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Offshore aquaculture as climate change adaptation in coastal areas: sea surface temperature trends in the Western Mediterranean Sea

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ABSTRACT: The warming of the Mediterranean Sea surface is currently estimated to have been 0.4°C per decade for the period 1985–2006, and the increase in water temperature may have negatively affected marine aquaculture, e.g. by decreasing productivity. Development of aquaculture without adequate planning can lead to unsustainable economic feasibility due to future climate stressors. In this sense, offshore mariculture could be an alternative for mitigating the effect of coastal warming. The purpose of this study was to evaluate the suitability of the coastline in terms of global warming and sea surface temperature trends in locations where fish aquaculture is currently being developed, as well as the spatial changes of thermal anomalies up to 30 km from the coast, during the last 31 yr in the western Mediterranean (Spanish coast). This study was conducted using EU Copernicus Marine Service Information, covering the period 1981–2018, with a spatial resolution of 4 × 4 km. The results show that, over the last decade, the Mediterranean coastal environment off the Iberian Peninsula has experienced an increase in temperature of around 1°C due to global change, with a clear latitudinal pattern modified by mesoscale oceanographic processes. The development of offshore aquaculture at some latitudes mitigates the extreme aestival effects on surface water temperatures. Strategic plans for aquaculture development should be able to forecast and incorporate future climate projections and local oceanographic conditions, and offshore aquaculture may provide an alternative in some regions, depending on local oceanographic conditions.

KEY WORDS: Climate change · Marine aquaculture · Offshore aquaculture · Marine spatial planning

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1. INTRODUCTION

In 2001, the Third Assessment Report from the Intergovernmental Panel on Climate Change warned that the climate within the Mediterranean Basin may become warmer and drier in the 21st century (Joos et al. 2001). More recently, a report published by MedECC (Cramer et al. 2019) indicated that accelerated climate change has exacerbated the existing environmental problems in the Mediterranean Basin, caused by a combination of land use changes, increasing pollution, and declining biodiversity. This report indicates that the warming of the Mediterranean Sea surface is currently estimated to have been 0.4°C per decade for the period 1985–2006, with the main rises occurring primarily during May, June, and July.

Due to the importance of temperature in many biological and ecological processes, this warming is affecting marine ecosystem services, including the support for aquaculture (FAO 2018). Oceanographic conditions will probably play a large role in determining which locations and species could be used by the expanding aquaculture sector, as ambient water temperature is a primary determinant of the growth

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rates of ectothermic fish and therefore the overall production efficiency of farms (Klinger et al. 2017). Nonetheless, the potential effects of increased surface temperature on coastal aquaculture are somewhat controversial, as they can be both negative and positive. Overall, the biological response to the increased water temperature affecting marine aquaculture, at the organism level, is likely to involve aerobic capacity, reproduction, maturation and development, growth rate, nutrition, immune function, and the timing of seasonal activities (Barange et al. 2018, Reid et al. 2019). Diseases of cultured fish and shellfish will be affected by a changing thermal regime, but in a largely unpredictable manner. However, when exposed to thermal stress, cultured species are likely to be more susceptible to disease (Rosa et al. 2012). Warmer conditions may also allow the establishment of exotic diseases (Gubbins 2006). Despite these negative side effects, increased growth rates due to warmer temperatures have also been predicted, particularly for molluscs (Reid et al. 2019, Hu et al. 2021). Increased temperatures could also generate the possibility of rearing warmer-water species at higher latitudes (Callaway et al. 2012), but that could involve the introduction of exotic species with potentially negative effects on native fauna. From a general perspective, the marine aquaculture production potential, based on thermal tolerance and growth data, shows an overall greater probability of decline worldwide over the coming decades. Finfish appear more resilient than bivalves in the changing climate, but other factors could limit growth and production for both taxonomic groups in the future, such as the higher frequency, extent and magnitude of harmful algal blooms, disease outbreaks, and hypoxia (Froehlich et al. 2018).

Currently, most of the intensive marine finfish aquaculture production in the Mediterranean takes place in floating cages, at depths of between 15 and 50 m, and within 10 km of the shore (Trujillo et al. 2012). These floating circular structures are an open-sea system, fully connected with the surrounding environment, and the same type is used throughout the Mediterranean (Rosa et al. 2012). Gilthead sea bream *Sparus aurata* and European sea bass *Dicentrarchus labrax* are the most important species produced in these systems along the Mediterranean coast. The total 2018 production of sea bream and sea bass in Europe and the rest of the Mediterranean was 246 839 and 196 573 t, respectively (FAO 2020).

The main fish-fattening cage facilities in the Mediterranean were developed at the end of the 20th and beginning of the 21st centuries. These semi-offshore aquaculture systems were positioned according to the prevailing environmental conditions at that time, including temperature range, as this facilitated greater and more profitable production (Ferreira et al. 2007). However, in terms of average temperature, seasonality, and variability of surface temperature oscillation in coastal environments, this environmental scenario has been altered. Due to climate change and competition for space with other activities in coastal waters, the development of new mariculture in coastal zones could be greatly limited (Dempster & Sanchez-Jerez 2008). If mariculture is to play a major role in meeting the rising demand for fish, it is essential that, in the near future, this sector identifies adequate localities for fish production in terms of thermal stability. With respect to coastal spatial planning and the definition of allocated zones for aquaculture, it is therefore key to consider climate change as part of the multi-criteria decision-making process (Sanchez-Jerez et al. 2016), making a prior analysis of the vulnerability of aquaculture to climate change at different scales (Soto et al. 2018). In the 21st century, considering the effect of climate change on physical and environmental factors will be central in fish farming site selection in addition to the efficiency and economy of the aquaculture operations. However, in general terms, marine spatial planning procedures are lacking legal tools for continuing adaptation and there is a need for flexibility in the legal conditions for the relocation of aquaculture facilities in the context of climate change. A regular review of marine spatial plans is therefore necessary to promote the adaptability of marine aquaculture to climate change, which in turn requires adaptive governance (Craig 2019). It will also be necessary to adapt the environmental management of aquaculture, since climate change may synergistically produce an increase in the ecological footprint of this activity on the surrounding ecosystems (Sarà et al. 2018a).

Therefore, haphazard development of aquaculture without adequate planning can lead to unsustainable environmental and economic feasibility due to future climate stressors, and thermal stability will be a determining factor in future aquaculture production. To date, coastal waters have been the most desirable location for marine aquaculture, but offshore mariculture could be an alternative for decreasing the competition for space and is also likely to mitigate the effect of coastal warming (Marra 2005, Gentry et al. 2017).

