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Frequent monitoring of temperature: an essential requirement for site selection in bivalve aquaculture in tropical–temperate transition zones

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Abstract

Frequent monitoring of temperature (FMT) for over 1 year at two aquaculture sites in the western Baja California peninsula was analysed in terms of hourly, daily and monthly variability, and with this information, temperature-change indices were calculated. These data were contrasted against a long-term series from a global database (Extended Reconstruction of Sea Surface Temperature (ERSST)) to evaluate whether these could substitute for FMT. The compatibility of species requirements with the thermal conditions was evaluated by comparing the temperature frequency distributions from the two FMTs, with the optimum and lethal temperature information available on five bivalve species of aquacultural interest. We concluded that there was no correlation between ERSST and FMT because the former underestimates the amplitude of real temperature fluctuations and exhibits a different pattern of variation during the year. Therefore, FMT was needed for a correct selection of an aquaculture site for bivalves. The FMT indicated high temperature variability at both sites studied on different time scales, with the site located at lower latitude (Rancho Bueno) warmer and with a higher variability than Laguna Manuela. Contrasting these results with optimum and lethal temperature values of bivalve species, it was possible to find the ideal site, for temperature, for culturing the species, taking into account the variability associated with large-scale phenomena.

Keywords: LD_{50}, temperature, oyster, scallop, penshell

Introduction

Site selection is a key factor in any successful bivalve aquaculture operation. In new ventures, one criterion followed by aquaculturists is to verify the presence of the target species in the area, and then the decision may be further based on results of preliminary growout experiments performed at the site for short periods. However, in this site selection process, the importance of climate variability is frequently neglected, with catastrophic results (Lechuga-Devéze, Morquecho-Escamilla, Reyes-Salinas & Hernández-Alfonso 2000; Carvalho-Saucedo 2003). In tropical–temperate transitional zones like those in the western Baja California peninsula (Lluch-Belda, Lluch-Cota & Lluch-Cota 2003a), Peru, Japan and Bengal (Olson 2001), strong climate fluctuations occur on many time scales, hourly, daily, seasonally (Ponce-Díaz, Lluch-Cota, Bautista-Romero & Lluch-Belda 2003), interannually (i.e. ENSO; Lluch-Belda, Lluch-Cota & Lluch-Cota 2003b, 2003c) and interdecadally (Lluch-Cota, Wooster & Hare 2001), resulting in highly variable biophysical settings including temperature and seston quality and concentration, which are the most important factors affecting the physiology of the organisms (Lodeiros, Maeda-Martínez, Freites, Uribe, Lluch-Cota & Sicard 2001). In the western Baja California peninsula, seasonal climate variations result from the interaction of the California Current during winter (Álvarez-Borrego, Galindo-Bect & Chee-Barragán 1975; Álvarez-Borrego & Álvarez-Borrego 1982), and the tropical North Equatorial Countercurrent during summer (Lluch-Belda *et al.* 2003a).

For evaluating potential aquaculture sites, an alternative for obtaining thermal data is accessing public databases such as satellite-derived databases (Smith 1992), the Comprehensive Ocean–Atmosphere Data Set (COADS; Mendelssohn & Roy 1996) or the Extended Reconstruction of Sea Surface Temperature (ERSST; Smith & Reynolds 2004), which provide information at different time and space resolutions. However, because of the influence of small-scale currents, bathymetry, land–sea interaction and other factors, these data may not reflect the conditions occurring at specific coastal locations. Carvalho-Saucedo (2003), in an attempt to explain mass mortalities of *Crassostrea gigas* in northwestern México, documented large daily temperature fluctuations at an aquaculture site in Laguna San Ignacio (between 26°43′ and 26°88′N and 113°′08′ and 113°16′W) based on recordings of frequent monitoring of temperature (FMT), which could not be observed in monthly resolution global databases.

