Effects of Climate Change on Coastal Aquaculture in British Columbia:

An Examination of Anticipated Impacts in the Strait of Georgia

by

Edson Anselmo José

BSc, Eduardo Mondlane University, 2004

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

Supervisory Committee

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Dr. Jack Littlepage (Center for Global Studies – University of Victoria)
Additional Member

Abstract

Supervisory Committee

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Departmental Member

Dr. Jack Littlepage – Center for Global Studies, University of Victoria
Additional Member

Climate change is one of the factors that pose new challenges to the sustainability of the capture fishery and aquaculture sector around the world. As concerns over the impacts of climate change on ecosystems have been increasing over the last few decades, this study investigated how anticipated changes in climatic conditions would affect Manila Clams and Pacific Oysters bottom culture in British Columbia (BC) and assessed the extent to which the environmental databases that have been assembled by various agencies and institutions in BC could support this type of analysis.

This study examined changes in sea surface salinity (SSS) and sea surface temperature (SST) developed scenarios of these changes and analyzed the trends based on projections of SST and SSS of open ocean adjacent waters of BC's coast. In addition, this study quantified beach exposure/inundation as result of sea level rise (SLR). Moreover, this study identified areas along the Strait of Georgia (SoG) that have capability for shellfish culture and defined capability indices for Manila Clams and Pacific Oysters bottom culture based on the physical conditions that characterize existing commercial aquaculture operations. Finally, this study assessed how bottom shellfish culture sites' capability in the SoG will be affected by changes in SST, SSS and beach exposure/inundation associated with SLR.

Results of the analysis indicate that the annual average projections of SST of open ocean adjacent waters of BC's coast will increase approximately 1^0C between 2012 and 2050 at a rate of 0.111^0C/year, and between 2051 and 2100 the SST will increase approximately 2^0C at a rate of 0.033^0C/year. The annual average projections of SSS of open ocean adjacent waters of BC's coast will decrease approximately 0.2 ppt between

2012 and 2050 at a rate of 0.0055 ppt/year. Furthermore, projections from 2051 to 2100 indicate that SST will decrease approximately 0.5 ppt at a rate of 0.0088 ppt/year.

In addition to the performed analysis, this study selected and simulated SLR on three sites (Buckley Bay and Fanny Bay in Baynes Sound, and Henry Bay on Texada Island). The results indicate that an increase of 1.2 m in sea level will inundate 121 ha of Buckley Bay and Fanny Bay combined and 37 ha of Henry Bay. An increase of 2 m in sea level will inundate 195.2 ha of Buckley Bay and Fanny Bay, and, 51.4 ha of Henry Bay. Capability indices' classes defined and mapped in this study for Manila Clams bottom culture are: Not advisable, Poor, Medium and Good; and Not Advisable, Medium and Good for Pacific Oysters.

This study concluded that the existing datasets provided by various agencies and institutions are accessible, and can be used to investigate the impacts of climate change on coastal aquaculture in BC, although there is lack of some datasets as well as there is a need to improve some available datasets. This study also demonstrated and concluded that site capabilities to support Manila Clams and Pacific Oysters culture in the SoG will not be affected by the expected changes of SST, SSS. Changes in SST and SSS associated with SLR will not adversely affect shellfish bottom culture in the SoG. In contrary, SLR will have a negative impact on shellfish bottom culture.

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Acknowledgments

My sincere gratitude goes to my advisory committee: Dr. Mark S. Flaherty, Dr. Stephen Cross and Dr. Jack Littlepage for their academic support and guidance. Thank you to my parents, brothers and sisters for their on-going support. I also want to extend my gratitude to Moussa Magassa and Betsy Alkenbrack for their warming hospitality while in Victoria for the first days. Thank you to Tito and his family, Eisa and his family, Anica Massas, Ana Madina and Mohammed for their friendship and support.

A special thanks to Ms. Maria Isabel and Fatima Mendes from the Instituto Nacional de Desenvolvimento de Aquacultura (INAQUA), Regina Tiba, Jessica Blythe and Dr. Eduardo Loos for their support and encouragement throughout my research process.

I would like to acknowledge the Canadian International Development Agency (CIDA) and the Southern Oceans Education and Development (SOED) project for their financial support without which this research would not have been possible. Finally, thanks to all my classmates at UVic and co-workers at INAQUA who provided me ongoing collegial support.

Dedication

To the very special people in my life:

Kewany and Bucha, you two inspired me to work hard and get this far, without your love and understanding I would not be able to make it. Mom and Dad, you have given me so much, thanks for your prayers and faith in me and for teaching me that I should never give up.

I made it!

Chapter 1

1.1 Introduction

Concerns over the impacts of climate change on people and ecosystems have been increasing over the last few decades. One key area of concern is the effects that changes in environmental conditions will have on global food security. It is anticipated that the world's food production systems will be affected by many factors such as changes in precipitation patterns that result in drought or flooding in different regions, as well as temperature fluctuations that will lengthen or shorten growing seasons thereby changing the suitability of areas for different crops. These changes will also affect food marketing systems and directly impact on food affordability (Gregory et al., 2005; Brander, 2007). Although most of the attention has focused on agriculture, climate change also poses new challenges to the sustainability of the capture fishery and aquaculture sector (Cochrane et al., 2009). Climate change will compound existing pressures on fisheries and aquaculture, and pose a serious threat to the livelihood and food security of millions of people (FAO, 2008; WorldFish Center, 2009).

Aquaculture is the fastest growing food-producing sector in the world. It plays an increasingly important role in maintaining a consistent supply of aquatic species for human consumption. Additionally, it makes significant contributions to the economies of many nations, both developing and developed, by improving incomes and providing employment opportunities (Subasinghe et al., 2009). According to Food and Agriculture Organization of the United Nations - FAO, (2010), global aquaculture production and capture fisheries supplied the world with an estimated 142 million tons of food fish in the year 2008. This figure represents an approximate per-capita consumption of 17 kilograms. In relation to total global marine production, both fish capture and aquaculture production, aquaculture accounted for 46 percent of the world's aquatic species supply in 2010. This represents a slight decrease from that reported in 2008 (FAO, 2010). Asia dominates world aquaculture production, accounting for 89 percent by quantity and 79 percent by value (Bostock et al., 2010). China is the world's largest aquaculture producer contributing with 62.3 percent of the total production in 2008 (FAO, 2010).

According to the WorldFish Center (2009), many fishery-dependent communities and aquaculture operations are in regions highly exposed to climate change. These regions include central and western Africa, north-western South America and Asia (Allison et al., 2009). The impacts of climate change result of many different factors such as (i) gradual warming; (ii) associated physical changes, and (iii) intensity and location of extreme events. The interaction of these factors takes place in the context is of other global socio-economic pressures on natural resources (Brander, 2010). The aquaculture sector will be affected both directly and indirectly as a result of climate change (FAO, 2008; Vadacchino et al., 2011). On the one hand, direct effects act on marine animals' physiology and behavior. Physiology and behavior can alter growth, development, reproductive capacity, mortality, and the distribution of marine and freshwater species (Daw et al., 2009; Brander, 2010; FAO, 2010) thereby influencing fish stocks and global supply. On the other hand, indirect effects alter the productivity, structure, and composition of the ecosystems on which fish depend for food and shelter (Brander, 2010; Mohanty et al., 2010), which in turn can influence fish prices and the cost of goods and services required by fishers and fish farmers (WorldFish Center, 2007).

In British Columbia (BC), the fisheries and aquaculture sector is comprised of four industries namely: commercial fishing, aquaculture (fish and shellfish farming), fish processing and sport fishing (freshwater and saltwater) (BC-Stats, 2007). According to the Ministry of Agriculture (2011a), aquaculture and commercial fisheries are significant contributors to the provincial economy. BC-Ministry of Agriculture and Lands (2005a) cited by Lemmen et al., (2008, p. 344), stated that the revenue of aquaculture sector in BC was about CAD$287 million in 2005 and it has created 1,900 jobs. Most aquaculture operations in the province are located in coastal communities (Lemmen et al., 2008).

There are increasing concerns over the impacts of climate change on aquaculture in BC (Johannessen & Macdonald, 2009). These impacts include: (a) changes in the average annual air temperature (Johannessen & Macdonald, 2009), (b) changes in sea surface salinity and temperature and precipitation pattern, (c) increased risk of flood in low-laying areas of the coastal zone due to relative sea level rise of about 88 centimeters along parts of BC's coast and (d) increasing storminess and the invasion of coastal waters by exotic species (BC-Ministry of Water Land and Air Protection, 2002). It is also expected that salmon migration patterns and success in spawning are likely to change, which may affect their survival and/or mortality resulting in reduced capture. Oceans and freshwater temperatures are expected to change and changes will occur in the temperature, amount and timing of river flows. These changes may bring an increase in water management conflicts for freshwater fishers and aquaculturists (BC-Ministry of Water Land and Air Protection, 2002; BC-Ministry of Environment, 2007). Nevertheless, these impacts may threat the sustainability of aquaculture sector in BC.

1.2 Problem statement

Analysis of historical data documented and observed by Ministry of Water, Land and Air Protection (2002), indicates that many properties of climate have changed during the 20th century, affecting marine, freshwater, and terrestrial ecosystems in BC. These changes have included but are not limited to: (i) sea level rise by 4 to 12 centimeters along most of the BC coast; (ii) sea surface temperature (SST) increase by 0.9 to 1.8°C (between 1914 and 2001); (iii) snow depth and snow water content decrease in some parts of BC (between 1935 and 2000); and (iv) lakes and rivers throughout BC became free of ice earlier in the spring between (1945 and 1993). The productivity, distribution and seasonality of fisheries, and the quality and availability of the habitats that support them, are sensitive to these climate change effects.

Sea level rise and flooding in coastal areas, resulting from temperature increase, will present considerable challenges for the aquaculture sector. This study focuses on two critical research questions:

1) How will changes in sea surface temperature, sea surface salinity, beach exposure/inundation and beach albedo associated with sea level rise impact on bottom shellfish culture in BC?
2) How will shellfish culture capability in BC be affected by the changes in physical conditions of the beach (sea surface temperature, sea surface salinity and beach albedo)?

Understanding the linkages between climate change, livelihoods and food security is critical for designing policies, adaptation measures and management strategies for fisheries and aquaculture in the communities that depend on them. Given the complexity and challenges associated with climate change and the expected impacts on aquaculture in BC, there is a need to identify adaptation strategies aimed at multiple scales for the aquaculture sector. These adaptation strategies should be designed to complement mitigative strategies and to assist aquaculture producers to respond, cope and adapt to a changing climate for the benefit of the provincial and/or federal fisheries and aquaculture sector.

Few studies (Noakes et al., (2002) and Hutchings, et al., (2012)) have been conducted in BC regarding the impacts of climate change on the aquaculture sector. Little is known about the potential impacts (Lemmen et al., 2008) of alteration on physical substrate, wave energy and sediment temperature change and beach albedo on shellfish culture.

1.3 Purpose and objectives of the study

The propose of this study is twofold: (a) evaluate whether the existing environmental database in various agencies and institutions can support studies of potential impacts of climate change on coastal aquaculture and; (b) investigate the impacts of climate change (changes in sea level, salinity and water temperature) on shellfish aquaculture in the Strait of Georgia, BC. The focus is on examining the relationship between alterations of the physical substrate, changes in sediment temperature, and beach albedo, and shellfish culture. The study takes into account selected climate change scenarios and incorporates the results from available predictive models for changes in sea level rise, temperature, salinity and beach albedo, to determine whether beach sediments will support larval settling and early growth.

The objectives of this study are to:

1. Examine expected changes on sea surface salinity, sea surface temperature, and beach albedo associated with sea level changes in BC;
2. Identify sites along the Strait that have capability for shellfish aquaculture and quantify changes in beach albedo, beach exposure/inundation (area and energy level) expected from sea level change;
3. Define capability indices for shellfish culture based on the physical conditions characterizing existing commercial aquaculture operations; and
4. Assess how bottom shellfish aquaculture capabilities in the northern Strait of Georgia will be affected by changes of the sea surface temperature, salinity, beach albedo and beach exposure/inundation;

1.4 Research outline

This thesis consists of five chapters. Chapter two provides the background for the study. It reviews the literature on global climate change, the development of scenarios, and defines key concepts. It also discusses the anticipated impacts of climate change on coastal aquaculture in BC, with a special focus on sea level rise, temperature fluctuation, salinity changes, and beach albedo. Research needs are then identified. Chapter three presents the methodology adopted for the research, describes the study area, and outlines the data analysis plan. Chapter four presents the main research findings and discusses their implications for coastal aquaculture in BC. Chapter five summarizes the study's findings and conclusions. It also sets out recommendations and makes suggestions for future research.

Chapter 2

2.1 Background to the study

This chapter reviews the literature on global climate change, scenarios and vulnerability, projected impacts of climate change in BC, as well as expected effects and impacts on coastal aquaculture in BC to provide a background for the remainder of the thesis. It also gives an overview of the marine aquaculture sector and the potential effects of climate change on aquaculture, focusing on shellfish aquaculture in BC. Finally, the chapter outlines research needs in designing strategies to adapt and/or mitigate these impacts.

2.2 Definitions

For theoretical references, this thesis adopts the definitions of the terms and concepts defined as follow:

Adaptation: adjustment of a system (ecological, social, or economic) in response to actual or expected climatic stimuli and their effects or impacts. Therefore, adaptation to climate change involves a very broad range of measures directed at reducing vulnerability to a range of climatic stimuli or takes advantage of new opportunities that may be presented (Fussel, 2007; Lemmen et al., 2008).

Aquaculture: the farming of aquatic organisms including fish, mollusks, crustaceans and aquatic plants in inland and coastal areas, involving intervention in the rearing process (regular stocking, feeding, protection from predators, etc.) to enhance production and the individual or corporate ownership of the stock being cultivated (De Silva & Anderson, 1995; FAO, 2011).

Climate change and variability: changes in the state of the climate that can be identified by changes in the mean and/or the variability of its properties (temperature, humidity, atmospheric pressure, wind, precipitation) and that persist for an extended period, typically decades or longer (IPCC, 2007). These changes can be caused by natural internal processes (e.g., condensation of water vapor in clouds), or external influences (e.g., changes in solar radiation and volcanism), or persistent anthropogenic changes in the composition of the atmosphere or in land use such as greenhouse gases, deforestation or mining exploitation, which can increase aerosol (Lemmen et al., 2008).

This definition of climate change adopted in this thesis differs from the one used by the United Nations Framework Convention on Climate Change - UNFCCC (2008) that attributes directly or inderectly changes of the climate properties to human activities that alter the composition of the global atmosphere in addition to natural climate variability observed over comparable time periods. The term “climate variability” is sometimes used interchangeably in this thesis to refer to climate change.

Mitigation: Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. These initiatives and measures can be anticipatory and reactive, private and public, and autonomous and planned (Tompkins & Adger, 2005; IPCC, 2007).

Vulnerability: the degree to which a natural or social system is susceptible to, and unable to sustaining damages from adverse effects of climate change, including climate variability and extremes (IPCC, 2007). Thus, the vulnerability of a system to climate change is determined by its exposure, by its physical setting and sensitivity, and by its ability and opportunity to adapt to change (Adger et al., 2003; Fussel & Klein, 2006).

2.3 Global climate change

Climate change imposes new challenges and opportunities that require collective actions from humanity around the globe. Observations and evidence reported by IPCC-Working Group I (WGI) (Houghton et al., 1990), indicates that the average global surface temperature has varied, increasing by 0.3 ^{0}C - 0.6 ^{0}C, and time scales of ocean circulation and deep ocean heat content have been changed leading to changes on climate patterns during the 18th century. In turn, the Fourth Assessment Report (AR4) by IPCC-WGI (Solomon et al., 2007) noted that the last eleven years (1995 - 2006) were ranked among the twelve warmest years on record for global surface temperature since 1850. Additionally, the global average surface air temperature has increased by 0.7 ± 0.18 ^{0}C during (1906 - 2005) comparing to the range 0.6 ± 0.2 ^{0}C during (1901- 2000). The temperature increase has been observed all over the globe, but is greater at higher northern latitudes. Land regions have warmed faster than the oceans (Solomon, et al., 2007). Figure 1 below illustrates the annual global average temperature observed during (1840-2000).

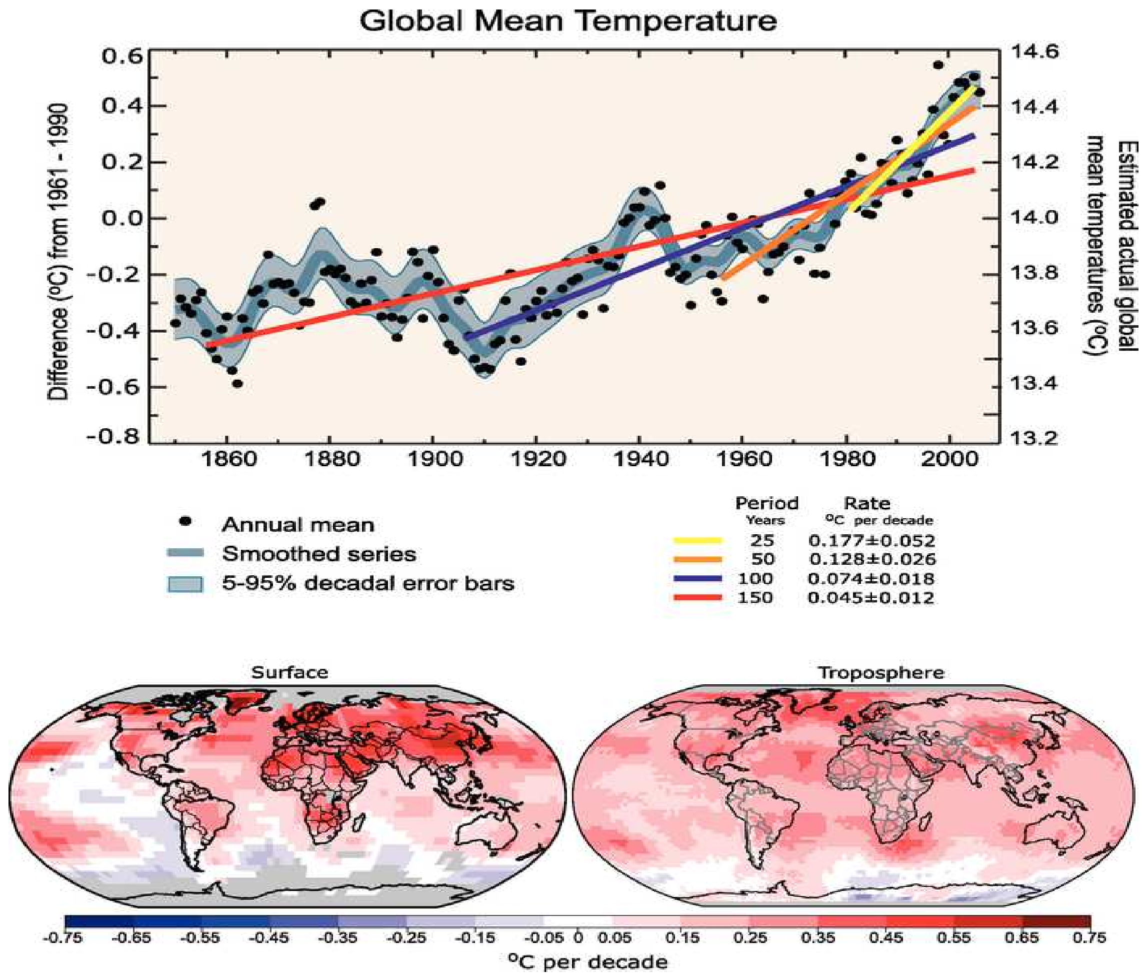

Figure 1: Annual global mean observed temperatures (black dots)

(Top) Annual global mean observed temperatures (black dots) along with simple fits to the data. The left hand axis shows anomalies relative to the 1961 to 1990 average and the right hand axis shows the estimated actual temperature (°C). Linear trend fits to the last 25 (yellow), 50 (orange), 100 (purple) and 150 years (red) are shown, and correspond to 1981 to 2005, 1956 to 2005, 1906 to 2005, and 1856 to 2005, respectively. (Bottom) Patterns of linear global temperature trends from 1979 to 2005 estimated at the surface (left), and for the troposphere (right) from the surface to about 10 km altitude, from satellite records. Grey areas indicate incomplete data. Source: IPCC-WGI (2007)

Moreover, global average sea level has risen since 1961 at an average rate of 1.8 ± 0.5 mm/yr and 3.1 ± 0.7 mm/yr since 1993. Annual average Arctic sea ice extent has shrunk by 2.7 ± 0.6% per decade since 1978 with larger decreases in summer of 7.4 ± 2.4% per decade and this has been accompanied by an observed decline in average mountain glaciers and snow cover in both hemispheres (Solomon et al., 2007). Figure 2 shows the evolution of global mean sea level in the past and as projected for the 21st century for the SRES A1B scenario.

