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Modelling the hydrodynamic conditions associated with *Dinophysis* blooms in Galicia (NW Spain)

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ABSTRACT

The northwestern Iberian coast (Galician Rías and shelf) is frequently affected by toxic harmful algal blooms (HABs) (mainly *Dinophysis* spp.), leading to lengthy harvesting closures in a region where aquaculture has a strong socioeconomic impact. The project ASIMUTH (http://www.asimuth.eu) aimed to develop forecasting capabilities to warn of impending HABs along the European Atlantic coast. Simulations with the ROMS model (hydrodynamical and ecological simulations complemented with Lagrangian particle tracking simulations) of the Galician coastal circulation have been performed in the framework of the ASIMUTH project to characterize and forecast oceanographic conditions before and during HAB periods. In this work, we present the Galician ASIMUTH forecast system and demonstrate its skill in predicting HAB transport and its usefulness to provide assessment for the management of the areas affected by toxic outbreaks. Experience gained during DSP events in 2005 and 2013 is shown. We also describe the Galician pilot HAB bulletins, aimed at distributing forecasts of HAB events that might induce closures of harvesting areas or, when the areas are already closed, at giving information on forthcoming oceanographic conditions that could favour or hamper the opening of an area. Our results show that the model forecasts and the bulletins can provide early warning of the risk of *Dinophysis* spp. events and the risk of closures linked to the presence of DSP toxins above regulatory levels in harvesting areas.

1. Introduction

The northwestern Iberian coast (Galician Rías and shelf) is frequently affected by HABs of dinoflagellate species during the upwelling season (spring and summer) and during the autumn transition from dominance of upwelling-favourable to downwelling-favourable winds (reviewed in Reguera et al., 2012). The main dinoflagellates causing toxic outbreaks in this region are *Dinophysis* spp. (*Dinophysis acuminata* and *Dinophysis acuta*) and *Gymnodinium catenatum* associated with diarrhetic (DSP) and paralytic shellfish poisoning (PSP) events, respectively. The initiation of *D. acuminata* growth here is linked to the beginning of the upwelling season (Díaz et al., 2013; Velo-Suárez et al., 2014). *D. acuminata* persists in the Rías throughout the upwelling season; variations in cell numbers are associated with wind event variability (González-Gil et al., 2010; Velo-Suárez et al., 2014). Downwelling and relaxation lead to the initiation or intensification of shellfish contamination due to retention of *Dinophysis* within the rías, while upwelling favours water renewal and detoxification. In contrast to *D. acuminata*, *D. acuta* is very seasonal and appears in late hot summer months when thermoclines are deeper (Escalera et al., 2006; Díaz et al., 2016). Sudden blooms of *D. acuta* and *G. catenatum* in the Galician Rías at the autumn transition have been linked to along-shore advection of shelf waters (Sordo et al., 2001; Escalera et al., 2010; Pitcher et al., 2010).

Dinophysis species are difficult to monitor since they usually appear in subsurface blooms that cannot be detected with satellite imagery. In addition, they appear in low densities ($<10^3$ cells l^{-1}), which comprise a small proportion of the microphytoplankton, and are difficult to detect with conventional monitoring sampling methods (Escalera et al., 2012). But even in low densities, these blooms cause shellfish toxicity that can induce gastrointestinal

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diseases. Further, conventional weekly monitoring is not frequent enough when wind reversals advect dense shelf populations into aquaculture sites in a matter of a few days (Escalera et al., 2010; Raine et al., 2010; Whyte et al., 2014). Given the limitations of satellite imagery and routine sampling methods for early warning of DSP events, numerical simulations of the local hydrodynamics may offer an ideal complementary tool for that purpose. The density of *Dinophysis* populations in Galicia and their subsequent effect on shellfish contamination and harvesting closures is strongly linked to the short-term variability of oceanographic conditions characteristic of upwelling systems (GEOHAB, 2005). Shelf and slope variability is concentrated at small spatial (1–4 km) and temporal (a few days) scales in coastal systems in general and in upwelling systems, such as Galician coastal waters, in particular. State of the art numerical coastal models are able to represent variability at these scales (e.g. Otero et al., 2008) and therefore, can be used as tools for circulation studies that give insight on the coupling of HAB populations to environmental variability. Once the *Dinophysis* populations are established and their densities routinely estimated by a monitoring programme, numerical models can be used in forecast mode to predict the potential coastward transport of HAB populations that proliferate in offshore shelf waters and affect coastal aquaculture sites. Consequently the application of hydrodynamical models that appropriately resolve the relevant spatial and temporal scales of variability is essential for any HAB warning system. Once the hydrodynamic model is proven suitable for modelling cross-shore and along-shore advection and variability in stratification and mixing, it can be used to give insight into the specific oceanographic conditions that shape the ecological niche of HAB species.

The ASIMUTH project (http://www.asimuth.eu) aimed to develop forecasting capabilities to warn of impending HABs along the European Atlantic coast (Mateus et al., 2012; Maguire et al., 2016). In this work, we describe the Galician early warning system, which intends to help managers of the monitoring system (INTECMAR, www.intecmar.org) in the risk assessment of HAB events as well as to provide forecasts to the aquaculture industry in Galicia. The Galician ASIMUTH HAB forecast system gathers and analyses information from numerical model forecasts, in situ networks including HAB monitoring data and satellite imagery. In this contribution, we also provide a report on the experience gained in predicting transport of HAB populations and in providing assessment for management of the area affected by HABs in the Galician Rias (NW Spain) during the DSP events in 2005 and 2013. Finally, the potential of the forecast system for early warning of DSP events is discussed.

2. Material and methods

The Galician HAB early warning system has three components:

- Current and forecast oceanographic conditions provided by the Regional Ocean Modeling System (ROMS) hydrodynamical model.
- Offline Lagrangian particle tracking simulations run with the results of the hydrodynamical model.
- Information on the current status of the HAB populations.

The combination of these three sources of information is analysed and summarised into a HAB bulletin, with the purpose of distributing information on the risk of development, and propagation and on the decline of HAB events in the Galician area.

2.1. The hydrodynamical model

In recent years, the Modelling Group at IEO-A Coruña has set-up a 3D model configuration of the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) for studying the western and northern Iberian shelf circulation and its effect on the ecosystem (e.g. Otero et al., 2009; Marta-Almeida et al., 2013). ROMS uses stretched, terrain following coordinates in the vertical, also known as s-coordinates. The hydrodynamic equations are solved numerically by applying a third order upstream scheme for the horizontal advection and a fourth order centered scheme for the vertical advection of tracers and momentum. Vertical mixing and turbulence is modelled by means of the nonlocal K profile parameterization. Atmospheric forcing at the surface is supplied at a spatial resolution of 30 km and a temporal resolution of 1 h by the regional meteorological agency Meteogalicia (http://www.meteogalicia.es), which runs a configuration of the WRF mesoscale model (http://www.wrf-model.org). In order to reproduce adequately river plume dynamics in the area and their effect on the ecosystem, the input of 26 rivers has been taken into account (see methodology in Otero et al., 2010). Open boundaries and initial conditions are obtained from a large scale model, MERCATOR PSY2V2 (Lellouche et al., 2006), which is an operational forecasting system for the North Atlantic characterized by a horizontal resolution of $1/15^{\circ}$ (5–7 km) and 43 vertical levels. Horizontal velocity, temperature, salinity and Sea Surface Height (SSH) fields from PSY2V2 output are imposed at the boundary following Marchesiello et al. (2001). To impose tides, Flather (1976) boundary conditions are used for the barotropic mode, with tidal forcing obtained from TPX0.6 (Egbert and Erofeeva, 2002). This model configuration has been applied for the study of the variability of shelf and slope circulation in response to wind events and topographic features in the area (Otero et al., 2008, 2009; Marta-Almeida et al., 2013). In the ASIMUTH forecast system we run this configuration of the ROMS model that provides operationally water temperature and salinity, surface elevation, currents and fluxes with a 3-d forecast horizon. The operational grids are a 4 km Iberian grid and a higher resolution 1.3 km grid nested in the previous one, centered on the Galician coast (see Fig. 1).

2.2. The Lagrangian particle-tracking model

Lagrangian particle-tracking models have been run coupled with our hydrodynamical model. They are very useful in depicting how plankton populations can be influenced by physical conditions. From a forecasting perspective, they are a tool for issuing predictions on the advection and dispersion of substances such as HAB cells. The first-order approach for representing HAB cells in a Lagrangian framework is to treat them as passive particles that move with the flow and do not have "behaviour". This has been the common approach in Lagrangian studies of HAB dynamics (Velo-Suárez et al., 2010; Dippner et al., 2011; Aoki et al., 2012). Depending on whether the Lagrangian particle module is run fully coupled with the hydrodynamic model or whether the Lagrangian module reads the output of the model, the Lagrangian simulations are called online or offline simulations. The advantage of offline simulations is the possibility of making use of available hydrodynamic simulations for running Lagrangian particle tracking experiments avoiding the computational costs of re-running the physics coupled to the Lagrangian module. In the development of the ASIMUTH forecast system, we have adapted the offline particle-tracking model Ichthyop (Lett et al., 2008) to be run using the output of the ROMS model. Hourly fields from our hydrodynamical model are used to force the Lagrangian particle tracking model offline.

