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Oceanographic conditions of salmon farming areas with attention to those factors that may influence the biology and ecology of sea lice, *Lepeophtherius salmonis* and *Caligus* spp., and their control

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Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

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TABLE OF CONTENTS

ABSTRACT

This research document summarizes the oceanographic factors in Canada that influence sea lice distribution and their control. Particular attention is paid to the differences between the east and west coasts. Information related to the specific conditions, such as temperature, salinity and current trends, is provided.

On the Pacific Coast, aquaculture activities occur in several regions, including the inlets along the west coast of Vancouver Island, the Discovery Islands and the Broughton Archipelago. These areas experience sea surface temperatures that vary seasonally and by region, from just above freezing to 18°C, creating an environment that is suitable for all sea lice life stages. Salinity in this region varies seasonally and by location, due to influx of freshwater from direct precipitation and snowmelt. The vertical and horizontal movement of water is driven by the energy from tides, waves and winds, as well as density differences.

On the East Coast, the two main areas of aquaculture are on the south coast of Newfoundland and the Maritimes Region, primarily the Bay of Fundy. On the south coast of Newfoundland, the majority of aquaculture activities occur in Bay d'Espoir, Fortune Bay and Hermitage Bay. These areas have quite different oceanographic characteristics in terms of temperature, salinity and currents, which results in a varied environment for sea lice.

In the Bay of Fundy, oceanographic conditions vary within the bay, with temperatures ranging from -2.4 to 24.3°C, salinity is generally around 30 psu and current speeds range from almost zero to over 100 cm s^{-1}. The duration of sea lice, nauplii and copepodid dispersal stages in this region range from about 1 to 10 days. Transport distances of pre-infective sea lice stages are on the order of 10-100 kilometers. This suggests that farms within bays or nearby bays may exchange sea lice, whereas farms in bays separated by distances greater than 100 km may have only limited sea lice exchange.

Additional oceanographic data are required to fully comprehend the potential influence of these factors on sea lice biology and ecology, as well as to further develop, test and validate physical/biological models for sea lice dynamics. Specifically, more information is needed on the influence of water velocities and sea lice behaviour on sea lice transport and dispersal. Consideration should also be given to the influence of other environmental factors, such as dissolved oxygen and pH, on sea lice biology.

This Research Document was presented and reviewed as part of the Canadian Science Advisory Secretariat (CSAS) National peer-review meeting, Sea Lice Monitoring and Non-Chemical Measures, held in Ottawa, Ontario, September 25-27, 2012. The objective of this peer-review meeting was to assess the state of knowledge and provide scientific advice on sea lice management measures, monitoring and interactions between cultured and wild fish.

Conditions océanographiques des zones de salmoniculture, en particulier les facteurs susceptibles d'avoir une incidence sur la biologie et l'écologie du pou du poisson (*Lepeophtherius salmonis* et *Caligus* sp.) et la lutte contre celui-ci.

RÉSUMÉ

Le présent document de recherche résume les facteurs océanographiques qui ont une incidence sur la répartition du pou du poisson et la lutte contre celui-ci au Canada. Une attention particulière est accordée aux différences entre les côtes Est et Ouest. Des renseignements sur les conditions particulières sont présentés, tels que sur la température, la salinité et les tendances de courant.

Sur la côte du Pacifique, les activités aquacoles se déroulent dans plusieurs régions, notamment dans les bras de mer le long de la côte ouest de l'île de Vancouver ainsi que dans la région des îles Discovery et de l'archipel Broughton. Dans ces zones, la température de la surface de la mer fluctue selon la saison ainsi que la région, et on observe des températures juste au-dessus du point de congélation et allant jusqu'à 18 °C. Ces températures créent un milieu propice à tous les stades biologiques du pou du poisson. Dans cette région, la salinité varie selon la saison et l'emplacement en raison de l'afflux d'eau douce provenant des précipitations et de la fonte des neiges. Le mouvement vertical et horizontal de l'eau est régi par l'énergie des marées, des vagues et des vents ainsi que les différences de densité.

Sur la côte Est, les deux principales zones d'aquaculture se trouvent sur la côte sud de Terre-Neuve et dans la Région des Maritimes, principalement dans la baie de Fundy. Sur la côte sud de Terre-Neuve, la majorité des activités aquacoles se déroulent dans la baie d'Espoir, la baie Fortune et la baie Hermitage. Ces zones présentent des caractéristiques océanographiques plutôt différentes en ce qui concerne la température, la salinité et les courants, ce qui signifie que le pou du poisson dispose d'un environnement diversifié.

Dans la baie de Fundy, les conditions océanographiques varient dans l'ensemble de la baie : les températures varient de -2,4 à 24,3 °C, la salinité se situe autour de 30 USP, et la vitesse des courants vari de presque zéro à plus de 100 cm s^{-1}. La durée des stades de dispersion du pou du poisson, les nauplii et les copépodes, varie de 1 à 10 jours dans cette région. Les distances de transport du pou du poisson avant ses stades infectieux sont de l'ordre de 10 à 100 km. Il pourrait donc y avoir des échanges de poux du poisson entre les exploitations aquacoles situées dans une même baie et dans des baies situées à proximité. Cependant, les échanges sont limités lorsque les exploitations sont situées dans des baies éloignées de plus de 100 km.

