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Spatial synchronies in the seasonal occurrence of larvae of oysters (*Crassostrea gigas*) and mussels (*Mytilus edulis/galloprovincialis*) in European coastal waters

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ABSTRACT

Reproductive cycles of marine invertebrates with complex life histories are considered to be synchronized by water temperature and feeding conditions, which vary with season and latitude. This study analyses seasonal variation in the occurrence of oyster (*Crassostrea gigas*) and mussel (*Mytilus edulis/galloprovincialis*) larvae across European coastal waters at a synoptic scale (1000s of km) using standardised methods for sampling and molecular analyses.

We tested a series of hypotheses to explain the observed seasonal patterns of occurrence of bivalve larvae at 12 European stations (located between 37°N to 60°N and 27°W to 18°E). These hypotheses included a model that stated that there was no synchronisation in seasonality of larval presence at all between the locations (null hypothesis), a model that assumed that there was one common seasonality pattern for all stations within Europe, and various models that supposed that the variation in seasonality could be grouped according to specific spatial scales (i.e., latitude, large marine ecosystems and ecoregions), taxonomic groups, or several combinations of these factors.

For oysters, the best models explaining the presence/absence of larvae in European coastal waters were (1) the model that assumed one common seasonal pattern, and (2) the one that, in addition to this common pattern, assumed an enhanced probability of occurrence from south to north. The third best model for oysters, with less empirical support than the first two, stated that oysters reproduced later in the south than in the north. For mussels, the best models explaining the seasonality in occurrence of larvae were (1) the model that assumed four underlying trends related to large marine ecosystems, and (2) the one that assumed one common seasonal pattern for larvae occurrence throughout Europe.

Such synchronies in larval occurrences suggest that environmental conditions relevant to bivalve larval survival are more or less similar at large spatial scales from 100s to 1000s of km. To unravel the underlying mechanisms for this synchronisation is of particular interest in the light of changing environmental conditions as the result of global climate change and the possible consequences for marine food webs and ecosystem services.

Keywords: spatial synchrony, synoptic scale, larval occurrence, *Crassostrea gigas*, *Mytilus edulis*, *Mytilus galloprovincialis*

1. Introduction

Evolution in marine invertebrates with complex life-cycles, such as bivalves, has resulted in synchronised reproductive cycles within species. The ultimate selective advantage of synchronization is to produce larvae under

those circumstances which maximise their survival (Olive, 1995). Knowledge of temporal patterns of occurrence of larval stages of various species under different ecological settings may help, therefore, to identify environmental factors that enhance species-specific larval survival. This information can only be gained from robust comparison of heterogeneity across broad geographical scales, and is crucial for predicting the consequences for invertebrate populations under environmental changes such as eutrophication and global climate change (Olive, 1995; Harley et al., 2006; Goberville et al., 2010).

Synchronized reproduction has often been linked with water temperature, which varies with season and latitude (Orton, 1920; Giese, 1959). However, seasonal cycles of photoperiod or changes in food availability may also steer the timing of reproduction of marine benthic invertebrates (Starr et al., 1990; Bentley and Pacey, 1992). Species with latitudinally separated populations may have, therefore, predictably different reproductive cycles (Orton, 1920; Thorson, 1946; Deksheniaks et al., 1993; Hofmann et al., 1994; Bhaud, 2000).

If waters are warm and food availability is relatively constant, e.g. in the tropics, bivalves generally display multiple spawning events within one year (Pouvreau et al. 2006). In continuously cold waters where food availability is strongly seasonal, such as polar regions, bivalves and other invertebrates often show one strong spawning peak per year (Thorson, 1959; Kang et al., 2009). In temperate waters where both temperature and food availability are seasonal, the timing of spawning of bivalves is also strongly seasonal. Furthermore, boreal-temperate invertebrates tend to spawn earlier and for a

more extended period in the warmer part than in the colder part of their distribution range (Thorson, 1959; Seed, 1976; Bauer, 1992; Defeo and Cardoso, 2002; O’Riordan et al., 2004).

Many of the findings corroborating a latitudinal gradient in environmental conditions and in bivalve reproduction come from large-scale (100s-1000s of km) observations in marine waters along long and uninterrupted north-south orientated coastlines such as the Pacific coast of North America (Bauer, 1992) and the Atlantic coast of South America (Defeo and Cardoso, 2002). More detailed studies along these coastlines, however, often revealed mesoscale (10s-100s of km) variation in reproductive factors which appears to be related to coastal topographic features such as bays and headlands (e.g., Lester et al., 2007). These features structure local hydrodynamics such as residence times (Frantzen, 2007) and upwelling events (e.g., Brink, 1983; Ebert and Russell, 1988; Connolly et al., 2001; Largier, 2003). The subsequent local and mesoscale variation in the timing of bivalve reproduction and in larval distribution may interfere with synoptic-scale relationships between latitude, environmental conditions and the seasonality in the presence of larvae in coastal waters.

In contrast to the Pacific coast of North America and the Atlantic coast of South America, Europe does not have an uninterrupted north-south orientated coastline because it comprises semi (e.g. North Sea) to almost fully (e.g. Baltic Sea, Mediterranean and Black Sea) land-locked seas. This topographical complexity may result in a decoupling of latitude and environmental conditions. Chlorophyll-a concentrations tend to be higher in coastal than open seas as the result of nutrient supply by rivers or upwelling

events (e.g., Babin et al., 2003). The enclosed seas have different SSTs compared to the more open marine waters of Europe at similar latitudes (Belkin, 2009).

In this paper, we investigated the presence of bivalve larvae at 12 sites in European coastal waters, ranging from 37°N to 60°N (distance \approx 2400 km) and from 27°W to 18°E (distance \approx 4000 km), during one year of observations. Although previous studies have examined mesoscale (100s of km) relationships between latitude, environmental conditions and invertebrate reproduction in European marine waters (e.g., Haury et al., 1978; Brown, 1984; Lewis 1986; Jenkins et al., 2000; O’Riordan et al., 2004; Cardoso et al., 2007; Burrows et al., 2010), our study was the first which examined the seasonality in bivalve larvae at a synoptic scale (1000s of km) in this part of the world.

We assumed that the presence of larvae in the water is a proxy for the timing of reproduction. We analysed the larval samples for the presence of two bivalve species, i.e. Pacific oysters (*Crassostrea gigas*) and mussels (*Mytilus edulis/galloprovincialis*). We tested how much of the observed seasonal patterns of presence of bivalve larvae at 12 European stations could be explained by various models, including one that stated that there was no synchronisation in seasonality of larval presence at all between the locations (null hypothesis), one that assumed that there was one common seasonality pattern for all stations within Europe, and various models which supposed that the variation in seasonality could be grouped according to specific spatial scales, taxonomic groups, or several combinations of these factors.

2. Materials and methods

2.1. Sampling

Sampling was carried out at 12 coastal sites in Europe. Sites were selected to maximise the range of environmental conditions and latitude in European coastal waters (Table 1). All study sites were permanently submerged, and preferably far from freshwater inputs and other major sources of impacts such as dredging activities and harbours. In addition, the sites were accessible throughout the year to be able to sample at the required frequency and for the full study period. Sites consisted of a single station except for the Azores where two stations were sampled.

To standardize sampling and laboratory procedures, the Royal Netherlands Institute for Sea Research (NIOZ) supplied all materials to filter and store the samples. Sampling started on December 15, 2006, and was aimed to take place once every two weeks throughout the year until December, 2007. Water samples of 10 L were taken from the water surface using a bucket, preferably at high tide for tidal stations and around noon for non-tidal stations. One subsample of 2 L was taken from the bucket, while the water was gently stirred to keep the larvae into suspension. This subsample was filtered over a 31.5 µm-mesh nylon filter with a diameter of 47 mm (tailor-made by “Merrem & la Porte BV”, Zaltbommel, The Netherlands) using minor suction of 0.5 to 1 bar. Material was washed down onto the filter with 0.2 µm-filtered seawater with salinity comparable to that of the samples. The filters were stored separately in pre-labelled cryovials at -80°C. At the end of the

field campaign, the frozen samples were transported by couriers on dry-ice to NIOZ and immediately stored at -80°C after arrival.