2.3. The Galician ASIMUTH system for early warning of HAB events

Early warning of HAB events requires the use of information on the current status of HAB populations. Initiation of a *Dinophysis*

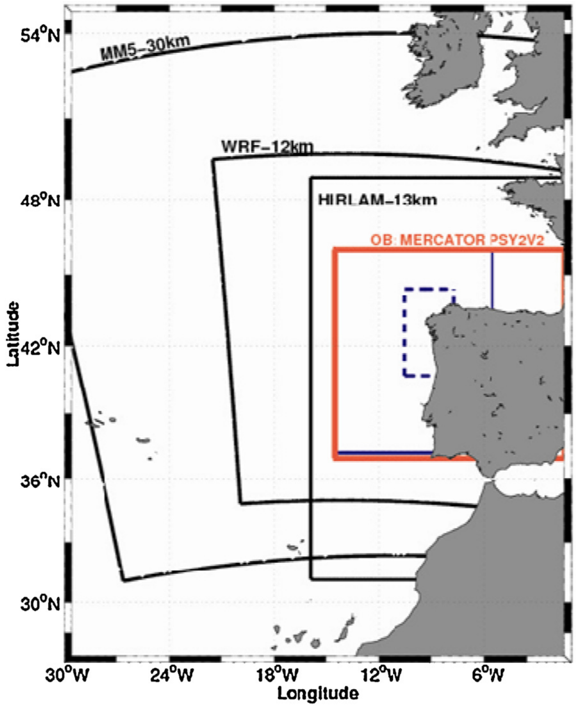

Fig. 1. Location of the study area and of the different model domains: the operational meteorological model domains (WRF used in the forecast and HIRLAM in some hindcast simulations) and the operational hydrodynamic model that is run at IEO (4 km resolution) on which a higher resolution grid (1 km) is embedded (dashed line) to properly simulate the dynamics of the Galician Rías.

bloom is considered when quantitative methods start detecting its presence (≥40 cells l^{-1} in the Galician monitoring system). Therefore, bloom initiation of low-biomass species, such as *Dinophysis* species, cannot be assessed directly by numerical models nor by satellite imagery. In Galicia, HAB monitoring data include phytoplankton counts of toxic species and data from toxin analyses from the weekly sampling of shellfish harvesting areas (mainly in the Galician Rías) performed by INTECMAR. This agency is responsible for monitoring shellfish harvesting areas in Galicia to ensure seafood safety and sustainability of aquaculture production. Additional HAB data acquired routinely are the monthly phytoplankton counts at stations in a transect through Ría de Vigo and the adjacent shelf carried out by IEO (Radiales programme). Reports on the status of harvesting areas (open or closed) are also available from INTECMAR (http://www.intecmar.org/informacion/biotoxinas/EstadoZonas/Informes.aspx?sm=a2).

Once the presence of *Dinophysis* is detected by the monitoring system, the analysis of *in-situ* and satellite data combined with model forecasts of oceanographic conditions can help assess the risk of transport of cells to adjacent areas. During ASIMUTH, the ongoing and forecast oceanographic conditions in the area, diagnosed by in situ, satellite and model data, were disseminated in the format of a HAB bulletin. HAB forecasts in the bulletins were based on the analysis of specific model products:

- Eulerian predictions of inflow-outflow into/out of the Galician Rías, where most of the aquaculture sites are located, as well as Eulerian predictions of along-shore transport in several cross-sections on the northern Portuguese shelf to help evaluate the possibility of across and along-shore transport, respectively.
- Lagrangian particle tracking simulations are run routinely for estimating along-shore transport from the northern Portuguese shelf and for exploring water exchange between the Rías and the adjacent shelf. Additionally, when a HAB event appears in one ría, Lagrangian experiments are run to predict its propagation to other rias.

In an initial phase the bulletin was published once a week at the beginning of the week, when the INTECMAR monitoring cruises take place. However, due to the fact that no measurements are taken by the monitoring system on weekends, the most useful three-day forecast would be that made on Friday to help plan harvesting activities during the weekend and on Monday before the results of the monitoring measurements are available. Therefore, we have realised that the three-day-range forecast is the most useful for the producers and the monitoring agency provided it is issued every Friday and occasionally on Monday.

3. Results

In this section, we report the experience gained during the ASIMUTH project in relating the variability of oceanographic conditions simulated with a numerical model with the onset of *Dinophysis* blooms in the Galician Rías during 2005 and 2013. From spring 2013, the forecast system was operated as a proof of concept of the ongoing ASIMUTH project. This demonstration period coincided with a *Dinophysis acuminata* event in Galician Rías which started in spring and lasted until autumn. At the upwelling transition in 2013, a *Dinophysis acuta* event in the Galician Rías occurred and could be analysed with the ASIMUTH system. Hindcast simulations of the last strong *D. acuta* event in the area (autumn 2005) are presented for further evaluation of the skill of the ASIMUTH system.

3.1. The spring–summer 2013 Dinophysis acuminata *event*

In spring 2013 there was a *Dinophysis acuminata* event that caused prolonged harvesting closures in the Galician Rías. Raft mussel harvesting polygons in Ría de Pontevedra were closed due to the presence of DSP toxins above regulatory levels since mid March. The evolution of the upwelling index computed from wind data from the Silleiro buoy (Fig. 2) showed frequent upwelling conditions during February. March began with strong and sustained downwelling conditions. On 12th March downwelling relaxed and upwelling conditions prevailed from the 13th to the 15th.

Weekly cell counts from monitoring stations in Ría de Pontevedra showed that from mid March, *D. acuminata* densities were within the range associated with the onset of mussel toxicity above regulatory levels (Figs. 3 and 4). In fact, raft mussel harvesting areas were closed from that time in that ría. After a period of cell densities causing closures, low densities were observed between late April and early May, with a new increase around 20th May. High densities in June were followed by a period of low densities in July. From 15th July, very high densities of *Dinophysis acuminata* reappeared, with a maximum on 22nd July. Our main objective in this contribution was to test if the forecast model run during the ASIMUTH demonstration period could help us to understand the observed variability in *D. acuminata* numbers in the Galician Rias and if it could be used for early warning of DSP events.

ASIMUTH forecast model results for the period 8th–15th March (spring tides) showed northward currents on the shelf from 8th to 10th March, followed by onshore currents on the 11th, relaxation on the 12th and southwards currents associated with upwelling during 13th–14th. On the 15th, currents were weak (Fig. 5). At the beginning of April, the occurrence of *Dinophysis acuminata* induced closures in mussel raft areas in Ría de Vigo. The ASIMUTH forecast system (Fig. 6) predicted downwelling and inflow of shelf waters into the rias on 2nd April, in a period of neap tides (minimum

