How can ocean warming at the NW Iberian Peninsula affect mussel aquaculture?

M. Des, M. Gómez-Gesteira, M. de Castro, L. Gómez-Gesteira, M.C. Sousa

PII: S0048-9697(19)36113-3

DOI: https://doi.org/10.1016/j.scitotenv.2019.136117

Reference: STOTEN 136117

To appear in: *Science of the Total Environment*

Received date: 17 October 2019

Revised date: 11 December 2019

Accepted date: 12 December 2019

Please cite this article as: M. Des, M. Gómez-Gesteira, M. de Castro, et al., How can ocean warming at the NW Iberian Peninsula affect mussel aquaculture?, *Science of the Total Environment* (2019), https://doi.org/10.1016/j.scitotenv.2019.136117

How can Ocean warming at the NW Iberian Peninsula affect mussel aquaculture?

M. Des[a,*], M. Gómez-Gesteira[a], M. deCastro[a], L. Gómez-Gesteira[a] and M.C. Sousa[b]

[a] Environmental Physics Laboratory (EphysLab), CIM-UVIGO, Universidade de Vigo, Edificio Campus da Auga, 32004 Ourense, Spain.

[b] CESAM, Physics Department, University of Aveiro, Aveiro 3810-193, Portugal.

[*]Corresponding author.

E-mail address: mdes@uvigo.es (M. Des).

Abstract

Understanding and forecasting future consequences of climate change in mussel aquaculture industry require the assessment of changes in physical parameters which may affect mussel growth. The FLOW module of Delft3D model forced with climatic data was validated and calibrated for the Rías Baixas (NW Iberian Peninsula), one of the areas with the highest mussel production in the world. This model was used to perform historical (1999-2018) and future (2080-2099) projections. Temperature and stratification water conditions were compared in order to determine at what extent climate change can affect mussel production. Thermal stress will increase in a non-homogeneous throughout the water column and the comfort level of mussels will be reduced by more than 60% in the upper layers and more than 30% in deep layers in most of the mussel raft polygons. Water column stratification will increase ~ 5-10 cycles h^{-1} in most of the polygons reducing the vertical exchange of nutrients and oxygen. Hereby changes in water temperature and stratification at the end of the century will not be favorable for mussel growth.

Keywords: climate change; mussel aquaculture; *Mytilus galloprovincialis;* Delft3D; CORDEX; CMPI5

1. Introduction

Climate change is expected to have a significant environmental impact affecting primary production, economy and society. In marine systems, sea-level rise, sea temperature changes, changes in circulation patterns and frequency, acidification, and severity of extreme events will impact the marine ecosystems and therefore, affect fisheries productivity. The analysis of the possible and probable vulnerabilities of these systems in a scenario of climate change allows establishing mitigation and adaptation procedures.

The aquaculture sector is growing rapidly and plays a key role in food production to sustain a growing human population. In recent years, capture fisheries have become relatively stable whereas aquaculture production has increased, providing up to 46.8% of the world combined capture and aquaculture production in 2016, of which 35.9% proceeded from marine aquaculture (FAO, 2018). In the coming years, the aquaculture sector will have to face climate-change impacts trough the management of mitigation and adaptation strategies (Duarte et al., 2017; FAO, 2017). Since changes associated with climate change will not be the same everywhere (Cane et al., 1997), the study of the possible effects on specific areas is essential.

This research is focused on the Rías Baixas (Fig. 1), located on the northwest coast of the Iberian Peninsula in the northern limit of the eastern North Atlantic Upwelling system. They are four flooded incised valleys (Evans and Prego, 2003) of high primary productivity, favoured by their location. The economy of the region depends mainly on the fishing, shellfish gathering and aquaculture sectors. This last one is mostly focused on the extensive culture of *Mytilus galloprovincialis* in mussel rafts. Data from the Spanish Ministry of Agriculture, Fisheries and Food show that approximately 279 000 tons of mussels were produced in 2018 in the region of Galicia, most of them within the Rías Baixas (https://www.pescadegalicia.gal), corresponding to up to 40% of the European and up to 15% of the World aquaculture production of mussels (Aguiar et al., 2017).

Growth rate, mortality and production of mussels are dependent on several environmental factors such as oxygen and phytoplankton availability, water temperature, salinity and ocean acidification among others (Pérez Camacho et al., 1995; Anestis et al., 2007; Mesas and Tarifeño, 2015).

Water temperature is one of the most relevant indexes of the quality of aquatic ecosystems due to its importance for biological and chemical processes and species interactions (Zippay and Helmuth, 2012; Gestoso et al., 2016). It is a critical factor in mussel growth, explaining independently 67% of the differences in growth (Kroeker et al., 2014). Biochemical and physiological rates benefit from moderate warming, but only up to an optimal temperature, which is specific for each species (Gillooly et al., 2002; Anestis et al., 2007). Greater warming beyond that optimal range can cause slower growth and reductions in performance and survival (Hrs-Brenko et al., 1977; Anestis et al., 2010).

As mussel aquaculture in the Galician coast depends on the collection of natural seed, both from intertidal rocky shore and collector ropes, most of the studies analyze its distribution and quality (Blanton et al., 1987; Cáceres-Martínez et al., 1993; Cáceres-Martínez and Figueras, 1998; Fuentes et al., 1998). There are numerous studies focused on the mortality of mussels based on the genetics of individuals (Fuentes et al., 1994; López et al., 2001; Fuentes et al., 2002; Diz and Presa, 2009), as well as studies on the factors that can influence mussel productivity, especially in relation with upwelling patterns (Blanton et al., 1987; Figueiras et al., 2002) the proliferation of harmful algae blooms (Álvarez-Salgado et al., 2008; Spyrakos et al., 2011) and the within-raft variability (Fuentes et al., 2000). Most of the studies on the possible impact of climate change on the Rías Baixas investigate the effects on upwelling events (Casabella et al., 2014; Cordeiro Pires et al., 2016; Sousa et al., 2017, Sousa et al., 2020). Few studies have been found that analyze its possible impact on the mussel production, in particular, Pérez Muñuzuri et al. (2009) conclude that if the upwelling weakens under climate change conditions, mussel production would be reduced and Gestoso et al. (2016) analyze the possible competition between the native *Mytilus galloprovincialis* and the invasive mussel *Xenostrobus securis* in a scenario of global ocean warming.

The present study attempts to determine how climate change will affect the Rías Baixas at the end of the century and its possible impact on mussel culture industry. To achieve this goal, numerical simulations using the FLOW module of Delft3D under imposed conditions from projection data were performed for historical and future periods. Firstly, the skill of the Delft3D-Flow to simulate future estuarine conditions was checked. The characterization of future water temperature and stratification obtained from Delft3D-Flow allows improving our knowledgement about how climate change can affect the mussel productivity in the Rías Baixas by the end of the 21st century.

2. Methodology

2.1. Numerical model

Calculations based on climate projections are an arduous task where different sources of error can appear. First, models must be accurate to reproduce *in situ* measurements when forced with real data. In addition, they must also represent mean conditions when forced with climatic data. Note that the results provided by climatic models for a certain period (e.g., June 2003) do not correspond to the actual conditions for that period, in such a way that a group of years must be averaged to obtain values representative of the climate conditions. Thus, models must be calibrated in two different ways: (i) forcing models with real conditions corresponding to a certain time interval (typically from days to months) and comparing the results with *in situ* data (date-to-date); (ii) forcing models with historical climatic data for longer periods (typically decades) and comparing the mean values with other source at that scale.

The FLOW module of the Delft3D numerical model was used to analyze global warming effects in the Rías Baixas. A detailed description of the numerical model parametrization, implementation and validation for the Galician Rías Baixas can be found in Des et al., (2019).

Two numerical experiments were used in the present manuscript. In the first one (Exp#1 from now on), Delft3D was forced with real conditions and run for the period 2009-2018 to be compared with *in situ* data. This setup was previously used by Des et al. (2019). In the second experiment (Exp#2 from now on), the model was forced with historical climatic data over the period 2009-2018 and values were averaged to be compared with average values provided by Exp#1. Finally, once the accuracy of Delft3D for the area under study was assessed the Exp#2 was extended, comprising the historical (1999 - 2018) and future (2080-2099) period under climate conditions. The RCP8.5 greenhouse gas emission scenario was considered for future projections.

