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Impacts of Climate Change on Marine Fisheries and Aquaculture in Chile

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10.1 Introduction

Chile, according to the criteria of the United Nations Framework Convention on Climate Change (UNFCCC), is highly vulnerable to climate change since it has coastline areas of low height, arid, semi-arid and forest areas, susceptibility to natural disasters, areas prone to droughts and desertification, urban areas with atmospheric pollution issues and mountain ecosystems. Ocean acidification, variations in the sea temperature and level, as well as the increase in the frequency and intensity of extreme events, such as surges, rainfall, El Niño-Southern Oscillation (ENSO), have a direct impact on the ocean's primary and secondary production, on the biological cycles and their seasonality, on the distribution of fishing resources, and on the supporting infrastructure for fisheries and aquaculture activities, which ultimately affect the benefits of the communities dedicated to the extraction of fishing resources and small-scale aquaculture activities. The assessment of these potential scenarios will demand further

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information and knowledge regarding the ocean–atmosphere system at regional and local levels, as well as the development and application of models that allow scenarios to be established with high confidence of occurrence in the future (Fuenzalida *et al.*, 2007; Yáñez *et al.*, 2014). At the same time, in order to adapt to future weather and ocean scenarios throughout Chile, knowledge and management actions for fisheries and aquaculture should be communicated.

In Chile, fisheries and aquaculture are amongst the most important economic and socially productive activities. In 2014, the number of artisanal fishermen registered in the Artisanal Fishing Register (RPA), that is, those allowed to conduct fishing activities, was 91,632, of whom 23% (21,232) were women and 77% (70,400) were men. The same year, the Registry of Artisanal Organizations (ROA) was composed of 1,131 organizations (including Unions, Trade Associations, Cooperatives, and Indigenous Communities). The total number of registered artisanal vessels (less than 18 m in length) in 2014 was 12,105. With respect to industrial fisheries, 137 vessels operated in 2014. Regarding aquaculture, 2,223 farming centers were operating (SERNAPESCA, 2014). Over the period January–December 2014, US$6,165 million were generated by Chilean fisheries and aquaculture exports, 17.6% higher than the previous year. Frozen products represented 57.1% of total incomes, fresh-refrigerated products 25.2%, meal (fish, crustacean and mollusk) 6.9%, oil 2.6% and dry algae 2.3%, among the main products (IFOP, 2015).

Although the fisheries and aquaculture sector is an important income and employment generator for the country, its relative significance represents only 1.8% of the gross domestic product (GDP), considering only the value of the raw material; if elaborated products are incorporated, it can reach between 3% and 3.5% of the GDP. High quality aquaculture exports have been increasing over the last years, particularly those related to the salmon industry, which represent over 70% of the total export amounts. In terms of employment, the sector's global contribution reaches around 1% of national employment. Together, fisheries and aquaculture landings averaged 3.8 million t annually in the last five years (SERNAPESCA, 1978–2014). Of these landings, 74% corresponds to fisheries (1.2 million t from the industrial sector and 1.6 million from the artisanal sector), while 26% of the production (1 million t) comes from aquaculture. The main products obtained from these landings are frozen, fish meal and fresh-refrigerated. If extended periods are considered for fishing landings (over 10 years), they show a clear tendency for reduction, from 8 million t in 1994 to 3.8 million t in 2014, reflecting a deterioration of the stocks. This situation implies socioeconomic impacts such as lower incomes for fishermen and problems for food security. In this sense, from the view of vulnerability and capability of adaptation to climate change, artisanal fisheries and small-scale aquaculture are identified as those requiring further attention given their socioeconomic relationship and dependence associated with the use of environmental services. The State of Chile, through the Undersecretariat for Fisheries and Aquaculture as the administrator of fisheries and aquaculture activities, is developing the general framework for improving the adaptation capability of fisheries and aquaculture communities, and for providing policy instruments to reduce vulnerability and to make the sector more resilient to climate change.

Since late 2015, the *Adaptation Plan to Climate Change for Fisheries and Aquaculture* (SUBPESCA, 2015) has been the general framework to develop public policy strategy to establish priorities regarding adaptation to climate change, development of capabilities, research, and coordination among the interest groups at a national level. This Plan provides guidelines that enable the strengthening of institutions, in order to focus and mobilize financing and the means required for contributing to the increase of the adaptation capacity in the most vulnerable sectors, to improve socioeconomic benefits of the fisheries and aquaculture sectors, to maintain food security and to safeguard marine biodiversity for the benefit of current and future generations. The Plan had a wide consultative process in which participants included fishermen, aquaculture producers, managers, researchers, and non-governmental organizations (NGOs), and it is consistent with the General Law on Fisheries and Aquaculture and the National Adaptation Plan to Climate Change.

10.2 Institutional Framework in Chile for Addressing Climate Change

10.2.1 Chile's Vulnerability and Contribution to Climate Change

As set forth by the nine criteria of Article 4 of the UNFCCC, Chile is a country highly vulnerable to climate change because of its low-lying coastal areas, arid, semi-arid, and woodland areas, and susceptibility to natural disasters. Other factors that contribute to the country's vulnerability include the existence of areas prone to drought and desertification, its urban air pollution problems, and the mountain ecosystems of the Coastal and Andes ranges. Studies conducted in Chile in recent years that address the impacts of and vulnerability to climate change have highlighted this situation while facilitating a better understanding of the phenomenon and its potential negative effects on the country's sustainable development plans (CEPAL, 2009). Along the same lines, the 5th Report of the Intergovernmental Panel on Climate Change (IPCC, 2014), highlights the severe impacts faced by the country's resources and ecosystems, particularly by its fishing, aquaculture, forestry, livestock and farming sectors, water resources and biodiversity. With respect to CO_2 emission, Chile's global contribution of about 0.25% and its per capita emission of 4.5 t in 2012 is well below the average of 9.7 t of the OECD countries.

10.2.2 Chile's Climate Change Policy and Institutions: 1994–2016

In 1994, Chile ratified the UNFCCC and subscribed to its Kyoto Protocol, convinced that a global response was required to address a phenomenon with such important environmental consequences, particularly for vulnerable nations like Chile. Recognizing the need to coordinate local efforts and foreign policy on climate change, in 1996 the Government of Chile issued a Supreme Decree establishing the institution that would address this task. The *National Advisory Committee on the Global Climate* was composed of representatives of the public and academic sectors and its mandate provided for including other institutions and private entities. In 2006, the Committee played a key role in preparing the *National Climate Change Strategy*, the focal areas of which include adaptation, mitigation, and the promotion and creation of capacities.

In 2008, the *National Climate Change Action Plan: 2008–2012* was passed, representing a concrete step toward implementing the National Strategy. In recognition of the issue's importance, and to strengthen inter-institutional efforts, particularly in the context of international climate change negotiations, in 2009 a presidential instruction led to the creation of the *Inter-Ministerial Committee on Climate Change*. The members of this Committee include representatives from Chile's Environment, Foreign Affairs, Agriculture, Energy, Economy, Finance, Mining, Public Works, and Transportation and Telecommunications ministries. The Committee also had a Technical Group that met more frequently to address technical issues and advise the ministerial representatives.

Other changes in the public sector which contributed to the foundation of Chile's new environmental institutional structure and which have strengthened climate change-related actions in Chile are:

(i) The launching in 2005 of the country's *National Energy Efficiency Program*, later renamed the *Chilean Energy Efficiency Agency*. This public–private institution has the mission of promoting, strengthening and consolidating the efficient use of energy and coordinating and implementing public–private initiatives in different sectors that consume energy at the national and international levels.

(ii) The creation in 2008 of the *Glaciology and Snow Unit* within the Ministry of Public Works' General Water Directorate (DGA), as a notable development in the area of water resources. This Unit is intended primarily to establish and implement a national glaciology program that will develop a glacier inventory, study and monitor glaciers in Chile, define present and future responses to climate change in regard to glaciers, and identify adaptation strategies for different climate scenarios.

(iii) The Ministry of Agriculture refocused the efforts of some of its agencies toward climate change, and in 2008 created the *Council on Agriculture and Climate Change*, presided by that institution's highest authority. The Council's other members include representatives from the public, private and academic sectors.

(iv) The creation in 2009 of the Center for Renewable Energies, to serve as a technological antenna for the development of renewable energies in Chile.

(v) The creation in 2010 of the Ministry of Energy, which was formed to foster the development of a comprehensive energy policy coherent with the objectives of security, quality and competitiveness of the country's energy supply and local and global environmental protection.

The year 2010 witnessed the completion of Chile's new environmental institutional structure, a process that began in 2006 and transformed the country's multi-sectoral model, in which environmental matters were coordinated by the *National Environmental Commission* (CONAMA), into a more centralized model under the newly created Ministry of the Environment. Today, the Chilean Ministry of the Environment is the national entity responsible for working with the President of the Republic on the design and application of environmental policies, plans and programs. Also under the preview of the Ministry are all efforts to protect and conserve the country's water, biological diversity, and renewable resources through the promotion of sustainable development and comprehensive environmental policies and regulatory frameworks. One of the Ministry's major areas of responsibility in this context is the development of the country's response to climate change. For the first time the country's legislation includes a government mandate that specifically addresses this issue, affirming that, "The Ministry shall be especially responsible for proposing policies and formulating plans, programs and plans of action in the area of climate change" (Art. 70, letter h of Law 20.417 of 2010). To facilitate organizational and administrative aspects, the Office of Climate Change (OCC) was formally created with its own annual budget and permanent staff to carry out its work. The creation of this office within the Ministry of Environment was a major milestone in building the institutional structure for climate change in Chile. The OCC has been charged to develop the Chilean climate change policy and strategies along the two major axes: mitigation and adaptation, with participation in international negotiations on the implementation of the UNFCCC, coordinating the Committee of the Clean Development Mechanism's Designated National Authority, and serving, among others, as a focal point for the IPCC and the Adaptation Fund of the Unites nations.

Since its creation in 2010, the OCC has coordinated in a multi-sectoral context the preparation of nine Nationally Appropriate Mitigation Actions (NAMAS); four of these are officially registered with the UNFCCC, a National Greenhouse Gas inventory, the Second National Communication to the UNFCCC (2011), the First Biennial Update Report to the UNFCCC (2014), the National Adaptation Plan to Climate Change (2014) and three sectoral

Adaptation Plans to Climate Change for: (i) forestry and agriculture (2013); (ii) biodiversity (2014); and fisheries and aquaculture (2015). A further six sectoral Plans will be developed until 2017 for: water resources, energy, cities, health, infrastructure and tourism. The Third National Communication to the UNFCCC and the new National Climate Change Action Plans: 2016–2021 were prepared during 2016. In 2015, coordinated by the Ministry of Environment, the Chilean climate change policy goals are reported in its "Intended Nationally Determined Contributions (INDC)" to the UNFCCC of 2015, which are targeting five key issues: mitigation, adaptation, capacity building, technology development and transfer and financing.

10.2.3 National Climate Change Action Plans: PANCC-I and PANCC-II

PANCC-I: The first systematic climate policy effort in Chile was the *National Climate Change Action Plan: 2008–2012* (PANCC-I) in 2008. The former CONAMA introduced this Plan as a short-term response to the priorities and objectives of the *National Climate Change* Strategy of 2006. The Action Plan sets out a series of public policy objectives for different public entities with climate change duties and responsibilities. The Plan also serves as guide for industry, the academic sector and NGOs by setting out the topics that Chilean society as a whole should address in confronting the impacts of climate change. By limiting its implementation period to five years, the Plan is intended as a short-term measure for generating the information needed by the end of the period to prepare longer-term national and sectoral adaptation and mitigation plans. The Action Plan contains some strategic considerations that should be taken into account as Chilean society confronts the challenges of climate change. These can be summarized as follows:

- Climate change as a key issue in Chilean public policy and regulations.
- Adaptation as a foundation for Chile's future development and as an early response to the impacts of climate change.
- Mitigation as a way to improve the quality of growth, reduce overall greenhouse gas emissions and decrease the cost of adaptation.
- Innovation in Chile's financial and business sectors to increase opportunities for investment in mitigation and adaptation projects.
- Assessment of future climate change commitments and their likely effects on international trade for a long-term strategic perspective.
- Development of a basic foundation of climate change related knowledge to support decision-making. This knowledge will be generated by means of comprehensive research, systematic climate observation, and citizen training, education and awareness-raising.

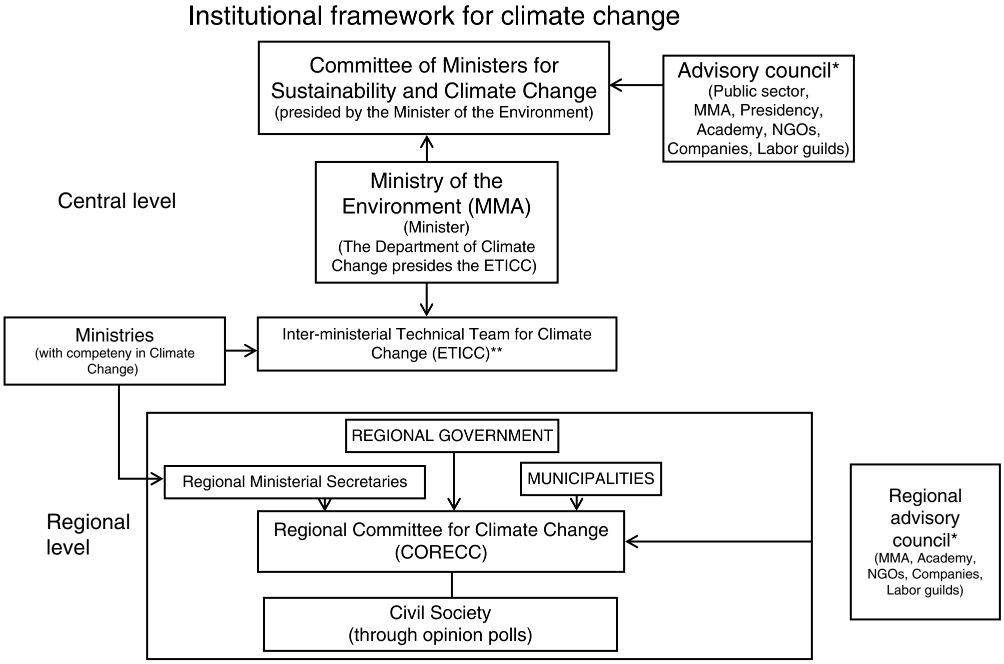
In 2014 the Chilean Government decided to update PANCC-I and charged the OCC (since 2015: Department of Climate Change (DCC)) with its elaboration of the new *National Climate Change Action Plan: 2017–2022* (PANCC-II), which will be available during the second half of 2016. The PANCC-II is organized along four major axes: mitigation, adaptation, means of implementation and climate change management on the local level, and provides an inter-sectoral institutional framework for climate change, adopted from the *National Adaptation Plan to Climate Change* (2014) which has been approved by the Council of Ministries for Sustainability and Climate Change.

10.2.4 Inter-Sectoral Institutional Framework for Climate Change

At the top of the new inter-sectoral institutional framework for climate change is the *Council of Ministries for Sustainability and Climate Change*, presided over by the Minister of

Environment, and charged with defining the national climate change policy. The elaboration and implementation of this policy to related plans, strategies and actions are in the hands of the DCC of the Ministry of Environment in close cooperation with other relevant government ministries. The DCC presides over, among others, the *Inter-Ministerial Technical Team for Climate Change* (ETICC in Spanish) which coordinates the climate change activities of the public sector and provides an annual report on these activities to the Minister of Environment. The first annual report was published in January 2015.

The ETICC is composed of the climate change focal points of 13 ministries who, for their part, head a climate change unit within their respective ministries. The implementation of the sectoral plans will be coordinated on the sectoral level through these focal points. The ETICC was put in place in July 2015 by the Ministry of Environment and still needs strengthening in its operational capacity and formal institutionalization. Due to the regional administrative structure of Chile, the regional implementation of the government's climate change policy will be headed by the Presidents (or "Intendentes" in Spanish) of the 15 regional governments. The Presidents will convoke and chair the Regional Committees for Climate Change (CORECC in Spanish) which consists of the secretaries of the regional ministerial offices, representatives of interested municipalities, and an advisory body ("Consejo Consultivo Regional" in Spanish) with representatives from the private sector, universities and civil society. The CORECCs were put in place during 2016 and are intended to be the appropriate bodies to implement and monitor climate change related actions within a multistakeholder environment. Figure 10.1 shows the concept of the institutional framework for climate change.



*Law 20417 (Law of the environment); ** Consisting of the focal points of the ministries with competency in Climate Change.

Figure 10.1 Institutional framework for climate change. Adapted from the Spanish version of "National Adaptation Plan to Climate Change of 2014" which is adopted in the new PANCC-II of 2016. Draw by the authors based on http://portal.mma.gob.cl/.

10.3 The Eastern South Pacific Climate System: Evidence and Projections

10.3.1 Oceanography in the Eastern South Pacific

The eastern South Pacific is characterized by a variety of oceanographic processes and structures which occur on different spatial and temporal scales. The South Pacific Subtropical Anticyclone (SPSA) and its seasonal latitudinal movement are primarily responsible for the surface circulation associated with the anticyclonic gyre, the position of the subtropical front, and the distribution and intensity of the South Pacific Current (Figure 10.2) (Strub *et al.*, 1998). This same anticyclone is also responsible for coastal upwelling processes along the eastern boundary of South America. Upwelling signals are markedly seasonal south of 35°S, and nearly permanent but weaker north of 24.5°S (Pizarro *et al.*, 1994; Hormazábal *et al.*, 2001; Letelier *et al.*, 2009). The currents along the South American coast are linked to the transport of water masses, which move towards the pole and the equator in overlapping, weakly mixed layers (Silva *et al.*, 2009): the subtropical waters at the surface and the more intermediate (100–400 m) Equatorial Subsurface Waters carry, respectively, higher salinity and lower oxygen concentrations poleward (Figure 10.3), whereas the Sub Antarctic, Antarctic Intermediate, and deep

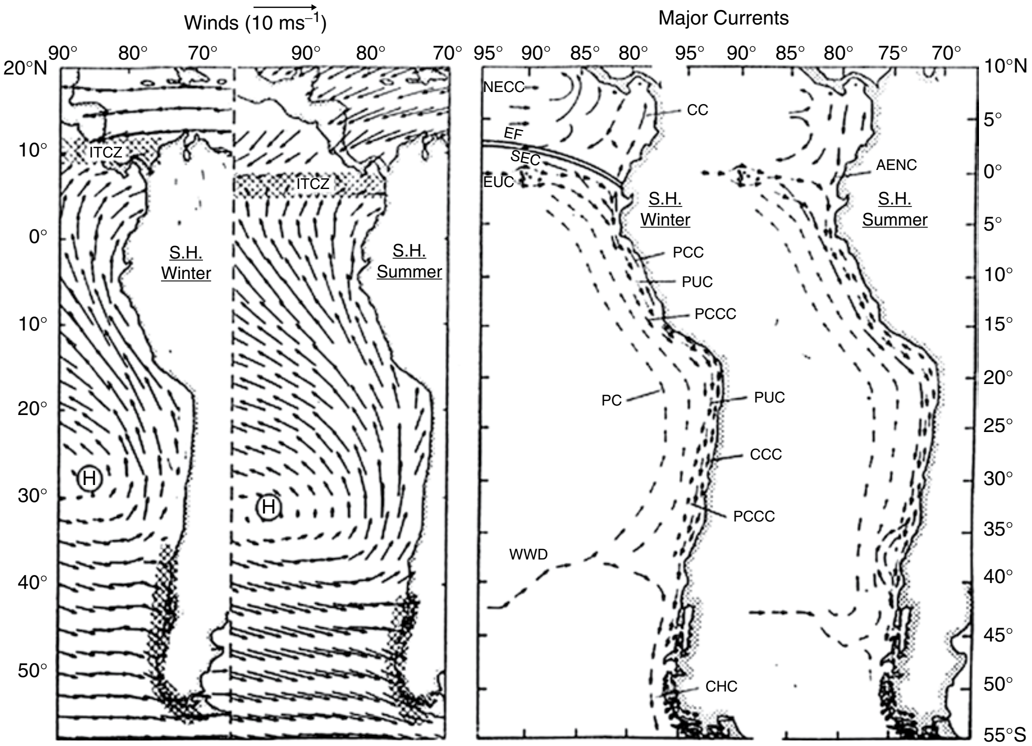


Figure 10.2 Climatological winds and currents, austral winter and summer. Winds are from NCEP reanalysis at 1,000 mb, averaged over austral summer and winter. The primary currents are the West Wind Drift (WWD), the Peru Current (PC), the Peru–Chile Countercurrent (PCCC), the Poleward Undercurrent (PUC), the Peru Coastal Current (PCC), the Coastal Current (CCC) and the Cape Horn Current (CHC). *Source:* Reproduced from Strub *et al.* (1998) with permission from John Wiley and Sons Inc.

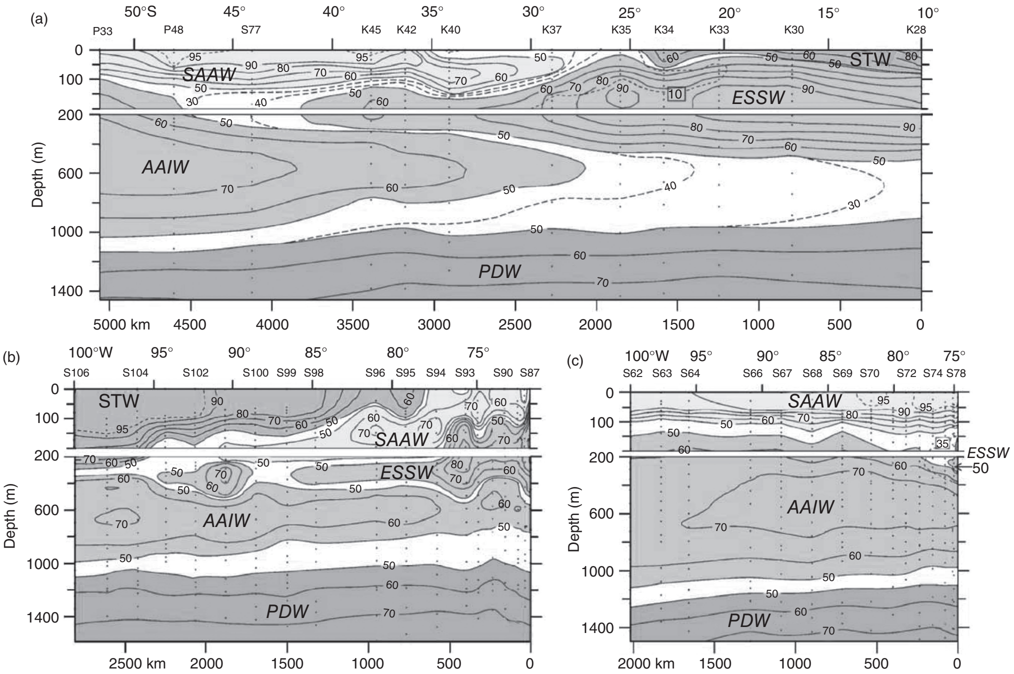


Figure 10.3 Vertical distribution of water mass percentages: (a) Longitudinal section off Peru and Chile (10°–52°S; KRILL, SCORPIO, PIQUERO expeditions); (b) latitudinal section off 28°S (SCORPIO expedition); (c) latitudinal section off 43°S (SCORPIO expedition). STW = Subtropical Water; SAAW = Sub Antarctic Water; ESSW = Equatorial Subsurface Water; AAIW = Antarctic Intermediate Water; PDW = Pacific Deep Water. *Source:* Reprinted from *Deep Sea Research Part II*, 56, Silva *et al*., Water masses in the Humboldt Current System: Properties, distribution, and the nitrate deficit as a chemical water mass tracer for Equatorial Subsurface Water off Chile, pp. 1004–1020, Copyright (2009), with permission from Elsevier.

water masses transport cooler, less saline, and more oxygenated waters equatorward (Silva, 1983; Silva *et al.*, 2009).

Intense coastal upwelling of Equatorial Subsurface Waters, which have low oxygen contents and high nutrient concentrations and are able to fertilize the photic zone (Hill & Johnson, 1974). Although the winds are relatively steady along the South American coast, upwelling centers are scattered along the coastline in association with irregular points. The major upwelling centers are found in central Peru (14°5’S) (Brink *et al.*, 1983; Gutiérrez *et al.*, 2011; Correa-Ramirez *et al.*, 2012) and central Chile (37°5’S) (Escribano & Schneider, 2007; Sobarzo *et al.*, 2007; Letelier *et al.*, 2009). A jet stream is produced in the area where the typical currents interact with upwelling zones (Letelier *et al.*, 2009; Aguirre *et al.*, 2012). The instabilities of the currents along the coast and the changes in wind direction over the continental shelf generate intense meander flows and the subsequent peeling off of mesoscale eddies that propagate westward (Hormazábal *et al.*, 2004; Chaigneau *et al.*, 2009; Morales *et al.*, 2012).

Occasionally, this area experiences disturbances caused by equatorial coastal-trapped waves that propagate towards the poles and the effects of ENSO. These disturbances can modify the vertical hydrographic structure, upwelling source water, coastal currents, and the composition of water masses, forcing the advection of warm (cold) water from the north (south) (Shaffer *et al.*, 1997, 1999; Strub *et al.*, 1998; Hormazábal *et al.*, 2001). Such phenomena also appear to be coupled to less frequent oscillations of the climate system such as the South Pacific Decadal Oscillation (PDO), which, in its positive (negative) phase can strengthen (attenuate) *El Niño* and in its negative phase (positive) phase, can intensify (weaken) *La Niña*. This positive or negative feedback helps generate warmer or colder periods that last from 20 to 30 years (Tollefson, 2014). The impact of climate change on the eastern South Pacific is unclear due to the limited number of long-term, adequately seasonal, hydrographic observations as well as our lack of understanding of the ocean–atmosphere system.

10.3.2 Evidence of Climate Change in the Eastern South Pacific

Globally, observations show that the earth is experiencing a net heat gain, in which the energy contained in the entire water column of the world oceans has increased over multiple decades (Figure 10.4). On the scale of the global ocean, an analysis of observations from the World Ocean Database 2009, XBT, and profiles from Argo buoys revealed an increment of 0.18°C in the average temperature of the water between the surface and 700 m, from 1955 to 2010. That is, the ocean accounts for 93% of the warming of the Earth’s system since 1955 (Abraham *et al.*, 2013).

Oceanic warming is not obvious in the eastern South Pacific. Indeed, historical records show a downward trend in surface temperatures along the coast between Callao, Peru (12°S), and Antofagasta, Chile (23°38’S), including Pisco (13.8°S), San Juan (15.5°S), Ilo (17°S) (Figure 10.5a), Arica (18°28’S), and Iquique (20°13’S) (Figure 10.5b). Although temperatures tend to increase beyond these latitudes, time series of sea surface temperatures (SST) between Callao and Antofagasta (12°–23.5°S) show a negative trend, revealing an apparently local cooling zone that is excluded from the process of global warming evident along the rest of the South American coast. This cooling trend was analyzed in Peru until 2010 (Gutiérrez *et al.*, 2011), and in Chile through 2015. Annual temperatures are lower in Callao (–0.02°C), in Pisco (–0.04°C), in San Juan (–0.04°C), and in Ilo (–0.02°C). Off Chile, oceanic temperatures are cooler in Arica (–0.005°C/year) and in Iquique (–0.04°C/year). This trend reverses in Valparaiso (+0.0008°C/year; 1945–2015) and Talcahuano (+0.003°C/year; 1949–2014), where the positive values are similar in magnitude to those of northern Chile. Limited data are available for the SST off Iquique, and the unusual order of magnitude of the cooling observed there could be due to an

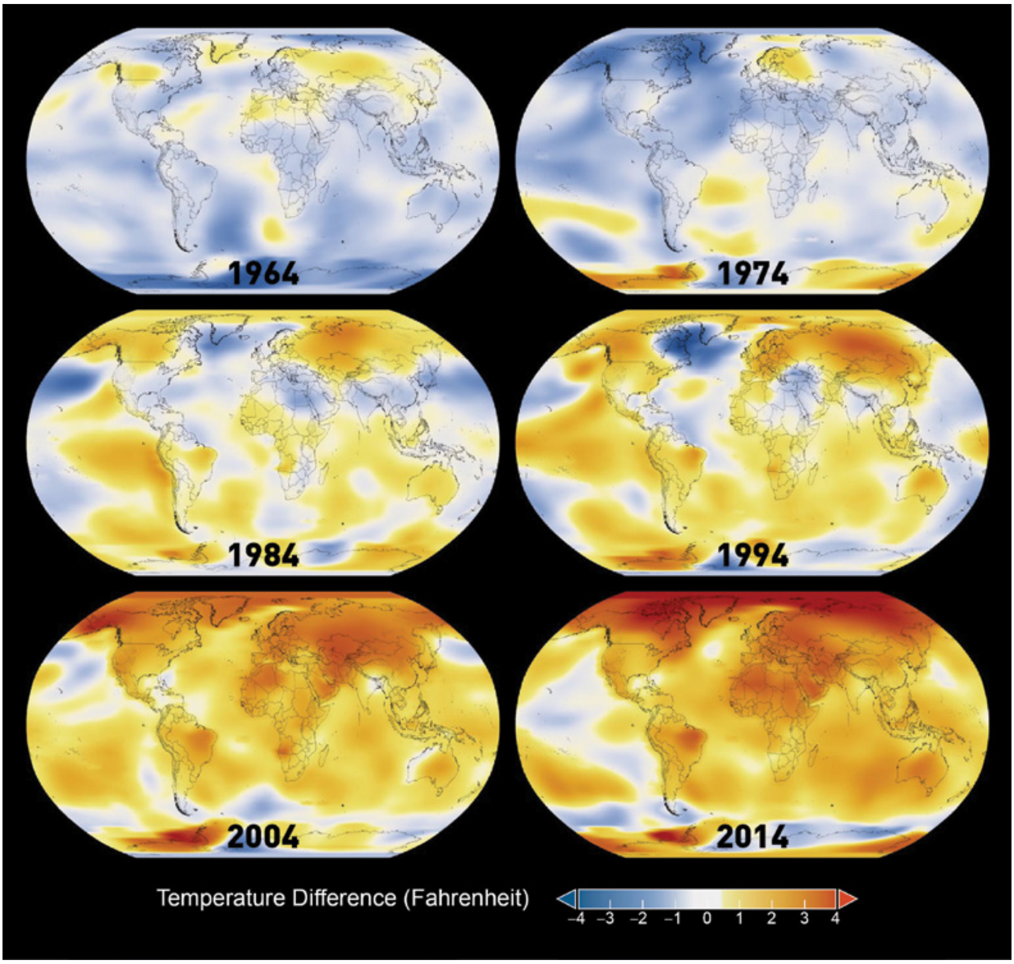


Figure 10.4 Average global atmospheric temperatures as deviations from the global mean. *Source:* http://climate.nasa.gov/interactives/climate_time_machine (*see color plate section for the color representation of this figure*).

undue influence from the negative phase of the PDO in recent decades. The rest of the series is long enough to attenuate the effect of both the PDO and ENSO cycles in historical records.