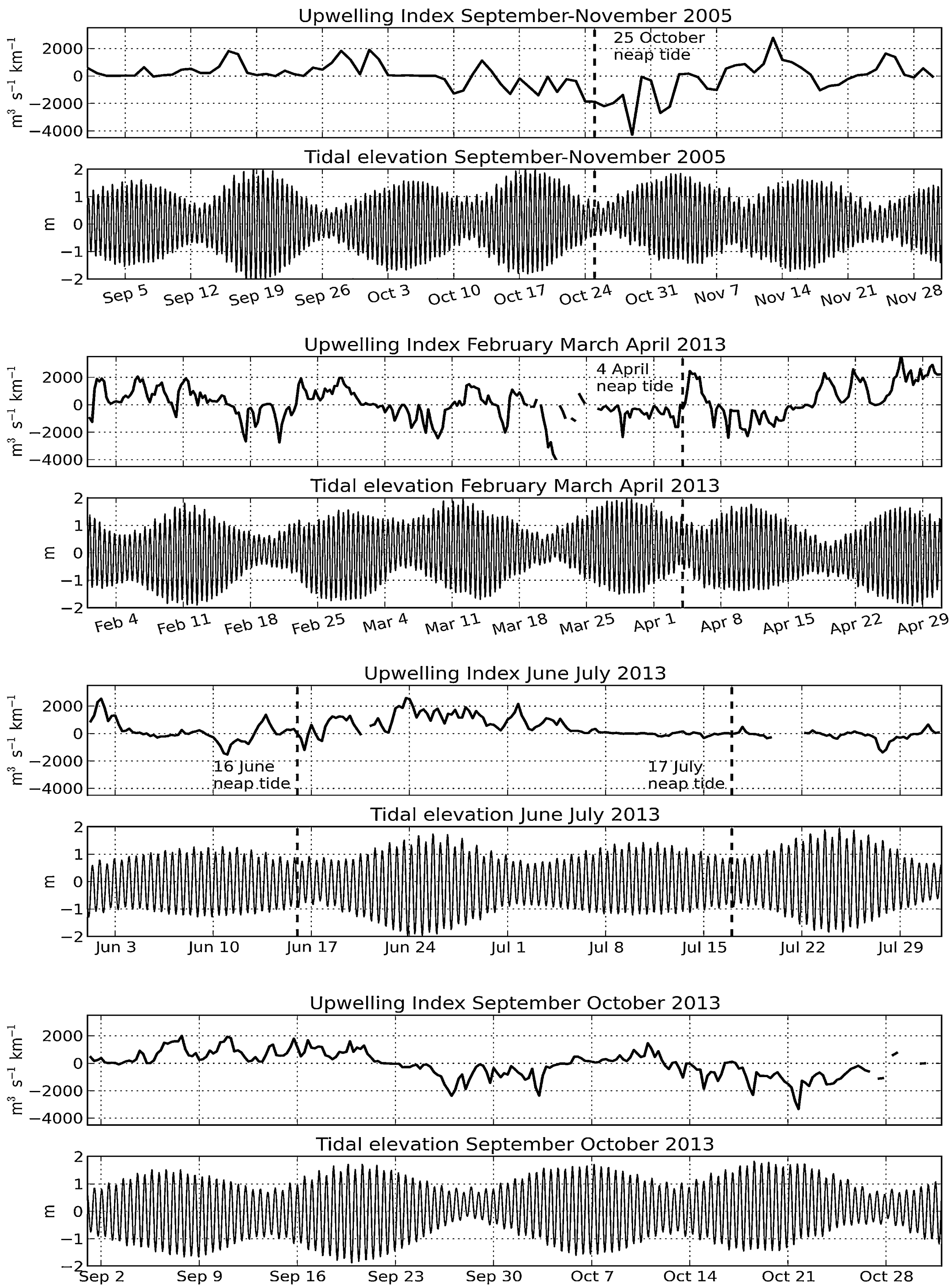

Fig. 2. Evolution of the upwelling index (positive values indicate upwelling) estimated from Silleiro buoy (southwestern Galicia) wind data and of tidal elevation during the periods in 2005 and 2013 mentioned in the text. Upwelling index has been downloaded from http://www.indicedeafloramiento.ieo.es (González-Nuevo et al., 2014). Tidal elevations in 2013 were recorded by the IEO tide gauge at Vigo harbour. Due to malfunction of the Vigo tide gauge in October 2005, the plot of tidal elevations in 2005 uses data recorded by the IEO tide gauge at A Coruña harbour (north from Vigo). Tidal phase lag between Vigo and A Coruña is of around 19 min. Tidal data were downloaded from http://indamar.ieo.es and http://www.emodnet-physics.eu.

around 4th April). Increased densities of *D. acuminata* in Ría de Pontevedra on 8th April were associated with intense downwelling, also in a period of neap tides increasing to spring tides (maximum on 11th April). However, in Ría de Vigo, the weekly monitoring reported decreased densities of *D. acuminata* (Fig. 7). Model results showed that the upwelling event in-between the two monitoring cruises on 2nd and 8th April initiated surface outflow from the rías. We emphasize that this upwelling event

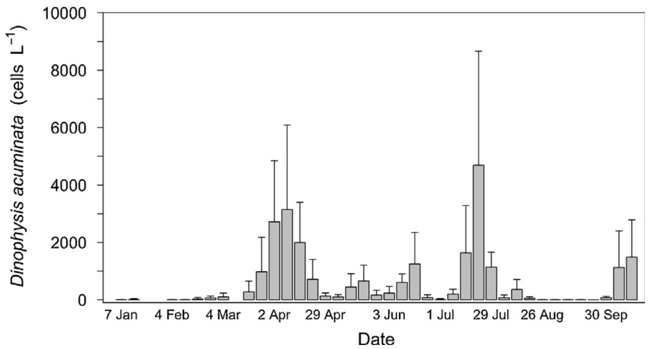

Fig. 3. Weekly variation of *Dinophysis acuminata* cell densities in Ría de Pontevedra (mean of 10 monitoring stations) during 2013 (data from INTECMAR). Error bars represent mean and standard deviation ($n = 10$).

coincided with neap tides. Therefore, the response of the ría to upwelling was more intense and this can be seen in the strong outflow depicted in Fig. 6.

At the beginning of June, downwelling conditions relaxed and changed to upwelling favourable from the second third of the month (Fig. 2). Figs. 4 and 7 show that *Dinophysis acuminata* densities increased around mid June in Pontevedra, Vigo and also in Arousa (not shown). Some closures at O Grove (Ría de Arousa) and Ría de Muros were reported from 15th June on. A zoom of the ASIMUTH forecast system model results in the rías from 12th to 17th June (Fig. 8) showed that outflow from the rías was clear only on 13th June (close to neap tides), whereas outflow or inflow currents in the Rías were weak during the rest of the period, indicating retention and conditions favourable for *D. acuminata* growth.

High densities of *Dinophysis acuminata* were also measured from mid July, when most of the mussel rafts areas that had been opened after the spring closures were closed again. Nevertheless, some hot spots in Ría de Pontevedra remained closed since March–April. The *D. acuminata* maximum was found at the mouth of Ría de Pontevedra on 22nd July (Fig. 4). Upwelling conditions, during which outflow at the surface of the Rías prevailed, occurred some days before the cruise (results from the ASIMUTH system not shown here). From 18th July onwards, wind relaxed and there were days with weak surface inflow into Ría de Pontevedra. It is interesting to note that these high densities of *D. acuminata* were observed around neap tides (17th July).

3.2. *The autumn 2013 blooms of* D. acuminata *and* D. acuta

The Galician Rías are regularly affected by toxic dinoflagellate blooms, in particular during the transition from upwelling to downwelling favourable conditions at the end of summer. This transition is associated with a replacement of cold shelf bottom waters by warm surface waters flowing northwards. A particularly intense *Dinophysis acuta* event took place at the end of September

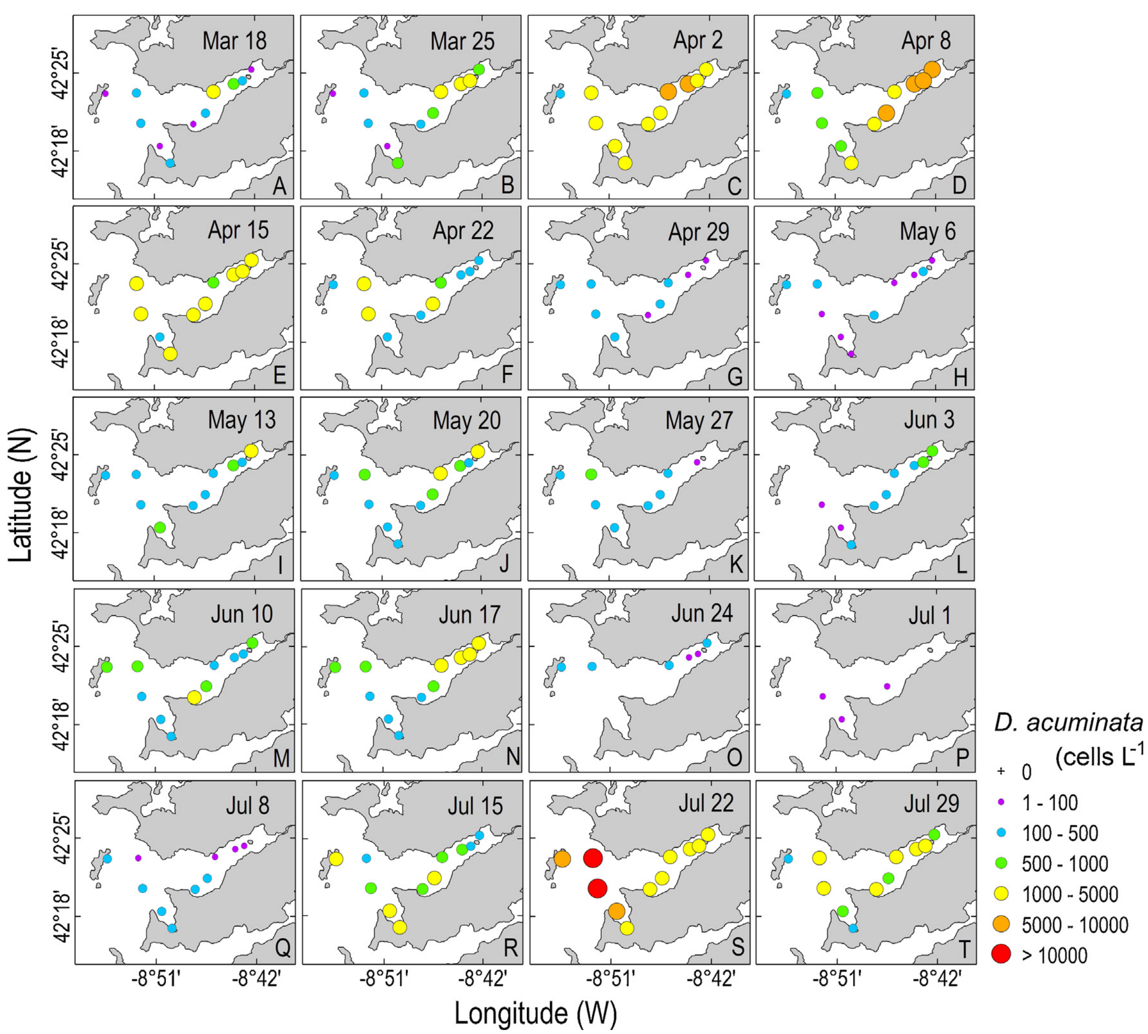

Fig. 4. Cell counts of *D. acuminata* in Ría de Pontevedra from March 2013 to July 2013 (data from INTECMAR).