Des données océanographiques supplémentaires sont nécessaires afin de comprendre pleinement l'incidence potentielle de ces facteurs sur la biologie et l'écologie du pou du poisson ainsi que pour développer, tester et valider les modèles physiques/biologiques de la dynamique de ce parasite. Plus précisément, des renseignements supplémentaires sont nécessaires au sujet de l'influence de la vitesse des courants et du comportement du pou du poisson sur le transport et la dispersion de ce dernier. Il est également nécessaire de tenir compte de l'incidence d'autres facteurs environnementaux, comme l'oxygène dissous et le pH, sur la biologie du pou du poisson.

Le présent document de recherche a été présenté et révisé lors d'une réunion nationale d'examen par les pairs (Surveillance du pou du poisson et mesures non chimiques) du Secrétariat canadien de consultation scientifique (SCCS) tenue à Ottawa, Ontario, du 25 au 27 septembre 2012. L'objectif de cette réunion d'examen par les pairs était d'évaluer l'état des connaissances et de fournir un avis scientifique sur les mesures de gestion du pou du poisson, la surveillance et les interactions entre le poisson d'élevage et le poisson sauvage.

INTRODUCTION

Sea lice species, *Lepeophtherius salmonis* and *Caligus* spp., are parasitic copepods of the family Caligidae that are responsible for many outbreaks of disease in marine aquaculture, more specifically salmonid aquaculture (Boxaspen 2006). The economic impact of these outbreaks in marine salmonid aquaculture within the principal farming countries (Norway, Chile, Scotland, Ireland and Canada) exceeds $100 million US every year (Johnson et al. 2004).

Sea lice are known to have a circumpolar distribution in the Northern Hemisphere; however *C. elongatus* has been also been found in the Southern Hemisphere (Tully and Nolan 2002). The sea life cycle consists of five distinct phases and ten stages (Schram 1993). There are two naupilii stages followed by the copepodid stage, which is the time at which the parasite needs to find a host. Once a host is found the sea lice move into the immobile chalimus phase, of which there are four stages (Chalimus I-IV). The final stages are the mobile pre-adult and the reproductive adult stages.

There are many factors that affect the development, dispersal and survival of sea lice in the marine environment. Water temperature plays a significant role in the reproductive capabilities and generation time from egg to mature adult, with the copepodid lifespan being prolonged at lower temperatures (Boxaspen and Naess 2000). Optimum temperatures, both high and low for *L. salmonis* are not fully understood, but it has been shown that in order to complete their life cycle water temperatures must be at least 4^oC (Boxaspen and Naess 2000). Personal observations from researchers in Norway indicate that the parasite has not been present on salmon farms when water temperatures reach 18^oC.

Salinity has been shown to severely impact planktonic stages and free swimming copepodids below 29 psu, but research is limited in most regions of Canada. Since the hosts of sea lice are anadromous fish, they can be subject to salinities that range between 0 and 35 psu (Connors et al. 2008).

Currents and tidal movements play an enormous role in determining dispersal and infestation rates of sea lice, specifically the planktonic and free-swimming stages. Sea lice are thought to behave much like static particles and essentially drift in the direction of the currents. When looking at infestation rates, researchers have identified proximity to salmon farms as one of the most important factors. Costelloe et al. (1999) determined that the concentration of copepodids decreased by two orders of magnitude within 100 m of the salmon farm cages.

The following section summarizes the oceanographic factors that influence sea lice, mainly *Lepeophtherius salmonis,* and their control paying particular attention to the differences between the east and west coasts. General considerations will be discussed as well as further details on specific conditions (temperature, salinity, currents, etc.).

GENERAL CONSIDERATIONS

PACIFIC REGION

At present there are 123 valid finfish aquaculture licence holders in British Columbia (BC). These tenures are located in several regions along the BC Coast which, in terms of physical oceanography, can be categorized as the Central Coast, the west coast of Vancouver Island, the Broughton Archipelago, Discovery Islands, and Jervis/Sechelt Inlets (Figure 1). While the physical oceanography of the latter three regions is similar, the relationship with sea lice control is sufficiently different to warrant them being examined separately.

As the physical oceanographic conditions that influence sea lice vary in space and time, so too do the management strategies required for their control. Knowledge of the physical oceanography promotes better management decisions in regards to siting of the farms, the stocking capacity of the pens, and the application of sea lice control treatments.

Common to all fish farm sites is the significance of water movement that can transport sea lice, at varying rates, towards and away from the fish farms. Winds play a significant role in defining the current regime on both the east and west coasts of Canada; with an influence that depends on location and time of year. Tide forced ocean currents are also common on both coasts, with less seasonal variation than winds. Fresh water input, particularly at point sources such as rivers, can vary in time due to precipitation and snowmelt, and set up density gradients causing water to flow in one direction at the surface, and another direction below the surface.

Water temperature and salinity are also relevant to the control of sea lice as these conditions determine the growth and development of the sea lice through its life cycle. Typically ocean temperatures on the East Coast vary annually from below 0 to the upper teens (degrees Celsius) whereas west coast temperatures are more often in the 5 to 15^{o}C range. Water salinity is determined primarily by the inputs of fresh water which vary in location depending on river discharge, which will vary by season due to snowmelt. The lower density, lower salinity water will cause surface conditions to vary from those deeper in the water column, which will influence the presence and viability of sea lice and thus management decisions.

The large scale physical setting of the BC Coast is defined by tectonic forces that have formed, and continue to shape the west coast of Canada. As an active seismic zone, all coastal activities are exposed to earthquakes and tsunamis on a range of strength scales. The coastal mountain ranges have experienced repeated advance and retreat of glaciers carving deep fjords, some with shallow sills, which control the sedimentary input to the continental shelf, and the freshwater input from precipitation and snowmelt to the marine environment. The physical and biological processes in each fjord are a complex interaction of the fresh water input, marine forcing, topography and bathymetry giving each a unique signature. The estuary and associated mud flats at the head of the fjords are often highly productive habitats with high salmon, and other wildlife values.