For several stations, we measured chlorophyll-a concentrations and sea surface temperature (SST) at or close to the larvae sampling stations (i.e., Sylt, Texel, Oostende and Lecce). Data on environmental conditions for Roscoff and Banyuls were provided by the French Coastal Environmental Monitoring Service (SOMLIT). For all other stations, monthly water temperatures (SST) were derived from monthly averaged satellite data (<http://oceancolor.gsfc.nasa.gov>) from December 2006 to December 2007.

2.2. Species

In the mid-1960s, the Pacific oyster (*C. gigas*) was introduced for commercial purposes from the Northwest Pacific to several locations in Europe. Since then it has spread widely and wild populations can now be found along most of Europe's coastlines, from the northern Mediterranean to southern Norway (Miossec et al., 2009). In northern European waters, there has been a transition from triploid sterile oyster populations sustained by hatchery production to recruitment from wild-settlement (Gollasch et al. 2009).

The absence of Pacific oysters in northern European waters may be caused by too low temperatures for survival and reproduction. Pacific oysters cannot survive at temperatures below 3°C (Kobayashi et al., 1997; Cardoso et al., 2007). While Pacific oysters initiate gametogenesis between 8 to 11°C , they spawn after a threshold temperature of 18 to 20°C has been reached (Mann, 1979; Fabioux et al., 2005). For optimal development, oyster larvae

need water temperatures of at least 22°C (Kobayashi et al., 1997; Shatkin et al., 1997; Rico-Villa et al., 2008). Reproduction appears to be more sensitive to low temperatures than survival. For example, although Pacific oysters can grow such as the Bay of Morlaix (Roscoff sampling station), they are not able to reproduce in these relatively cold waters (Lejart, 2009).

The southern edge of distribution may also be temperature-limited. The temperature tolerance of Pacific oysters ranges between 3°C and 35°C (Cardoso et al., 2007), and summer adult mass mortalities have been documented at hatcheries in France and Ireland since the mid-1980s and mid-1990s, respectively (Cotter et al., 2010; Huvet et al., 2010).

The *Mytilus edulis* complex comprises three nominal species, namely *M. edulis*, *M. galloprovincialis* and *M. trossulus* (Śmietanka et al., 2009). Whilst *M. trossulus* inhabits the Baltic Sea and Loch Etive in Scotland, *M. edulis* occurs from the Barents Sea in the north to the Atlantic coast in France to the south, and *M. galloprovincialis* extends from the Orkney Island in the north to the Mediterranean and Black Sea in the south (Gosling, 1992; Berge et al., 2005; Zbawicka et al., 2010). These mussel species can also interbreed and produce fertile hybrids where their distributions overlap, i.e. the French Atlantic coast up to northern Scotland (Bierne et al., 2003; Śmietanka et al. 2004, 2009).

Whilst *M. edulis* is genetically homogeneous throughout its range, *M. galloprovincialis* is subdivided into a Mediterranean group and an Atlantic group with a break point at the Almeria-Oran oceanographic front in the Mediterranean Sea (Quesada et al., 1995). *M. galloprovincialis* is slowly spreading northwards invading territory once exclusive to *M. edulis* which may

be a result of global climate change (Beaumont et al., 2007). Adults of *Mytilus* species are virtually absent in the Azores (Hawkins et al., 2000) and whether larvae of mussels are present is still unknown.

2.3. Molecular analyses

Total DNA was extracted by the UltraClean™ Soil DNA Isolation Kit (MOBIO Laboratories Inc.) using the alternative protocol for maximum yields (version 03252005). The filter was incised by a sterile scissor to increase the surface area before being subjected to the steps in the extraction protocol. The DNA extracts were checked on a 1% agarose gel stained with ethidium bromide and visualized.

Specific primers for *Crassostrea gigas* and *Mytilus edulis/galloprovincialis* were developed to amplify a part of the cytochrome oxidase subunit I (COXI) mitochondrial gene (Table 2). Primers for *C. gigas* had at least one mismatch at the 3' terminal base with *C. angulata*, *C. sikamea*, *C. nippona*, *C. ariakensis*. Primers for *M. edulis/galloprovincialis* matched exactly with most sequences of female individuals of these species, except for some sequences from Nedlands (Australia) and Dichato (Chile). The primers did not match with the male lineage of *M. edulis/galloprovincialis* (two mismatches in the final four bases at the 3' side). For *M. trossulus* (both females and males), there were no mismatches in the final four bases at the 3' side, but three mismatches further on.

Each PCR reaction mixture contained: 2.5 µL BioTherm™ PCR Buffer (contains 15mM MgCl₂), 2.5 µL dNTP's (Bioline, 2.5 mM), 0.25 µL of each

primer (50 μM), 0.5 μL BSA (20 mg ml^{-1}), 0.125 μL BioThermPlus™ Taq (5 units μl^{-1}), 15.875 μL PCR H_2O , 3 μL DNA template. After an initial denaturation step at 94°C for 120 seconds, the PCR programmes followed 36 cycles at 94°C for 30 seconds, annealing at 52.5°C (*C. gigas*) or at 50°C (*M. edulis/galloprovincialis*) for 30 seconds, extension at 72°C for 60 seconds and a final extension step at 72°C for 420 sec.

Presence of PCR inhibitors in a sample (e.g. from the seawater) may result in a false negative, i.e. a negative amplification result whilst larvae were present in that sample. Our results were therefore checked by means of PCR inhibition tests. For this test we used the protocol as described above, but instead of 3 μl sample we used 2 μl of the diluted sample (1:1, 1:5, 1:25 and 1:125) and added 1 μl of positive control consisting of adult DNA of each target species and visualized the results on gel.

The presence/absence of larvae of the target species was scored from the gels immediately after PCR amplification. Presence was detected if there was at least one D-larva (early veliger larval stage of bivalves) larger than 50 μm in the 2-L sample. This implied that it was possible to score larvae from mean concentrations of 0.5 – 2.5 larvae per litre (= 500 – 2.500 larvae per m^3) onwards. We scored the visibility of the bands as an index of presence: larvae were assumed to be absent (0) if no band was visible, and present (1) if the bands were weakly to strongly visible. Molecular analyses, including scoring, were performed by only one person (BTR).

2.4. Spatial scales

We tested if the observed seasonal patterns of presence of bivalve larvae at 12 European stations could be best explained:

- by local variation dominating the geographical variation in larval presence (null hypothesis), or
- by one common seasonality pattern for all stations within Europe (Hypothesis 1), or
- by groups of seasonal patterns which are related to specific spatial scales such as latitude, large marine ecosystems, and marine ecoregions (Hypotheses 2 to 5), or
- by taxonomic groups (Hypothesis 8), or
- by several combinations of these factors (Hypotheses 6, 7 and 9) (Table 3).

European marine waters can be classified into several Large Marine Ecosystems, LMEs (Table 1; Fig. 1). These LMEs are relatively large regions on the order of 200,000 km² or greater, characterized by distinct bathymetry, hydrography, productivity, and trophically dependent populations (see <http://www.lme.noaa.gov>). Based on a more detailed distribution overview of marine species than the one that was originally used for the definition of the LMEs, Spalding et al. (2007) subdivided the coastal and shelf areas of the world into 232 marine ecoregions (MEs). Within European marine waters, however, most MEs more or less overlap with LMEs with exception of the Iceland Shelf and the Norwegian Sea (which are each split into 2 ecoregions) and the Mediterranean (which is subdivided into 7 ecoregions).

2.5. Statistical analyses

Following the protocol in Zuur et al. (2010), an initial data exploration was applied. Hereafter, we modelled the data by means of a generalised additive mixed effects model (GAMM) with a binomial distribution, i.e.:

$$M_{is} = \text{Binomial}(p_{is}, 1)$$
$$\text{logit}(p_{is}) = \alpha + \text{covariates} + a_i + \varepsilon_{is}$$

where M_{is} is the observed presence or absence of *Crassostrea gigas* or *Mytilus edulis/galloprovincialis* at site i at time s , and p_{is} is the probability that larvae of oysters or mussels are present at site i at time s . The random intercept a_i allows for a random variation around the intercept α , and is assumed to be normally distributed with mean 0 and variance σ^2_{site} . The random intercept ensures that observations from the same site are allowed to be correlated. Due to the short length of the time series, we did not apply more advanced correlation structures like auto-regressive correlation (Zuur et al., 2009), but instead only used the symmetric compound correlation as imposed by the random intercept.