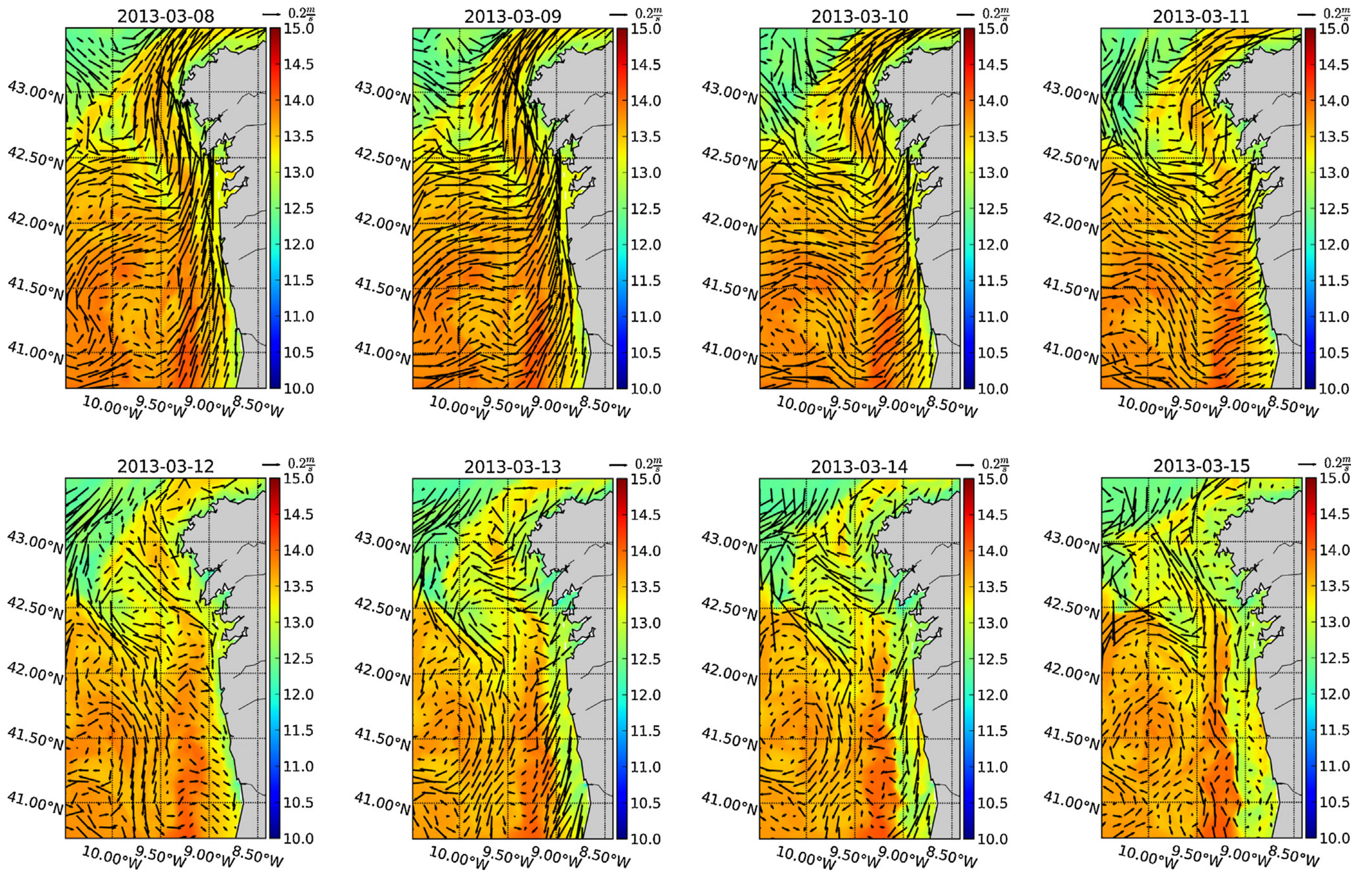

Fig. 5. Model generated SST and surface currents from 8th to 15th March 2013.

2013 in the Galician Rías, causing the closure of almost 100% of the harvesting polygons in the area from the beginning of October. The last intense event of *D. acuta* in the rías had occurred in 2005, but in 2013 *D. acuta* appeared together with *Dinophysis acuminata*, and unlike 2005, densities of *Gymnodinium catenatum* were not significant.

Fig. 9 shows the sequence of *Dinophysis acuta* and *Dinophysis acuminata* densities measured in the weekly monitoring cruises during the weeks preceding the intense autumn outbreak on 30th September 2013. Scattered cells of *D. acuminata* (present in the Rías since spring) were detected. On 23rd September, *D. acuta* numbers detected in the Ría de Pontevedra were low, but based on previous experience, their presence at this time of the year was already indicative of a high risk of forthcoming closures. The presence of *D. acuta* (and *D. acuminata*) on the northern Portuguese shelf in September was detected by the Portuguese monitoring system and harvesting areas close to Aveiro and to the south (zones L3 and L4, see http://www.ipma.pt/pt/pescas/bivalves/index.jsp) were closed due to the presence of DSP toxins above regulatory levels. A northwards transport was also suggested by Portuguese monitoring data since northernmost harvesting areas in Portugal (zones L1 and L2), still open on 27th September, had to close after the appearance of *Dinophysis* in the monitoring data on 4th October.

The Galician ASIMUTH forecast system predicted northwards transport on the week before the monitoring cruise on Monday 30th September (see results in the format of the Galician bulletin in Fig. 10). The model forecast a northwards transport on the shelf able to transport HAB populations from Portuguese waters. This was clearly seen in along-shore sections but also in the results from the Lagrangian simulations tracking particles emitted on the shelf from the latitudes of the northernmost Portuguese bivalve monitoring areas.

3.3. *The autumn 2005* D. acuta *event*

The last intense event of *Dinophysis acuta* in the Rías before 2013 had occurred in 2005 (see Díaz et al., 2016). Below we describe the development of the *D. acuta* bloom in 2005 and report on the results of a hindcast simulation with our modelling system. The evolution of the 2005 *D. acuta* bloom, based on measurements from Portugal and Galicia was described by Escalera et al. (2010). In August, *D. acuta* densities in Aveiro were relatively high ($\sim 10^3$ cells l^{-1}) and reached record values (12×10^4 cells l^{-1}) during the first week of September. Low numbers ($<10^2$ cells l^{-1}) 1) were measured in Galicia until the last week of October, when a sudden increase of *D. acuta* was observed after a strong downwelling event. This *D. acuta* bloom (maximum cell densities of 1.8×10^4 cell l^{-1}), which started end October and lasted until mid-December, affected most of the Galician coast, with closures that persisted until early March 2006 (ICES, 2006). Estimates of division rates of *D. acuta* indicated that increased numbers were not due to intrinsic growth, but to physical accumulation, probably after introduction of a population advected from the south (Escalera et al., 2010). The *D. acuta* bloom coincided with a bloom of *Gymnodinium catenatum* (recorded again after 10 years of absence!). All production areas on the Galician coast were affected, including sites north of Cape Finisterre that rarely get contaminated, and some production sites suffered harvesting closures until the following May due to PSP toxins in shellfish above regulatory levels (ICES, 2006). Maximum values of *G. catenatum* density and PSP contamination were 1.7×10^5 cell l^{-1}