Throughout the study area the seasonal temperature cycle is similar with colder winters and warmer summers separated by spring and fall transition periods. Situated between the Coast Mountains and the northeast Pacific Ocean, the large scale meteorology of the area is dominated by the Aleutian Low Pressure system in winter and the North Pacific High in summer. These winds are modified at smaller scales by the passage of storm fronts, coastal lows, and outflow conditions. The steep sided topography characteristic of fjords, determines the strength and direction of local winds by steering them along the channel. Over the Pacific, winter storms absorb moisture as they track from west to east, and much of this falls as precipitation along the coast of BC making it the wettest region in Canada.

El Niño and La Niña event years occur on irregular basis – approximately every two to seven years – and in these years the climatological wind patterns are modulated. In El Niño years northeast Pacific storm tracks are shifted further south than normal and storms tend to be stronger. The ridge of high pressure that forms over northwestern Canada in winter is generally stronger than normal with resulting large-scale winds having a more southerly component and warmer temperatures. During La Niña years storm tracks are shifted further north and closer to the coast than normal. Storms tend to be weaker than normal in La Niña years and the wintertime ridge over northwestern Canada is flatter than normal, resulting in more westerly and colder than normal flow into western Canada.

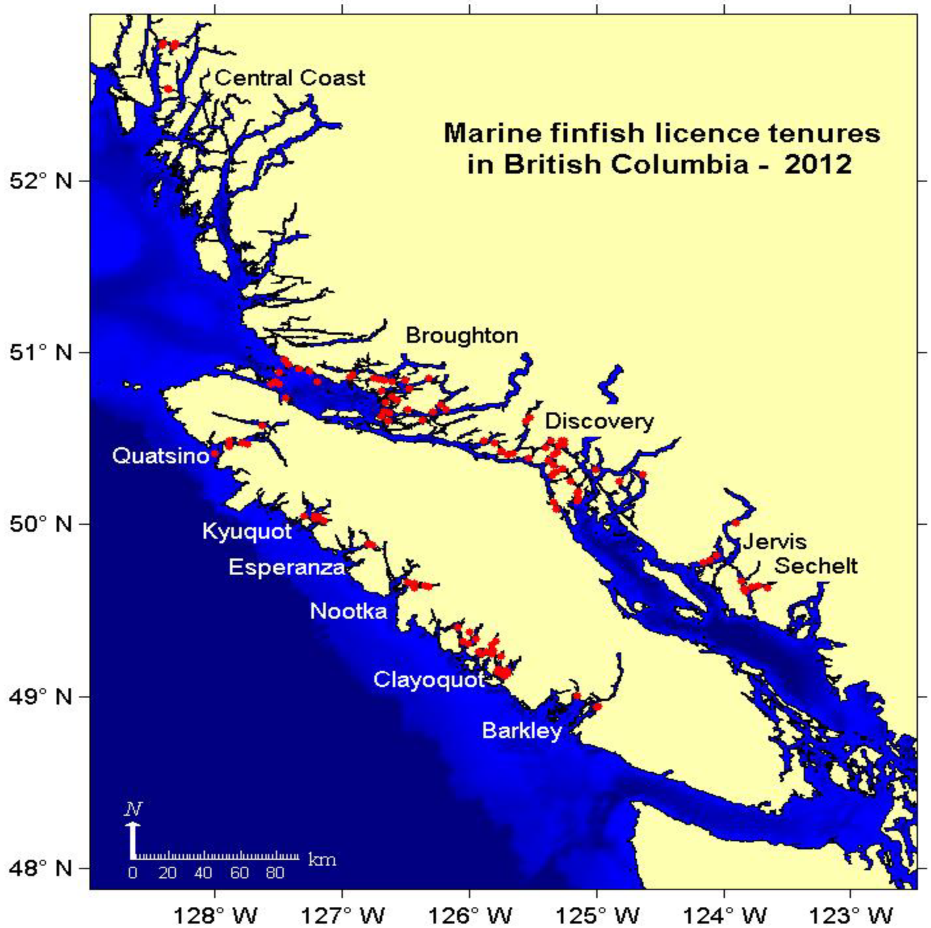

Figure 1. The location of finfish tenures in British Columbia.

The regional differences in the physical and biological processes that are relevant to sea lice control are discussed first in general terms, and later with more region-specific information.

General Considerations for the West Coast of Vancouver Island

Finfish aquaculture sites on the west coast of Vancouver Island are typically situated at the head of glacially formed inlets, in the shelter of smaller islands that protect them from the high energy wave climate of the exposed coast. Water circulation in these inlets is influenced by the tide from the Pacific Ocean which propagates northward as a wave giving an average range in water level of about 3 m from Barkley to Quatsino Sound. Tidal forcing of currents, however, is often exceeded by wind driven and estuarine forcing.

Estuarine circulation is the most important long-term residual circulation in many of the west coast inlets, even in the summer when freshwater input is low. Estuarine circulation begins as fresh water is delivered to the estuary by rivers and streams which, because freshwater is lighter than seawater, creates a horizontal density gradient that drives the surface layer seaward. As the low salinity surface water flows seaward, mixing occurs deeper in the water column at the interface (about 5-10 m depth) between this surface layer and bottom water. Some of the bottom water is entrained into the surface outflow causing the volume of water leaving the estuary to exceed the volume of freshwater entering the estuary. Mass balance is maintained by a subsurface inflow of seawater into the estuary. Entrainment is important to phytoplankton growth within an estuary, because it ensures a residual supply of nutrients from subsurface seawater into surface waters.