Another important issue in site selection is the knowledge of the physiological constraints and preferences of target species to important variables (e.g. temperature). Of the 54 native species of molluscs distributed along the Pacific coast of México (Baqueiro 1984) regarded as good candidates for aquaculture, only four native species (*Argopecten ventricosus*, *Nodipecten subnodosus*, *Atrina maura* and *A. tuberculosa*) and the introduced Pacific oyster (*C. gigas*) have been the subject of ecophysiological studies for the determination of optimum temperatures for growth (temperature value or range, where the growth rate of a given species is maximum) and their upper and lower thermal limits (Nieves-Soto 1988; Bougrier, Geairon, Deslous-Paoli, Bacher & Jonquieres 1995; Monsalvo-Spencer, Maeda-Martínez & Reynoso-Granados 1997; Sicard 1999; Sicard, Maeda-Martínez, Reynoso-Granados, Ormart-Castro & Carvalho-Saucedo 1999; Leyva-Valencia, Maeda-Martínez, Sicard & Robles-Mungaray 2001; Rodríguez-Jaramillo, Maeda-Martínez, Vadéz, Reynoso-Granados, Monsalvo-Spencer, Prado-Ancona, Cardoza-Velazco, Robles-Mungaray & Sicard 2001; Carvalho-Saucedo 2003; González-Estrada 2003; Salazar-Virgen 2004). Optimum temperatures for growth have been determined in the laboratory by measuring growth rates in long-term experiments, or by estimating several physiological indices like scope for activity (Fry 1947), scope for growth (Warren & Davis 1967) and irrigation efficiency (Jørgensen 1960) at different temperatures. The upper and lower thermal tolerances have been estimated using the lethal-dose method (LD_{50}), at different exposure times (usually 96 h).

The resolution of FMT vs. ERSST data series was compared to evaluate their use in site selection for mollusc aquaculture. For this, we analysed as examples two FMT data series lasting for more than 1 year at two aquaculture sites in the western Baja California peninsula, and contrasted the FMT data with those from a long-term series from a global database for the same sites. We took the most reliable data series (FMT), and plotted temperature frequency distributions, together with the optimum and lethal temperature information available on five bivalve species of aquacultural interest in México, to determine the best match between species tolerances and requirements, with environmental thermal variability.

Material and methods

One digital temperature recorder (model WTA32-5+37; Onset Computer Corp., Bourne, MA, USA) was deployed at each of the two study sites for at least 1 year (Table 1). The recorders were programmed to record the water temperature at 0.5 h intervals. Recordings were downloaded to a computer, processed for outliers and backed up by the Data Management Laboratory at Centro de Investigaciones Biológicas del Noroeste (CIBNOR) for later inclusion into a public access database (not yet available). We also included in the analysis data from the NOAA NCDC ERSST V. 2 database as available from the IRI/LDEO Climate Data Library website; http://iridl.ldeo.columbia.edu. ERSST was recently built by Smith and Reynolds (2004), using improved statistical methods on the most recent available COADS. This database has time coverage of more than a century, and is available for the entire globe as monthly 2° latitude by 2° longitude matrices. For our work, we selected the boxes corresponding to the two study sites for the period 1903–2004 centred at 22°N, 115°W and 28°N, 112°W.

Study sites

The study sites (Laguna Manuela and Rancho Bueno; Fig. 1) were selected because these reflect the temperature conditions likely to be found in most potential aquaculture sites along the southern half of the Baja California Peninsula. Laguna Manuela is a coastal lagoon 40 km north of Guerrero Negro, México. This is a shallow irregular lagoon nearly

Table 1 Results from the analyses of the frequent monitoring of temperature (FMT) at Laguna Manuela and Rancho Bueno (western Baja California peninsula, Mexico) and the corresponding Extended Reconstruction of Sea Surface Temperature (ERSST) boxes

	Laguna Manuela		Rancho Bueno	
	FMT	ERSST	FMT	ERSST
Record span	12/2001–03/2004	1903–2004	02/2001–05/2002	1903–2004
Data gaps	12/2002–02/2003, 12/2003	–	–	–
Average temperature (°C) ± *sd*	19.38 ± 2.98	18.18 ± 2.76	23.02 ± 3.35	22.44 ± 1.81
Maximum temperature (°C)	30.27	22.95	31.58	28.74
Minimum temperature (°C)	10.71	14.17	16.31	16.96
Temperature range (°C)	19.56	8.78	15.27	11.78
Warmest month	September	September	August	September
Coldest month	February	March	December	April

SD, standard deviation.