PDO may affect records shorter than 20 years because more intense and frequent *El Niño* events are now observed in the equatorial zone. The models suggest that these changes in *El Niño* events are due to climate change (Cai *et al.*, 2014; Tollefson, 2014). The marked drop in temperature is greater along the coast of Peru than in northern Chile because Peru is in an area influenced by one of the ocean's most extensive and intense upwelling centers. Gutiérrez *et al.* (2011) report evidence of significant steady cooling in the second half of the 20th century based on alkenone SST reconstructions from a high-resolution coastal sediment core off Peru.

Research suggests that this coastal cooling could be associated with the onset of the cool phase of the PDO, observed from 2001 (Figure 10.6), or to increased coastal upwelling due to increased wind stress along the coast resulting from climate change (Bakun, 1990). The PDO lasts 20 to 30 years and would explain how, in the past 10 years, lower temperatures have prevailed along the South American coast, but not why this occurs only between 12°S and 23.5°S.

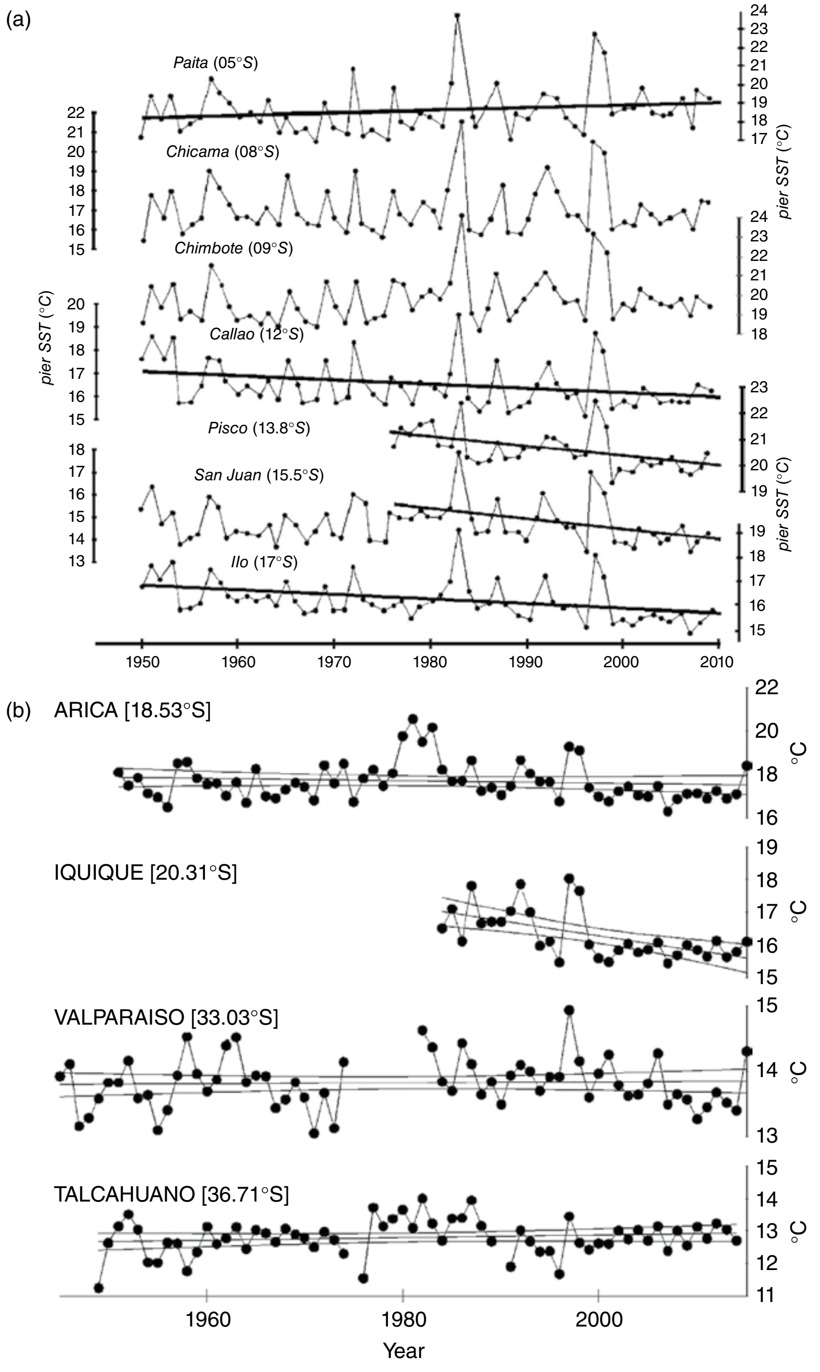


Figure 10.5 Sea surface temperature (annual means) measured in the piers (a–d). The solid lines depict linear regression fits for Callao (>1950: -0.02 ± 0.01°C y^{-1}, $p < 0.05$), Pisco (>1976, no data before: -0.04 ± 0.02°C y^{-1}, $p < 0.05$), San Juan (>1976: -0.04 ± 0.02°C y^{-1}, $p < 0.05$), and Ilo (>1950: -0.02 ± 0.01°C y^{-1}, $p < 0.05$). Reprinted from *Environmental Development*, 17, Gutiérrez *et al.*, Productivity and sustainable management of the Humboldt Current Large Marine Ecosystem under climate change, pp. 126–144, Copyright (2011), with permission from Elsevier. Below: Annual average SST in Arica, Iquique, Valparaíso, and Talcahuano. *Source:* drawn by the authors based on Centro Nacional de Datos Hidrográficos y Oceanográficos de Chile (CENDHOC) del Servicio Hidrográfico y Oceanográfico de la Armada de Chile.

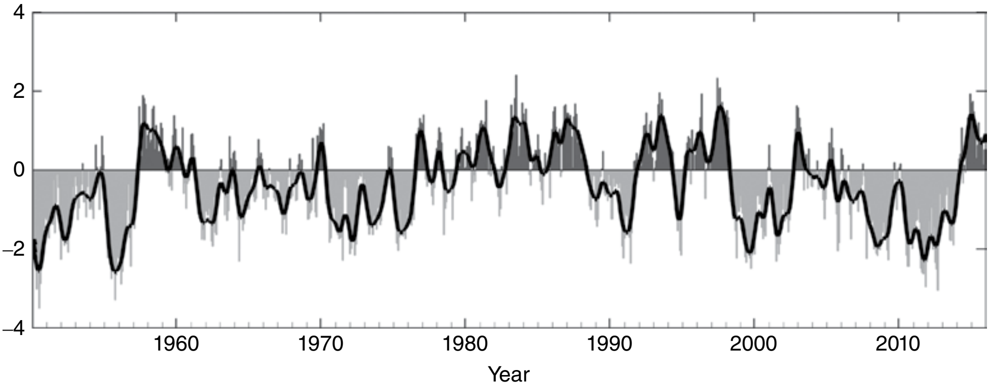


Figure 10.6 Pacific Decadal Oscillation Index, 1950–2015. *Source:* National Climatic Data Center/NESDIS/NOAA.

On the other hand, increased thermal gradients, which would intensify the SPSA and, therefore, increase coastal wind stress and upwelling, would explain why the cooling trend is limited latitudinally and zonally in the coastal strip. Increased wind stress is only predicted by the models and no clear evidence is found in the observations. A new analysis of historical data with assimilation models shows that, along the Peruvian coast, the trend is for increased upwelling-favorable winds, generating coastal cooling (Bakun *et al.*, 2010; Narayan *et al.*, 2010; Gutiérrez *et al.*, 2011; Goubanova *et al.*, 2011; Rahn & Garreaud, 2014). The results differ for Chile depending on whether the analysis considers the entire Chilean coast (neutral) or only northern Chile (+) (Garreaud & Falvey, 2009; Aravena *et al.*, 2014; Rahn & Garreaud, 2014). Thus, the major sources of wind information are based on ship measurements and modeling simulations along with observed data assimilation. These sources lead to disagreement about the present response of upwelling systems to climate change (Wang *et al.*, 2015).

The upwelling-favorable winds along the Chilean coast exhibit distinct seasonality and interannual variability. Whereas alongshore winds are present year-round in northern Chile (18°–30°S), in central and southern-central Chile (30°–41°S), upwelling is limited to spring, summer, and early autumn (Pizarro *et al.*, 1994). The SPSA is the main large-scale circulation system driving upwelling-favorable winds along north and central Chile. The year-round persistence of the SPSA and the regional land–sea thermal contrast are responsible for the constant presence of alongshore winds in northern Chile (Rutllant *et al.*, 2003). Changes in the SPSA position (especially its north/south migration in winter/summer) and intensity explain the seasonality of coastal winds in central and southern-central Chile (Fuenzalida, 1982). Muñoz & Garreaud (2005) describe an equatorward low-level coastal jet off central Chile forced by a meridional pressure gradient, ageostrophically balanced by the friction imposed by the Andes Mountains, due to mid-latitude surface anticyclones. As to ENSO-related interannual variability, upwelling-favorable winds in northern Chile are not modulated by ENSO, whereas in southern-central Chile (35°–41°S), *El Niño* (*La Niña*) causes the onset of the upwelling season to be delayed (earlier–normal) and its end to be normal (delayed) (Montecinos, 1991; Montecinos & Gomez, 2010).

The ERA 40 (Uppala *et al.*, 2005) equatorward winds along the coast of Peru have shown a significant positive trend since the 1960s. A recent work by Sydeman *et al.* (2014) confirms the intensification of upwelling-favorable winds in three major upwelling systems, including the Peru–Chile system, over the last 60 years. This finding agrees with the work of Narayan *et al.* (2010), who report the positive trend of the equatorward winds in four upwelling systems based on the meridional wind from gridded products: Comprehensive Ocean Atmosphere Dataset (COADS; Slutz *et al.*, 1985), the National Center for Environmental Prediction NCEP/NCAR reanalysis (Kalnay *et al.*, 1996), and the ERA-40 reanalysis from the European Centre for Medium Range Weather Forecast. However, based on adjusted ship-based measurements and WASWind products (Tokinaga & Xie, 2010), a study by Belmadani *et al.* (2013) showed no significant trend of the upwelling-favorable winds off Peru and northern Chile. The Belmadani *et al.* (2013) research also found a positive trend for alongshore winds off central Chile in summer and winter. On the other hand, Rahn & Garreaud (2014), based on the high resolution Climate Forecast System Reanalysis (CFSR; Saha *et al.*, 2010), reported no significant trends for alongshore winds in three prominent upwelling regions (15°S, 30°S, 37°S) since the late 1970s.

Garreaud & Falvey (2009) show a cooling trend, both for sea and air surface temperatures, for coastal areas along northern and central Chile; whereas inland, near the Andes, air surface temperatures have been warming since the end of the 1970s. According to these authors, the intensification of the SPSA and the related coastal upwelling of recent decades are probably playing a major role in forcing the cooling trend off Chile. The coastal cooling off Chile and Peru is part of a large-scale cooling of the Pacific basin, and it has been related to a slowdown (or hiatus) in global warming observed by several authors (e.g., Chen & Tung, 2014) in recent decades. Among several hypotheses, some authors suggest that the shift from the warm to the cold phase of the Interdecadal Pacific Oscillation is responsible for the cooling in the Pacific and the hiatus in climate change (e.g., Meehl *et al.*, 2013).

Scenarios A2 and B2 of the IPCC predict intensified seasonality and magnitude for upwelling-favorable winds, expanding the zone of influence of this process (Garreaud & Falvey, 2009). The upwelling season is expected to increase at higher latitudes (central Chile), e.g., an earlier onset and delayed end together with greater intensity, especially in summer (Garreaud & Falvey, 2009; Goubanova *et al.*, 2011; Belmadani *et al.*, 2013; Rykaczewski *et al.*, 2015; Wang *et al.*, 2015). This strengthening of coastal upwelling could be forced, in part, by a poleward expansion of the Hadley circulation along with the associated subtropical high pressure systems, like the SPSA. Despite spatial and temporal heterogeneity, global trends in sea level have increased approximately 1.7 to 3 mm/year in the last 20 years, with a large contribution of thermal expansion (Church & White, 2006; Abraham *et al.*, 2013). Within this context and coinciding with the latitudinal band that presents coastal cooling, sea levels are dropping along the Chilean coast between Arica and Antofagasta (Figure 10.7), although farther south, rising sea levels are in keeping with global trends. In Arica, a daily record covering 1951 through 2015 shows a decline of –0.1 mm/year; in Iquique and Valparaiso this is –0.1 and –0.02 mm/year, but with a significantly shorter series (1984–2015). To the south, in Talcahuano (1949–2014), the increase is positive (+0.098 mm/year) and of the order of magnitude found in northern Chile. No sea level data are available for the coast of Peru, so this parameter cannot be compared with the band of cooler waters in that area.

In eastern boundary systems, the presence of a subsurface oxygen minimum layer is a critical component due to the coastal contribution of nutrients produced by upwelling (Paulmier & Ruiz-Pino, 2009). This layer of water is associated with Equatorial Subsurface Waters, which project towards the poles (Silva *et al.*, 2009). In the eastern Pacific, the thickness and extent of the oxygen minimum layer decreases gradually southwards, from 3,000 km at 15°S, to 25 km at 30°S, to a thin band beyond 37°S (Fuenzalida *et al.*, 2009). The extent of this area may vary in response to climate changes such as temperature increases due to lower ventilation stemming from greater stratification, increased freshwater inputs, or decreased oxygen solubility (Paulmier & Ruiz-Pino, 2009). Hydrographic evidence from the North and Equatorial Pacific shows that the oxygen concentration in the water column tends towards deoxygenation, e.g., an increase in oxygen minimum zones (Figures 10.8 and 10.9) (Whitney *et al.*, 2007; Stramma *et al.*, 2008; Stramma *et al.*, 2010) with potential implications for the habitat throughout the ocean (Morales *et al.*, 1999; Stramma *et al.*, 2010). The preliminary results of a coastal time series around Iquique (1997–2016) show a positive trend at the depth of the 1 mL/L isoline (Figure 10.10), e.g., a shoaling (+0.13 m/year) of

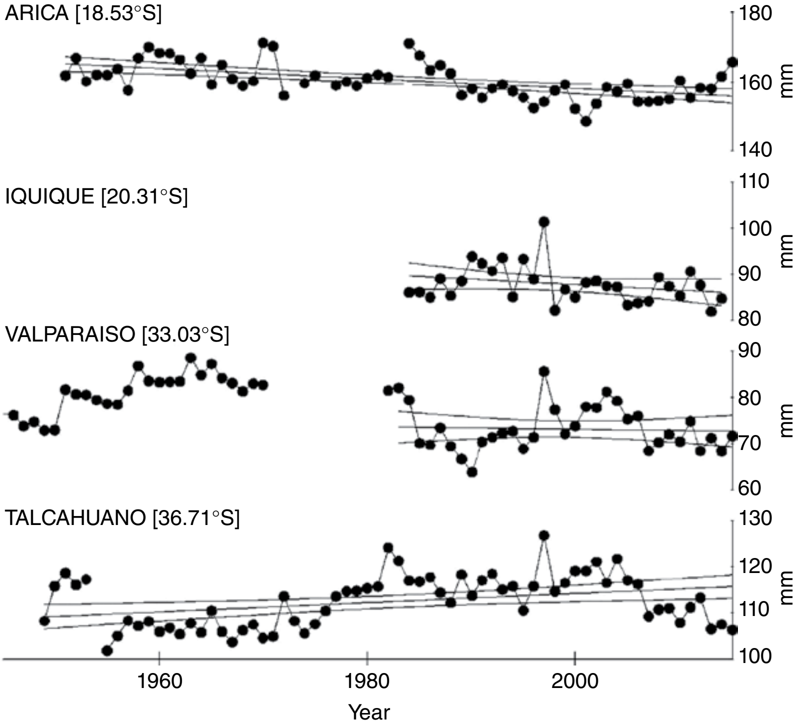


Figure 10.7 Average annual sea level in Arica, Iquique, Valparaiso, and Talcahuano. *Source:* Centro Nacional de Datos Hidrográficos y Oceanográficos (CENDHOC), del Servicio Hidrográfico y Oceanográfico de la Armada de Chile.

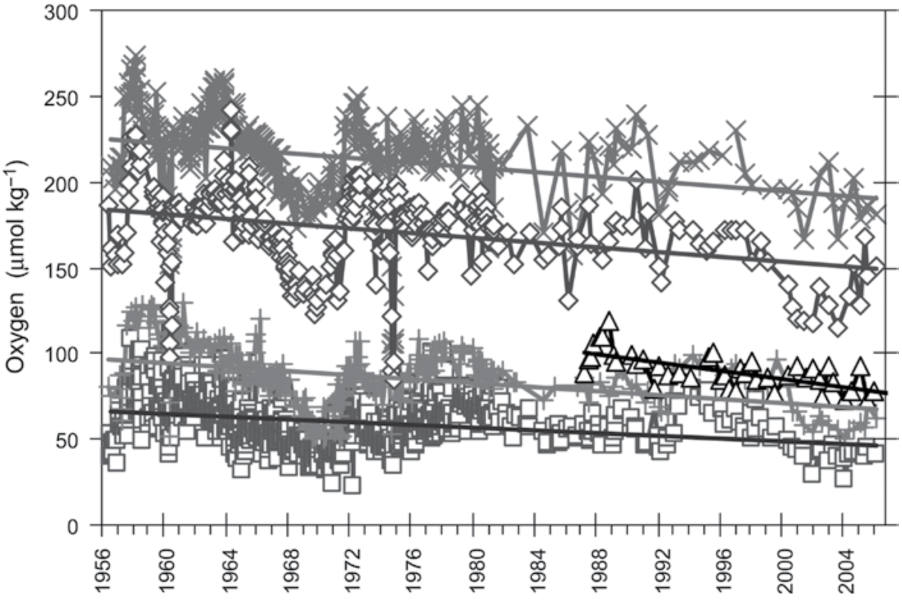


Figure 10.8 Oxygen trends at Ocean Station P on the 26.5 (X), 26.7 (◊), 26.9 (+) and 27 (□) isopycnal surfaces and at station P4 (Δ) on the 26.7 surface. O_2 declining at 1.22 μmol kg^{-1} y^{-1}. *Source:* Reprinted from *Progress in Oceanography*, 75, Whitney *et al.*, Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific, pp. 177–197, Copyright (2007), with permission from Elsevier.

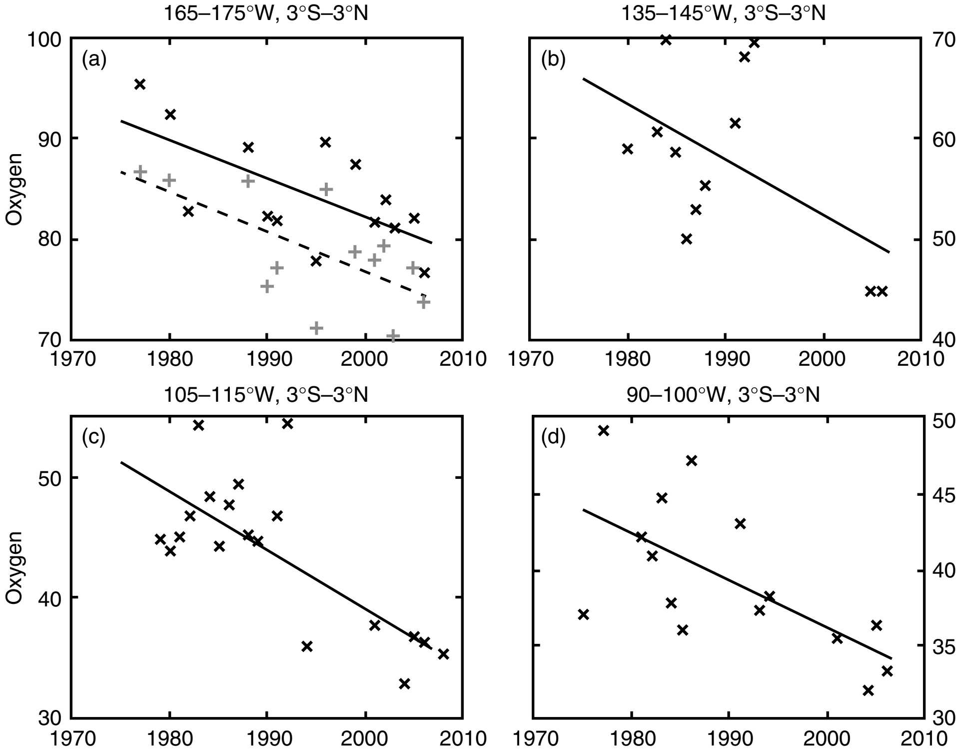


Figure 10.9 Time series of annual mean 200–700 m dissolved oxygen concentrations (x) since 1975 (μmol kg^{-1}) with linear fits. Analyzed between 3°S and 3°N at (a) 165°–175°W, (b) 135°–145°W, (c) 105°–115°W, (d) 90°–100°W. (a) Includes time series of 26.2–27.8 kg m^{-3} isopycnal layer. *Source:* Reprinted from *Deep Sea Research Part I*, 57, Stramma *et al.*, Ocean oxygen minima expansions and their biological impacts, pp. 587–595, Copyright (2010), with permission from Elsevier.

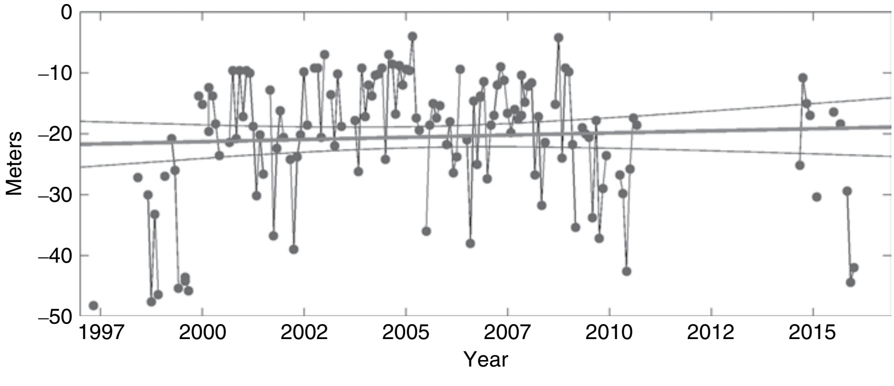


Figure 10.10 Time series of the monthly average depth of the upper limit of the oxygen minimum layer off Arica. *Source:* Instituto de Fomento Pesquero, Valparaíso Chile.

the upper limit of the minimum oxygen layer. Because this value is probably overestimated, it is being reanalyzed in terms of the function of the effects of ENSO events on the series. Nonetheless, this trend is undeniably consistent with the results of other studies that indicate the greater extent of anoxic zones in the ocean.

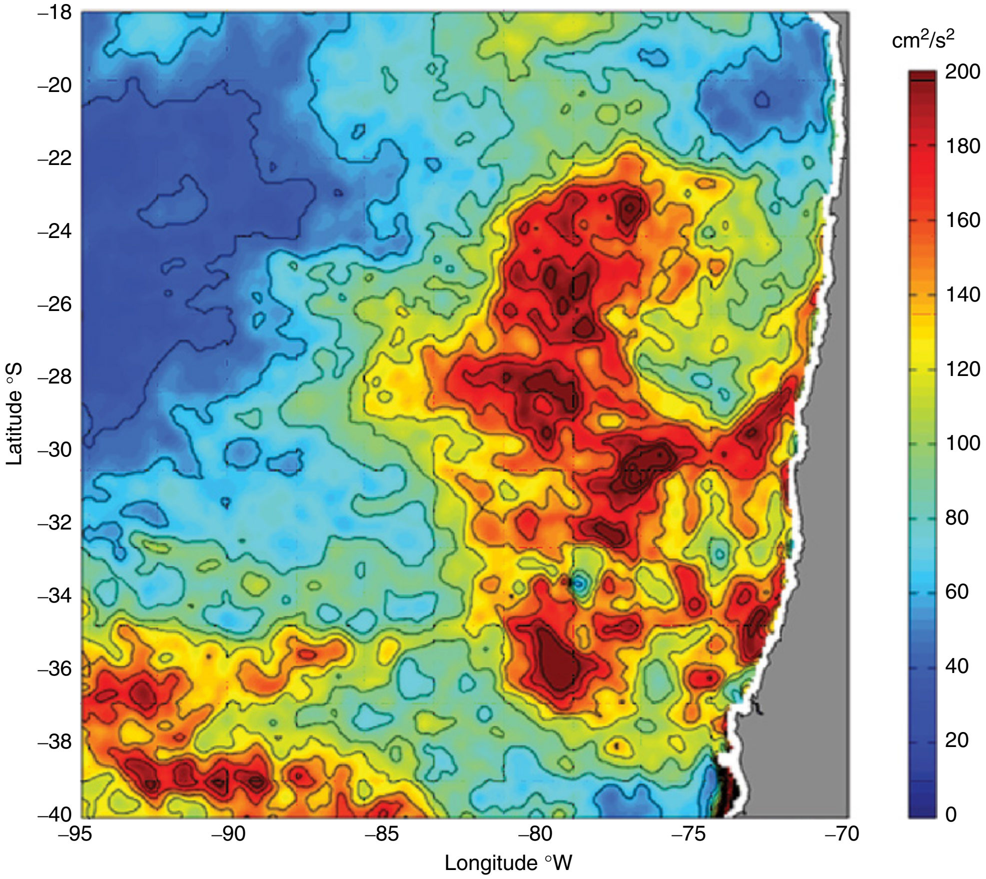


Figure 10.11 Average kinetic energy (EKE; cm^{-2} s^{-2}) calculated from the sea level extracted from the IPSL-CM4 model given the most extreme 4CO$_2$ event. *Source:* CLIPESCA, 2016 (*see color plate section for the color representation of this figure*).

10.3.3 Projections

As part of a national project associated with the effects of global warming on pelagic species (CLIPESCA, 2016), we implement a two-stage Regional Oceanic Modeling Systems (ROMS) model. In the first “normal” stage (1984–2007), the model is implemented using surface forcings, boundary conditions, and initial conditions proposed, respectively, by three international agencies: National Center for Environmental Prediction (NCEP), Comprehensive Ocean-Atmosphere Data Set (COADS) and Simple Ocean Data Assimilation (SODA). In the second phase, the coupled IPSL-CM4 climate model proposed by the IPCC is used. Projections for this model are done by quadrupling the carbon dioxide concentration in the atmosphere from 2000 to 2100. Earlier studies also use this model to study the variability of wind stress (Goubanova *et al.*, 2011) and the Humboldt Current System in the eastern South Pacific (Echevenin *et al.*, 2011).

Numerical simulations are performed using the hydrodynamic ROMS model (Shchepetkin & McWilliams, 2005; http://www.romsagrif.org/). The configuration covers a domain from 10°S to 43°S and from 87°W to the South American coast, with open boundaries to the north, south, and west. ROMS resolves primitive hydrostatic equations using vertical curvilinear coordinates (sigma) that follow the shape of the topography. We use 32 vertical layers to cover a depth of 6,000 m; these layers are distributed such that there is a higher concentration of surface layers. For this, we modify the vertical parameters $\Theta_s = 6$ and $\Theta_b = 0$. For the treatment of the lateral boundaries, we use a 2° sponge layer (~220 km). The bottom topography comes from the ETOPO2 database (Smith & Sandwell, 1997), and it is interpolated and smoothed according to the grid (200 × 400 nodes) of the ROMS model. The ROMS grid is adjusted using curvilinear coordinates with coarse resolution in the open ocean (9 km × 9 km) and fine resolution nearer the shore (4 km × 4 km). The stabilization process of the model lasts approximately three years and the calculations of the output parameters (T, S, U, V, and η) are 10 minutes each. The variables are captured every three days.

The first phase of the ROMS model provides a very good reproduction of the climatological structures of temperature and salinity when compared with historical hydrographic data from the Fisheries Development Institute (IFOP). In the second phase, the average kinetic energy is calculated from the sea level (Figure 10.11) and is sufficiently similar to reports from other authors (Hormazábal *et al.*, 2004; Echevenin *et al.*, 2011). The IPCC's fifth assessment report (IPCC, 2014) considers four possible future climates that vary according to future greenhouse gas emissions. The four representative concentration pathways (RCP2.6, RCP4.5, RCP6, RCP8.5) refer to a range of possible values of radiative forcing for the year 2100 relative to the respective pre-industrial levels (+2.6 +4.5, 6.0, 8.5 W/m^2). The RCPs estimate average global temperatures fluctuating between 0.3° and 4.8°C at the end of the 21st century.

In this paper, the ROMS fed with normal forcings (Figure 10.12a) and with four times the CO_2 concentrations (Figure 10.12b) increase, on average, ~1.7°C over 100 years. For example,

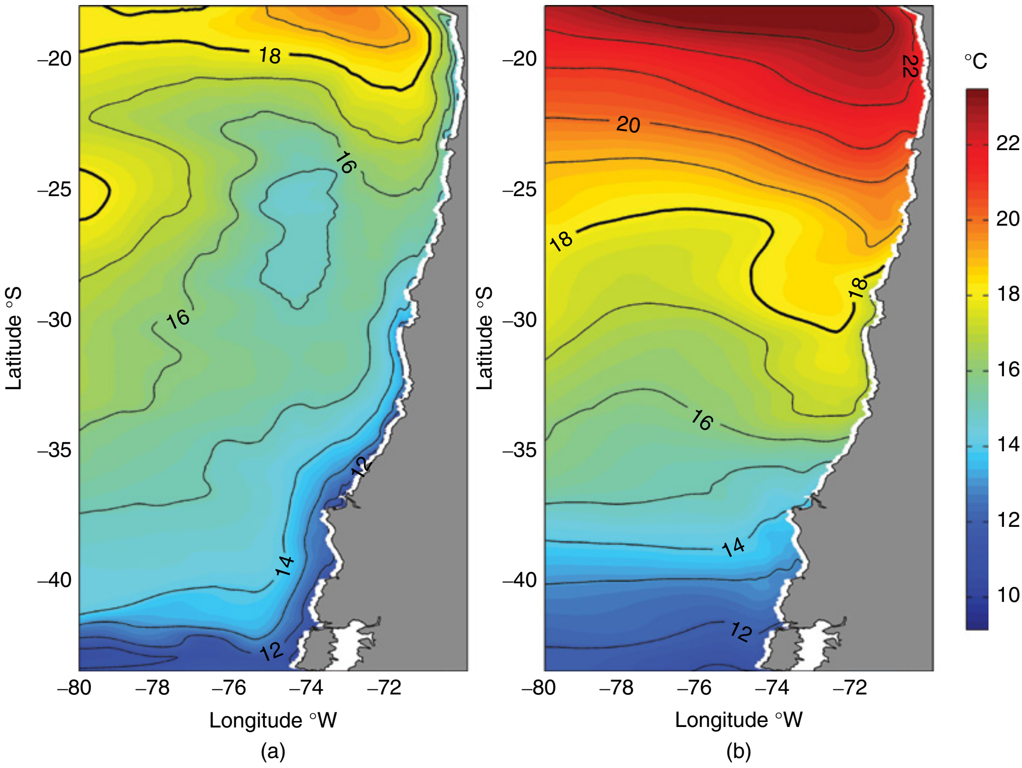


Figure 10.12 Average sea surface temperature simulated with ROMS using: (a) historic forcings (1984–2007), and (b) IPSL-CM4 forcings (2000–2100). Solid black line corresponds to the 18°C isotherm. *Source:* CLIPESCA, 2016 (*see color plate section for the color representation of this figure*).

the spatial differences in the average SST off the coast of Chile between phase 1 and phase 2 show, in particular, the 18°C isotherm moving southwards by about ~5° latitude. SST averaged over 100 years (Figure 10.12b) does not show cooling along the coast due to upwelling processes. This cooling is not simulated by any of the coupled global climate models used in the climate projections that appear in the IPCC reports. Global trends of heightened ocean temperatures and levels are associated with local opposite-phase responses due to the positive and negative feedback between atmospheric and oceanic processes. Water temperatures and sea levels have been higher in the eastern South Pacific in recent decades, except along the coastal strip between central Peru and northern Chile (12°–23.5°S). This area is experiencing the opposite phase due to a possible increase in upwelling associated with a strengthening of the SPSA.