The purpose of this study was to analyse sea surface temperature (SST) trends in the period 1988–2018 in the western Mediterranean (Spanish coast), focusing on the suitability of the coastline fish aquaculture facilities with regard to global warming. For this purpose, the climatic mean, thermal variability, and thermal anomalies over the last 2 decades (1999–2008 and 2009–2018) were compared against the mean temperature from 1988 to 1998 along the Spanish Mediterranean coast. This period was when most of the marine aquaculture projects were implemented and the temperature range of the different water bodies was initially considered. The complex interactions between users of coastal areas often leave little space for aquaculture, particularly since this production method requires coastal waters with specific environmental and water-quality characteristics. Indeed, areas with a higher probability of thermal instability are a major barrier to sustainable production. As offshore mariculture may be a viable alternative (Lester et al. 2018), we investigated the spatial changes of thermal anomalies up to 30 km from the coast in each of the areas housing existing aquaculture facilities along the latitudinal gradient of the Spanish Mediterranean coast. To date, this aspect has not been analysed in depth.

2. MATERIALS AND METHODS

This was a large-scale study that encompassed the entire Mediterranean coastline of the Iberian Peninsula. The study area was situated between latitudes 42.5 and 36° N and longitudes 6° W to 5.7° E (Fig. 1). Using the aquaculture industry database of the Spanish Ministry of Agriculture, Fisheries and Food (https://servicio.pesca.mapama.es/acuivisor/), the fish farms along the Mediterranean were geo-referenced and labelled with a letter from A to R, so that they remained anonymous. Some facilities located in the same pixel were eliminated.

This study was conducted using EU Copernicus Marine Service Information. The temperature data used in this study are publicly available and provided by the Copernicus Marine Environment Monitoring Service (CMEMS), which has been operational since May 2015 (EU Copernicus Marine Service Information). In this work, SST products from the data set SST_MED_SST_L4_REP_OBSERVATIONS_010_021 were employed. The Consiglio Nazionale delle Ricerche, Istituto di Scienze dell'Atmosfera e del Clima–Gruppo di Oceanografia da Satellite, Italy (CNR-ISAC-GOS) has reprocessed Pathfinder V5.3 (PFV53) AVHRR data (Walker & Wilkin 1998) covering the period 1981–2018 and combined this information with a bias-corrected version of the CMEMS NRT L4 data up to 2017 to provide a full time series of consistent daily gap-free maps (L4) at the original PFV53 resolution (0.0417° × 0.0417°, i.e. 4 km × 4 km). The data are interpolated using an optimal interpolation algorithm applied on the original Pathfinder grid at 0.0417° × 0.0417° spatial resolution and are representative of night-time SST values (00:00 UTC). Further details can be found in Pisano et al. (2016) and Buongiorno Nardelli et al. (2013).

The selected data set ranges from 1988 to 2018, constituting a 31 yr time series, which is large enough for anomaly analysis. The 4 km × 4 km spatial resolution is also suitable for performing the analysis at the fish farm scale. Employing the Matlab program, a matrix of surface temperature data was processed for which the thermal anomaly was calculated. In order to holistically visualise the results of the anomaly analyses, a geospatial representation system was used to produce several different maps to display the data. First, 3 time periods were differentiated: 1988–1998 (11 yr), 1999–2008 (10 yr), and 2009–2018 (10 yr). For each period, the mean and standard deviation (SD) of the SST were calculated. The different period lengths (i.e. 11 vs. 10 yr) did not affect the statistical behaviour, as we found negligible differences in both SD and mean values for the whole region when comparing the sta-

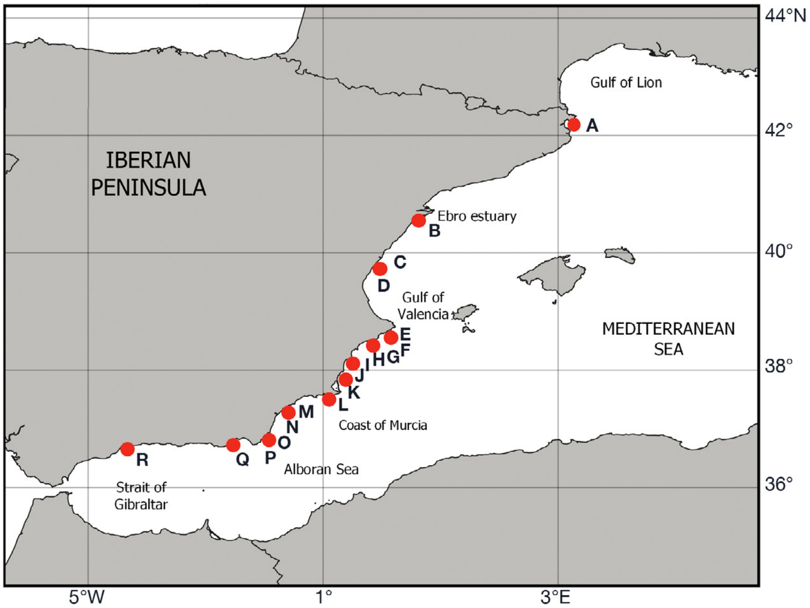

Fig. 1. Study area along the eastern Iberian peninsula. Red dots indicate sampled fish farm sites, labelled with individual letters (A–R)

tistics of both an 11 and a 10 yr reference period. The data were represented using the Mercator projection to assess the geographical variation of those statistics for each particular period and the thermal stability of the periods. From this information, 2 maps of thermal anomalies were also obtained, using the period 1988–1998 as a reference for comparing to 1999–2008 and 2008–2018. By doing so, we provide a first insight into the overall dynamics of SST during these 31 yr. In particular, our purpose is to show the increasing trend of SST at a regional scale, also highlighting the transitional thermal behaviour from 1999 to 2008 where the SST increase started to be more noticeable. Additionally, we also computed the SST SD maps for all 3 periods considered. These spatial patterns exhibit the SST variability either over 11 or 10 yr, respectively, and the increasing trend observed in this parameter was a noticeable feature to be linked to our analysis of thermal instability within the region.

To be able to make an in-depth analysis of the temporal changes in temperature, and to compare latitudinal changes, farms at sites A, D, I, M, and R were selected (see Fig. 1 for locations). Once the data had been extracted, seasonally adjusted time series were run for each data set taken from 1988 to 2018 and the linear fit was obtained. A 10-sample (i.e. 10 d) median filter was applied on the time series to minimise the noise effect on SST values. The locations were selected on the basis of their relevance as sea bream and sea bass production areas and their distribution along a latitudinal gradient wide enough to be able to compare changes in mean temperature trends along the Spanish Mediterranean coastline over the time series analysed.