Storms are frequent and intense, especially in winter. Storms from the southeast are most severe along the west coast of Vancouver Island, and several per year with wind speeds exceeding 100 knots can be expected. Storms from the west and northwest, although less frequent, can also be intense. In general, winter storms with winds exceeding 50 knots will occur every 2-3 weeks, but can also occur one after another over a ~10 day period.

The summer wind pattern associated with the North Pacific High pushes the surface water along the west coast of Vancouver Island to the southeast. This surface layer gets deflected away from the coast because of the earth's rotation, and its place is taken by upwelled deeper water. This upwelling process influences the coastal inlets by providing a source of cool, nutrient-rich water.

The presence of islands in the inlets contributes to the complexity of the circulation pattern as water flow is constricted between islands. For those inlets with sills at the entrance, the exchange with deeper ocean water is restricted resulting in poorly ventilated low-oxygen deep water in the fjord, and long residence times for water trapped behind the sill.

The application of computationally intensive hydrodynamic models to simulate the water temperature, salinity and current fields of west coast inlets such as Kyuquot are being developed. Using site observations of tides, fresh water input and winds, a three-dimensional representation at spatial scales of tens of metres can be produced to simulate the distribution of sea lice due to water circulation, and to simulate the growth of sea lice as it is influenced by temperature and salinity.

The annual sea surface temperature and salinity cycle for the west coast of Vancouver Island is shown in Figure 2. The data have been collected at lighthouse stations in Barkley and Quatsino Sound. Monthly averaged sea surface temperatures range from about 8-13^{o}C, and salinities between 28 and 32 psu. The increased winter precipitation results in a season of low salinity (less than 29 psu) between November and February.

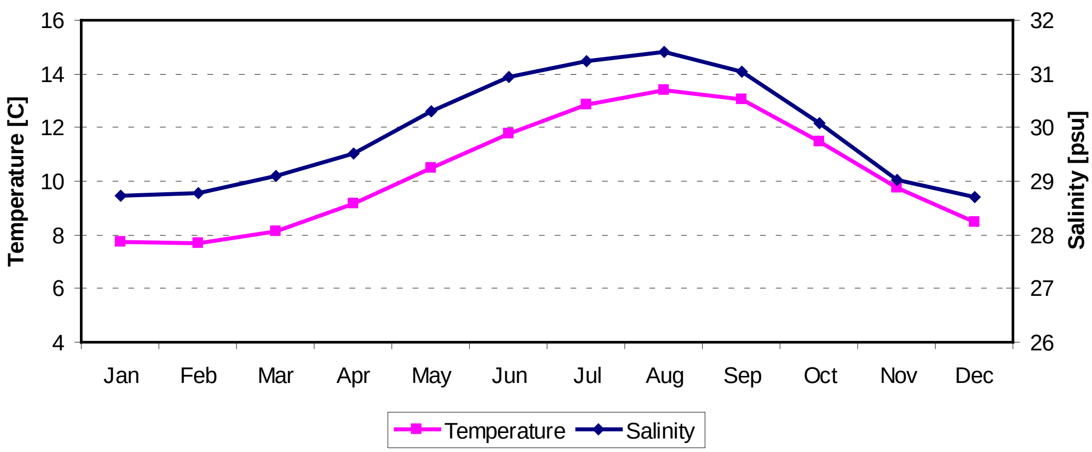

Figure 2. The annual surface temperature and salinity cycle for the west coast of Vancouver Island. Source: Lighthouse data from Amphitrite Point and Kains Island, 1935-2012.

This small seasonal temperature range is due to the influence of the Pacific Ocean, maintaining relatively cool conditions along the coast in summer, and warm conditions in winter.

Temperatures below 30 m to 50 m range around 8°C to 10°C and gradually decrease with depth.

Studies carried out in Clayoquot Sound suggest that salinity is a significant physical factor in determining the distribution of sea lice. Both prevalence and abundance of sea lice infestation on chum salmon showed a stepwise increase with increasing salinity (Beach 2009).

General Considerations for the Central Coast

The Central Coast region can be categorized as open coast, archipelago, fjord, strait and channel. The meteorology and oceanography of this region reflect the large scale influences of the Pacific High and Aleutian Low pressure systems and the northward propagating tidal wave. The prevailing winds are modulated by coastal topography and interrupted by eastward bound high and low pressure systems which can produce intense storms, particularly in the winter when the jet stream deflects to the south providing for the outflow of arctic air.

There are six active fish farm tenures in this region, all are located in the Finlayson Channel area. This area of open ended passages is dominated more by currents rather than waves, where the maximum fetch direction is parallel to shore. High mixing in channels tends to make the water more marine than estuarine. Storm driven currents, modified by bathymetry, produce complex circulation patterns that present major challenges to understanding the fate and dispersal of sea lice larvae. However, the observations of sea lice are relatively few compared with other regions in British Columbia.

The annual temperature cycle determined from the average monthly data collected at seaward end of Finlayson Channel given in Figure 3, shows a range typical of the West Coast. The salinity remains relatively constant throughout the year, with only a few months during the rainy season where salinities are less than 30 psu.