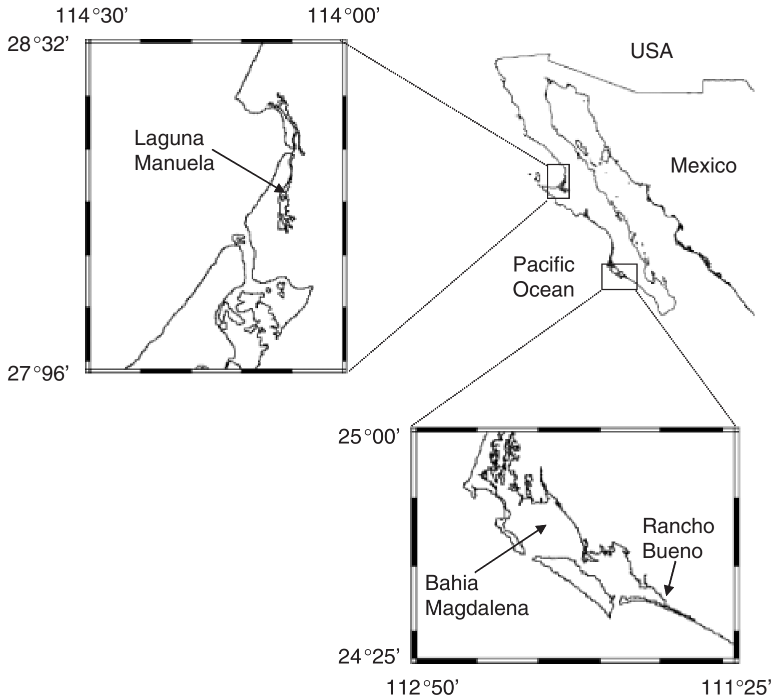

Figure 1 Geographic locations of the thermographs for frequent monitoring of temperature at Laguna Manuela and Rancho Bueno, Baja California Sur, México.

20 km long by 3 km wide, with a total surface of about 5 km^2. Depths range between 3 and 6 m in most of the area, and there is a permanent water exchange with the Pacific Ocean through two shallow mouths. Current aquaculture activities in the lagoon include the cultivation of the Pacific oyster (*C. gigas*) and the giant lion's-paw scallop (*N. subnodosus*). The recorder was tied to the steel structure of one of the bottom oyster racks, at a depth of 1.9 m below the mean sea level (28°08′13.6″N – 114°04′18.9″W).

Rancho Bueno is an 8 km long by 0.5 km wide channel at the southern tip of Bahia Magdalena, 170 km from La Paz, México. Depths are less than 5 m with irregular bathymetry, and hydrodynamics are dominated by strong tidal currents associated with a 2.25 m tidal range (Mendoza-Salgado & Lechuga-Devéze 1995). Because of the strong currents and great abundance of phytoplankton, Rancho Bueno has been regarded as an adequate site for bivalve aquaculture (Maeda-Martínez, Ormart-Castro, Méndez, Acosta & Sicard 2000). In this place, several bivalve species have been successfully cultured, including the catarina scallop (*A. ventricosus*), pearl oyster (*Pteria sterna*), penshell (*A. maura*) and the Pacific oyster (*C. gigas*). The logger was tied to a rock and later deployed at 2 m depth at a site (24°18′47.0″N – 111°24′15.7″W) close to the bottom cultures of oyster and catarina scallop.

Data analysis

From the temperature data (FMT and ERSST), we computed the average, maximum and minimum temperatures for the entire period and for each month of the series. We then averaged repeated months (i.e. all Januaries and all Februaries, and so on) to generate a climatology (even when in some cases we only recorded 1 month). From the annual cycles, we identified the warmest and coldest months of the year and estimated the annual amplitude as the difference between the warmest and coldest months. For ERSST, only the average and maximum monthly change rates were computed. Monthly temperature averages from both data sources were plotted together for comparison.

The ERSST data were also processed for plotting purposes by computing monthly anomalies as deviations from the climatology through the entire period (i.e. January 1980 minus the average of all Januaries from 1903 to 2004), and we also estimated 11 month moving averages. We created two new variables for each recorder series: an hourly change rate (absolute temperature differences between consecutive hours at each time step), and similarly the daily change rate (differences between the maximum and minimum values within 12 h windows). From there, we estimated the frequency distribution of values in the temperature domain for each location.

Finally, to determine the potential of a site in terms of temperature as a place for culturing a given mollusc species, FMT data were plotted in terms of frequency, obtaining the distributions at both sites, together with the optimum and lethal values of temperature (from the literature), and the range of temperatures studied for five mollusc species.