Based on the underlying questions (see section 2.4), a series of hypotheses and models were used for the ‘covariates’ part (Table 3). The smoothers $f(\cdot)$ were estimated using the R package (R Development Core Team, 2009), gamm4 (Wood, 2009) and cubic regression splines. The covariate Subspecies was fitted as a categorical variable. In order to fit all models on the same data, the observations from the Azores (Faial North and South) were removed from the analysis.

To compare models, we followed an Information Theoretic approach (Anderson and Burnham, 2002). We calculated differences Δ_i between the Akaike Information Criterion (AIC) of each model and the minimum AIC. Anderson and Burnham (2002) state that the level of empirical support for model i is:

- substantial if Δ_i is between 0 and 2 (hence, these are models with similar AICs as the optimal model),
- considerable less if Δ_i is between 4 and 7, and
- essentially none if Δ_i is larger than 10.

Akaike weights w_i were calculated following Anderson and Burnham (2002), which place the Δ_i on a more interpretable scale by using:

$$w_i = \frac{e^{-\frac{1}{2} \times \Delta_i}}{\sum_i e^{-\frac{1}{2} \times \Delta_i}}$$

These weights have the convenient ability that they can be interpreted as probabilities that a given model is judged the best model on repeated sampling. If the weight for a particular model has a value of 0.75, for example, this implies that this model has a probability of 75% of being the best model within the series tested. Note that the AIC values obtained by a GAMM with a binomial distribution should be considered as approximate.

3. Results

3.1. Oysters (*Crassostrea gigas*)

Larvae of *C. gigas* were observed at 5 of the 12 sites, and occurred more often at Sylt, Texel and Roscoff than at Oostende and Algarve (Fig. 2). The values of the Akaike weights w_i indicated that model H1 has the highest probability (58%) of being the best model within the series tested, followed by model H2 (25%) and model H3 (17%) (Table 3).

The best model explaining the presence/absence of oyster larvae in European coastal waters was the one that assumes one common seasonal trend at all stations (H1 in Table 4). This model suggested that oyster larvae are most likely to occur in summer with peak values around early August (day number experiment ≈ 230) (Table 5; Fig. 3).

The other model for which the level of empirical support is substantial (i.e. the value of Δ_i is between 0 and 2, so its AIC is considered to be similar to that of the optimal model H1) was the one that assumes one underlying seasonal trend and one latitudinal effect for all the time series (H2; Table 5; Fig. 4) with higher probability of occurrence in the north than in the south.

The model that assumes that the latitude effect changes over time (H3) had some empirical support as well ($\Delta_i = 2.4$). The results of model H3 suggested that larvae have a higher probability of occurrence at higher latitudes and exhibit a seasonal pattern for day number with earlier occurrences at higher latitudes in the range of those tested (Fig. 5).

3.2. *Mussels (Mytilus edulis/galloprovincialis)*

Mussel larvae were observed at all 12 sites, and were present during most of the year at Povoia, Sylt, Texel, Oslo and Banyuls but were rarely observed at Helgoland and Mallorca (Fig. 2). The values of the Akaike weights w_i indicate that that model H4 has the highest probability (52%) of being the best model within the series tested, followed by model H5 (25%) (Table 3).

The best model explaining the presence/absence of mussel larvae in European coastal waters was the one that assumed four different seasonal trends, one for each LME (H4 in Table 3). For the North Sea and the Iberian Coast, this model suggested that the highest probability of occurrence of mussel larvae was in late winter (end of February) and around the end of September (Table 6; Fig. 6). The Celtic-Biscay Shelf was characterised by an increase in probability of occurrence of mussel larvae between February and June, whilst the Mediterranean shows a decrease in probability of occurrence of mussel larvae throughout spring and summer (Fig. 6).

The other model for which the level of empirical support is substantial (i.e. the value of Δ_i is between 0 and 2) is the one that assumes that all the time series have one underlying seasonal trend (H1 in Table 3) with peak values around mid-April (day number experiment ≈ 120) (Table 6; Fig. 7).

4. Discussion

4.1. Limitations of our study

At optimal water temperatures and feeding conditions, larvae of oysters and mussels may reach metamorphosis within two weeks (Satuito et al., 1994; Rico-Villa et al., 2009). This implies that only under such maximum growth conditions for larvae, reproductive periods could have been missed for those stations where we were able to sample as planned, i.e. once every fortnight.

Due to the presence of a detection limit of larvae in our samples, we cannot distinguish between the presence of larvae at low densities (< 500 larvae per m³) and the actual absence across sampling sites and/or sampling periods. We might, therefore, have missed the presence of larvae if their densities were low, e.g. as the result of low reproductive output of bivalve stocks and/or as the result of dilution if the sampling site was not close to the nearest spawning stock.

In addition, our sampling and analyses techniques were not quantitative and did not allow us to discriminate between a few larvae exceeding the threshold or higher larval densities. Interpretation of the results should, therefore, be done within the light of these limitations.

The strength of our methods, however, lies within the standardisation of the sampling techniques throughout Europe and the consistency of the analyses of the samples which were performed in one laboratory by one person. This reduced the possible noise in the data as the result of variation in sampling and analysis techniques between laboratories to a large extent.

4.2. Oysters (*Crassostrea gigas*)

The best model on the occurrence of oyster larvae in European coastal waters (Fig. 3) suggested that the reproduction of oysters most probably exhibit one common seasonal trend at all stations where larvae were observed, with highest probability of larval occurrence around early August. This is in agreement with previous observations that natural populations of Pacific oysters in north-western Europe generally spawn in summer and autumn (Pouvreau et al., 2006; Cardoso et al., 2007; Enríquez-Díaz et al., 2009; Troost et al., 2009; Dutertre et al., 2010).

The second best but comparably good model (Fig. 4) suggested that larvae exhibit one seasonal trend and one underlying latitudinal effect in probability of occurrence, while the third best model (Fig. 5) suggested that oyster larvae also occurred earlier at higher latitudes in the range of those tested. If the timing of reproduction is predominantly triggered by a threshold in temperature, it would be expected that spawning would occur earlier in the south than in the north. Our findings were in agreement with previous observations by Cardoso and co-authors (2007), however, who showed that spawning events (identified by sudden decreases in gonadal mass) of Pacific oysters occurred earlier in northern than in southern sites along the west European coast (from 46 to 53°N).

The above evidence suggests that the onset of spawning is not only determined by temperature but also by other factors, possibly food availability. Energy flow models of *Crassostrea virginica* indicated, for example, that both temperature and food supply affect the timing of the spawning season and the reproductive output (Dekshenieks et al., 1993; Hofmann et al., 1994). Within NW-Europe, increased food conditions in the north were suggested to

advance the timing of spawning of Pacific oysters during the warmest months of the year (Cardoso et al., 2007). Their suggestion on the importance of food availability on the timing of spawning of Pacific oysters were corroborated by our findings that chlorophyll a concentrations were considerably higher at the northern locations than at Roscoff (Fig. 2).

Larvae of *Crassostrea gigas* were detected by molecular techniques in winter and spring at the sampling site near Sylt (Fig. 2) which was confirmed by microscopic analyses of water samples taken at the same time (R. Asmus, unpublished data). These observations suggest that spawning can occur at much lower temperatures (less than 10⁰C; Fig. 2) than previously indicated as threshold values (Mann, 1979; Fabioux et al., 2005; Lejart, 2009). Whether this might be the result of rapid adaption of the invasive Pacific oysters towards a relatively new environment (Prentis et al., 2006) or that Sylt harbours a different subpopulation of Pacific oysters remains to be investigated, e.g. by determining the traits with regard to phenology and larval survival of oysters from various origins and possible subpopulations.

4.3. Mussels (*Mytilus edulis/galloprovincialis*)

The timing of reproduction and the duration of the reproductive cycle in *Mytilus edulis*, *M. galloprovincialis* and their hybrids have been shown to vary both spatially and temporally under local environmental conditions like temperature and food availability (Wilson and Seed, 1974; Bayne, 1975, 1976; Pieters et al., 1980; Sunila, 1981; Kautsky, 1982; Lowe et al., 1982; Sprung, 1983; Villalba, 1995; Pulfrich, 1997; Cáceres-Martínez and Figueras,

1998; Frantzen, 2007; Duinker et al., 2008; Dias et al., 2009; Doherty et al., 2009; Troost et al., 2009).