As offshore aquaculture represents an alternative scenario, we also tested the effect that distance from the coast had on the temperature along the longitudinal gradient. To do this, the thermal anomalies from 18 aquaculture facilities distributed throughout our study area were analysed for the period 2009–2018, using the period 1988–2008 as a reference. From the coast, a straight line was drawn in the direction of the open sea, passing through the location of the cages and extending a total of 6 pixels (i.e. an average distance of 30 km). The thermal anomaly gradient was analysed as an annual mean and according to seasons: summer (July–September) and winter (January–March). The R Studio software package was used to perform linear regression adjustments using the 'lm()' function (https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/lm), and the data were represented using GGPLOT2 (Wickham 2016).

3. RESULTS

3.1. Latitudinal gradient: a comparison between decades

Overall, the thermal anomaly trend along the Mediterranean coastline of the Iberian Peninsula is positive. Between 1999 and 2008 (Fig. 2a), the surface thermal anomaly was around 0.4°C, although there was an elevated thermal anomaly in the area of the Gulf of Valencia (39° N) and along the coast of Tarragona (41° N). In the second period, from 2009 to

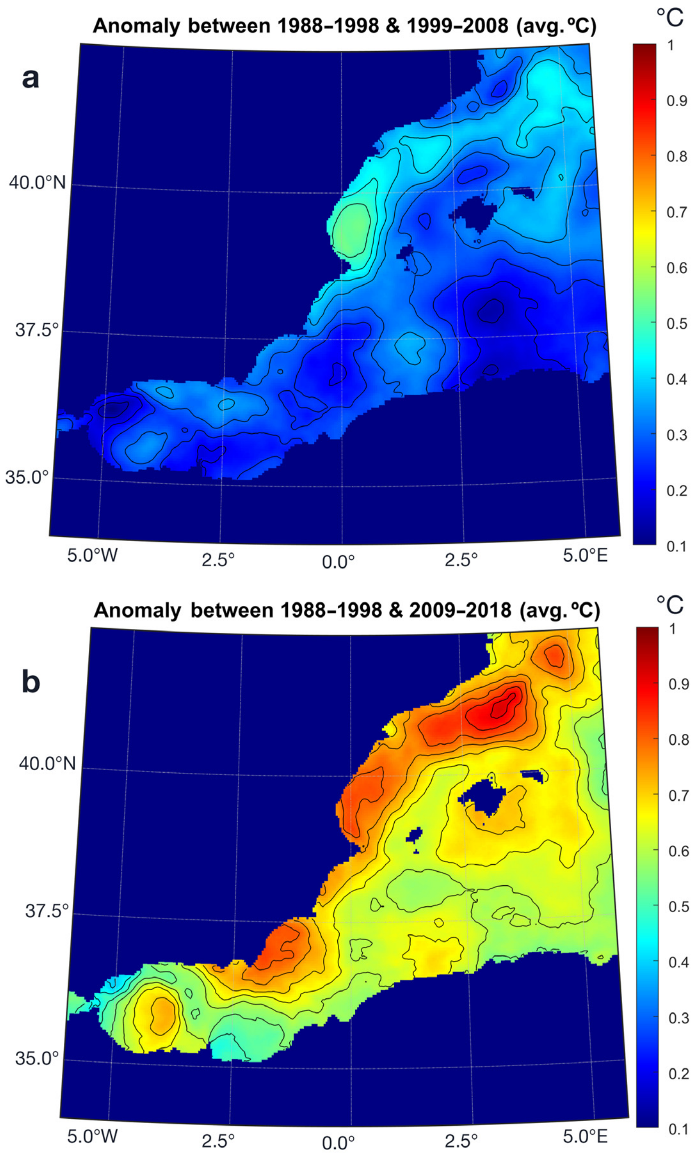

Fig. 2. Thermal anomaly for the period (a) 1999–2008 compared to 1988–1998 and (b) 2009–2018 compared to 1988–1998. Generated and provided by Copernicus Marine Service and Consiglio Nazionale delle Ricerche–Gruppo di Oceanografia da Satellite (CNR–GOS), Rome

2018 (Fig. 2b), the thermal anomalies were more pronounced. The warming intensified along the Mediterranean coastline, with the exception of the Ebro estuary area (40.8° N), where the value of the anomaly decreased. Additionally, another important hot point appeared to the south, along the coast of Murcia (37°–38° N). In general, over only 10 yr, the thermal anomaly increased along the entire coast by almost 0.5°C. The SD has a marked gradient from north to south, with higher values of up to 5°C on the Catalan coasts. It can be seen that as the decades pass, the SD is increasing southward, reaching the isoline of 4.5°C from being above Cape San Antonio to Cape of Palos on the Murcian coasts, and the isoline of 4°C to Cape of Gata on the Andalusian coasts (Fig. 3).

The temporal trend at 5 locations, i.e. A, D, I, M, and R, confirmed this intense increase in water temperature (Fig. 4). The location with the fastest increasing mean temperature was D, followed by installations M and I, A in the north and R in the south. The facilities with the highest mean temperature to date are I and M; furthermore, the trends at these facilities show very similar gradients, presenting an equivalent temporal evolution. If the temporal trend is analysed for extreme events, several episodes of climatic anomaly can be seen, which affect each facility differently. From 1991 to 1994 (Fig. 4), there were 3 sudden drops in temperature that were more pronounced at R and M than at the other locations. Three temperature peaks were observed in 1997, 1999, and 2003, which were very well differentiated