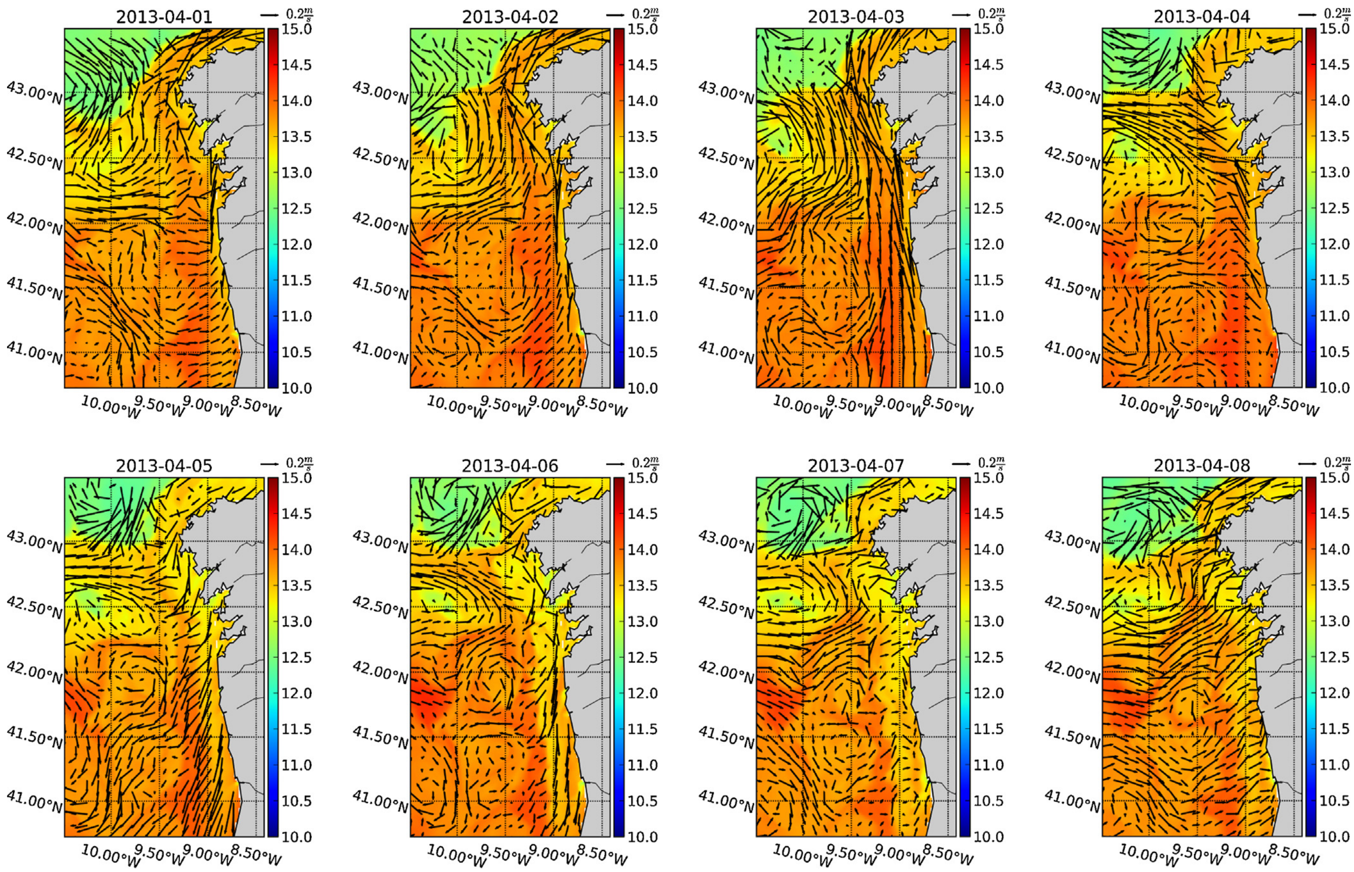

Fig. 6. Model generated SST and surface currents from 1st to 8th April 2013.

and 40,800 μg STX eq kg^{-1} meat (ICES, 2006). The chronology of detection of the species cell maxima and associated PSP and DSP events that started in northern Portugal in late summer suggested a northward propagation (Pitcher et al., 2010; Escalera et al., 2010).

During September 2005, winds were upwelling favourable and more intense to the north. In early October, a relaxation of upwelling winds occurred (see Fig. 2), and by 24th October (around neap tides) a downwelling pulse was evident, which lasted until the first days of November, with a relaxation of this downwelling pulse around 30th October. Results from a hindcast hydrodynamical simulation with our modelling system are shown in Fig. 11. The monitoring system first detected high concentrations of *Dinophysis acuta* in the ría de Vigo on 24th October (see Fig. 6 in Escalera et al., 2010). The model shows northwards flow on the shelf from northern Portugal to western Galicia from 19th October, and coastwards flow on 22nd October, coinciding with the intensification of downwelling winds. This inshore poleward current could have transported *D. acuta* populations from the south to the shelf off Galicia, and the onshore flow on 24th October could have introduced them in the ría de Vigo. From 25th October to 30th October, this inshore poleward current can be observed in surface current and a warm tongue in front of the Galician Rías can be seen in model SST, as well as in the satellite imagery corresponding to 30th October (not shown). On 2nd November (see again Fig. 6 in Escalera et al., 2010), *D. acuta* concentrations in Rías de Vigo and Pontevedra increased. Comparing Fig. 11 with Fig. 10, it can be confirmed that the model showed the presence of a poleward shelf current in 2005 previous to the detection of *D. acuta* and *Gymnodinium catenatum* in the Galician Rias.

4. Discussion

4.1. Early warning of the risk of closures due to the presence of D. acuminata

Advances in the study of harmful *Dinophysis* species have been recently reviewed by Reguera et al. (2012). In the following, we summarise the knowledge gained about *Dinophysis* spp. relevant for early warning of closures due to variations of *Dinophysis* densities. *Dinophysis* is an obligate mixotroph that requires light and live prey (*Mesodinium* spp.) to grow; division rates in laboratory cultures have been found to be maximal when there is no limitation of prey. Based on observations on frequency of recently fed (full of digestive vacuoles) specimens, field populations of *Dinophysis* often seem to be prey-limited (Velo-Suárez et al., 2014). Red patches of the ciliate *Mesodinium rubrum* are commonly reported in upwelling systems (Park et al., 2006; Hansen et al., 2013). On the other hand, *Mesodinium* needs nutrients and live cryptophytes prey (*Teleaulax* spp.) to grow. These two steps (the growth of *Mesodinium* and its predation by *Dinophysis*) can be segregated in time and space, rendering modelling of *Dinophysis* growth and how it is influenced by the variability of oceanographic conditions a difficult task. However, a bloom of *D. acuminata* requires upwelling for *Mesodinium* to grow, on the one hand, followed by physical-biological interactions favouring the encounter of *Mesodinium* and *Dinophysis*. Consequently, upwelling events (favourable for *Mesodinium* growth) followed by advection of shelf populations into the rías and retention in the rias constitute the optimal scenario for the onset of *D. acuminata* blooms.