10.4 Case Studies

10.4.1 Benthic Fisheries

> *We cannot rely just on a fishery legislation based on the unknown... let us start first managing and conserving our marine resources based on what we know relatively well, and, at the same time, explore and investigate the unknown.*
>
> J.C. Castilla

In the last decade, the Chilean coast has been reported among the most important ecosystems in terms of fishery landings (FAO, 2010), ranging *ca.* 4.1 million t year^{-1}, and almost 50% of these landings come from the artisanal fisheries operating within the first 10 miles offshore (Castilla, 2010). The artisanal fleet of the Chilean coast supplies important landings of mollusks (Table 10.1), crustaceans and other invertebrates such as sea urchins and tunicates (Table 10.2), and seaweed resources (Table 10.3). Gelcich *et al.* (2015), reported for the 2005–2012 period that the artisanal fishery extracted about 222,260 mt year^{-1} of benthic invertebrates (*ca.* US$340 million year^{-1}) and 338,389 t year^{-1} of algae (*ca.* US$250 million year^{-1}). This benthic fishery strongly relies on the exploitation of wild resources in open access areas. However, the Chilean legal framework also provides management policies such as those which allocate exclusive territorial users rights for fisheries (TURFs, hereafter), where predefined extraction quotas are based on management plans sanctioned by the fishing authority (Castilla, 2010). The TURFs system is based on common-property and co-management principles (e.g., Ostrom & Schlager, 1996), but particularly, on engaging fisher organizations to develop management plans, area surveillance and anti-poaching measures (Castilla, 1994; Gelcich *et al.*, 2015). Management plans performed for TURFs consider economically important benthic species, such as the gastropod *Concholepas concholepas*, a species that is targeted in 80% of established TURFs; keyhole limpets (70%), sea urchin (30%) and macro-algae species account for the rest (Castilla *et al.*, 1998, 2007; Tables 10.1 and 10.2). Ecological studies addressing the impacts of the TURFs policy on ecosystem sustainability suggest that these areas sustain high densities and biomass of reef fishes, macro-invertebrates, along with higher species richness, as compared with open-access areas (Castilla *et al.*, 1998; Gelcich *et al.*, 2012, 2015). Currently, there are 683 TURFs formally allocated to fisher organizations along the Chilean coast (SERNAPESCA, 2014; Figure 10.13), accounting for more than 1,100 km^2 of the nearshore benthic ecosystem, averaging *ca.* 100 h in area and separated by 4–10 km (Gelcich *et al.*, 2010). Around 90% of these TURFs are located along the northern-central Chilean coast (e.g., 18–45°S) with absence of legally established TURFs in southern Patagonia.

Table 10.1 Landings of the target mollusks resources in the benthic fisheries along the Chilean coast during 2014.

Common name			
English	**Chilean**	**Scientific name**	**Landings in 2014 (t)**
Bivalves			
Clam	Almeja	*Venus antiqua**	9,105
Clam	Taquilla	*Mulinia edulis**	1,743
Clam	Tumbao, Disco	*Semele solida**	535
Clam	Culengue	*Gari solida**	1,439
Baby clam	Juliana, Tawera	*Tawera gayi*	5,087
Razor clam	Macha	*Mesodesma donacium**	832
Sea asparagus	Huepo, navaja de mar	*Ensis macha*	2,960
Hard razor clam	Navajuela	*Tagelus dombeii**	4,317
Scallop	Ostion del norte	*Argopecten purpuratus**	4,146
Scallop	Ostion del sur	*Chlamys vitrea*	771
Chilean oyster	Ostra chilena	*Ostrea chilensis*	244
Cholga mussel	Cholga	*Aulacomya ater**	4,519
Blue mussel	Chorito, mejillon	*Mytilus chilensis**	238,827
Giant mussel	Choro zapato	*Choromytilus chorus**	2,089
Gastropods			
Key-hole limpets	Lapa	*Fissurella* spp.*	7
Key-hole limpets	Lapa negra	*Fissurella latimarginata**	887
Key-hole limpets	Lapa picta	*Fissurella picta**	13
Key-hole limpets	Lapa reina	*Fissurella maxima**	226
Key-hole limpets	Lapa rosada	*Fissurella cumingi**	32
Chilean abalone	Loco	*Concholepas concholepas**	2,250
Snails	Locate	*Thais chocolata**	682
Snails	Caracol rubio	*Xanthochorus cassidiformis**	1
Snails	Chochas	*Calyptraea trochiformis*	5
Pustular triton	Palo-palo	*Argobuccinum* spp.	258
Red snail	Picuyo	*Odontocymbiola magellanica*	5
Tegula snail	Caracol	*Tegula atra*	78
Giant rock shell	Trumulco	*Chorus giganteus*	119
		Total	281,177

* = species included in TURFs management plans.

In the context of projected climate change scenarios for the Chilean benthic ecosystem, the key achievements of TURFs, promoting the conservation of key resources and signaling a possible strengthening of ecosystem resilience through the empowerment of local communities, could be at risk. Upwelling ecosystems have been recognized as regions showing early signals of ocean acidification, de-oxygenation and warming due to the sink of anthropogenic-increased CO_2 from the atmosphere (Torres *et al.*, 2011; Gruber *et al.*, 2012). The synthesis of empirical studies suggests that these climate change projections could become evident in the decades ahead compromising the sustainability of benthic ecosystems (e.g., Feely *et al.*, 2008; Bakun *et al.*, 2015). Large extensions of the Patagonian waters are net CO_2-sink areas evidencing the compromises of ecosystem sustainability and aquaculture production performed in these areas (Navarro *et al.*, 2013). Additionally, several concomitant stressors such as land-based runoff and the inputs of pollutants (Medina *et al.*, 2005) and nutrient trough freshwater discharges (Pérez *et al.*, 2015, 2016), micro-plastics (Hidalgo-Ruz & Thiel, 2013), the presence of invasive species (Castilla & Neill, 2009), red tides (Mardones *et al.*, 2010), and overfishing are relevant along these near-shore areas.

Ocean acidification and global warming are two of the main stressors associated with atmospheric CO_2 accumulation (Solomon *et al.*, 2007; Feely *et al.*, 2008) that can have significant effects on marine resources. These effects include, but are not restricted, to well-documented alterations in marine organisms' physiology, growth and calcification rates (e.g., Gattuso *et al.*, 2015). Such responses vary considerably among species and among populations of a same

Table 10.2 National Landings of crustacean and echinoderms resources in the benthic fisheries along the Chilean coast during 2014.

	Common name				
	English	**Chilean**	**Scientific name**	**Landings in 2014 (t)**	**Stressor**
Crustaceans					
	Rock shrimp	Camarón de roca	*Rynchocinetes typus*	–	T[1,2]
	Golden crab	Cangrejo dorado	*Chaceon chilensis*	8	–
	King crab	Centolla	*Lithodes santolla*(+)	6,207	O[3,6,7], T[4,5,8]
	King crab	Centollón	*Paralomis granulosa*	2,251	T[5,9], F[9]
	Lemon crab	Jaiba limón	*Cancer porter*	667	T[10]
	Crab	Jaiba marmola	*Cancer edwardsii*	4,106	T[10], S[11]
	Stone crab	Jaiba mora	*Homalaspis plana**	110	O[12]
	Crab	Jaiba paco	*Mursia gaudichaudii*	2	–
	Kelp crab	Panchote	*Taliepus dentatus*	4	T[13,14], O[13]
	Shore crab	Pancora	*Hemigrapsus crenulatus*	1	S[18]
	Kelp crab	Jaiba patuda	*Taliepus marginatus*	30	–
	Crab	Paiba peluda	*Cancer setosus**	525	T[10,15,16], O[12,17]
	Edible crab	Jaiba reina	*Cancer coronatus**	99	T[10]
	Paddle crabs	Jaiba nadadora	*Ovalipes trimaculatus*	299	O[19]
	Rock lobster	Langosta	*Jasus frontalis*	90	P[20], C[21]
	Giant barnacle	Picoroco	*Austromegabalanus psittacus**	132	O[22], T[24], Ph[24], S[23]
	Amphipod	Pulga	*Gammarus* spp.	6	–
				Total 14,537	

Table 10.2 (Continued)

	Common name				
	English	**Chilean**	**Scientific name**	**Landings in 2014 (t)**	**Stressor**
Echinoderms					
	Sea urchin	Erizo rojo	*Loxechinus albus**	32,343	
	Sea cucumber	Pepino de mar	*Athyonidium chilensis*	60	
Tunicates	Sea squirt	Piure	*Pyura chilensis**	1,895	

1) Dupre *et al.*, 1992;
2) Correa & Thiel, 2003;
3) Alter *et al.*, 2015;
4) Anger *et al.*, 2004;
5) Calcagno *et al.*, 2005;
6) Urbina *et al.*, 2013;
7) Paschke *et al.*, 2010;
8) Paschke *et al.*, 2013;
9) Anger *et al.*, 2003;
10) Muñoz *et al.*, 2006;
11) Pardo *et al.*, 2011;
12) Fernández *et al.*, 2003;
13) Storch *et al.*, 2009;
14) Storch *et al.*, 2011;
15) Fischer *et al.*, 2009;
16) Fischer & Thatje, 2008;
17) Baeza & Fernández, 2002;
18) Urbina *et al.*, 2010;
19) Fernández & Brante, 2003;
20) Petit *et al.*, 2015;
21) Porobic *et al.*, 2012, 2013;
22) López *et al.*, 2003;
23) López *et al.*, 2005;
24) López *et al.*, 2008.

Asterisk indicates species included in TURFs management plans. Stressor refers to studies assessing the role of environmental and biotic factors on the species performance: T = Temperature; O = Oxygen; F = Food availability; S = Salinity; P = Predation; C = Currents; Ph = Photoperiod.

species (Duarte *et al.*, 2014, 2016; Navarro *et al.*, 2016). In addition, we are still far from understanding how these stressors work when combined with other sources of stress. Indeed, it is difficult to predict whether their combined effects on shellfish, for example, will follow additive, antagonistic or synergistic patterns (e.g., Kroeker *et al.*, 2013; Steckbauer *et al.*, 2015). Information gathered thus far makes it impossible to predict whether marine species will have the capacity to cope with these stressors. It is therefore a priority to assess inter- and intra-specific variability in the responses of these organisms to these stressors (Sunday *et al.*, 2011; Duarte *et al.*, 2014). Determining the biological responses to ocean warming/cooling, ocean acidification and de-oxygenation is critical to understand how marine ecosystems may be altered under future scenarios of anthropogenic global environmental change. Increasingly, the complexity of organism responses to elevated atmospheric and ocean CO_2 appears to stem, in part, from insufficient knowledge and thus appreciation of the scales of natural physical and chemical variability experienced by marine organisms in their habitats (Hofmann *et al.*, 2011).

Table 10.3 Principal seaweeds harvested in the benthic fisheries along the Chilean coast during 2014.

Common name			
English	**Chilean**	**Scientific name**	**Landings 2014 (t)**
Red algae	Chasca, chasca delgada	*Gelidium* spp.	576
Turkish towel	Chicorea del mar	*Chondracanthus chamissoi*	2,715
Sea lettuce	Lechuguilla	*Ulva lactuca*	136
Nori	Luche	*Porphyra* spp.	132
Luga spoon or short	Luga cuchara o corta, yapin	*Mazzaella laminarioides*	4,607
Gigartina radula type pig skin	Luga negra o crespa, paño	*Sacorthalia crispate*	34,693
Gigartina radula type pig skin	Luga roja, cuero de chancho	*Gigartina skottsbergii*	27,068
Gracilaria, ogonori	Pelillo	*Gracilaria chilensis*	45,144
Southern Bull-kelp	Cochayuyo, ulte, coyofe	*Durvillaea antarctica*	8,508
Giant kelp	Huiro pato	*Macrocystis* spp.	25,626
Chilean kelp	Chascón, huiro negro, coto	*Lessonia berteorana/L. spicata*[1]	219,998
Chilean kelp	Huiro palo	*Lessonia trabeculata*	60,531
		Total	429,734

1) ex *L. nigrescens.*

This is particularly true for benthic fisheries performed in coastal environments, where the majority of ecological and economically important marine resources spend all or part of their life-cycle (Harley *et al.*, 2006). In terms of these climatic stressors, benthic organisms must experience more variable habitats than organisms inhabiting open ocean areas, owing to seasonal cycles in biological productivity (Wootton *et al.*, 2008), acidic river discharges (Salisbury *et al.*, 2008), diurnal fluctuations, upwelling intensity, frequency and duration (Feely *et al.*, 2008; Bakun *et al.*, 2015), and/or human influences along coastlines (Borges & Gypens, 2010).

To confront these complexities in order to provide realistic regional climate change projections for planning appropriate management and policy responses along the Chilean coast, it is urgent that we improve our understanding about multiple interacting stressors and the potential impacts on benthic resources. Regrettably, study on the impacts of climate change and their relationships with variability of the benthic ecosystems along the Chilean coast (e.g., 18°–56°S; Figure 10.13) is still limited. Only a few direct evidence reports, from field studies, have been reported about the relationship of marine resources along spatial variation in climate stressors such as changes in temperature, carbonate chemistry and oxygen over space (e.g., Torres *et al.*, 2011; Mayol *et al.*, 2012; Ramajo *et al.*, 2013, 2015). In temporal terms, there are important limitations in the availability of coastal time series that could be associated with the productivity of marine resources on local scales (e.g., Aravena *et al.*, 2014; Lagos *et al.*, 2016). A relatively recent economic valuation of the impact of the climate change in Chile highlights the importance and vulnerability of coastal zones, benthic fisheries and aquaculture in terms of projected changes in oceanographic climate stressors and sea level changes, but this report also indicated that the information available was not sufficient to provide a probably estimation

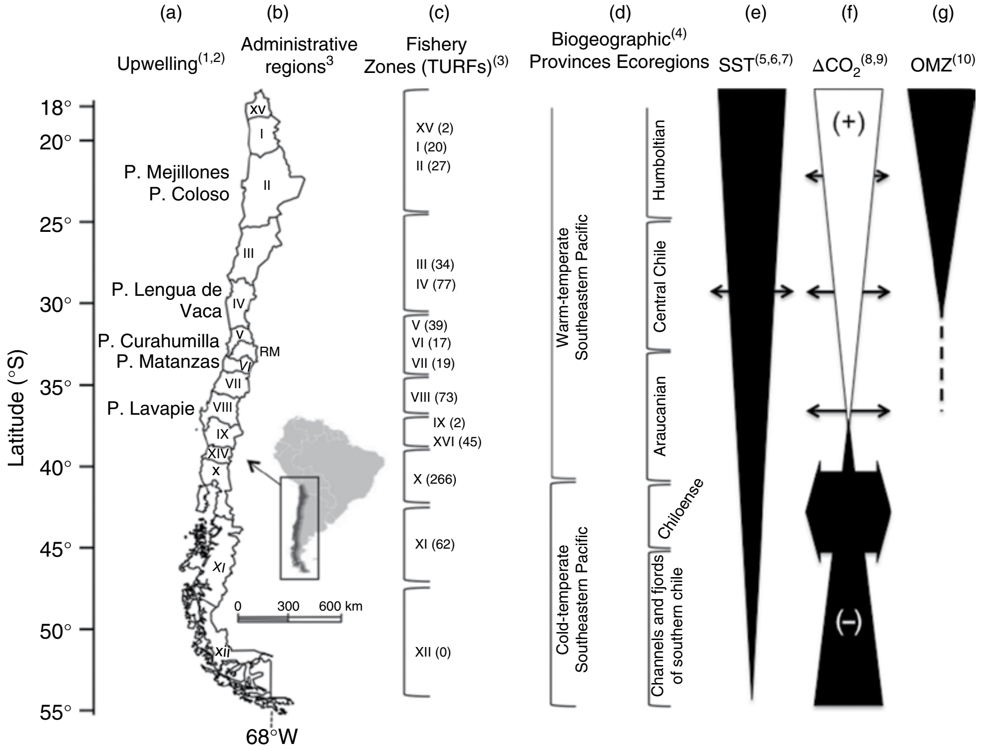


Figure 10.13 Administrative and environmental zonification relevant to the benthic fishery of the Chilean coast. (a) Major and persistent upwelling regions; (b) Superior administrative division of the Chilean territory; regions XIV and XV were created in 2007; (c) Sub-division for administration in fisheries zones; in brackets are shown the number of official territorial users rights for fisheries (TURFs) in each zone. Classification of the coastal ecosystem in: (d) provinces; (e) eco-regions. Schematic latitudinal gradients, (f) ΔCO_2 fluxes (pCO$_2$ atmosphere – pCO$_2$ seawater), where (+) and (–) indicate CO$_2$ net outgassing and sequestration, respectively. (g) Oxygen minimum zone; horizontal arrows in SST and DCO$_2$ indicate the occurrence of significant anomalies associated to upwelling regions and the inner sea of the Chiloe Island. [1]Strub *et al.* (1998); [2]Thiel *et al.* (2007); [3]SERNAPESCA (2014); [4]Sullivan *et al.* (1997); [5]Ramajo *et al.* (2013); [6]Ramajo *et al.* (2015); [7]Lardies *et al.* (2014); [8]Torres *et al.* (2011); [9]Mayol *et al.* (2012); [10]Fuenzalida *et al.* (2009).

for the occurrence of different types of impacts (CEPAL, 2009). These limitations, knowledge gaps and needs must promote the study of long-term and spatially extended research and monitoring along the diverse types of benthic ecosystems of the Chilean coast. In the meanwhile, and based on these restrictions, this chapter describes the ecology and eco-physiology of the most important resources targeted by the Chilean benthic fishery in the context of established and potential impacts of global stressors such as ocean acidification, de-oxygenation and temperature. We also describe the potential relevance of regional oceanographic variables such as changes in salinity and freshwater discharges into the benthic realm. These environmental changes are described in the context of potential biological responses of benthic resources along critical stages of their life-cycles.

10.4.1.1 Global and Regional Stressors along Benthic Ecosystems of the Chilean Coast

On a biogeographical scale, the long coastline of Chile has been classified in terms of the interaction of characteristic climate processes and geomorphological features (Figure 10.13). Along the Southern Pacific Coastal Ecosystems (SPACE, hereafter), two major provinces are distinguished based on the almost linear coastline from the 18°S to 40°S (e.g., warmer-temperate province) and the complex coast of small islands, fiords and channels in the Patagonian ecosystem (cold-temperate province). Both upwelling ecosystems and benthic fisheries TURFs, are located in the warm-temperate province, which can be subdivided into three eco-regions: the Humboltian, encompassing from central Peru (12°S) to the south of Pt. Mejillones and Pt. Coloso in the Antofagasta region of Chile (25°S), where the influence of ENSO is stronger; the central Chile eco-region from 25°S to *ca.* 33°26'S including Pt. Lengua de Vaca, Pt. Curaumilla and Pt. Matanzas upwelling centers, with moderate influence of ENSO and permanent discharges of numerous rivers; and finally the Araucanian ecoregion extending until Chiloé (41°30'S), characterized by increased river drain from melting and rainfall that influence salinity and input of sediments, and with low influence of ENSO events (Spalding *et al.*, 2007) and including the large upwelling center off Pt. Lavapie (36°30'S). During 2010, the benthic fishery along these three eco-regions accounted for *ca.* 60% of national landings with more than 40 species included in TURFs management plans (Tables 10.1–10.3). The remaining 26% came from the southern cold-temperate province, an area where target species are endemic to the region, and include Lithoid (king) crabs, mussels, the algae *Gracilaria chilensis* and the broadly distributed red sea urchin *Loxechinus albus* (ACS, 2011).

Along the warm-temperate province, coastal upwelling generates significant environmental variability in SST, salinity and carbonate systems parameters (e.g., pH, pCO_2 and carbonate saturation state Ω), which modulate ecological process sustaining benthic fisheries and generates substantial spatial structure in the benthic zone (Valdivia *et al.*, 2015). From northern (18°S) to central Chile (37°S), alongshore-coastal winds promote upwelling of cold, low oxygen, but high nutrient and high pCO_2 waters (Strub *et al.*, 1998). These upwelling ecosystems are the southern part of the Humboldt Current systems, which jointly with Peruvian coastal upwelling are hotspots of marine biological productivity yielding biomasses higher than any other eastern boundary current of the planet (Chavez *et al.*, 2008). The elevated coastal productivity is directly linked to significant fisheries and aquaculture activities in the region. Following global climate change projections, current and future alterations of these coastal upwelling ecosystems will be important since they will involve clear socioeconomic impacts. It has been postulated that an increment occurs in alongshore wind stress and coastal upwelling as a response to global warming, due to increasing thermal gradients between the hot dry coast, particularly in Peru and Northern Chile, and the adjacent cold ocean (Bakun, 1990; Bakun *et al.*, 2015). Long-term trends analysis of SST for the Chilean coast showed that from 1960 until the present, the mean maximum and minimum annual SST increased *ca.* +0.05°C and +0.18°C per decade, respectively (CONAMA, 2006; Falvey & Garreaud, 2009), while in Pisco (central Peru), the SST data indicate that after 1950 the coastal upwelling it has been characterized by cooling conditions *ca.* –0.36 ± 0.07°C per decade (Gutiérrez *et al.*, 2011). This trend is clear during the satellite era (Lima & Wethey, 2012), but its strength is still controversial (Sydeman *et al.*, 2014). Evidence suggests that climate change projections and their interaction with global climate stressors are already occurring in the upwelling regions of the Humboldt Current System, but with variable trajectories (Bakun *et al.*, 2015).

The interaction of wind with geomorphologic features such as headlands or points, determine the spatial location or *foci* of the upwelling center, influencing large areas and determining the spatio-temporal fluctuations in SST along the coast (Lagos *et al.*, 2008; Aravena *et al.*, 2014). Thus, the smooth latitudinal gradient in SST along the Chilean coast is divided into two upwelling regimes separated at 30°S. A northern region (18°–30°S) differs in terms of frequency, magnitude and seasonality of upwelling process with respect to the central region (30°–41°S) (e.g., Aravena *et al.*, 2014; Figure 10.13). In addition to these latitudinal (Lardies *et al.*, 2014; Ramajo *et al.*, 2015) and upwelling-induced variations in SST (Strub *et al.*, 1998; Aravena *et al.*, 2014), important changes in SST distributions are associated with the regular penetration of equatorial waters during ENSO events that also reduce the biological productivity in the surface waters (Chavez *et al.*, 2008). In addition, carbon system parameters measured in the Chilean coastal ocean between 20°–55°S, which showed a significant latitudinal gradient in air–sea CO_2 fluxes, change from CO_2 out-gassing in the permanent and seasonal upwelling region, but with a significant change in the direction to the fluxes at 37°S and southward areas where conditions change to net CO_2-sequestering along the Patagonian waters (Torres *et al.*, 2011; Figure 10.13). Thus, both the coastal ocean of both warm- and temperate-biogeographical provinces showed naturally low pH seawater. In the northern region, low pH occurs because upwelled subsurface waters are CO_2-enriched from the re-mineralization of organic matter in the ocean interior (e.g., Feely *et al.*, 2008; Bakun *et al.*, 2015). Currently, upwelling centers located in central Chile evidenced ocean acidification conditions projected for the year 2300 (e.g., Pt. Lengua de Vaca: CO_2 ~1000 μatm, pH ~7.6; Torres *et al.*, 2011; Lagos *et al.*, 2016). In addition, acidic conditions along Patagonian waters result from the net sink for CO_2 on the ocean surface and its interaction with changes in alkalinity induced by freshwater input from rainfall and melting, which further decrease the buffer capacity and pH in the region of channels and fiords (Torres *et al.*, 2011). The progressive occurrence of acidified, corrosive, cold SST and hypoxic conditions along SPACE of the Chilean coast highlight risk for shell-carbonate producers such as mollusks and other shellfish resources (Mayol *et al.*, 2012; Bakun *et al.*, 2015, Lagos *et al.*, 2016).

The increased primary production occurring in the surface waters of upwelling systems along the Humboltian and Central Chile eco-regions, is followed by sedimentation and decomposition in the water column, which consume the dissolved oxygen, producing the sub-surface oxygen minimum zone (OMZ, <20 mmol kg^{-1}; Diaz & Rosenberg, 2008). This OMZ influences large areas of the coastal ocean, with a very shallow upper boundary depth (*ca.* 25–50 m) in front of Peru and northern Chile, and weakening in intensity, it deepens its upper boundary near Concepcion at 37°S (Fuenzalida *et al.*, 2009; Mayol *et al.*, 2012; Figure 10.13). The occurrence of hypoxic conditions in the benthic realm may affect production and restocking processes, and in the core of the OMZ off Peru and Chile, there is a substantial reduction of the macrozoobenthos (Arntz *et al.*, 2006). Fuenzalida *et al.* (2009) suggest that the benthic fauna respond to better and lower oxygenated conditions during ENSO and *La Niña* events, respectively. This variation could result in proliferation and emigration or massive mortalities that reset the ecosystems, affecting the benthic fishery at local and regional scales (Arntz *et al.*, 2006). Therefore, under such an environmental template, it is possible to suggest that benthic fisheries occurring along the Chilean coast will require either physiological adjustment (acclimation) or evolved adaption in order to confront the acidified, cold and eventually de-oxygenated coastal habitats. This also highlights that the variability in climate stressors occurring along the SPACE provides a natural laboratory with unique opportunities to explore the biological responses of shellfish resources when confronting variable environments.

Another important global climate stressor projected to impact on benthic resources and the infrastructure and facilities associated with the fisheries is related to changes in sea level due to warming-induced expansion of the sea and ice melting (IPCC, 2014). In the case of the Chilean coast, these projections must be contrasted with the impacts of coastal up-lift and/or subsidence provoked by catastrophic earthquakes. Recent studies focused on Chile's 2010 M_w 8.8 earthquake, report the loss of inter- and sub-tidal habitats and communities in areas of subsidence and uplift, respectively, and that when the uplift process interacts with human-altered shoreline, a restoration may occur of previous habitats and communities, leaving complex and long-lasting footprints in coastal ecosystems (e.g., Jaramillo *et al.*, 2012). Further research is necessary to determine the area to be affected by sea level rising along the Chilean coast,

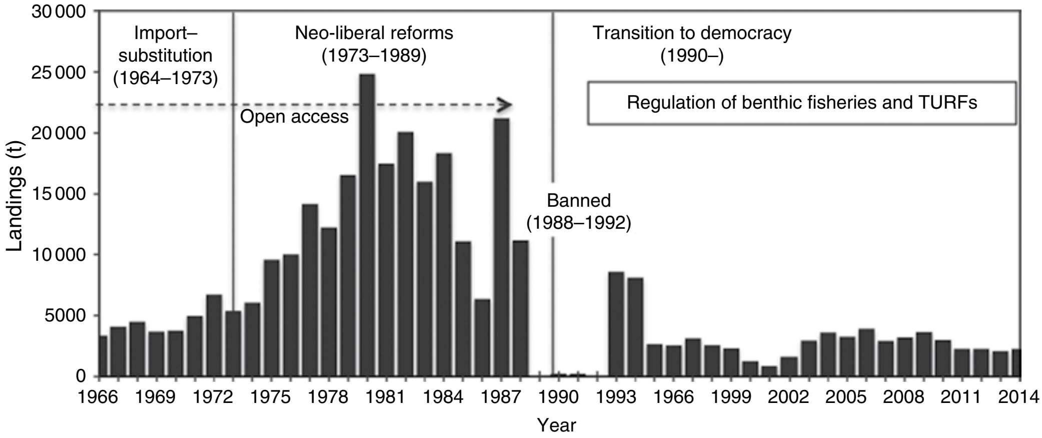


Figure 10.14 Evolution of *Concholepas concholepas* landings from 1966 to 2014 are related to changes in the Chilean economic and political models along with regulations of the benthic fisheries. Overexploitation and decline of stocks resulted in a total closure (ban) of the *C. concholepas* fishery during 1988 to 1992.

according to the climate projections and the tectonic processes regularly impacting the shoreline (CEPAL, 2009).

Finally, Chile is the world's largest copper producer, and has approximately a quarter of the world's known copper reserves. Environmental impacts associated with mining have a long history in Chile especially in the northern zone. At some sites along the coast, copper mining operations have deposited hundreds of millions t of tailings into coastal habitats over decades. Impacts have been documented, including ecological perturbations to intertidal and sub-tidal coastal ecosystems, through direct effects by toxic metals and indirect effects associated from stress produced by fine sediment loading (Medina *et al.*, 2005). Thus, the impacts of mining as a regional stressor and the potential interaction with the climate stressor deserve attention (e.g., Freitas *et al.*, 2016).

10.4.1.2 The Ecology and Fishery of *Concholepas concholepas* (Loco or Chilean Abalone)

Concholepas concholepas (Bruguière, 1789) (Gastropoda, Muricidae) is a characteristic species of rocky and exposed benthic environments (Castilla & Cancino, 1976). This species is distributed from Peru (*ca.* 6°S, commonly named "chanque") to Cabo de Hornos in Chile (*ca.* 55°S). This broad latitudinal distribution also includes Juan Fernandez Archipelago (Stuardo, 1979). Vertically, *C. concholepas* is distributed from the intertidal zone to 30–40 m in depth (Manríquez & Castilla, 2001). The broad latitudinal range along the coast of Peru-Chile of *C. concholepas* distribution implies that this species is exposed to a wide environmental variability influenced by processes operating at different spatial and temporal scales (Manríquez *et al.*, 2012; Ramajo *et al.*, 2013, 2015). Historically, the "loco" fishery has been important in terms of landings, reaching during 2014 a total of 2,041 t (SERNAPESCA, 2014). Important changes in the fisheries have occurred in the last four decades (Figure 10.14). The economic relevance of the *C. concholepas* landings is reflected by the levels of extraction occurring during the 1960s and early 1970s, when major changes were introduced by neoliberal political and economic reforms. After 1973, the landings increased substantially reaching a maximum of 25,000 t during 1980, and then the overexploitation and decline of natural stock led to a total closure (ban) of the fishery from 1988 to 1992. This regulation occurred simultaneously with a transition to democracy in Chile, and resulted in important changes in the regulation of the fishery and the introduction of co-management tools as the establishment of official TURFs. During the last decade, the landings of *C. concholepas* fluctuated below 3,000 t (Figure 10.14), but with important variability across the Chilean coast. The dynamics in the landings of *C. concholepas* reflect the need for transformation in order to buffer market pressures and overfishing, which are part of the climate changes stressors, but also the political changes with regard to the sustainability of natural resources and regulatory frameworks. Results from TURFs, showed that this co-management tool could strengthen ecosystem resilience and sustainability of benthic fisheries.