Results

In Laguna Manuela, FMT was recorded for 24 months from December 2001 to March 2004, with a 3 month gap from December 2002 to February 2003 and one gap in December 2003 (Table 1, Fig. 2). In Rancho Bueno, FMT was recorded for 15 months without gaps, from February 2001 to May 2002

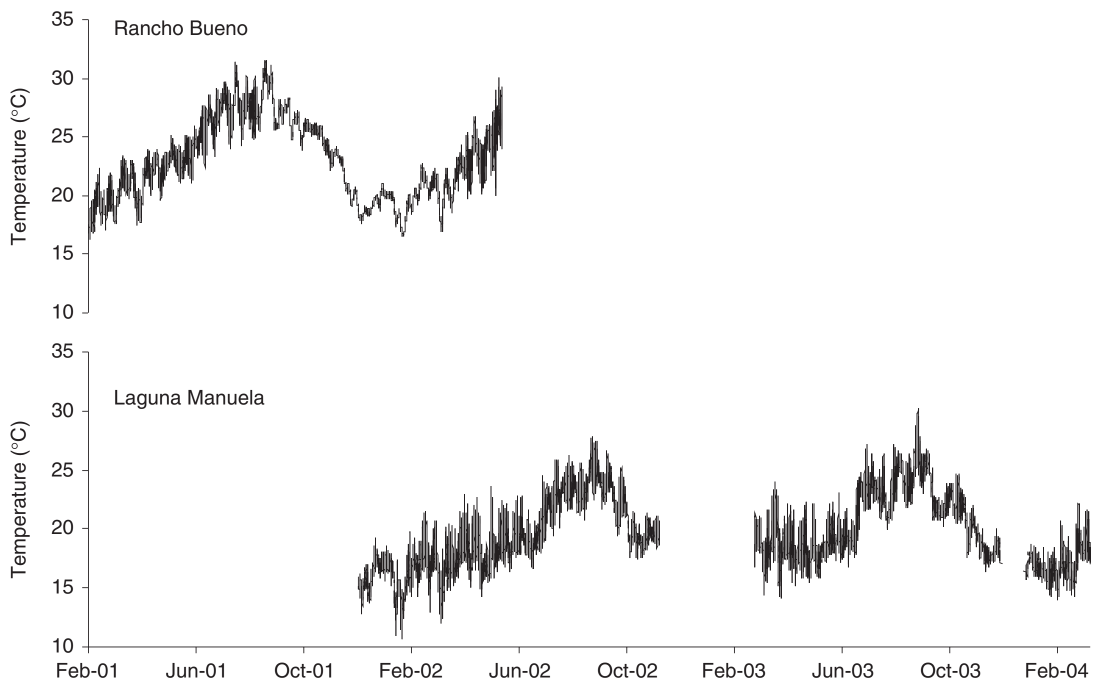

Figure 2 Raw data from the frequent monitoring of temperature installed at Rancho Bueno and Laguna Manuela.