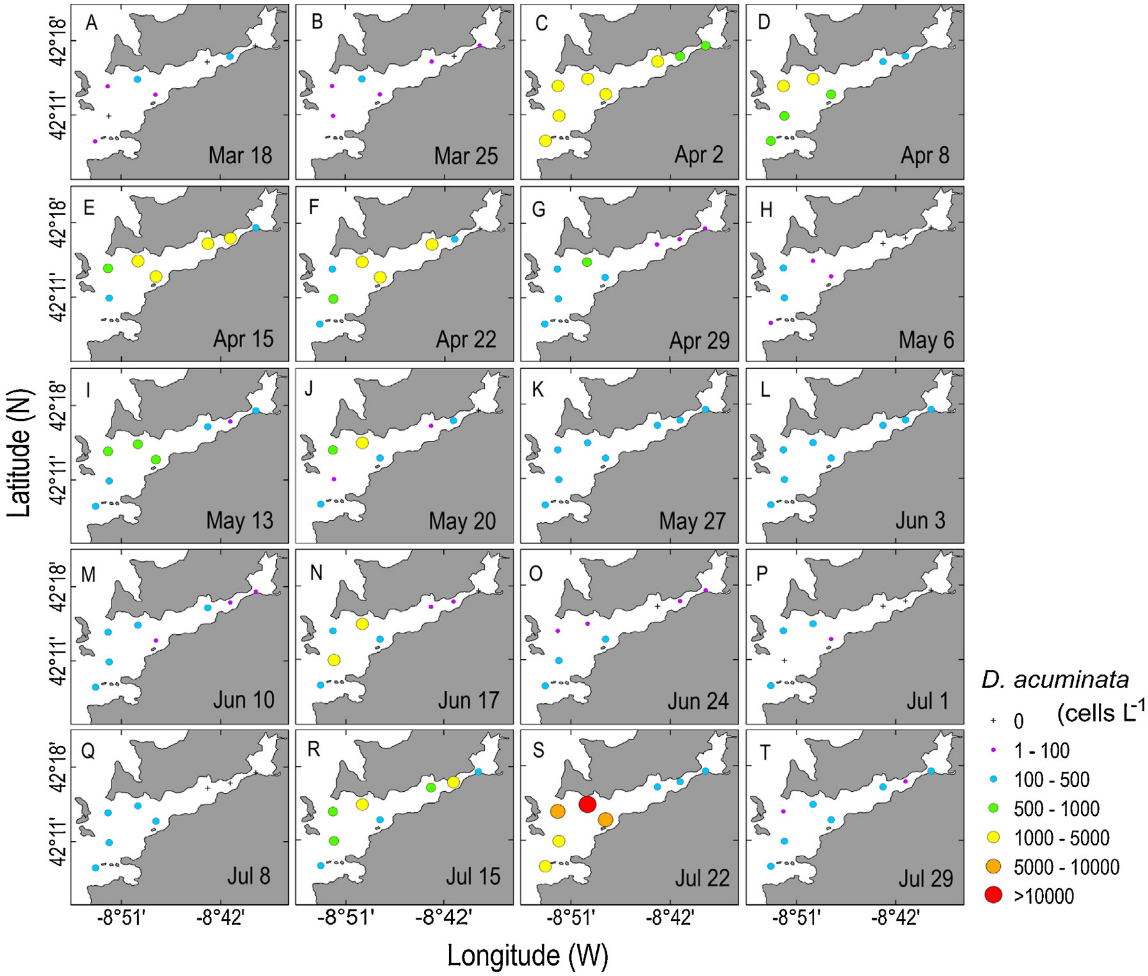

Fig. 7. Cell counts of *D. acuminata* in Ría de Vigo from March to July 2013 (data from INTECMAR).

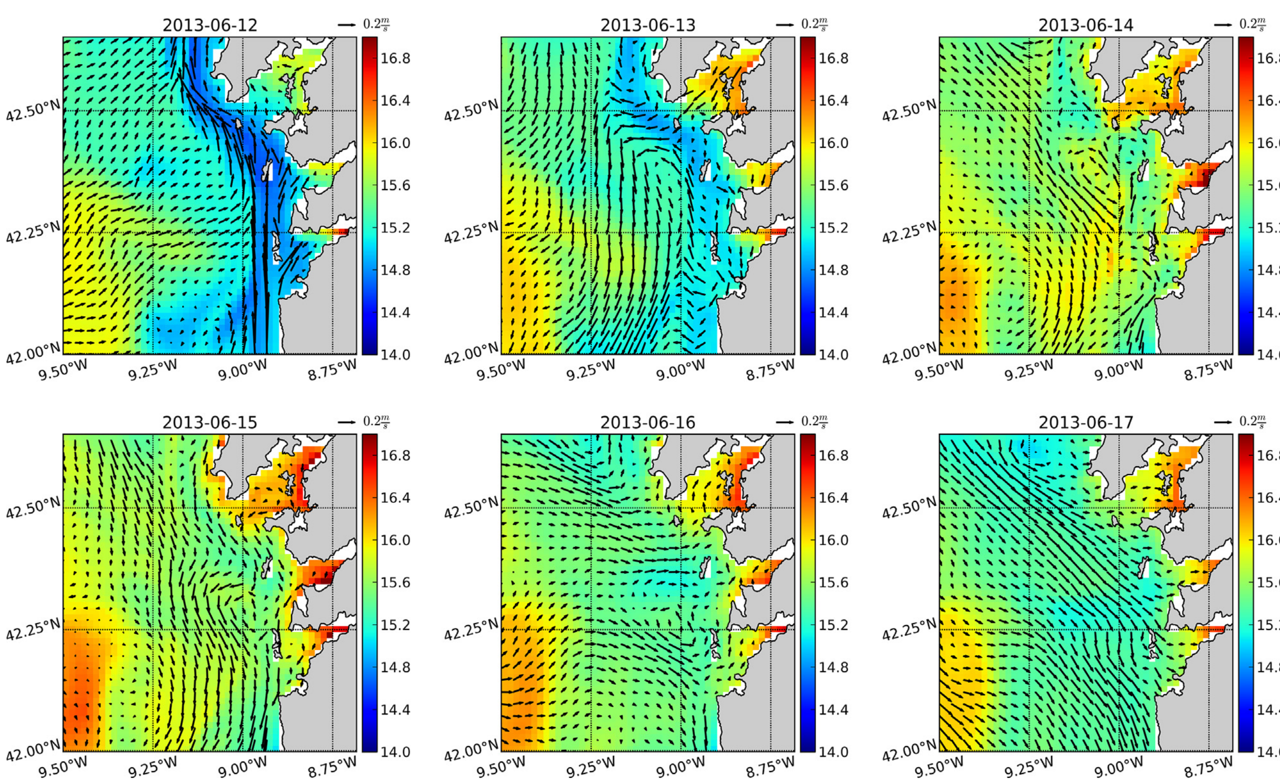

Fig. 8. Zoom of model results of SST and surface currents from 12th to 17th June 2013.

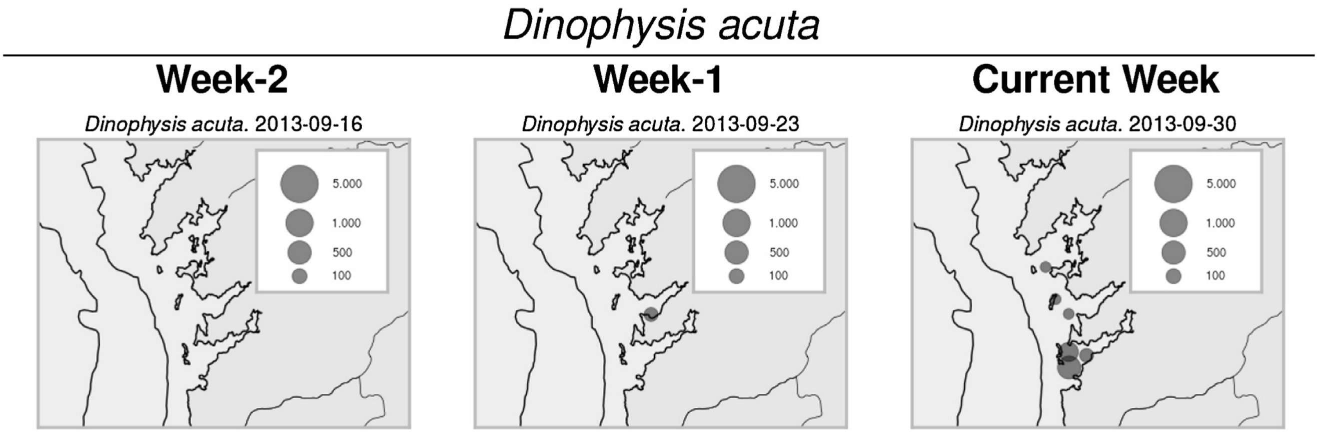

Fig. 9. Cell counts of *D. acuta* and *D. acuminata* from samples taken during the weekly monitoring cruise on 30th September 2013 and during the monitoring cruises in the previous two weeks (source INTECMAR).

Even though our forecast system does not incorporate a model with detailed description of *Dinophysis* behaviour, since the observed variability of *Dinophysis acuminata* in the Galician Rías can be related to the variability in upwelling-downwelling conditions, there is potential in our forecast model for early warning of *Dinophysis* events. However, although rías and shelf water exchanges are controlled by wind induced upwelling-downwelling cycles (meteorological event scale), this exchange is modulated by tides. Díaz et al. (2014) showed in an analysis of CTD, currentmeter and phytoplankton counts in the Ría de Pontevedra that ría and shelf water exchanges are controlled by wind induced upwelling-downwelling cycles (meteorological event scale). In addition, the results presented in Section 3 confirm Díaz et al. (2014) observation that the