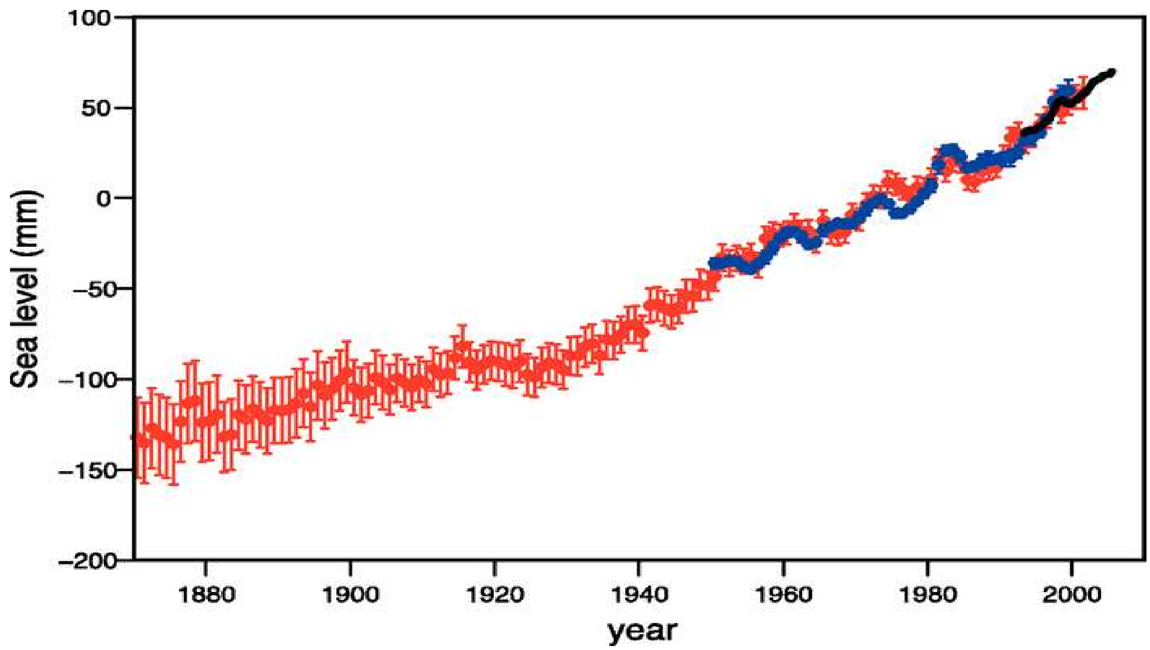

Figure 2: Annual averages of the global mean sea level

The red curve shows reconstructed sea level fields since 1870; the blue curve shows coastal tide gauge measurements since 1950 and the black curve is based on satellite altimetry. The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals. Source: IPCC-WGI (2007).

Projections from the Special Report on Emissions Scenarios (SRES) indicate that an increase of global greenhouse gas (GHG) emissions by 25 to 90% (CO_2-eq) is expected between 2000 and 2030. Based on these projections, the next two decades are expected to be 0.2 ^{0}C warmer; sea level rise is expected to intensify inundation, storm surge, erosion and other coastal hazards threatening vital infrastructure, settlements and facilities that support the livelihood of coastal communities (IPCC, 2000). Furthermore, climate change is expected to reduce freshwater resources in many small islands to the point where they become insufficient to meet demand during low-rainfall periods. Also, climate change is expected to have physical and ecosystem impact in the freshwater and marine environments in which aquaculture is situated (De Silva & Soto, 2009). Additionally, water and air temperatures in mid- to high latitudes are expected to rise, with a consequent extent of the growing season for cultured fish and shellfish and increasing the occurrence of invasion of non-native species (Kent & Poppe, 1998).

2.3.1 Climate change vulnerability, adaptation and mitigation

Vulnerability, adaptation and mitigation have been discussed in the literatures of climate change as key concepts for understanding how the issues of the current status of the climate can be approached (Tompikins & Adger, 2005; Fussel, 2007; Mertz et al., 2009). These emerging concepts for climate science and policy are receiving considerable international attention. They are reflected in many reports of the Intergovernmental Panel for Climate Change (IPCC, 2007) and have been deeply discussed among researchers and policymakers as the confidence in climate change projections are increasing.

Despite the definition of vulnerability from the Intergovernmental Panel on Climate Change adopted in this study, there have been many attempts to define and characterize vulnerability in relation to climate change. Dolan & Walker (2003), Adger et al. (2003) and Fussel & Klein (2006) define vulnerability in the context of climate change as a physical risk and a social response within a defined geographic context (nations, regions, communities and individuals). Additionally, they characterize and conceptualize vulnerability in three perspectives: first in terms of exposure to hazardous events (e.g. droughts, floods) and how people and structures are affected; second, characterize vulnerability as human relationship, not a physical one. To this extent, vulnerability is related to social conditions and historical circumstances that put people at risk to a diverse range of climate-related, political, or economic stresses (e.g., poverty, development in marginal or sensitive areas); finally, the third perspective integrates both physical events and social response within a defined geographical context, i.e. the vulnerability of a system to climate change is determined by its exposure, its physical environment and sensitivity, and its ability or capacity to adapt to changes.

According to the IPCC-Working Group II (IPCC, 2001b), the vulnerability of human populations and natural systems to climate change differs substantially across regions and across populations within regions. Even within the regions, the impacts, adaptive capacity, and vulnerability will vary (National Academies, 2008). For instance, in Africa and Asia the impacts are related to water resources, food production, human health, desertification and coastal zones; in Europe there is risk of significant biodiversity loss through species extinction in many tropical areas, significant changes in water availability for human consumption, agriculture and energy generation (IPCC, 2001b). Indeed, potential direct effects of climate change such as changes in water availability, crop yields and inundation of coastal areas will all have further indirect effects on food security and human health, as well as on the ecosystems (Scheraga & Grambsch, 1998).

As climate changes imposes challenges and risks to natural and social systems, the two fundamental societal response options for reducing these risks and face the challenges are adaptation and mitigation. Adger et al. (2005), argues that adaptation to climate change involves a broad range of measures directed at reducing vulnerability to a range of climatic stimuli (changes in means, variability, and extremes), shares many common features with risk management but above all it requires close collaboration of climate and impact scientists, sectoral practitioners, decision-makers and other stakeholders, and policy analysts. In turn, Fussel (2007) and Smit et al. (2000) refer that the nature of adaptation process and forms can be destinguished by numerous attributes including climatic-sensitivy domain (e.g. agriculture, water management, fisheries, etc.), types of climatic hazard (observed and expected changes), predictability of climatic changes (e.g. changes in average temperature), non-climatic conditions (economic, political and cultural conditions), purposefulness (e.g adopting new measures), timing (reactive, proactive or anticipatory) , planning horizon and actors. Therefore, each of these elements play a role in adaptation assessment and implementation and, are complemented by mitigation measures where mitigation seeks to protect natural systems against human systems, whereas adaptation aims to protect the human systems against nature.

Mitigation has received much greater attention in the climate change community than adaptation although they are both responses to climate change (Grasso, 2010). The reason for the focus on mitigation is its ability to reduce impacts on all climate-sensitive systems, whereas adaptation is limited for many systems (Fussel, 2007) such as ethics (how and what we value), knowledge (how and what we know), risk (how and what we perceive) and culture (how and why we live). Mitigation policies produce extensive benefits by promoting sustainable development, reduction of health problems, increased employment, reduced negative environmental impacts, protection of wildlife and promotion and diffusion of technological change (Grasso, 2010). Klein et al. (2005) and Biesbroek et al. (2009) argue that mitigation and adaptation differ for two important reasons: the first relates to the temporal and spatial scale. The benefits of mitigation are experienced several decades after the implementation of reduction in greenhouse gas, whereas the benefits of adaptation are generally experienced immediately; the second reason for the difference between mitigation and adaptation resides in the comparison and aggregation of costs and benefits. Mitigation concerns a limited number of sectors, e.g. energy, crucial industries (such as construction, cement production, paper manufacture), transport and agriculture. Conversely, adaptation initiatives cover a large number of different sectors in local economies and societies.

2.4 Scenarios of climate change and vulnerability

To assist in climate change analysis, including climate modeling, impacts assessment, adaptation, and mitigation, the IPCC scientific body decided in 1996 to develop a set of scenarios to represent the range of driving forces and emissions. These scenarios aimed to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties from demographic to technological and economic developments (IPCC, 2000). The scenarios encompass different future developments that might influence GHG sources and sinks, such as alternative structures of energy systems and land-use changes. The following terminology was used:

(i) *Storyline:* a narrative description of development in many different social, economic, technological, environmental and policy dimensions highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces;

(ii) *Scenario:* projections of a potential future, based on a clear logic and a quantified storyline;

(iii) *Scenario family:* one or more scenarios that have the same demographic, politico-societal, economic and technological storyline;

The Special Report on Emissions Scenarios (SRES) team (IPCC, 2000) defined four narrative storylines represented in Figure 3, labeled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally.

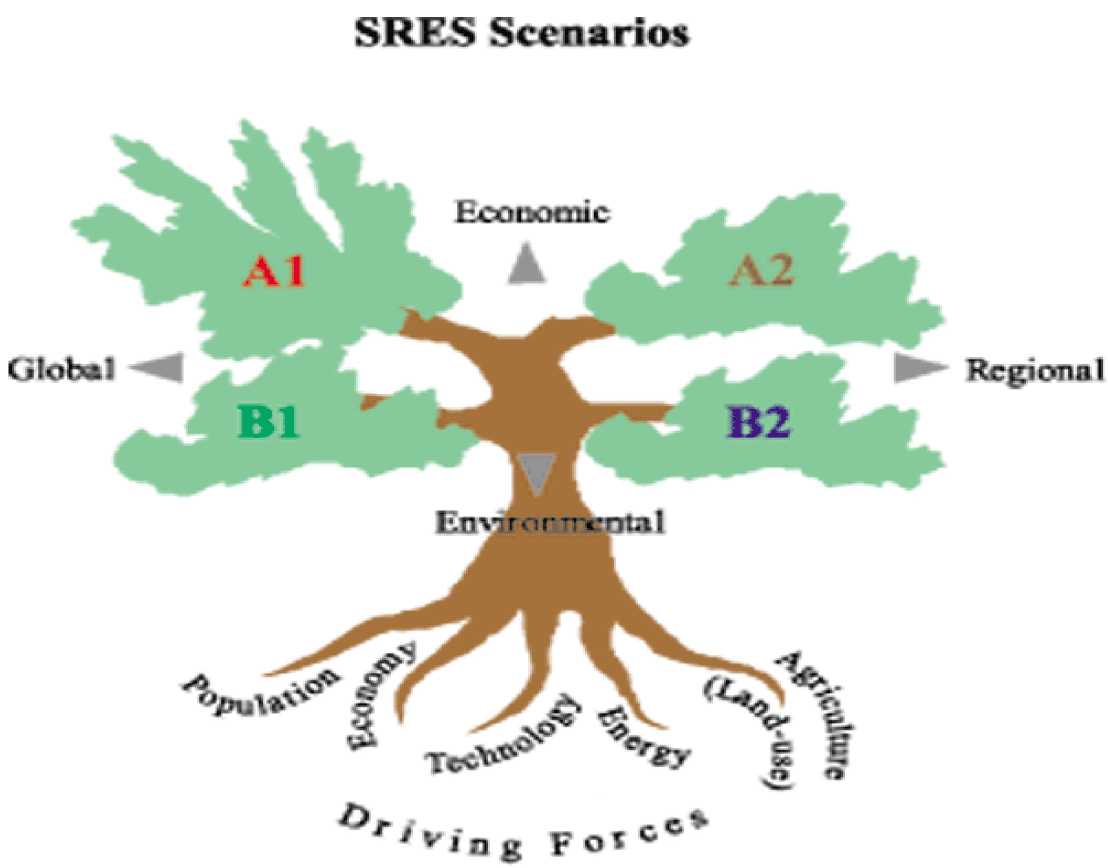

Figure 3: Schematic illustration of the emission scenarios

Source: (IPCC, 2000)

“The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels”.

The four storylines from the IPCC SRES scenarios assume separately different directions for future development, including population growth, economic development, and technological change. The scenarios suggest that climate change will be noticeable by various impacts. Temperatures and precipitation will change, sea levels will rise and droughts and floods will occur more frequently which in turn may bring profound implications for marine ecosystems and the economic and social systems that depend upon them (Harley, et al., 2006).

2.5 Impacts of climate change on marine ecosystem and aquaculture

Coastal marine areas are among the most ecologically and socio-economically vital on the planet (Harley, et al., 2006). They contribute significantly to the life support system of most coastal community societies' and contribute to the economy growth in many coastal regions. For example, the contribution of marine ecosystems to the economy of China, Norway, Thailand, USA and Canada as result of exportation of fish and fishery products in 2008 (in US$ millions) was about 10,114 for China, 6,937 for Norway, 6,532 for Thailand, 4,463 for USA and 3,706 for Canada (FAO, 2010).

There is a strong scientific consensus that coastal marine ecosystems, along with the goods and services they provide, are threatened by global climate change (Fabry et al., 2008) exacerbated by human activities (fossil fuel burning and deforestation) that lead to higher concentrations of GHG in the atmosphere, which in turn leads to a set of physical and chemical changes in coastal oceans, that are considered an additional and important component to the climate system as illustrated in Figure 4.

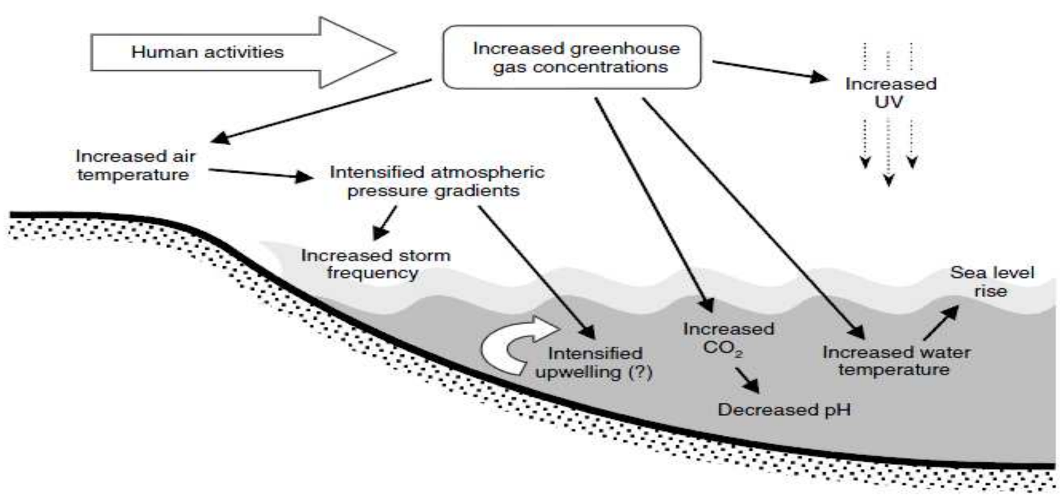

Figure 4: Important abiotic changes associated with climate change

Source: Harley et al., (2006)

As result of climate change, sea surface has warmed (e.g. Northeast Atlantic) accompanied by increasing phytoplankton abundance in cooler regions and decreasing phytoplankton abundance in warmer regions (Richardson & Schoeman, 2004). This impact propagates up the food web (bottom-up control) through copepod herbivores to zooplankton carnivores because of tight trophic coupling.

In terms of global climate change, the environmental factors that are expected to have the greatest direct effects on estuarine and marine systems are temperature change, sea-level rise, availability of water from precipitation and runoff, wind patterns, and storminess (IPCC, 2001a). Thus, climate change is likely to alter patterns of wind and water circulation in the ocean environment, which in turn may cause substantial changes in regional ocean and land temperatures and the geographic distributions of marine species. Such changes may influence the vertical movement of ocean waters (i.e., upwelling and downwelling), increasing or decreasing the availability of essential nutrients and oxygen to marine organisms (Kennedy et al., 2002).

The ecological systems which support primary production are sensitive to climate variability. The ecological systems' sensitivity include loss of coastal wetlands, coral whitening, changes in the distribution and timing of fresh water flows, uncertain effect of acidification of oceanic water which is predicted to impact marine ecosystems (Rosenzweig et al., 2007; Chen, 2008) leading to widespread changes on the ecosystems (Fabry et al., 2008).

Fishing and aquaculture communities are expected to be exposed to a diverse number of direct and indirect climate impacts, including displacement and migration of human populations, impacts on coastal communities and infrastructure due to sea level rise, and changes in the frequency, distribution or intensity of tropical storms (Lemmen et al., 2008; Daw et al., 2009).

Indeed, aquatic ecosystems will respond to climate changes in different ways or as equally significant as the responses of the terrestrial and atmospheric environments because of the ability of the oceans and large water bodies to absorb and distribute heat (Lemmen et al., 2008). Changes in sea temperature and current flows will likely bring shifts in the distribution of marine fish stocks, with some areas benefiting while others losing. Higher inland water temperatures may reduce the availability of wild fish stocks by harming water quality, worsening dry season mortality, bringing new predators and pathogens, and changing the abundance of food available to fishery species (WorldFish Center, 2007). Possible impacts of climate change on fisheries and aquaculture are summarized in Table 1.