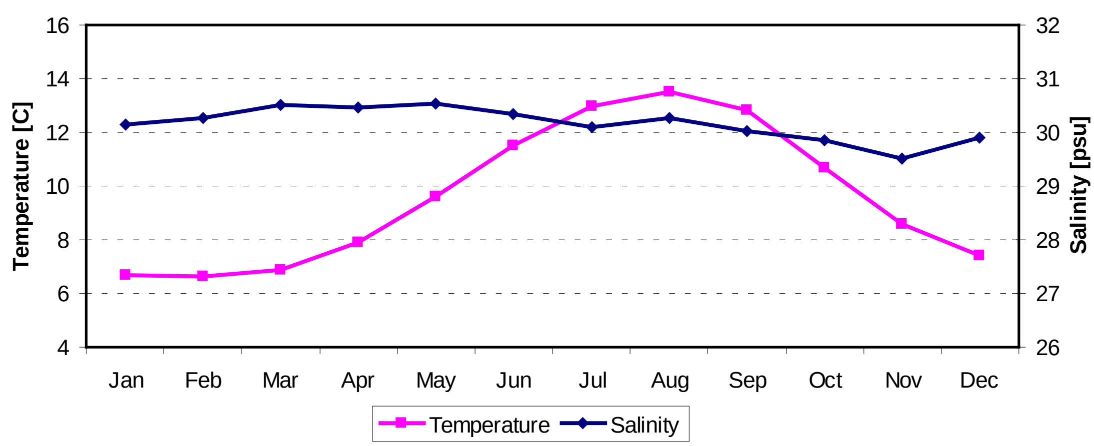

Figure 3. The annual surface temperature and salinity cycle for the Central Coast. Source: Lighthouse data from McInnes Island, 1954-2011.

General Considerations for the Broughton / Discovery / Sechelt Region

This region is the most intensively salmon-farmed region in British Columbia with sub-areas of active tenures in the Broughton Archipelago, the Discovery Islands, and in Jervis and Sechelt Inlets. In general, the physical oceanography and meteorology is similar throughout the region but the impact on the control of sea lice in each sub-area is subject to factors that will be discussed under specific considerations.

Tides in this region are mixed, predominantly semi-diurnal and co-oscillate with the tides in the adjacent North Pacific Ocean. As the ocean tidal wave travels northwards off Vancouver Island it forces tidal currents to flood into the Juan de Fuca Strait and north through the Strait of Georgia. This water movement is met by tidal currents flooding south from Queen Charlotte Strait as the tidal wave continues to propagate northward along the outer coasts of BC. The strength of the tidal current varies over 15 days with ebb currents tending to be stronger than floods. Tidal currents in Queen Charlotte Strait and the Strait of Georgia are generally weaker than in Johnstone Strait and Discovery Passage due to less constricted passages, but the surface currents (about 10 m s^{-1}) are still strong enough to make a short, steep chop, even in moderate winds. Wave activity in Queen Charlotte Strait can be higher than the inlets due to its greater width and the remnants of low, eastward propagating oceanic waves. Wave heights in the inlets are greatly limited by the reduced fetch, and narrow, winding channels.

The strength of the tidal forcing in the constricted passages and channels of this region is sufficient to mix the entire water column such that there is no change in temperature or salinity from the surface to the bottom. While Skookumchuk Rapids on Sechelt Inlet may be famous as the fastest flowing salt water rapids in North America, there are many other waterways in this region that are similarly tidal driven with intense ebb and flood currents separated by brief periods of slack water.

Despite the strong tidal currents, and the mixing that they cause, there is sufficient fresh water input to the region from the watersheds draining the Coast Mountains that an estuarine circulation dominates at many locations. The Klinakini River connects an interior watershed of thousands of square kilometres containing several permanent ice fields and contributes an annual mean freshwater flow of over 400 m^3 s^{-1} to the Broughton sub-area. The discharge from these rivers generally peaks in July from snow and ice melt, and causes the surface low-salinity layer to become deeper during the spring and summer months.

Observations of temperature and salinity in this region can provide some insight into the variability in the water properties of the area but the few observations that exist are better served as input to computer models that can numerically simulate the complexity of the hydrodynamic regime in this region.

Figure 4 shows the grid of thousands of elements used to model the hydrodynamics of the Broughton Archipelago and the Discovery Islands using the Finite Volume Coast Ocean Model (FVCOM). In addition to defining the bathymetry at this resolution, observation of winds, tides and fresh water input are required to force the model and to validate the model output.

The temperature, salinity and current fields can then be used to examine the growth and dispersion of sea lice under a range of scenarios varying the initial distribution and abundance of sea lice. Further use of the models can be found by incorporating behaviour of wild fish to evaluate various methods of sea lice control in sympatric populations of wild and farmed fish.