The model uses a mesh covering an area from 41.18ºN to 43.50º N and from 10.00º to 8.33ºW (Fig. 1, rectangle). The horizontal resolution increases gradually from 2200 m x 800 m on the oceanic West boundary to 220 m x 140 m in the Rías Baixas and to 50 m x 77 m in the Minho River estuary. The vertical resolution is 16 sigma layers with top layers refined.

The bathymetry used for numerical simulations was elaborated by compilation from different sources. The bathymetries for the rias of Arousa, Muros and adjacent shelf area were digitalized from nautical charts elaborated by the Spanish Navy Hydrographical Institute. The multibeam-sourced bathymetries of the rias of Vigo and

Pontevedra with a horizontal resolution of 5 m were provided by the General Fishing Secretary, dependent on the Spanish Ministry of Agriculture, Fisheries and Food. Portuguese Navy Hydrographic Institute provided the bathymetry of the Minho estuary. Bathymetry gaps were covered using data from the General Bathymetric Chart of the Oceans (GEBCO, https://www.gebco.net/) which has a spatial resolution of 30 arc seconds.

The oceanic boundary was divided into 127 sections and was forced with water level and transport conditions. Thirteen main tidal harmonic constituents obtained from the model TPXO 7.2 TOPEX/Poseidon Altimetry (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_sF, MM, M_4, MS_4, MN_4) were prescribed as astronomical forcing. Salinity and water temperature (transport conditions, from now on), were specified per layer. Transport conditions for Exp#1 were imposed using daily data from the operational Atlantic-Iberian Biscay Irish-Ocean Physics Reanalysis, with a horizontal resolution of 1/12º and a vertical resolution of 50 sigma coordinate levels. Data are available through the Copernicus Marine Service website (http://marine.copernicus.eu). For the Exp#2, the transport conditions were retrieved from the GCM MOHC-HadGEM2-Es GCM in the framework of phase 5 of the Coupled Model Intercomparison (CMIP5) project.

As surface boundary conditions (air temperature, relative humidity, net solar radiation, surface pressure and wind), Exp#1 used hourly data from MeteoGalicia Weather Research and Forecasting Model, with a resolution of 4 km, Exp #2 were obtained from the MOHC-HadGEM2-Es-RCA4 RCM in the framework of the Coordinated Regional Climate Downscaling Experiment (CORDEX) project. MOHC-HadGEM2-Es-RCA4 is the RCM, which better reproduces historical climate conditions in the area under study, as stated in Sousa et al. (2020).

Freshwater discharges were imposed as fluvial open boundary conditions. Minho River discharge data was provided by the Confederación Hidrográfica Miño-Sil, where the Verdugo-Oitavén, Lérez, Ulla, and Umia river discharge data were retrieved from the MeteoGalicia database for Exp#1. In the Exp#2, the climatologic river discharge data were obtained by accessing to the Hype Web portal. In this setup, a reduction of 25% in river discharges and the RCP8.5 greenhouse gas emission scenario were considered for future projections, following the most pessimistic predictions (https://hypeweb.smhi.se/explore-water/climate-impacts/europe-climate-impacts/).

Both experiments were run for July and August using a spin-up period of two weeks.

2.2. Processing of numerical data

The skill of numerical simulations carried out using Exp#1 to reproduce thermohaline variables was evaluated through root mean square error (RMSE) and bias indicators. Weekly *in situ* vertical salinity and temperature profiles at 38 sampling stations distributed within the four rias (Fig. 2) were compared with the predicted values date-to-date. These *in situ* data were collected using a SBE25 CTD at 38 field stations (8 at the Ría de Muros, 11 at the Ría de Arousa, 11 at the Ría de Pontevedra and 8 at the Ría de Vigo, Fig. 2) and were downloaded from the Instituto Tecnolóxico para o control do Medio Mariño de Galicia (INTECMAR) website (www.intecmar.gal). Thompson Tau test, with α = 0.1, was used to detect and remove outliers in data. Additionally, gaps were filled using a cubic interpolation.

Statistical analysis over the historical period for each atmospheric and oceanic variable was carried out. Atmospheric dataset from MOHC-HadGE2-Es-RCA4 RCM was compared with ERA-Interim dataset while oceanic data from MOHC-HadGE2-Es GCM were compared with *in situ* data from Cabo Silleiro buoy (Fig. 1). This statistical analysis shows a good agreement for all variables except for the air temperature, for which a bias of 2 ºC was observed. Thus, a reduction of 2 ºC was applied to predicted air temperature data before entering it into the Delft3D-Flow model.

To assess the impact of the climate change on the aquaculture sector of the Rías Baixas hourly model outputs were used to characterize 44 points located within areas of mussel rafts (referred as mussel raft polygons).

Thermohaline variables were used to analyze the stratification using the Brunt-Väisälä frequency (N). Hourly Brunt-Väisälä frequency was averaged obtaining a representative value for historical ($\overline{N}^H$) and future periods ($\overline{N}^F$).

3. Results and discussion

3.1. Skill of Delft3D- Flow

The capability of the numerical model (Exp#1) to reproduce thermohaline variables in the rias was evaluated by the average of bias and RMSE for each station (Fig. 2). Then, the mean RMSE and bias for each station are averaged for every ria (Table 1). The model overestimates salinity (positive bias values), being the bias for the rias of Pontevedra and Vigo close to zero. Regarding water temperature, the model overestimates *in situ* data for the Ría de Muros and underestimates it in the rias of Pontevedra and Vigo. In the Ría de Arousa, the bias is almost zero. Both bias and RMSE values are similar to those obtained by Des et al. (2019) for the same area using the same numerical model and set up.

Additionally, Figure 3 shows both measured (blue line) and computed (red line) salinity and water temperature vertical profiles for a station located in the middle part of each ria during July and August averaged from 2009 to 2018. Shadows represent measured and numerical standard deviations. These vertical profiles show the accuracy of numerical simulations to reproduce field data.

Once the accuracy of the model to reproduce *in situ* data was assessed using the configuration of Exp#1, the average temperature field of Exp#1 and Exp#2 for July-August was compared over the period 2009 to 2018. Top layer temperature outputs for both experiments are depicted in Fig. 4a and Fig. 4b, respectively. Fig. 4c shows the difference between these two outputs ($\Delta T = T^{Exp\#2} - T^{Exp\#1}$). The histogram of Fig. 4d shows that more than 90% of the ΔT values are within the range -1 to 1 ºC. In addition, ΔT tends to be positive, mostly between 0 and 0.75 ºC with an average bias of 0.40 ºC (Fig. 4c). Despite the different nature of data sources used to force the model, both configurations provide, in general, a similar pattern, although numerical results from Exp#2 tend to overestimate the results of Exp#1. The agreement between both setups shows that Delft3D-Flow forced with climatic data can be accurately used to simulate future temperature conditions in the Rías Baixas.

3.2 Physical parameters that can affect mussel production under the future climate warming

Different physical parameters that can change in the future affecting mussel production, like water temperature and stratification, will be analyzed in next subsections. Temperature will be responsible of mussels comfort conditions related to thermal stress while stratification will be a proxy to assess the capability of the water column to allow vertical movements and, hence, the vertical exchange of nutrients and oxygen.

3.2.1. Water temperature

Water temperature is the main physical parameter that affects the mussel productivity of the Rías Baixas. Mussels survive in a wide range of temperature, being able to withstand high temperatures (Goslin, 1992), although the optimal range for mussel growth is narrower. The mechanisms of mussels' adaptation to the water temperature increase may be limited by their physiological limits. Some studies indicate that mussel has a limited capacity to modify their physiological tolerance limit and that they are experiencing temperatures close to it (Tomanek, 2008; Ioannou et al., 2009). The optimal range for *Mytilus galloprovincialis* growth was determined between 14 and 20 ºC following previous research on the effect of water temperature on the growth and mortality of mussels (https://longline.co.uk/meta/List; Hrs-Brenko et al., 1977; Anestis et al., 2007; Peharda et al., 2007; Sánchez-Lazo and Martínez-Pita, 2012; Kroeker et al., 2014). The comfort index was considered as the percentage of time in which water temperature remains within that optimal range. Mussel comfort is 80-100% at the upper layers (0-6 m) for all mussel rafts for the historical period (Fig. 5a). However, comfort at these upper layers will be considerably reduced by the end of the century (Fig. 5b) with a percentage ranging from 40% to 60% in the outer areas of the rias and from 20% to 40% in the middle part, especially near the north shore. The lower values (0-20%) are observed near the mouths of the rivers, possibly due to the shallowness of the zone. Changes in comfort ($\Delta C = \text{Comfort}^F - \text{Comfort}^H$ in Fig. 5c) will be always negative, reaching values < -60% in most of the points, which results in a remarkable loss in the comfort conditions for the future, which can eventually cause biological stress and reduce mussel growth.