Chilean abalone is a dioecious species with reproduction that includes mating and egg-capsule deposition that takes place mainly during the first 4–5 months of the year (Castilla, 1982; Manríquez & Castilla, 2001). In *C. concholepas* sexual maturity is achieved at body sizes of about 3–4 cm (Stotz, 1997), which can be reached in a year of benthic life, and field evidence about females laying egg-capsules suggests that individuals from northern Chile reach sexual maturity at lower sizes than females from central and southern Chile (Manríquez *et al.*, 2009). Whether or not stressors such as ocean acidification and warming have consequences on the onset of sexual maturity in *C. concholepas* is still a matter of research. However, stressors, and particularly SST, may have consequences on the time needed to reach the threshold body size for the onset of sexual reproduction in this species, which might have important consequences for legal capture size that should be taken into account in the future to protect the reproductive stock.

After mating, females attach egg-capsules to the rocky substrate (Castilla & Cancino, 1976), where intra-capsular development occurs for approximately 2 to 3 months (Castilla, 1982; DiSalvo, 1988; Manríquez & Castilla, 2001; Manríquez *et al.*, 2014). Recent studies have determined that the duration of this phase shows inter-population variability, which decreased from northern to southern populations (Manríquez *et al.*, 2014). This may be attributed to SST (Garavelli *et al.*, 2014), delayed by ocean acidification (Manríquez *et al.*, 2014). Inside the egg-capsules the developing embryos need between 1–2 months for development before hatching (Castilla & Cancino, 1976). Fecundity, measured as the number of embryos/area deposited in egg-capsules, showed a reverse gradient increased in southern populations (Fernandez *et al.*, 2007); thus under increased temperature projections for southern Chile, these results indicate a positive implication in early development of *C. concholepas*. Other recent studies have found that near-future changes in pCO_2 levels will extend the intra-capsular developmental time, but reduce both hatching and post-hatching success (Manríquez *et al.*, 2014), but these results might be also modulated by near-future increments in temperature (Manríquez *et al.*, unpublished data). This suggests that projected conditions of ocean acidification may have important consequences in both decoupling hatching time of *C. concholepas* from the most appropriated oceanographic conditions for larval dispersion, and impact larval production negatively. The larvae collected from egg-capsules of *C. concholepas* showed reduced tolerance to low salinity levels. Central Chile populations tolerate salinity of 25 psu and an optimum range between 28-3 psu, while for larvae from northern Chile populations, salinity levels of 25 psu are lethal. Because freshwater inputs are largely responsible for changes in salinity along the coast (Davila *et al.*, 2002; Pérez *et al.*, 2015, 2016; Ramajo *et al.*, 2016a), these results also have implications for the marine conditions along the coast which favor habitat suitability for larval development of *C. concholepas*. This is particularly the case for the northern populations, where the projected occurrence of extreme events of precipitation and floods (IPCC, 2014), may reach the coastal zone and dilute the seawater influencing the benthic rocky shores.

After the encapsulated development, larvae of *C. concholepas* hatch and then need about 3 months to reach a competent stage (DiSalvo, 1988). The developmental time of competent larva increases from 2–3 months in northern localities (DiSalvo, 1988), to 3–4 months

(Moreno *et al.*, 1993) or even up to 1 year (Molinet *et al.*, 2005) in the southern Patagonia. This long larval period provides the opportunity for dispersion and population connectivity at regional scales, which is very important for recolonization of exploited stocks (Kinlan & Gaines, 2003). Genetic homogeneity indicates that the population of *C. concholepas* represents a single stock, and suggests that the larvae of *C. concholepas* are able to disperse over hundreds of kilometers (Cárdenas *et al.*, 2009). There is no empiric evidence that these this larvae would be able to disperse over greater scales and, based on chemical signatures of statoliths, it is suggested that different stocks may be separated on biogeographic scales (Manríquez *et al.*, 2012). This is in agreement with modeling approaches that suggest connectivity patterns and subpopulations of *ca.* 300 km along the costal of northern Chile, which is modulated by the interaction of biological and physical oceanographic processes (Garavelli *et al.*, 2014). For instance, in central Chile the larval dispersion of *C. concholepas* is modulated by the interaction of competent larval behavior with physical transport due to wind-induced advection of water masses (Stotz, 1997; Poulin *et al.*, 2002a), suggesting that this interaction may prevent offshore larval dispersion maintaining the larvae of *C. concholepas* near to their habitat of settlement (Poulin *et al.*, 2002b).

Experimental studies suggest that variability in SST (between 8°S to 15°C) impact positively on the size and abundance of newly hatched larvae in southern Chile (44°S, Moreno *et al.*, 1993; Molinet *et al.*, 2005). Although the relationship between the size and abundance of hatched larvae with salinity is weak, lower larval abundance has been observed at salinities <15–20 psu (Molinet *et al.*, 2005), which is in agreement with the low salinity tolerance recorded for encapsulated larvae (Gallardo, 1994). During this dispersive phase, veliger larvae feed on diatoms and dinoflagellates. However, environmental factors such as pH determine the filtration rates (decreasing) and modify the selectivity towards small nano-flagellates and bacteria (Vargas *et al.*, 2013).

Attempts at rearing larvae of *C. concholepas* to competence under laboratory conditions have been futile, and limited the implementation of laboratory experiments aiming to investigate the consequences of climate stressors during its pelagic larval phase. The production of newly hatched larvae from laboratory reared egg-capsules (Manríquez *et al.*, 2014) and the facility to collect late larval stages or competent larvae of *C. concholepas* from the field (Manríquez & Castilla, 2011) allowed experiments for investigating the effects of ocean acidification and temperature on relevant larval traits such as early larval survival and larval size (Manríquez *et al.*, 2014), larval swimming behavior (Manríquez *et al.*, unpublished data), and larval feeding (Vargas *et al.*, 2013). Similar experimental studies have been used to evaluate the effects of $p\mathrm{CO}_2$ levels on the capacity of competent larvae to delay settlement and metamorphosis (Manríquez *et al.*, unpublished data). The consequences of ocean acidification on these biological traits might have important implications for larval dispersion and survival in near-future scenarios. However, these results and ongoing studies should be considered in combination with other expected stressors associated with climate change such as increments in SST and salinity changes.

Competent larvae settle in the intertidal and sub-tidal zones during the spring–summer season (Moreno *et al.*, 1993). The settlement rate of *C. concholepas* larvae is highly variable across spatial scales, and it is influenced by coastal oceanographic parameters (Poulin *et al.*, 2002a, b). Spatial variability of the settlement and abundance patterns of juveniles and adults have been assessed in relation to the types of rocky habitats and intertidal levels (Stotz, 1997), human impact (Castilla & Duran, 1985; Stotz, 1997), and biological interactions such as the abundance of prey such as barnacle stands and mussels supporting early development (Di Salvo & Carriker, 1994). Other studies indicate that in the absence of these specific biological cues, the settlement can be delayed with or without consequences on early benthic survival depending on the extension of the competence period (Manríquez, unpublished data). However, it has been suggested that the highest proportion in settlement is accounted for by sub-tidal habitats between 30 to 40 m in depth. Little is known about how ocean acidification may affect settlement of marine invertebrates. Since chemosensory factors are involved in settlement of marine fish and invertebrates, ocean acidification may also affect settlement in other species such as *C. concholepas*. After settlement, cryptic shell coloration of juvenile individuals of *C. concholepas* plays an important role in preventing lethal attack of visual predators, an ability mediated by the color of the most abundant prey items occurring in the settlement habitat (Manríquez *et al.*, 2009). The potential effects of acidification and temperature on the capacity to achieve cryptic shell coloration by *C. concholepas* is still unknown, but under current investigation (Manríquez *et al.*, unpublished data). Finally, metabolic rates of juveniles also are affected by the SST gradient along the Chilean coast. Juveniles from northern areas (23°S) have elevated metabolism compared with southern populations (37°S) (Lardies *et al.*, 2014). Ramajo *et al.* (2015) report an inverse geographic pattern in the calcite: aragonite ratio recorded along the newly deposited shell margin of juveniles, increasing significantly from northern to southern populations. These results suggest that precipitation of the calcite mineral phase may be favored under lowered metabolic rates, due to the carbonate phase (calcite) being less energetically costly for the organism. In gastropods, the main structure that protects them from predators is the shell. This calcareous exoskeleton enclosing the soft body parts in these species is built of calcite and aragonite and their proportions change across ontogeny (Ramajo *et al.*, 2013, 2015). These studies suggest that biomineralization changes of *C. concholepas* can be ascribed to latitudinal variation in temperature and salinity (alkalinity) occurring along the Chilean coast (e.g., Davila *et al.*, 2002).

Finally, biotic interactions also have important individual and population consequences during the early ontogeny of *C. concholepas*. For instance, escape behavior plays an important role preventing attack by predators, and the available evidence indicates that ocean acidification speeds up this process, suggesting a positive effect on this behavioral trait (Manríquez *et al.*, 2014). In addition, fast growth leading to escape by size and predator avoidance are other important traits for juvenile survival in nature. In *C. concholepas*, the evidence suggests a negative impact on the ability of this species to perceive predation risk, but no effects on shell growth, calcification rate and prey detection (Manríquez *et al.*, 2014). This suggests that this stressor may not affect the integrity of the shell and growth in this species. However, recent studies have found that in this species the combined effect of elevated $p\mathrm{CO}_2$ levels and temperature on growth is more complex, and suggests that near-future conditions associated with climate change may affect shell growth, calcification and susceptibility to shell boring invertebrates (Manríquez *et al.*, 2016). A recent study reported negative and synergistic impacts of acidification and hypoxia on the adult metabolism of this species (Steckbauer *et al.*, 2015), indicating that climate stressor may compromise the overall organismal performance. Since *C. concholepas* is a keystone species of the rocky shores along the Chilean coast (Castilla, 1999), knowledge about the effects of ocean acidification on this species and field patterns suggest that the impact of global stressors can go beyond individual and population impacts, and involve broader effects on benthic ecosystems and the socioecological system relied upon in their production.

10.4.1.3 Fisheries of Benthic Mollusks in Soft-Bottom Habitats

The landing of Chilean soft-bottom fishery resources started in the 1940s (Techeira *et al.*, 2011). Historically, most of them were categorized as “clams” (“almejas”) and included at least nine different species (Romero *et al.*, 2011; Table 10.1). Although there have been many attempts to develop an aquaculture of soft-bottom bivalves, none of them has moved beyond a pre-market stage. Hence, the landing of these resources remains circumscribed to the exploitation of natural shellfish beds (Murillo *et al.*, 2010). The harvesting of these resources is undertaken by artisanal fishermen both in open access areas and in areas under the TURFs regimes, as described above.

On a national scale, the harvesting of clams has historically been linked to the landing of *Venus antiqua* in southern Chile (Region de los Lagos). The clam harvesting was at a developmental phase until 1967, when landings were relatively low (9,072 t year^{-1}), and were intended for domestic consumption only. This was followed by a growth phase between 1968 and 1979, when landings increased; the industry further developed, and opened up to foreign markets. The industry then underwent a phase of strong landing fluctuations during the 1980s and early 1990s, with national landings ranging between 18,143 and 36,287 t^{-1}. Then the industry faced depressed landings, reaching levels as low as 4,535 t in 2002. A slight upturn has brought landing to its current level of near 14,515 t year^{-1} (Barahona *et al.*, 2013). The exploitation of *Mesodesma donacium* ("macha") also shows several phases. A long development phase took place between 1945 and 1982 with annual landings below 4,535 t. A growth phase took place between 1983 and 1989, when landings increased up to *ca.* 15,422 t year^{-1} due to exportation to foreign markets. This period was followed by a decline in the landings (up to a maximum of 9,071 t). Since 1999, "macha" landings have remained below 3,629 t year^{-1} (Techeira *et al.*, 2011).

The harvesting of soft-bottom shellfish has been deemed secondary to resources exploited in pelagic and rocky shore habitats. At the local scale, the fishery of soft-bottom resources has been economically and culturally relevant. Thus, it is crucial to provide further understanding about the potential influence of environmental stressors on soft-bottom bivalves occurring along the Chilean coast. Chilean species are all associated with the cold-water Humboldt system, so large-scale changes in SST associated with periodic ENSO events have multiple direct and indirect impacts on these fishery resources. For the surf clam (*M. donacium*), thermal anomalies linked to ENSO have been shown to influence its life-history and population persistence (Riascos *et al.*, 2009); harvesting and landings (Ortega *et al.*, 2012); thermal tolerance and distributional ranges (Compton *et al.*, 2007). SST anomalies affect the life-cycles of southern populations of the razor clam *Ensis macha*, and combined with low salinities, increase the risk of disease in clams like *V. antiqua* populations (Aranda *et al.*, 2015). ENSO alterations on the distribution and magnitude of SST and salinity variations have been also shown to affect the spawning and larval availability of well-priced bay scallops (*Argopecten purpuratus*) (Avendaño *et al.*, 2008), in addition to their recruitment and subsequent growth in Northern Chile (Stotz & González, 1997). Temperature anomalies, have also been linked to biological stressors like biotoxins, red tides and parasitic infections affecting commercial species such as *Gari solida* (Cremonte *et al.*, 2015), *Mulinia edulis* (Alvarez *et al.*, 2010), *Mesodesma donacium* (Riascos *et al.*, 2008; Alvarez *et al.*, 2010; Lopez *et al.*, 2014), *Ensis macha* (Williams *et al.*, 2007; Orellana & Lohrmann, 2015) and the razor clam *Tagelus dombeii* (Navarro *et al.*, 2014; Fernández-Reiriz *et al.*, 2013).

Additional stressors like runoffs and chemical pollutants also play a role in the life-history of soft-bottom bivalves. For instance, variations in particulated organic matter, food concentration and/or seston are known to affect the life-cycle of commercial clams like *M. edulis* (Velasco & Navarro, 2002; Stead *et al.*, 1997). Increased deposition due to rainfall and estuarine runoffs have been found to affect the fishery and landings of *V. antiqua* and *Protothaca taca* in central Chile (Montes & Quiñones, 1999), whereas increased storm surges (linked or not to ENSO) have been shown to increase the incidence of parasites in *M. donacium* (Riascos *et al.*, 2011). Exposure to chemicals like pesticides influence the physiology of the commercial clam *Semele solida* (Srain & Rudolph, 2008). Studies on widespread stressors remain limited in scope. For instance, basic records on thermal tolerance are site-specific and, in the case of Chilean commercial clams, are restricted to *Gari solida*, *P. thaca*, *V. antiqua*, *S. solida* and the razor clams *T. dombeii* and *E. macha* (Urban, 1994). No studies have been conducted on the influence of other well-known stressors like ocean acidification and global warming on Chilean soft-bottom bivalves (see below).

As indicated above, most studies addressing the influence of ocean acidification and global warming (or their combination) have focused on commercial rocky shore species (e.g., Manríquez *et al.*, 2013; Vargas *et al.*, 2013; Lardies *et al.*, 2014). Duarte *et al.* (2014a) showed that net calcification and growth rate in *Mytilus chilensis* were both negatively affected by ocean acidification. Navarro *et al.* (2013) propose that acidification could diminish the potential production of Chilean mytilids by nearly 30% at the end of this century. Duarte *et al.* (2014a) evaluated the combined effects of acidification and warming on the same species, and documented that acidification (but not warming) affected net calcification and growth rates in the mussel. Navarro *et al.* (2016) proved that both stressors affected the scope for growth in *M. chilensis*. Similarly, Duarte *et al.* (2014a) showed that the response of mussels to acidification varied widely among different populations.

Even though some of the effects of ocean acidification on soft-bottom species have been already shown in studies elsewhere (Ries *et al.*, 2009), no such studies on Chilean soft-bottom species have yet to be found in the literature. The exception is the native scallop *Argopecten purpuratus*. This species presents a wide geographic distribution (10°N–30°S) (Avendaño, 1993). In Chile, *A. purpuratus* is the most important culture commercial bivalve with an annual production of 18,781 t (von Brand *et al.*, 2006). Due to overexploitation the fisheries collapsed during the mid-1980s, and is still banned, being replaced by production from suspended culture activities. During the last decade, the Chilean landings of mollusks in general have ranged from 272 to 453,592 t (Figure 10.14) and over the same period, the production of scallops showed a decreasing trend, with the production in 2014 of *ca.* 4,536 t, representing almost 25% of the landings recorded ten years before (SERNAPESCA, 2014). To date, *A. purpuratus* scallop studies have been concentrated on the description of larval and population dynamics (e.g., Avendaño *et al.*, 2007, 2008); genetic (Moragat *et al.*, 2001); physiology (e.g., Hégaret *et al.*, 2012) and behavior. Growth or metabolic energy studies have been lower and mainly focused on environmental variables such as salinity, temperature or feeding regimes (Martínez *et al.*, 2000; González *et al.*, 2002; Thébault *et al.*, 2008). These studies have observed that temperature and feeding regimes affect the gonadal maturation and larvae viability, thus affecting the entire reproductive process, while salinity values under 27 psu decrease the scope for growth (Navarro & González, 1998) and energetic balance of adults (Fernández-Reiriz *et al.*, 2005). In terms of carbonate system parameters, studies conclude that acidified environmental conditions imposed by coastal upwelling, in areas where this species is currently cultured, will determine physiological susceptibility and vulnerability, in terms of calcification, growth, metabolism and shell integrity, to future global warming and ocean acidification (Ramajo *et al.*, 2016a) and temperature (Lagos *et al.*, 2016) in juveniles of *A. purpuratus*. It is projected that the increased upwelling (cold and low pH; e.g., Bakun hypothesis) may compromise the shell integrity and thus the mechanical sorting performed during the thinning process of the scallops industry (Lagos *et al.*, 2016).

Although limited in scope and potential application due to obvious life-history differences, the information highlighted above on rocky shore species may shed some light on the response of soft-bottom organisms to acidification and warming. Without attempting to extrapolate those findings, such information provides some directions as to which are the most pressing questions to be addressed in soft-bottom resources. This brief overview on the effects of climate stressors on Chilean species highlights two preliminary conclusions. First, ocean acidification and warming are most likely playing (and will continue to play) a role on soft-bottom bivalves. Habitat differences, although obvious, do not overshadow life-history and shell growth pattern similarities, and so both stressors should play a significant role on the ecology and commercial management of soft-bottom resources. Second, there is no reason to expect that some of the interaction changes detected in rocky shore species in response to climate stressors would not apply to soft-bottom species as well. Such variation applies to species and population levels and constitutes an aspect that is being increasingly recognized by the scientific community. The lack of studies on climate stressor effects upon Chilean soft-bottom commercial species, also calls for much needed research, as these resources may provide interesting (new) findings on a pressing area of study. Areas to consider include, but are not restricted to, differential responses by species inhabiting different soft-bottom habitats, range distributions and their potential change, and quantitative (molecular, physiological and behavioural) responses of soft-bottom species to ocean acidification and warming.

Combined, chemical, physical and biological stressors as those identified above, introduce considerable uncertainty on the life-history and fishery of Chilean soft-bottom resources (Montes & Quiñones, 1999; Ortega *et al.*, 2012; Aburto *et al.*, 2014; Riascos *et al.*, 2009; Compton *et al.*, 2007; Defeo *et al.*, 2013). This is particularly serious for species that show a boom-and-bust dynamics, such as surf clams (*M. donacium*) and bay scallops (*A. purpuratus)* (Aburto *et al.*, 2014; von Brand *et al.*, 2006), but may well apply to other soft-bottom species that have not been consistently studied. The strength and irregularity of regional events like ENSO, add additional layers of uncertainty. The lack of proper baselines and databases on these commercial species (this applies to most species of Chilean soft-bottom bivalves) remains a major challenge for their sustainable management. It is therefore a priority to assess interspecific and intraspecific variability in the responses of these organisms to local, regional and global stressors (Sunday *et al.*, 2011; Duarte *et al.*, 2014a).

10.4.1.4 Benthic Fishery of Crustaceans

The rise of economically important crustacean benthic fisheries (e.g., shrimps, lobsters and crabs; Table 10.2) along the Chilean coast has been accompanied by an increasing number of studies of their population biology leading to the current interest in their ecology, behavior and physiology. This group is ecologically important and represents primary and secondary consumers in the marine food web and an important food source for higher trophic levels (Paschke *et al.*, 2010, 2013). For instance, crustacean species form the core of the zooplankton and can be present in vast numbers, either as pelagic larvae or as adults (Whiteley, 2011). Shellfish culture, which includes both crustaceans and bivalves reaches 20% of the global seafood production (Whiteley, 2011). However, farming of marine crustaceans in Chile is practically absent, and is only incipient in the cultivation of the river prawn (*Cryphiops caementarius*), which is constrained by the scarcity of wild and hatchery produced juveniles. Chilean benthonic crab fisheries are mostly concentrated in the southern regions (40°–48°S, where 72% of the catch is landed (SERNAPESCA, 2014). Chilean crab fisheries, which are artisanal and industrial, are sustained by around 20 species of crustaceans (Table 10.2). During the last decade, the Chilean landing of crustaceans has ranged from 8,165 to 13,154 t. There are 10 exploited Brachyuran crab species, four species of lithoids (king crabs), three lobster species, one amphipod species and one giant barnacle species (Table 10.2). The principal target species in each group is: *Cancer edwardsii*, which represents almost 78% of crab landings; the species *Lithodes santolla* (61% of lithoids); and the lobster *Jasus frontalis;* these represent together *ca.* 99% of the crustacean catch reported over the last ten years (SERNAPESCA, 2014).

Recent studies on Crustacea have reported the influence of environmental stressors such as ocean warming, deoxygenation, salinity decrease, and unpredictability of food availability on physiological performance of benthic crustaceans (Anger *et al.*, 2004; Fischer & Thatje, 2008; Paschke *et al.*, 2013; Pardo *et al.*, 2011). In general, temperature is the main studied stressor in Chilean crustaceans and their effects have been demonstrated in crustacean physiology (Paschke *et al.*, 2010; Lardies *et al.*, 2011; Urbina *et al.*, 2013) and reproduction (Calcagno *et al.*, 2005). Theoretically the costs of maintenance may have important effects on the quantity of energy available for activity and reproduction (Sibly & Calow, 1986; Angilletta, 2001). Temperature has also been recognized as a factor stimulating growth and early ovarian development in crustaceans. The evaluated impact of sea temperature increase considers consequences on growth (López *et al.*, 2003, 2008; Calcagno *et al.*, 2005); reproductive traits (Fernández *et al.*, 2003); and mating behaviour (Hall & Thatje, 2011).

In the lithodid group, the number of species remains stable or increases with increasing latitude (e.g., Arntz *et al.*, 1997; Zaklan, 2002), and several species represent economically valuable fishery resources in sub-polar regions (Lovrich, 1997). Recent studies suggested that the deviating distributional pattern of the Lithodidae among decapods is due to special adaptations of their early life-history stages to conditions of cold and food-limitation in high latitudes, namely tolerance of low temperatures and a lecithotrophic larval development (Anger *et al.*, 2003; Calcagno *et al.*, 2004; Thatje *et al.*, 2003). The southern king crab *Lithodes santolla* (Molina) is one of the most important shellfish resources in austral Chile. The species is broadly distributed along the southeastern Pacific and southwestern Atlantic coasts, stretching from the sub-Antarctic waters off the Beagle Channel. This species probably inhabits a wider range of temperatures compared to other lithodids. There is evidence indicating that migratory movements of juveniles might be related to temperature changes (Hall & Thatje, 2011). Anger *et al.* (2004) indicate that the early life-history stages of *L. santolla* tolerate moderate cold stress as well as planktonic food-limitation in winter, implying that this species is well-adapted to sub-Antarctic environments with low temperatures and a short seasonal plankton production. Calcagno *et al.* (2005) indicate that juvenile stages of *L. santolla* and *P. granulosa* are well-adapted to 5°–10°C; higher rearing temperatures (12°–15°C) should accelerate the rates of growth and maturation. Paschke *et al.* (2013) reported that age is a key factor to be considered in thermal tolerance of *L. santolla*, because the thermal tolerance can change, depending on the age/size and life-cycle stages.

SST shows a clear gradient along the coast of Chile (Thiel *et al.*, 2007; Ramajo *et al.*, 2013, 2015) and has been shown to affect several interdependent reproductive variables of brachyuran crabs; embryo oxygen consumption, embryo ventilation by females, reproductive output, and embryo loss (Fernández *et al.*, 2002). Fischer & Thatje (2008) demonstrate that the annual number of egg-masses produced by the crab *C. setosus* is primarily dependent on temperature when food is not limited, and represents a key reproductive parameter to be considered when comparisons of reproductive output and effort along latitude are performed. Fischer *et al.* (2009) demonstrate that the production of larger eggs with a high fatty acid content appears to be adaptive not only to fuel larval development, but is also as a response to prolonged egg developmental times at lower temperatures.

The rock shrimp, *Rynchocinetes typus* is endemic on the coast of Chile and commercially important in the artisanal fisheries. Correa & Thiel (2003) established that environmental and demographic variations (e.g., habitat, refuge availability, ontogenetic stage and others) might cause variations in the mating and sexual system of the shrimp. Dupré *et al.* (1992) showed the duration of embryonic development and growth of *R. typus* varies according to seawater temperature (21 days at 19°–21°C and 52 days at 13°–14°C). A contrasting effect was recorded by López *et al.* (2008) suggesting that decrease of temperature has a positive effect in the giant barnacle *Austromegabalanus psittacus* cultivated in suspended and controlled conditions, reaching higher growth rates at greater depths when conditions are associated with low luminosity.

A few studies (e.g., Steckbauer *et al.*, 2015) have evaluated how environmental stressors (e.g. ocean acidification, pollution, hypoxia) and their possible interactions may affect rock shrimps, crabs and giant barnacles and their fisheries. The studied impacts suggest that a climate-warming scenario with an increasing frequency and intensity of extreme thermal events might affect the present distribution of crustacean species (Paschke *et al.*, 2013). For example, *L. santolla* may explore higher latitudes when temperature rises, whereas as decreased temperature juveniles may search for particular colder habitats, near to the critical thermal minimum (CTmin), which might be detrimental to the population, or might allow for a gradual invasion of polar regions by pre-adapted subpolar, and perhaps deep-sea dwelling lithodid crabs. A precautionary note on this global warming scenario should be mentioned for the Chilean coast, where increasing SST is weaker there than any other part of the world (Falvey & Garreaud, 2009; Aravena *et al.*, 2014). These authors propose that the intensification of the SPSA during recent decades, which is also a simulated consequence of global warming, is likely to play a major role in maintaining cooler temperatures off the coast of Chile at a rate of −0.2°C/decade.

Oxygen uptake is considerably more expensive in water, because of the medium's density, viscosity and low capacitance for oxygen (O'Mahoney & Full, 1984). Also, temperature has a variety of effects on respiration gas exchange and acid–base regulation in crustaceans, as described by Whiteley *et al.* (1997). Among the physiological parameters correlated with environmental changes, the respiration rate and its dependence on oxygen partial pressure are very appropriate because they are strictly related to the metabolic work and energy budget of the organism that may be involved in homeostatic control mechanisms (Salvato *et al.*, 2001). Paschke *et al.* (2010) demonstrate in *L. santolla* juveniles a moderate tolerance to low oxygen availability by modifying the concentration of hemolymph proteins, allowing *L. santolla* juveniles to inhabit temporarily low oxygen zones in the deep ocean and providing an advantage for culture conditions. Urbina *et al.* (2013) determined a high tolerance of this species to aerial exposure being mainly related to adaptations to low oxygen conditions due to, mainly, the hypoxic events that occur naturally in their habitat. In brachyuran crabs, different studies demonstrate in *C. setosus* the presence of a direct link between active brood care and oxygen provision, indicating that the constraint of oxygen provision in marine invertebrates may have important ecological and evolutionary consequences (Baeza & Fernandez 2002). Moreover, López *et al.* (2003) observed that the combined effect of two functional capacities, an efficient control of water loss and anaerobic metabolism, account for the elevated capacity of the giant barnacle *Austromegabalanus psittacus* to colonize habitats often exposed to prolonged emersion periods.

Salinity may also influence reproduction and development of crustaceans living in habitats subject to fluctuations (Pequeux, 1995). For instance, *L. santolla* larvae show high survivorship at increased salinity (~35 psu). As an indirect effect of salinity, larvae decrease their pigment concentration on erythrophores (Vinuesa *et al.*, 1985). The crustacean euryhaline species present behavioral strategies that provide tolerance to salinity fluctuations in order to deal with the negative effect of hyposalinity events as is observed in the estuarine crab, *Hemigrapsus crenulatus*, which uses a compensatory behavior (e.g., increasing ingestion rates) to recover energy lost when exposed to low salinities (Urbina *et al.*, 2013). Other examples are found in the crab *C. magister* which has the ability to isolate the branchial chambers during exposure to low salinities (Sugarman *et al.*, 1983), or in other *Cancer* species which actively search for areas with higher salinities or became quiescent by closing their respiratory openings (Curtis *et al.*, 2007). Pardo *et al.* (2011), showed hyposaline tolerance in *C. edwardsii*, when burying behaviour was associated with a drop in salinity and increasing survival (up to 30%). Therefore, behavioural strategies to deal with periods of low salinity should be well-developed (McGaw *et al.*, 1999).

The lobster fishery (*Jasus frontalis*) is one of the main economic activities in the archipelago of Juan Fernandez and the Desventuradas Islands (Ernst *et al.*, 2010). During the last decade, the Chilean landings of *J. frontalis* have increased, ranging from 40 to 110 t (SERNAPESCA, 2014, Table 10.2). Porobic *et al.* (2012) showed that recruitment of *J. frontalis* larvae is determined by biological and oceanographic factors such as area, month of release, duration of larval stage and variations in intensity and presence of mesoscale processes. Porobic *et al.* (2013) determined that the gene flow of this species is primarily modulated by oceanographic factors on the mesoscale, where the constant increase in the effective size of the population is highly correlated with changes in sea level during the last glacial maximum. Additionally, Petit *et al.* (2015) determined that a biological driver such as predation is also one of the key factors affecting the juvenile benthic phase of *J. frontalis*.