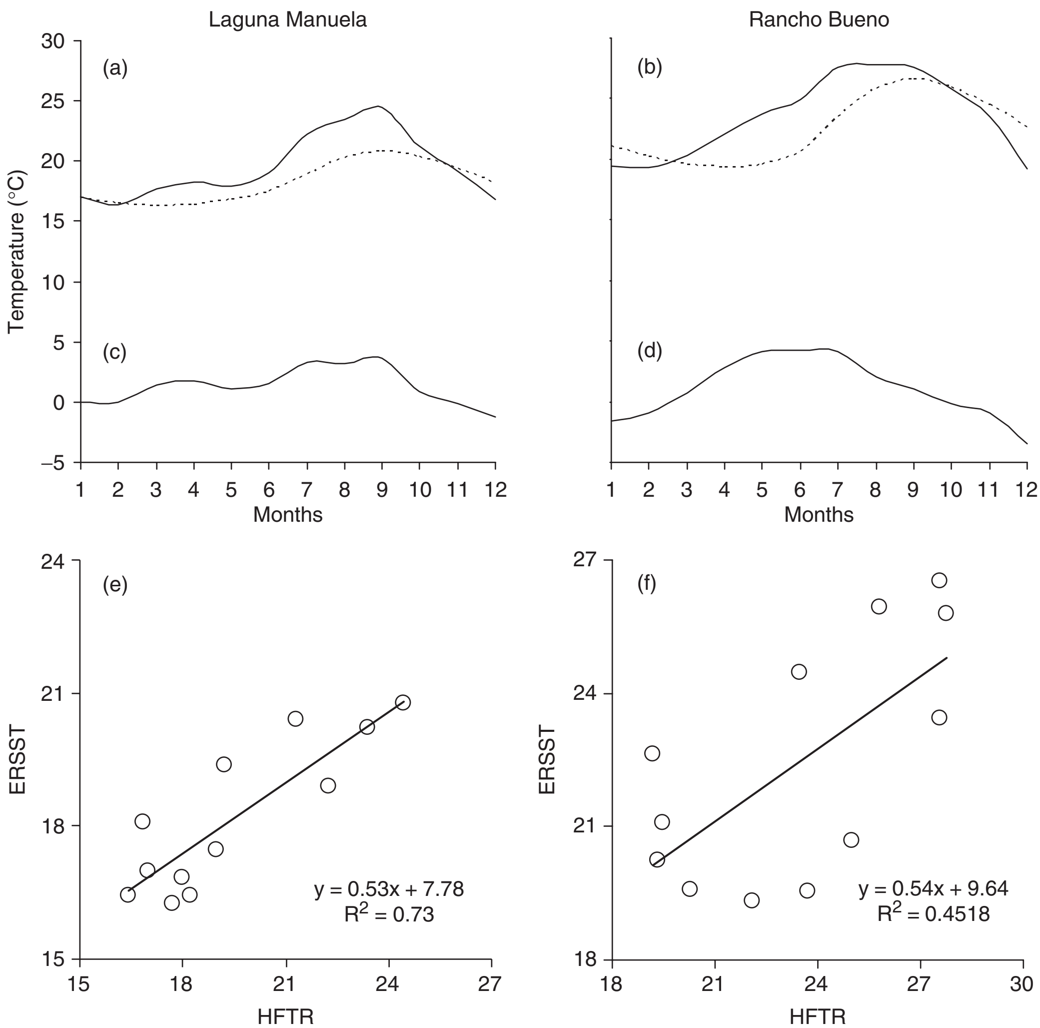

Figure 3 Average monthly temperatures from Laguna Manuela (a) and Rancho Bueno (b) for the frequent monitoring of temperature (FMT; solid line) and the corresponding Extended Reconstruction of Sea Surface Temperature (ERSST) box (dashed line). Differences between FMT and ERSST at Laguna Manuela (c) and Rancho Bueno (d) are also shown, together with a regression analysis of both databases (e, f).

(Fig. 2). From Table 1, differences between sites of average (3.64 °C), maximum (1.31 °C) and minimum (5.6 °C) temperatures were found. These were higher at Rancho Bueno, a site located at a more southerly latitude than Laguna Manuela. On comparing average FMT values with those from their corresponding ERSST boxes (Fig. 3a and b), values of the former series were some degrees (max 4 °C) higher (Fig. 3c and d) than the latter in Laguna Manuela (from February to November) and Rancho Bueno (February to October). However, the FMT was lower than ERSST in December in Laguna Manuela and for 3 months in Rancho Bueno (January, November and December). Regression analyses (Fig. 3e and f) between FMT and ERSST were not significant at $P > 0.05$. Comparing the maximum temperature values of Table 1, FMT was 7 and 3 °C higher than ERSST in Laguna Manuela and Rancho Bueno. Conversely, there were also differences on comparing the minimum values, but here the ERSST values were higher than the FMT at both sites.

Maximum amplitudes calculated as the difference between maximum and minimum values were also different between sites and data sets for the whole series. A higher FMT amplitude was found at Laguna Manuela (19.56 °C) than at Rancho Bueno (15.27 °C),

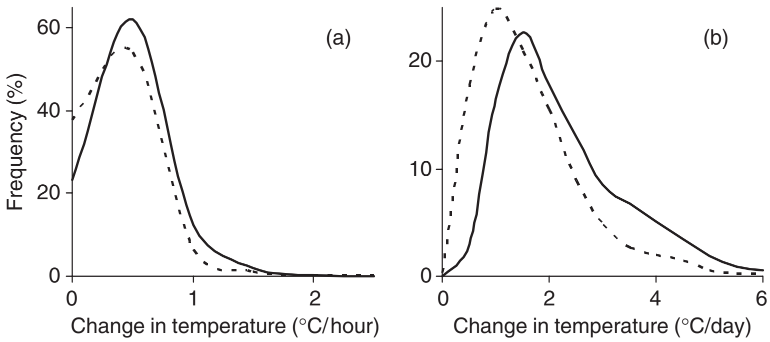

Figure 4 Frequency distribution of hourly (a) and daily (b) change rates of temperature at Laguna Manuela (dashed lines) and Rancho Bueno (solid lines).