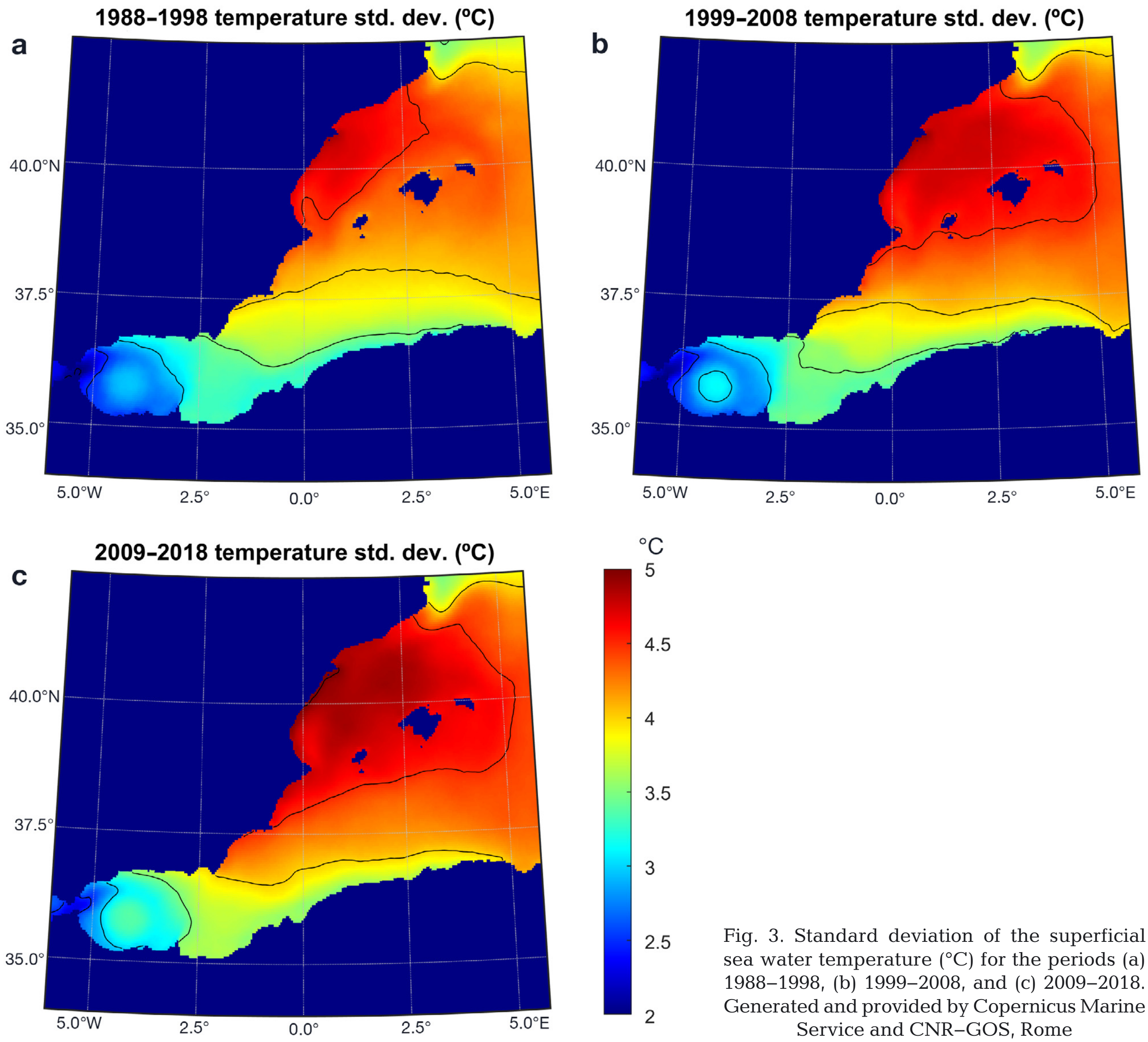

Fig. 3. Standard deviation of the superficial sea water temperature (°C) for the periods (a) 1988–1998, (b) 1999–2008, and (c) 2009–2018. Generated and provided by Copernicus Marine Service and CNR–GOS, Rome

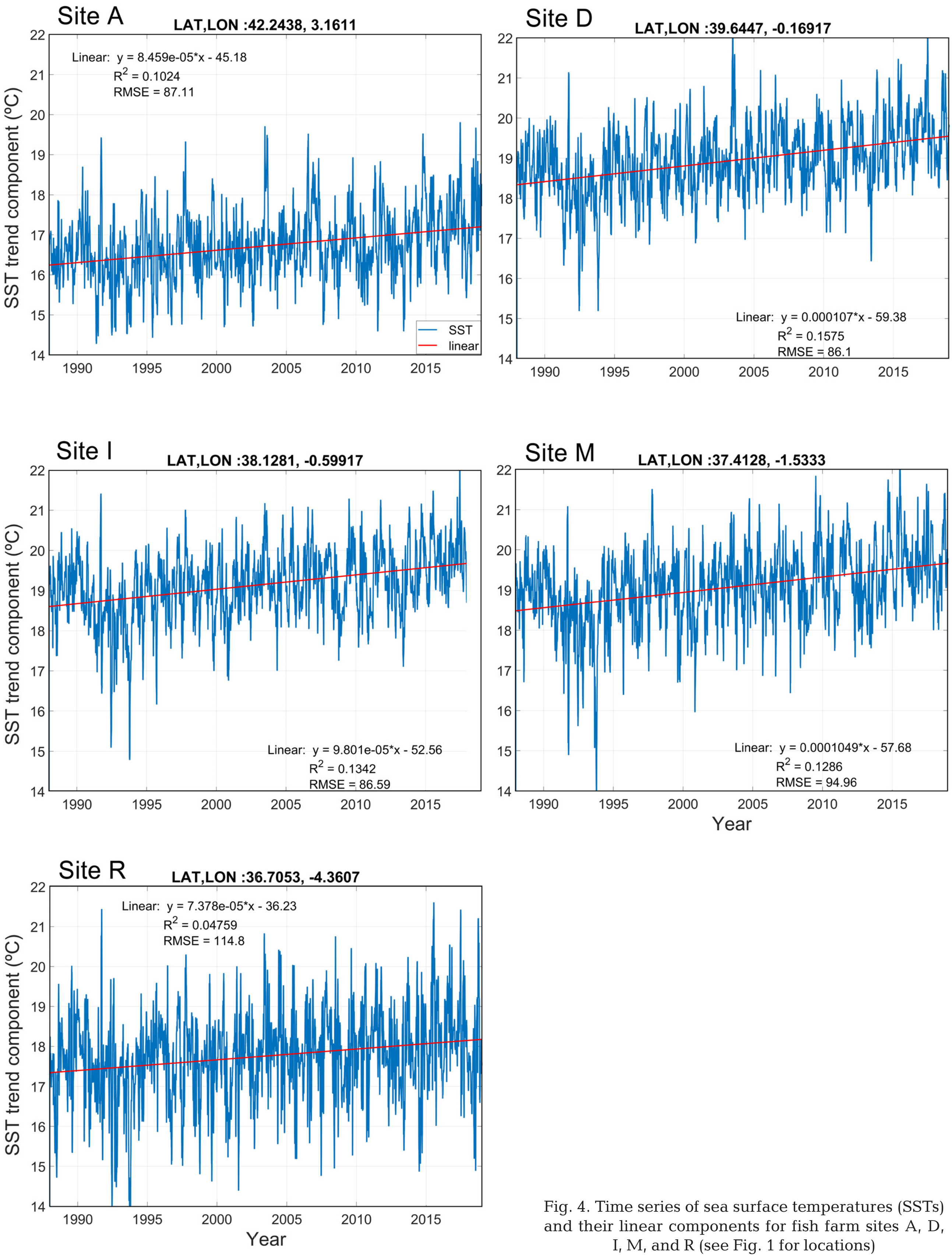

Fig. 4. Time series of sea surface temperatures (SSTs) and their linear components for fish farm sites A, D, I, M, and R (see Fig. 1 for locations)

at A and D, but not noticeable south of Cap de la Nau, at I and M. At R, only 2 of these events were recorded, in 1997 and 2003. Finally, a last remarkable event was an abrupt temperature peak between 2015 and 2016 that was only recorded at A and R.