Food availability has important implications for coping with stressful conditions such as temperature, salinity, and hypoxia, which has been documented in crustaceans in several studies (Somero, 2002); however how food supply could mitigate the negative effects of ocean acidification on marine crustaceans has received limited attention to date (Pansch *et al.*, 2014). A recent experimental study (Ramajo *et al.*, 2016b) reported that food availability plays a major role modulating organismal response in order to counteract ocean acidification effects by providing the energy budget needed to respond to acidification conditions. Studies in *C. magister* demonstrated that the nutritional state of crabs modulate the physiological responses to low O_2 concentration (McGaw, 2005). Thus, it is necessary to examine the effects of ocean acidification and other stressors on a wider range of species, especially those that are considered to be tolerant of ocean acidification, such as crustaceans (Whiteley, 2011). Previous meta-analyses identified significant variation in response to ocean acidification among broad taxonomic groups (Kroeker *et al.*, 2013) and show high sensitivity among heavily calcified organisms, while on the other hand the study determined an elevated tolerance among more active and fleshy organisms (e.g., crustaceans and polychaetes). Steckbauer *et al.* (2015) evaluate the combined effect of ocean acidification and hypoxia on four non-commercial crustacean species and observed a synergistic effect of pH and oxygen on their metabolic rates.

The different studies reveal that a wide range of responses of marine crustacea is affected by environmental stressors, whereas other aspects such deoxygenation and ocean acidification have received no or little attention so far. Translating the wide range of responses to ecosystem consequences, management actions, and policy decisions requires a synthetic understanding of the sources of variability in species responses to climatic change and the corresponding levels of certainty of the impacts (Kroeker *et al.*, 2013). Recent ecosystem-based management directives, as recommended by many experts, require considering fishery effects; for example, the maximum landings of king crabs in Chile were 2,500 t in 1983. During the period from 1967 to 1982, landings of king crab oscillated around 182 t, remaining almost constant since 1982. The maximum landing occurred in Chile in 1991 with approximately 3,084 t, and currently the landings of *L. santolla* and *P. granulosa* fluctuate between a total of 42,637 and 26,852 t in the last decade (SERNAPESCA, 2014). Another example of overfishing in Chilean crustaceans occurred in rock shrimp *Rynchocinetes typus* which was the subject of an artisanal fishery with traps until the 1950s, before the start of intensive shrimp trawling off the Chilean coast (Vásquez & Castilla, 1982). The fishery collapsed in the late 1990s and extraction is now limited with the objective of allowing resource recuperation. The over-exploitation of these resources years ago generated the implementation by the authorities of fishing bans for many crustaceans.

Although more information on the effects of fishing on crustacea is needed in order to a better understand the consequences of over-fishing, current information about fishing and environmental stressors, as well as their interaction, is urgent. Several environmental stressors affect the performance of crustaceans either directly or indirectly. Also, an interesting alternative is to assess how global scale stressors could affect some life-history traits of species that are not commercially important. Duarte *et al.* (2016) suggest that changes in nutritional value of algae under ocean acidification conditions induce changes in algal palatability, modifying the preference and performance of the amphipod *Orchestoidea tuberculata*, which establishes that indirect effects of ocean acidification can be equally or even more important than the direct effects. Also there is a necessity to focus on studies on the intra-specific, geographic variation in response to environmental stressors (e.g., Benítez *et al.*, 2016). Lagos *et al.* (2014) observed that *Cyclograpsus cinereus* populations from lower latitudes were significantly different from higher latitudes (central and southern Chile) which showed a higher hemolymphatic pH variation and higher Ca^{2+} level, along with lower levels of Cl^{-} and hemolymphatic lactate dehydrogenase enzyme activity (LDH), suggesting that populations from lower latitudes, which are subject to higher air temperatures during emersion, present higher homeostatic capacities than those of intermediate and higher latitudes.

10.4.1.5 *Loxechinus albus* (Red Sea Urchin)

The edible sea urchin *Loxechinus albus* is an important benthic herbivore in Chilean coastal ecosystems (Vásquez, 2007). This species is widely distributed along the west coast of South America (6°–55°S), occurring from the intertidal zone down to 100 m (Molinet *et al.*, 2012), suggesting that it has the physiological capacity to cope with environmental variation. However, the consequences associated with near-future climate change on different stages of the life-cycle of this key herbivore species are largely unknown. The species represents one of the largest urchin fisheries in the world. The over-exploitation of this fishery has led to drastic consequences on the associated marine community (Stotz, 2004). During the last decade, a decreased trend has been recorded in the landing of sea urchins on a national scale in Chile, showing a decrease from *ca.* 45,359 t during 2004 to *ca.* 29,029 during 2014 (Table 10.1).

Studies conducted with other urchin species have found negative effects of elevated $p\text{CO}_2$ levels on gonad growth and development (Siikavuopio *et al.*, 2007; Kurihara *et al.*, 2013). A negative and interactive effect of elevated $p\text{CO}_2$ and increased temperatures has been also reported in other species of urchins (Uthicke *et al.*, 2014). This suggests that ocean acidification and warming may have drastic consequences on urchin populations. The urchin *L. albus* is a free spawner species that reproduces seasonally by the release of gametes into the water column (Gutiérrez & Otsú, 1975; Guisado & Castilla, 1987; Zamora & Stotz, 1992). The reproductive season and massive spawning match the months with lower SST (Guisado & Castilla, 1987); the season changes with latitude (Vásquez, 2007). It is expected that changes in temperature and $p\text{CO}_2$ will have important consequences in sperm swimming behavior (Schlegel *et al.*, 2012), fertilization success (Moulin *et al.*, 2011), and larval development (Kurihara *et al.*, 2013). The effects of ocean acidification on sea urchins varied markedly between individuals, and suggest that some individuals will exhibit enhanced fertilization success (Schlegel *et al.*, 2012). Similar consequences are expected to happen in *L. albus*, which might impair fertilization success, normal larval development and benthic life in near-future scenarios of climate change.

In species such as *L. albus* and others in which semi-commercial aquaculture practices have been developed, there is a chance that the results derived from manipulative experiments conducted to investigate the consequences of climate change may guide future manipulative practices in order to minimize the harmful effects of near-future elevated $p\text{CO}_2$ and temperature levels. Protocol for successful hatchery production of larvae and small juveniles of *L. albus* are well-described in the literature (Bustos & Olave, 2001). In Chile, aquaculture practices have only been developed on a semi-commercial scale and most of the fisheries rely on natural stocks. The evidence also suggests that exposure of adult sea urchins to elevated $p\mathrm{CO}_2$ levels might also have negative consequences on larval, post-settlement traits, and survival (Dupont *et al.*, 2012; Chan *et al.*, 2015). The settlement of *L. albus* takes places in natural and "biologized" artificial (e.g., collectors) substrata (Kino & Kani, 2009). Small juvenile individuals feed on crustose calcareous algae, benthic diatom films, and pieces of drift algae (Vásquez, 2007). This suggests that in this species settlement cues associated with prey items that support the early ontogeny of this species play an important role. Recent evidence suggest that ocean acidification impairs the olfactory capacity to recognize chemical cues associated with predators of marine fish. Available information suggests that ocean acidification reduces settlement of the coral-eating sea star *Acanthaster planci* (Uthicke *et al.*, 2013). However, no negative consequences of the combined effect of ocean acidification and warming on the settlement success of the urchin *Paracentrotus lividus* have been found (García *et al.*, 2015). This suggests that effects of elevated $p\mathrm{CO}_2$ and temperature are species-specific.

The prey items of *L. albus* during their larval phase in nature are largely unknown. The main items that are usually used for hatchery-reared larvae of this species are *Isochrysis galbana* and *Chaetoceros gracilis* at cell concentrations ranging from 20 to 40 cells/mL/day (Zamora & Stotz, 1994). After settlement small *L. albus* feed on crustose calcareous algae, benthic diatom films, and pieces of drift algae (Vásquez, 2007). Decrease in the abundance of crustose algae (Kuffner *et al.*, 2008) and negative changes in algal nutritional quality (Duarte *et al.*, 2015) have been found in response to ocean acidification. Studies in several urchin species have reported negative effects of ocean acidification on digestion, arm morphology, swimming and feeding performance of urchin larval stages, and larval growth (Brennand *et al.*, 2010; Stumpp *et al.*, 2013). This suggests that changes induced by ocean acidification may have negative consequences on settlement and growth during the benthic ontogeny of *L. albus*. Manríquez *et al.* (2017) report that ocean acidification and warming have negative effects on the growth of small juveniles of *L. albus* and affect algal quality. The same study reports feeding preferences of *L. albus* for algae reared at present day rather at near-future conditions of ocean acidification and warming. Studies indicate that ocean acidification may impair growth in juvenile sea urchins (Shirayama & Thornto, 2005; Albright *et al.*, 2012; Manríquez *et al.*, 2017).

10.4.1.6 Aquaculture Activities Involving Suspended Aquaculture

The blue mussel, *Mytilus chilensis* is restricted from 37°S to 56°S) (Toro *et al.*, 2006) inhabiting rocky substrates from intertidal to 10 m of depth (Barria *et al.*, 2012; Molinet *et al.*, 2015). Due to its wide geographical distribution, reproductive aspects (e.g. extension or spawning season) are highly variable affecting the different life-stages of this species (Toro *et al.*, 2008). In northern Patagonia, this species represents the second resource cultured with a high socioeconomic importance; however, as with Chilean scallop, the seedling depends on both natural and cultured adult stocks. It is suggested that natural populations of *M. chilensis* are more susceptible to environmental changes than those that are cultured. For instance, mussels from natural populations invest major energy in order to cope with environmental fluctuations by increasing shell thickness and the strength of abductor muscle, which finally impact over growth rates (Valladares *et al.*, 2010). Temperature has a determining role in larval development by affecting the spawning number (Oyarzun *et al.*, 2011) and larval growth rate (Lagos *et al.*, 2012). However, other biological and physical conditions such as larval density, organic seston and chlorophyll concentration also are responsible of the larval population dynamics of *M. chilensis* (FIP 2005–18). On the contrary, salinity seems to have a minor role during this life-stage (Barria *et al.*, 2012); *M. chilensis* salinities ranged between 9 to 26 psu (Molinet *et al.*, 2005). During the settlement period, the final larval size is a result of growth rate during the pelagic stage and temperature (Lagos *et al.*, 2012), while after the settlement period, juvenile individuals are affected by fluctuations in temperature, salinity and food supply, which finally impact over several physiological responses, growth rate, some reproductive aspects and finally, the entire fitness of the species (Velasco & Navarro, 2002; Navarro *et al.*, 2003; Lagos *et al.*, 2012). Increasing $p\text{CO}_2$ (lower pH) has a negative impact over the growth rates and biomass of *M. chilensis* (Navarro *et al.*, 2013; Duarte *et al.*, 2014a,b); however, temperature seems to have a positive effect on the growth and calcification rates in juveniles and adults conferring some advantage to cope with ocean acidification (Duarte *et al.*, 2014a).

10.4.1.7 Extraction of Benthic Macro-Algae

Marine algae are an important economic resource in Chile, where they are a raw material in the local alginate, carragenan and agar industries. Over the last decades, the economic importance of seaweeds in Chile has increased dramatically, with countrywide levels of exploitation increasing from 27,000 dry t in 1991 to over 371,945 dry t in 2014 (SERNAPESCA, 2014). The collection of these species is largely important for fishermen livelihoods (Vásquez & Westermeier, 1993; Vásquez, 2008). One of the most important marine algae fisheries in Chile is that of brown kelp, which in the northern and central part of the country is comprised of two genera: *Lessonia* sp. and *Macrocystis* sp. (SERNAPESCA, 2014). 11,000 people depend directly or indirectly on the collection and harvesting of brown kelp, with an estimated total value of US $540 million (Vásquez *et al.*, 2014). Approximately 75% of this estimated economic value is accounted for directly by the kelp harvest, while associated-species fisheries account for 15% (Vásquez *et al.*, 2014). Hence, any potential detrimental effect of climate change on brown kelp populations in Chile may have profound ecological, social and economic impacts. The temporal trend in the landings of three brown kelp species illustrates the steady increase in commercial landings (SERNAPESCA, 2014). Up until 2002, brown kelp harvest was mainly sustained by natural mortality, with plants cast ashore being collected by artisanal fishermen (Vásquez, 2008; Vásquez *et al.*, 2012). After 2002, the species of major economic importance were the *Lessonia nigrescens* complex (González *et al.*, 2012), *L. trabeculata* and *Macrocystis* sp. (Vásquez, 2008; Vásquez *et al.*, 2012). All three have been intensively harvested in coastal areas between 18°S to 32°S as raw material for alginate extraction (Vásquez *et al.*, 2012).

Many seaweed species of economic importance also fulfill important ecological functions in coastal marine ecosystems. This is also the case for brown kelp. Along the northern coast of Chile, coastal intertidal and shallow sub-tidal ecosystems are dominated by these three species of brown kelp, which are important sources of habitat and shelter, providing breeding grounds for many species of invertebrates and fish which are found associated with the brown kelp holdfasts, both in sub- and intertidal habitats (Vásquez & Vega, 2005). Brown kelp aid larval settlement and recruitment of juveniles and adults of a diverse array of taxa including limpets, loco, sea urchins and rockfish (Vásquez *et al.*, 2001; Vega *et al.*, 2005). These algae have a distinct latitudinal distribution. *L. trabeculata* is an endemic species of the coast of Chile (23°–41°S), with no other registered distribution point. On the other hand, *L. nigrescens* is found throughout the Chilean coast from Arica to Cape Horn (18°–55°S). Recent research has shown this latter species to be a species complex (González, 2012). *M. integrifolia* is distributed from Arica to Concepción (18°–36°S). From a phytogeographical perspective, the original species *Lessonia nigrescens* has been described as distributed in the sub-Antarctic regions, including the Falkland Islands, Heard and Kuerguelen Islands, while *M. integrifolia* is a species with a wide distribution in temperate regions of the eastern Pacific Ocean, both in North America and the South Cone of America.

All these three species of brown kelp have complex life-cycles, with an alternation of heteromorphic generations. Spore production is carried out in structures in sporophyte fronds, called *sori*. A large spherical cell, where meiosis is performed, generally forms these unilocular organs, producing four or more haploid spores (always in multiples of four) (Mansilla & Alveal, 2004). These spores are released to the water column and eventually recruit on available rocky substrates, allowing the establishment of microscopic gametophytes. These release haploid gametes, which after fecundation will give rise to the juvenile sporophytes. In these brown kelps, both the zoospores and the male and female gametes are dispersive phases, which are transported by the surrounding water column. Both settled gametophytes and the fertilized zygote are sessile, and are associated with rocky substrates. Zygotes give rise to juvenile and adult sporophytes, which develop their life-cycle in association with rocky substrate. The complex life-cycle of these kelp species is characterized by different life stages which exhibit unique combinations of morphology, physiology and size, which enable them to exploit two broadly different types of essential habitats: (i) benthic habitat of rocky intertidal and sub-tidal substrates; and (ii) neritic habitat in the coastal ocean. As a result, the species are able to disperse over long distances over the water column (Bobadilla & Santelices, 2005).

Due to their sizes and low densities in the field, the microscopic stages of these species of macroalgae (both dispersive and sessile) are not easily studied. The most common approach is the collection and concentration of propagules by filtration in water samples, followed by culture under controlled laboratory conditions. Studies on *L. nigrescens* have shown that the effect of concentrations of nutrients, specifically nitrate and phosphate, were crucial for adequate development of different stages (Hoffman & Santelices, 1982; Hoffman *et al.*, 1984). The development of fertile gametophytes was seen to occur at intermediate, optimal concentrations, with higher values, as in the case of nitrate, inhibiting spermatogenesis (Hoffman & Santelices, 1982). Hoffman *et al.* (1984) found that both nutrients interact with each other, determining the morphology and fertility of the gametophytes, supporting the hypothesis that the development of sporophytes occurs under particular nutrient concentration conditions. Avila *et al.* (1985) evaluated the effects of different combinations of temperature, photon flux density and photoperiod on the development of meiospores of *L. nigrescens* from Pelancura (central Chile, 33°32′S–71°38′W). An important result is that the different stages of development presented different ranges of tolerance to changes in the abiotic factors evaluated. So while it was observed that meiospores develop in relative independence of the conditions used, the gametophytes presented two development patterns under these conditions. One way involves multicellular filaments which remain sterile for extended periods, while the second involves gametophytes with few cells which rapidly give rise to fertile reproductive structures (Avila *et al.*, 1985). The process of fertilization occurs in a restricted range of conditions. The sporophytes are morphologically normal in most of the environmental conditions in which they develop, but the higher growth rate is obtained at 10°C, with a photoperiod of 12 h, 50 µE m^{-2}s^{-1} and average concentration of nutrients (0.1–0.5 pmol P1^{-1} and 10–50 pmol N 1^{-1}). Thus, optimum performance is determined by interactions between the various environmental factors (Hoffman *et al.*, 1984; Avila *et al.*, 1985). Results suggest that potential impacts of resource changes may interact with environmental shifts due to climate change, such as increase in surface water temperature. A crucial factor that emerges from these studies is the importance of temperature for microscopic stages of brown algae in the *L. nigrescens* complex. A similar study on the reproductive phenology of *L. trabeculata* examined seasonal changes of morphological and reproductive characteristics of macroscopic and reproductive gametophytes and sporophytes, using comparative cultures of spores (Tala *et al.*, 2004). While the authors were able to determine that this species is perennial, with presence of reproductive tissues throughout the seasonal cycle, they did find differences in reproductive phenology over time and between populations (Tala *et al.*, 2004). The size of the fronds presents increases in spring and summer, while their reproductive potential (area and proportion of reproductive tissue and release of spores) increases in autumn and winter. The success of zoospores released in spring–summer was less than that of zoospores released in autumn. Thus, the development of different phases of the life-cycle of *L. trabeculata* may be affected by local conditions, as well as by seasonal changes. These seasonal and environmental responses may be understood as part of the adaptations which allow the species to breed throughout the year, and enables persistence despite a high mortality rate of the macroscopic sporophytic life stages (Tala *et al.*, 2004). The success of the microscopic phases depends on local conditions, being modulated by seasonal variation. The reproductive pattern observed in *L. trabeculata* resembles the one described for seasonal variation in reproduction of algae in cold and temperate environments, where maximum growth is observed in spring and summer, and a maximum reproduction in autumn (Tala *et al.*, 2004) is observed. These results have been supported by experimental assessment of the role of irradiance and temperature on gametogenesis in *L. trabeculata* (Murua, 2010). Examination of the development of microscopic stages in this species showed the effect of latitudinal and seasonal variability, with a significant impact of irradiance–temperature effect. Again, environmental temperature has been shown to be one of the main environmental factors that modulate the various reproductive variables (Murua, 2010).

The macroscopic juvenile and adult sporophytes of these three species share the same rocky exposed habitats along the coast of Chile. These are intertidal benthic habitats in the case of *L. nigrescens* and *L. trabeculata*, and subtidal benthic habitats in the case of *L. nigrescens* and *M. integrifolia* (Molinet *et al.*, 2005). Within these habitats, significant spatial variability in density and population size structure may be observed, such as in *L. nigrescens* (González, 2002). This likely reflects the role of adult and juvenile mortality as well as the heterogeneous rate of success for the microscopic forms. One of the key factors in determining growth rate and fecundity of the macroscopic life stages is environmental sea temperature. In addition to temperature, the irradiance or availability of solar energy is also of crucial importance for the juvenile and adult macroscopic forms, determining the amount of solar energy available for photosynthesis (Murua, 2010). The characteristic pattern of penetration of the visible light spectrum then defines a range of depths in which there is availability of energy for carrying out the process of photosynthesis, defining a restriction on depth distribution. However, given the importance of productivity and the presence of particulate matter in absorbing the energy of the visible light spectrum, the pattern observed in the field is dynamic, and depends heavily on productivity and oceanographic dynamics of the area being studied. This helps to constrain the range of depths to which a photosynthetic organism can develop successfully, and is reflected in bathymetric restrictions on the distribution of brown kelp. Another important variable for these species of brown algae is seawater salinity. Factors such as desiccation, water movement, light and temperature may trigger the release of algal spores and their viability. Santelices (2002) showed that salinity could affect polyspermy and viability of gametes. Another potential effect may be alterations in the rate and efficiency of photosynthesis in macroscopic sporophytes. Variations in salinity found in the ocean are a consequence of the origin of the water masses and may be affected by proximity to the discharges of rivers and inland watercourses. The intrusion of inland water or upwelling not only alters seawater salinity, but may also shift the chemistry of the seawater through ocean acidification, altering the balance in the carbonate system as a result of decreased seawater pH. In conjunction with these physico-chemical variables, macroscopic macroalgae may also respond to the impact of changes in the concentration of nutrients. While algae have the ability to store nutrients at a cellular level, temperate seas often show important fluctuations in the availability of nutrients, and hence these may become limiting for the development and physiological functioning of these plants, limiting the growth of algae (Edding *et al.*, 2006). This situation usually occurs in late summer when the supply of nutrients to water masses is poor, which may then be reflected in different processes such as reduced growth and fertility (Murua, 2010). In a similar way to what has been discussed for microscopic stages of brown algae, nutrient concentrations may also impact or limit the growth and fecundity of macroscopic forms. While experimental approaches have focused on macronutrients (those nutrients found in sea water in concentrations greater than 0.02 mmol kg^{-1}), there is also room for potential for effects of micronutrients (those nutrients found in concentrations from 0.5×10^{-6} mmol kg^{-1}). However, these physico-chemical and environmental variables do not change independently in nature, and may often covary as a reflection of mesoscale or global scale events. One of these events is ENSO, which in addition to altering the physico-chemical properties of algae conditions also causes ecological impacts of great magnitude. In Chile, ENSO effects on coastal communities in the north have been well-documented from the occurrence of *El Niño* 1982–1983 onwards (Soto, 1985). Following these events researchers have reported strong detachments and mortality of macroscopic algae in association with the occurrence of *El Niño* (Vásquez, 1999). The time scale of the recovery processes after these massive mortalities has been estimated at a period of not less than ten years. The available data indicate that the kelp practically disappeared during the event, especially *L. nigrescens* and *M. integrifolia*, as a result of the emersion levels, while *L. trabeculata* had a lower mortality rate. Following the almost complete extirpation of these algae, different hypotheses were postulated to account for their expected dynamics of natural repopulation. One of these postulated that repopulation should occur gradually from south to north, starting from populations south of the impact area, as well as from "isolated populations" or individuals that may have survived the impact (González *et al.*, 2002). However, after the year 1983 it could be seen that further recovery of populations of *Lessonia nigrescens* occurred north of Iquique, with a full recovery by the end of the 1990s in sectors such as Mejillones and Caleta Buena in Pisagua. Similarly, southern sectors experienced a recovery from points where *Lessonia* survival was observed. As a result, by the end of 1990 an incomplete and patchy pattern of recovery was observed, with populations being confined to some sites along the coast. An important factor in the recovery from these large-scale disturbance events, is the degree of demographic (and community) resilience or the ability to return to population (or community) states similar to those observed prior to the observed disturbance. Ecological resilience refers to the degree or magnitude of change or disturbance that is required to transform an ecological system from a given state and functioning (Peterson *et al.*, 1998). In this case, an important resilience mechanism is the ability of macroalgal populations to recover by dispersion, or colonization by dispersal of different life stages. These events may couple or link spatially disjunct patches or habitats to source populations, which may then eventually repopulate impacted areas. In the case of the brown macroalgae, dispersion by the microscopic stage may be supplemented by scattering events of large scale macroscopic structures where whole plants or fragments can emerge, being dragged by the system currents and other processes in the coastal ocean. As indicated by Martin (2011) these dispersal events may include the dispersion of propagules discussed above, but may also include: (i) Movement of whole plants, whose holdfasts may have detached, or partially dislodged rocky substrate. These may move at a rate that spans between 10 and 100 m per year. (ii) Dispersion of detached algae or drifting fragments ("drifting"). This phenomenon would be able to cover an intermediate spatial scale, with dispersal rates ranging between 100 and 1000 m per year. (iii) Large-scale dispersion, associated with passive motion in assemblies of floating algae drifting. While only kelps such as *Macrocystis* sp. have specialized structures to facilitate dispersion through flotation and drift, other brown macroalgae species may become entangled with *Macrocystis* sp. fragments and hence may potentially be scattered over larger scales (100 to 5,000 km). The information available for these species may be summarized for the different

Table 10.4 Habitats and parameter conditions relevant for different life stages of brown macroalgae of the Chilean coast.

Habitat level/ life-cycle stage	Zoospores	Microscopic gameotphytes	Juvenile sporophytes	Adult sporophytes
Size/age	Microscopic[1,2]	Microscopic/1 to 20–30 days[1,2]	27–30 days[1,2]	Holdfast >10 cm/ >6 months[1,2]
Conditions or resources		Substrate	Substrate	
	Temperature	Temperature	Temperature	Substrate
	Photoperiod	Photoperiod	Photoperiod	Temperature
	Irradiance	Irradiance/intensity	Irradiance	Photoperiod
	Nutrients	Nutrients	Nutrients	Irradiance
	UV	UV	UV	UV
		Conspecifics	Conspecifics	
Substrate	Water column[1,2]	Rocky shore[1,2]	Rocky shore[1,2]	Rocky shore[1,2]
Exposure	–	Exposed and cleared shores[1,2]	Exposed or semi- exposed[1,2]	Exposed or semi-exposed[1,2]
Seasonality	Spring and Summer[3,4]	Winter–Spring[3,4]	Yearly recruitment, with winter maxima[3,4]	Spring and summer (growth/productivity)[3,4]

1) Santelices, 1989;
2) Hoffman & Santelices, 1997;
3) Edding *et al*., 1990;
4) Tala *et al*., 2004.

stages in the algal life-cycle, thus indicating both the habitat and broad limits of the Grinellian niche of brown kelps (Tables 10.4 and 10.5).

10.4.1.8 Concluding Remarks

Physiological performance is the principal determinant of a species' tolerance to environmental variability and change. As climate or other conditions shift, organisms initially respond based on physiological and behavioral adaptations molded through their evolutionary history. New conditions may be physiologically tolerable, allowing acclimatization (an adjustment of physiology within individuals) or adaptation (increased abundance and reproduction of tolerant genotypes over generations); or may be intolerable, promoting migration (by individuals or populations), change in phenology (timing of annual events), or death and local extinction if adaptation is not possible (Parmesan, 2006). Effects of changes in SST and ocean chemistry may alter the physiological functioning, behavior, and demographic traits (e.g., productivity) of organisms, leading to shifts in the size structure, spatial range, and seasonal abundance of populations (Anger *et al*., 2003). The physiological responses of marine organisms to multiple stressors described here is an issue of increasing global concern (Doney, 2010). This suggests that the evaluation of the impact of climate change may need to consider multiple stressors and its related effects on the organisms as well as the ecological repercussions these effects may have. For instance, the muricid gastropod *C. concholepas* and the urchin *L. albus* are two key stone species and the two most important species for small-scale fishers in Chile (Leiva & Castilla, 2002). For *C. concholepas* no aquaculture practices exist and for *L. albus* only a semi-commercial aquaculture has been developed. The fishery of both species is artisanal and based exclusively on the extraction of wild stocks by divers and rocky intertidal gatherers. Both

Table 10.5 Summary of the main habitat conditions and resources for life stages in brown kelps of the Chilean coast.

Habitat level/ life-cycle stage	Zoospores	Microscopic gameotphytes	Juvenile sporophytes	Adult sporophytes
Temperature	15°C[1,2,3,8]	15°C[1,2,3,8]	15°C[1,2]	10–23[1,2]
pH	7.5–8.5	7.5–8.5	–	–
Irradiance[4–8]	0–100 µE m^{-2} s^{-1}	90 µmol m^{-2} s^{-1}	90 µmol m^{-2} s^{-1}	
		0–100 µE m^{-2} s^{-1}	5°C:10–50 µE m^{-2} s^{-1}	–
			10°C:10–100 µE $m^{-2} s^{-1}$	
UV	UVB: 0–18 (kjm^{-2})[7]	–	–	UVB+UVA: 0–20BED_{300}(kjm^{-2})
	UVA: 0–74 (kjm^{-2})			UVA: 0–50 BED_{300}(kjm^{-2})

1) Edding *et al.*, 1990;
2) Tala *et al.*, 2004;
3) Alveal, 1995;
4) Hoffman & Santelices, 1982;
5) Ávila *et al.*, 1985;
6) Hoffman *et al.*, 1985;
7) Gómez *et al.*, 2007;
8) Murúa, 2010.

shellfish species are distributed along most of the Chilean coast covering the warm and cold waters in the northern and southern end respectively. This should raise awareness that climate change might have potential impacts at the ecologic, economic and societal levels. Recent studies conducted in both species are in different research phases and may contribute to both an understanding of future vulnerability of these key species within the scope of a climate change scenarios and as a guide for future research and management and potential aquaculture practices. Moreover, these results may help to implement manipulative practices in order to minimize in particular the harmful effects of near-future elevated pCO_2 and temperature levels projected for upwelling ecosystems occurring along the Chilean coast.

Despite uncertainty in the level of impact over benthic resources, in general benthic fisheries are going to have to adapt to fluctuations in catch. Under these circumstances, fishermen's adaptive capacity is considered a desirable characteristic. However, certain responses, which from a social perspective can be viewed as positive in the short term, may feed back into the ecological system, eroding the resilience (Gundersson *et al.*, 1995). For example, fishers' responses to declining local stocks may include increasing effort, targeting different stocks or changing gear; responses that all have the potential to sequentially deplete fish stocks, subsequently affecting ecosystem services and livelihoods (Cinner *et al.*, 2012). Alternatively, fishers may adapt by reducing effort, increasing market values or even stopping fishing, which are responses that could mitigate negative trends in the ecosystem by decreasing fishing pressure. Research should begin distinguishing between social adaptations that undermine or not; social–ecological resilience is becoming a key element to anticipate future change (Cinner *et al.*, 2012). In this sense, the challenge for successful adaptation for benthic fisheries and shellfish aquaculture to adapt necessarily involves understanding the biological implications of stressors and the social drivers of different adaptation strategies which can increase or buffer the ecological consequences of climate change. As such, research must begin addressing both social and ecological dimensions of climate change. The challenge for policy makers, managers and governance will be to create incentives and support decisions and institutions of fishers and shellfish aquaculture that adapt by strengthening feedbacks that increase resilience in times of lower productivity and uncertainty.

10.4.2 Principal Pelagic Resources Landings in Chile under Climate Change Scenarios

The exploitation of pelagic resources in central-southern Chile (32°–42°S) began in the early 1940s. Landings reached 94,000 t of anchovy (*Engraulis ringens*) in 1969 and 113,000 t of common sardine (*Strangomera bentincki*) in 1974. Landings later decreased and remained low until 1988, when they exceeded the previous highs of 520,000 t for anchovy in 2007 and 886,000 t for common sardine in 2011 (SAG, 1950–1977; SERNAPESCA, 1978–2012). After 1974, there was also a notable increase in landings of jack mackerel (*Trachurus murphyi*), which reached 4.4 million t in 1995. Afterwards, the landings decreased and stabilized at approximately 1 million t until 2007, when the decrease continued to 230,000 t by 2012. The fluctuations in these fishing activities are related to the intensity of the exploitation and environmental changes associated with *El Niño* events, interdecadal phenomena (Yáñez *et al.*, 1992, 2001; Chávez *et al.*, 2003) and possibly climate change (Cheung *et al.*, 2009; Merino *et al.*, 2012; Yáñez *et al.*, 2014).