The comfort index at deep layers (6-12 m, Fig. 6) shows a similar pattern than at surface ones. For the historical period, it is in the interval 80-100% (Fig. 6a) for all mussel rafts, equal than previously calculated for surface layers (Fig. 5a), and it is also reduced for the future projections (Fig. 6b). In these future projections the comfort index ranges from 60% to 100% in the outer areas of the rias, from 40% to 80% in the middle part and from 0% to 40% near the mouths of the rivers. These results show that the shallow areas will be more affected by ocean warming. Regarding ΔC (Fig. 6c), values are always negative but only reach < -60% near the river mouths, in general deep layers lose fewer comfort conditions than the upper ones. The locations were lower ΔC are observed correspond to the areas most affected by summer upwelling. The upwelled water, whose current temperature tends to range from 12 to 14 ºC (Blanton et al., 1987; Prego et al., 2001; Alvarez et al., 2005), mitigate the water temperature rise in deep layers.

As for the future thermal comfort at deep layers (Fig. 6b), in general, it will be higher than at surface layers (Fig. 5b). This fact can have a negative impact on the productivity since, at present, the upper part of the ropes (first meters) tends to be more productive than the lower part (Fuentes et al., 2000; Figueras, 2007). On the other hand, although all of the locations show negative values, the reduction in future comfort will affects less to the outermost stations (Figs. 5b and 6b) and mainly in the deep layers. In summary, the outermost stations, where productivity is higher at present (Navarro et al., 1991; Pérez Camacho et al., 1995; Figueras, 2007) will be affected differently by ocean warming depending on the depth. The temperature rise of the deep layers will not have a very significant impact in comfort conditions while temperature will increase at surface layers leading to more stressed conditions for mussel growth.

Finally, it should be noted that this index only refers to thermal comfort not to the concentration of nutrients or oxygen of the upwelled water or to the light conditions.

3.2.2. Water stratification

Water stratification is another important physical parameter to analyze the future survival of mussel aquaculture activities within the Rías Baixas. Water stratification reduces vertical exchange and is usually related to the occurrence of harmful algae blooms (Álvarez-Salgado et al., 2008; Pitcher et al., 2010). The Brunt-Väisälä frequency was calculated and averaged through the water column to determine the stratification of the rias. The Brunt-Väisälä frequency (Fig. 7) shows that the innermost part of the rias is more stratified than the outermost one as it can be observed both for the historical (Fig. 7a) and future (Fig. 7b) period.

The percentage of change in future stratification relative to the historical one is shown in Figure 7c. This percentage is calculated as $\Delta\bar{N} = 100 \times (\bar{N}^F - \bar{N}^H)/\bar{N}^H$, where the superscripts F and H refer to the future and historical period respectively. An increase in the future stratification is observed in most of the points, being the most significant changes (between 10% and 15%) located in the external part of the south coast of the rias of Pontevedra and Arousa. In general, the percentage of change decreases for the northern shores and, especially, in the areas most influenced by river discharge. Values can even be negative (less stratified conditions in the future) in the area affected by the Ulla River, the river with the highest runoff in the area and, at a lesser extent, in the areas of influence of Umia River (also in the ria of Arousa) and Tambre River (Ría de Muros) (Fig. 1). The same behaviour was not observed in Vigo and Pontevedra due to the long distance between the mouth of the river and the sampling stations. The pattern is possibly related to the circulation pattern of the rias, where the outer area is more influenced by oceanic conditions while the inner part is controlled by river discharge. It was also observed that the thermocline will be deeper. According to Sousa et al. (2020), the future deepening of the thermocline will counteract the increase in upwelling favorable winds and will induced thermal stratification. The stratification will be more marked in the outer part of the rias while the future reduction in river discharge (https://hypeweb.smhi.se/explore-water/climate-impacts/europe-climate-impacts/) will diminish the haline stratification of the inner part of the rias. The projected increase in stratification, especially at the outer stations (the most productive ones according to Navarro et al. (1991), Pérez Camacho et al. (1995) and Figueras, (2007) will constitute a clear drawback for mussel exploitation. It will limit the vertical exchange of nutrients and oxygen and will give rise to the probable intensification of harmful algae blooms, increasing the number of days that mussel raft polygons are inactive.

Conclusions

Numerical simulations using Delft3D-FLOW under historical and future RCP8.5 conditions were used to analyze how climate change will affect the Rías Baixas at the end of the 21st century and its possible impact on the main physical parameters (water temperature and stratification) that affect mussel aquaculture productivity.

The general rise in water temperature will increase the time during which mussels will be subjected to thermal stress conditions. The impact on the water column will not be homogeneous, upper layers will be more affected than the deep ones. The comfort level of mussels will be reduced by more than 60% in the upper layers in most of the mussel raft polygons. Regarding deeper layers, the mussels comfort conditions will be reduced but less than in the upper layers.

Water column stratification will increase in most of the stations, particularly in the outer areas of the rias. A reduction in stratification is only observed in the areas most affected by river discharge~~s~~. This increase in water stratification will limit the vertical exchange of nutrients and oxygen and will give rise to less favorable conditions for aquaculture.

The present work helps to improve knowledge about how climate change can affect mussel industry in the Rías Baixas. Analysis of physical parameters shows that changing the location to most suitable areas to ensure aquaculture of mussel raft polygons may help to mitigate the effect of climate change in mussel productivity. The outer areas of the rias seem to be more advisable for new locations.

Acknowledgments

The authors thank the *Instituto Tecnolóxico para o Control do Medio Mariño de Galicia* (INTECMAR), for the production and distribution of *in situ* salinity and water temperature data, the *Confederación Hidrográfica Miño-Sil*, *MeteoGalicia and* the Hype Web portal for the distribution of river discharge data, the Copernicus Marine Service website for the distribution of IBI data, *Puertos del Estado* for the distribution of tidal data and data from Cape Silleiro buoy, the General Fishing Secretary, the Spanish Navy Hydrographical Institute and General Bathymetry Chart of the Oceans for the bathymetry data, the WCRP's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups for producing and making available their models' outputs that can be downloaded at http://www.cordex.org/.

M.D. was supported by the Xunta de Galicia through a doctoral grant (ED481A-2016/218). MCS was supported by national funds (OE), through FCT, I.P., in the scope of the framework contract foreseen in the numbers 4, 5 and 6 of the article 23, of the Decree-Law 57/2016, of August 29, changed by Law 57/2017, of July 19. This study was partially funded under the project MarRISK (0262_MARRISK POCTEP 2014-2020) co-funding by the FEDER.This work was partially supported by Xunta de Galicia under project ED431C 2017/64-GRC (Grupos de Referencia Competitiva) and by

Ministerio de Economia y Competitividad under project CGL2015-66681-R, co-founded by European Regional Development Fund (ERDF).

References

Aguiar, E., Piedracoba, S., Álvarez-Salgado, X.A., Labarta, U., 2017. Circulation of water through a mussel raft: clearance area vs. idealized linear flows. Reviews in Aquaculture 9, 3–22. https://doi.org/10.1111/raq.12099

Alvarez, I., deCastro, M., Gomez-Gesteira, M., 2005. Inter- and intra-annual analysis of the salinity and temperature evolution in the Galician Rías Baixas–ocean boundary (northwest Spain). Journal of Geophysical Research 110. https://doi.org/10.1029/2004JC002504

Álvarez-Salgado, X.A., Labarta, U., Fernández-Reiriz, M.J., Figueiras, F.G., Rosón, G., Piedracoba, S., Filgueira, R., Cabanas, J.M., 2008. Renewal time and the impact of harmful algal blooms on the extensive mussel raft culture of the Iberian coastal upwelling system (SW Europe). Harmful Algae 7, 849–855. https://doi.org/10.1016/j.hal.2008.04.007

Anestis, A., Lazou, A., Pörtner, H.O., Michaelidis, B., 2007. Behavioral, metabolic, and molecular stress responses of marine bivalve *Mytilus galloprovincialis* during long-term acclimation at increasing ambient temperature. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 293, R911–R921. https://doi.org/10.1152/ajpregu.00124.2007

Anestis, A., Pörtner, H.O., Karagiannis, D., Angelidis, P., Staikou, A., Michaelidis, B., 2010. Response of *Mytilus galloprovincialis* (L.) to increasing seawater temperature and to marteliosis: Metabolic and physiological parameters.

Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 156, 57–66. https://doi.org/10.1016/j.cbpa.2009.12.018

Blanton, J.O., Tenore, K.R., Castillejo, F., Atkinson, L.P., Schwing, F.B., Lavin, A., 1987. The relationship of upwelling to mussel production in the rias on the western coast of Spain. Journal of Marine Research 45, 497–511.

Cáceres-Martínez, J., Robledo, J.A.F., Figueras, A., 1993. Settlement of mussels *Mytilus galloprovincialis* on an exposed rocky shore in Ria de Vigo, NW Spain. Mar. Ecol. Prog. Ser. 93, 195–198. https://doi.org/10.3354/meps093195

Cáceres-Martínez, J., Figueras, A., 1998. Distribution and abundance of mussel (*Mytilus galloprovincialis* Lmk) larvae and post-larvae in the Ria de Vigo (NW Spain). Journal of Experimental Marine Biology and Ecology 229, 277–287. https://doi.org/10.1016/S0022-0981(98)00059-8

Cane, M.A., Clement, A.C., Kaplan, A., Kushnir, Y., Pozdnyakov, D., Seager, R., Zebiak, S.E., Murtugudde, R., 1997. Twentieth-Century Sea Surface Temperature Trends. Science 275, 957–960. https://doi.org/10.1126/science.275.5302.957

Casabella, N., Lorenzo, M.N., Taboada, J.J., 2014. Trends of the Galician upwelling in the context of climate change. Journal of Sea Research 93, 23–27. https://doi.org/10.1016/j.seares.2014.01.013

Cordeiro Pires, A., Nolasco, R., Rocha, A., Ramos, A.M., Dubert, J., 2016. Climate change in the Iberian Upwelling System: a numerical study using GCM downscaling. Climate Dynamics 47, 451–464. https://doi.org/10.1007/s00382-015-2848-y

Des, M., deCastro, M., Sousa, M.C., Dias, J.M., Gómez-Gesteira, M., 2019. Hydrodynamics of river plume intrusion into an adjacent estuary: The Minho

River and Ria de Vigo. Journal of Marine Systems 189, 87–97. https://doi.org/10.1016/j.jmarsys.2018.10.003

Diz, A.P., Presa, P., 2009. The genetic diversity pattern of *Mytilus galloprovincialis* in Galician Rías (NW Iberian estuaries). Aquaculture 287, 278–285. https://doi.org/10.1016/j.aquaculture.2008.10.029

Duarte, C.M., Wu, J., Xiao, X., Bruhn, A., Krause-Jensen, D., 2017. Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Front. Mar. Sci. 4:100. https://doi.org/10.3389/fmars.2017.00100

Evans, G., Prego, R., 2003. Rias, estuaries and incised valleys: is a ria an estuary? Marine Geology 196, 171–175. https://doi.org/10.1016/S0025-3227(03)00048-3

FAO (Ed.), 2017. Adaptation strategies of the aquaculture sector to the impacts of climate change. Rome.

FAO (Ed.), 2018. Meeting the sustainable development goals, The state of world fisheries and aquaculture. Rome.

Figueiras, F.G., Labarta, U., Reiriz, M.F., 2002. Coastal upwelling, primary production and mussel growth in the Rías Baixas of Galicia, in: Sustainable Increase of Marine Harvesting: Fundamental Mechanisms and New Concepts. Springer, pp. 121–131.

Figueras, A., Caceres-Martinez, J., 2007. Cultivo del mejillón en Galicia. In: FiguerasA, editor. Biología y Cultivo del Mejillón (*Mytilus galloprovincialis*) en Galicia.Madrid: Consejo Superior de Investigaciones Científicas, 19-43

Fuentes, J., Reyero, I., Zapata, C., Alvarez, G., 1994. Production traits of the mussel *Mytilus galloprovincialis* cultured in Galicia (NW of Spain) : relative effects of source of seed and growing environment. Aquaculture 122, 19–31.

Fuentes, J., Molares, J., Villalba, A., 1998. Growth, mortality and parasitization of mussels cultivated in the Ría de Arousa (NW Spain) from two sources of seed: intertidal rocky shore vs. collector ropes. Aquaculture 162, 231–240.

Fuentes, J., Gregorio, V., Giráldez, R., Molares, J., 2000. Within-raft variability of the growth rate of mussels, *Mytilus galloprovincialis*, cultivated in the Ría de Arousa (NW Spain) 14.

Fuentes, J., López, J.L., Mosquera, E., Vázquez, J., Villalba, A., Álvarez, G., 2002. Growth, mortality, pathological conditions and protein expression of *Mytilus edulis* and *M. galloprovincialis* crosses cultured in the Ría de Arousa (NW of Spain). Aquaculture 213, 233–251. https://doi.org/10.1016/S0044-8486(02)00046-7

Gestoso, I., Arenas, F., Olabarria, C., 2016. Ecological interactions modulate responses of two intertidal mussel species to changes in temperature and pH. Journal of Experimental Marine Biology and Ecology 474, 116–125. https://doi.org/10.1016/j.jembe.2015.10.006

Gillooly, James.F., Charnov, E.L., West, G.B., Savage, V.M., Brown, J.H., 2002. Effects of size and temperature on developmental time. Nature 417, 70–73. https://doi.org/10.1038/417070a

Gosling, Elizabeth (ed.), 1992. The mussel Mytilus: ecology, physiology, genetics and culture. Amsterdam: Elsevier.

Hrs-Brenko, M., Claus, C., Bubic, S., 1977. Synergistic effects of lead, salinity and temperature on embryonic development of the mussel Mytilus galloprovincialis. Mar. Biol. 44, 109–115. https://doi.org/10.1007/BF00386951

Ioannou, S., Anestis, A., Pörtner, H.O., Michaelidis, B., 2009. Seasonal patterns of metabolism and the heat shock response (HSR) in farmed mussels Mytilus galloprovincialis. Journal of Experimental Marine Biology and Ecology 381, 136–144. https://doi.org/10.1016/j.jembe.2009.09.014

Kroeker, K.J., Gaylord, B., Hill, T.M., Hosfelt, J.D., Miller, S.H., Sanford, E., 2014. The Role of Temperature in Determining Species' Vulnerability to Ocean Acidification: A Case Study Using *Mytilus galloprovincialis*. PLoS ONE 9, e100353. https://doi.org/10.1371/journal.pone.0100353

López, J.L., Mosquera, E., Fuentes, J., Marina, A., Vázquez, J., Alvarez, G., 2001. Two-dimensional gel electrophoresis of *Mytilus galloprovincialis*: differences in protein expression between intertidal and cultured mussels. Mar. Ecol. Prog. Ser. 224, 149–156. https://doi.org/10.3354/meps224149

Mesas, A., Tarifeño, E., 2015. Temperaturas letales superiores para el mejillón, *Mytilus galloprovincialis* (Lamarck, 1819), en la costa de Chile central. Latin American Journal of Aquatic Research 11.

Navarro, E., Iglesias, J.I.P., Perez Camacho, A., Labarta, U., Beiras, R., 1991. The physiological energetics of musselsd (*Mytilus galloprovincialis* Lmk) from different cultivation rafts in the Ria de Arosa (Galicia, N.W. Spain). Aquaqulture 94, 197–212.

Peharda, M., Župan, I., Bavčević, L., Frankić, A., Klanjšček, T., 2007. Growth and condition index of mussel *Mytilus galloprovincialis* in experimental integrated aquaculture. Aquaculture Res 38, 1714–1720. https://doi.org/10.1111/j.1365-2109.2007.01840.x

Pérez Camacho, A., Labarta, U., Beiras, R., 1995. Growth of mussels (*Mytilus edulis galloprovincialis*) on cultivation rafts: influence of seed source, cultivation site and phytoplankton availability. Aquaculture 138, 349–362. https://doi.org/10.1016/0044-8486(95)01139-0

Pérez Muñuzuri, V., Fernández Cañamero, M., Gómez Gesteira, J.L., 2009. Evidencias e impactos do cambio climático en Galicia. Consellería de Medio Ambiente e Desenvolvemento Sostible, Santiago de Compostela.