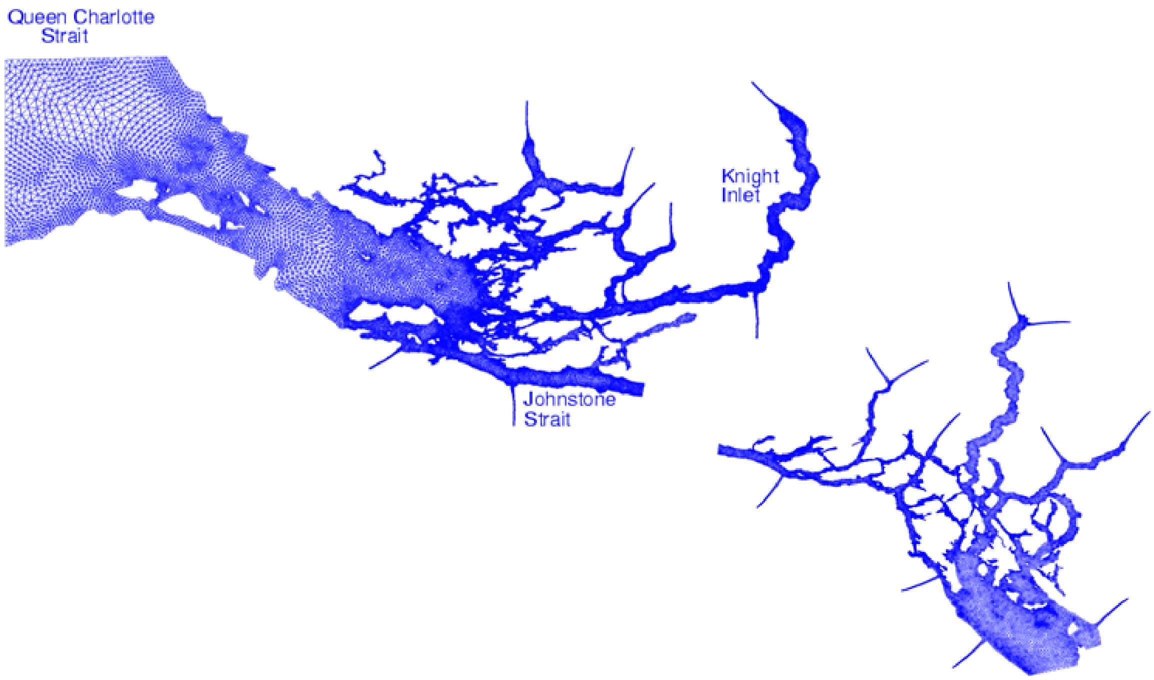

Figure 4. The grid for the Finite Volume Coast Ocean Model (FVCOM) hydrodynamic model of the Broughton Archipelago and the Discovery Island sub-areas.

The annual cycles of sea surface temperature and salinity for the waters from the Strait of Georgia to Queen Charlotte Strait are given in Figure 5. These monthly data do not reflect the range of values that can be experienced in the region on a daily basis, which will directly impact the behaviour and fate of sea lice. Surface salinity can range from less than 5 psu up to 35 psu, and surface temperatures from just above freezing to over 18^{o}C. The clear distinction between this region and the others on the BC coast is the volume of freshwater input during the spring and summer which lowers the salinity to levels significant to the control of sea lice during the out migration of juvenile salmon.

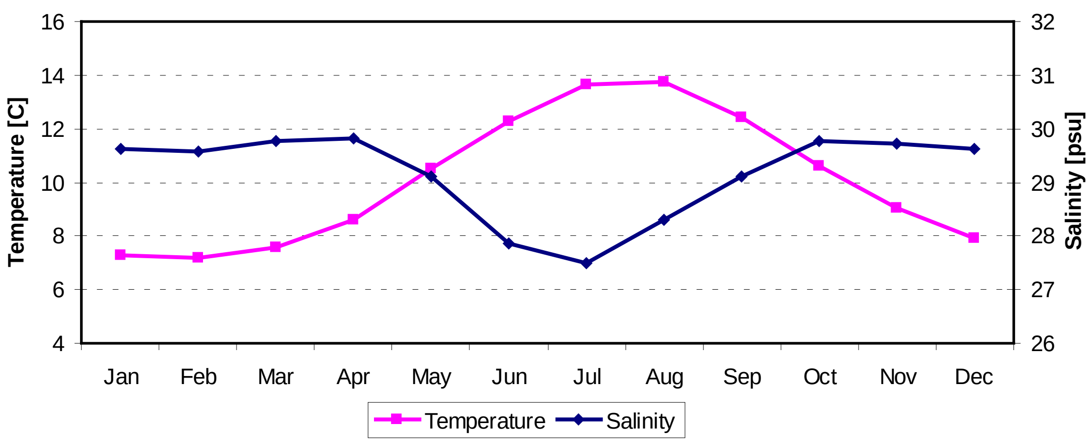

Figure 5. The annual surface temperature and salinity cycle for the Broughton Archipelago, Discovery Islands and Jervis/Sechelt Inlet region. Source: Lighthouse data from Pine Island and Entrance Island, 1937-2012.

Climate Change

Considerable research is underway to better understand the trends and cycles of the climate, and how that affects the physical and biological processes of British Columbia coastal waters. Some of the changes that are expected in the next 10-30 year time period include:

1- Increasing frequency and severity of storm events, including precipitation.

2- Changes in the timing and volume of river runoff.

3- Shrinking of mountain glaciers and snow pack.

4- Rising sea level.

5- Changes in water temperature and salinity which may affect density dependent circulation.

6- Acidification of coastal waters.

EAST COAST- SOUTH COAST OF NEWFOUNDLAND AND LABRADOR

The aquaculture industry in Newfoundland and Labrador has been increasingly growing, particularly salmon farming on the South Coast. Total aquaculture export values were in excess of $120.1 million with an expected increase in value for 2012 (Newfoundland and Labrador Department of Fisheries and Aquaculture 2012). The number of sites has increased and the location of these sites has expanded from Bay D'Espoir to Fortune Bay and Hermitage Bay. As of November 2011, there were 81 salmonid licences, of which 44 were active. The main regions (Figure 6) can be separated in three main bays: Bay d'Espoir, Hermitage Bay, and Fortune Bay. Both Bay d'Espoir and Fortune Bay are fjord-like bays with the former being more elongated and the latter much wider. Hermitage Bay is also wide and connects Bay d'Espoir with the open ocean. Due to their location and the general factors that drive the oceanography, the three bays have quite different characteristics as far as temperature, salinity, and ocean currents are concerned. The principal differences lie on factors such as amount of freshwater runoff discharged into the bay, the size, and the topographic shape of the bay. The freshwater runoff presents a seasonal variability with mixing occurring at the top layer. The topography and bathymetry of the area are complex and steep with high mountains, deep basins, and numerous sills, some of them relatively shallow. The topography has an important effect on the circulation of the atmospheric wind field, which drives the surface water circulation, while the bathymetry and shape of the bay have the potential of restricting or enhancing the water circulation. All these will affect the mixing of water masses within the bay.