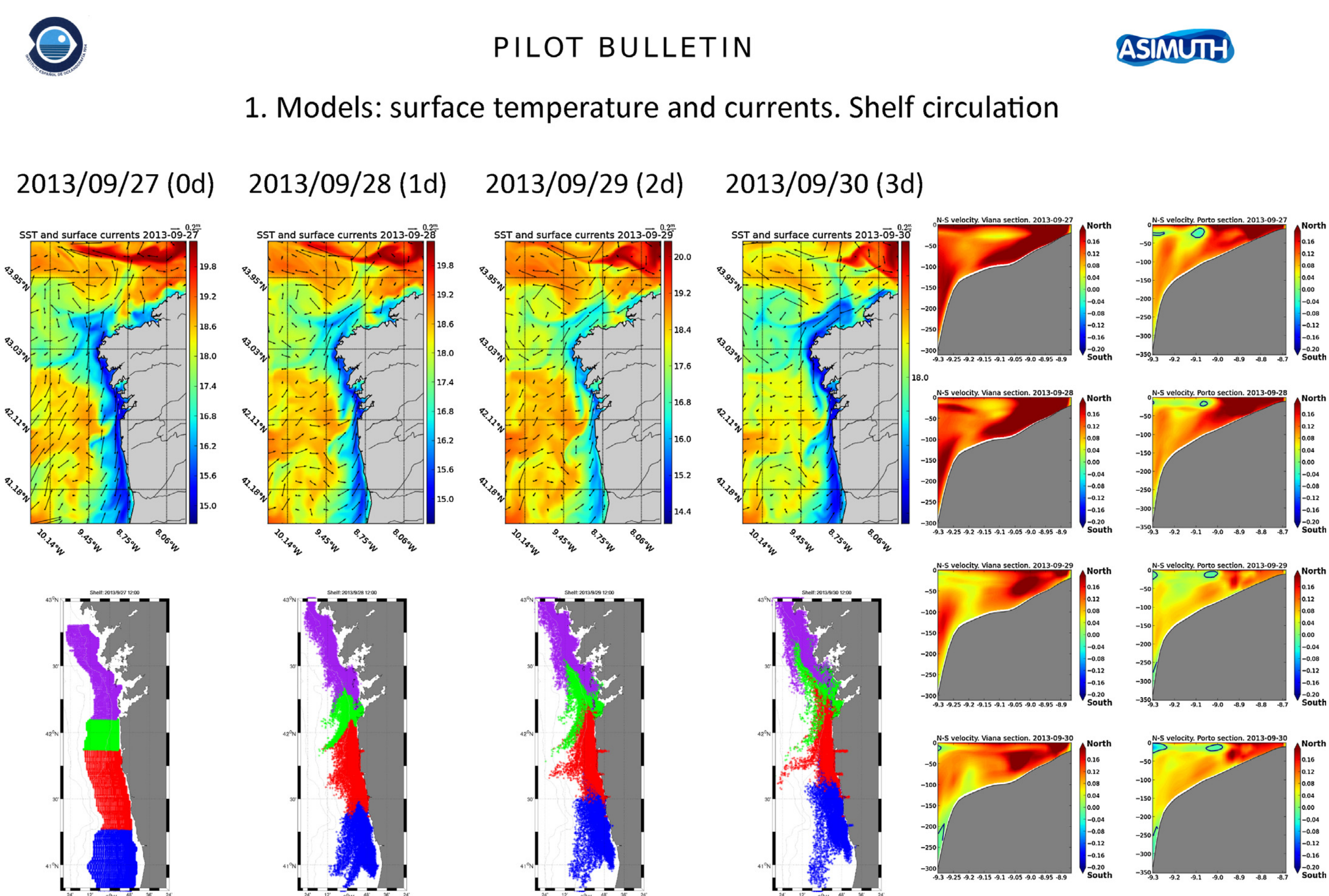

Fig. 10. Model results of the Galician ASIMUTH forecast model (as shown in the bulletin) for Friday 27th September 2013. Top panel: 3-day forecasts of model-generated SST and velocities. Bottom left panels: 3-day evolution of particles released from the two northernmost Portuguese bivalve monitoring areas and from areas off the Galician coast (the shelf between River Minho and Ría de Vigo and the shelf off the Rías). Left panel: 3-day forecast of north-south velocities (red and blue, respectively) along cross-shore sections at the latitudes of the Portuguese monitoring areas (left, Viana, right, Porto).(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

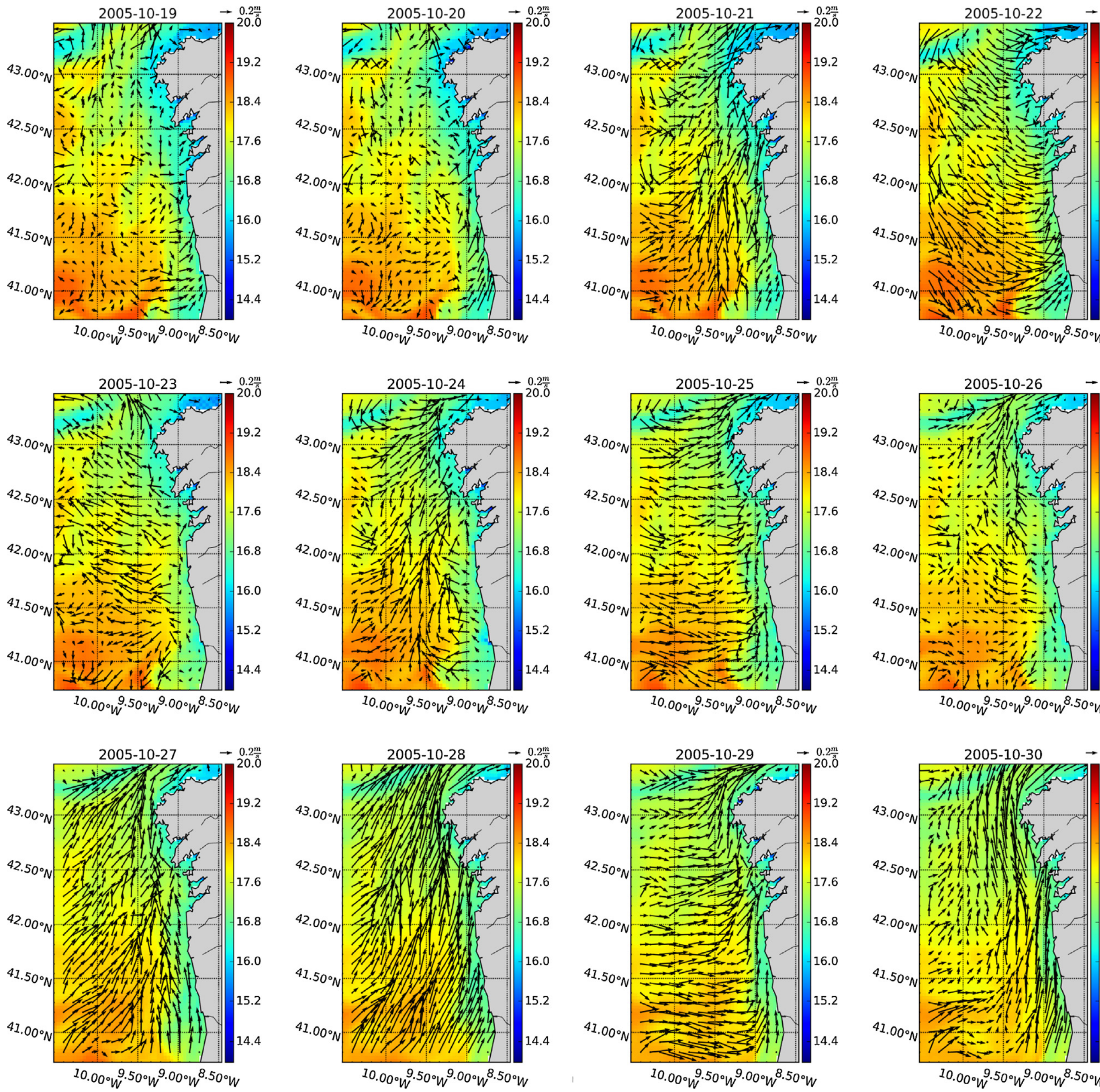

Fig. 11. Model-generated SST and surface currents from 19th to 30th October 2005.

response of the rías to wind events is modulated by the fortnightly spring-neap tidal cycle and by semi-diurnal tides and that the relative phase of tides and wind events has a strong impact on the variability of the phytoplankton assemblage. The interaction between tides and upwelling-downwelling events is complex, and can only be properly addressed with a numerical model. As mentioned in the introduction, *Dinophysis* species usually appear in low densities and are difficult to detect with conventional sampling in monitoring cruises. Contamination of shellfish by DSP toxins above regulatory levels often occurs on a shorter timescale than the typical weekly sampling of monitoring agencies. Therefore, forecasting models provide a reliable tool for early warning, in particular when shifts in wind circulation lead to very rapid changes in cell densities (Velo-Suárez et al., 2014; Whyte et al., 2014).

Although *Dinophysis acuminata* events are recurrent in the Galician Rías, interannual variability in the initiation of the presence of the *D. acuminata* is high. Díaz et al. (2013) linked phenological changes in *D. acuminata* bloom initiation in 2012 with anomalous upwelling patterns in winter and early spring. A similar situation of early commencement of upwelling occurred in spring 2013, and *D. acuminata* was detected from mid March in densities leading to harvesting closures. Although the forecast model has potential to warn of the peaks and troughs in *D. acuminata* densities associated with wind variability and inflow-outflow in the rías, the initiation of the *D. acuminata* growth season in the Rías is still difficult to predict. Key issues are to identify conditions leading to survival of overwintering cells of *Dinophysis* in adjacent shelf waters (providing the *inoculum* for future blooms) and where they go when they are not detected (see Díaz et al., 2016). Further research is needed, which certainly will benefit from the availability of a numerical model configuration characterizing oceanographic conditions.

