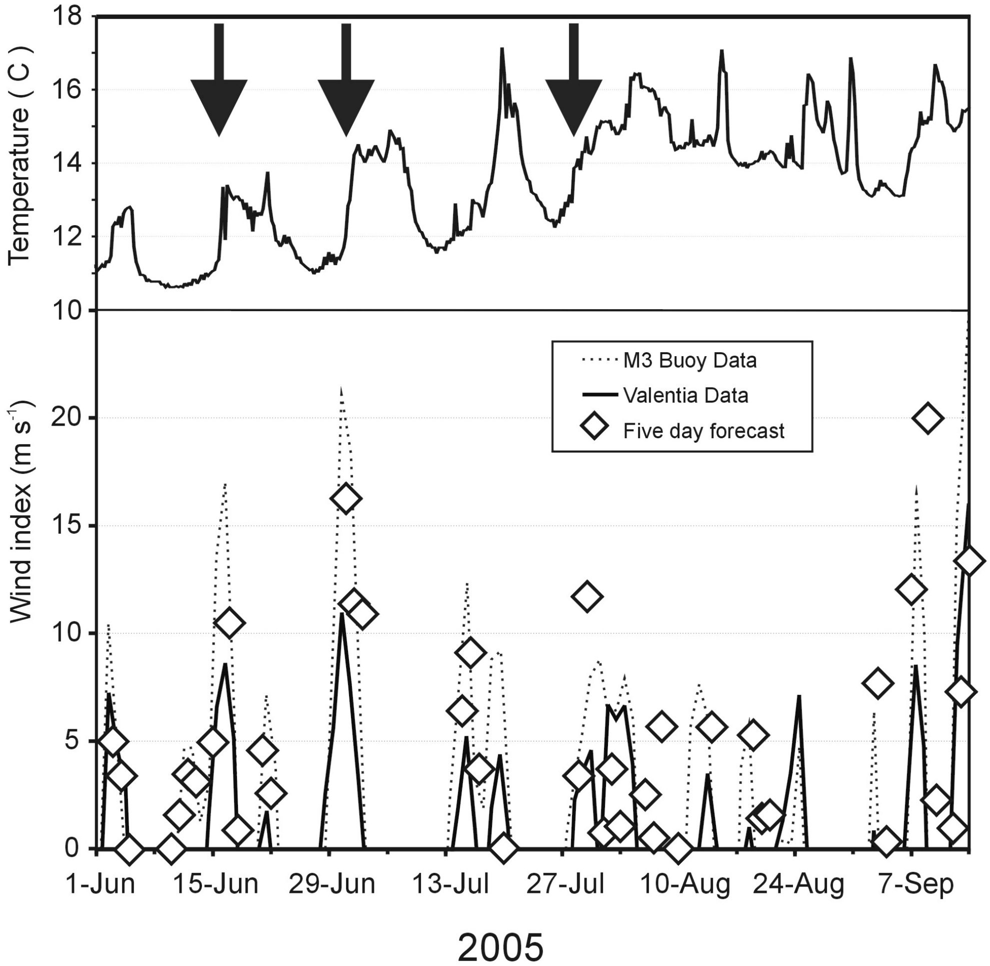

Figure 5. The use of wind indices to predict harmful algal events in Bantry Bay. The wind index obtained from the 5-day weather forecast is plotted against actual values calculated from measurements at both Valentia and the M3 Weather Buoy (see Figure 1 for respective locations). Exchange events are 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.

Discussion

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 & McMahon 1998). The principal feature of this flow is a narrow (<15 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 (see Raine *et al*., 2010a).

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 & McMahon, 1998). It takes approximately 2-3 days under east wind conditions for water to flow from a region off Galley Head (Figure 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 & McMahon 1998), and one of 55,000 cells l^{-1} of *D. acuta* in 2007 (Raine *et al*., 2010). On both occasions the populations were directly observed (in 2007) or inferred to exist (in 1992) in sub-surface 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 modifications will be necessary for bays where freshwater input contribute 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.

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, 2009). 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 (Raine *et al*., 2010b), 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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References

Botana,. L.M., Rodriguez-Vieytes, M., Alfonso A., and Louzao M.C. 1996. Phycotoxins: Paralytic shellfish poisoning and Diarrhetic Shellfish Poisoning. In Nollet, L.M.L. Ed. Handbook of Food Analysis – Residues and other food component analysis, Volume 2, pp. 1147 – 1169.

Edwards, A., Jones, K., Graham, J.M., Griffiths, C.R., MacDougall, N., Patching, J., Richard, J.M. and Raine, R. 1996. Transient coastal upwelling and water circulation in Bantry Bay, a ria on the SW coast of Ireland. Estuarine, Coastal and Shelf Science, 42, 213-230.

Farrell, H. 2009. Sub-surface Thin Layers: The influence of physical processes on phytoplankton distributions in stratified marine systems. Ph.D. Thesis, National University of Ireland. 330 pp.

Fernand, L., Nolan, G.D., Raine, R., Chambers, C.E., Dye, S.R., White, M. and J. Brown. 2006 The Irish coastal current: A seasonal jet-like circulation. Continental Shelf Research, 26, 1775-1793.

GEOHAB. 2008. Global Ecology and Oceanography of Harmful Algal Blooms, GEOHAB Core Research Project: HABs in Stratified Systems. P. Gentien, B. Reguera, H. Yamazaki, L. Fernand, E. Berdalet and R. Raine, eds. IOC and SCOR, Paris, France and Newark, Delaware, USA, 59 pp.