Based on our results, larval presences of mussels appear not to be determined by small-scale (local) variation in environmental conditions (null hypothesis), but by environmental conditions that operate at larger (100s to 1000s of km) spatial scales. The best model (Fig. 6) suggested that, for the North Sea and the Iberian Coast, the probability of occurrence of mussel larvae is high at the end of March with a second peak in end September (North Sea) to the beginning of November (Iberian Coastal). The model results for the Celtic-Biscay and Mediterranean areas were different for the beginning and the end of the year (Fig. 6), which suggested that conditions in the study year and the following year were different. To exclude the possibility of an artefact in the models, this type of study ideally needs to be conducted across more than a single year. The second best but comparably good model (Fig. 7) suggested that on seasonality in occurrence of mussel larvae showed a common seasonal pattern with one peak around mid-April for all sites.

Previous observations on the reproductive cycle of *M. edulis* suggested a shift from one to two periods of reproduction within a year during the past decades, i.e. the observations of a single spawning event in spring were made in the 1950s to the 1980s (Chipperfield, 1953; Pieters et al., 1980; Sunila, 1981; Kautsky, 1982; Sprung, 1983), whilst multiple spawning in both spring and autumn was observed from the 1990s onwards (Villalba et al., 1995; Pulfrich, 1997; Cáceras-Martinez and Figueras, 1998; Frantzen, 2007; Duinker et al., 2008; Dias et al., 2009; Troost et al., 2009). It is not possible, however, to infer from this information whether the reproductive behaviour of

mussels has actually changed during the past decades, because most observations in the older publications were restricted to a limited period of the year.

This possibility of long-term changes in phenology of mussels deserves future investigation, e.g. by studying the phenology of spawning of mussels from various origins under different temperature and food conditions, because climate-induced changes in spawning frequencies have been observed for other marine invertebrates in Europe during the past decades. In south-west Britain, for example, *Patella depressa* (a warm temperate gastropod species) originally showed single spawning events only in the 1940s whilst multiple periods of spawning and gonad redevelopment occurred during the reproductive season throughout the 2000s (Moore et al. 2011).

5. Conclusion

Based on the variety in environmental conditions such as temperature and chlorophyll-a concentrations at our sampling stations (Fig. 2) and potential patchiness in larval distributions, we would have expected that the null hypothesis (local variation) would best explain observed occurrence of oyster and mussel larvae throughout Europe. Both bivalve species, however, exhibited synchronised patterns in occurrence of larvae at mesoscale (100s of km) to synoptic scales (1000s of km). Such synchrony in larval occurrence suggests that environmental conditions relevant to bivalve reproduction and larval survival are more or less similar at these spatial scales.

As the result of our comparative approach, we cannot determine the actual underlying mechanisms for these patterns, nor exclude the possibility that different locations harboured different subpopulations adapted to local conditions. Our results might help, however, to design experiments to test competing hypotheses regarding causal mechanisms such as food availability and temperature at the appropriate ranges and scales (Underwood and Petraitis, 1993; Jenkins et al., 2000). The unravelling of the nature and strength of structuring factors of phenology of bivalve reproduction is of particular interest in the light of changing environmental conditions as the result of global climate change and the possible consequences for marine food webs and ecosystem services (e.g., Philippart et al., 2003; Kirby et al. 2009).

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1 **Table 1.** Name and positioning of sampling sites, ranked from high to low latitudes, and the name of the Large Marine Ecosystem
2 (www.lme.noaa.gov) and Marine Ecoregion (Spalding et al., 2007) in which the sites are situated. Furthermore, the potential
3 presence of *Mytilus* groups is indicated (Mt = *M. trossulus*, Me = *M. edulis*, MgA = Atlantic *M. galloprovincialis*, MgM =
4 Mediterranean *M. galloprovincialis*) based on literature (Quesada et al., 1995; Śmietanka et al. 2004, 2009).
5

| Name Site | Ctry | Latitude | Longitude | Samples | | Large Marine Ecosystem (LME) | Marine Ecoregion (ME) | <i>Mytilus</i> groups | | | |
|--------------|------|------------|-------------|---------|-------------|------------------------------------|-----------------------------|-----------------------|----|-----|-----|
| | | | | n | Period | | | Mt | Me | MgA | MgM |
| Oslo | N | 59°53'57"N | 010°39'03"E | 15 | Mar07-Dec07 | North Sea | North Sea | x | x | | |
| Sylt | GER | 55°01'00"N | 008°26'24"E | 27 | Dec06-Dec07 | North Sea | North Sea | | x | | |
| Helgoland | GER | 54°10'45"N | 007°53'36"E | 27 | Dec06-Dec07 | North Sea | North Sea | | x | | |
| Texel | NL | 53°00'19"N | 004°47'46"E | 27 | Dec06-Dec07 | North Sea | North Sea | | x | | |
| Oostende | B | 51°14'14"N | 002°54'05"E | 17 | Dec06-Dec07 | North Sea | North Sea | | x | | |
| Roscoff | F | 48°42'30"N | 003°57'09"W | 25 | Jan07-Dec07 | Celtic-Biscay | Celtic Seas | | x | x | |

| | | | | | | Shelf | | | | | |
|----------|-----|------------|-------------|----|-------------|-----------------|-------------------------------------|--|--|---|---|
| Banyuls | F | 42°29'26"N | 003°09'38"E | 25 | Jan07-Dec07 | Mediterranean | Western Mediterranean | | | | x |
| Povoa | P | 41°21'01"N | 008°46'21"W | 27 | Dec06-Dec07 | Iberian Coastal | South European Atlantic Shelf | | | x | |
| Lecce | IT | 40°15'08"N | 017°54'23"E | 23 | Jan07-Dec07 | Mediterranean | Ionian Sea | | | | x |
| Mallorca | ESP | 39°31'14"N | 002°39'12"E | 17 | Feb07-Dec07 | Mediterranean | Western Mediterranean | | | | x |
| Arrabida | P | 38°39'08"N | 009°20'09"W | 6 | Sep07-Dec07 | Iberian Coastal | South European Atlantic Shelf | | | x | |
| Faial-N | P | 38°37'23"N | 028°38'22"W | 21 | Mar07-Dec07 | (NE Atlantic) | Azores Canaries | | | | |

| | | | | | | | | | | | |
|----------|---|------------|-------------|----|-------------|-----------------|-------------------------------------|--|--|---|--|
| | | | | | | | Madeira | | | | |
| Azores-S | P | 38°33'34"N | 028°46'08"W | 21 | Mar07-Dec07 | (NE Atlantic) | Azores Canaries Madeira | | | | |
| Algarve | P | 36°58'14"N | 007°58'21"W | 25 | Dec06-Dec07 | Iberian Coastal | South European Atlantic Shelf | | | x | |

6 (Abbreviations countries: N=Norway, GER=Germany, NL=The Netherlands, B=Belgium, F=France, P=Portugal, ESP=Spain,

7 IT=Italy)

8 **Table 2.** Primer sequences and additional information

9

| Species | Primer Name | Sequence (5'-3') | Length |
|---|-------------|--------------------|--------|
| <i>Mytilus edulis/galloprovincialis</i> | Myt3L | CTCTATTAGTAGGTGGTA | 18-mer |
| | Myt6H | AATACGGCAGTAACTCT | 17-mer |
| <i>Crassostrea gigas</i> | GigasF | TCTCTTATTCGTTGGAGA | 18-mer |
| | GigasR | ACCTTAATAGATCAAGGG | 18-mer |