Table 1: Possible impacts of climate change on fisheries and aquaculture systems

Drivers of change	Impacts on culture system	Operational impacts
Sea surface temperature changes	• Increase in harmful algal blooms that release toxins in the water and produce fish kills; • Decreased dissolved oxygen; • Increased incidents of diseases and parasites; • Enhanced growing seasons; • Change in the location and/or size of the suitable range for a given species; • Lower natural winter mortality; • Enhanced growth rates and feed conversions (metabolic rate); • Enhanced primary productivity (photosynthetic activity) to benefit production of filters-feeders; • Altered local ecosystem-competitors and predators; • Competition, parasitism and predation from exotic and invasive species;	• Change in infrastructure and operation costs; • Increase infestation of fouling organisms, pests, nuisance species and/or predators; • Expanded geographic distribution and range of aquatic species for culture; • Changes in production levels;
	• Damage to coral reefs that may have helped protect shoreline from wave action – may combine with sea level rise to further increase exposure	• Increase change of damage to infrastructures from waves or flooding of inland coast areas due to storm surges

Change in other oceanographic variables (variations in wind velocity, current and wave action)	• Decreased flushing rate that can affect food availability to shellfish; • Alterations in water exchanges and waste dispersal; • Change in abundance and/or range of capture fishery species used in the production of fishmeal and fish oil	• Accumulation of waste under pens; • Increased operation costs;
Sea level rise	• Loss of areas available for aquaculture • Loss of areas such as mangroves that may provide protection from waves/surges and act as nursery areas that supply aquaculture seed • Sea level rise combined with storm surges may create more severe flooding; • Salt intrusion into ground water	• Damage to infrastructure • Change in aquaculture zoning • Competition for space with ecosystem providing coastal defense services (i.e. mangrove)
Increase in frequency and/or intensity of storms	• Large waves; • Storm surges; • Flooding from intense precipitation; • Structural damage • Salinity changes • Introduction of disease or predators during flood episodes	• Loss of stock; • Damage to facilities; • Higher capital costs, need to design cages moorings, jetties etc. that can withstand events; • Negative effect on pond walls and defenses; • Increased insurance costs
Higher inland water temperatures (Possible causes: changes in air temperature, intensity of solar radiation and wind speed)	• Reduced water quality specially in terms of dissolved oxygen; • Increased incidents of disease and parasites; • Enhanced primary productivity may benefit production • Change in location and/or size of the suitable range for given species; • Increased metabolic rate leading to increased feeding rate, improved food conversion ratio and growth provided water quality and dissolved oxygen levels are adequate otherwise feeding and growth performance may be reduced	• Changes in level of production; • Changes in operating costs; • Increase in capital costs, e.g. aeration, deeper ponds; • Change of culture species
Floods due to changes in precipitation (intensity, frequency, seasonality, variability)	• Salinity changes; • Introduction of disease or predators; • Structural damage; • Escape of stock	• Loss of stock; • Damage to facilities; • Higher capital costs involved in engineering flood resistance; • Higher insurance costs
Drought (as an extreme event (shock), as opposed to gradual reduction in water availability)	• Salinity changes; • Reduced water quality; • Limited water volume;	• Loss of stock; • Loss of opportunity – limited production (probably hard to insure against)
Water stress (as gradual	• Decreased water quality leading to increased diseases;	• Costs of maintaining pond levels artificially;

reduction in water availability (trend) due to increasing evaporation rates and decreasing rainfall)	• Reduced pond levels; • Altered and reduced freshwater supplies – greater risk of impact by drought if operating close to the limit in terms of water supply	• Conflict with other water user; • Lost of stock; • Reduced production capacity; • Increased per unit production costs; • Change of culture species;

Source: WorldFish Center (2009).

2.6 Impacts of changes in sea level, SST, SSS and beach albedo on aquaculture

Determining the effect of climate change on marine environment populations is complex as multitude of environmental factors that may impact various physical processes at different levels of biological organization will be affected (Rijnsdorp et al., 2008). To demonstrate, even if the effect of changes on the physiology of an organism is known, it will be difficult to evaluate the physiological response of this organism at the population or ecosystem level (Mackenzie & Köster, 2004). In addition to the difficulty associated with evaluating the physiological response of organisms at the level of the population or ecosystem, shellfish and other aquatic organisms grow several orders of magnitude in size and often change habitats within which they are exposed to a specific set of environmental factors (e.g., temperature, salinity, oxygen, prey availability, water current) (Rijnsdorp et al., 2008) which can create different rates of growth and mortality as well as physiological tolerances to abiotic and biotic factors.

For the purpose of this study, the focus will be on following environmental physical parameters: sea surface temperature, sea level rise, sea surface salinity, and beach albedo. The choice of the these parameters is justified by the facts that: first, temperature directly affect shellfish growth; second, wave height, water movement, substrate, and beach slope directly affect shellfish survival; and finally, salinity, indirectly affect shellfish growth and survival. Beside the effects on the shellfish survival and growth, these parameters are major indicators of climate change.

2.6.1 Sea level rise

Sea level changes when the mass of water in the ocean increases or decreases as result of exchange of ocean water with the water stored on land (water frozen in glaciers or ice sheets). The level of the sea at the shoreline is determined by many factors in the global environment that operate over a great range of time-scales. These time scales range from hours characterized by tidal, to decades or centuries causing ocean basin changes due to land movements and sedimentation (Najjar, et al., 2000). According to IPCC (2001b), thermal expansion of ocean waters is believed to be one of the major contributors to historical sea level changes. In addition to thermal expansion and increase or decrease of ocean water, sea levels can change due to coastal subsidence in river delta regions. Vertical land movements caused by natural geological processes, such as slow movements in the Earth's mantle and tectonic displacements of the crust, can have effects on local sea level that are comparable to climate-related impacts (IPCC, 2001b). One example of this is the relative sea-level in BC which differs from the global trend due to vertical land movements. As result to these vertical movements, during the 20th century sea level rose 4 cm in Vancouver, 8 cm in Victoria and 12 cm in Prince Rupert, and dropped by 13 cm in Tofino (BC-Ministry of Water Land and Air Protection, 2002).

Accelerated rates of sea level rise will change some of the major controls of coastal wetland maintenance causing wetland dependent species of fish/shellfish and birds to have reduced population sizes. Tidal marshes and associated submerged aquatic plant beds are important spawning, nursery, and shelter areas for fish and shellfish and other aquatic species; sea level rise may increase or decrease tidal marshes, consequently increasing on one hand potential areas for wetlands, on the other hand resulting in degradation and loss of tidal marshes which will affect fish and shellfish production in both the marshes themselves and adjacent estuaries (Najjar, et al., 2000). In summary, rising sea level erodes beaches, drowns wetlands, submerges low-lying lands, exacerbates coastal flooding, and increases the salinity of estuaries and aquifers and shift of species distribution.

2.6.2 Sea surface temperature

Temperature is one of the primary factors, together with food availability and suitable spawning grounds, which determines the large-scale distribution patterns of intertidal animals including fish and shellfish, and plays an important role in species interaction (e.g., predator-prey, parasite-host, competition for resources in ecosystems). In addition to determining intertidal animal distribution and interaction, temperature influences growth and metabolism, governs animal behaviour, and acts in concert with other environmental variables such as dissolved oxygen. Moreover, it influences the timing of reproduction and controls rates of egg and larval development (Kennedy et al., 2002). Since most fish and shellfish species or stocks tend to prefer a specific temperature range (Coutant, 1977; Scott, 1982), an expansion or contraction of the distribution range often coincides with long-term changes in temperature (Pinnegar et al., 2008). Therefore, understanding the geographical distribution of sea surface temperature and its temporal variation is essential for predicting the dynamical behavior of the atmosphere and the ocean and aquatic life distribution. It is also an important indicator of climate and climate change. Rijnsdorp et al. (2008), argue that at the level of the ecosystem, both bottom-up and top-down trophodynamic processes are influenced by temperature and other physical factors affected by climate. For these reasons, changes in temperature can lead to a temporal and spatial compatibility or incompatibility in the overlap of competitor's organisms. Secondly, intra or inter-specific interactions among organisms, either through competition or predation, may lead to non-linear dynamics of populations and ecosystems.

Temperature variation may have positive or negative effects on aquatic organism. Positive effects of higher temperatures (Lehtonen, 1996) on marine species are observed in some commercially valuable estuarine-dependent species in the lower latitudes such as shrimp that have higher growth rates and larger annual harvests when temperatures are higher (Kennedy et al., 2002). In addition to higher growth rates and large annual harvests, elevated temperatures of coastal waters also could lead to increased production of aquaculture species by expanding their range (Kennedy et al., 2002).

2.6.3 Beach albedo

Albedo plays a role in the energy balance as it defines the rate of the absorbed portion of the incident solar radiation. According to Hays, et al. (2001), albedo is a term commonly used to describe the fraction or ratio of incident solar radiation reflected from a surface. Albedo is measured on a scale from 0 (for no reflecting power of a perfectly black surface) to 1 (perfect reflection of a white surface) (Feister & Grewe, 1995). The complementary value to albedo is absorptance, which is the amount of the incident solar radiation absorbed by a surface. Darker surfaces have low albedo and high absorptance, while lighter colored surfaces will have high albedo and low absorptance (Hays, et al.,

2001) consequently, determining the temperature of the absorbing surface (e.g. beach sand). According to Davies & Idso (1979); Berge (1986); Oke (1987) and Campbell & Norman (1998), soil albedo depends on the surface's colour and on the moisture content. Albedo values for dry soil vary from 0.14 (clay) to 0.37 (dune sand). Table 2 below shows the albedo values for selected surface type.

Table 2: Albedo values for wet and dry soils

Surface Type	Wet	Dry
Dune sand	0.24	0.37
Sandy loam	0.10 – 0.19	0.17 – 0.23
Clay loam	0.10 – 0.14	0.20 – 0.23
Clay	0.08	0.14

Source: Davies and Idso (1979); Berge (1986); Oke (1987); Campbell and Norman (1998).

According to Dobos (2003), changes in soil moisture content alter the absorbance and reflectance characteristics of the soil. For instance, an increase in soil moisture content increases the portion of the incident solar radiation absorbed by the soil system. Beach sand temperature plays an important role in the distribution and growth rate of intertidal animals (McLachlan & Young, 1982). Similarly to water temperature, sand temperature is influenced by solar radiation (and corresponding air temperature), sand moisture, and sand albedo. Beach sand temperature plays an important role in burrowing species development. Avissar (2006), concluded that temperatures that are too cool can result in slower egg development, whereas excessively hot temperatures can destroy horseshoe crab eggs. Additionally, Hays, et al. (2001) state that sand albedo influences thermal conditions on beaches having major implications for the sex ratios and reproduction of sea turtles.

2.6.4 Sea surface salinity

Along with sea surface temperature, sea surface salinity provides information on how global precipitation, evaporation, and the water cycle are changing. Defined as total salts dissolved in 1000 g of water (Williams & Sherwood, 1994), salinity is a parameter used in oceanography to describe the concentration of dissolved salts in seawater (normal seawater salinity is 35 parts salt per 1000 parts water) (Lewis & Perkin, 1978). Salinity is a variable parameter reflecting the input of fresh water from precipitation, the melting of ice, river runoff, the loss of water through evaporation, and the mixing and circulation of ocean surface water with deep water below (Koblinsky, et al., 2003). The variability of the sea salinity may occur as a result of increased evaporation with increased temperature and changes in ocean circulation or induced by climate change (Cooper, 1988; Robinson, et al., 2005).

Changes in sea water salinity may have significant negative impacts on fresh water quality and estuarine affecting fish and shellfish and other aquatic species production in both the marshes themselves and adjacent estuaries. McKay & Gjerde (1985) noted that an increase in water salinity content, increases mortality and as concluded that salinities above 20 ppt may have prejudicial effects on trout biomass production. Furthermore, Baker et al. (2005) showed that a decrease in water salinity may cause mortality on clams or susceptibility to bacterial invasion in oysters. They argue that a combination of factors such as increased temperature and turbidity and decreased phytoplankton concentration compound the effects of salinity on clam seed health and survival. On the other hand, Rodrick (2008) concluded that variations in salinity could affect the ability of oyster hemocytes (blood cells) to resist foreign bacterial invasion.

Indeed, changes in sea water salinity content may have significant effects on marine species including shellfish growth and survival.

2.7 Fisheries and aquaculture in BC

Aquaculture activities in Canada occur in all provinces and in the Yukon Territory. Aquaculture operations for several marine finfish and shellfish species are established on the east and west coasts, while freshwater trout operations can be found in almost every province. However, British Columbia is the major finfish aquaculture region in Canada, where more than two-thirds of the country's production (161,000 tons in 2010) is located (Hutchings, et al., 2012; DFO, 2012). Moreover, BC is considered to be Canada's major producer of oysters (non-native species, primarily *Crassostrea gigas*, and C. *Virginica* and *Ostrea. edulis*), clams (non-native *Nuttallia obscurata* and *Tapes phillippinarum* and, to a lesser extent, the native *Protothaca staminea*), and scallops (non-native hybrid *Patinopecten caurinus* X *P. yessoensis*), including small production of mussels (non-native *Mytilus edulis* and *M. galloprovincialis*) (Hutchings, et al., 2012). The fisheries and aquaculture sector in BC is comprised of four industries namely: commercial fishing, aquaculture (fish and shellfish farming), fish processing and, sport fishing (freshwater and saltwater) (BC-Stats, 2007).

Aquaculture and commercial fisheries are significant contributors to BC's provincial economy. The sector employs about 20,000 people (Lemmen et al., 2008). In 2010, BC's fisheries production totaled 264,400 tons with a landed value of CAD $863.8 million. Commercial capture fisheries harvested 173,800 tons worth CAD $330 million to the fishers, while aquaculture operations produced 90,600 tons with a farmgate value of CAD $533.8 million (BC-Ministry of Agriculture, 2011b).

Salmon and other finfish, shellfish and marine plants are the three main groups cultured in BC. Atlantic salmon and chinook are the predominant salmon. Other species currently being cultured in limited or experimental quantities include: sablefish, tilapia, sturgeon, geoduck clams, abalone, sea cucumbers and crayfish (BC-Ministry of Agriculture, 2011b). The commercial fisheries industry includes the commercial harvesting of more than eighty different species of finfish, shellfish, and marine plants from both freshwater and marine environments (DFO, 2012).

Shellfish production is an increasing activity in BC. In fact, cultured shellfish production grew 30 per cent to 10,000 tons in 2010 and capture shell fisheries harvested 14,000 tons (BC-Ministry of Agriculture, 2011b). In 2010 the most harvested species included cultured oysters with a harvest of 7,400 tons, followed by crabs at 4,900 tons and sea urchins with 2,300 tons. Other cultured shellfish production volumes experienced notable increases with scallops and mussels up 57 percent to 1,100 tons and clams (*Manila, littleneck and geoduck*) up 15 percent to 1,500 tons (BC-Ministry of Agriculture, 2011b). Despite all the aquaculture production in BC, climate change, along with fish disease and limited feed availability, threatens aquaculture sustainability (Naylor & Burke, 2005). To overcome these challenges, sustainable fisheries and aquaculture management will require opportune and accurate scientific information on the environmental conditions that affect fish stocks and institutional flexibility to respond quickly to such challenges.

2.7.1 Climate change and marine aquaculture in BC

Growing confidence and evidence on climate variability and change noted by increasing amount of research on climate issues, suggests that the impacts of climate change pose risks to natural, social, cultural and economic systems. Certainly aquaculture is not apart from the effects of climate change. Climatic factors, such as air and water temperature, precipitation and wind patterns, strongly influence fish health, productivity, abundance and distribution (Brander, 2010) which in turn influences aquaculture production and productivity. This is because most aquatic organisms including fish and shellfish have a distinct set of environmental conditions under which they experience optimal growth, reproduction and survival (Rijnsdorp et al., 2008). Indeed, changes in these conditions in response to climate change may bring considerable shifts in marine resource availability and distribution (Lemmen & Warren, 2004).

Projected potential impacts of climate change that may affect coastal aquaculture industry in BC include, but are not limited to, increased sea level by up to 88 centimeters along parts of the BC coast which may threaten culture facilities if the region's sea-level rise results in higher storm surges (Kenedy et al., 2002), and inundation of areas for shellfish bottom culture. Besides sea level rising, sea surface temperature is expected to increase between 1^{0}C to 2 ^{0}C during the course of the current century all along the BC coast (BC-Ministry of Environment, 2007; Okey et al., 2012) which may lead to an increased the risk of disease and compromised water quality by affecting bacteria levels, dissolved oxygen concentrations and algal blooms (Okey et al., 2012).

Observed sea surface salinity at three representative BC lighthouses (Langara Island, Amphitrite Point and Departure Bay in the Strait of Georgia), show different variability along the coast, however, with distinct low frequency variations and tendency to decrease at a rate of 0.0036 ppt/year over the past 50 years (Whitney et al., 2007; Ianson & Flostrand, 2010). As result of changes in salinity, for example, the distribution of bivalve mollusks may be affected (Fuersich, 1993), filtration rate (Villiers et al., 1989) and oxygen consumption influenced (Bernard, 1983). Moreover, changes in salinity may have major impacts on growth and survival of cultured bivalves (Cross & Kingzett, 1992; Taylor et al., 2004). Observed dissolved oxygen and pH levels are decreasing and dissolved CO_2 levels are increasing in intermediate waters of the NE Pacific basin and are likely to impact marine ecosystems over the shelf (Ianson & Flostrand, 2010). Barton et al. (2012) have reported variability of carbonate chemistry of water intake from an oyster hacthery on the Oregon coast. Observed data indicated variation on aragonite saturation state, ranging between <0.8 to > 3.2; pH <7.6 to >8.2 having an impact on oyster larve production and growth. As shown, changes in sea surface temperature, sea surface salinity, sea level, pH and dissolved oxygen and dissolved CO_2 may have positive and/or negative effects on aquaculture in BC, emerging from direct and indirect impacts on the natural resources that aquaculture requires such as land, seed and feed. Negative impacts of climate change on marine aquaculture in BC could arise from increased physiological stress, shift on cultured species, affecting not only productivity but also increase vulnerability to diseases and, consequently impose higher risks and reduce returns to farmers. On the other hand, positive impacts may come from higher temperatures, which could the enhance growth rates of cultured species, and allow for the culture of species in areas that are currently too cold for them.

2.7.2 Research needs

Given the complexity, uncertainty and the expected impacts of climate changes on marine ecosystems and aquaculture particularly in BC, there is a strong need to improve our understanding of the relationship between aquatic habitat and fish and shellfish populations, as well as the linkages between climatic parameters and aquatic habitat in order to better interpret these habitats response to climate change. To understand how British Columbia's marine and coastal ecosystems will be affected by climate change, and how coastal aquaculture operations may be influenced by these changes, there is a need to investigate, examine and monitor the expected impacts on these ecosystems. This study will contribute to the examination of anticipated impacts of climate change on coastal aquaculture in BC. The study was done by investigating how changes in sea level, sea surface salinity, sea surface temperature and beach albedo may affect shellfish culture in BC.