Goward, R. and Savidge, G. 1993. The influence of cool water incursions on phytoplankton populations in Bantry Bay, South-West Ireland. ICES. C.M. C:31. 1-13.

Greenfield, D.I., Marin R., Jensen, S., Massion, E., Roman, B., Feldman, J., and Scholin, C.A. 2006. Application of Environmental Sample Processor (ESP) methodology for quantifying *Pseudo-nitzschia australis* using ribosomal RNA-targeted probes in sandwich and fluorescent in situ hybridization formats. Limnology and Oceanography Methods, 4, 426-435.

Hill, A.E., Brown, J., Fernand, L., Holt, J., Horsburgh, K.J., Proctor, R., Raine, R., and Turrell, W. R. 2008. Thermohaline circulation of shallow tidal seas. Geophysical Research Letters, 35, L11505, doi:10.1029/2008GL034005.

Keafer, B.A., Churchill, J.H., McGillicuddy, D.J., Anderson, D.M. 2005. Bloom development and transport of toxic *Alexandrium fundyense* populations within a coastal plume in the Gulf of Maine. Deep-Sea Research, 52, 2674-2697.

Jones, K. and Gowen., R. 1990 Influence of stratification and irradiance regime on summer phytoplankton composition in coastal and shelf seas of the British Isles. Estuarine, Coastal and Shelf Science, 30, 557-567.

Lindahl, O. 1986. A dividable hose for phytoplankton sampling. In Report of the ICES Working Group on Exceptional Algal Blooms, Hirtshals, Denmark, 17-19 March, 1986. ICES, C.M. 1986/L:26.

McDermott, G., and R. Raine. 2010. Settlement Bottle Method for Quantitative Phytoplankton Analysis, p. 21-24. *In* B. Karlson, C. Cusack and E. Bresnan [eds.], Microscopic and Molecular Methods for Quantitative Phytoplankton Analysis. IOC of UNESCO, Paris.

McMahon, T., Silke, J., Nixon, E., Taafe, B., Nolan, A., McGovern, E. and Doyle, J. 1996. Seasonal variation in diarrhetic shellfish toxins in mussels from the Southwest coast of Ireland. In "Irish Marine Science, 1995" eds. B.F. Keegan and R. O'Connor, Galway University Press, Ireland. pp. 417-432.

Moran, S., Silke, J., Salas, R., Chamberlain, T., Lyons, J., Flannery, J., Thornton, V., Clarke, D. and Devilly, L. 2006. Review of Phytoplankton monitoring 2005. In Proceedings of the 6th Irish Shellfish Safety Workshop, MEHS Series No. 23. Marine Institute, Galway, Ireland. pp 37-46.

Park, M.G., Kim S., Kim, H.S., Myung, G., Kang, Y. G., and Yih, W. 2006. First successful culture of the marine dinoflagellate *Dinophysis acuminata*. Aquatic Microbial Ecology, 45, 101-106.

Parsons, A. 2005. State of Irish Aquaculture 2004. Marine Institute, Galway, Ireland, 59 pp.

Raine, R. and T. McMahon. 1998. Physical dynamics on the continental shelf off southwestern Ireland and their influence on coastal phytoplankton blooms. Continental Shelf Research, 18, 883-914.

Raine, R., Joyce, B., Richard, J., Pazos, Y., Moloney, M., Jones, K. and Patching, J.W. 1993. The development of an exceptional bloom of the dinoflagellate *Gyrodinium aureolum* on the southwest Irish coast. ICES Journal of Marine Science, 50, 461-469.

Raine, R., S. O'Boyle, T. O'Higgins, M. White, J. Patching, B. Cahill, and T. McMahon. 2001. A satellite and field portrait of a *Karenia mikimotoi* bloom off the south coast of Ireland, August 1998. Hydrobiologia **465:** 187-193.

Raine, R., H. Farrell, P. Gentien, L. Fernand, M. Lunven, B. Reguera and S. Gonzalez-Gill. 2010a Transport of toxin producing dinoflagellate populations along the coast of Ireland within a seasonal coastal jet. ICES CM 2010/N:05. 8pp.

Raine, R., G. McDermott, J. Silke, K. Lyons, G. Nolan and C. Cusack. 2010b. A simple short range model for the prediction of harmful algal events in the bays of southwestern Ireland. J. Mar. Systems. In the press.

Roden, C., T. Ryan, and H.J. Lennon. 1980. Observations on the 1978 red tide in Roaringwater Bay, Co. Cork. Journal of Sherkin Island, **1:** 105-18.

Roden, C., H.J. Lennon, E. Mooney, P. Leahy, and W. Lart, 1981. Red tides, water stratification and phytoplankton species succession around Sherkin Island, south west Ireland, in 1979. Journal of Sherkin Island, **1:** 50-68.

Silke J., O'Beirn F., and Cronin M. 2005a. *Karenia mikimotoi*: an exceptional dinoflagellate bloom in western Irish waters - Summer 2005. MEHS Series No. 21. Marine Institute, Galway.

Silke, J., McMahon, T., and Hess, P. 2005b. Irish Shellfish Biotoxin Monitoring Programme. In "Molluscan Shellfish Safety", Proceedings of the 5th International Conference on Molluscan Shellfish Safety (Eds. Henshilwood, K., Deegan, B., Mc Mahon, T., Cusack, C., Keaveney, S., Silke, J., O'Cinneide, M., Lyons, D. and Hess, P.) Marine Institute, Galway, Ireland. pp. 483-488.