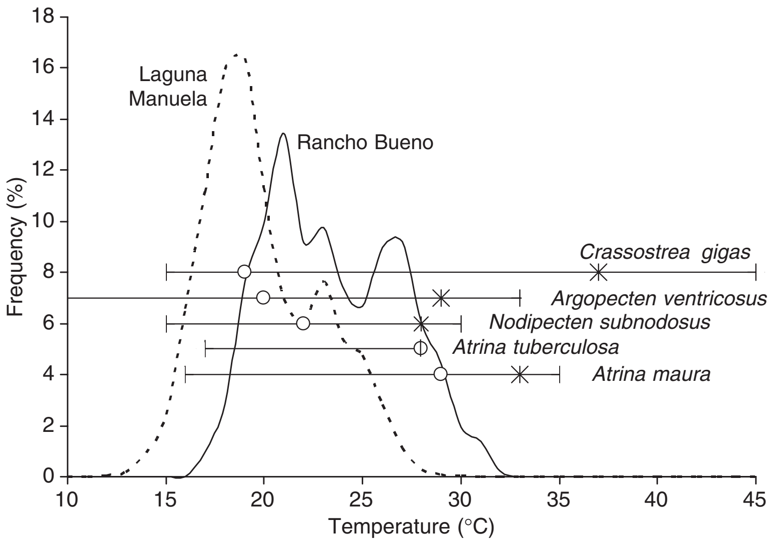

Figure 5 Temperature-dependent frequency distribution (%) for the raw data from the frequent monitoring of temperature at Laguna Manuela (dashed line) and Rancho Bueno (solid line), and representation of ecophysiological measurements for the five selected bivalve species of aquacultural interest; horizontal lines with vertical end lines indicate the temperature ranges studied in laboratory experiments, the open circle the optimum temperature for growth and crosses the upper lethal temperatures of the species.

but in turn, both amplitudes were higher than those found in the ERSST records (8.78 and 11.78 °C). Annually, both databases agreed that the warmest month at Laguna Manuela was September, but disagreed on the coldest month: February for FMT and March for ERSST. Similarly, the warmest month at Rancho Bueno was August according to FMT, but September according to ERSST. For the coldest month at Rancho Bueno, a larger discrepancy was found. Here, FMT indicated December and ERSST April.

The rate of temperature change affects the physiology and survival of poikilotherm organisms. In Fig. 4, the frequency of FMT temperature changes, hourly and daily, is plotted. A similar pattern was observed at both places but Rancho Bueno showed slightly higher change rates. This Figure (Fig. 4a) shows that nearly 60% of the hourly changes were about 0.6 °C h^{-1} at both places, but there were a certain percentage of changes of 1.5 °C h^{-1}. This analysis on a daily basis (Fig. 4b) shows that more than 20% of the changes varied on the order of 1.5–2.0 °C day^{-1} at both places, but at least 2% of these were 5 °C day^{-1} at Rancho Bueno.