3.2. Thermal anomalies from coastal to offshore aquaculture

The values of the regression lines and their significance for the mean, summer, and winter values in the distance-to-shore gradient for thermal anomalies are provided in Tables S1–S3 in the Supplement at www.int-res.com/articles/suppl/q013p515_supp.pdf. In terms of thermal anomaly means (Fig. 5), all fish farms except R showed a similar pattern, with an increase of between 0.4 and 0.6°C towards the south, and with no important variations with respect to distance from the coast. L, M, and N presented a steeper slope with a significant adjustment in the anomaly increase as the distance from the coast increased. Location R showed a somewhat different trend, with a lower anomaly relative to its latitudinal position and a higher increase in the anomaly with respect to distance from the coast.

When considering the thermal anomalies in the summer months, the latitudinal change was very pronounced (Fig. 5), with an increase from 0.4°C at A to about 1.2°C at Q. In certain locations (C, D, I, and O), there was a negative and significant trend; again L, M, and N showed a significant slope increase with respect to distance from the coast, with the change varying between 0.8 and 1°C. R showed a smaller anomaly with a sharp gradient increase as distance from the coast increased (Table S1).

The winter anomalies showed an opposite latitudinal pattern, with a decreasing trend from 0.4°C at A to anomalies close to 0°C at Q. In this period, a certain increasing trend was noted with respect to distance from the coast, especially at E, I, and J. Again, R showed the largest negative anomaly (0.2°C) in the winter, with a more evident increase farther from the coast.

4. DISCUSSION

The results of our work show that over the last decade, the Mediterranean coastal environment of the Iberian Peninsula has suffered an important increase in both average temperature and the SD due to global warming. This trend shows a clear latitudinal pattern, modified by mesoscale processes such as the effect of estuaries or coastal upwelling. The development of offshore aquaculture further than 30 km from the coast could, in some circumstances, mitigate the extreme aestival effects on surface water temperatures. All of these processes may be extremely pertinent to the marine aquaculture industry and should be taken into consideration in the future for spatial planning and production management.

4.1. Global warming in the Mediterranean: effects on aquaculture

The warming pattern for this Mediterranean area detected in our work is coincident with the spatial and temporal trends reported in other scientific studies, such as that by Pastor et al. (2019). Many studies have validated the effects of climate change in different regions of the Mediterranean Sea (Vargas-Yáñez et al. 2008, 2010, Coma et al. 2009, Vallis 2017). It can be confirmed that the coastal areas where aquaculture facilities are located have already experienced temperature changes in recent decades, and this may have positively or negatively influenced fish production and the management of marine aquaculture. The effects of a mean temperature increase on the growth of species such as seabream and seabass have been previously analysed. An increase in temperature could have a positive effect on the harvest size of these species (Hernández et al. 2007, Besson et al. 2016) and could also reduce the negative effects of chronic exposure to low temperatures. For seabream, 12°C seems to be the lower limit for growth (Hernández et al. 2003). The environmental occurrence of this 12°C limit appears to decrease as the mean temperature increases, with warmer winters and fewer episodes of excessive surface water cooling. In this sense, climate change could reduce episodes of heat stress due to low temperatures.

In addition to the changes in average SSTs, the effects of fluctuating temperature regimes on the temperature tolerance, thermal stress accumulation and recovery, and growth of many fish species could be quite relevant, but they are still largely unknown (Bevelhimer & Bennett 2000). In this sense, it seems that temperature variability could negatively influence production. For example, sea bass has a low thermal resistance and a low capacity to survive in aquatic systems characterised by wide temperature fluctuations (Kır & Demirci 2018). The production of this species in certain regions, such as along the