10

11 **Table 3.** Hypotheses and statistical models for the presence/absence data of larvae of *Crassotrea gigas* and *Mytilus*
 12 *edulis/galloprovincialis* in coastal European waters at a synoptic scale. (LME = Large Marine Ecosystem, ME = Marine Ecoregion).
 13

| # | Hypothesis | Statistical model |
|----|---|---|
| H0 | There is no trend, just noise (local variation dominates geographic variation in larval presence) | $\text{logit}(p_{is}) = \alpha + a_i + \varepsilon_{is}$ |
| H1 | All the time series have one (similar) underlying seasonal trend | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_s) + a_i + \varepsilon_{is}$ |
| H2 | There is one underlying latitude effect and one underlying seasonal trend for all the time series | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_{is}) + f(\text{Latitude}_{is}) + a_i + \varepsilon_{is}$ |
| H3 | The latitude effect changes over time | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_{is}, \text{Latitude}_{is}) + a_i + \varepsilon_{is}$ |
| H4 | All the time series have four underlying seasonal trends which are related to LMEs | $\text{logit}(p_{is}) = \alpha + f_j(\text{DayNr}_{is}) + a_i + \varepsilon_{is}$ $j = 1, \dots, 4$, where j refers to LMEs |

| | | |
|-----------|---|--|
| H5 | All the time series have five underlying seasonal trends which are related to MEs | $\text{logit}(p_{is}) = \alpha + f_k(\text{DayNr}_{is}) + a_i + \varepsilon_{is}$ $k = 1, \dots, 5, \text{ where } k \text{ refers to MEs}$ |
| H6 | There is one seasonal trend and the latitude effect differs per LME | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_{is}) + f_j(\text{Latitude}_{is}) + a_i + \varepsilon_{is}$ $j = 1, \dots, 4, \text{ where } j \text{ refers to LMEs}$ |
| H7 | There is one seasonal trend and the latitude effect differs per ME | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_{is}) + f_k(\text{Latitude}_{is}) + a_i + \varepsilon_{is}$ $k = 1, \dots, 5, \text{ where } k \text{ refers to MEs}$ |
| H8 | There is one seasonal trend and there is a subspecies effect | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_{is}) + \textit{Subspecies} + a_i + \varepsilon_{is}$ |
| H9 | There is one seasonal trend, the latitude effect is the same for all the time series and there is a subspecies effect | $\text{logit}(p_{is}) = \alpha + f(\text{DayNr}_{is}) + f(\text{Latitude}_{is}) + \textit{Subspecies} + a_i + \varepsilon_{is}$ |

Table 4. Values and differences of the Akaike Information Criterion (AIC), and the Akaike weight (w_i) for models 0 to 9 in Table 4. Models for which the level of empirical support for model i is substantial (i.e. the value of Δ_i is between 0 and 2) are underlined, the best fit (for which AIC has the lowest value) is printed in bold.

| | <i>Crassostrea gigas</i> | | | <i>Mytilus edulis/galloprovincialis</i> | | |
|-----------|-------------------------------|-------------------|---------------------|---|-------------------|---------------------|
| | AIC | Δ_i | w_i | AIC | Δ_i | w_i |
| H0 | 119.9 | 16.0 | 0.000 | 281.0 | 6.6 | 0.019 |
| H1 | <u>103.9</u> | <u>0.0</u> | <u>0.576</u> | <u>275.9</u> | <u>1.5</u> | <u>0.246</u> |
| H2 | <u>105.6</u> | <u>1.7</u> | <u>0.246</u> | 279.2. | 4.8 | 0.047 |
| H3 | 106.3 | 2.4 | 0.173 | 281.1 | 6.7 | 0.018 |
| H4 | 116.6 | 12.7 | 0.001 | <u>274.4</u> | <u>0.0</u> | <u>0.519</u> |
| H5 | 120.6 | 16.7 | 0.000 | 277.7 | 3.3 | 0.100 |
| H6 | 114.6 | 10.7 | 0.003 | 288.0 | 13.6 | 0.001 |
| H7 | 118.5 | 14.6 | 0.000 | 291.5 | 17.1 | 0.000 |
| H8 | not relevant for this species | | | 281.8 | 7.4 | 0.013 |
| H9 | not relevant for this species | | | 279.7 | 5.3 | 0.037 |

Table 5. *Crassostrea gigas*. The estimates, estimated degrees of freedom (obtained by cross-validation) and approximate significance for intercepts and smoothers of best models for oyster larvae (see Table 4). Day number is referring to the day number of the experiment, ranging from 1 (December 15, 2006) to 368 (December 18, 2007). To fit models 2 and 3, both covariates were scaled to have the same variation.

| Model H1. One underlying seasonal trend | | | | |
|---|-----------------|------------------|----------------|--------------------|
| Parameter | Estimate | Std Error | T value | Pr(> t) |
| Intercept | -5.4958 | -10.55 | <2e-16 | 0.001 |
| Smooth terms | edf | Ref.edf | F | p-value |
| Day number | 3.758 | 3.758 | 4.264 | 0.003 |
| Model H2. One underlying seasonal trend + one underlying latitude effect | | | | |
| Parameter | Estimate | Std Error | T value | Pr(> t) |
| Intercept | | | | |
| Smooth terms | edf | Ref.edf | F | p-value |
| Day number (scaled) | 3.718 | 3.718 | 4.124 | 0.004 |
| Latitude (scaled) | 2.932 | 2.932 | 1.872 | 0.136 |
| Model H3. Latitude effect changes over time | | | | |
| Parameter | Estimate | Std Error | T value | Pr(> t) |
| Intercept | | | | |
| Smooth terms | edf | Ref.edf | F | p-value |
| Day number, latitude (scaled) | | | | |

Table 6. *Mytilus edulis/galloprovincialis*. The estimates, estimated degrees of freedom (obtained by cross-validation) and approximate significance for intercepts and smoothers of the best models for mussel larvae (see Table 4). Day number is referring to the day number of the experiment, ranging from 1 (December 15, 2006) to 368 (December 18, 2007). (CBS = Celtic Biscay Shelf; IC = Iberian Coastal; M= Mediterranean; NS = North Sea).

| Model H4. Four underlying seasonal trends related to LMEs | | | | |
|--|-----------------|------------------|----------------|--------------------|
| Parameter | Estimate | Std Error | T value | Pr(> t) |
| Intercept | 0.2776 | 0.1861 | 1.491 | 0.137 |
| Smooth terms | edf | Ref.edf | F | p-value |
| Day number CBS | 1.896 | 1.896 | 2.945 | 0.057 |
| Day number IC | 4.607 | 4.607 | 3.088 | 0.012 |
| Day number M | 1.698 | 1.698 | 2.999 | 0.060 |
| Day number NS | 4.562 | 4.562 | 3.205 | 0.010 |
| Model H1. One underlying seasonal trend | | | | |
| Parameter | Estimate | Std Error | T value | Pr(> t) |
| Intercept | | | | |
| Smooth terms | edf | Ref.edf | F | p-value |
| Day number (scaled) | 3.833 | 3.833 | 4.307 | 0.003 |

FIGURE CAPTIONS

FIGURES

Figure 1. Locations of sampling sites, projected on annual average of sea surface temperatures in 2007 as measured by the MODIS sensors aboard the Aqua EOS PM satellite (<http://oceancolor.gsfc.nasa.gov>).