Discussion

High temperature variability at both sites was found at different time scales. Rancho Bueno was warmer with a greater variability than Laguna Manuela. When the FMTs were compared with ERSST data, we found that there was no significant correlation ($P > 0.05$) between databases, and that ERSST underestimated real temperature fluctuations in amplitude and had a different pattern of variation during the year. Therefore, FMTs are needed for a correct evaluation of potential sites. To determine the potential of a site in terms of temperature as a place for culturing a given mollusc species, it is necessary (a) to test how closely is the optimum temperature reached for growth of the species from the distribution of temperatures occurring at a site during a year, (b) whether the tolerance of the species fits within the range of temperature at the site and (c) whether the temperature-change rates negatively affect the species. In Fig. 5, the frequency distribution of temperature at both sites, together with the optimum temperature for growth and the upper temperature tolerance of several species (Table 2), shows that Laguna Manuela is a good place for *C. gigas, A. ventricosus* and *N. subnodosus* aquaculture. Their optimum temperature for growth closely agrees with the maximum frequency of the temperature recorded there. However, *C. gigas* would be cultured at Rancho Bueno under suboptimal conditions during most of the year, probably affecting growth rate and quality. The Rancho Bueno site, however, is amenable to grow the rest of native bivalves studied, except the giant lion's-paw (*N. subnodosus*), as temperature exceeded the upper lethal limits of the species. This scallop is the most susceptible species to high temperature of all species studied with an LD_{50} of 28 °C, but this matches with the upper limit of the frequency distribution of temperature at Laguna Manuela. This means that Laguna Manuela is an ideal place to grow this scallop. However, at Rancho Bueno, 14% of temperatures will surpass the upper limit of the species, explaining those mortalities ranging from 3% to > 50% that occurred in the same species and in the same bay where Rancho Bueno is located (Bahía Magdalena) (Koch, Mazón-Suástegui, Sinsel, Robles-Mungaray & Dunn 2005). The same situation is found for the catarina scallop (*A. ventricosus*) at Rancho Bueno, but here only 7% of the data surpassed the tolerance limit (29 °C) of the species. This percentage does not seem limiting as demonstrated in a commercial aquaculture project on this scallop that successfully produced more than 20 t of meat with negligible mortality (Maeda-Martínez *et al.* 2000). The upper thermal limits of the penshell (*A. maura*) and the Pacific oyster (*C. gigas*) are several degrees higher than the temperature distributions at both sites, and we then assume that these species can be safely cultured there. However, care must be exercised when considering the typical interannual variations in temperature found in tropical–temperate transitional zones. In Fig. 6a, the sea surface temperature (SST) anomalies recorded in the $2^\circ \times 2^\circ$ boxes at Laguna Manuela and Rancho Bueno, from 1903 to 2004, are shown. Here, is evident that several warm (El Niño) events occurred (1958, 1972, 1982/1983 and 1997/1998). During such years, daily fluctuations are expected to be smaller but extreme values can be several degrees larger (Ponce-Díaz *et al.* 2003). Frequency temperature distributions of Fig. 5 could be shifted several degrees to the right as our FMT corresponds to a normal period (Fig. 6b), and therefore the upper tolerance of species like scallops would be exceeded even at the coldest site studied (Laguna Manuela). For instance, Ponce-Díaz *et al.* (2003), when using temperature recorders, reported an increase of 6 °C during the strong El Niño of 1997–1998 in Bahia Asunción, located 110 km south of Laguna Manuela. It must be considered, however, that the LD_{50} method used for upper thermotolerance determinations is just a standardized indicator that may overestimate the limits. In the LD_{50} method, the organisms are exposed to acute temperature shocks from the acclimation temperature to the test temperature, and are held at such temperatures for 96 h. These conditions are not likely to occur in the field. From the upper lethal limits of the penshell (*A. maura*), this organism would seem to be an excellent alternative for aquaculture in northwestern México and other tropical regions.

It is interesting that the interval between optimum and upper lethal temperatures in the Pacific oyster is extremely high (18.5 °C) when compared with those for catarina and giant lion's-paw scallops and the penshell *A. maura* (9, 9.4 and 4.2 °C respectively). This probably explains the cosmopolitan distribution of *C. gigas*.

The limited ecophysiological information of native species and of FMT data at the potential sites could be the cause for the slow growth of a mollusc aquaculture industry in México, despite the great efforts made by the government, research institutions, companies and individuals. Both types of studies are needed to find the correct match between optimum and tolerance limits of mollusc species with FMT data at potential sites, always taking into account the variability associated with large-scale phenomena. Finally, in this paper, we addressed the importance of temperature on site selection, but other factors such as seston abundance and quality, salinity, currents and dissolved oxygen (Lodeiros *et al.* 2001) have to be considered in this task. Although these factors exhibit some fluctuations in the western Baja California peninsula, none of them seem to play such an important role as a potential limiting factor for bivalve aquaculture as does temperature. More research is needed to determine the combined effect of these factors with temperature.

Table 2 Laboratory estimations of optimum temperature for growth and temperature tolerances of selected bivalves of Baja California and Baja California Sur, México