Pitcher, G.C., Figueiras, F.G., Hickey, B.M., Moita, M.T., 2010. The physical oceanography of upwelling systems and the development of harmful algal blooms. Progress in Oceanography 85, 5–32. https://doi.org/10.1016/j.pocean.2010.02.002

Prego, R., Dale, A.W., deCastro, M., Gómez-Gesteira, M., Taboada, J.J., Montero, P., Villareal, M.R., Pérez-Villar, V., 2001. Hydrography of the Pontevedra Ria: Intra-annual spatial and temporal variability in a Galician coastal system (NW Spain). Journal of Geophysical Research 106, 19845–19857. https://doi.org/10.1029/2000JC000775

Sánchez-Lazo, C., Martínez-Pita, I., 2012. Effect of temperature on survival, growth and development of *Mytilus galloprovincialis* larvae. Aquaculture Research 43, 1127–1133. https://doi.org/10.1111/j.1365-2109.2011.02916.x

Sousa, M.C., deCastro, M., Alvarez, I., Gomez-Gesteira, M., Dias, J.M., 2017. Why coastal upwelling is expected to increase along the western Iberian Peninsula over the next century? Science of The Total Environment 592, 243–251. https://doi.org/10.1016/j.scitotenv.2017.03.046

Sousa, M.C., Ribeiro, A., Des, M., Gomez-Gesteira, M., deCastro, M., Dias, J.M., 2020. NW Iberian Peninsula coastal upwelling future weakening: Competition between wind intensification and surface heating. Science of The Total Environment 703, 134808. https://doi.org/10.1016/j.scitotenv.2019.134808

Spyrakos, E., González Vilas, L., Torres Palenzuela, J.M., Barton, E.D., 2011. Remote sensing chlorophyll a of optically complex waters (rias Baixas, NW Spain):

Application of a regionally specific chlorophyll a algorithm for MERIS full resolution data during an upwelling cycle. Remote Sensing of Environment 115, 2471–2485. https://doi.org/10.1016/j.rse.2011.05.008

Tomanek, L., 2008. The Importance of Physiological Limits in Determining Biogeographical Range Shifts due to Global Climate Change: The Heat‐ Shock Response. Physiological and Biochemical Zoology 81, 709–717. https://doi.org/10.1086/590163

Zippay, M.L., Helmuth, B., 2012. Effects of temperature change on mussel, *Mytilus*. Integrative Zoology 7, 312–327. https://doi.org/10.1111/j.1749-4877.2012.00310.x

Figure Legends:

Fig. 1. (a) Location of the study area. (b) The box indicates the modeled area. The black square indicates the location of Cabo Silleiro buoy. The black dots indicate the location of the stations used to perform the vertical profiles. Contour bathymetry lines (shown in gray) were elaborated using the General Bathymetric Chart of the Oceans (GEBCO) from the British Oceanographic Data Centre (BODC).

Fig. 2. Mean values of bias (upper number) and RMSE (lower number) obtained comparing Delft3D-Flow predicted and measured weekly vertical profiles of salinity (a) and water temperature (b) for August 2009 to 2018. Red dots indicate that the model overestimates *in situ* data, positive bias. Blue dots indicate that the model underestimates *in situ* data, negative bias. Dot size indicates the bias percentile.

Fig. 3. Measured (blue line) and computed (red line) vertical profiles of salinity (upper row) and water temperature (lower row) in a sampling station located in the middle part of the rias of Muros, Arousa, Pontevedra and Vigo during July- August from 2009-2018. Shadows represent measured and numerical standard deviations.

Fig. 4. Delft3D-Flow predicted water temperature (upper layer) using Exp#1 (a) and using Exp#2 (b) for July- August over 2009- 2018. Difference between predicted water temperature using Exp#1 and Exp#2 (Exp#2 - Exp#1) (c). Histogram showing the frequency of the temperature differences shown in c (d).

Fig. 5. Percentage of time (July-August) during which mussels are within the comfort temperature range (14-20 ºC) for the historical period (a), the future (b) and the difference (Future-Historical, c) considering surface layers [0-6] m.

Fig. 6. Percentage of time (July-August) during which mussels are within the comfort temperature range (14-20 ºC) for the historical period (a), the future (b) and the difference (Future-Historical, c) considering deep layers (6-12] m.

Fig. 7. Predicted mean Brunt-Väisälä frequency for July and August using Exp#2 at mussel raft polygons for (a) historical (1999-2019) period, (b) future (2080-2099) and (c) percentage of change in predicted future Brunt-Väisälä frequency respect to the historical one.

Table Legends:

Table 1. Model accuracy in reproducing *in situ* data of salinity and water temperature in each ria calculated averaging the values of all stations per ria.

Ria	**Salinity**		**Temperature (ºC)**	
	Bias	RMSE	Bias	RMSE
Muros	0.26	0.33	0.25	0.90
Arousa	0.16	0.21	0.01	0.88
Pontevedra	0.06	0.14	-0.63	1.06
Vigo	0.09	0.14	-0.32	0.89

Table 1

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Analysis of climate change impact on mussel aquaculture using numerical predictions
- Water temperature and stratification will increase
- The comfort level of mussels will be reduced, especially in surface layers
- Changing the mussel raft polygons location may mitigate the climate change impact

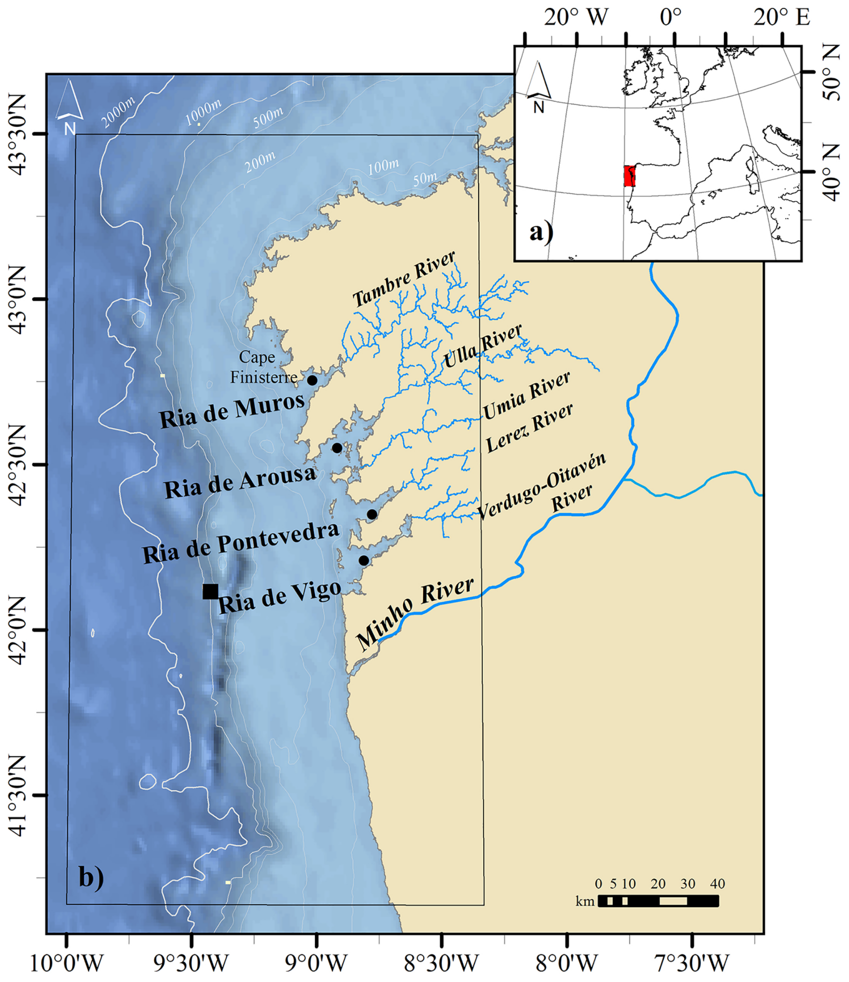

20° W
0°
20° E
50° N
40° N
N
a)
N
2000m
1000m
500m
200m
100m
50m
43°30'N
43°0'N
42°30'N
42°0'N
41°30'N
Tambre River
Ulla River
Umia River
Lerez River
Verdugo-Oitavén River
Minho River
Cape Finisterre
Ria de Muros
Ria de Arousa
Ria de Pontevedra
Ria de Vigo
b)
0 5 10 20 30 40
km
10°0'W
9°30'W
9°0'W
8°30'W
8°0'W
7°30'W