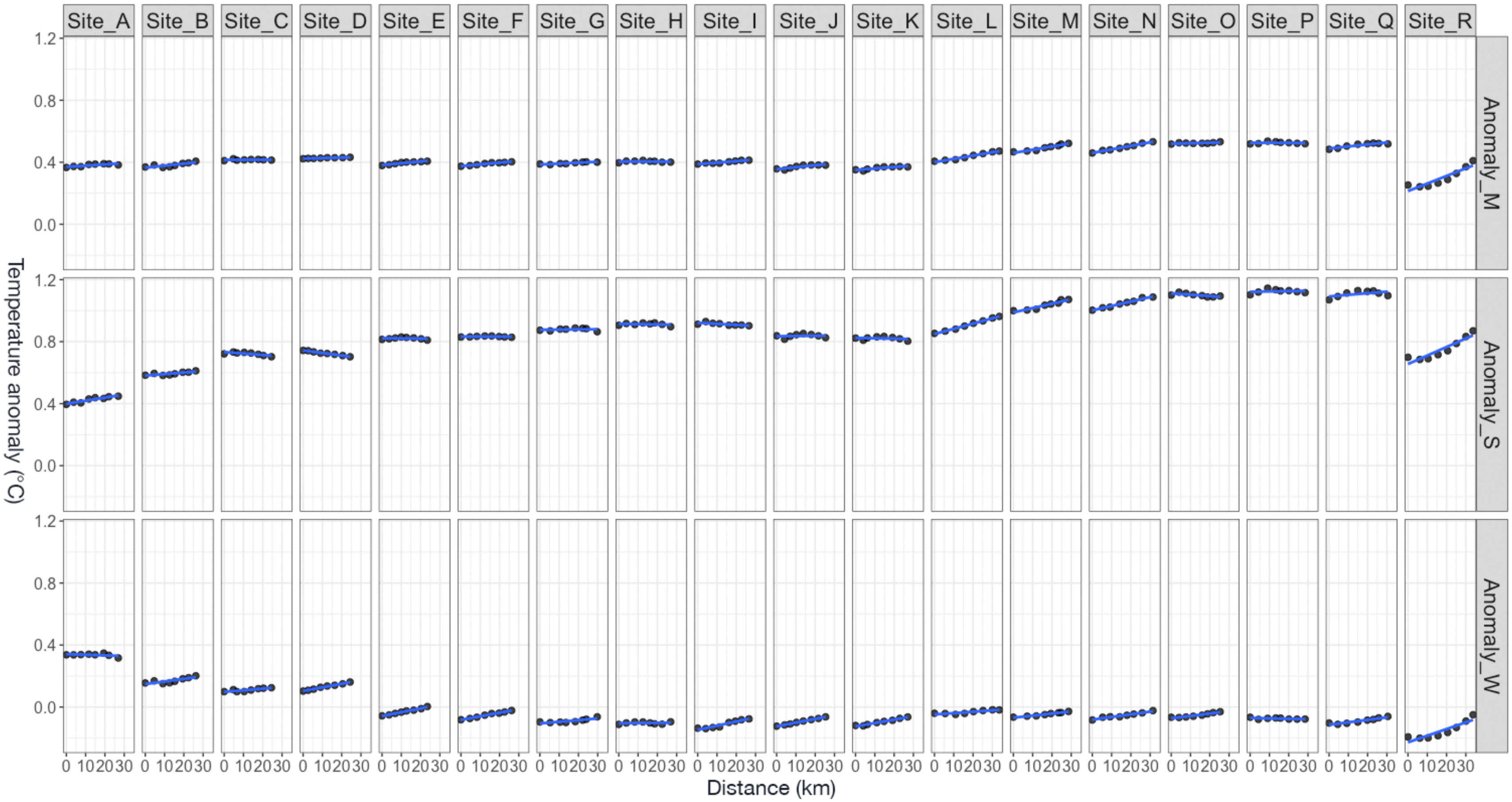

Fig. 5. Sea surface thermal anomaly represented as a function of distance to the coast (up to 30 km). Anomaly_M: annual mean; anomaly_S: summer anomalies; anomaly_W: winter anomalies. Each site (A–R) represents a single spatial point within which there is an aquaculture facility (see Fig. 1 for locations)

coast of Murcia or in the Gulf of Valencia, may be compromised if this species of commercial interest does not become acclimated to thermal fluctuations involving high summer temperatures. A similar problem could occur with sea bream, since this species also tolerates a relatively narrow temperature range, and consequently has a low acclimatisation capacity in terms of aquatic systems characterised by temperature variations (Kır 2020). Bioeconomic models of sea bass considering changes in mean temperature and dissolved oxygen also indicate that economic income increases when the SD of temperature decreases (Besson et al. 2016), as a lower amplitude reduces the periods where fish are exposed to extreme temperatures (higher or lower than 24°C).

For sea bream, the risk related to unpredictable variations in water temperature may have an important effect on the dispersion of the optimal harvesting size. Estimates of the mean harvest size for seabream in the face of increases in the SD of daily seawater temperature predict significant reduction in weight as the SD increases, and farmers would also face a high risk due to the lower likelihood of implementing the optimal management strategy (Hernández et al. 2007). The amplitude of water temperature also seems to have an effect on fish growth rate, a small amplitude being apparently more favourable to growth, which makes sense if the growth function is concave downwards (Seginer 2016). For this reason, it is not only the increase in mean temperature that is important, its temporal variability may play a relevant role in coastal aquaculture. Therefore, in order to predict the effect of changes in SST on aquaculture production, it is highly advisable to model changes in the growth of target species with respect to thermal anomalies. It is possible that fluctuating temperature regimes could increase the tolerance of fish to higher temperatures, but in addition to bioeconomic modelling, it is necessary to experimentally research the effect these fluctuating temperature regimes may have on fish health and the potential future acclimation of sensitive species.

It is worth indicating that future sustainable aquaculture development will have to take into account interaction among multiple stressors, including rising average temperatures and SDs, changes in oceanic circulation and mixing, eutrophication, oceanic acidification, oceanic deoxygenation (i.e. the global trend of decreasing oxygen as a result of oceanic warming and increasing stratification), coastal hypoxia (i.e. low dissolved oxygen environments due to increased nutrient levels or organic enrichment), and pollution (Sarà et al. 2018b). Future research should consider the synergistic effects that different stressors could have on marine aquaculture, considering the effect of several stressors working at various spatial and temporal scales. For example, increases in SSTs could lead to augmented fish growth (Hernández et al. 2007) but could also impact the occurrence and severity of diseases caused by parasites, bacteria, viruses, and biotoxins (Rosa et al. 2012). In addition, a temperature increase may simultaneously affect oxygen demand, stressing the farmed fish (Besson et al. 2016).

4.2. Mesoscale and regional oceanographic processes that modify thermal anomalies

As demonstrated in this study, the thermal latitudinal gradient along the Spanish Mediterranean coast is affected by mesoscale oceanographic processes, which are also relevant for understanding the water mass circulation in the Mediterranean Sea (Pinardi & Masetti 2000). Aquaculture facilities along the Spanish Mediterranean coast may be affected by 2 main processes: the circulation in the Gulf of Lion to the north and the entry of Atlantic water through the Strait of Gibraltar in the south. In general, it can be hypothesised that aquaculture facilities will suffer greater thermal stress the farther south they are located from the Iberian Mediterranean coasts, where they are dominated by stable conditions, such as the Ligurian-Provencal current and the Lion Gyre. However, to the south of the Iberian Mediterranean coast, the water masses are affected by the Modified Atlantic Water, which is able to buffer extreme summer temperatures as far into the Mediterranean as Cabo de Gata. In our study, the aquaculture facility located off the Malaga coast is clearly affected by the Alboran upwelling. The Alboran Sea has seasonal circulation, generating upwelling and consequent cooling of the surface water in winter and recirculation and heating of the coastal water in summer by displacing more surface water mass (Renault et al. 2012). The Atlantic water in the Alboran Sea describes a quasi-permanent anticyclonic gyre in the west and a more variable circuit in the east, reducing the effect of global warming in near-coastal locations. This pattern is coupled with the regime in the Strait of Gibraltar, the general pattern of the Atlantic flow in the Alboran Sea, and the circulation of the underlying Mediterranean water (Millot 1999). Additionally, the western circulation of the Mediterranean Sea is affected by eddies that modify the mean climatological circulation and mix properties within the different sub-basins, with mesoscale eddies ranging from 10s to 100s of km in size (Millot 1999). At a smaller scale, the Ebro River plume, the largest delta in the Mediterranean (Rodríguez-Santalla & Somoza 2019), seems to drive thermal stability, an aspect that could be very important for the mollusc production industry in this area. For this reason, any action or infrastructure that modifies the flow of the river would be counterproductive, as this would decrease thermal damping, thereby increasing ecosystem stress and affecting the viability of aquaculture companies.