In fisheries management, the main objective is to identify the permissible level of catches to ensure resource sustainability. In most cases, achieving this objective is challenging due to the need to predict uncontrollable events (Gutiérrez *et al.*, 2007, 2009). One alternative for modeling nonlinear relationships is the use of Artificial Neural Networks (ANNs) which perform better than linear models and have the capacity to generalize new data (Lek *et al.*, 1996; Özesmi *et al.*, 2006). In recent years, the application of ANNs has increased in different fields of science and engineering, including fisheries science (Gutiérrez *et al.*, 2007, 2009; Yáñez *et al.*, 2010; Naranjo *et al.*, 2015). Given the importance of pelagic resources, the present study analyzes the performance of ANNs in the prediction of monthly landings of anchovy, common sardine and jack mackerel based on fishing effort and environmental variables. Forecasted landings of each species are calculated through 2065 and take into account the selected ANN models under the A2 and 4xCO2 IPCC climate change scenarios, and three fishing effort projections (2010–2012 average, average +50% and average −50%).

10.4.2.1 Materials and Methods

Artificial Neural Networks Model Applications The study zone comprises the purse seine fleet operating area off central-southern Chile (32°–42°S) from the coast to 60 nm offshore for anchovy and common sardine (73°W), and over 200 nm from the exclusive economic zone (EEZ) for jack mackerel (78°W). The analyzed data include environmental and fishing data for the period of 1983–2012 for anchovy and common sardine, and 1973–2012 for jack mackerel. The total monthly landings (in t) were obtained from the Agriculture and Livestock Service Reports (SAG, 1973–1977), and the Fishing Statistics Annual Report of the National Fishing Service (SERNAPESCA, 1978–2012). The joint statistics on landings and fishing effort of the industrial purse seine fleet and the artisanal fleet were obtained from the Monitoring Program of the Principal National Fisheries gathered annually by the Institute of Fishing Development.

The environmental data comprised the monthly averages of 12 variables recorded at weather and oceanographic stations located off the coast of Talcahuano (36°S–73°W) and included in reports by global climate centres (www.cpc.ncep.noaa.gov/data/indices). The environmental variables included the following: SST and mean sea level (MSL) from oceanographic stations; SST from NCEP/NCAR reanalysis data (Kistler *et al.*, 2001) for the common sardine-anchovy and jack mackerel fishing zones (SST-NOAA); air temperature (AT); PDO; SST in the *El Niño* 1+2 region (SST NIÑO 1+2); SST in the *El Niño* 3.4 regions (SST NIÑO 3.4); Southern Oscillation Index (SOI); Cold Tongue Index (CTI) and Antarctic Oscillation (AAO). The wind speed and direction at Carriel Sur (36°46'S–73°03'W) were used to estimate the Ekman Transport (ET) (Bakun *et al.*, 1974) and the turbulence index (TI) (Elsberry & Garwood, 1978). The data for all these variables are available on the CLIPESCA website (www.clipesca.cl/index.php/productos/info-historica/ambiental-temporal).

The fishing and environmental data were analyzed to determine which variables to include in the ANN models. First, any strongly correlated variables were excluded from the analysis. A principal component analysis was conducted to visualize the level of representation of each variable on the main axes (Yáñez & Barbieri, 1983); these are the variables that present an individual value that is higher than the average of the values generated by each factor (Hair *et al.*, 1999). A cross-correlation analysis was performed for the selection of time lags in time series models based on a 95% confidence level ($\alpha = 0.05$). To decrease high frequency noise and, thus, clearly identify trends, the data were smoothed out through the use of a mobile mean centered around three months of data (Freón *et al.*, 2003). Regionalized projections of SST for central-southern Chile were used to forecast landings with ANN models, considering the fishing zones of anchovy–common sardine and jack mackerel for the period 2015–2065 (Figures 10.15 and 10.16).

The ANN models included monthly landings, fishing effort and environmental variables with time lags for the period of 1983 to 2012 for anchovy and common sardine, and 1973 to 2012 for jack mackerel. Regarding modeling, 60% of the data is used in the calibration step, the network (training), 20% for the selection stage (learning verifies the network) and 20% for the test step (validation model), all randomly selected (e.g., Makkearsorn *et al.*, 2008; Gutiérrez *et al.*, 2009; Yáñez *et al.*, 2010, Naranjo *et al.*, 2015). Monthly landing estimates for anchovy, common sardine and jack mackerel were the models' output variables. The software STATISTICA 7.0 was used to run the ANN models. With a randomly selected data set (20%),

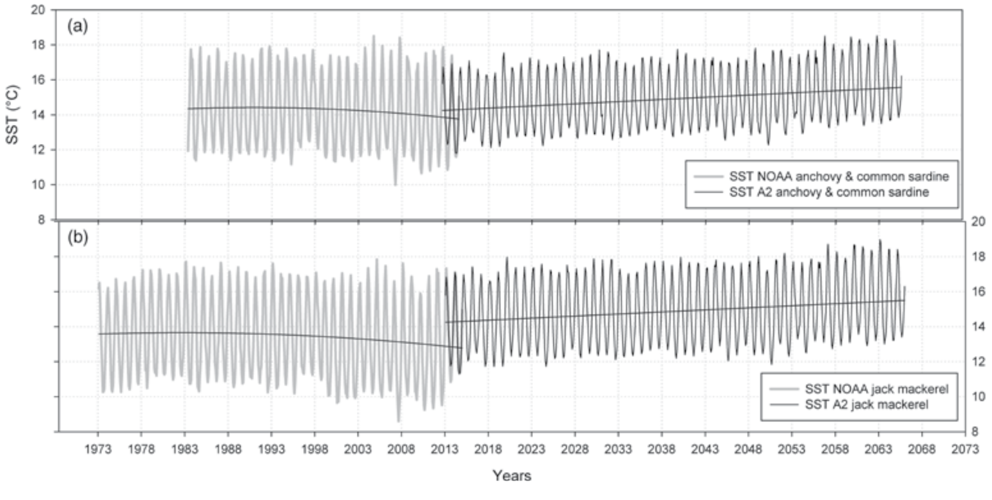


Figure 10.15 Sea surface temperature; NOAA monthly records and projections until 2065 for the A2 climate change scenario for (a) anchovy and common sardine (1983–2014); (b) jack mackerel (1973–2014).

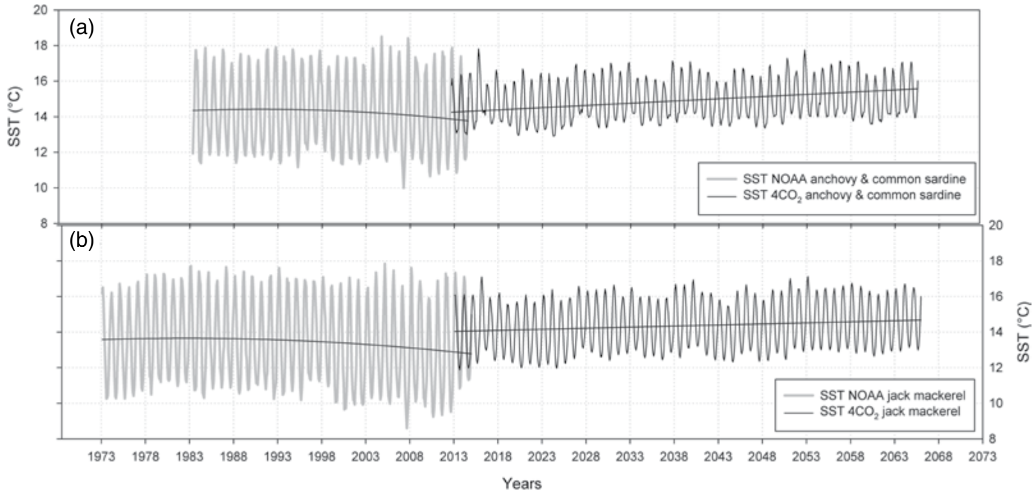


Figure 10.16 Sea surface temperature; NOAA monthly records and projections until 2065 for the 4×CO$_2$, climate change scenario for (a) anchovy and common sardine (1983–2014); (b) jack mackerel (1973–2014).

the functioning of the ANNs was evaluated using the coefficient of determination (r^2), the percentage standard error of prediction (%SEP) (Ventura *et al.*, 1995), the coefficient of efficiency (E) (Nash & Sutcliffe, 1970; Kitanidis & Bras, 1980), and the absolute error measurements (RMS). In order to accept the fit, the values of r^2 and E must be close to one, and the values of %SEP must be near zero. The persistence index (PI) was also used to assess the models (Kitanidis & Bras, 1980). A PI value of one indicated a perfect fit between the estimated and observed values, whereas a zero value indicated that the model was no better than a “naïve” model which always gives the previous observation as the next prediction.

A sensitivity analysis was conducted to identify the most significant input variables. This analysis treats each input variable on the neural network as if it were unavailable in the model (Hunter *et al.*, 2000). To evaluate the sensitivity of variable X, the network was executed with a set of test cases, and the resulting error was saved. The same network was then used again replacing the observed values of X with the estimated values by substituting the missing values, and the resulting error was again saved. Because information used by the network had been removed (e.g., one of the input variables), the level of error was greater. The basic measurement of sensitivity was the quotient between the network error without the input variable and the original error. If the value was less than or equal to one, adding or removing the variable did not have any significant effect.

Statistical and Dynamical SST Downscaling The SST future simulations come from the National Center for Atmospheric Research (NCAR) Community Climate System Model 3.0 (CCSM3), considering the high future CO$_2$ emission scenario known as A2 (IPCC, 2007). The NCAR CCSM3 is the same model used at higher resolution for the IPCC-AR4 projections of future climate, with an ocean horizontal resolution corresponding to a nominal grid spacing of approximately 1° latitude × 1° longitude. However, the resolution of the NCAR-CCSM3 model is coarse, potentially limiting the use of this model to assess regional changes in marine ecosystems, particularly in coastal and shelf waters. For this reason, there is a need to use better spatially resolved climate and oceanographic projections (e.g., using statistical downscaling) in regional assessments (Stock *et al.*, 2011). In this study, the change factor (CF) or Delta method was applied because it is a relatively straightforward and popular downscaling method for the rapid impact assessment of climate change (Wilby & Wigley, 2000; Silva *et al.*, 2015). Details regarding the methodology employed for the statistical downscaling are described by Silva *et al.* (2015). Numerical simulations and hydrodynamic modeling were carried out by ROMS, from 10°–43°S and 87°W to the coast. ROMS considers the most extreme climate change scenario, which means four times the CO_2 concentration. The implementation and validation of this model are presented in the section 10.3.2. This dynamical model is also employed for downscaling the SST in anchovy–common sardine and jack mackerel fishing zones.

Landings Forecasts The reduced ANN models calibrated for the three fishing activity types were used to forecast landings. The averages of fishing effort, considering the last three years of each fishing activity (2010–2012), were used as input values. SST output predictions based on the A2 and $4{\times}CO_2$ climate change scenarios were also used. To force the ANN models, SST time series predictions were extracted according to the anchovy–sardine and jack mackerel fisheries areas in central-southern Chile and for the period 2015–2065 (Figures 10.15 and 10.16). In order to simulate and identify the effects of climate change in the aforementioned fisheries, downscaled SST (A2 and $4{\times}CO_2$) predictions (2015–2065) and three scenarios of future fishing effort (2010–2012 average, average + 50% and average –50%) were used as input for landing simulations.

10.4.2.2 Results

Artificial Neural Network Models The SST–NOAA for the common sardine and anchovy fishing zone is strongly correlated with AT, SST, and NIÑO 1+2 (0.93, 0.69 and 0.67, respectively); similar correlations were found between SST NIÑO 3.4 and the variables CTI (0.83) and SOI (–0.66). The correlation matrix for jack mackerel has similar values among these environmental variables and the SST-NOAA (more oceanic fishing zone): AT, SST, and NIÑO 1+2 (0.89, 0.72 and 0.75, respectively); and between SST NIÑO 3.4 and the CTI (0.81) and SOI (–0.67). Principal component analysis (PCA) leads to 12 factors that together explain 100% of the variance. For anchovy and common sardine, factors 1, 2, 3 and 4 were selected. When combined, these factors account for 29.4%, 26.2%, 11.2% and 8.8% of the variance, respectively; therefore, they explain 75.6% of the total variance. For jack mackerel, factors 1, 2, 3 and 4 account for 30.4%, 25.2%, 11.8% and 9.2% of the variance, respectively, which results in a combined total variance of 76.6%. For anchovy and common sardine, the correlation matrix of environmental variables with each principal factor shows the highest values for SST-NOAA (0.96), AT (0.91) and SST (0.81) with factor 1; SST NIÑO 3.4 (0.91), CTI (0.90) and SOI (–0.81) with factor 2; MSL (–0.83) and TI (–0.74) with factor 3; and ET (0.76) with factor 4. For jack mackerel, these correlations are similar for factor 1 ((SST–NOAA (0.97), AT (0.93) and SST (0.83)) and factor 2 ((SST NIÑO 3.4 (0.92), CTI (0.88) and SOI (–0.82)); but ET (–0.79) is the highest value for factor 3, and AAO (0.82) for factor 4. Considering the correlation matrix results between the environmental variables and the PCA, the pre-selected variables for anchovy and common sardine are SST-NOAA, SST NIÑO 3.4, ET, TI and MSL, and the variables for jack mackerel are SST-NOAA, SST NIÑO 3.4, ET and AAO.

For anchovy, SST-NOAA has significant values for crossed correlation with the rectangular hyperbolic II function and time lags of –2, –7, –14 and –19 months. For common sardine, significant values are achieved with the Cauchy function with time lags of –1, –6, –16 and –18 months. The Cauchy function also produces significant values for jack mackerel but with time lags of –2, –14, –26, –38, –50 and –62 months. SST NIÑO 3.4 reaches its maximum correlation value at –22 months with the rectangular hyperbolic II function for anchovy, at –3 months with the reciprocal rectangular hyperbolic I function for common sardine and at −46 months with the rectangular hyperbolic II function for jack mackerel. The TI attains significant correlations with the rectangular hyperbolic II function, particularly at −8 and −21 months for anchovy and at −8 and −20 months for common sardine with the parabolic function. The MSL attains its maximum significant correlation value for anchovy at −21 months with the parabolic function and for common sardine at −5 and −17 months with the Cauchy function. The standard fishing effort (fe) shows significant crossed correlation values with the reciprocal rectangular hyperbolic I function at 0 and −12 months for anchovy and at 0, −12, −24 and −36 months for jack mackerel and with the parabolic function at 0, −11 and −22 months for common sardine.

After initial data treatment, phase 1 defined the ANN models with their respective input variables and corresponding time lags: SST-NOAA, fe, MSL, TI and SST-NIÑO 3.4 for anchovy and common sardine, and SST-NOAA, SST NIÑO 3.4 and fe for jack mackerel. Therefore, the best architecture for anchovy was 10:9:1 (10 nodes on the input layer, 9 nodes on the hidden layer and 1 node on the output layer) which gave an r^2 of 90% and PI of 0.92, indicating a good degree of fit. However, a slight degree of dispersion between the observed and estimated series is evident in the %SEP and RMS values of 28% and 7,275 t. For common sardine, the best model has a 12:12:1 architecture with an r^2 of 96%, E of 96% and PI close to 1; the %SEP and RMS values are 22% and 10,039 t. For jack mackerel, the best model has an 11:13:1 architecture with an r^2 of 88% and E of 89%. The standard error is 34.75%, indicating that there is dispersion between the observed and estimated series, whereas the RMS is 39,790 t.

The variables selected to reduce the models were only fe and SST-NOAA whose ratios in the phase 1 models were above the median. Therefore, in the phase 2 the anchovy model considers the following variables (and ratios): $fe_{(t-0)}$ (2.50), $SST\text{-}NOAA_{(t-14)}$ (2.10), $SST\text{-}NOAA_{(t-7)}$ (1.14) and $SST\text{-}NOAA_{(t-2)}$ (1.04); for common sardine the input variables are $fe_{(t-0)}$ (2.77), $SST\text{-}NOAA_{(t-1)}$ (1.55), $SST\text{-}NOAA_{(t-13)}$ (1.31), $SST\text{-}NOAA_{(t-6)}$ (1.24) and $SST\text{-}NOAA_{(t-18)}$ (1.17); and for jack mackerel the variables to be included are $fe_{(t-0)}$, (2.23), $SST\text{-}NOAA_{(t-38)}$ (1.68), $fe_{(t-36)}$.(1.50), $SST\text{-}NOAA_{(t-50)}$ (1.37), $SST\text{-}NOAA_{(t-50)}$ (1.37), $fe_{(t-12)}$ (1.33) and. $SST\text{-}NOAA_{(t-14)}$ (1.19). SST-NOAA and fe are of particular importance in the models. The SST-NOAA is included in models to allow the use of future temperature scenarios of climate change as inputs for the fisheries landings simulation. However, MSL was discarded for anchovy and common sardine despite giving a ratio above the median value in the phase 1. Compared with the phase 1 models, in the phase 2 anchovy model (architecture = 4:10:1) and common sardine model (architecture = 5:3:1) show r^2 (0.87 and 0.92) and RMS (10.187 and 12.716) values with minimal differences. Although increases in %SEP are more notable as they suggest slightly more dispersion between the observed and estimated data, while the PI values (0.87 and 0.92) indicate a similar quality of fit. For jack mackerel, the indices of error show practically no variation, except for a lower index of persistence; therefore, the models were simplified without losing any predictive capacity (architecture = 6:10:1); r^2 = 0.88; RMS = 40,373; %SEP = 33.2; E = 0,88; PI = 0,88).

Temperature Downscaling A noticeable difference between SST-NOAA for anchovy and sardine from 1980–2014 and for jack mackerel from 1973–2014 and SST projections under A2 and 4×CO_2 climate change scenarios from 2015–2065 for both fishing areas were observed. A correction factor was obtained by calculating the difference between projected and observed SST, considering monthly data from 2013–2014. The results showed a correction factor of 0.2 for anchovy and sardine and −1.02 for jack mackerel for the A2 climate change scenario, and 3.54 for anchovy and sardine and 3.14 for jack mackerel in the

Table 10.6 SST projections for each fishing area and scenarios of climate change.

Scenarios	Method	Anchovy–common sardine	Jack mackerel
A2	Beginning and end of lineal adjustment	1.26	1.20
	Differences between 2056–2065 and 2005–2014	1.59	2.51
$4 \times CO_2$	Beginning and end of lineal adjustment	0.58	0.61
	Differences between 2056–2015 and 2005–2014	1.11	1.53

Table 10.7 Landing projections for fishing effort and sea surface temperature (SST) scenarios (comparison between 2015 and 2065 of lineal adjustment).

		Fishing effort scenarios		
	Scenarios	**50% +**	**Mean**	**50% –**
Anchovy	A2	3%	−1%	−8%
Common sardine	A2	−6%	−4%	−2%
Jack mackerel	A2	9%	13%	17%
Anchovy	$4 \times CO_2$	0%	0%	0%
Common sardine	$4 \times CO_2$	0%	0%	2%
Jack mackerel	$4 \times CO_2$	8%	10%	14%

$4{\times}CO_2$ climate change scenario. So, third-grade polynomial regressions were fitted to the SST-NOAA data for anchovy–common sardine and jack mackerel fishing areas both showing a cooling trend in the last years (Figures 10.15 and 10.16). The latter could be related with interdecadal-scale variability (Yáñez *et al.*, 2001; Chávez *et al.*, 2003). This SST decrease of 0.2°C every decade could have started by the early 1980s (Falvey & Garreaud, 2009). For NCAR and IPSL corrected SST forecasts, the linear regressions were fitted, showing a positive trend for anchovy-sardine (Figures 10.15a and 10.16a) and jack mackerel (Figures 10.15b and 10.16b). Considering the start (2015) and the end (2065) of the fitted linear regressions, Table 10.6 shows increase in projected SST for anchovy–common sardine and jack mackerel fishing areas. Also, a comparison between monthly projected averages for 2056–2065 and 2005–2014 periods is shown, as do Cheung *et al.* (2009), Merino *et al.* (2012) and Silva *et al.* (2015).

Landing Projections In Table 10.7, based on the A2 climate change and the fishing effort scenarios, anchovy and common sardine landings would decrease, and jack mackerel landings would increase, slightly. Regarding change, the $4{\times}CO_2$ climate change, and fishing effort scenarios, showed increases only in jack mackerel landings. When comparing changes between observed landings in 2003–2012, and the landing predictions for 2056–2065 with A2 and $4{\times}CO_2$ and the fishing effort scenarios, landings would increase notably, but not for anchovy and common sardine with the −50% fishing effort (Table 10.8). The opposite situation occurs when using mean fishing efforts and the averages increased by 50%, when anchovy, sardine and jack projected landings increase.

Table 10.8 Landing projections for fishing effort and sea surface temperature (SST) scenarios (comparison between 2056–2065 projected landings and 2003–2012 observed landings).

		Fishing effort scenarios		
	Scenarios	**50% +**	**Mean**	**50% –**
Anchovy	A2	96%	40%	–29%
Common sardine	A2	15%	6%	–25%
Jack mackerel	A2	128%	92%	44%
Anchovy	$4 \times CO_2$	97%	43%	–19%
Common sardine	$4 \times CO_2$	33%	11%	–21%
Jack mackerel	$4 \times CO_2$	162%	102%	43%

10.4.2.3 Discussion

The aim of using predictive models with fishing activities is to provide those responsible for resource management and other users with information on the biological and/or environmental effects of fishing on available stocks. Conventional production models are not always adequate, as variations in fishing effort account for only a part of the changes in landings; there is often a variation caused by environmental phenomena that affect abundance and/or catchability of stocks from one year to the next (Freón & Yáñez, 1995). Variables with close-to-one ratios in the sensitivity analysis did not have an important effect on the ANN models, and the variables selected in phase 2, including fe and SST-NOAA, whose ratios are above-the-median, were sufficient to fit the models and achieved a similar predictive capacity that the models generated in phase 1. These simplified models were carried out for the 2015–2065 landings projection, based on the A2 and $4{\times}CO_2$ climate change scenarios from the IPCC. With these scenarios, the estimated SST changes for anchovy–common sardine and jack mackerel fishing areas showed an increase by 0.58°–1.59°C and 0.62°–2.51°C for both fishing areas until 2065, respectively. According to IPCC (2013), central-southern Chile temperatures would increase by 0.7°–3.5°C until 2100.

Gutiérrez *et al.* (2007, 2009) and Yáñez *et al.* (2010) relate to the anchovy and sardine biological processes, associated to landings with environmental variables lagged in time. Similar results were obtained in this work: for SST-NOAA the time lags of −2, −7, −14 and −19 months for anchovy and −1, −6, −13 and −18 months for common sardine could possibly imply two different effects, one associated with recruitment, and another with distribution. Braun *et al.* (1995) and Castillo *et al.* (2002) indicate that anchovy recruitment occurs at 5–7 months, whereas temperatures at 2–3 months before hatching affect fertility of the clupeiform species (Tanasichuk & Ware, 1987); for common sardine, the recruitment occurs at 11–12 months (Castillo *et al.*, 2000).

Pelagic fish depends on physiological thermoregulation process. Anchovy and common sardine are stenothermic species (e.g., capable of living or surviving only within a narrow temperature range) and has been reported to spawn in a wide range of upwellings, particularly at low and high values. Jack mackerel presents a high plasticity for hydrological conditions such as temperature, and can adapt to most of the water masses inside its limitations and preference, but is usually encountered inside subtropical waters (Bertrand *et al.*, 2006). SST is considered as a proxy of ecosystem variability (Yáñez *et al.*, 2008), which would indicate changes in primary productivity, food, fertility, egg and larvae survival due to upwelling turbulence, and consequently in recruitment and landings. Further, the probability of catch for certain species is affected by trapped waves on the coast, which increase MSL and deepen the thermocline when passing through fishing zones, leading to a lower availability of small pelagic species (Yáñez *et al.*, 2008; Parada *et al.*, 2013). For anchovy, recruitment related effects could affect the landings in higher-than 6-month lags and for common sardine in higher than 12-month lags, similarly, for lower-than 6 month-lags for anchovy and lower-than 12 months for common sardine lags are associated with distribution changes (Yáñez *et al.*, 2010).

For jack mackerel the models consider the fishing effort of the year and also the fishing effort delayed by −12, −24 and −36 months as these variables affect the resources and future catches. Significant time delays in SST-NOAA show a strong environment/resource correlation, which is mainly associated with recruitment because the most significant classes in the jack mackerel landings are those of 4–9 years with variations over time (Naranjo, 2015; SUBPESCA, 2012). Since the mid-1970s, jack mackerel landings have increased considerably in the coastal zone due to higher availability and a notable increase in fishing effort. This increase in fishing effort is related to the technological development of the fleet, which added boats with storage capacities up to 2,200 m^3 in 2000, and a level of autonomy that allows them to go farther offshore beyond the EEZ (Aranis *et al.*, 2012). The displacement of jack mackerel towards more oceanic zones increases the duration of fishing journeys (6–7 days) and the number of casts per trip (six or more), thus leading to higher fishing effort to maintain performance. There is evidence that increases in fishing effort were associated with interdecadal environmental changes with a warmer regime change from 1976 to the 1990s (Yáñez *et al.*, 1992; Yáñez, 1998). These temporal correlations are also shown in a spatial scale, particularly between the distribution of pelagic resources and SST (Barbieri *et al.*, 1995; Maravelias & Reid, 1995; Yáñez *et al.*, 1996), which is consistent with the variables selected in the present ANN modeling. Using data from 1973 to 2008, Yáñez *et al.* (2014) evaluated jack mackerel fishery variability through global production models that account for the abundance index of catch per unit effort (CPUE) and for the level of catches using variations in SST and fishing effort. One of these models which considered only fishing effort achieved a correlation of only 32%, but would have achieved a stronger correlation ($r^2 = 0.89$) by incorporating SST.

According to the sensitivity analysis of the best validated models, the most influential variables for the three fishing operations are fe and SST-NOAA, implying a dependence on anthropogenic and environmental effects. A great effort is made to reduce-select the best combination of input variables. The most important variable for the three models (anchovy, common sardine and jack mackerel) corresponded with fe(t–0). This seems obvious because the fishing effort is significantly and linearly correlated with landings. But, since these models are used for simulation of climate change scenarios, the 1-month-ahead predictive capacity for the ANN models is not needed. When the variables were reduced to include only fe and SST-NOAA in the models, the fit lost practically no predictive capacity, especially for the jack mackerel. The sensitivity analysis shows the importance of fe in explaining the landings of the fish species. However, the fe averages over the last three years were maintained constant in the predictions to estimate the net effect of CC on future landings of the resources. It should be noted that the temperature range in which pelagic species in central-southern Chile develop is wider (14°–23°C) than that shown in this study as an effect of CC on SST (Yáñez, 1998; Bertrand *et al.*, 2008; Brochier *et al.*, 2013). Merino *et al.* (2012) estimated a decrease of 3% in pelagic fish catches in Chile by 2050, based on predictions using temperature and scaled primary productivity in biochemical and ecological models for different EEZ, including the Humboldt Current System (HCS). Falvey & Garreaud (2009) forecast a decrease in SST which may imply increases in anchovy landings in northern Chile (Yáñez *et al.*, 2014).

The results of these simulations provide important information on the possible changes in pelagic fishing operation landings in central-southern Chile in the face of climate change.

Yáñez *et al.* (2008) suggested that anchovy and sardine landings in northern Chile are an indicator of the species abundance given that they show fluctuations that may be directly related to the biomass of the resource. The positive projections of catches to 2065 (Tables 10.7 and 10.8), particularly of jack mackerel, could be related to changes in distribution that would favor greater availability and catchability of this fisheries resource. This could be happening with the large pelagic swordfish (*Xiphias gladius*), whose projection to 2065 indicates a change in the distribution to the south and near the coast, favoring accessibility and vulnerability; while the coastal sardine is distributed farther south (Figure 10.17). Thus, the influence of climate change on the resource abundance (before spawning, in early life stages, in pre- and post-recruitment) is not ruled out. In this regard, it should identify the key environmental variables, biological mechanisms involved, time period of the effects, the lags on production, and types and signs (positive + or negative –) of effects (on abundance and/or availability). Possible changes in biodiversity due to climate change and its effects on biological interactions (e.g., food, predation and competition) that would influence this fisheries resource, should also be dimensioned. Possibilities of adaptation of the different resources, depending on whether changes are tolerable or not, should also to be considered (see section 10.4.1.8).

The approach used by this study consists in modeling temporal data (time series) which are restricted to a specific area. To improve the quality of living marine resource assessments and forecasts, spatial–temporal models formalizing the variation over time and across space and adapted for climate change applications may be used. The main spatial–temporal models used to make predictions about living marine resources under climate change include ecosystem approaches such as habitat suitability or bioclimate envelope models (Cheung *et al.*, 2009; Silva *et al.*, 2015, 2016), ecotrophic models (Howard *et al.*, 2008), individual-based models (IBM) (Brochier *et al.*, 2013), end-to-end models that combine climate, planktonic, fishery and socio-economic models (Barange *et al.*, 2010) and species distribution models such as MAXENT (Jones *et al.*, 2012). Spatial–temporal models use various statistical and mathematical methods to predict effects of climate change on living marine resources. These methods include predictive GAMs (Willis-Norton *et al.*, 2014), GAM-GLM (Silva *et al.*, 2015), fuzzy logic (Cheung *et al.*, 2009), and machine learning maximum entropy approaches to species distribution modeling (Gormley *et al.*, 2015).

In conclusion, based on the results of the present study, there is a need for improved scaling of the variables incorporated into the simulations, as well as incorporating new variables such as chlorophyll and salinity. Thus, considerations of regional oceanographic models and the incorporation of a spatial component are fundamental to the development of this type of research (Cheung *et al.*, 2009; Merino *et al.*, 2012; Silva *et al.*, 2015). It is expected that a finer resolution will be obtained from global climate models such as NCAR-CCSM3 and IPSL-CM4 (Echevin *et al.*, 2012), in order to improve climate-based projections and enhance its applicability in marine resources and related activities.