Figure 1

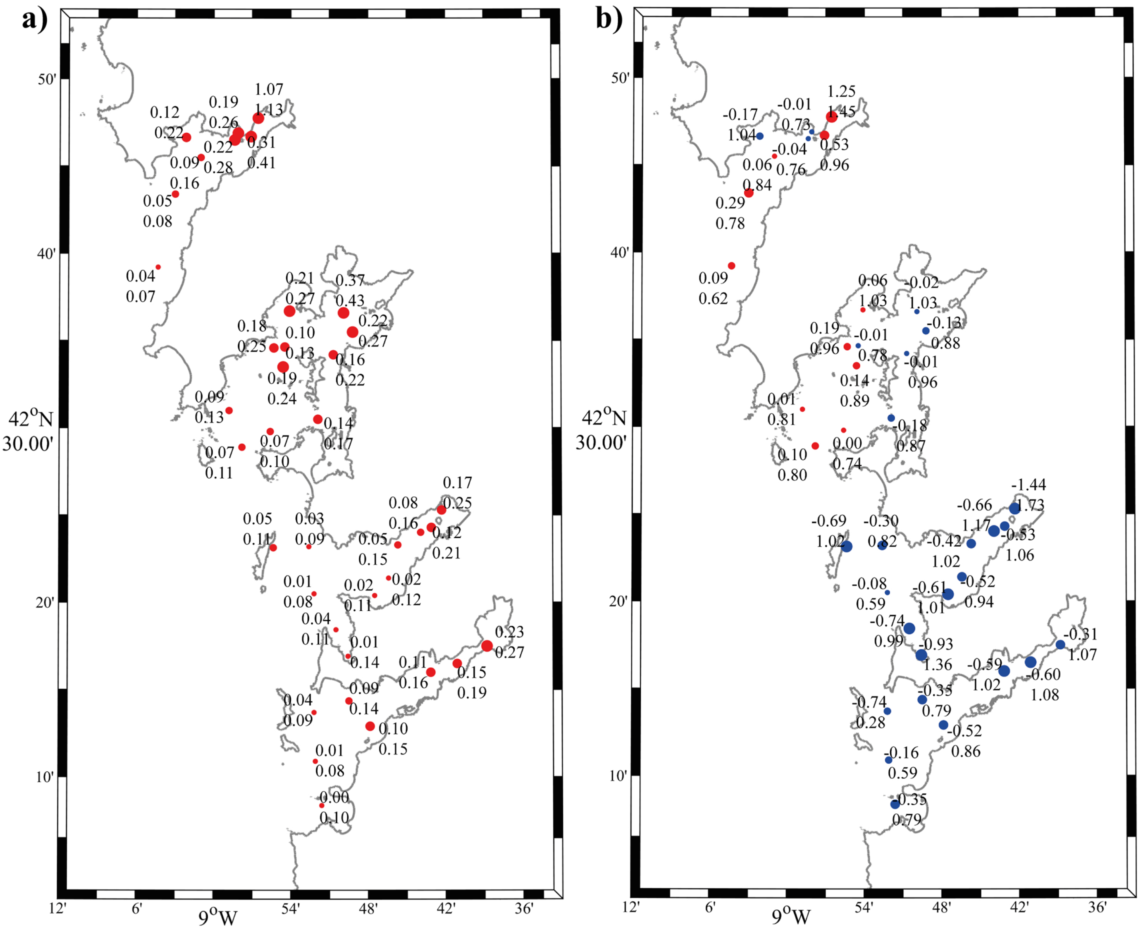
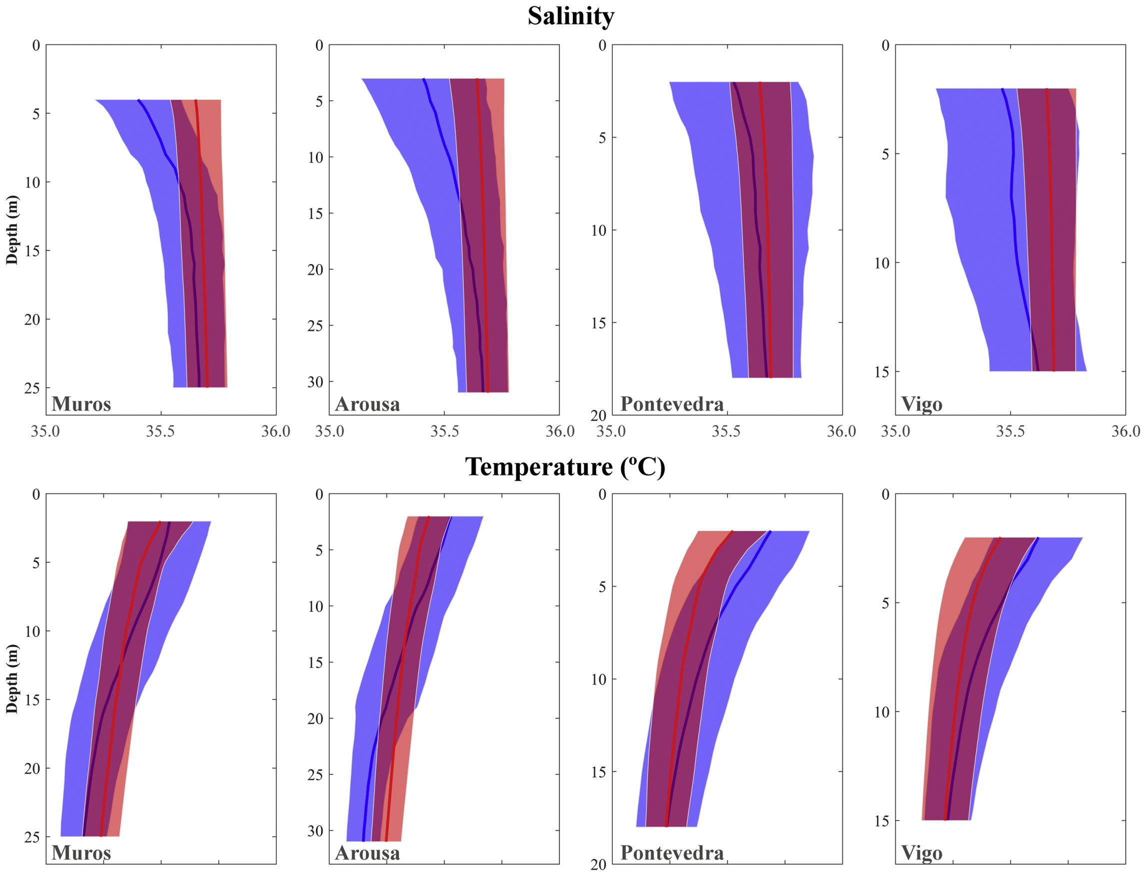

a)
50'
40'
42°N 30.00'
20'
10'
12'
6'
9°W
54'
48'
42'
36'
0.12
0.22
0.19
0.26
1.07
1.13
0.22
0.28
0.31
0.41
0.09
0.16
0.05
0.08
0.04
0.07
0.21
0.27
0.37
0.43
0.22
0.27
0.18
0.25
0.10
0.13
0.16
0.22
0.19
0.24
0.09
0.13
0.14
0.17
0.07
0.10
0.07
0.11
0.17
0.25
0.08
0.16
0.12
0.21
0.05
0.11
0.03
0.09
0.05
0.15
0.01
0.08
0.02
0.11
0.02
0.12
0.04
0.11
0.01
0.14
0.23
0.27
0.11
0.16
0.15
0.19
0.09
0.14
0.04
0.09
0.10
0.15
0.01
0.08
0.00
0.10
b)
50'
40'
42°N 30.00'
20'
10'
12'
6'
9°W
54'
48'
42'
36'
-0.17
1.04
-0.01
0.73
1.25
1.45
-0.04
0.76
0.53
0.96
0.06
0.84
0.29
0.78
0.09
0.62
0.06
1.03
-0.02
1.03
-0.13
0.88
0.19
0.96
-0.01
0.78
-0.01
0.96
0.14
0.89
0.01
0.81
-0.18
0.87
0.00
0.74
0.10
0.80
-1.44
1.73
-0.66
1.17
-0.53
1.06
-0.69
1.02
-0.30
0.82
-0.42
1.02
-0.08
0.59
-0.61
1.01
-0.52
0.94
-0.74
0.99
-0.93
1.36
-0.31
1.07
-0.59
1.02
-0.60
1.08
-0.35
0.79
-0.74
0.28
-0.52
0.86
-0.16
0.59
-0.35
0.79