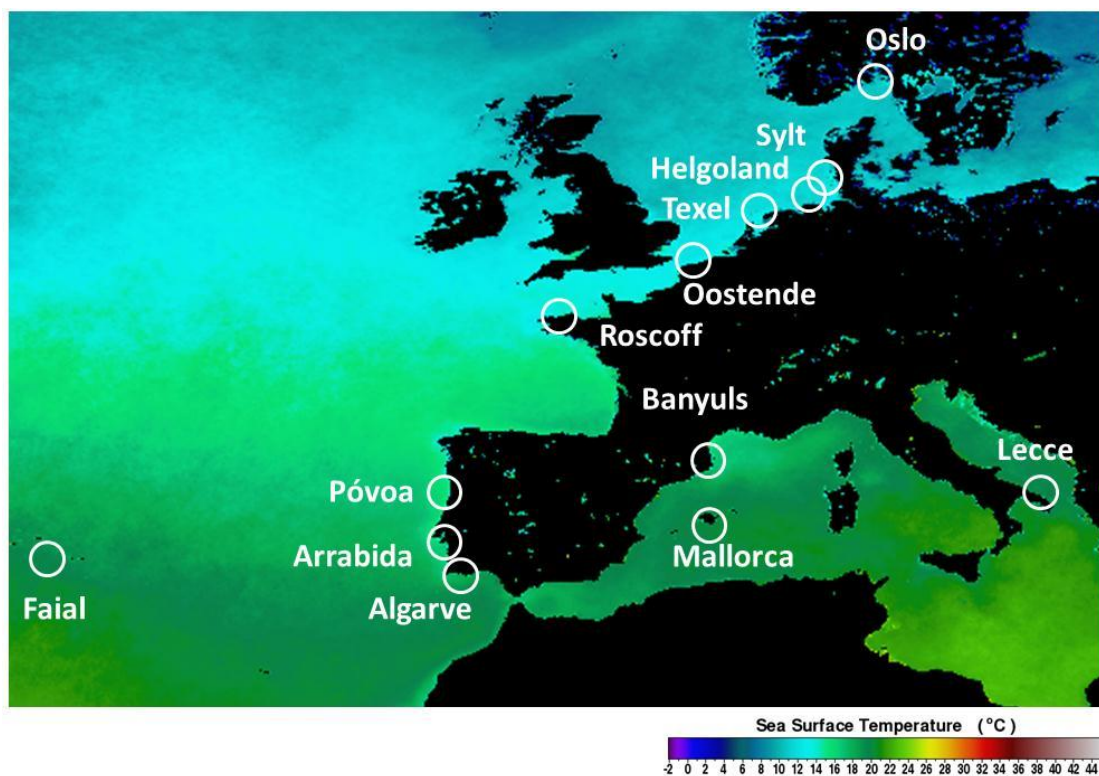
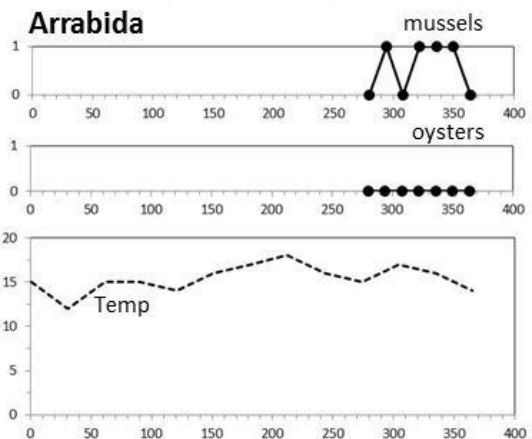
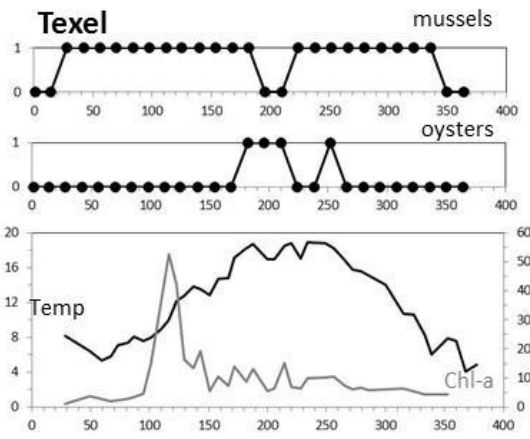
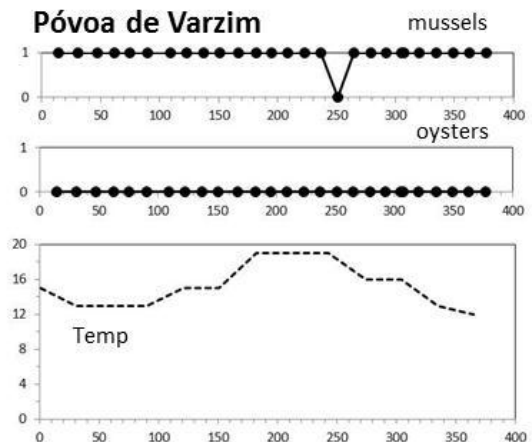
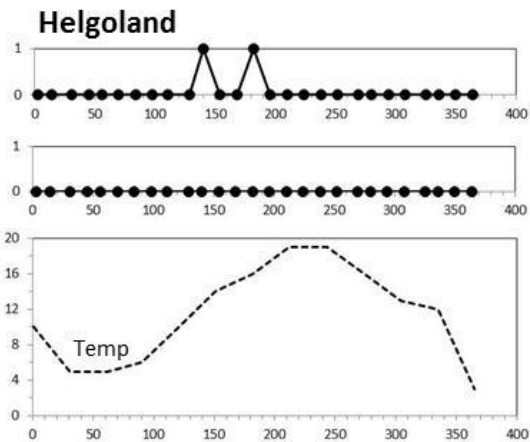
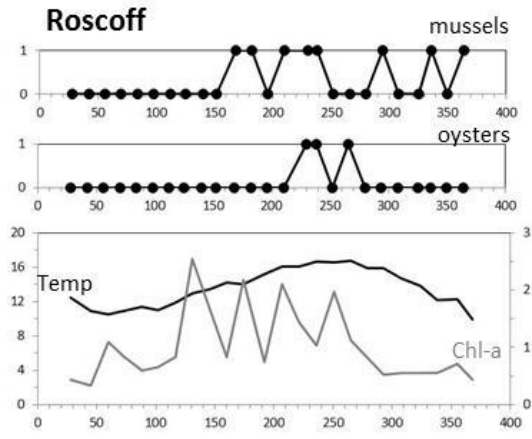
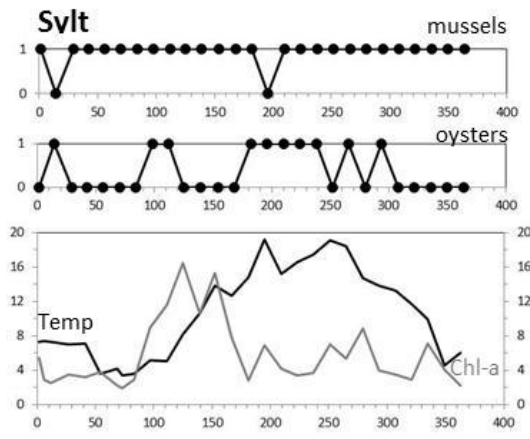
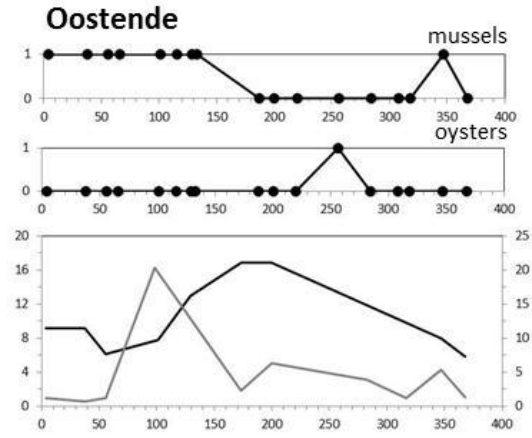
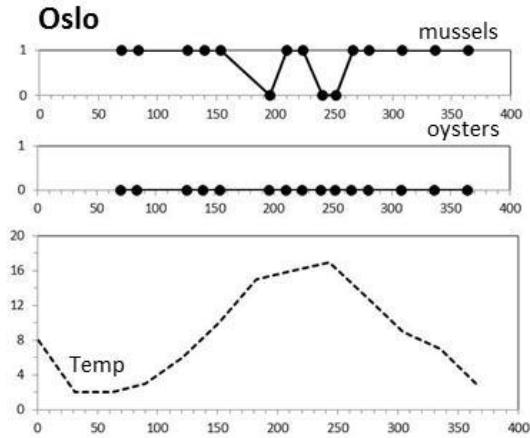


Figure 2. Occurrence of larvae of Pacific oysters (*Crassostrea gigas*), occurrence of mussels (*Mytilus edulis/galloprovincialis*), water temperature (°C; black line; left y-axis) and chlorophyll-a concentrations ($\mu\text{g l}^{-1}$; grey line; right y-axis) at 12 sites within European coastal waters between December 15, 2006 (Day number experiment = 1) and December 18, 2007 (Day number experiment = 368). Presence of larvae in the samples is indicated by 1, their absence by 0. The environmental conditions were determined *in situ* (solid lines) at several stations (i.e., Sylt, Texel, Oostende, Roscoff, Banyuls and Lecce) and derived from satellite images (dotted lines) for the others.