10.4.3 Aquaculture and Climate Change

Climate change will have substantial impact on ecosystems, societies and economies and increase the pressure on all livelihoods and food supplies, including those from the fisheries and aquaculture sector. To meet the demand of the growing population a significant increase in the supply of food from aquatic ecosystems is needed in the next 20–30 years, during which it is expected that the consequences of climate change will expand and worsen (Cochrane *et al.*, 2009). Climate change promotes multiple tensions and stress at different temporal and spatial scales, as well as biophysical, social entities and the environment. Some of these changes will be abrupt, while others will be gradual (e.g., temperature, land cover change, and supplies of

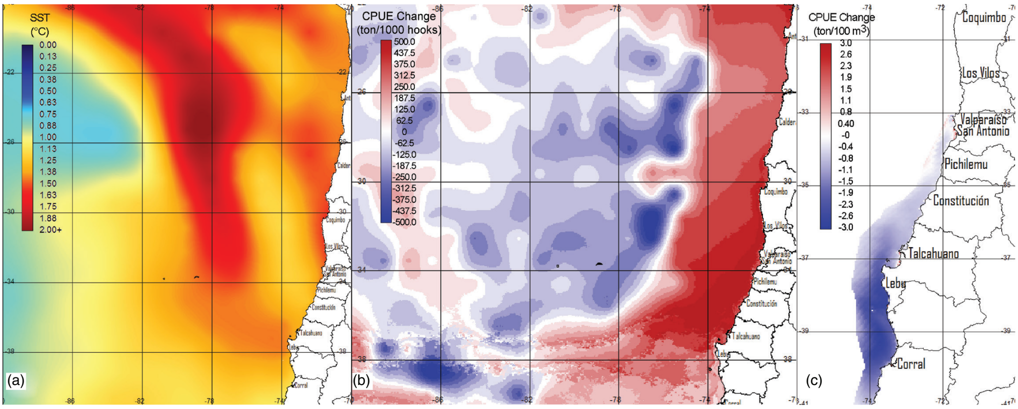


Figure 10.17 Climate change impacts on the physical ecosystem and relevant fisheries off Chile by 2065. Data shown are absolute and relative differences between future A2 high CO_2 emissions in 2065 and the base period (2001–2012) for (a) sea surface temperature (SST); (b) swordfish catch per unit effort (CPUE); (c) common sardine CPUE. *Source:* Reprinted from *Progress in Oceanography*, 154, Silva *et al*., Forecasts of swordfish (*Xiphias gladius*) and common sardine (*Strangomera bentincki*) off Chile under the A2 IPCC climate change scenario, pp. 343–355, Copyright (2015), with permission from Elsevier (*see color plate section for the color representation of this figure*).

fish). To the extent that these climate changes involve risks such as drought, heavy rain, and heatwaves, they can also lead to secondary stresses such as the extension of a plague, which in turn can mean increased competition for resources, collapse of financial institutions, migration of species and humans, and loss of biodiversity (De Silva & Soto, 2009).

During the last decade Chile has been among the 10 major aquaculture countries. The harvest of aquaculture resources had a variation close to 700% over the last 30 years (1985–2014), while returns on exports have grown 80 times in the same period. At a national level, over the past decade, aquaculture has been the second sector of the economy in the value of its exports. Chile currently grows 15 species commercially at different scales: from large-scale aquaculture with intensive use of technology and capital (salmon, mussels, abalone, scallop) to extensive small-scale aquaculture with less technology and capital support (seaweeds, mytilids, scallop). In several coastal towns aquaculture is an important engine of the local economy and generates thousands of jobs, especially in southern Chile. In this context, it can be said that Chilean aquaculture has been oriented almost exclusively to international markets, with limited participation in production for domestic consumption.

Chilean aquaculture has been developed in various coastal ecosystems in the eastern Pacific Ocean south margin, with latitudinal distinctive oceanographic and climatic characteristics. The northern and central coast of Chile is characterized by its direct exposure to the Pacific Ocean, with few sheltered bays where scallop, Pacific oyster, abalone and seaweed farming has been possible. The south-southern zone is characterized by an archipelago, with numerous channels, fjords and bays protected from the direct influence of the Pacific Ocean, offering environments for developing various types of aquaculture. One of the greatest challenges to understand the potential effects and consequences of climate change on marine socioecological systems (e.g., fisheries and aquaculture) has been the development of regional and local models to establish scenarios that scale on the variability of the ocean-atmosphere along the Chilean coast. In Chile there are still no studies that attribute the effects and consequences on aquaculture due to climate change. This absence of evidence does not preclude an analysis of the potential impacts of climate change on aquaculture, considering global and local climate scenarios available. González *et al.* (2013) assessed the vulnerability of Chilean aquaculture considering potential impacts, the system sensitivity and its adaptive capacity. This section presents the current state of Chilean aquaculture, analyzes the information available to major climate forcings and establishes scenarios of potential impacts on farmed resources and on productive activities. Finally, we address the adaptations which should be considered by this socioecological system to face the future climate scenario and its potential impacts.

10.4.3.1 The Issue of Attribution: Sorting Natural from Man-Made Perturbation

For most natural and essentially all human systems, climate is only one of many drivers that cause change; other factors such as technological innovation, social and demographic changes, and environmental degradation frequently play an important role as well (Cramer *et al.*, 2014). “Detection of impacts” of climate change addresses the question of whether a natural or human system is changing beyond a specified baseline that characterizes its behavior in the absence of climate change (Stone *et al.*, 2013). “Attribution” addresses the question of the magnitude of the contribution of climate change to a change in a system. In practice, an attribution statement indicates how much of the observed change is due to climate change with an associated confidence statement. Hence, attribution requires the evaluation of the contributions of all external drivers to the system change.

On a global scale IPCC (2014) established the following conclusions on climate scenarios: (i) Ocean warming: the surface and the upper 75 m warmed by 0.11°C per decade over the period 1971 to 2010. (ii) Acidification of the ocean; the pH of ocean surface water has decreased by 0.1

corresponding to a 26% increase in acidity, measured as hydrogen ion concentration. (iii) Antarctic ice sheets have been losing mass. (iv) Over the period 1901 to 2010, global mean sea level rose by 0.19 m. (v) There is high confidence that marine organisms will face progressively lower oxygen levels and high rates and magnitudes of ocean, with associated risks exacerbated by rising ocean temperature extremes. (vi) Global marine species redistribution and marine biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem services.

The key factors associated with climate change that can have an effect on aquaculture are changes in temperature, ocean currents, winds, nutrient supply, rain, ocean chemistry and extreme weather conditions (Hobday *et al.*, 2008). Climate change effects on marine and inland ecosystems are in addition to changes in land-use, including changes in sediment loads, water flows and physical–chemical consequences (hypoxia, stratification, salinity changes). Climate change is expected to drive most terrestrial and marine species ranges toward the poles, expanding the range of warmer-water species and contracting that of colder water species. There is little evidence in support of an increase in outbreaks of disease linked to global warming, although spread of pathogens to higher latitudes has been observed. At "rapid" time scales (a few years) there is high confidence that increasing temperatures will have negative impacts on the physiology of fish, causing significant limitations for aquaculture, changes in species distributions, and likely changes in abundance as recruitment processes are impacted. Climate changes and in particular global warming, could both directly and indirectly impact on mariculture in temperate regions. Species cultured in those regions, predominantly salmonids (e.g. *Salmo salar*) and emerging culture of cod, *Gadus morhua*, have a relatively narrow range of optimum temperature. The challenge of detecting impacts on aquaculture due to climate change and to assess the extent of their contribution to the observed changes will require great efforts of monitoring and modeling the ocean–climate system on a global and local level. For Chile, climate trends and scenarios at global (IPCC) and national (Garreaud *et al.*, 2009) level are available.

10.4.3.2 Current Status Chilean Aquaculture

During the last decade Chile has been among the 10 major aquaculture countries. The harvest of aquaculture resources had a variation close to 700% in the last 30 years (1985–2014) while returns on exports have grown 80 times in the same period. Figure 10.18 shows the evolution of harvests from main grown resource groups between 1997 and 2014, exceeding 1.2 million t during this last year. Salmon and mussels harvest have sustained over 95% of the national harvest between 2010 and 2014. The salmon farming is eminently on an industrial scale and it is developed in bays, fjords and channels of Chilean Patagonia. It is an activity that intensively uses the technology available to their farming systems in the sea (cages) and in its fish farms on land (recirculation systems) for the production of early stages of development (eggs, smolts). This activity is concentrated in 25 companies whose products reach 70 markets. In parallel, there are hundreds of suppliers of various goods and services necessary for the operation of the production centers. In recent years, the salmon industry has generated about 70,000 direct and indirect jobs.

Meanwhile, commercial cultivation of native mussel (*Mytilus chilensis*) has been developed exclusively in bays, canals and fjords in the region of Los Lagos; it is an extensive crop that depends exclusively on natural food (phytoplankton) available in the environment. It is an activity represented by growers on an industrial, medium and small scale; they have progressively incorporated more technology in their production processes (long-lines, harvest, processing). The ongrowing phase depends on the supply of seeds that can be can be their own supply or supplied by third parties. This supply has high uncertainty as it depends on the success of larval recruitment into the millions of collectors arranged for this purpose. In 2012

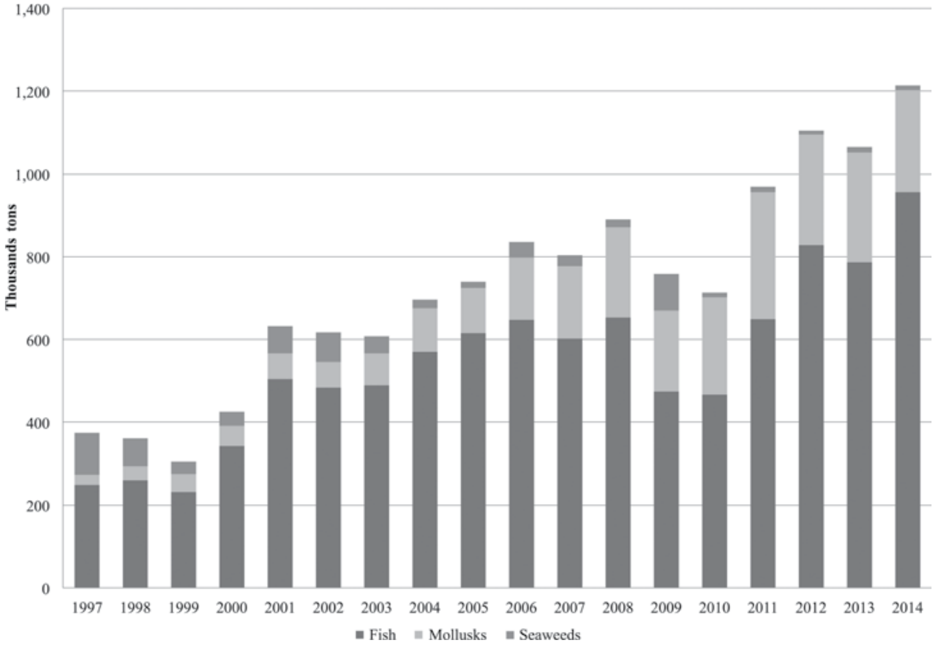


Figure 10.18 Evolution of Chilean aquaculture harvests by group of resources. *Source:* based on statistics from the Undersecretariat for Fisheries and Aquaculture.

there were 619 farmers of which 89% are medium and small, and 11% are large companies, which manage a total of 1,133 aquaculture licenses for the production of mussels. The growth and development of this activity has been driven by strong demand for mussels from markets such as Spain, France, and Italy, which together with Russia and the United States are destinations that account for 65% of total exports from Chile.

The cultivation of scallop (*Argopecten purpuratus*) is developed in protected bays of northern Chile using long-line and lantern systems for the ongrowing phase, which depends on the supply of seeds that can be satisfied by own supply or by third parties. However, this industry depends on natural settling of wild seed, which produces significant variations in production due to environmental problems such as the recurrent ENSO phenomenon. After a growth of almost 50% between 1995 and 2005, with a peak of 25,000 t in 2004, there was a significant decrease in production since 2008 due to the global economic crisis and the entry of competitors into the international market, reaching a total harvest close to 5,000 t during 2014. There are 401 authorized aquaculture concessions (licenses) with an average of 17 ha/concession. This activity contributes US$5.5 million to the country's export basket, with a wide diversification of product target markets which are, in order of importance, Spain, France, Singapore and Brazil. Cultivation of *Gracilaria* is a predominantly small-scale productive activity developed by hundreds of growers mainly in the southern part of Chile, using techniques of direct planting and seeding of spores on suspended culture lines. Currently there are than 615 authorized farms to cultivate *Gracilaria* (mean = 3 ha/center) in a total area of 2,300 ha. In 2014 they operated about 250 farms where they harvested 45,000 t of wet biomass. The fate of this crop is the manufacture of agar in Chile and the rest is exported. In 2014 2,037 t of dry *Gracilaria* were exported, yielding returns of US$45.7 million.

Chile is administratively divided into 15 regions. To reconcile with climate study areas, the harvest of the most important species were grouped in: (i) Northern Zone: includes the regions

Table 10.9 Geographical distribution of main commercial aquaculture in Chile, 2014 (Compiled data from the National Fisheries and Aquaculture Service).

	Northern Zone		Central Zone		Southern Zone	
	Harvest (t)	**%**	**Harvest (t)**	**%**	**Harvest (t)**	**%**
All species	2,558	100.0	4,859	100.0	1,207,022	100.0
Gracilaria chilensis	1,398	54.7	1,253	25.8	10,157	0.8
Argopecten purpuratus	806	31.5	3,340	68.7		
Haliotis rufescens	311	12.2	215	4.4		
Salmo salar					644,459	53.4
Mytilus chilensis					238,072	19.7
Oncorhynchus kisutch					158,947	13.2
Oncorhynchus mykiss					151,773	12.6

of Arica and Parinacota, Tarapaca, Antofagasta and Atacama. (ii) Central Zone: includes the regions of Coquimbo, Valparaíso, O'Higgins, Maule and Biobio. (iii) Southern Zone: includes the regions of Araucanía, Los Ríos, Los Lagos, Aysen and Magallanes. In 2014 the National Registry of Aquaculture, totaled 3,734 centers (including those located both in water and on land), corresponding to the group of fish with the highest representation with a total of 1,743 centers (46.7%), followed by mollusks with 1,392 centers and finally by seaweeds with 562 centers. Most of these centers are located in the Southern Zone (3,417) followed by the Central Zone (172) and Northern Zone (145). At a national level, only 1,232 centers reported harvests during 2014. During 2014, there were 3,057 farms which occupied 32,518 hectares of water and ground, of which 60% are located in the region Los Lagos. Table 10.9 summarizes the harvest of the main resources grown in the northern, central and southern areas of Chile, highlighting the latter area by concentrating 99% of the total harvest of 2014.

Local (Indigenous) versus Human Transported Species Fifteen species are commercially cultivated (2014), of which eight are indigenous and seven have been introduced (Table 10.10). The main indigenous species are cultivated mussels, pelillo (*Gracilaria*) and scallops; secondarily, other bivalves. Meanwhile, three introduced species of salmon sustained 79% of the national harvest. And although on a smaller scale, red abalone cultivation continues progressively growing in the north and south of the country.

Markets and Globalization At a global level, in 2014 harvests from aquaculture amounted to 73.8 million t, with an estimated first-sale value of US$160.2 billion, consisting of 49.8 million t of finfish (US$99.2 billion), 16.1 million t of mollusks (US$19 billion), 6.9 million t of crustaceans (US$36.2 billion), and 7.3 million t of other aquatic animals including frog (US$3.7 billion). World aquaculture production of fish accounted for 44% of total production (including for non-food uses) from capture fisheries and aquaculture in 2014, up from 42.1% in 2012 and 31.1% in 2004 (FAO, 2014). In the last three decades a growth trend in the relative importance of fisheries in the Americas region (e.g., North America, Central America and South America), passed from representing less than 5% of total regional fish production in 1985 to represent approximately 17% of total regional fish production in 2014. FAO (2014) reports that fish is among the most traded food commodity worldwide and that fish trade has greatly expanded

Table 10.10 Farmed species in Chile for the period 2010–2014.

Common name	Scientific name	Origin
Haematococcus	*Haematococcus pluvialis*	Indigenous
Giant kelp	*Macrocystis* spp.	Indigenous
Gracilaria	*Gracilaria* spp.	Indigenous
Atlantic salmon	*Salmo salar*	Introduced
Coho salmon	*Oncorhynchus kisutch*	Introduced
Rainbow trout	*Oncorhynchus mykiss*	Introduced
Turbot	*Scophthalmus maximus*	Introduced
Yellowtail	*Seriola lalandi*	Indigenous
Ezo awabi abalone	*Haliotis discus hannai*	Introduced
Red abalone	*Haliotis rufescens*	Introduced
Mussel	*Aulacomya ater*	Indigenous
Blue mussel	*Mytilus chilensis*	Indigenous
Giant mussel	*Choromytilus chorus*	Indigenous
Scallop	*Argopecten purpuratus*	Indigenous
Chilean oyster	*Ostrea chilensis*	Indigenous
Pacific oyster	*Crassostrea gigas*	Introduced

in recent decades due to the globalized environment under which the activity operates. The way fish products are prepared, marketed and delivered to consumers has changed significantly and commodities may well cross national boundaries several times before final consumption. The same author identifies six driving forces behind generating this globalized fisheries and aquaculture value chain, moving fish product consumption from local to international markets. These are, namely, relevant decreases in transport and communication costs; outsourcing of processing to countries with lower wages and production costs; increasing consumption of fish commodities; favorable trade liberalization policies; more efficient distribution and marketing; and continuing technological innovations in processing, packaging and transportation.

In addition to aquaculture growth during this period and as trade is highly dependent on consumer behavior and overall economic conditions, there has been a reduced demand in many key markets as a consequence of the economic contraction still affecting consumer confidence. FAO (2014) reports demand has been particularly uncertain in many developed countries, the main importers of fish for human consumption, thus driving exporters to develop new markets in a number of emerging economies still presenting healthy demand. FAO (2014) also reports that at present, the global economy appears to be transitioning towards more stable but slower growth. Economic conditions are rebounding in both developed and developing economies, but the resurgence in both trade and output remains slower in developed countries. In addition, demand is also increasing steadily in emerging economies for high-value species such as salmon, tuna, bivalves and shrimp. With capture production stable and various factors restricting aquaculture supply of shrimp and salmon, two of the world's major traded species, the upward pressure exerted on prices by continued global demand growth may be significant.

Since 2009, the FAO Fish Price Index 12 has been illustrating both relative and absolute fish price movements, which have shown a rapid increase since the beginning of the 21st century. A rise in prices for farmed species, particularly shrimp, is the major component of this rapid increase, although positive developments in prices for some wild species such as cod and certain pelagic species is another important driver. The main causes for divergence in price trends for capture and aquaculture products appear to be on the supply side and in the respective cost structures: higher energy prices on fishing vessel operations than on farmed ones, and supply lower than demand for certain species (FAO, 2014). Aquaculture has benefited to a greater degree from cost reductions through productivity gains and economies of scale, but it has recently been experiencing higher costs, in particular for feeds, which have affected production of carnivorous species in particular. Aquaculture production also responds to price changes with a time lag, given the stocking and production cycle for most species. In recent decades, the growth in aquaculture production has contributed significantly to increased consumption and commercialization of species that were once primarily wild caught, with a consequent price decrease (FAO, 2014).

Chilean Aquaculture Exports Exports reached little more than US$4.75 billion in 2014 with a total of approximately 733,000 t. Atlantic salmon, rainbow trout, Pacific salmon and Chilean blue mussel represented a 95% and 86% of total Chilean aquaculture export value and volume in 2014, respectively (Figure 10.19). Relative order of importance for these four species in value terms is Atlantic salmon, rainbow trout, Pacific salmon and Chilean blue mussel and it is reduced when exports are analyzed by volume, as non-specified (Salmon n/s) increases in importance from 3% in value to 13.6% in volume. Real value of Chilean aquaculture exports (base USD 2014) had a twofold increase over 12 years, growing from US$2.17 billion in 2003 to US$4.77 billion in 2014. This growth pattern was not exempt of problems as shown by the fall in export value observed between the years 2008 and 2010, a result of the ISA virus crisis experienced by the Chilean industry. Years 2012 to 2014 depict a rapid recovery and increase in export value (Figure 10.20). Export volume has also shown an increasing trend throughout the two first decades of the 21st century (Figure 10.4) with the exception of the ISA virus crisis between 2009 and 2010, which resulted in relevant reductions in production volume with respect to the levels reached by 2008. Figure 10.21 shows a recovery in the growth trend of Chilean salmon production from 2011 onwards, but Figure 10.20 shows that recovery of growth trend in export value took two years longer than production.

10.4.3.3 Main Climate Drivers

A wide range of weather conditions characterizes the climate along the Chilean coast considering its latitudinal extension (*ca.* 38°, 4,300 km): coastal desert climate in northern Chile to alpine tundra and glaciers in the east and southeast, oceanic in the south and Mediterranean climate in central Chile with marked four seasons in most of the territory. The SPSA, the Humboldt Current System (HCS) and the Andes mountains mainly control the climate in Chile. The HCS is one of the four sets of current on the eastern edge of the world, which is characterized by coastal upwelling areas, and cold water with a high concentration of nutrients which generates a high primary (phytoplankton) and secondary productivity (zooplankton and fish). Off the Chilean coast the HCS includes two areas showing marked differences in oceanographic conditions: (i) Arica area off-Coquimbo (18°–30°S), corresponding to an area characterized by the occurrence of moderate upwelling and SST relatively warm, which is quasi-periodic on-year and decadal scale. This region is susceptible to disturbance annual events such as ENSO. (ii) Area off central Chile (30°–42°S), region marked by a seasonal cycle

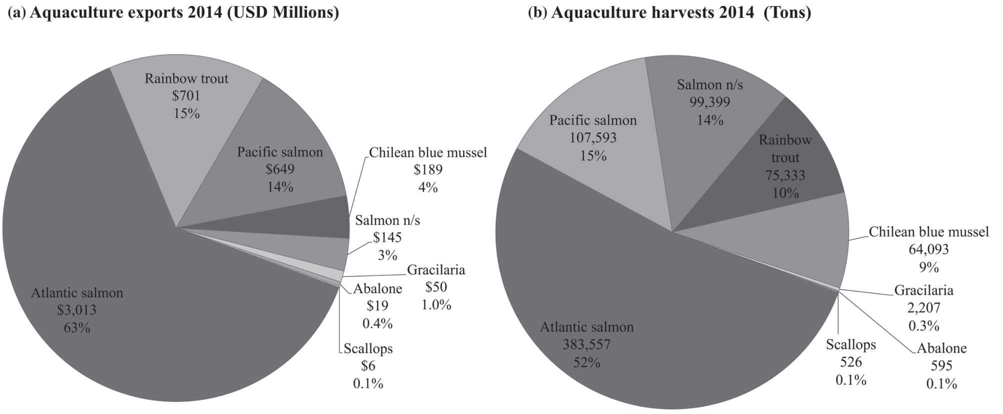


Figure 10.19 Species distribution of Chilean aquaculture export value in USD (a) and volume in t (b), 2014. *Source:* based on statistics from the Undersecretariat for Fisheries and Aquaculture, Chile.

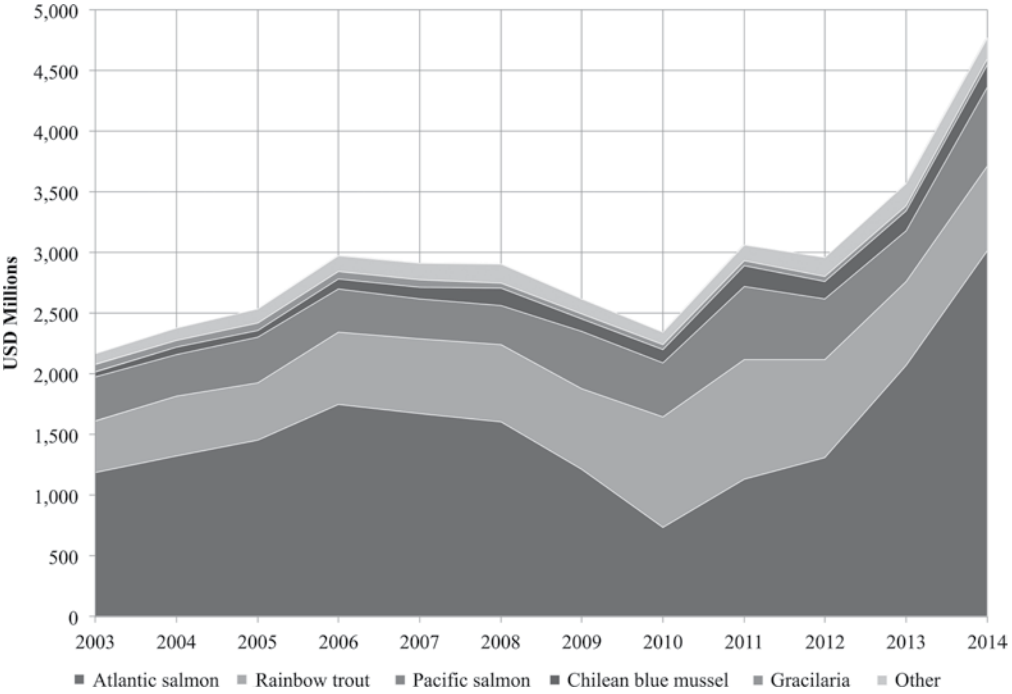


Figure 10.20 Evolution of Chilean aquaculture export value (Million USD base 2014) by species, for the period 2003–2014. *Source:* based on statistics from the Chilean Undersecretariat for Fisheries and Aquaculture, Chile.

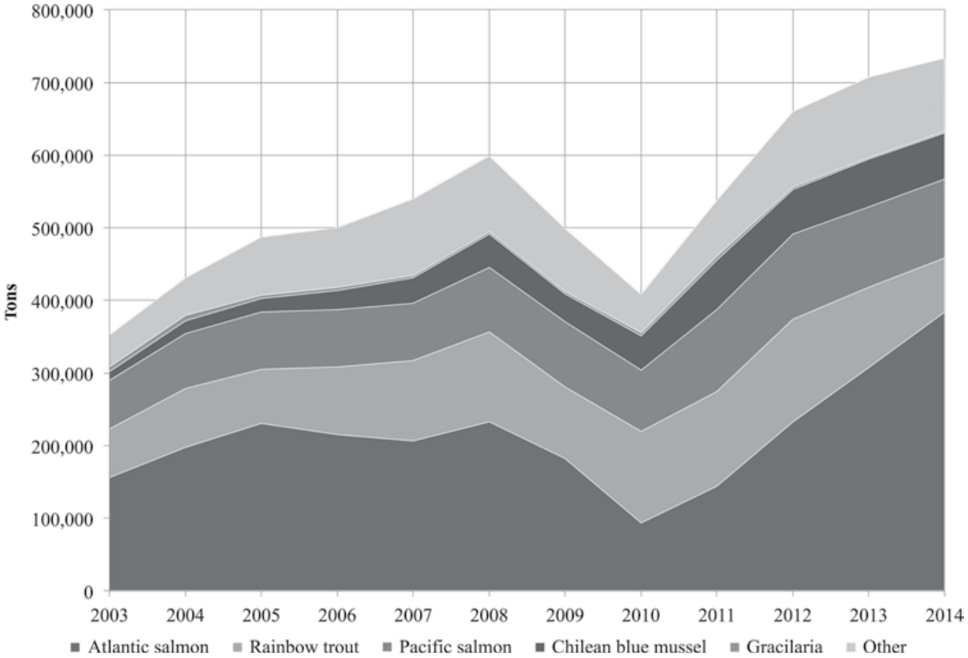


Figure 10.21 Evolution of Chilean aquaculture volume by species, for the period 2003–2014. *Source:* based on statistics from the Chilean Undersecretariat for Fisheries and Aquaculture, Chile.

of upwelling, with coastal convergences during the winter and moderate when during the summer period (October–March) but with a very high turbulent mixing due to wind action. The effects of the interannual ENSO events are minimal in this region, except for events which are very powerful.

South of these two HCS areas, and separated by the West Wind Drift, is the ecosystem of channels and fjords due to a cold temperate eco-region (south of 42°S and to Cape Horn). This system is extremely complex, characterized by fjords, straits, channels and islands that define a single eco-region, with high diversity and planktonic productivity that support a diverse fauna of polychaetes, mollusks, crustaceans and fish, some of them endemic. It is a recognized feed zone and reproduction of birds and marine mammals such as the blue whale. It should be noted that in this area most of the aquacultured salmon and mussels are developed. In the Los Lagos region, this system is connected to the Pacific Ocean through the Chacao Channel to the north and Boca del Guafo the south. From Puerto Montt to the limit with the Aysén region there are 247 km in a straight line, while the mirror surface of water in the analyzed geographical area reaches 15,577 km^2. The total length of the coastline of the inland sea of Chiloé, including 228 islands, reaches 4,663 km. In a meso-scale analysis, it is possible to identify deeper areas (greater than 300 m) located in the Seno Reloncaví and Golfo Ancud. These areas tend to form channels or narrow depressions with approximate NW–SE direction (Rodrigo, 2006).

As the models and data about the potential effects of climate change improve, higher resolution projections become available for both the scientific community and the general public. Chile is not the exception, and over the previous years remarkable efforts have been made to provide high-resolution data to assess the effects of climate change in the country. Studies are still scarce and only a handful of evaluations are available that cover the potential impacts of climate change at the country level. To the best of our knowledge, there are three comprehensive climate change studies that explored the current and future effects for Chile, namely: (i) Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century (Carrasco *et al.*, 2005). (ii) Estudio de la variabilidad climática en Chile para el siglo XXI (Fuenzalida *et al.*, 2006). (iii) UNDP Climate Change Country Profiles: Chile (New & Lizcano, 2010). There are several studies that cover the effects of climate change in specific regions and industries. Documents published by the Chilean Government (MMA, 2011) collect together most of the studies available for the country. Also, there are a handful of global studies available that could shine a light on the potential changes in the south Pacific and their effects on marine resources. Such studies include the report from the IPCC (IPCC, 2013) and many published scientific papers and technical reports that cover the potential effects of climate change for a variety of environmental indicators (Brander, 2007; Cochrane, 2009, De Silva & Soto, 2009). To describe the current and potential effects for the main climate drivers, we will refer to the studies available at the country level. We summarize the available projections for all climate change scenarios and relevant variables reported (see Table 10.11 for a summary of the predictions currently available in the literature).

Changes in Temperature Observed trends show that mean temperature has been increasing at an average of 0.5°C; forecasts predict the same pattern and mean temperatures are expected to increase about 0.05 to 2.0°C over the next decades, and about 0.3°–5°C in the long term (Fuenzalida *et al.*, 2006; Falvey & Garreaud, 2009). Current projections suggest that these differentials will be more severe in the northern region, which is more exposed to global current patterns (Fuenzalida *et al.*, 2006). The central and southern regions will also be affected; however, the projected changes available suggest that temperature increases will be ameliorated as

Table 10.11 Climate drivers projections available for the Chilean territory (Short term refers to projections of 10 to 20 years; Long term refers to projections of 30 or more years)

	Climate drivers variation							
Scenario	**Surface temperature (°C)**		**Wind speed (m/s)**		**Precipitation (%)**		**Sea level (m)**	
	Short-term	**Long-term**	**Short-term**	**Long-term**	**Short-term**	**Long-term**	**Short-term**	**Long-term**
A1B[1]	+0.8	+1.6/+2.4			−2	−3/−4		
A1FI[2]							+0.6/+1.0	
A2[3]	+0.05/+2.0	+2.0/+4.0	+0.6/+2.5	+6	−1	−25/−50	+0.05/+0.08	+0.1/+0.3
A2[4]	+1.5/+5.5							
A2[5]			+1					
A2[6]		+0.5/+5.0			−10/−70			
A21	+0.7	+1.5/+2.8			−1	−3/−5		
B1[1]	+0.7	+1.2/+1.7			−1	−2/−3		
B2[3]	+0.05/+2.0	+1.0/+5.0	+0.6 / +2.5	+6	−1	−25/−40	+0.04/+0.08	+0.1/+0.2
RCP 2.6[7]		+0.3/+1.7						+0.26/+0.55
RCP 4.5[7]		+1.1/+2.6						
RCP 6.0[7]		+1.4/+3.1						
RCP 8.5[7]		+2.6/+4.8						+0.45/0.82

[1] Karmalkar *et al.* (2013);
[2] Nicholls & Cazenave, 2010;
[3] Fuenzalida *et al.* (2006);
[4] Nuñez *et al.* (2009);
[5] Aiken *et al.* (2011);
[6] Garreaud (2011); [7]IPCC (2013).

the latitude increases farther south. According to the different scenarios reported, changes in mean temperature are very elastic, and regardless of the policies simulated, they are expected to differ significantly across scenarios. These changes in temperature are expected to influence the oxygen solubility of water bodies (Pörtner & Kunst, 2007), which can greatly influence aquaculture operations. First, habitat feasibility could be effectively modified across a wide range of species, potentially switching optimal farm locations and altering the current suitable areas currently defined by the government. Second, positive temperature gradients may increase the occurrence of algal blooms, which can drastically increase non-expected mortalities in fish and mussel production (Dear & Seaton, 1989; Shumway, 1990; Hallegraeff, 1993).