2.8 Summary

The Earth's climate is changing as a result of both natural and anthropogenic processes leading to global warming of the atmosphere and oceans. Climate change is projected to impact broadly across ecosystems, societies and economies, increasing pressure on all livelihoods and food supplies, including those in the fisheries and aquaculture sector. Additionally, climate change is likely to alter patterns of wind and water circulation in the ocean environment. Such changes may influence physical parameters of ocean waters such as temperature, salinity and vertical movement of ocean waters increasing or decreasing the availability of essential nutrients and oxygen to marine organisms. Temperature changes in coastal and marine ecosystems will influence organism metabolism and alter ecological processes such as productivity and species interactions, which may affect critical coastal ecosystems such as wetlands, estuaries, coral reefs including aquaculture.

In British Columbia, projected results of climate change that may have an impact on aquaculture include changes in sea level, increased storm surges, changes in sea surface temperature, sea surface salinity, changes in dissolved oxygen and CO_2 concentration. Therefore, there is a need to investigate and develop adaptation strategies to complement mitigative strategies that are aimed at addressing climate variability and to adequately respond, cope and adapt to living in a changing climate for the benefit of the provincial and/or federal fisheries and aquaculture sector.

Chapter 3

3.1 Methodology

This chapter describes the study area, discusses the sources of data used for the analysis and interpretation of the results, and outlines the research methodology. It describes the methods used to perform analysis in *Arcmap 10* and scenarios of changes in physical conditions regarding sea level rise, sea surface temperature, sea surface salinity and beach albedo. It also defines the capability indexes for shellfish culture, quantifies beach exposure and it assesses how shellfish aquaculture capability in BC can be affected by changes in the above mentioned physical conditions.

3.2 Study area

This section describes the study area selected for this research. It presents the geographic description of the area, including the geology, oceanographic characteristics, biology and socio-economic context.

3.3 The Strait of Georgia

3.3.1 Geography

The study was conducted in the Upper Strait of Georgia, British Columbia (Figure 5), where many aquaculture operations are located (Figure 6).

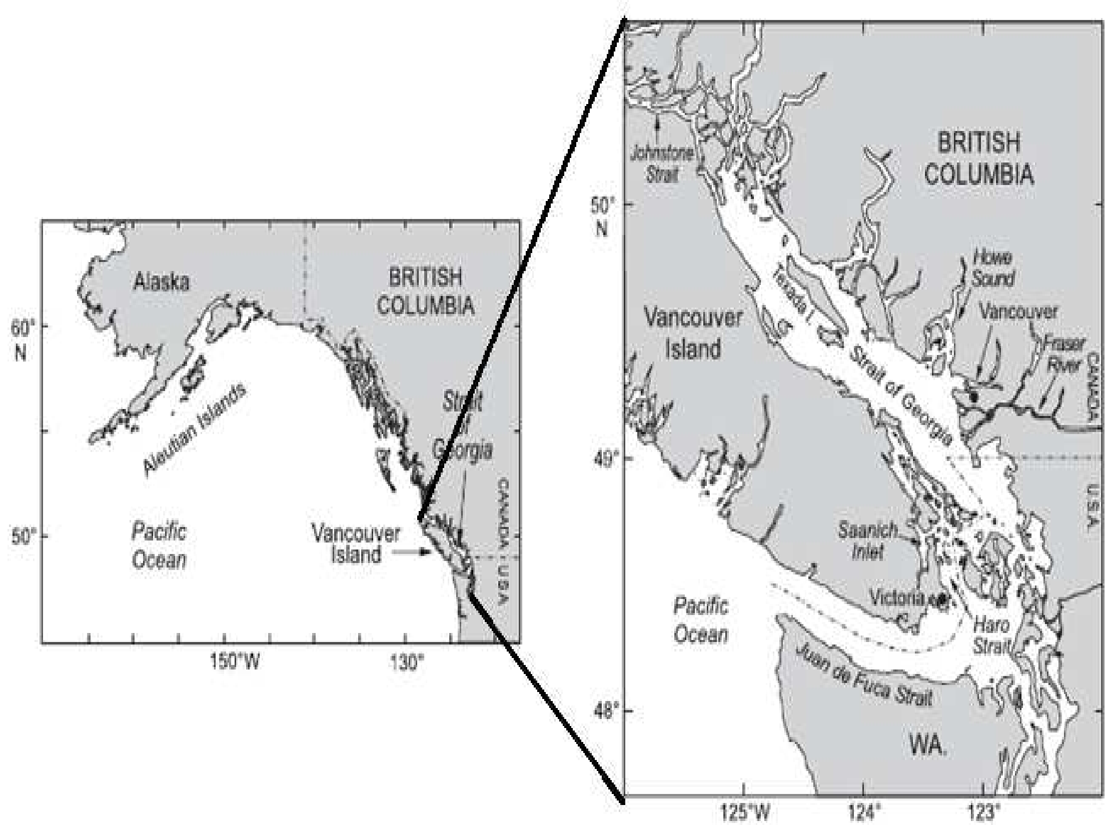

Figure 5: Regional map showing the Strait of Georgia

Source: Johannessen & Macdonald (2009); and Carswell, Cheesman, & Anderson (2006).

The Strait of Georgia (SoG) trends southeast-northwest from a latitude of 48^0 50' to 50^0 00' N., and is approximately 220 km long (Masson, 2002; Barrie et al., 2005). The Strait lies between Vancouver Island and the British Columbia mainland (Waldichuk, 1957). Each end of the Strait is marked by archipelagos and narrow channels, the Gulf Islands and San Juan Islands in the south, and the Discovery Islands in the north. The Strait is connected to the Pacific Ocean by Johnstone Strait to the north (Thomson, 1981; Beamish et al., 2008) through the Discovery Passage channel and to the south Haro Strait and Rosario Strait channels links the strait to the Strait of Juan de Fuca (Masson, 2002). For convenient description, the Strait of Georgia has been arbitrarily divided into three sections: (l) the Southern Strait covers the region from the northern boundary of the San Juan Archipelago to a line between Point Roberts and Active Pass; (2) the Central Strait extends from Point Roberts to the southern ends of Texada and Lasqueti Islands; and (3) the Northern Strait extends from southern Texada Island to the mouths of the northern channels. The Southern Strait is influenced by intensive tidal mixing from the open ocean and the Fraser River, the Central Strait is influenced by the Fraser River and the runoff of the northern coast and the Northern Strait is under combined influence of the northern inlet and the Fraser River.

The average width of the Strait of Georgia is 33 km, the perimeter is 1,200 km, the surface area is 6,900 km^2, 480 km^2 of which consists of inland area and the mean volume is 1025 m^3 (Waldichuk, 1957; Thomson, 1981). In the central basin of the Strait of Georgia, waters reach depths of up to 420 meters (Masson , 2002). It is one of the largest estuarine marine waterways on the west coast of North America (Waldichuk, 1957; Masson, 2002).

3.3.2 Geology

The Strait of Georgia which is bounded by islands to the south and west and the lower mainland and the city of Vancouver to the east, is one of the three areas surrounding the Georgia basin. These areas lie within the most seismically active zone in Canada (Rogers, 1998). According to Barrie et al. (2005) and James et al. (2005), the Georgia basin overlaps two older sedimentary basins, namely a Late Cretaceous foreland basin known as the Nanaimo Group and an early Tertiary non-marine basin dominated by the sedimentary rocks of the Chuckanut formation. The Strait of Georgia can be divided by its bottom materials into three sections: (l) the Northern Strait with mainly sand (2) the Central Strait dominated by mud from the Fraser River sedimentation (Barrie et al., 2005); and (3) the Southern Strait with a heterogeneous assembly of bottom types, but predominantly rocky outcrops, boulders, and cobbles (Waldichuk, 1957).

It is important to highlight that the Fraser River plume controls the surficial sediment distribution pattern from the central Strait of Georgia, just south of Texada Island, to just past the US-Canada border in the south. However, the sediment deposition is not uniformly distributed in the central and southern of the Strait. This results in limited or no sedimentation in some parts of the basin (Barrie et al., 2005). Sediment distribution pattern for the Fraser River Delta is described by (Pharo & Barnes, 1976; Barrie & Currie, 2000).

> “Generally, the sediments grade from fine grained sands in the delta front, the wave-influenced part of the delta at the seaward limit of the tidal flat, to silt on the delta slope to clay on the pro-delta. On the north part of the delta, the surficial sediment distribution pattern is dominated by local sediment inputs and sediment reworking by wave and tidal energy in the shallower waters. On the western side of the basin into Boundary Pass and opposite the delta, bedrock is well exposed. On southern Roberts Bank, this sediment distribution pattern changes from a dominant sandy delta plain that

> continues and coarsens well out onto the delta slope, but becomes finer grained at the base of the slope. The mean grain size of the sediment of the delta front and slope is coarser than the present sediment load carried by the Fraser River".

The shallow coastal plain along eastern Vancouver Island consists largely of low-gradient broad sand and gravel beaches, derived mainly through erosion of abundant unconsolidated sediment underlying the lowland. The coastal plain is exposed to the dominant southeasterly storm direction, resulting in northerly transport of sandy sediments. In the deeper troughs of northern Strait of Georgia, the sediments are primarily silty clay (Barrie et al., 2005).

3.3.3 Oceanography

As an oceanographic region, the Strait of Georgia has a marine entrance at both ends and receives runoff from many rivers. The Fraser River is the dominant river in the Strait and contributes approximately 80 percent of the total runoff (Waldichuk, 1957). The Fraser River discharges its waters into the central strait, mixing fresh water with the changing tides and seasons (Masson, 2006; Davenne & Masson, 2011). The Strait of Georgia and Juan de Fuca Strait (part of Salish Sea) system is influenced by two dominating physical factors namely fresh water runoff and tides resulting in a high water exchange (Masson, 2006). In the Strait, fresh water leaves the Fraser River estuary in brackish surface layer mixing and entraining sea water in its seaward flow (Masson, 2002).

Water salinity and temperatures in the Strait of Georgia vary seasonally depending on the Fraser River discharge, salinity of the inflowing Pacific water, and insolation (Masson & Cummins, 2007). The water temperature within the Strait of

Georgia varies with depth, proximity to the Fraser River delta, and season (Thomson, 1981). The maximum discharge of the Fraser River is reached during the period of rapid snow melting in the watershed, between June and mid-July, while the minimum discharge is reached in mid-March (Masson, 2006).

Like temperature, the salinity distribution in the Strait of Georgia has a marked two-layer structure. The top of the lower layer lies approximately 50 m deep and is delineated by a salinity of 29.5 ppt; below this value, the salinities gradually increase to near-bottom values of 30.5 ppt in summer and 31.0 ppt in winter. Above 50 m, on the other hand, salt content varies considerably with season and distance from the mouth of the Fraser River estuary, where salinities are always comparatively low (Thomson, 1981). The salinity of inflowing Pacific water reaches a peak in late August and a minimum in late February or early March (Waldichuk, 1957; Masson, 2006).

Tides in the Strait of Georgia are of the mixed type (semidiurnal and strong tidal currents) characteristic of the Pacific coast of North America (Masson, 2006). The tides are subject to a diurnal inequality because of the declination of the moon. This affects both their time and height, lasting a maximum one or two days after the moon is at its extreme declination and at a minimum one or two days after the moon is at the equator (Waldichuk, 1957; Masson, 2006).

The Strait of Georgia-Salish Sea system actually represents three types of estuaries based on the vertical structure of salinity: (1) the strongly stratified water of the Strait of Georgia owing its characteristics to predominance of the Fraser River discharge, (2) the weakly or vertical mixed water of the channels of the San Juan Archipelago resulting from intensive tidal turbulence, and (3) the slightly stratified water of Juan de

Fuca Strait combining fresh water outflow near the surface with strong tidal mixing (Masson, 2006). The fact that the Strait of Georgia-Salish Sea system comes under the influence of two dominating physical factors, fresh water runoff and tide, gives it a distinctive mechanism in water exchange (Davenne & Masson, 2011). In the Strait of Georgia fresh water leaves the Fraser River estuary in a brackish surface layer and mixes with sea water in its seaward flow. The loss of sea water in the Strait is replaced by a compensating deep flow from the sea. However, intensive tidal action in the channels of the San Juan Archipelago mixes the brackish surface layer with the saline deep water to near homogeneity (Waldichuk, 1957). Thus the deep water which flows into the basin of the Strait of Georgia is not ”pure" sea water but a mixture of sea water and Fraser River water of a certain age (Masson, 2006; Davenne & Masson, 2011). The salinity and temperature of this water vary seasonally depending on the Fraser River discharge, salinity of the inflowing Pacific water, and isolation effects undergo seasonal changes (Masson & Cummins, 2007).

3.3.4 Biology

It is estimated that the Strait supports about 3000 species of marine life including seals, porpoises, killer whales, sea lions and other marine mammals; at least 200 species of fish including five species of wild salmon, more than 1,500 invertebrate species, hundreds of species of seabirds and shorebirds and about 500 marine plant species, including 200 varieties of seaweeds exist in the Strait (Georgia Strait Alliance, 2012). The deep subtidal habitat of the Strait of Georgia are dominated by burrowing macrofauna such as holothurians, bivalves, and the heart urchin, *Brisaster latifrons* (Levings et al., 1983).

3.3.5 Economy

More than 70 percent of the population of BC is located on the periphery and shores of the Strait of Georgia. It provides a foundation for expanding development and industrialization (Thomson, 1981). About 460 licensed shellfish tenures occupy 2,114 ha in BC (BC-Ministry of Agriculture, 2011a) (Figure 6). The majority of these tenures are located within the Strait of Georgia or around Vancouver Island, with the exception of one farm in the Queen Charlotte Islands and one south of Prince Rupert. Accounting for 29 percent of the tenured area and 52 percent of shellfish farm gate value, Baynes Sound is the most important shellfish growing area in British Columbia (VIU, 2012).

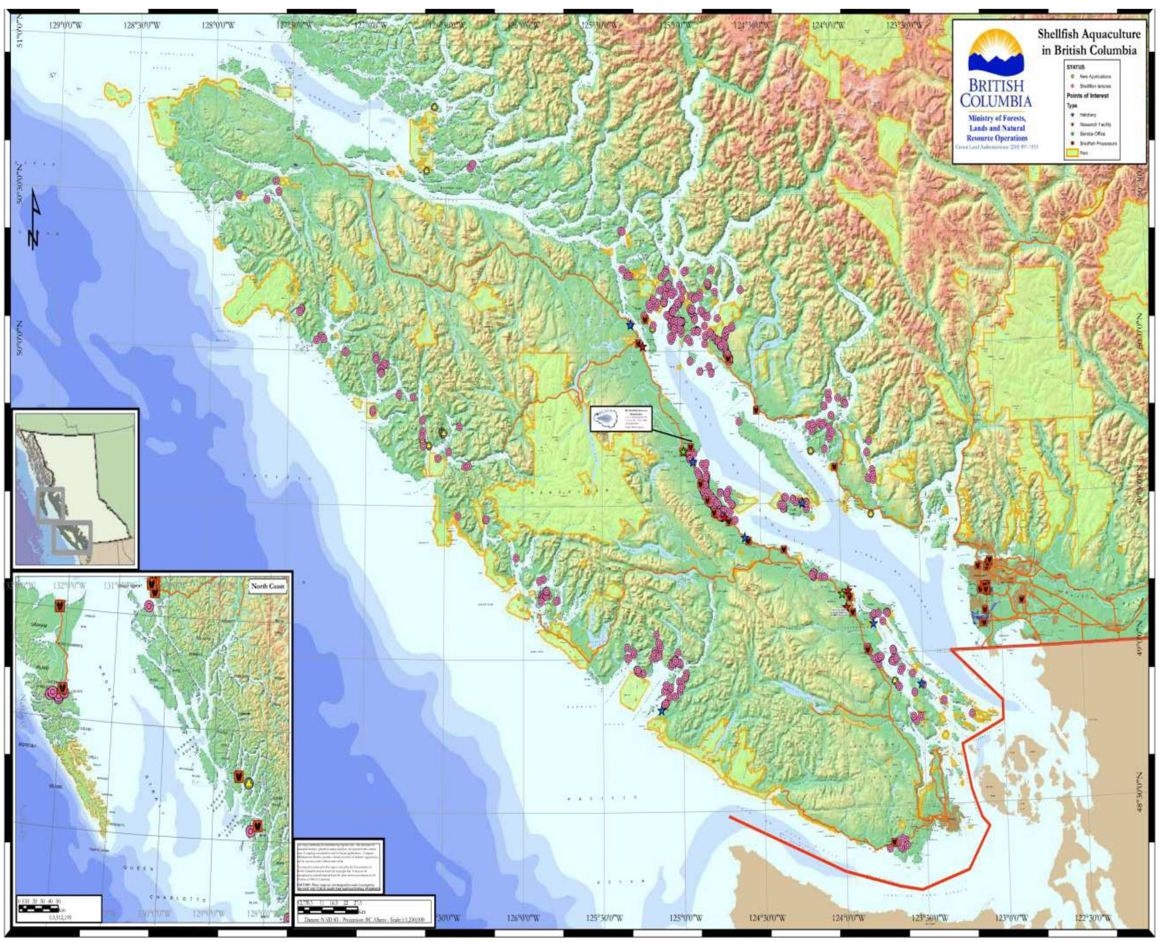

Figure 6: Tenure locations (pink dots) within the SoG and around Vancouver Island

Source: BC-Ministry of Agriculture, 2011c

As result of human population activities (increased habitat disruption/destruction both along shorelines and in river basins) and related economic, commercial and recreational activities and, land use around the Strait, the marine ecosystem has experienced significant changes (Perry et al., 2009) which in turn may bring changes in its valuable contribution to the BC province's economy.

3.4 Research approach and methodology

This study focuses on the bottom culture of the Pacific Oyster (*Crassostrea gigas*) and the Manila Clam (*Venerupis philippinarum*). The main concern is with the survival and growth rates of these species, taking into account the predicted impacts of climate changes on fisheries and aquaculture in BC. The methodology used in this study is based on the set of Biophysical Criteria for Shellfish Culture proposed by Cross and Kingzett in 1992. These criteria are considered to be appropriate for general evaluation of capability of potential sites and culture techniques for Pacific Oyster (*Crassostra gigas*), Japanese Scallop (*Patinopecten yessoensis*) and Manila Clam (*Venerupis philippinarum*). The implementation of the research program is based on the following sequence:

- Gather information of scenarios of expected changes in physical conditions sea surface salinity (SSS), sea surface temperature (SST), and beach albedo that are associated with climate change in British Columbia;
- Identify beach areas that have the capability for shellfish aquaculture and quantify changes in beach exposure (area and energy level) expected from sea level change;
- Assess how the shellfish aquaculture capabilities of the selected beaches will be affected by changes in the physical conditions of the beach; and

- Develop capability indices for shellfish based on the physical conditions characterizing existing commercial aquaculture operations.