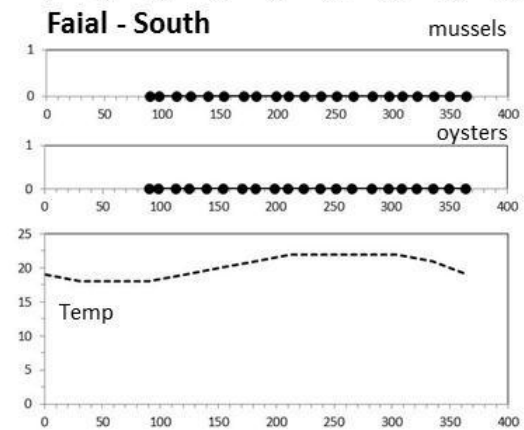
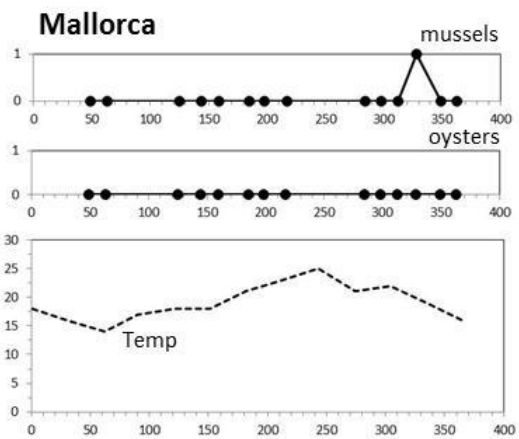
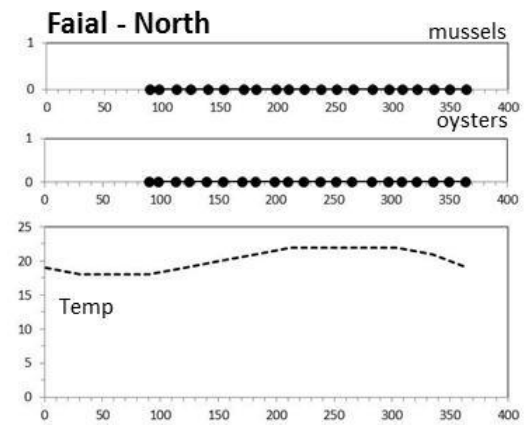
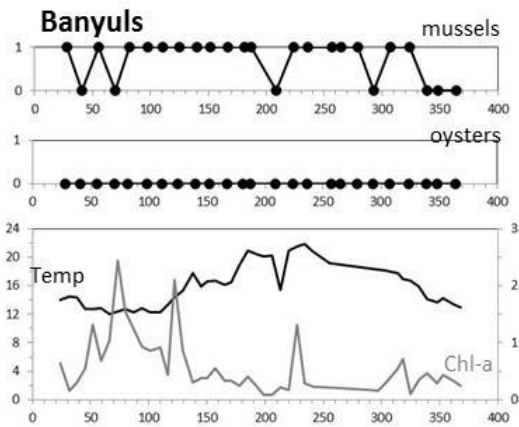
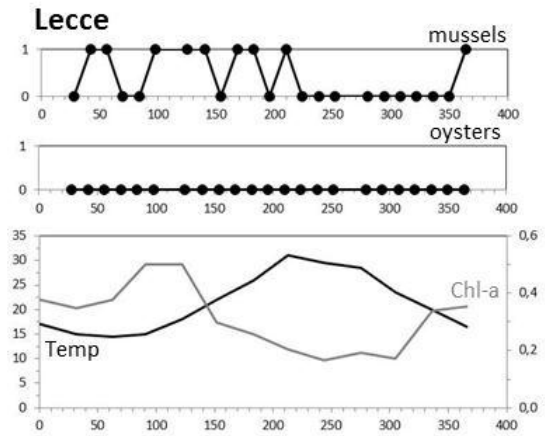
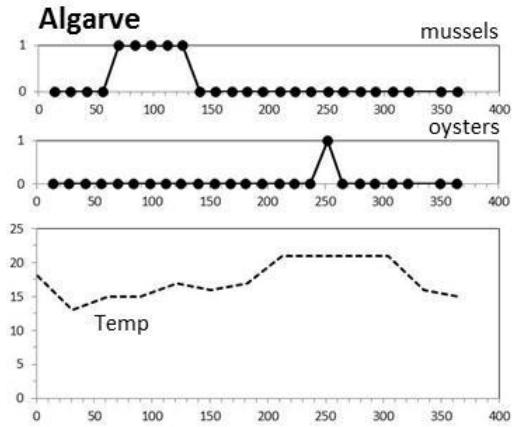


Figure 3. Estimated smoother obtained by the model in H1 (see Table 4) for the occurrence of Pacific oyster (*Crassostrea gigas*) larvae in European coastal waters between December 15, 2006 (Day number experiment = 1) and December 18, 2007 (Day number experiment = 368). The solid line is the smoother (plus the intercept) and the grey area determines the 95% confidence bands. Confidence bands are calculated by adding the estimated smoother and 95% confidence bands, and then applying the logit transformation. The white dots are the observations on presence (value = 1) and absence (value = 0) of larvae of the Pacific oyster at the sampling sites.

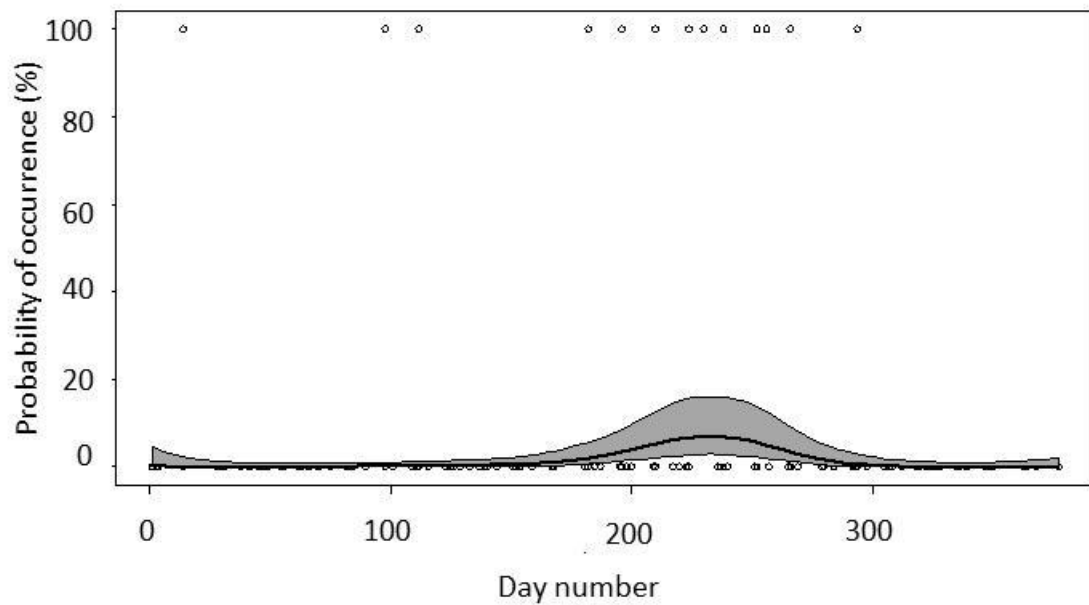


Figure 4. Fitted values on field observations on probability of occurrence of Pacific oyster (*Crassostrea gigas*) larvae as measured at 12 sampling sites in European coastal waters between 15 December 2006 and 18 December 2007, obtained by Generalized Additive Mixed Modelling (GAMM) with a 1-dimensional smoother (see Model H2 in Table 4). Top panel: The vertical axis shows the fitted values (logistic scale) and the horizontal axis the day number (with values between 1 and 368). Bottom panel: The vertical axis shows the fitted values, and the other axis the latitude (from 45°N to 80°N).