It should be noted that while in many regions of the planet there has been a warming of surface waters of the sea, on the west coast of South America the sea has been cooling from late 1970, in the order of 0.1° to 0.2°C per decade. This is confirmed by TSM satellite information, observing a clear cooling off the south-central and northern Chile area after 1979 (Falvey & Garreaud, 2009). It is important to note that this cooling is not simulated by any of the coupled global climate models used in climate projections contained in the IPCC reports. The most likely factor explaining the cooling of the SST is the intensification of the wind stress along the coast and therefore by coastal upwelling, which transports cold water from the deep to the surface. Garreaud & Falvey (2008) indicate that surface winds in these areas would be strengthened from a peak average of 6.5 m/s in 2000–2005 to 7.5 m/s in the period 2071–2100. This effect associated with coastal upwelling would cool surface waters. Increase in winds on the Chilean coast, may contribute through the processes of upwelling and continuous cooling of surface waters, or rather a non-warming of waters in these areas (Cubillos *et al.*, 2013).

Information about the changes in wind patterns is very scarce. The available forecasts point to an increase in mean coastal wind intensities of about 1–5 m/s in the upcoming decade, and about 6 m/s in the long term (Fuenzalida *et al.*, 2006). By the same pattern as with temperatures, the northern coast of the country is likely to be more affected by these changes (Fuenzalida *et al.*, 2006). These contrasting findings demonstrate the high degree of uncertainty regarding the future trends of key oceanographic variables that affect primary productivity, distribution of fisheries resources and effects on aquaculture along the Chilean coast. Changes in coastal wind patterns can have significant effects on several other relevant variables for aquaculture production. First, harsher conditions may require significant engineering adaption measures, or even the shift of entire production operations to less technically demanding environments (Badjeck & Allison, 2006). Second, if there are shifts in the composition of water layers, there could be potential changes in plankton distribution, which could lead to severe impacts in the productivity of mollusk farming (Muller-Feuga, 2000). Changes in oxygenation caused by increases in wind intensity could also modify the current distribution of appropriate locations for aquaculture production, rendering the current zoning scheme obsolete. Another indirect consequence of these changes is the possibility that pelagic species that compose a significant share of current aquaculture diets may be negatively affected (MacKenzie, 2000); the associated adaptation measures could render, in extreme cases, some aquaculture activities unprofitable (Tacon, 2008).

Pluviometry Regimes Average precipitation levels in the country have been showing a steady decrease over the last three decades (Fuenzalida *et al.*, 2006). Similar trends are consistently projected with decreases that could reach an average of 3–4 mm/day in the next couple of decades, and even 6 mm/day decreases in the long term for worst-case scenarios. As with the previous climate drivers, the central and southern coastline is likely to suffer the most extreme changes, where the worst predictions suggest a decrease of more than 50% in mean precipitation (Fuenzalida *et al.*, 2006). Changes in precipitation have a direct impact on fresh water supply, which is a key factor for salmon production (Ryther & William, 1972). An increase in use conflicts can significantly increase the operational costs for smolt producing facilities, with significant economic consequences. Estuarine conditions across the country could be severely modified by changes in runoff regimes, effectively altering salinity, pH and nutrient concentrations (Hopkinson & Vallino, 1995). Such modifications in chemical and physical properties could render some locations unfeasible for a given set of species. The potential combined effects of changes in precipitation may also force current zoning plans obsolete, and require them to be modified.

Sea Level Contemporary observations show that there has been a steady increase in sea level; available reports account for an increase of about 1 to 4 cm (Fuenzalida *et al.*, 2006). Climate projections estimate that increases could reach an average of 6 cm in the upcoming decades, and increases of more than 50 cm in the long term worldwide. It is expected that the northern region of the country will suffer the biggest shifts in magnitude, where the available worst-case scenario predicts increases of more than 30 cm (Fuenzalida *et al.*, 2006). The implications of these changes can have two potential impacts. First, they could alter the prevailing conditions of estuaries, having similar consequences as stated above in the pluviometry regimes section. Second, despite not affecting farming species directly, it is possible that sea level rise could constrain logistics in terms of infrastructure location; such new conditions may force operations to relocate and even develop new technology to withstand these new environmental drivers; these adaptation measures could entail significant levels of investment and may lower current levels of profitability for aquaculture activities.

10.4.3.4 Main Impacts

Salmon Salmonids (e.g., *Salmo salar*) have a relatively narrow range of temperature optima (De Silva & Soto, 2009). In Chile, the average farming cycle lasts 24 months for coho and trout and 30 months for salar. The first phase (6–12 months) takes place in controlled freshwater environments (fish farm inland) and in cages located in lakes to produce smolts. Geller (1992) measured temperature profiles in 24 lakes in summer along a latitudinal transect from central Chile (32°S) to Patagonia (47°S). The lakes of the temperature zone, between 47°S and 38°S, are warm monomictic with surface and deep-water temperatures ranging from 12° to 21°C and from 5.5° to 10°C, respectively. In the second phase, smolts are transferred and farmed in seawater cages for 12–18 months. The necessary conditions for salmon growth include: cold waters, a sheltered coast line and optimal biological conditions. Atlantic salmon grows best in sites where water temperature extremes are in the range 6°–16°C and salinities are close to oceanic levels (33–34‰) (FAO, 2016). Optimum water temperature range for most salmons is 12.8°–17.8°C. Warmer summers are also raising stream temperatures, making salmon more susceptible to predators, parasites and disease. Massive fish kills have occurred at or above 22°C (NWF, 2016).

Scallops They are most abundant within the bathymetric range 4–10 m and occur mainly at salinities of 32–34 psu on sand and firm sandy/mud substrates interspersed with rocks. Optimal growth temperature is 4°–8°C and the tolerance range is from −2° to 26°C. Inshore distribution is limited by ice depth during winter. Optimum temperature for larval development is 15° + 2°C and optimum salinity 30 + 2 psu. Other authors show ranges of 8°–28°C (Shumway *et al.*, 2011).

Blue Mussel Chanley & Chanley (1991) showed that based on distributional patterns it seems likely that these mussels can survive at least over the range of 10° to 18°C and salinities of 15 to 40 psu. Highly tolerant of a wide range of environmental conditions, the blue mussel is euryhaline and occurs in marine as well as in brackish waters down to 4 psu, although it does not thrive in salinities of less than 15 psu and its growth rate is reduced below 18 psu. Blue mussels are also eurythermal, even standing freezing conditions for several months. The species is well-acclimated for a 5°–20°C temperature range, with an upper sustained thermal tolerance limit of about 29°C for adults.

Gracilaria For *G. chilensis* in Southern Chile, the mean annual water temperature is about 13°C, with an annual range from 7.5° to 20°C (Westermeier *et al.*, 1991) with salinity varying between 17–31 psu (Santelices *et al.*, 1993). The lowest salinity values were observed during low spring tides throughout the austral winter months (e.g., June–August), when heavy rains occur in this area (Santelices *et al.*, 1993).

Changes in Resistance to Pathogens and Pests Burge *et al.* (2014) reviewed climate change impacts on marine host–pathogen–environment relationships. Diseases have had large impacts on both cultured and wild harvests of commercially important species, such as salmon (e.g., *Ichthyophonus* infection in marine and anadromous fish and viral infections in Atlantic and Pacific salmon), abalone (e.g., withering syndrome) and crustaceans (e.g., protozoan infections of natural populations and viruses in farmed species). In both terrestrial and marine systems, interactions between hosts, pathogens, and the environment govern disease outbreaks, and a change in any of these components can shift the balance toward or away from a high-intensity disease state. Shifts in the global environment are leading to physical ocean changes, including changes in temperature, increases in CO_2 concentrations/decreases in pH, changes in precipitation (leading to changes in salinity), and exposure to storms and cyclones. All of these factors are shifting the host–pathogen–environment equilibrium. There are several reasons that more is known about certain host–pathogen–environment interactions compared with others in marine systems. Some of these systems may be particularly sensitive to climate variability and change and therefore respond strongly. Some systems may be easily monitored (e.g., slow-moving or sessile taxa and taxa that show clear and distinguishable signs of infection) and therefore have more baseline data available. Commercial species (e.g., oysters) and those with human health consequences (e.g., *Vibrio* in seafood and water) are often well-monitored owing to their direct economic and societal consequences.

From a disease point of view an increase in temperature can have many effects. Bacterial, viral and fungal disease will have shorter generation times. It is possible that some diseases, which transmit above a minimum temperature, will increase in prevalence. Not all effects on disease will be detrimental. For example the seasonal window of infectivity of some serious infectious conditions such as Viral Hemorrhagic Septicemia Virus (VHSV) or the freshwater viral disease infectious pancreatic necrosis virus (IPNV) could be shortened, whilst others that requires a minimum temperature to cause clinical symptoms and transmission, such as bacterial kidney disease (BKD) in freshwater salmonids, could be lengthened. However, as most fish are poikilothermic their physiology is largely governed by the temperature of their surrounding environment and warmer water will mean the immune system of these animals will function more effectively in preventing the establishment of infections (up to the thermal optimum of the animal). It is therefore possible that clinical infections will not increase as fewer infections become established in the host. Once the thermal optimum is exceeded, then the function of the immune system will decline and physiological stress and oxygen depletion (warmer water holds less oxygen in solution than cold water) may well lead to disease and welfare issues. Some viral infections can only occur between narrow temperature ranges, often 10°–12°C, usually during spring and autumn. Warmer water conditions may allow the establishment of exotic diseases, which are currently excluded, as the climate is too cool to permit transmission. Beneficially, diseases that occur under cool environments (e.g., cold water vibriosis) may become much rarer if the ecosystem is not cold enough for their biology. If shellfish experience super-optimal thermal conditions (as will be more likely, particularly for intertidally cultivated species, given the predicted changes in temperature for the regions where they are cultivated) they may be more susceptible to bacterial, viral and parasitic infections. By their nature it is difficult to understand the response of diseases of unknown etiology to increase in temperature.

Bacterial Infections As a rule of thumb as temperature increases the generation time of bacteria decreases so under higher temperature regimes most bacterial infections would be predicted to progress faster once the host was infected; however, as mentioned above, assuming the animal is not at its thermal limit the fish's immune system will be operating more effectively and may well overcome the infection (Gubbins *et al.*, 2013). Under a rising temperature regime some bacterial diseases of fish, such as *Moritella viscose* and cold water may decline in abundance as these diseases are characteristically seen in winter under cold-water conditions and the new warmer environment may well adversely affect these bacteria. *Aeromonas salmonicida* and BKD, however, tend to occur under rising temperature regimes and during the summer months. If the environment warms by 2°C then it is possible that diseases such as these will occur earlier in the year (as the spring will be warmer and earlier) and the period in which these diseases are common may well be extended, increasing the infectious pressure of these pathogens in the environment. Warmer conditions may also favor currently rare bacterial infections such as *Mycobacterium marinum* and *M. chelonae*, allowing these pathogens to extend their range further north.

Increased water temperatures could also increase the risk of vibriosis infections of shellfish. Recent studies in the Mediterranean have shown a link between vibrio infections, seasonality and temperature. Changes in precipitation (increases in winter in the north) could also influence bacterial loading to the coastal environment where fish and shellfish farms are situated. This could increase the rate of infection. Viruses effectively hijack the host's cells to replicate, and the rate of replication is governed by the animal's physiology. As most fish are poikilothermic the temperature of their surrounding environment largely governs their physiology and warmer water will mean the animals will have a faster metabolism, which in turn could lead to increased viral replication within the host. It is worth pointing out again that, assuming the animal is not at its thermal limit, the fish's immune system will be operating more effectively and may well overcome the infection as described above. As parasites of fish and shellfish often have very complex life-cycles involving many intermediate hosts, understanding how climate change would affect parasite abundance and the incidence of infection is more difficult to predict.

Salinity changes resulting from perturbed precipitation could also affect sea lice. At salinity values <29 psu lice survival is compromised (Bricknell *et al.*, 2006b), which might suggest potential for increased infection rates in estuaries. In Chile, the gradual loss of efficacy of emamectine benzoate has been reported, the only currently available and registered drug in Chile; this was possibly related to increased salinities which are preferred by this parasite. On the other hand, Harmful Algal Blooms (HABs) are a recurring phenomenon in the south-southern region of Chile where most of the Chilean aquaculture is developed. Guzmán (2016) noted that:

> *Presence of blooms cannot be described as an abnormal situation, but can be expressed with varying intensity and covering different, more or less extensive geographic coverage, which is dependent on environmental conditions that determine the initiation, maintenance and decline of these events… Currently, there is no information to indicate categorically that what we are watching is linked with what is defined as Global Change,*

> *but it is estimated that the conditions are forecast to occur linked to this change, determine an increased occurrence of blooms harmful. However, these changes should wait for several decades now the situation should be explained by ENSO 2015–2016.*

Changes in Productivity While there is no specific information and findings generated by climate change on aquaculture productivity effects, it is possible to rescue information about events elsewhere that have been attributed to climate effect. In Chile, HABs have affected mainly the salmon farming industry since 1988 when the flagellate *Heterosigma akashiwo* caused major mortalities over 2,000 t in the area of Hornopirén, Seno Reloncaví and inland sea of Chiloé, among others in the fledgling salmon industry. Subsequently, there have been other harmful events caused by diatoms *Leptocylindrus minimus* and *Chaetoceros convolutus* and dinoflagellates *Alexandrium catenella* and *Gymnodinium* sp. There have also been harmful effects on fish due the rafidoficean *Chattonella* sp. Loss of appetite, behavior irregularities and mortalities of fish were mainly caused by two factors: mechanical problems on gills by specific phytoplankton and secondly the presence of ichthyotoxic flagellates affecting cells and also gill tissues. Therefore, both problems generate disturbances to the normal process of gas exchange and therefore a negative effect on fish metabolism. With the results of statistical analysis, it can be deduced that the flagellates (*Heterosigma* and *Gymnodinium* sp.) produce very severe impacts on salmon crops. However, so far the occurrence has been low. The growing season is usually in late summer and early autumn, especially in years with less rainfall. It can be assumed that after of at least one year of significant deficit of rainfall, there is greater probability of occurrence of blooms of flagellates in the inner waters of the Los Lagos region. The surface temperature distribution shows oscillations from 1992 to 2005, but it is striking that the highest averages were produced in 1994 and 1998–1999 periods when ENSO events occurred. Furthermore, areas with higher average temperatures are Reloncaví estuary, Seno Reloncavi and Hornopirén, also including observed seasonal differences. During last summer (2016), more than 24 million salmon, equivalent to 38,000 t of mortality, was the result of the emergency caused by the bloom of the alga *Pseudochattonella* cf. *verruculosa* in fish farms located within Reloncaví and the north of Chiloé Island, in the Los Lagos region. The main consequences were the loss of US$200 million and 4,000 unemployed people until April 2016.

HABs around the world have generated high economic and social impacts on affected areas. Chile has not been an exception. For a few years, there have been large areas of Southern Chile (44°–55°S) closed to shellfish fishing areas that potentially accumulate marine toxins. HAB presence also has a negative impact on susceptible species (filtering species) inhabiting neighboring areas to those areas which are closed or banned due to direct HAB presence. The establishment of national surveillance and control programs for domestic consumption and export products have enabled production, despite extensive precautionary closures in southern Chile, as well as significantly reducing cases of human poisoning (Suárez-Isla & Guzman, 1999). The observation of increases in the incidence of the potentially toxic HAB genus *Pseudo-nitzschia* diatoms, detection of domoic acid in 1997, and the detection of sub-toxic levels of saxitoxin in northern coastal areas of the country unaffected, indicate that the risk of spread of HAB is always present and may affect the current production of toxins. It is therefore relevant to assess the economic impact of HAB occurrence along the coast of Chile in unaffected areas. The presence of the HAB means no commercialization or stopping exploiting areas with potential production, which in economic terms implies a reduction of seafood supply. The risk of the appearance of HAB in Chile increased; considering that mining activity or tiller seafood can be affected by the HAB, it is highly concentrated in some regions: Atacama (Bahía Inglesa), Coquimbo and Los Lagos (Chiloé).

Socio-Ecological Changes During the last two decades in Chile there have been several outbreaks caused by toxic seafood consumption. In 2002, an outbreak of PSP caused by *Alexandrium catenella* on the coast of Chiloé, affected 73 people, three of whom died. The economic impact was estimated at US$3 million, due to a ban that lasted 80 days. *V. parahaemolyticus* bacteria caused several outbreaks affecting 297 people in 1998, 1,500 in 2004, and 10,205 people in 2005. The last outbreak affected much of the Chilean coast and one death was recorded.

Tables 10.12, 10.13 and 10.14 summarize the oceanographic and meteorological changes expected due to climate change, the types of potential threats and consequences for growing salmon, mussels, oysters and algae. The main consequences in the short and medium term are reduction of productivity and production, increase of maintenance measures for waste removal and increase of measures for water oxygenation, and increase of preventive and urgency treatments. In the long term the main consequences are associated with the relocation or closure of farms.

10.4.3.5 Adaptation

The extent and nature of the negative impact imposed by climate change can be managed by effective adaptation. In this context, climate change and adaptation refer to adjustments in human and natural systems to respond to the expected climate changes. Many of the ecological and social systems have preset forms and rhythms to build their resilience, but the rate at which climate change is happening can impose new and potentially unbearable pressures on existing adaptation systems. This may be particularly true for secondary changes induced by the expected climate changes that undermine the ability of people and ecosystems to cope with the recovery from the effects of extreme weather changes and other risks (IPCC, 2014). This highlights the importance of generating knowledge at the speed and intensity with which climate change can affect natural systems, and the sensitivity of these changes to systems and their ability to adapt. This is in order to be able to anticipate and minimize the impacts of climate change on people. Coastal settlements and activities of fisheries and aquaculture can be human systems strongly affected by climate change and may generate knowledge about its current status, sensitivity and vulnerability. It is crucial to design actions to mitigate and minimize the effects of climate change on them.

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive and in some cases irreversible detrimental impacts (IPCC, 2014). Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change. A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability. Integration of adaptation into planning, including policy design and decision-making can promote synergies with development and disaster risk reduction. Building adaptive capacity is crucial for effective selection and implementation of adaptation options. Climate change exacerbates other threats to social and natural systems, placing additional burdens, particularly on the poor. Aligning climate policy with sustainable development requires attention to both adaptation and mitigation. Delaying global mitigation actions may reduce options for climate-resilient pathways and adaptation in the

Table 10.12 Expected changes and possible consequences on salmon industry

Expected change	Threat	On salmon	Productive and operational	Socioeconomic
SST increase	Higher frequency on microalgae blooms that release toxins with harmful effects on the farmed species and human beings	Increase of mortality due gills obstruction	Reduction of productivity and production	Profit reduction Job losses
			Increase of measures for water oxygenation	Reinvestments
	Decreasing of oxygen dissolution capacity Changes on location and width of geographic ranges appropriate for the farmed species	Increase of mortality due hypoxia/anoxia	Increase of maintenance measures for waste removal	
	Disturbance of local ecosystems Increased occurrence of pest outbreaks Increased occurrence of disease outbreaks	Growth reduction due to stress	Increase of preventive treatments	
			Increase of urgency treatments	
			Farming relocation	
			Farming closure	
	Decreasing in the ventilation capacity of the ecosystem Decreasing in fishing resources availability for feeding Increasing in the meteorological reduction	Increase of mortality due to anoxia	Increase of measures for water oxygenation	Profit reduction
			Increase of maintenance measures for waste removal	Job losses
			Reduction of productivity and production	
		Does not apply	Farming closure	Increasing in food costs
				Profit reduction
		Does not apply	Loss of operative days	Job losses

Increasing of sea level	Losses in suitable areas for aquaculture	Does not apply	Farming relocation	Profit reduction
			Farming closure	Job losses
				Reinvestments
	Increasing of floods at productive centers in land	New parasites and diseases outbreaks	Increasing of prevention measures against floods	Profit reduction
				Job losses
			Increase of preventive treatments	Reinvestments
			Increase of urgency treatments	
	Increasing of salinity in continental waters	Reduction on fingerling growth due stress	Increasing of treatments for water utilization	Profit reduction
				Job losses
				Reinvestments
Increase of frequency or intensity storms	Waves size increasing	Does not apply	Increasing of structure resistance	Increased investment
	Increasing in occurrence of storm surges			
	Increasing of floods at productive centers	Possible trespass of parasites and diseases	Increasing of prevention measures against floods	Profit reduction
	Salinity changes			Job losses
	Higher recurrence in occurrence of plagues	Reduction on growth due to stress	Increasing of prevention measures against floods	Reinvestments
			Increase of preventive treatments	
	Higher recurrence in occurrence of diseases	Increasing mortality	Reduction of productivity and production	
	Structural damages	Possible leak of cultivated species	Farming relocation	
			Farming closure	

Table 10.12 (Continued)

Expected change	Threat	On salmon	Productive and operational	Socioeconomic
Increase on continental water temperature	Decreasing of oxygen dissolution capacity	Increase of mortality due to anoxia	Reduction of production	Profit reduction
			Shutdown of farming centers	Job losses
	Changes on location and width of geographic ranges appropriate for the farmed species	Reduction of growth due to stress	Increase of measures for water oxygenation	Reinvestments
			Farming relocation	
			Increase of preventive treatments	
	Change in local ecosystems		Increase of urgency treatments	
	Higher recurrence of plagues outbreaks			
	Higher recurrence in occurrence of diseases			
	Salinity changes	Reduction on growth due to stress	Reduction of productivity and production	Profit reduction
	Water quality reduction		Relocation of farming centers	Job losses
			Farming closure	Reinvestments
			Adoption of technologies for improvement of water quality	
Reduction of rainfall	Reduction of fresh water availability	Does not apply	Adoption of recirculation technologies	Profit reduction
			Reduction of production	Relocation of farming centers
			Farming relocation	
			Farming relocation	Shutdown of farming centers
	Changes on feasible locations for farming of species	Does not apply	Reduction of productivity and production	Profit reduction
			Farming relocation	Job losses
			Farming closure	Reinvestments

Table 10.13 Expected changes and possible consequences on scallop industry.

Expected change	Threat	On species	Productive and operational	Socioeconomic
SST increase	Higher frequency of HAB	Does not apply	Reduction of productivity and production	Profit reduction Job losses Reinvestments
	Decreasing of oxygen dissolution capacity	Increase of mortality due to anoxia	Reduction of productivity and production	Profit reduction
	Changes on location and width of geographic ranges appropriate for the farmed species	Reduction of growth due to stress	Increase of measures for water oxygenation Increase of maintenance measures for waste removal	Job losses Reinvestments
	Disturbance of local ecosystems	Reduction of food availability	Increase of preventive treatments	
	Increased fouling	Increase of mortality	Increase of urgency treatments	
	Increased occurrence of pest outbreaks		Farming relocation	
	Increased occurrence of disease outbreaks		Farming closure	
Wind, currents and waves changes	Decreasing in food availability at the water column	Reduction of growth	Reduction of production	Profit reduction
	Decreasing in the ventilation capacity of the ecosystem	Increase of mortality due to anoxia	Increase of measures for water oxygenation Farming relocation Farming closure	Job losses Reinvestments
Increase of frequency or intensity of storms	Increasing of bad weather conditions	Does not apply	Loss of operative days	Profit reduction Job losses
	Waves size increasing	Does not apply	Increasing of structures resistance	Higher levels of investments
	Increasing in occurrence of storm surges			
	Salinity changes	Reduction on growth due to stress	Reduction of productivity and production	Profit reduction
			Increase of preventive treatments	Job losses
	Higher recurrence in occurrence of plagues	Increasing mortality	Increase of urgency treatments	Reinvestments
	Higher recurrence in occurrence of diseases	Possible leak of cultivated species	Farming relocation Farming closure	
	Structural damages			

Table 10.14 Expected changes and possible consequences on mussel industry.

Expected change	Threat	On species	Productive and operational	Socioeconomic
SST Increase	Higher frequency of HAB	Does not apply	Reduction of productivity and production	
	Decreasing of oxygen dissolution capacity	Increase of mortality due to hypoxia/anoxia	Reduction of productivity and production	
	Changes on location and width of geographic ranges appropriate for the farmed species.	Reduction of growth due to stress	Increase of measures for water oxygenation	Profit reduction Job losses
	Disturbance of local ecosystems	Reduction of food availability	Increase of maintenance measures for waste removal	Reinvestments
	Increased occurrence of pest outbreaks			
	Increased occurrence of disease outbreaks		Increase of preventive treatments Increase of urgency treatments Relocation of farming centers	
Wind, currents and waves changes	Decreasing in food availability in water column	Reduction of growth	Reduction of production	Profit reduction
	Decreasing in the ventilation capacity of the ecosystem	Increase of mortality due to anoxia	Increase of measures for water oxygenation Farming relocation Farming closure	Job losses Reinvestments
	Increasing in the meteorological reduction	Does not apply	Loss of operative days	Does not apply
Increasing of sea level	Losses in suitable areas for aquaculture	Does not apply	Farming relocation Farming closure	Profit reduction Job losses
	Increasing of floods at productive centers	Possible trespass of parasites and diseases	Increasing of prevention measures against floods	Reinvestments
	Increasing of salinity in continental waters	Reduction on fingerling growth due to stress	Increase of preventive treatments Increase of urgency treatments Increasing of treatments for water utilization	

Table 10.14 (Continued)

Expected change	Threat	On species	Productive and operational	Socioeconomic
Increase of frequency or intensity of storms	Waves size increasing	Does not apply	Increasing of structures resistance	Higher levels of investments
	Increasing in occurrence of storm surges			
	Increasing of floods at productive centers	Possible trespass of parasites and diseases	Increasing of prevention measures against floods	
	Salinity changes			
	Higher recurrence in occurrence of plagues	Reduction on growth due to stress	Increase of preventive treatments	
			Increase of urgency treatments	
	Higher recurrence in occurrence of diseases	Increasing mortality	Reduction of production	Profit reduction
	Structural damages	Possible leak of cultivated species	Relocation of farming centers	Job losses
			Shutdown of farming centers	Reinvestments
Reduction of rainfall	Salinity changes	Reduction on growth due to stress	Reduction of production	
	Water quality reduction		Increase of measures for water oxygenation	
			Farming relocation	
			Farming closure	
	Changes on feasible locations for farming of species	Does not apply	Reduction of production	Profit reduction
			Farming relocation	Job losses
			Farming closure	Reinvestments

future. Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, encompassing connections among human health, water, energy, land use and biodiversity (IPCC, 2014). Considering the last policy principles and recommendations, Chilean governance have developed an Adaptation Plan to Climate Change for Fisheries and Aquaculture which involves developing country initiatives and policies on climate change and resource sustainable management of fisheries, aquaculture and general conservation of marine biodiversity. The objectives related with this plan are: (i) Promote the implementation of the precautionary and ecosystem approach to fisheries and aquaculture as a way to improve the resilience of marine ecosystems and coastal communities, which make use of aquatic resources and the sector in general. (ii) Develop the necessary research to improve knowledge on the impact and climate change scenarios on the conditions and ecosystem services in which the activity of fishing and aquaculture is based. (iii) Disseminate and report on the impacts of climate change for the purpose of educating and training users and stakeholders of the fisheries and aquaculture sector. (iv) Improve legal, political and administrative frameworks to effectively and efficiently address the challenges and opportunities of climate change. (v) Develop direct adaptation measures aimed at reducing vulnerability and the impact of climate change on fisheries and aquaculture activities.

In a socioecological system where there is human intervention, its adaptability to climate change is a function of the capacity to understand the problems of climate and its impact on system components; the capacity to identify appropriate adaptation measures; and the capacity to implement the identified measures. Among the 29 measures proposed for the fishery and aquaculture sector, we can highlight those applying to aquaculture industry: (i) determination of suitable areas for aquaculture in accordance with the possible future climate scenarios. (ii) Analysis of environmental and oceanographic variables that affect production mussel seeds. (iii) Study of vulnerability to climate change for aquatic resources important for fisheries and aquaculture. (iv) Prediction systems for weather conditions and artisanal fishery aquaculture. (v) Evaluation of species of interest for aquaculture under different weather scenarios. (vi) Study of the change in the geographical distribution of *Alexandrium catenella* in fjords and channels of southern Chile. (vii) Effects of climate change on aquaculture activities developed in river and lake areas. (viii) Local training or through pilot projects. (ix) Information on climate change in fisheries and aquaculture. (x) Adaptation of regulations for immediate responses to climate variability and extreme events. (xi) Insurance systems for farmers and small-scale fishers to weather events.

10.4.3.6 Conclusion

There is global evidence that climate change is happening and it is affecting fisheries and aquaculture at different spatial and temporal scales. However, the implementation of regional climate models indicate that in recent years the coastal ocean off Chile is cooling or at least is not warming as in other areas of the world. These contrasting findings indicate the need to strengthen the quantity and quality of meteorological and oceanographic information and the development of regional/local models to reduce the uncertainty associated with future climate scenarios that will accompany aquaculture over the coming decades. Chilean aquaculture as a relevant socioecological system must make extra effort on the actual application of the ecosystem and take precautionary approaches if needed to reduce the risks and uncertainties associated with future climate scenarios along the Chilean coast. In this context, one of the main challenges is to advance the identification and attribution of observed effects on physical, biological and ecological systems. This means investing in timely systematic, rigorous and simultaneous achievement of environmental, biological, productive, health and ecological information both at farm scale and mesoscale. This is the only way to establish adaptation plans that take advantage of opportunities or face threats to productive and economic sustainability.

Because of the scarcity of basic and applied information, it is essential to strengthen research programs that establish a baseline reference for which it is possible to assess the physiological tolerance ranges of resources grown exposed to future weather and oceanographic scenarios. Catastrophic events for aquaculture recorded during the last decade suggest the need to define regulatory and financial scenarios, to face the recurrence of such events whose productive, economic and social effects are extremely high for both the public and the private sectors. In the above context it is essential to design and implement early warning systems to mitigate the effects generated by extreme changes of climate and ocean that directly or indirectly affect the resources of cultivated and farming systems.

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