4.3. Management recommendations and offshore aquaculture as a solution to the effects of global warming

The basic goal of marine aquaculture spatial planning is to determine which areas are likely to be the most productive and profitable not only at the present, but also in the short-term future, which is particularly relevant at this time of accelerated global warming. One of the options for mitigating the effects of temperature increase is to relocate fish farms to areas less sensitive to climate change. Offshore aquaculture may be a solution, although there is no clear consensus on the definition of what this term really means (Froehlich et al. 2017). In our study, we identified some locations where the effect of aestival thermal anomalies could be mitigated if the farms were relocated farther from the coast, up to 30 km offshore. It is remarkable how, in the coastal area of the Murcia region, offshore aquaculture worsens the summer conditions of thermal anomalies, whereas on the coast of the Valencian region, the opposite occurs, as offshore aquaculture seems to improve conditions. In this sense, offshore aquaculture could be considered key in mitigating the effects of global warming, also linked to a reduced environmental impact and decreased negative interactions with other coastal users. In other locations, however, offshore aquaculture does not appear to be a solution for minimising the impact of thermal stress on cultivated species, and it may even be counterproductive as the coastal area remains more thermally stable than the open waters.

It may be very useful to develop 3-D models that predict temperature changes in certain regions of interest in a gradient from the coast, as developed by Shettigar et al. (2020) for the Aegean Sea, as changes in aquaculture depth using closed cage systems to mitigate the effect of temperature increases in the water column could be a useful tool, and such models may help predict the necessary changes in depth. At the global scale, some studies have analysed the relationship between growth and temperature for several species (e.g. Klinger et al. 2017), indicating that biophysical spatial models can be a powerful tool for understanding and optimising the development of natural-resource-based economic sectors in the face of current and future environmental conditions. However, it is quite important to consider the adverse impact that translocating exotic species might have on the local biodiversity, as the expected increase in extreme weather events resulting from climate change raises the likelihood of a greater number of escapees from aquaculture farms (Beveridge et al. 2018).

It is therefore crucial that future spatial planning for marine aquaculture takes into account local forecasts of global warming. Marine spatial planning seeks to reduce conflict and environmental impact as well as promote the sustainable use of marine ecosystems (Lester et al. 2018). Optimal spatial marine plans have minimal impact on wild fisheries, viewshed quality, and the health of the benthic environment, and they also minimise the risk of disease outbreaks while generating significant revenue and seafood supply from marine aquaculture facilities. In addition to these goals, marine spatial planning should ensure, in the near future and in a scenario of rapid climate change, thermal stability for the species being cultivated. To maximise the use of maritime space and its resources, spatial planning of marine offshore aquaculture should incorporate climate change regimes in the oceanic environment, which are characterised by fluctuations of high interannual and decadal amplitude (Sainz et al. 2019). It is essential that, for the future placement of allocated zones for aquaculture (Sanchez-Jerez et al. 2016), mesoscale oceanographic processes and the thermal anomaly forecasts for different locations must be taken into account at a scale of 10s to 100s of km.

In conclusion, in the present scenario of accelerated climate change, the future of aquaculture will be closely linked to adequate marine spatial planning, considering the relocation of farms which are already being affected by high thermal anomalies. Strategic plans for aquaculture development should be able to forecast and incorporate future climate projections and local oceanographic conditions, and offshore aquaculture may provide an alternative depending on local oceanographic conditions. The latitudinal analysis of the SD of temperature carried out in this study showed that temperature oscillation is greater at higher latitudes, but the variability of the largest magnitude is shifted southward when comparing the decades 1999–2008 and 2009–2018. At the local scale, the temporal trends in the areas where aquaculture is already operating present significant thermal fluctuations, with extreme thermal anomaly events. This pattern is corroborated by the trend obtained from the Marine Copernicus service, whose data encompass the entire Mediterranean Sea (Von Schuckmann et al. 2018) and which demonstrates considerable thermal fluctuation, such as in 2003 and 2015. This aspect of thermal instability must be incorporated into the management of aquaculture facilities, which, linked to adequate spatial planning, must be adjusted to a future with relevant changes in average temperatures, the maximum and minimum temperature peaks, and the oscillation regime. It should not be forgotten that other extreme events, including heavy storms or torrential rain, can act synergistically with global warming, as can small-scale local stressors (e.g. sewage pollution). These complex interactions of stressors affecting coastal aquaculture at different temporal and spatial scales (Sarà et al. 2018b) must be considered in the spatial planning and environmental management of this activity.

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LITERATURE CITED

Barange M, Bahri T, Beveridge MCM, Cochrane KL, Funge-Smith S, Poulain F (eds) (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Fish Aquacult Tech Pap 627. FAO, Rome

Besson M, Vandeputte M, van Arendonk JAM, Aubin J, de Boer IJM, Quillet E, Komen H (2016) Influence of water temperature on the economic value of growth rate in fish farming: the case of sea bass (*Dicentrarchus labrax*) cage farming in the Mediterranean. Aquaculture 462:47–55

Bevelhimer M, Bennett W (2000) Assessing cumulative thermal stress in fish during chronic exposure to high temperature. Environ Sci Policy 3(Suppl 1):211–216

Beveridge MCM, Dabbadie L, Soto D, Ross LG, Bueno PB, Aguilar-Manjarrez J (2018) Climate change and aquaculture: interactions with fisheries and agriculture. In: Barange M, Bahri T, Beveridge MCM, Cochrane KL, Funge-Smith S, Poulain F (eds) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Fish Aquacult Tech Pap 627. FAO, Rome, p 491–500

Buongiorno Nardelli B, Tronconi C, Pisano A, Santoleri R (2013) High and ultra-high resolution processing of satellite sea surface temperature data over southern European seas in the framework of MyOcean project. Remote Sens Environ 129:1–16

Callaway R, Shinn AP, Grenfell SE, Bron JE and others (2012) Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquat Conserv 22: 389–421

Coma R, Ribes M, Serrano E, Jiménez E, Salat J, Pascual J (2009) Global warming-enhanced stratification and mass mortality events in the Mediterranean. Proc Natl Acad Sci USA 106:6176–6181

Craig RK (2019) Fostering adaptive marine aquaculture through procedural innovation in marine spatial planning. Mar Policy 110:103555

Cramer W, Guiot J, Marini K (2019) Risks associated to climate and environmental changes in the Mediterranean region — a preliminary assessment by the MedECC Network Science-policy interface. http://www.medecc.org/wp-content/uploads/2018/12/MedECC-Booklet_EN_WEB.pdf

Dempster T, Sanchez-Jerez P (2008) Aquaculture and coastal space management in Europe: an ecological perspective. In: Holmer M, Black K, Duarte CM, Marbà N, Karakassis I (eds) Aquaculture in the ecosystem. Springer, Dordrecht, p 87–116