4.2. Forecast of along-shore transport and its relationship with autumn HABs

In contrast to *Dinophysis acuminata*, *Dinophysis acuta* blooms are very seasonal and appear at the autumn transition from upwelling to downwelling favourable conditions. They occur as sudden blooms which have been linked to along-shore advection of shelf waters (Escalera et al., 2010). As previously shown, a hindcast simulations of the dinoflagellate blooms during the autumns of 2005 and 2013 was run during the ASIMUTH project. The presence of *D. acuta* on the northern Portuguese shelf during summers 2005 and 2013 and of *Gymnodinium catenatum* during summer 2005 was detected by the Portuguese monitoring system. The ASIMUTH system was able to forecast along-shore advection associated with the autumn arrival of HAB populations to the Galician Rías in both years.

The sequence of meteorological events in 2005 is very similar to that in 2013 before the detection of *Dinophysis acuta* in the Ría de Vigo. The northwards shelf current appeared in the numerical simulations during low winds or relaxation of a downwelling event around neap tides. Our results suggest that during autumn transition conditions, along-shore advection is responsible for the appearance of *D. acuta* in the Galician Rías after *D. acuta* populations had been detected in northern Portugal. Considering that northwards advection (and onshore transport) can be forecast by our numerical model, we can assert that the ASIMUTH forecast system can provide early warning of the risk of autumn toxic dinoflagellate blooms in the Galician Rías if toxic species are detected previously by the Portuguese monitoring system.

4.3. On the forecast of the opening of areas affected by a DSP closure

Once harvesting areas are closed, the information of the forecast system must be oriented to provide information on conditions favourable or unfavourable to detoxification. However, detoxification of shellfish is a complex process affected not only by the toxic potential of the cells (toxin profile and content) but also by the ratio between toxic cells/total seston available ("toxic quality" of the food) and by the shellfish species-specific metabolism (Blanco et al., 2013). For example, mussels degrade DTX2 more slowly than okadaic acid (OA). The consequence of this for the Galician mussel industry is that the most noxious DSP events will be those caused by *Dinophysis acuta* (which includes DTX2 in addition to OA and PTX in its toxin profile) during the autumn transition (Reguera et al., 2014).

Another important piece of information provided by the forecast model is the flux between rías. Once a HAB event appears

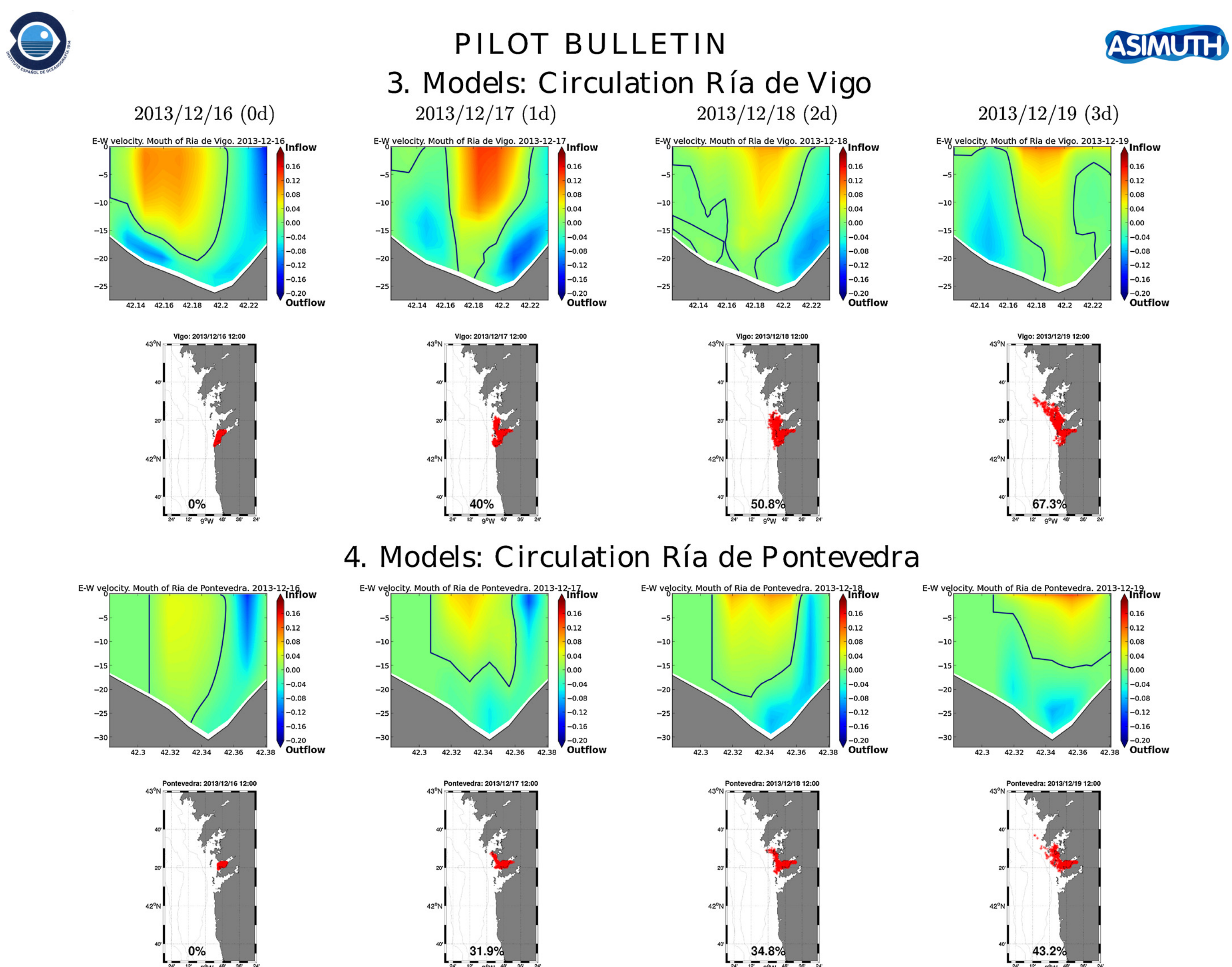

Fig. 12. Galician bulletin for 16th December 2013 showing Lagrangian particle tracking simulations of particles released in Rías de Vigo and Pontevedra. The percentage in the figures corresponds to the percentage of particles leaving the ría. Bulletins are written in Spanish and Galician languages, the two official languages of the Galician autonomous region.

in one ría, Lagrangian experiments can predict the risk of propagation of the HAB event to other rías. Therefore, retention estimates and transport between rías using Lagrangian particle tracking models were incorporated in the Galician bulletins. The bulletin of 16th December, when the Lagrangian model predicted northwards transport along the shelf as well as an influence of Ría de Pontevedra outflow on the mouth of Ría de Arousa, is shown as an example (Fig. 12). This fact, together with the high level of retention in Ría de Arousa, resulted in favourable conditions for retention and hence, for the maintenance of harvesting closures in this Ría. The possibility of simulating the transport among rías once DSP closures in a ría occur allows warning of the risk of contamination of other areas not affected by DSP closures.

5. Concluding remarks

We have shown that model simulations during the growth season of *Dinophysis* species in the Galician upwelling region provide insight into the conditions promoting transport of toxic *Dinophysis* populations into and out of the rías and the onset of DSP outbreaks. The ASIMUTH forecast system was able to describe and predict seawater inflows and outflows affecting harvesting sites in Galicia and their variability during spring-summer 2013. It is known that highest net growth of *Dinophysis acuminata* is observed during relaxation and downwelling following upwelling events. Although the upwelling index is a first order indicator of variability, we have shown how the forecast model describes in more detail the oceanographic conditions in response to upwelling-downwelling cycles and the interplay of different physical forcing (wind events, tides..). The forecast model is able to warn of the conditions favourable for *D. acuminata* growth: upwelling events (favourable for *Mesodinium* growth) followed by retention in the rias (favourable for the encounter of *Dinophysis* and *Mesodinium*). Particularly, the model is able to warn of potentially rapid changes in cell densities linked to shifts in winds. Therefore, the forecast model can warn of the risk of a *D. acuminata* population that may lead to closures of harvesting areas. Autumn blooms cause high economic losses to the shellfish industry when closures last for several months, including the winter (Christmas) harvest season. In the case of dinoflagellate blooms during the autumns of 2005 and 2013, the model was able to forecast along-shore advection associated with the arrival of autumn HABs to Galicia. Consequently, during autumn, a forecast system based on modelling, such as the ASIMUTH Galician system, can provide assessment for monitoring agencies and the aquaculture industry to implement protective measures on time.

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