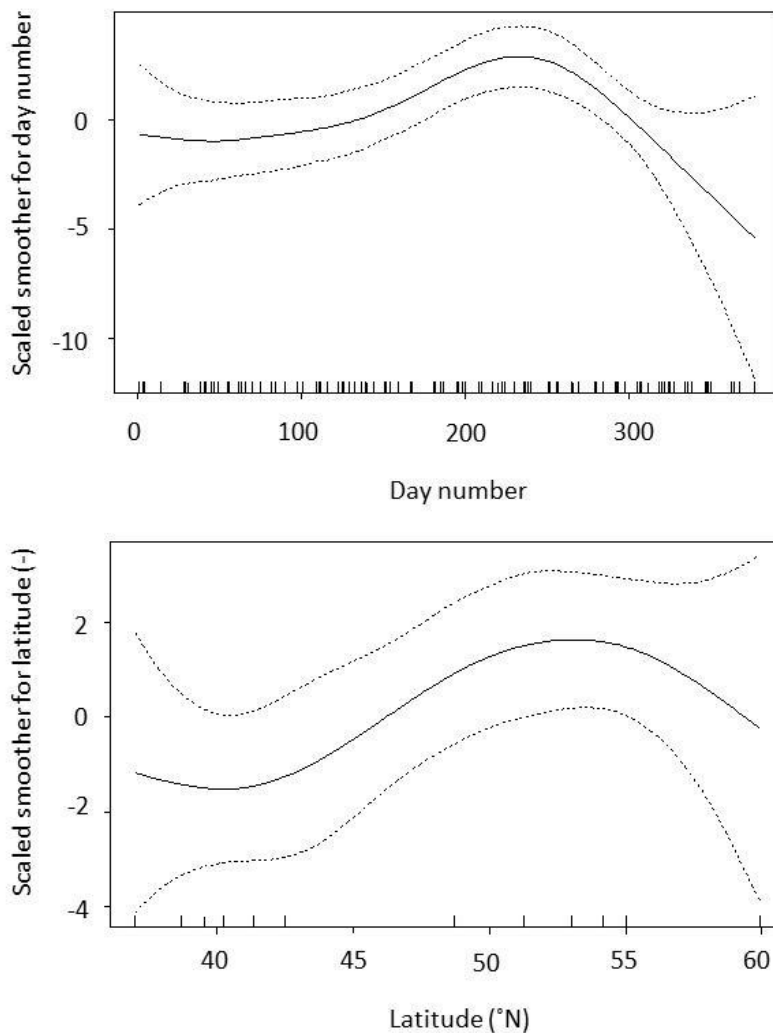


Figure 5. Fitted values on field observations on probability of occurrence of Pacific oyster (*Crassostrea gigas*) larvae as measured at 12 sampling sites in European coastal waters between 15 December 2006 and 18 December 2007, obtained by Generalized Additive Mixed Modelling (GAMM) with a 2-dimensional smoother (see model H3 in Table 4). The vertical axis shows the fitted values (logistic scale) and the horizontal two axes the day number of the experiment (with values between 1 and 368) and the latitude (H2-LAT; from 45°N to 80°N). To fit the two-dimensional smoother, both covariates were scaled to have the same variation, but this did not affect the AIC.

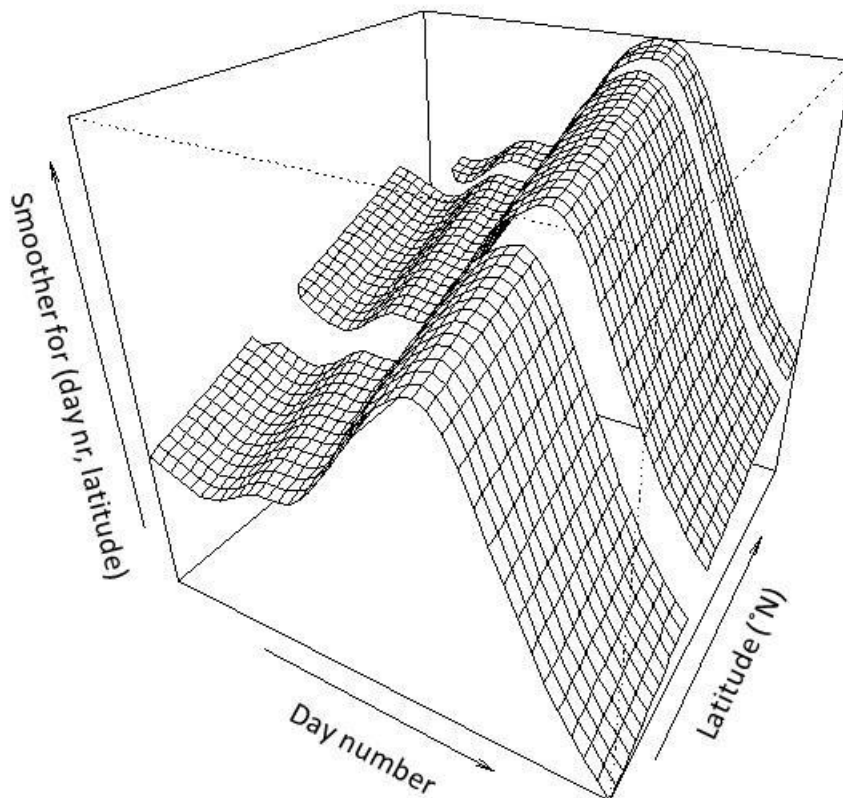


Figure 6. Estimated smoothers obtained by the model in H4 for the presence/absence of mussel (*Mytilus edulis/galloprovincialis*) larvae in European coastal waters. The solid line is the smoother (plus the intercept) and the grey areas determine the 95% confidence bands. Confidence bands were calculated by adding the estimated smoothers and 95% confidence bands, and then applying the logit transformation.

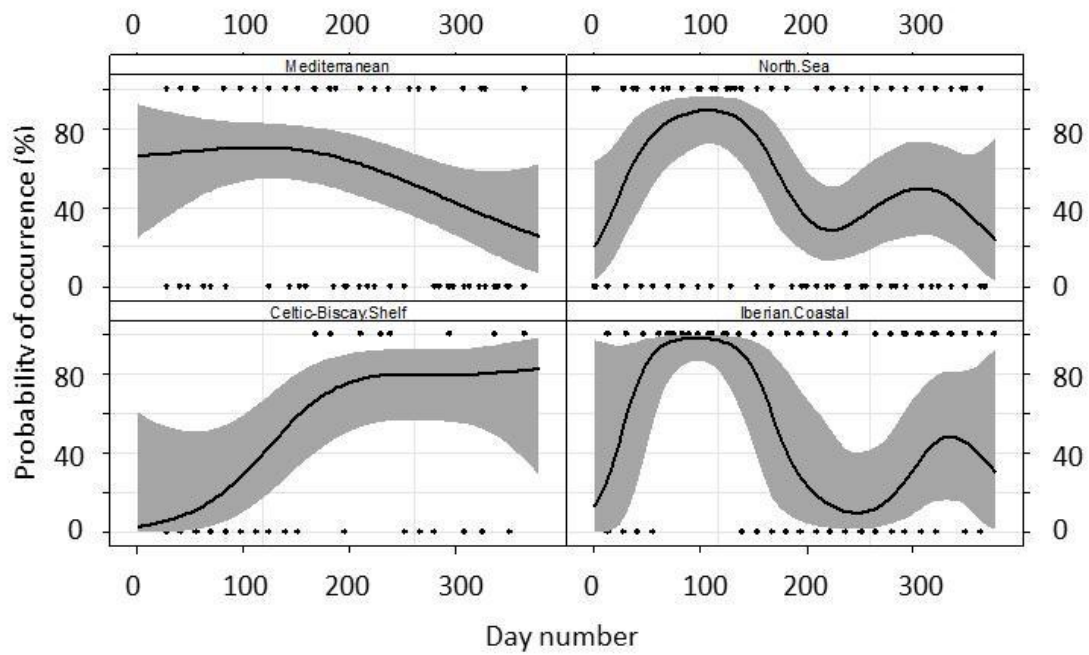


Figure 7. Fitted values on field observations on probability of occurrence of mussel (*Mytilus edulis/galloprovincialis*) larvae as measured at 12 sampling sites in European coastal waters between 15 December 2006 and 18 December 2007, obtained by Generalized Additive Mixed Modelling (GAMM) with a 1-dimensional smoother (see Model H1 in Table 4). The vertical axis shows the fitted values (logistic scale) and the horizontal axis the day number (with values between 1 and 368).