Following the atmospheric conditions, seasonal temperature cycle is observed with colder surface water found during Northern Hemisphere winter season and warmer surface water during summer season. The large scale predominant wind pattern for the region is a south westerly wind during summer season. The south coast of Newfoundland typically experiences many storms, particularly from the southwest. These storms can bring strong surface winds, consequently driving intense water surface currents. The wind undergoes local steering effect due to the presence of high mountains in the area.

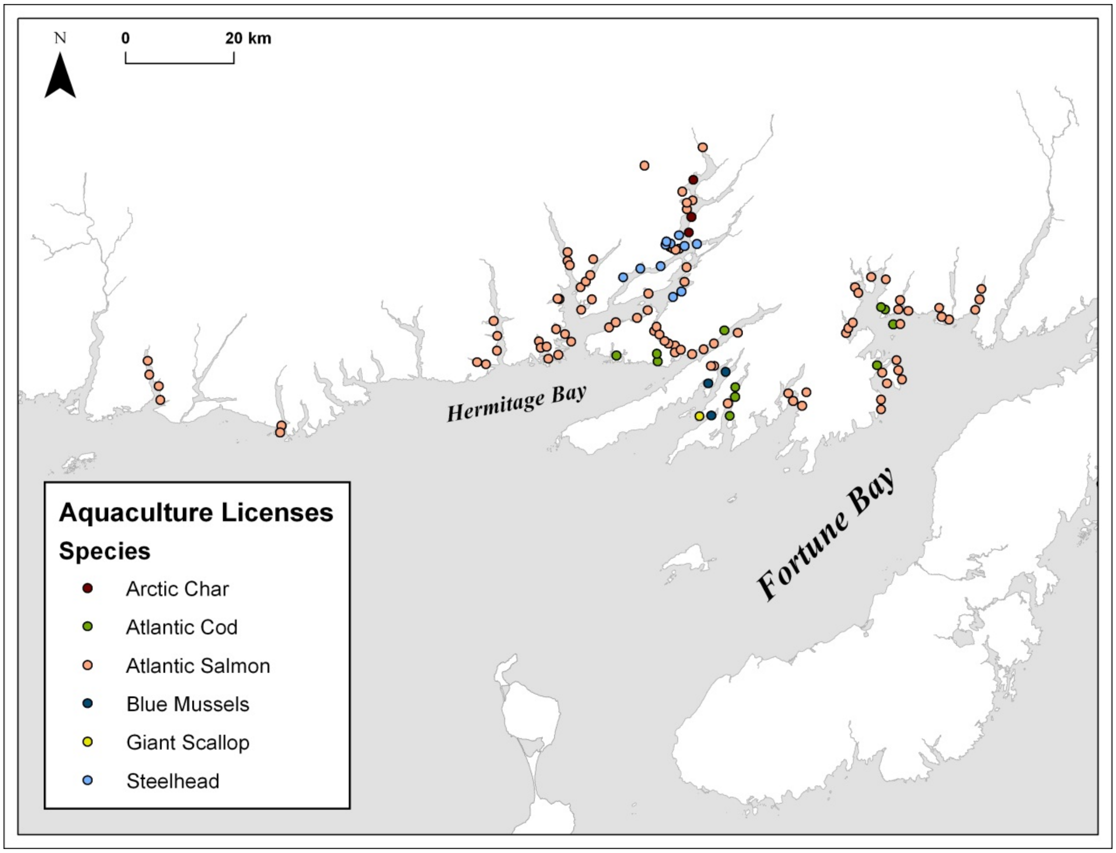

Figure 6. Map of the south coast of Newfoundland with the locations of the aquaculture licence sites.

EAST COAST- MARITIMES REGION

Within the DFO Maritimes Region, salmon netpen aquaculture takes place in the coastal zone of southwest New Brunswick (swNB) in the Bay of Fundy and at various locations along the coast of Nova Scotia (NS) (Figure 7).

The salmon farms in swNB are located within sheltered areas and in areas exposed to offshore winds and waves. The significant wave height in the exposed areas is typically about 3 m, although the 100 year wave can exceed 10 m in height (Trites and Garrett 1973). The first commercial harvest of netpen reared salmon within the Region was in the swNB area in 1979 (Chang 1998). The commercial industry expanded rapidly during the late 1980s and throughout the 1990s, but since 2001 few new sites have been added (Chang et al. 2011). At the time of this writing there are 90+ sites, with about 50 sites active at any one time. In 2010 these sites produced 25,625 t of Atlantic Salmon having a value of approximately $162 million (Statistics Canada 2011). Further information on the history of the swNB industry can be found in Chang (1998) and Chang et al. (2014).

The salmon net pen industry in Nova Scotia began in 1984 (Chang 1998). There are now 35 marine salmon / trout sites with more than ten being active in 2012. Marine salmon / trout production in 2010 was estimated at 4,960 t, with a value of approximately $29 million (Statistics Canada 2011). The sites are often located in areas exposed to offshore winds and swell. In some areas the significant wave height can at times exceed 10 m. The industry is hoping to continue expansion in Nova Scotia, adding sites in the Eastern Shore, Shelburne, St. Mary's Bay and Digby areas. There is also some interest in experimenting with aquaculture in the offshore but there are no true offshore sites at the time of this writing.