FAO (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. https://www.fao.org/3/I9705EN/i9705en.pdf

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. https://doi.org/10.4060/ca9229en

Ferreira J, Hawkins A, Bricker S (2007) Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model. Aquaculture 264:160–174

Froehlich HE, Smith A, Gentry RR, Halpern BS (2017) Offshore aquaculture: I know it when I see it. Front Mar Sci 4:154

Froehlich HE, Gentry RR, Halpern BS (2018) Global change in marine aquaculture production potential under climate change. Nat Ecol Evol 2:1745–1750

Gentry RR, Lester SE, Kappel CV, White C, Bell TW, Stevens J, Gaines SD (2017) Offshore aquaculture: spatial planning principles for sustainable development. Ecol Evol 7: 733–743

Gubbins M (2006) Impacts of climate change on aquaculture. In: Buckley PJ, Dye SR, Baxter JM (eds) Marine climate change impacts annual report Card 2006. Online Summary Reports. MCCIP, Lowestoft

Hernández JM, Gasca-Leyva E, León CJ, Vergara JM (2003) A growth model for gilthead seabream (*Sparus aurata*). Ecol Model 165:265–283

Hernández JM, León-Santana M, León CJ (2007) The role of the water temperature in the optimal management of marine aquaculture. Eur J Oper Res 181:872–886

Hu N, Yu Z, Huang Y, Liu D, Wang F, Zhang T (2021) Elevated temperatures increase growth and enhance foraging performances of a marine gastropod. Aquacult Environ Interact 13:177–188

Joos F, Prentice IC, Sitch S, Meyer R and others (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Global Biogeochem Cycles 15:891–907

Kır M (2020) Thermal tolerance and standard metabolic rate of juvenile gilthead sea bream (*Sparus aurata*) acclimated to four temperatures. J Therm Biol 93:102739

Kır M, Demirci Ö (2018) Thermal tolerance and standard metabolic rate of juvenile European sea bass (*Dicentrarchus labrax*, Linnaeus, 1758) acclimated to four temperatures. J Therm Biol 78:209–213

Klinger DH, Levin SA, Watson JR (2017) The growth of finfish in global open-ocean aquaculture under climate change. Proc R Soc B 284:20170834

Lester SE, Stevens JM, Gentry RR, Kappel CV and others (2018) Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. Nat Commun 9: 945

Marra J (2005) When will we tame the oceans? Nature 436: 175–176

Millot C (1999) Circulation in the western Mediterranean Sea. J Mar Syst 20:423–442

Pastor F, Valiente JA, Palau JL (2019) Sea surface temperature in the Mediterranean: trends and spatial patterns (1982–2016). In: Vilibic I, Horvath K, Palau JL (eds) Meteorology and climatology of the Mediterranean and Black Seas. Springer, Cham, p 297–309

Pinardi N, Masetti E (2000) Variability of the large scale general circulation of the Mediterranean Sea from observations and modelling: a review. Palaeogeogr Palaeoclimatol Palaeoecol 158:153–173

Pisano A, Nardelli BB, Tronconi C, Santoleri R (2016) The new Mediterranean optimally interpolated pathfinder AVHRR SST Dataset (1982–2012). Remote Sens Environ 176:107–116

Reid GK, Gurney-Smith HJ, Marcogliese DJ, Knowler D and others (2019) Climate change and aquaculture: considering biological response and resources. Aquacult Environ Interact 11:569–602

Renault L, Oguz T, Pascual A, Vizoso G, Tintoré J (2012) Surface circulation in the Alborán Sea (western Mediterranean) inferred from remotely sensed data. J Geophys Res 117:C08009

Rodríguez-Santalla I, Somoza L (2019) The Ebro River delta. In: Morales JA (ed) The Spanish coastal systems: Springer, Cham, p 467–488

Rosa R, Marques A, Nunes ML (2012) Impact of climate change in Mediterranean aquaculture. Rev Aquacult 4: 163–177

Sainz JF, Di Lorenzo E, Bell TW, Gaines S, Lenihan H, Miller RJ (2019) Spatial planning of marine aquaculture under climate decadal variability: a case study for mussel farms in southern California. Front Mar Sci 6:253

Sanchez-Jerez P, Karakassis I, Massa F, Fezzardi D and others (2016) Aquaculture's struggle for space: the need for coastal spatial planning and the potential benefits of Allocated Zones for Aquaculture (AZAs) to avoid conflict and promote sustainability. Aquacult Environ Interact 8:41–54

Sarà G, Gouhier TC, Brigolin D, Porporato EMD and others (2018a) Predicting shifting sustainability trade-offs in marine finfish aquaculture under climate change. Glob Change Biol 24:3654–3665

Sarà G, Mangano MC, Johnson M, Mazzola A (2018b) Integrating multiple stressors in aquaculture to build the blue growth in a changing sea. Hydrobiologia 809:5–17

Seginer I (2016) Growth models of gilthead sea bream (*Sparus aurata* L.) for aquaculture: a review. Aquacult Eng 70:15–31

Shettigar NA, Bhattacharya B, Mészáros L, Spinosa A, El Serafy G (2020) 3D ensemble simulation of seawater temperature — an application for aquaculture operations. Front Mar Sci 7:592147

Soto D, Ross LG, Handisyde N, Bueno PB and others (2018) Climate change and aquaculture: vulnerability and adaptation options. In: Barange M, Bahri T, Beveridge MCM, Cochrane KL, Funge-Smith S, Poulain F (eds) Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options. Fish Aquacult Tech Pap 627. FAO, Rome, p 465–490

Trujillo P, Piroddi C, Jacquet J (2012) Fish farms at sea: the ground truth from Google Earth. PLOS ONE 7:e30546

Vallis GK (2017) Atmospheric and oceanic fluid dynamics, 2nd edn. Cambridge University Press, Cambridge

Vargas-Yáñez M, García MJ, Salat J, García-Martínez M, Pascual J, Moya F (2008) Warming trends and decadal variability in the Western Mediterranean shelf. Global Planet Change 63:177–184

Vargas-Yáñez M, Moya F, García-Martínez MC, Tel E and others (2010) Climate change in the Western Mediterranean Sea 1900–2008. J Mar Syst 82:171–176

Von Schuckmann K, Le Traon P, Smith N, Pascual A and others (2018) Copernicus marine service ocean state report. J Operational Oceanogr 11(Suppl 1):S1–S142

Walker AE, Wilkin JL (1998) Optimal averaging of NOAA/NASA Pathfinder satellite sea surface temperature data. J Geophys Res Oceans 103:12869–12883

Wickham H (2016) ggplot2: Elegant graphics for data analysis. Springer-Verlag, New York, NY

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