3.5 Data acquisition

Relevant databases that are used for analysis and interpretation of results for this study were identified at the following agencies:

- Canadian Centre for Climate Modelling and Analysis (CCCma)

  http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=4A642EDE-1

  The CCCma provides a number of climate models used to study climate change and variability, and to understand the various processes which govern the climate system. These models are also used to make quantitative projections of future long-term climate change (given various greenhouse gas and aerosol forcing scenarios), and increasingly to make initialized climate predictions on time scales ranging from seasons to decades.

- Government of British Columbia (GeoBC)

  GeoBC provides information about coastal and offshore British Columbia freely available for the public on:

a) Benthic Marine Ecounits intended to describe the sea bed and nearshore selected from seven variables (depth, slope, relief, temperature, exposure, current and substrate)to derive the benthic ecounits; https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=3631&recordSet=ISO19115;

b) Pelagic Marine Ecounits intended to describe the sea surface and water column, selected from two variables (salinity and stratification) to derive the pelagic ecounits; https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=4001&recordSet=ISO19115;

- Federal, provincial and territorial government initiative (GeoBase) overseen by Canadian Council on Geomatics (CCOG)
  http://www.geobase.ca/geobase/en/about/index.html;
  The GeoBase provides reviewed and detailed description of the Canadian Digital Elevation Data. Product specifications, metadata and other supporting documentation are also available for public download at no cost

- Fisheries and Oceans Canada and Institute of Ocean Sciences
  http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.htm
  The Fisheries and Oceans Canada and Institute of Ocean Sciences agencies provide archived values of monthly mean temperatures and salinities and photographs of the sites observed at the current and old lighthouses around the coast of British Columbia.

- Ministry of Agriculture BC through Department of Fisheries and Oceans (DFO)
  http://www.gov.bc.ca/agri/;
  The Ministry of Agriculture provides data on current aquaculture tenures, shapefile and database;

3.6 Data analysis plan

3.6.1 Scenarios of changes in physical conditions

Existing information regarding scenarios of changes in physical conditions (sea level, sea surface salinity, sea surface temperature, and albedo) due to climate change based on available regional climate model that predict changes of the above mentioned physical conditions was collected to examine expected changes in sea level rise and its implications on British Columbia coastal aquaculture. Evaluation criteria applied to use this information included understanding how the data results were obtained. These criteria included acquire information about:

1. The scale of the models; and
2. Model resolution, inputs and outputs);

Finally, the information obtained from the predicted scenarios was used to evaluate how shellfish culture in BC will be affected by sea level rise, change in sea surface salinity, sea surface temperature, and beach albedo.

3.6.2 Sea level rise scenarios and mapping

The next step was to simulate and map areas along the Strait of Georgia prone to flood risk due to sea level rise. For this purpose, *Arcmap*[1] *10* was used to perform the analysis. For this step, digital elevation model (DEM) of the study area was needed to delineate potentially inundated areas, parts of land at or below a given sea-level scenario.

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[1] Arcmap is the main component of Esri's ArcGIS suite of geospatial processing programs, and is used primarily to view, edit, create, and analyze geospatial data. Arcmap allows the user to explore data within a data set, symbolize features accordingly, and create maps.

Calculation of the potential inundation zones was accomplished with an approach similar to those used in other studies (Mazria & Kershner, 2007; Poulter & Halpin, 2007; Rowley et al., 2007; Gesch, 2009) in which raster elevation data are “flooded” by identifying the land cells that have an elevation at or below a given sea-level rise scenario and are connected hydrologically to the ocean. This study used a simple “bathtub” approach wherein a grid cell is inundated if its elevation is less than or equal to the projected sea level. The method was implemented as the following steps in a GIS raster analysis framework:

1. Define the current extent of sea-level (i.e. any DEM cell that has an elevation less than or equal to zero);
2. Select DEM cells that have an elevation at or below projected sea level rise;
3. Create a potential inundation areas layer by overlapping cells that were land but are now considered to be flooded with the current extent of sea-level;

3.6.3 Beach exposure quantification

Beach exposure is defined as the area where change in tidal height creates aerial exposure of the sediment which in turn affects dehydration of any organisms and drying of the sediment in warm conditions. More often, these areas are located in the intertidal zones where changes in tidal height create a less predictable environment as there may be more extreme changes in temperature, salinity, dissolved oxygen and water content (Hayward, 1994). To quantify changes in beach exposure, results from the mapped areas prone to flood risk were compared with the current characteristics of areas inundated or exposed. This analysis was performed in *ArcMap10* using the Spatial Analyst extension.

3.6.4 Capability indices definition for shellfish culture

Proper selection of a growing site is critical to any shellfish culture operation. Suitability of a culture site is determined by multiple parameters. Factors including socio-economic conditions, resource use, infrastructure, marketing and biophysical parameters all affect the viability of a proposed operation. Biophysical parameters that can influence growth and survival of shellfish species include: temperature, food availability, water movement, disease prevalence, fouling potential, predation potential, substrate, beach slope, salinity, dissolved oxygen, and pH (Cross & Kingzett, 1992).

In this study, the capability of a shellfish culture site refers to environmental parameters which may affect a site's ability to support the proposed culture. However, to identify beach areas in the Strait of Georgia that have capability for bottom culture of the selected species (Pacific oyster and Manila clam), environmental variables that meet the requisites for culture of these species were used as criteria (as described by Cross and Kingzett, 1992) to evaluate the capability of the areas taking into account the range of critical and preferential levels of tolerance of the species. These variables include temperature, salinity, substrate, exposure and slope. This analysis was performed in *ArcMap10* using the Spatial Analyst extension.

According to Cross and Kingzett (1992), the biophysical parameters mentioned above can be employed to determine whether a site is capable of sustaining a specific commercial shellfish operation. A brief description of these variables is provided below and summarized in the Tables 3 and 4.

Water temperature **(^{0}C) –** water temperature affects the growth rate and in some instances the survival (tolerance) of a species. It is necessary to have information on both high and low temperatures encountered at the site to have a sense of critical tolerance levels.

***Exposure* (distance from low water) –** the exposure of an area can be defined as the extent to which it is affected by wind and wave action (Cross, 1993). All intertidal heights are reported from Mean Low Low Water (MLLW).

***Substrate* –** bottom type may affect the growth and survival of species in intertidal culture. Certain bottom types may not be capable of supporting culture. This variable ranges from soft mud to rock ledges.

***Beach Slope* –** this variable is expressed as the horizontal distance (meters) at which the site increases in tidal height one meter. The physical characteristic of a beach, in addition to the overlying water quality and site exposure are important features to consider in the shellfish capability evaluation. The capability of a site to support the culture of Manila clams or Pacific Oyster decreases as the slope of a beach increases (Cross & Kingzett, 1992).

***Salinity* –** salinity is a major environmental factor determining the distribution of bivalve mollusks (Fuersich, 1993; Taylor et al., 2004). Changes in salinity affect a broad range of physiologic responses in bivalves and have been shown to influence filtration rates (Riva & Masse, 1983; Villiers et al., 1989), oxygen consumption (Bernard, 1983), and the rate of particle transport over the gills (Paparo, 1981; Paparo & Dean, 1982). Given these responses, salinity may have a major impact on the growth and survival of cultured bivalves. Values in excess of known critical tolerances for the cultured species will make a site incapable of supporting culture.

In addition to identifying beach areas that have capability for shellfish bottom aquaculture, the capability index of these areas was evaluated. To do so, the range of tolerances of the selected species for a particular environmental variable was assigned a numerical value between 0 and 4. A value of 0 indicates that the site unable to support aquaculture, while 4 represents optimal conditions for aquaculture.

Tables 3 and 4 below provide the environmental conditions favorable to the culture of Pacific Oyster and Manila Clam using bottom/near-bottom techniques, respectively according to Cross and Kingzett (1992) characterization. It should be noted that these environmental conditions namely, temperature, salinity, slope, exposure (water movement) and substrate were selected from a number of possible variables that are recognized as being important in estimating the capability of a site to sustain the production of shellfish species.

Table 3: Criteria used to assess the capability for Pacific Oyster – Bottom Culture

Parameter	Reference Source	Criteria	
		Range	Optimum
Water Temperature (^{0}C)	Quayle, 1988; Malouf & Breeese, 1977; Bernard, 1983; Pauley, 1988; Brown, 1986; Brown & Hartwick, 1988;	8.0 – 34.0	15.0 – 18.0
Exposure (water movement)	Westley, 1965; Walne, 1972; Frechette & Bourget, 1985;	----	Tidal flow which avoids heavy waves action or stagnant water
Salinity (ppt)	Hopkins, 1936; Qayle, 1988; King, 1977; Bernard, 1983; Pauley et. Al, 1988; Brown, 1986;	10.0 – 35.0	24.0+

	Nell & Holliday, 1988;		
Substrate	Quayle, 1988;	Mud - rock	Firm gravel/sand/mud
Slope	Quayle, 1988;	5:1 to >15:1	>15:1

Source: Cross and Kingzett, (1992)

The Pacific Oyster is generally capable of growing over a wide range of environmental conditions. Its normal range extends between 8^0C and 34^0C, and it will tolerate freezing temperatures while exposed intertidally. Optimal temperatures for growth are between 15^0C and 18^0C. Bottom culture oysters are subject to sediment movement and physical displacement on exposed beaches. Gradually sloping, firm beaches between one and two meters above low water are preferred for bottom culture (Cross & Kingzett, 1992).

Table 4: Criteria used to assess the capability Manila Clam – Bottom Culture

Parameter	Reference Source	Criteria	
		Range	Optimum
Water Temperature (^{0}C)	Robinson & Breese, 1988; Bourne, 1982; Anderson et. al, 1982; Goulletquer et. al, 1989; Mann, 1979	0.0 – 30.0	8.0 – 25.0
Exposure (water movement)	----	----	Tidal flow which avoids heavy waves action or stagnant water
Salinity (ppt)	Robinson & Breese, 1984; Anderson et. al, 1982	13.5 – 35.0	24.0+
Substrate	Anderson et. al. 1982; Quayle & Bourne, 1972;	Mud/sand to large gravel	Gravel to sand/pea-gravel
Slope	Anderson et. al, 1982; Kuwatani & Nish, 1969;	Limited at 1:10	>1:20

Source: Cross and Kingzett, (1992)

Different from the Pacific Oyster, the Manila Clam has a wide range of tolerances for environmental variables determining growth and survival. Some of the parameters of concern for a culture operation include substrate composition and beach slope. Optimal beaches are typically sheltered with the substrate composed of mixture of gravel (approximately 1.0 cm diameter), sand and a minor mud component. Beach gradient should be greater than 1:20 (1 up for every 20 across) at a tidal elevation of one to two meters above Mean Low-Low Water (MLLW) (Cross & Kingzett, 1992).

3.6.5 Capability sites' impacts due to changes in SST, SSS and beach albedo

The adaptive response of different shellfish permits some to live within a narrow and specific type of environment while others may be able to survive within a relatively wide range of environmental conditions (Cross & Kingzett, 1992). Thus, changes in sea level, temperature and salinity are likely to create significant changes in the capability of a site to sustain the production of shellfish species. To assess how shellfish aquaculture capability will be affected by changes in sea-level rise, SSS, SST and beach albedo, critical and preferential levels of tolerance of the species to these physical parameters were used as evaluation criteria.

3.7 Summary

This chapter has described the study area and has defined and set out the research approach and methodology. It has also presented the data acquisition strategy. The analysis of sea-level rise scenarios, beach exposure and capability index was performed using GIS techniques. The capability index analysis applies the methodology proposed by

Cross and Kingzett (1992). The environmental variables considered important in the selection of a site capable of sustaining cultures of various shellfish species are outlined with respect to the biological requirements of each species. Tolerances (ranges) and optima for each of the shellfish species by parameter were employed in the development of numerical criteria system which provides the basis upon which areas can be ranked according to the culture capability.

Chapter 4

This chapter presents and discusses the results of the data analysis. It also describes the data acquisition process as well as the data analysis plan.

4.1 Acquired data

4.1.1 Digital elevation model (DEM) specifications

Canadian Digital Elevation Data (CDED) were used to simulate scenarios of sea-level rise changes in the Strait of Georgia. These data were downloaded from http://www.geobase.ca/geobase/en/about/index.html (Natural Resources Canada, Earth Sciences Sector and Centre for Topographic Information). The data are an ordered array based on National Topographic Data Base (NTDB) at a scale of 1:50,000. About 60 tiles (raster dataset) (Figure 7) were downloaded to cover the study area. The grid spacing, based on geographic coordinates varies in horizontal resolution from a minimum of 0.75 arc seconds to a maximum 3 arc seconds. The ground elevations are recorded in meters relative to Mean Sea Level (MSL) at regularly spaced intervals, based on the North American Datum 1983 (NAD83) horizontal reference datum. The vertical reference system is Canadian Vertical Geodetic Datum of 1928 (CVGD28). The vertical resolution is 1 meter. Oceans and estuaries at Mean Sea Level were assigned an elevation value of zero meters and all other water bodies were assigned their known elevations or estimated values.

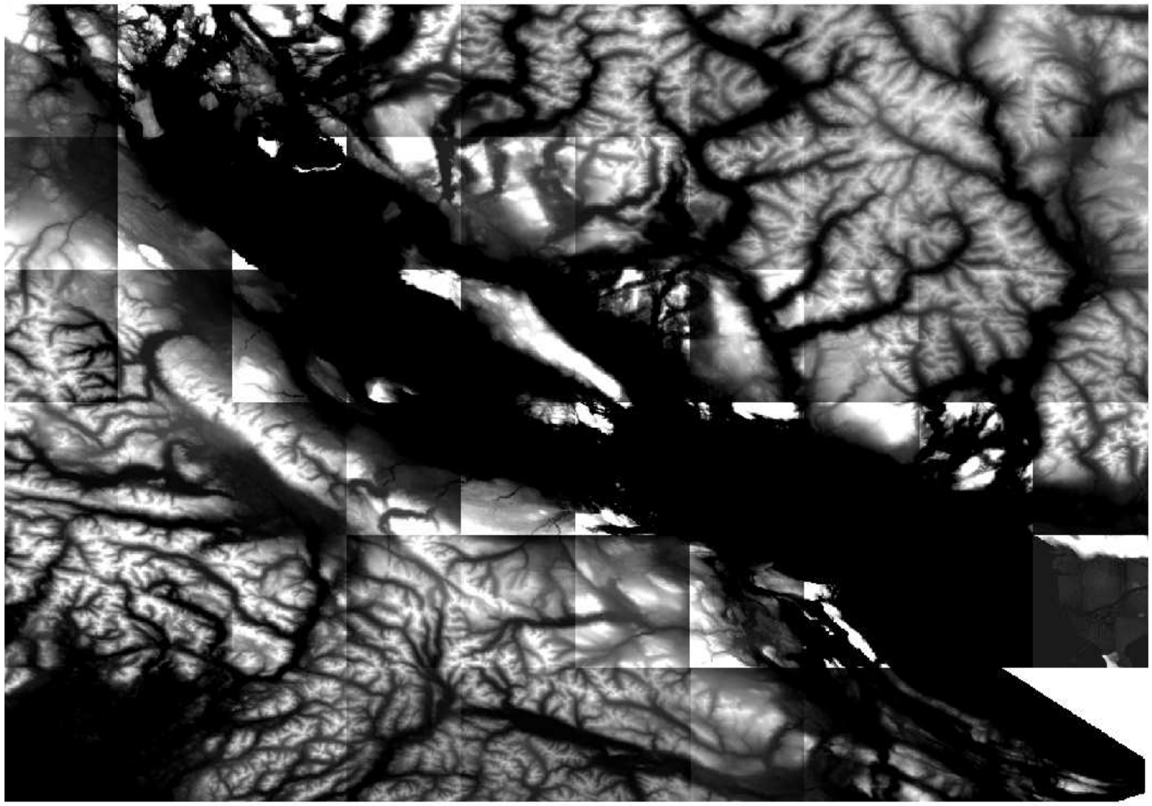

Figure 7: Array of tiles that comprises the study area Strait of Georgia-BC (Canada)

Source: Natural Resources Canada, Earth Sciences Sector and Centre for Topographic Information, (2010)

Since the raster dataset were downloaded as individual images, there was a need to create a single and uniform raster dataset. This procedure consisted in creating a mosaic performed, in Arcmap 10, by merging the individual images. The result is shown in Figure 8 below.

Figure 8: Compiled mosaic of the study area Strait of Georgia-BC (Canada)

Source: Natural Resources Canada, Earth Sciences Sector and Centre for Topographic Information, (2010)

The newly created raster dataset has the same set of properties as the original individual images, i.e. same number of bands, same cell size, and same spatial reference.

4.1.2 Benthic and pelagic marine ecounit dataset

Benthic and pelagic marine ecounit information is provided by the Province of British Columbia under the Open Government License for Government of BC Information v.BC1.0.

a) Benthic ecounits

Benthic Marine Ecounits is a dataset that describes the sea bed and nearshore areas of British Columbia. Seven variables, namely depth, slope, relief, temperature, exposure, current and substrate, were used to describe the ecounits. The dataset is distributed in shapefile format.

b) Pelagic ecounits

Pelagic Marine Ecounits is a set of information that describes the surface and water column. Two variables (salinity and stratification) were used to derive the pelagic ecounits.

4.1.3 British Columbia commercial shellfish aquaculture tenures

The commercial marine shellfish tenures in British Columbia were obtained from the website of the Ministry of Forests, Lands and Natural Resources Operations. The information provided in shapefile format includes the company name, number and license information, reference number, location, legal description, area occupied, the status of the tenure, and the type of culture.

4.1.4 Projected sea surface temperature and sea surface salinity

Sea surface temperature and sea surface salinity projections of open ocean waters adjacent to the BC coast were acquired from the Third Generation Coupled Global Climate Model (CGCM3) from the Canadian Centre for Climate Modelling and Analysis (CCCma, 2010). The ocean component is described in detail in paper by Flato & Boer, (2001), and by Kim et al., (2002) and Kim et al., (2003). The main features of the model are briefly summarized here. The atmosphere model output is provided on a 96x48

Gaussian grid (approximately 3.75° lat x 3.75° long). The ocean model output is provided on a 192 x 96 grid (2 x 2 oceanic grid boxes for each atmospheric grid box). Monthly data are available from five runs for the years 2001-2100. Daily data are available for years 2046-2065 and 2081-2100. Daily data for several 2-D variables are available for the years 2001-2100. The dataset summary is presented in the Appendix I.

4.1.5 Observed sea surface temperature and sea surface salinity

Observed sea surface temperature and sea surface salinity data of five lighthouses (Entrance Island, Chrome Island, Sister Island, Departure Bay and Active Pass) were obtained from Fisheries and Oceans Canada and the Institute of Ocean Sciences (IOS/DFO, 2009) website. This dataset contains monthly average sea surface temperature and salinity measurements from 1915 to 2011. The data were obtained from the current and old lighthouses sampling locations around the Strait of Georgia.