Species	Stage	Shell height or length (mm)	Method	Thermal range studied (°C)	Optimum temperature for growth (°C)	Acclimation temperature (°C)	Thermotolerance Minimum (°C)	Thermotolerance Maximum (°C)	References
Crassostrea gigas	Juvenile	10.0	LD_{50}-96 h	30–45	–	15	–	32.5	Carvalho-Saucedo (2003)
					–	22	–	37.5	
					–	28	–	37.5	
	Juvenile	10.0	Growth	15–30	18	15–30	–	–	Salazar-Virgen (2004)
	Juvenile to adult		Clearance rates	5–32	19	5–32	–	–	Bougrier *et al.* (1995)
Argopecten ventricosus	Juvenile	22.3	Growth rates	20–28	20	20–28	–	–	Monsalvo-Spencer *et al.* (1997)
	Juvenile	18.1	LD_{50}-96h	16–33	–	19	–	29	Sicard (1999)
	Adults	42.5	LD_{50}-96h	16–33	–	19	–	29	
	Juvenile	10.0	Scope for activity, irrigation efficiency, growth	12–28	19	12–28	–	–	Sicard *et al.* (1999)
	Juvenile	22.5	VO_2 uptake	10–30	20	–	–	–	
	Adults	48.4	VO_2 uptake	10–30	20	–	–	–	
Nodipecten subnodosus	Juvenile	72.9	LD_{50}-96 h	15–30	–	15	5.1	27.6	Silva-Loera (1986)
					–	18	7.5	28.1	González-Estrada (2003)
	Juvenile	72.9	Scope for growth, irrigation efficiency, growth	15–30	22	15–30	–	–	
	Juvenile	72.9	LD_{50}-96 h	15–30	–	22	7.5	28.0	
					–	26	7.5	28.5	
					–	30	12.5	31.4	
			Gradual change	15–30	–	15–30	< 3	32	
Atrina tuberculosa	Adult	190.0	Scope for growth	17–28	28	17–28	–	–	Nieves-Soto (1988)
A. maura	Juvenile	23.0	LD_{50}-96 h	19–35	–	22	–	33.2	Leyva-Valencia *et al.* (2001)
	Juvenile	23.0	Scope for activity, irrigation efficiency, growth	16–29	29	16–29	–	–	
	Adult	98.0	Histology, aiming for broodstock maturation	20–30	20	20–30	–	–	Rodríguez-Jaramillo *et al.* (2001)

LD_{50} -96 h, median lethal temperature at 96 h; VO_2, oxygen uptake.

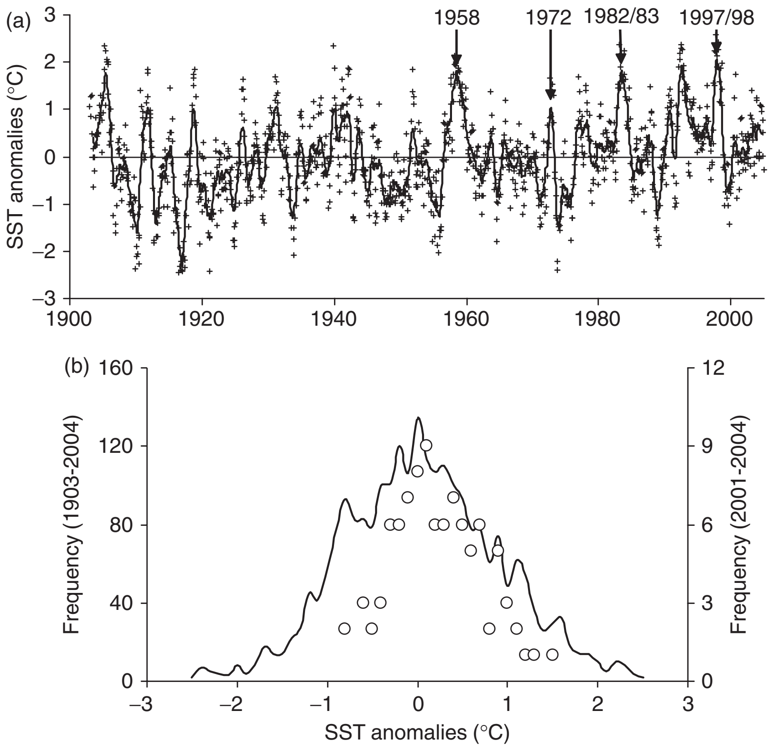

Figure 6 Sea surface temperature (SST) anomaly time-series for the Extended Reconstruction of Sea Surface Temperature (ERSST) 2° × 2° boxes off Laguna Manuela (centered at 115°W and 28°N, dots) and Rancho Bueno (centred at 112°W and 24°N, crosses), and smoothed series from the average of the two boxes' series (line) (a). The main extreme warm events of ENSO occurring during the last 50 years are shown (Schwing, Murphree & Green 2002). Frequency distribution of ERSST temperature anomalies data for the entire period (1903–2004) and those corresponding to the 2001–2004 period (open circles) (b).

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