Figure 2



Salinity
Temperature (ºC)
Depth (m)
Muros
Arousa
Pontevedra
Vigo
0
5
10
15
20
25
30
35.0
35.5
36.0
12
14
16
18
20

Figure 3

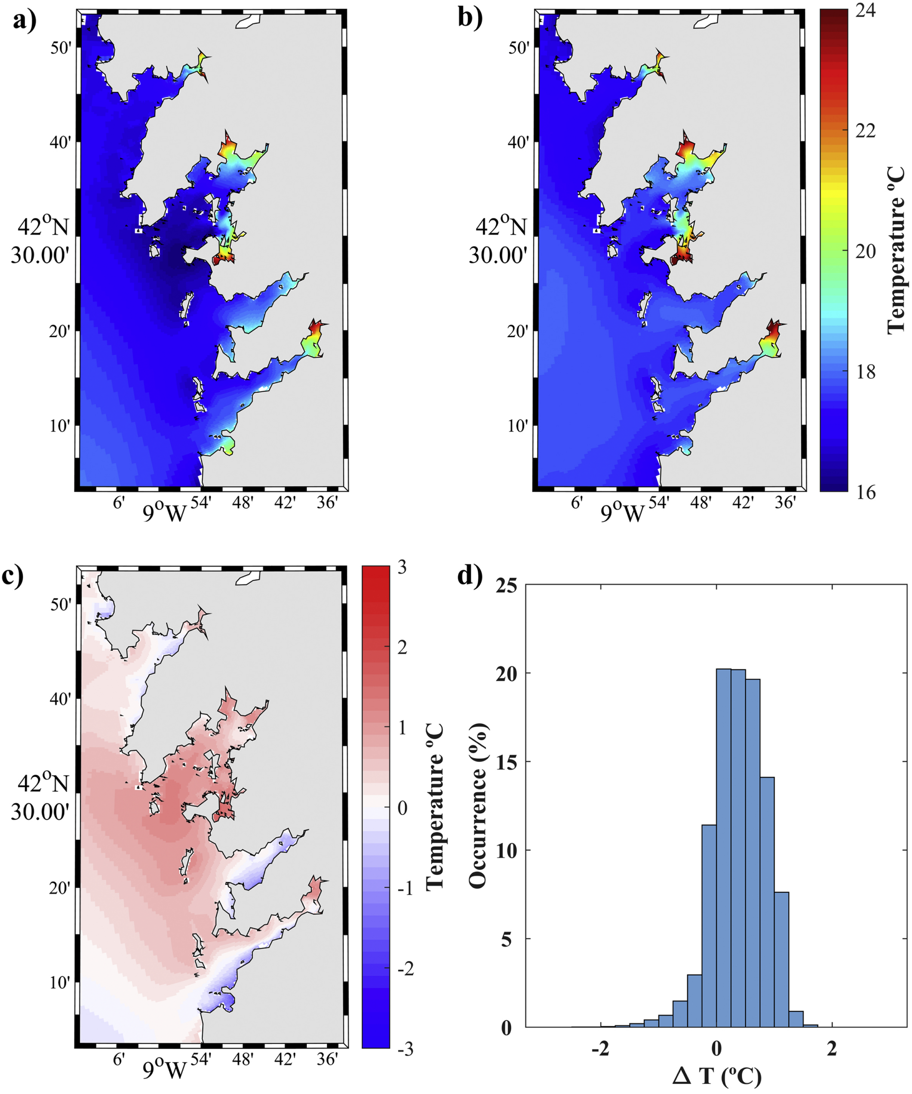

a)
b)
c)
d)
50'
40'
42°N
30.00'
20'
10'
6'
9°W
54'
48'
42'
36'
24
22
20
18
16
Temperature °C
3
2
1
0
-1
-2
-3
25
20
15
10
5
0
-2
2
Occurrence (%)
Δ T (°C)

Figure 4

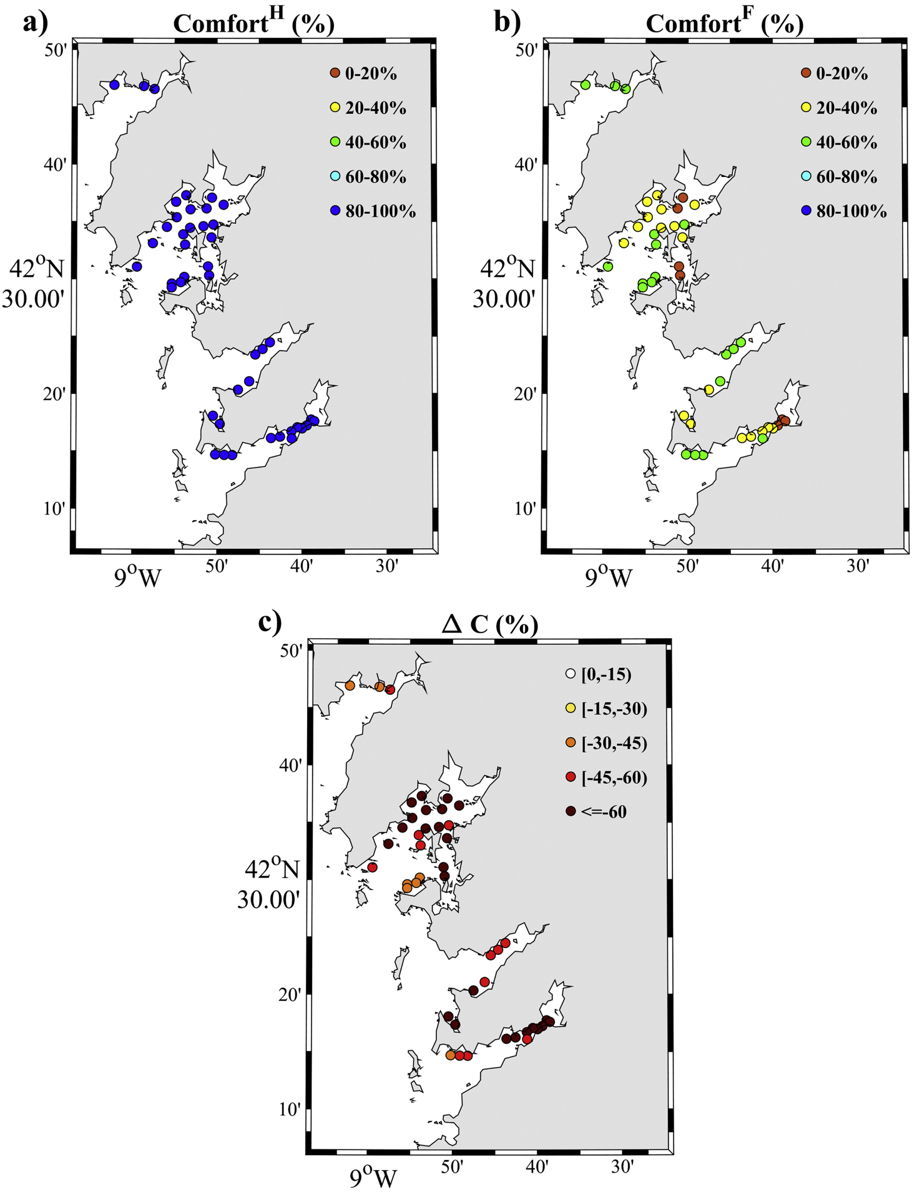

a)
Comfort^H (%)
0-20%
20-40%
40-60%
60-80%
80-100%
50'
40'
42^{o}N
30.00'
20'
10'
9^{o}W
50'
40'
30'
b)
Comfort^F (%)
0-20%
20-40%
40-60%
60-80%
80-100%
50'
40'
42^{o}N
30.00'
20'
10'
9^{o}W
50'
40'
30'
c)
Δ C (%)
[0,-15)
[-15,-30)
[-30,-45)
[-45,-60)
<=-60
50'
40'
42^{o}N
30.00'
20'
10'
9^{o}W
50'
40'
30'