4.1.6 Projected sea level rise in British Columbia's coast

Projections of sea-level rise for the 21st Century in BC were obtained from Thomson and collegues (2008). This report summarizes current trends in sea level variability in the world's oceans, with particular focus on the coastal regions of BC and northwestern Washington State. Projected sea level rise in BC's coast was based on tide gauge and Global Positioning System (GPS) measurements for Alaska-British Columbia-Washington, taking into account predictions of eustatic sea level rise in associated with melting of continental ice sheets, water confined in reservoirs and global ocean thermal expansion. The projections of sea level rise in BC's coast also considered predictions of regional changes in relative sea level that incorporate the effects of oceanographic and tectonic processes and sediment compaction.

4.2 Analysis and results

4.2.1 Scenarios of changes in SST and SSS

Scenarios of change by 2100 for SST (^{0}C) and SSS (ppt) of open ocean adjacent waters of BC's coast under IPCC SRES A2 Experiment with Canadian Centre for Climate Modelling and Analysis (CGCM3.1/T47) are presented in Figures 8, 9, 11 and 12 divided in two sets. The first set presents changes from 2012-2050. The second set presents changes 2051-2100.

a) Projected changes in SST (2012-2050) of open ocean adjacent waters to the BC's coast

According to the (Canadian Centre for Climate modeling and analysis, 2010) (CGCM3.1/T47), the temperature of open ocean waters adjacent to the B.C. coast will increase approximately 1 ^{0}C between 2012 and 2050. These projections indicate an increase rate of 0.0222 ^{0}C/ year as shown in Figure 9.

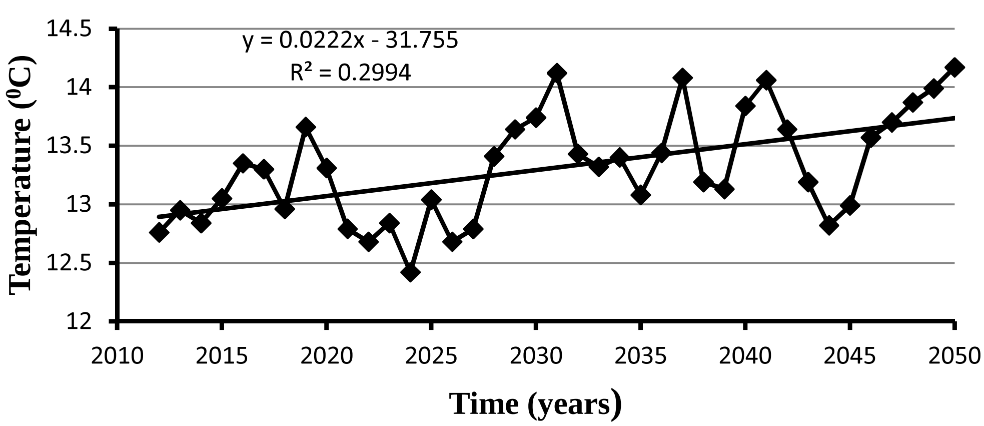

Figure 9: Projected SST (2012-2050) of open ocean adjacent waters to the BC's coast

b) Projected changes in SST (2051-2100) of open ocean adjacent waters to the BC's coast

The temperature of open ocean waters adjacent to the B.C. coast is expected to have a rapid increase between 2051 and 2100 compared to expected changes in the previous fifty years. Approximately 2°C water temperature increase is expected between 2051 and 2100. The linear trend indicates an increase rate of 0.033^{0}C/year as shown in Figure 10.

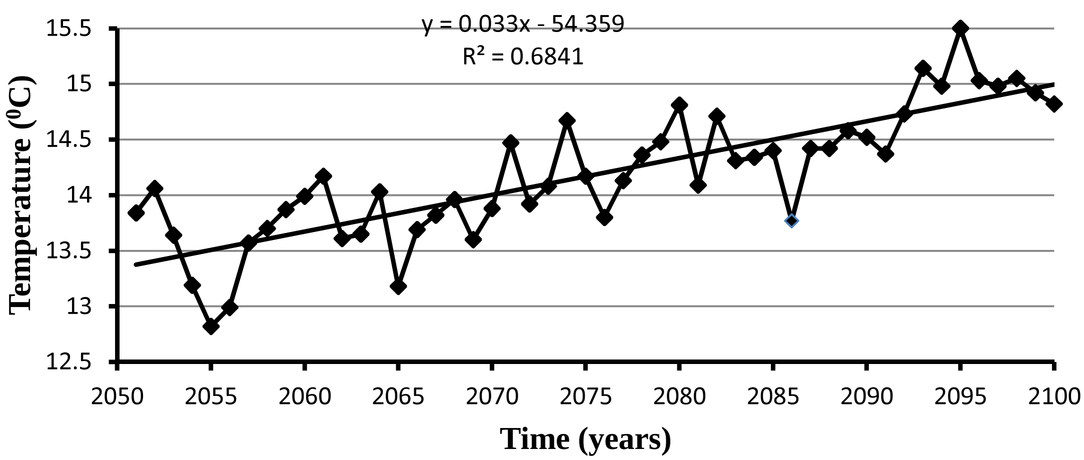

Figure 10: Projected SST (2051-2100) of open ocean adjacent waters to the BC's coast

c) Observed SST (1915-2011) in the Strait of Georgia

Observed sea surface temperatures in the Strait of Georgia have increased by about 1°C during the last century. This increase is consistent with that projected from 2012 to 2050. The linear trend (Figure 11) indicates an increase rate of 0.0085^{0}C/year.

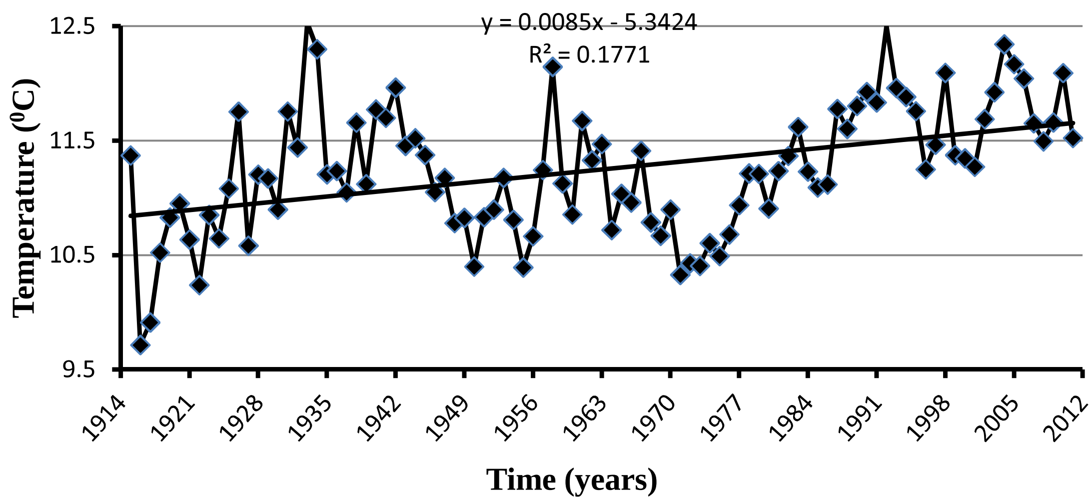

Figure 11: Observed SST (1915-2011) in the Strait of Georgia

d) Projected changes in SSS (2012-2050) of open ocean adjacent waters to the BC's coast

According to the (Canadian Centre for Climate modeling and analysis, 2010) (CGCM3.1/T47), projections of salinity of open ocean waters adjacent to the B.C. coast will decrease 0.21 ppt between 2012 and 2050. Surface salinity of these waters is predicted to decline at a rate of 0.0055 ppt/year as shown in the Figure 12 below.

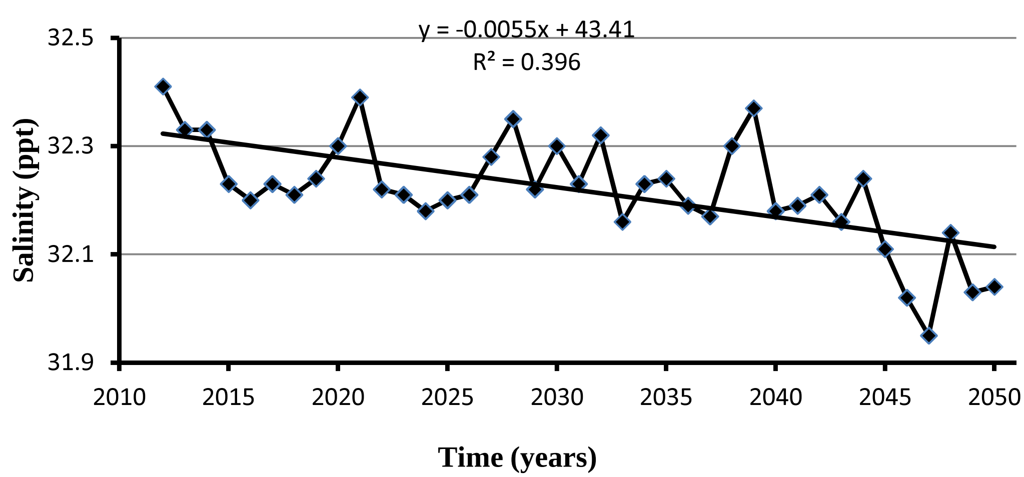

Figure 12: Projected SSS (2012-2050) of open ocean adjacent waters to the BC's coast

e) Projected changes in SSS (2051-2100) of open ocean adjacent waters to the BC's coast

The salinity of open ocean waters adjacent to the B.C. coast is expected to have a rapid decrease 0.43 ppt between 2051 and 2100 comparing to expected changes between 2012 and 2051. Freshening of these waters is expected to increase at a rate of 0.0088 ppt/year as shown in Figure 13.

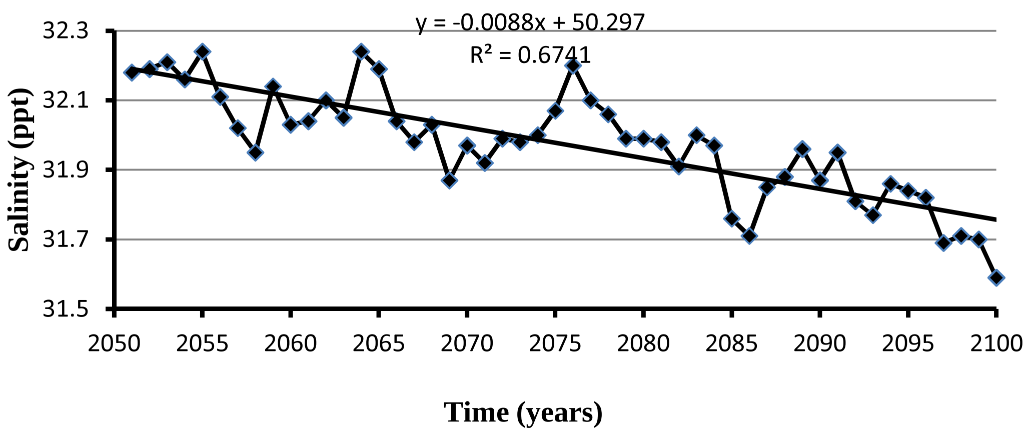

Figure 13: Projected SSS (2051-2100) of open ocean adjacent waters to the BC's coast

f) Observed SSS (1915-2011) in the Strait of Georgia

Overall observations of sea surface salinity from five lighthouses in the Strait of Georgia from 1915 to 2011 indicate an increase of 1.68 ppt at a rate of 0.0175 ppt/year (Figure 14) below. This trend is contrasted with projections of open ocean waters adjacent to the BC's coast which indicated a freshening of the waters. The increasing trend can be explained by the fact that the selected lighthouses are located on the northern part of the Strait and the influence of freshwater from the Fraser River[2] is reduced or almost null. However, from the five selected lighthouses locations, only one

[2] The Fraser River is the most important source of freshwater of the Strait of Georgia (Masson, 2006)

observational location (Departure Bay) indicates a freshening of the water salinity where the decline rate observed from 1915 to 2011 is 0.003 ppt/year.

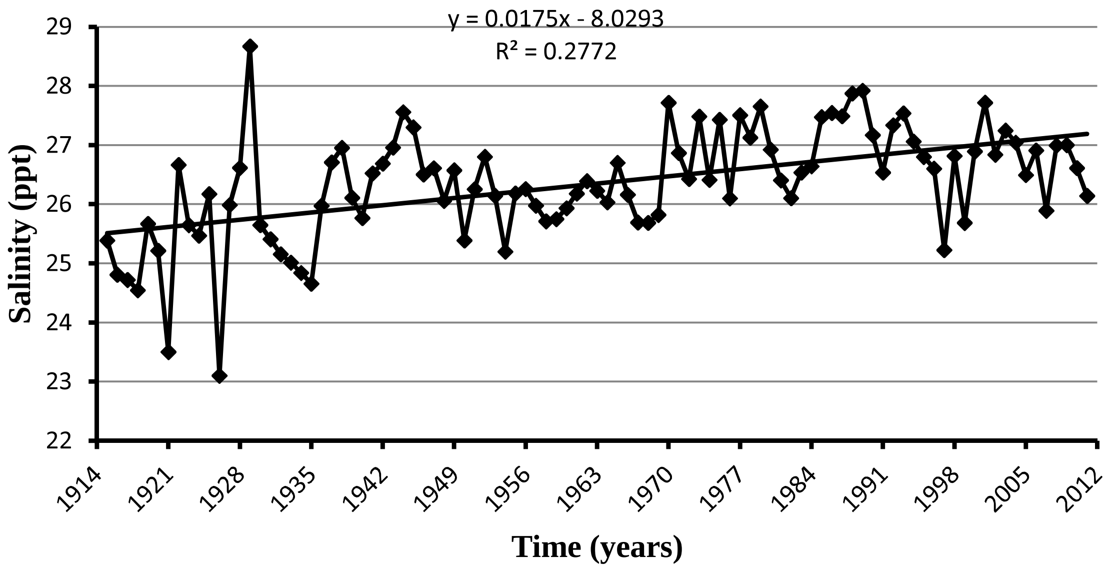

Figure 14: Observed SSS (1915-2011) in the Strait of Georgia

4.2.2 Scenarios of changes of SLR in BC's coast for 21st Century

Scenarios of sea level changes for various locations along the B.C. coast for the end of the 21st century using extreme low, mean and extreme high estimates of global sea level rise are summarized in Table 5.

Table 5: Estimated relative SLR by 2100 for selected locations along BC's coast

Location	Sea Level Rise based on extreme low estimate of global sea level rise (m)	Sea Level Rise based on mean estimate of global sea level rise (m)	Sea Level Rise based on extreme high estimate of global sea level rise (m)
Prince Rupert	0.10-0.31	0.25	0.95-1.16
Nanaimo	-0.04	0.11	0.80
Victoria	0.02-0.04	0.17-0.19	0.89-0.94
Vancouver	0.04-0.18	0.20-0.33	0.89-1.03
Fraser River Delta	0.35	0.50	1.20

4.3 Areas prone to flood risk due to sea level rise in the Strait of Georgia

Taking into account the projections of sea level rise along the BC's coast (Table 5), three representative sites (Buckley bay and Fanny bay in Baynes Sound and, Henry bay on Texada Island) in the Strait of Georgia were used for analysis of the impacts of sea level rise on the aquaculture tenured sites. These locations (Buckley bay, Fanny bay and Henry bay) were selected using significant flooded area as criteria. Three simulations level (1.2 m and 2 m) were used in the analysis. To minimize errors derived from the vertical accuracy of the Digital Elevation Model (DEM) which is 1 m, the simulations started from 1.2 m. The results are shown from Figure 15 to Figure 20.

4.3.1 Scenarios of SLR in Buckley bay and Fanny bay (Baynes Sound)

Figure 15: Current sea level in Buckley bay and Fanny bay (1:25,000)

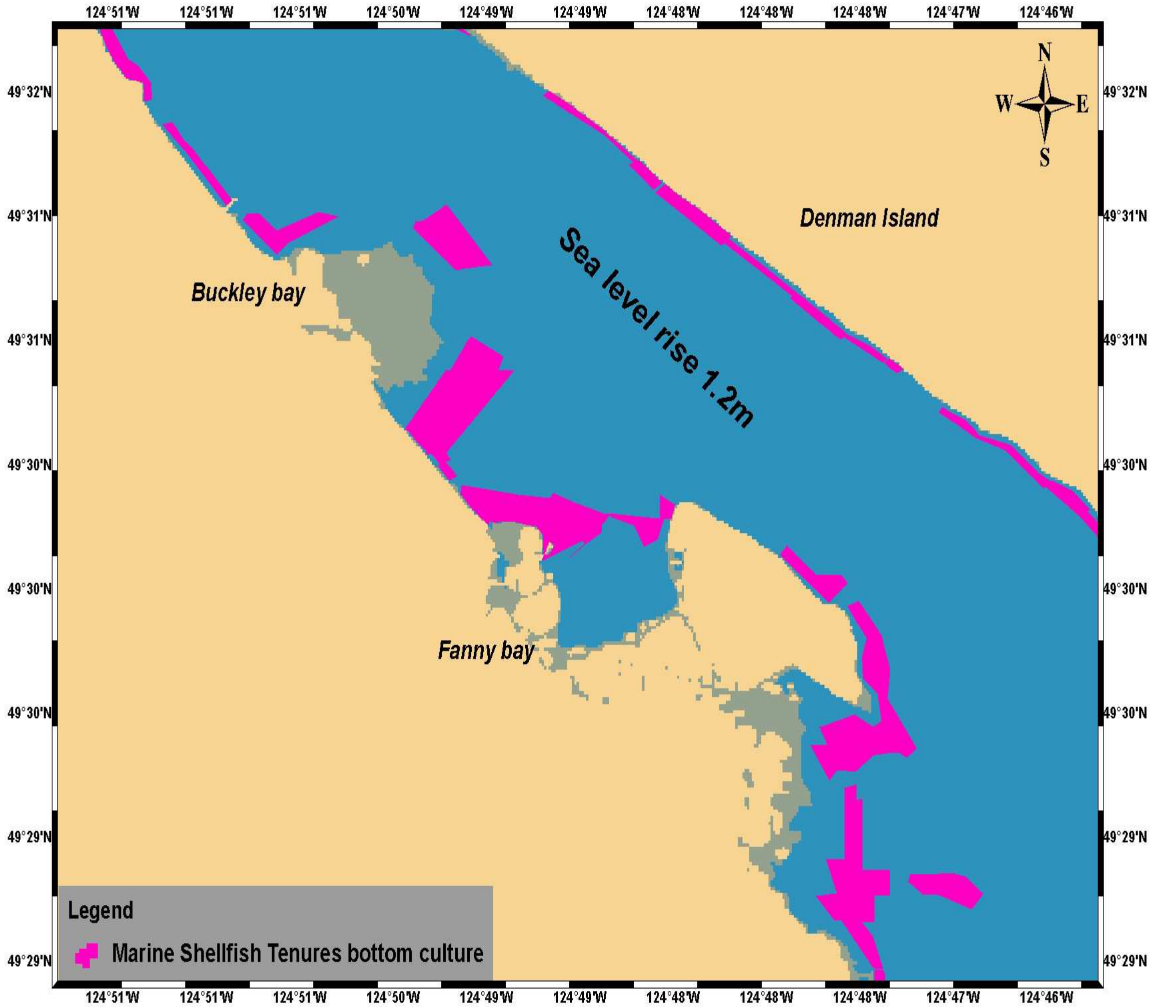

Figure 16: Simulation of 1.2 metre SLR in Buckley bay and Fanny bay (1:25,000)

Figure 17: Simulation of 2 metres SLR in Buckley bay and Fanny bay (1:25,000)

4.3.2 Scenarios of Sea level rise in Henry bay (Texada Island)

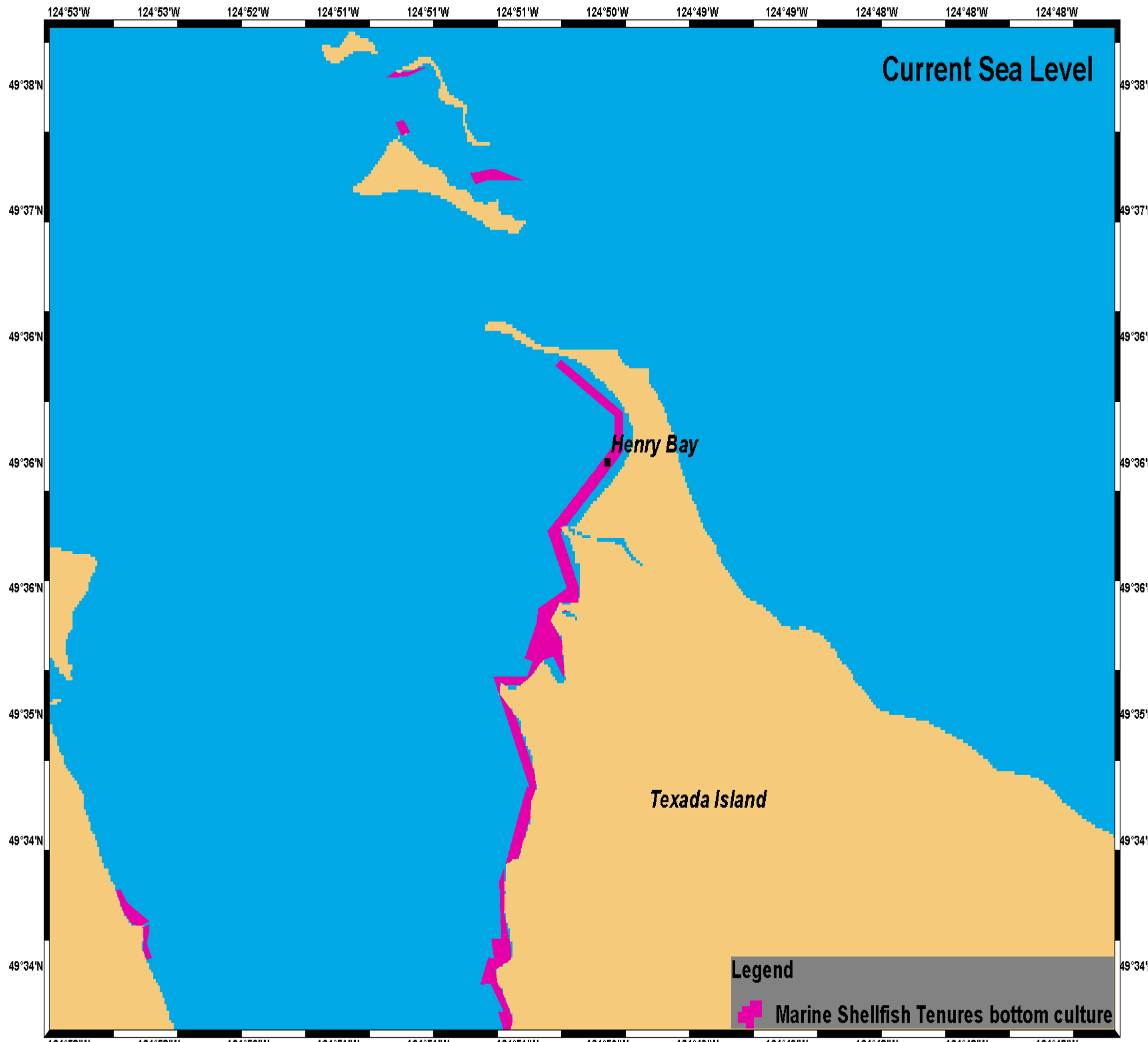

Figure 18: Current sea level in Henry bay (1:26,000)

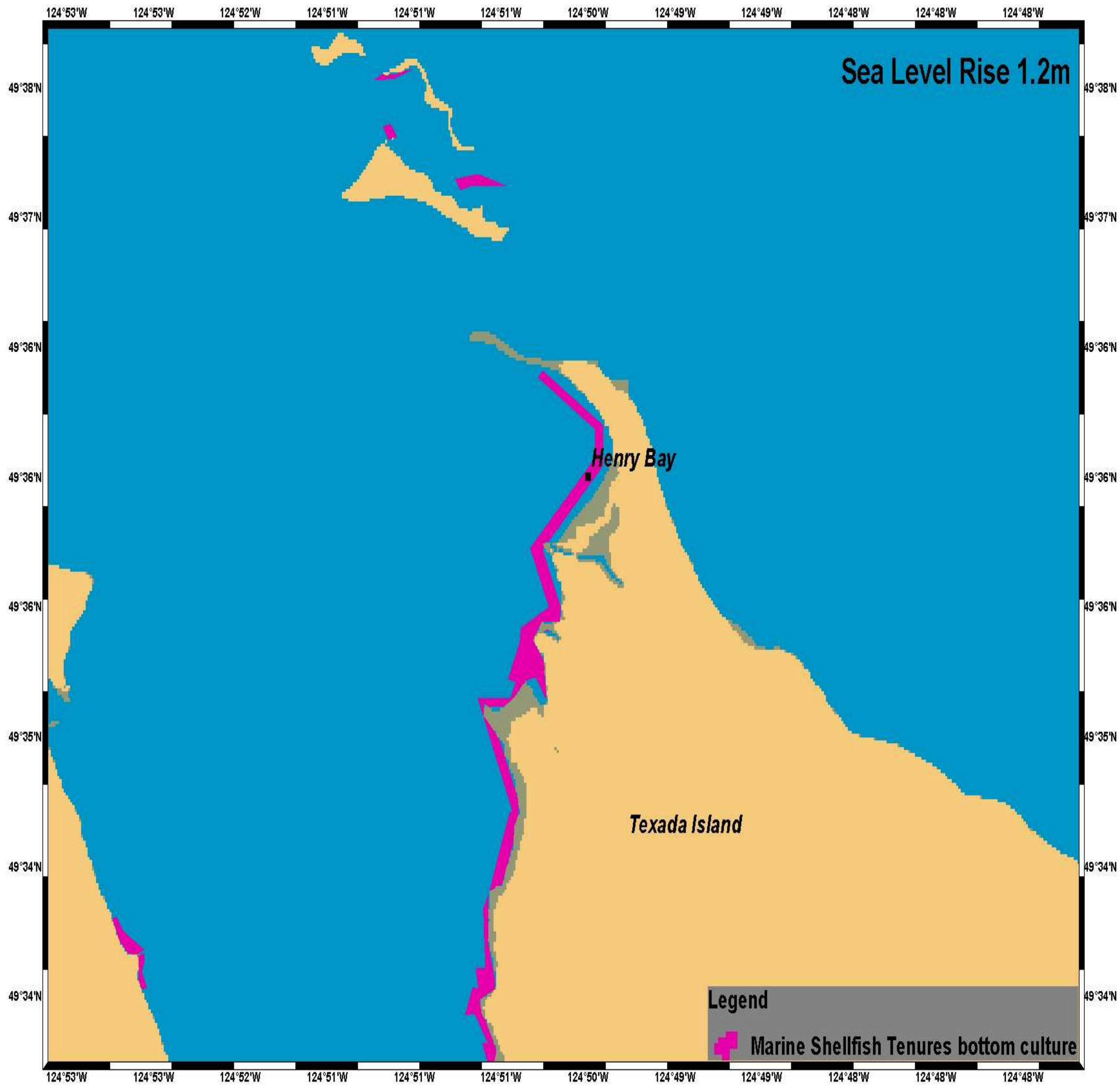

Figure 19: Simulation of 1.2 metre SLR in Henry bay (1:26,000)

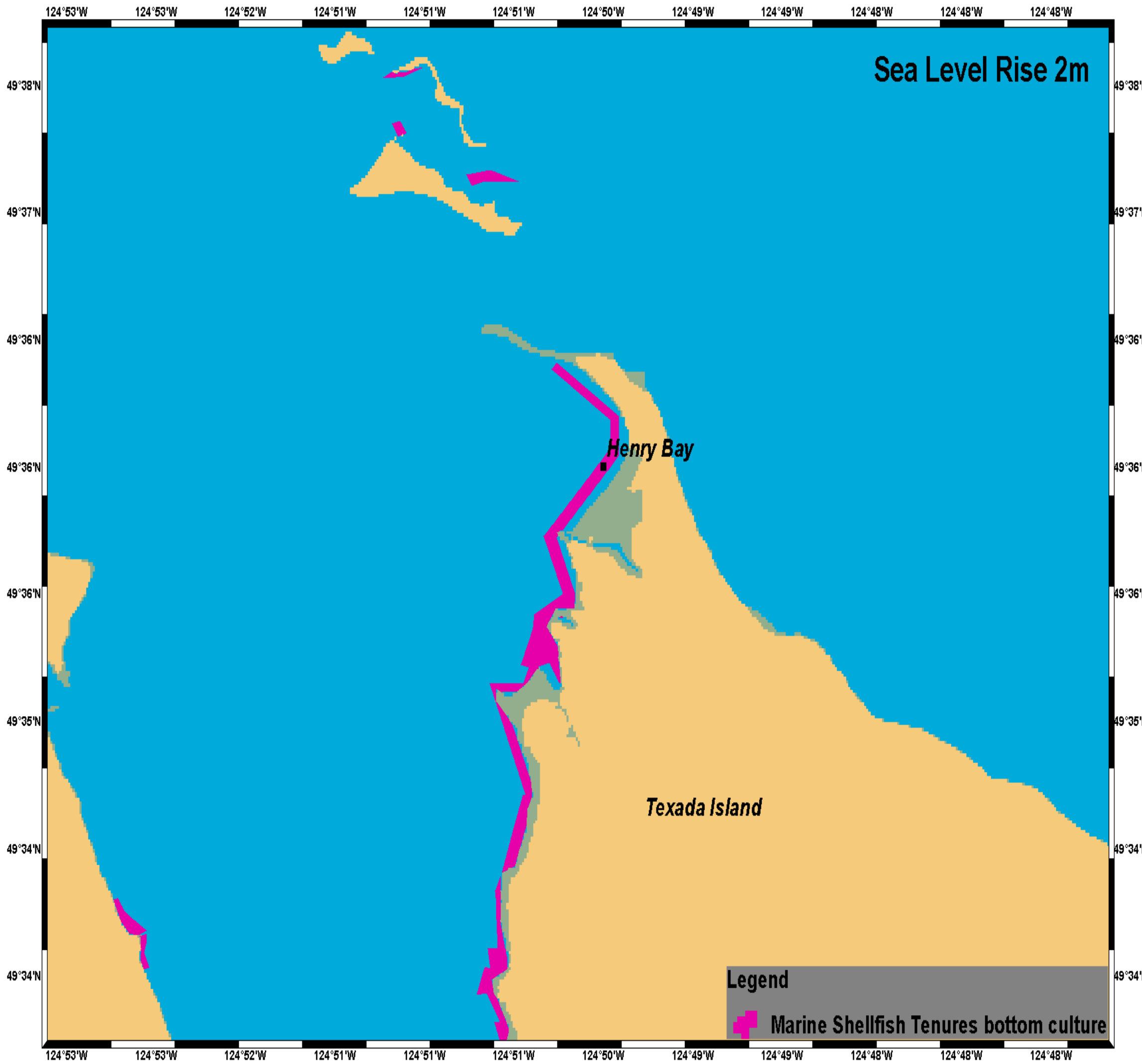

Figure 20: Simulation of 2 metres SLR in Henry bay (1:26,000)

4.4 Beach inundation quantification

Based on the sea level rise simulations described in section 4.3, the sizes of the inundated areas (Buckley Bay, Fanny Bay and Henry Bay) were calculated. The results are presented in Table 8.

Table 6: Inundated areas (ha) of selected sites

<table>
<tr><th></th><th></th><th>Inundated area for SLR 1.2 m</th><th>Inundated area for SLR 2 m</th></tr>
<tr><td rowspan="2">Baynes Sound</td><td>Buckley Bay</td><td rowspan="2">121.0 ha</td><td rowspan="2">195.2 ha</td></tr>
<tr><td>Fanny Bay</td></tr>
<tr><td>Texada Island</td><td>Henry Bay</td><td>37.3 ha</td><td>51.4 ha</td></tr>
</table>

4.5 Capability index definition for bottom shellfish culture

Six parameters were used to define the Capability Index for the sites: (i) water temperature; (ii) exposure (water movement); (iii) salinity; (iv) substrate; (v) depth and (vi) slope. These parameters were rated (1 to 3) as follows: 1- not capable for culture; 2- moderately capable for culture; 3- capable for culture. Moreover, the parameters were weighted according to their capability to support culture. The weights estimates were adapted from Cross and Kingzett (1992). Determination of the site's capability was defined by three categories of variables: **Growth –** temperature; **Survival –** substrate, beach slope and exposure (water movement) and; **Survival and growth –** salinity; the categorical assignment for capability comprises the following:

Not advisable: the site does not support culture;

Poor: the site may support culture but it is not recommended;

Medium: the site is capable of supporting culture; however, mitigation measures are needed to improve culture

Good: the site is capable of supporting culture

The site capability index (SCI) was calculated using the equation 1:

$$SCI = \sum_{i=1}^{n} w_i C_i \qquad (01)$$

$$SCI = w_{tem}C_{temp} + w_{sal}C_{sal} + w_{slo}C_{slo} + w_{sub}C_{sub} + w_{exp}C_{exp} + w_{dep}C_{dep}$$

Where:

w_{temp} & C_{temp}: Weight and criteria for water temperature;

w_{sal} & C_{sal}: Weight and criteria for salinity;

w_{slo} & C_{slo}: Weight and criteria for slope;

w_{sub} & C_{sub}: Weight and criteria for substrate;

w_{exp} & C_{exp}: Weight and criteria for exposure;

w_{dep} & C_{dep}: Weight and criteria for depth;

4.5.1 Parameters rating and weights for Manila Clam bottom culture

Table 7: Parameters rating for Manila Clam bottom culture

Parameter	Class	Range	Rate
Temperature (^{0}C)	Warm	9-15	3
	Cold	<9	1
Salinity (ppt)	Mesohaline	5-18	1
	Polyhaline	18-28	2
	Euhaline	28-35	3
Substrate	Sand		3
	Hard		1
	Mud		2
Exposure	Low		3
	Moderate		2
	High		1
Slope (%)	Flat	0-5	3
	Sloping	5-20	2
	Steep	>20	1
Depth	Shallow	0-20	3
	Photic	20-50	2
	Mid-depth	50-200	1
	Deep	200-1000	1

Table 8: Parameters weight for Manila Clam bottom culture

Parameters	Weight (%)
Temperature (^{0}C)	10
Salinity (ppt)	10
Substrate	30
Exposure	20
Slope	10
Depth	20

The capability indices in the Strait of Georgia are presented in Figure 22

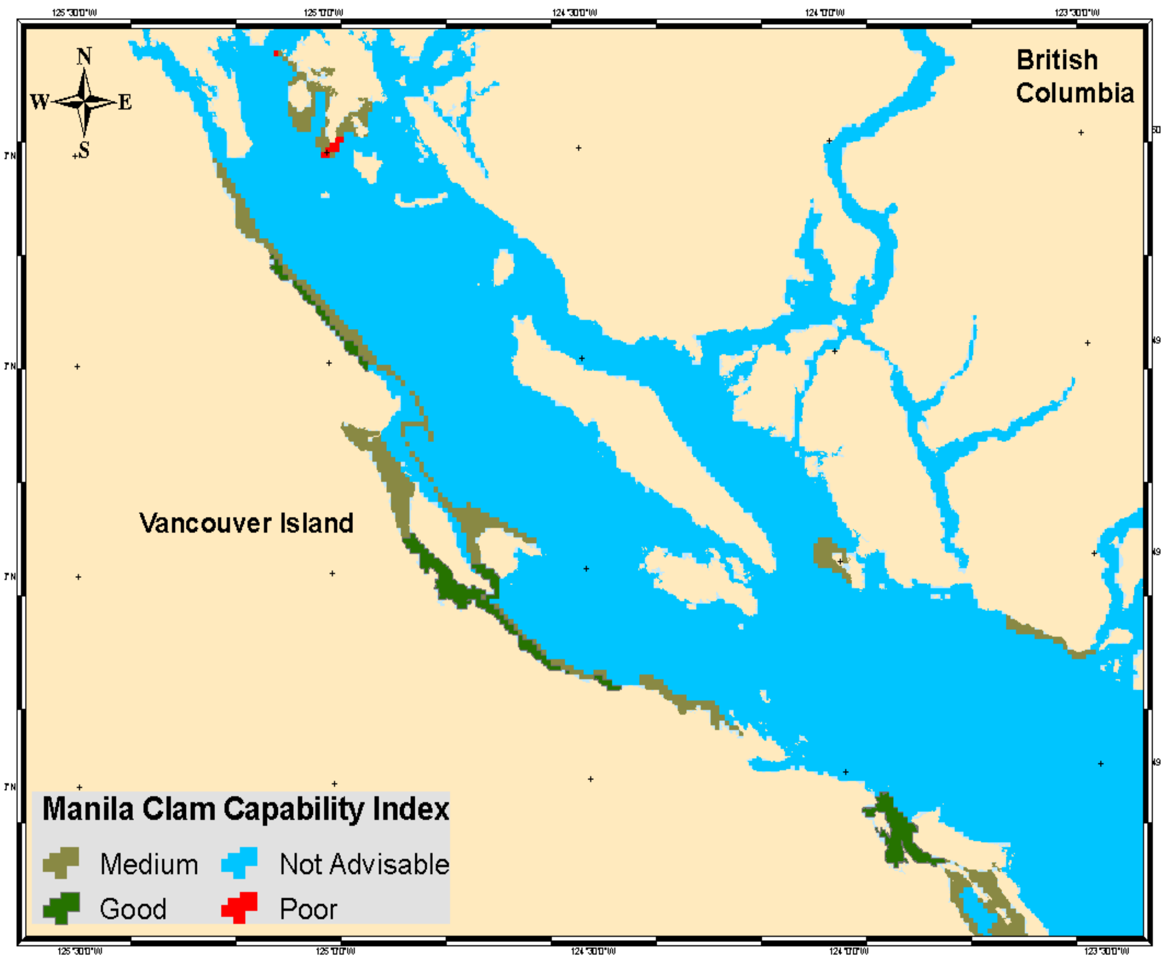

Figure 21: Manila Capability Indices (1:590,000)