Figure 5

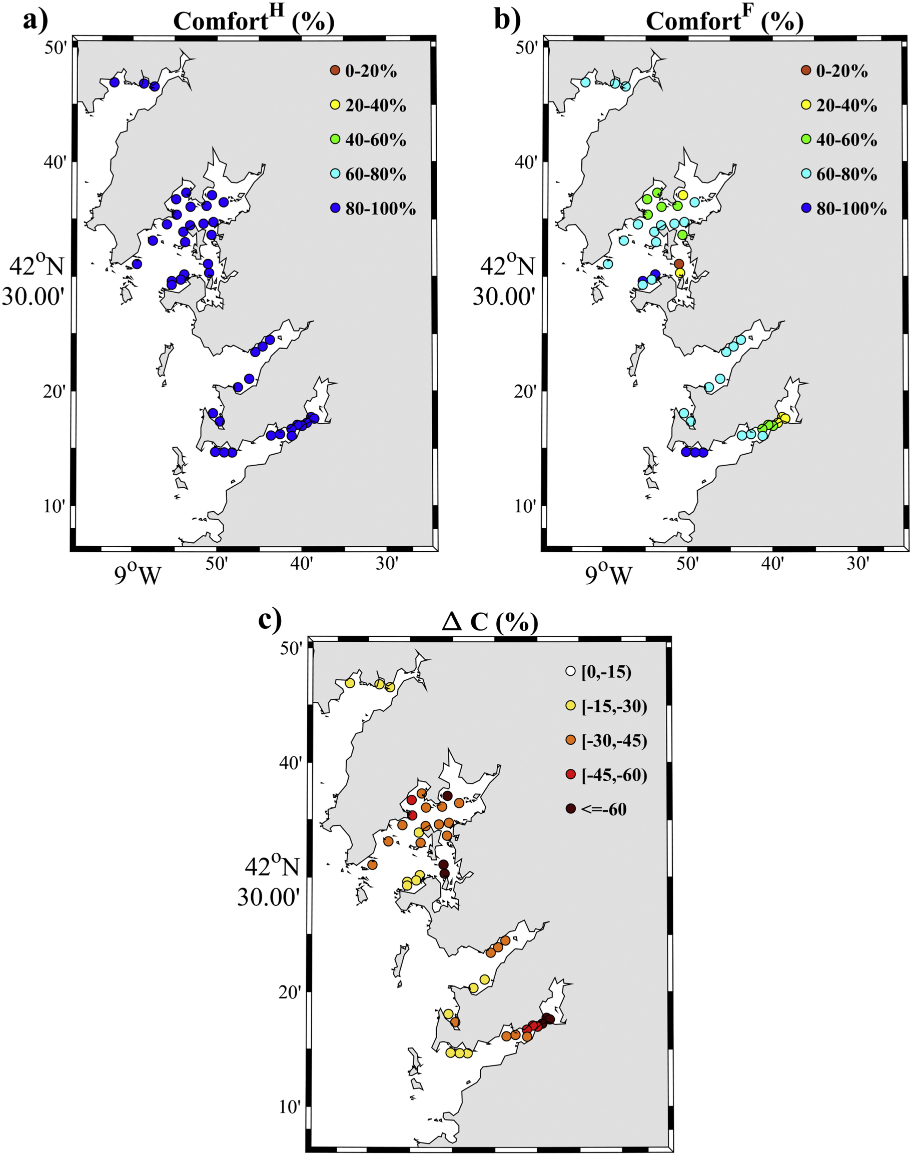

a)
Comfort^H (%)
0-20%
20-40%
40-60%
60-80%
80-100%
b)
Comfort^F (%)
0-20%
20-40%
40-60%
60-80%
80-100%
c)
Δ C (%)
[0,-15)
[-15,-30)
[-30,-45)
[-45,-60)
<=-60
50'
40'
42°N
30.00'
20'
10'
9°W
50'
40'
30'

Figure 6

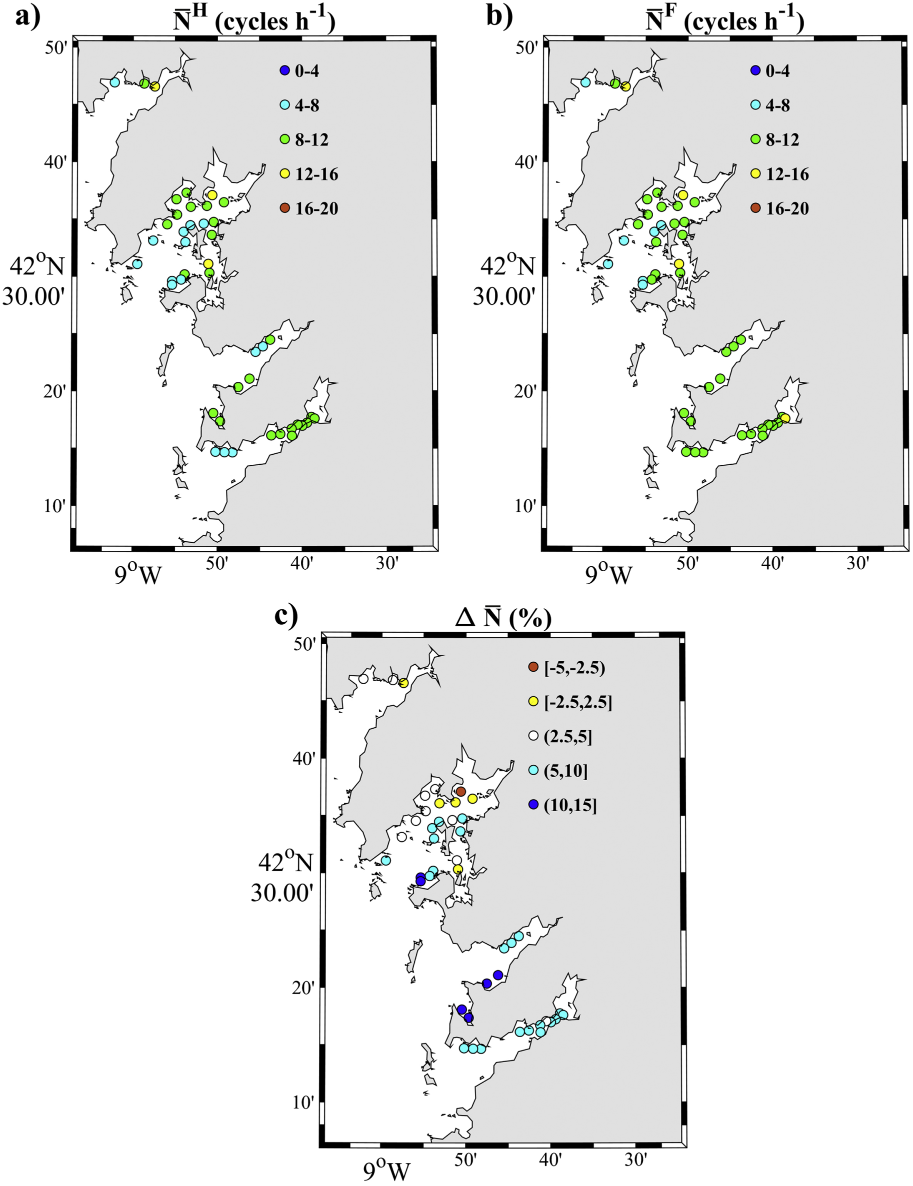

a)
$\bar{N}^H$ (cycles h^{-1})
0-4
4-8
8-12
12-16
16-20
b)
$\bar{N}^F$ (cycles h^{-1})
0-4
4-8
8-12
12-16
16-20
c)
$\Delta\ \bar{N}$ (%)
[-5,-2.5)
[-2.5,2.5]
(2.5,5]
(5,10]
(10,15]
50'
40'
42°N 30.00'
20'
10'
9°W
50'
40'
30'

Figure 7