4.5.2 Parameters rating and weights for Pacific Oyster bottom culture

Table 9: Parameters rating for Pacific Oyster bottom culture

Parameter	Class	Range	Rate
Temperature (^0C)	Warm	9-15	3
	Cold	<9	1
Salinity (ppt)	Mesohaline	5-18	1
	Polyhaline	18-28	2
	Euhaline	28-35	3
Substrate	Sand		1
	Hard		3
	Mud		2
Exposure	Low		3
	Moderate		2
	High		1
Slope (%)	Flat	0-5	3
	Sloping	5-20	1
	Steep	>20	1
Depth	Shallow	0-20	3
	Photic	20-50	1
	Mid-depth	50-200	1
	Deep	200-1000	1

Table 10: Parameters weight for Pacific Oyster bottom culture

Parameters	Weight (%)
Temperature (^0C)	10
Salinity (ppt)	10
Substrate	25
Exposure	20
Slope	10
Depth	25

The capability indices in the Strait of Georgia are presented in the Figure 23

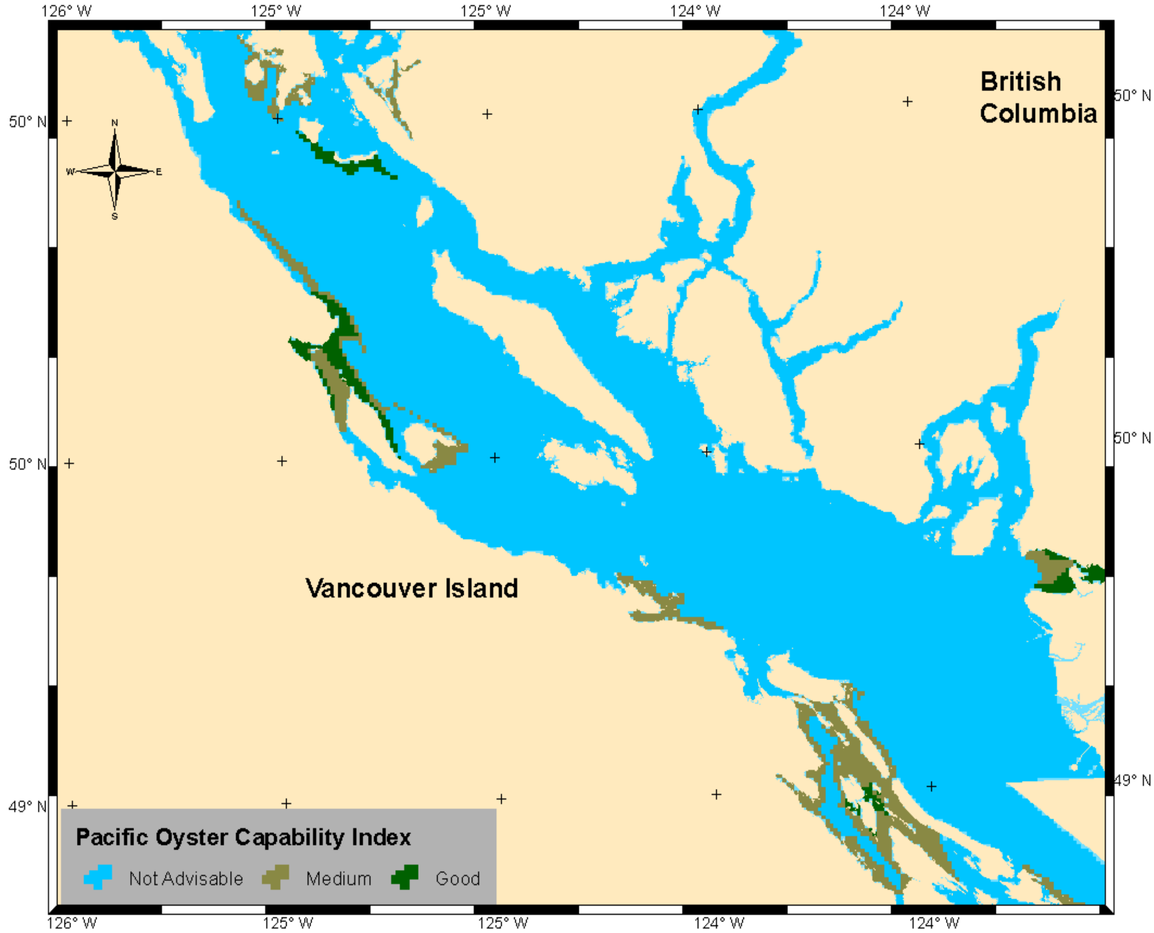

Figure 22: Pacific Oyster Capability Indices (1:700,000)

4.6 Impacts of aquaculture sites' capability due to changes on SST and SSS

To assess how aquaculture site's capability will be affected by changes in SST and SSS, results of scenarios of expected changes in the above mentioned parameters developed previously in this study, were compared with the critical and preferential parameters levels of tolerance of the species to evaluate whether the selected species can withstand these changes. The Table 11 summarises the variables and parameters used in the assessment process.

Table 11: Shellfish tolerance range vs. expected changes in SST and SSS

	Manila Clam range	Pacific Oyster range	Observed average (2011)	Expected change (2012-2050)	Expected change (2051-2100)
Salinity (ppt)	13.5 to 35	10 to 35	26.14	-0.21	-0.43
Temp. (^{0}C)	0 to 30	8 to 34	11.52	0 to 1	1 to 2

*The (-) signal means a decrease.

4.7 Summary

This chapter has described the steps undertaken to analyse the acquired data. The processing steps included the creation of a Digital Elevation Model mosaic for the study area, and screening for both the projected and observed salinity and temperature data. It also presented the results of the analysis carried out to examine the observed and projected trends of sea surface temperature, sea surface salinity, as well as projected sea level rise. Beach inundation was quantified based on the simulations of sea level rise. Finally, a site capability index was calculated, taking into account sea level, salinity and temperature projections for the 21st century.

Chapter 5

5.1 Summary of the thesis

Climate change is expected to have a variety of impacts on aquaculture around the globe (World Fish, 2010). This has resulted in many countries developing programmes to deal with the anticipated changes in environmental conditions. It is widely acknowledged, however, that policy-makers in the aquaculture sector need better information with which to formulate strategies to help aquaculture producers mitigate/adapt to a changing climate.

The overall purpose of this study was to investigate how anticipated changes in climatic conditions would affect shellfish aquaculture in British Columbia. An important component of this investigation was to assess the extent to which the environmental databases that have been assembled by various agencies and institutions in BC could support this type of analysis. The focus for the study was how Manila Clams and Pacific Oysters would be affected by changes in sea surface temperature and sea surface salinity, as well as how bottom shellfish capability in the Strait of Georgia in British Columbia will be affected by changes in theses physical conditions. As the financial and human resources available for this study were limited, the investigation focused on the northern Strait of Georgia. Nevertheless, the results from this study provide additional knowledge to policy-makers for formulating mitigative strategies and adaptation measures that would assist shellfish producers to respond, cope and adapt to a changing climate.

The first objective of this study was to examine expected changes on sea surface salinity, sea surface temperature, and beach albedo associated with sea level changes in the province of British Columbia. To examine these changes, this study developed scenarios of changes and analysed the trends based on projections of sea surface temperature and sea surface salinity of open ocean adjacent waters of BC's coast obtained from models of the Canadian Centre for Climate modeling and analysis (CGCM3.1/T47) with A2 storyline and scenario family. The trends of both parameters were then compared with the trends of the same observed parameters in five selected stations (Entrance Island, Chrome Island, Sister Island, Departure Bay and Active Pass) collected from 1915 to 2011 in the Strait of Georgia to make an inference about the projections taking into account the observed values.

Divided in two sets of period 2012-2050 and 2051-2100, the annual average projections of sea surface temperature in open ocean adjacent waters suggest an increase of approximately 1^{0}C between 2012 and 2050 at a rate of 0.0222^{0}C/year and, an increase of approximately 2^{0}C between 2051 and 2100 at a rate of 0.033^{0}C/year. The increasing trends of projected temperature are consistent with the annual average trend observed in the Strait. However, observed temperature indicated an increase approximately 1^{0}C between 1915 and 2011 at a rate of 0.0085^{0}C/year.

Annual average of projected sea surface salinity of open ocean adjacent waters, suggest a decrease approximately 0.2 ppt between 2012 and 2050 at a rate of 0.0055 ppt/year. Moreover, projections between 2051 and 2100 suggest a decrease in salinity approximately 0.5 ppt at a rate of 0.0088 ppt/year. Differing from the projected trends of open ocean waters adjacent to BC's coast, the mean annual average of observed sea surface salinity of the five selected stations in the Strait of Georgia indicate that the water salinity has increased approximately 2 ppt during the period 1915-2011 at a rate of 0.0175 ppt/year. However, one of the five selected stations has observed water freshening at a rate of 0.003 ppt/year. This increasing trend of the four stations (Entrance Island, Chrome Island, Sister Island and Departure Bay) is explained by the fact that these sampling stations are located away from the influence of the Fraser River that discharges significant amount of freshwater in the Strait, as well as the mixing process and turbulence around these stations are reduced.

This study identified gaps of data availability during the period this study was carried out. Numerical models that predict sea surface temperature and sea surface salinity at local scale in the Strait of Georgia do not exit, even though there have been efforts to model the circulation in Salish Sea[3] (Sutherland, MacCready, Banas, & Richey, 2011) for 2005-2006. Also, beach albedo projections and/or observed data in the Strait of Georgia or adjacent areas do not exist in the same detail as other published data (C. Sean, personal communication, April 26th, 2012 and C. Jim, personal communication, September, 2012). As a result of lack of beach albedo data, this study was unable to developed scenarios for this parameter. Additionally, LIDAR (Light Detection and Ranging) dataset for the Strait of Georgia does not exist. Available Lidar dataset exists only for parts of the Victoria area, including the shores of Saanich Inlet and some Gulf Islands (J. Bednarski, communication, August 27th, 2012).

The second research objective was to identify areas along the Strait that have capability for shellfish aquaculture, and to quantify the changes in beach albedo, beach exposure/inundation associated with sea level change. Three sites were selected for evaluation: Buckley Bay and Fanny Bay in Baynes Sound, and Henry Bay on Texada Island. The analysis was based on the SLR projections developed Thomson et al., (2008).

[3] The Salish Sea encompasses the complex estuarine systems of Puget Sound, WA, Strait of Georgia, BC, and the Strait of Juan de Fuca, as well as the coastal waters off Vancouver Island, Washington, and Oregon (Sutherland, MacCready, Banas, & Richey, 2011).

Two simulations of sea level rise (1.2 m and 2 m) were performed in this study. The results indicate that an increase of 1.2 m in sea level will inundate 121 ha of Buckley Bay and Fanny Bay combined and an additional 37 ha of Henry Bay. A 2 m rise in sea level will inundate 195.2 ha of Buckley Bay and Fanny Bay, and 51.4 ha of Henry Bay. Due to the beach albedo data scarcity, it was not possible to quantify changes in beach albedo. Therefore, as soil moisture content, organic matter content and soluble salts, and parent material are some of the factors that significantly affect soil albedo (Dobos, 2003) and due to sea level rise the beach albedo in the newly inundated areas may decrease as the content of mud and organic matter in these areas will increase.

Given the projected results of beach inundation, this study demonstrated (with simulations of sea level rise) that changes in sea level along the BC's coast will have impacts on bottom shellfish culture. This is explained by the fact that an increase in sea level will require changes in the current location of the aquaculture tenures, in order to meet the bottom culture requirements in terms of exposure (water movement) defined by the mean low-low water. These changes in tenured site locations may raise land use conflicts with other users.

The third objective of this study was to define capability indices for shellfish (Manila Clams and Pacific Oysters bottom culture) based on the physical conditions characterizing existing commercial aquaculture operations. Four indices were defined in this study to characterize site capability to support Manila Clams and Pacific Oysters bottom culture in the Strait, based on six biophysical parameters: salinity, temperature, substrate, slope, depth and exposure. These parameters comprise three categories of factors that are recognized as important for estimating the capability of a site for shellfish production. The categories include: growth – temperature; survival – substrate, beach slope, depth and exposure (water movement); survival and growth – salinity. From the analysis performed in this study, four classes of capability indices were defined and mapped for Manila Clams bottom culture in the Strait of Georgia. They are: *Not Advisable*; *Poor*; *Medium* and *Good*. Additionally, three classes of capability indices were defined and mapped for Pacific Oysters bottom culture: *Not Advisable; Medium and; Good*. Maps were developed delineate the culture areas based on the above criteria.

Finally, the last objective of this study was to assess how bottom shellfish aquaculture sites' capabilities in the Strait of Georgia will be affected by changes of sea surface temperature, salinity, beach albedo and beach exposure/inundation associated with sea level rise. Scenarios of expected or projected changes in the above mentioned parameters developed earlier in this thesis, were compared with the critical and preferential parameters levels of tolerance of the species, so as to evaluate whether the selected species can withstand the projected changes. Based on the sea level scenarios developed, and the ranges that the species can withstand compared to the changes of the selected parameters with the exception of beach albedo, this study demonstrates that site capabilities to support Manila Clams and Pacific Oysters culture will not be adversely affected by the expected changes.

5.2 Conclusion

This study concluded that the existing environmental databases that have been assembled by various agencies and institutions in BC are accessible and could support this type of analysis; however there is a need to provide additional datasets such as numerical models that project changes in sea surface salinity and sea surface temperature at local scale taking into account climate change driving forces, beach albedo and LIDAR dataset for the Strait of Georgia. These needed additional datasets will help to improve in future similar studies the results obtain in this research. This study also concluded that changes in sea surface temperature and sea surface salinity associated with sea level rise will not adversely affect Manila Clams and Pacific Oysters bottom culture in the Strait. Also site capabilities to support bottom culture of these shellfish will not be impacted by expected changes in the selected physical parameters (sea surface salinity and sea surface temperature). This study concluded that sea level rise will have negative impact on shellfish bottom culture, as most of the operations in the Strait of Georgia occur on the intertidal substrate (BC-Shellfish Grower's Association, 2012), where SLR will directly affect access to these lands through changes in the high and low tidal ranges. Since beaches adjust to sea level rise, coastal property lands and intertidal aquaculture tenures will need to be redefined through the existing property laws, as SLR will change beach profiles landward and reduce access to the aquaculture sites due to increased water coverage. The optimal growing areas may also be shifted off of the grower’s tenures.

The average high tide is presently treated as a stable boundary limit that separates upland property from inter-tidal growing areas used for shellfish aquaculture (Fisheries and Oceans Canada, 2012). Expected sea level rise may create uncertainty in the definition of the coastal properties limits due to a change in where the current high tide occurs. Given these uncertainties, a suggestion from this study would be to maintain the definition of inter-tidal and shoreline property limits, however, recognizing that these boundaries are moving landward as sea level rises and the inter-tidal properties or tenures may move upland if justified.

5.3 Recommendations

Existing datasets provided by various agencies and institutions are accessible, and it is possible to perform evaluation and/or analysis of the impacts of climate change on coastal aquaculture in BC. However, it should be noted that there is need to improve some of the existing environmental datasets as well as provide additional datasets. A recommended improvement should be on the benthic marine and pelagic marine ecounits dataset that are provided by BCGOV FLNRO GeoBC. These datasets are available in shapefile (ArcView) format. The nature of benthic and pelagic shapefile distribution provided is discrete data. Given that these environmental (temperature, salinity, slope, substrate, depth and exposure) datasets do not have defined boundaries, this study suggests and/or recommends that these datasets should be provided as continuous data. Besides improving the existing datasets, this study recommends that should be provided numerical models that predict sea surface temperature and salinity changes at local scale in the Strait of Georgia and elevation datasets with higher accuracy in order to meet the objectives proposed in this study and the data requirements of future similar studies. Therefore it is recommended that elevation data be acquired with higher vertical resolution than the DEM (Digital Elevation Model) used in this study. The DEM data used in this study have a vertical resolution of 1 m. To determine an accurate representation of sea level rise, the use of LIDAR is suggested. Lidar datasets have vertical accuracy ranging from 10 cm to 30 cm.

As this study was unable to locate appropriate beach albedo information (observed and projected data) for BC's coast including the Strait of Georgia, this study recommends additional research be undertaken to provide beach albedo data and to assess the impacts of changes in the albedo of shellfish bottom culture, given the climate change projections. This would determine if the beach sediments will support larval settling and early growth, as well as, would investigate whether changes in beach area may result in cooler or warmer micro-environments which could reduce or increase habitable areas.

In addition, since projections of temperature and salinity due to future climatic changes are not expected to negatively impacts the bottom culture of Manila Clam and Pacific Oyster, and given that several studies (Harley, et al., 2006; Barton et al., 2012; BC-Shellfish Grower's Association, 2012) suggest that increasing CO_2 concentrations are causing changes in seawater pH, this study recommends that the impacts of water pH on shellfish aquaculture in BC should be investigated.

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Appendix I

Dataset and climatic model description of the projected sea surface temperature and sea surface salinity of open ocean waters adjacent to British Columbia's coast. The data and information were obtained from the Canadian Centre for Climate modeling and analysis.

Model		**CGCM3.1/T47**		
Run		1		
Variables		tos, sea surface temperature (K)		
		so, sea surface salinity (ppt)		
Level		1 (0-25 m)		
Years		2012 - 2100		
Coordinates	Lower left corner	I_1=120	J_1=69	(135.94W, 38.05N)
	Lower right corner	I_2=126	J_1=69	(124.69W, 38.05N)
	Upper left corner	I_1=120	J_2=78	(135.94W, 54.75N)
	Upper right corner	I_2=126	J_2=78	(124.69W, 54.75N)
Area dimensions		7 grid cells (longitude) x 10 grid cells (latitude)		

VITA

Surname: José **Given Names:** Edson Anselmo

Place of Birth: Quelimane, Zambézia – Mozambique

Educational Institutions Attended:

Escola Primária de Samúgue, Quelimane, Mozambique	1985 - 1991
Escola Secundária e Pré-Univ. 25 de Setembro, Quelimane, Mozambique	1992 - 1997
Universidade Eduardo Mondlane, Maputo, Mozambique	1999 - 2004
University of Victoria, British Columbia, Canada	2011 - 2012

Publications:

José, E. A., & Banze, I. S. (2011). *Relatório de Actualização do Inventário de Zonas Potenciais para o Desenvolvimento de Aquacultura Marinha.* 215pp. Ministério das Pescas. Maputo - Moçambique: Instituto Nacional de Desenvolmvimento de Aquacultura;

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Victoria, BC – Canada
November 26th, 2012