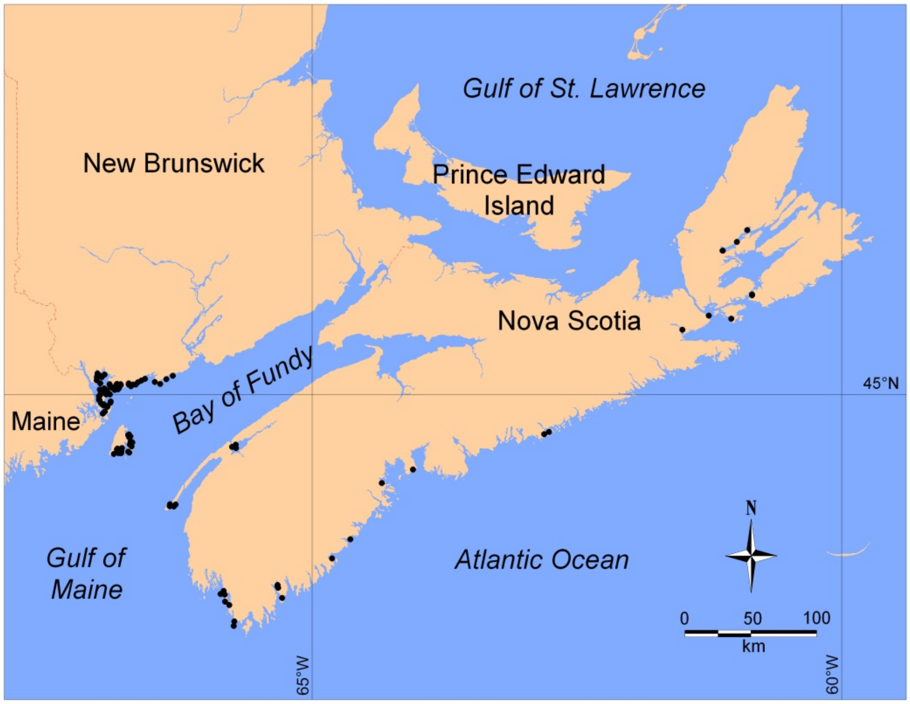

Figure. 7. Map showing the location of approved salmonid fish farms in the Maritimes Region, as of 2012. Information sources: New Brunswick Department of Agriculture, Aquaculture and Fisheries; Nova Scotia Department of Fisheries and Aquaculture.

SPECIFIC CONSIDERATIONS

PACIFIC COAST- BROUGHTON ARCHIPELAGO REGION

The Broughton Archipelago is a network of fjords and islands located along the mainland coast and adjacent to the northeastern side of Vancouver Island. The Broughton Archipelago supports significant stocks of wild salmon that migrate in cycles from their spawning grounds in the Broughton Archipelago to the Pacific Ocean and then return to their original spawning grounds.

The Broughton Archipelago is also a significant salmon farming area with 26 licences held by different companies operating in the area. The interaction between the sympatric populations of wild and farmed fish and sea lice is primarily influenced by three elements of the physical oceanography; the currents, the salinity, and the seawater temperature.

Since 2003 a monitoring program in the Broughton Archipelago has been carried out to assess the abundance and distribution of sea lice during the juvenile salmon out-migration period in the spring and early summer. As part of this program, temperature and salinity is recorded in addition to the observations of the fish and sea lice. In 2010 the Broughton Archipelago Monitoring Plan (BAMP) was established as a multiyear sea lice monitoring and research program involving Fisheries and Oceans Canada (DFO), the three salmon farming producers in the archipelago (Marine Harvest Canada, Mainstream Canada and Grieg Seafood), member groups of the Coastal Alliance for Aquaculture Reform (CAAR), and researchers from universities. Monitoring data from the Broughton Archipelago collected since 2003 has been quality controlled and complied into the BAMP database.

The development and survivability of sea lice depends both on temperature and salinity. There is a temperature dependence on the time needed for sea lice to develop to an infective stage, as well as a temperature dependence on how quickly a female sea louse can produce successive generations. As salinity decreases so too does the viability of sea lice. For wild Pink Salmon there is a temperature dependence on when the fry emerge from their natal streams, and a salinity effect where adults shed sea lice when they return to the low salinity spawning grounds. Temperature and salinity are also relevant to the duration of the effectiveness of parasiticide treatment.

Figure 8 shows temperature data collected in the Broughton Archipelago between 2000 and 2011. There are two sources of data; those collected during the wild fish surveys carried out by DFO, and those archived at the Institute of Ocean Sciences from CTD (conductivity, temperature, depth) profiles taken in the area. Juvenile wild salmon migrate seaward through the Broughton Archipelago during the months of March through June and are more vulnerable to the effects of sea lice at this time. Data representing surface conditions (from the surface to 5 m depth) during the March to June out migration period are shown.

In Figure 8 the difference between the survey data and the CTD profile data demonstrate the larger range of temperatures that are observed in the near shore locations of the survey data. The best linear fit to the data shows the expected rise in temperature in both datasets with a mean increase from 6 to 13^{o}C and an associated increase in the range of temperature during this time period.

The four maps in Figure 9 also show the temperature distribution throughout the area of interest becoming warmer during the out migration period, as well as a greater range in temperature between the different areas of the archipelago. The spatial distribution of the temperature shows the northeast sector as the fastest warming region of the archipelago.

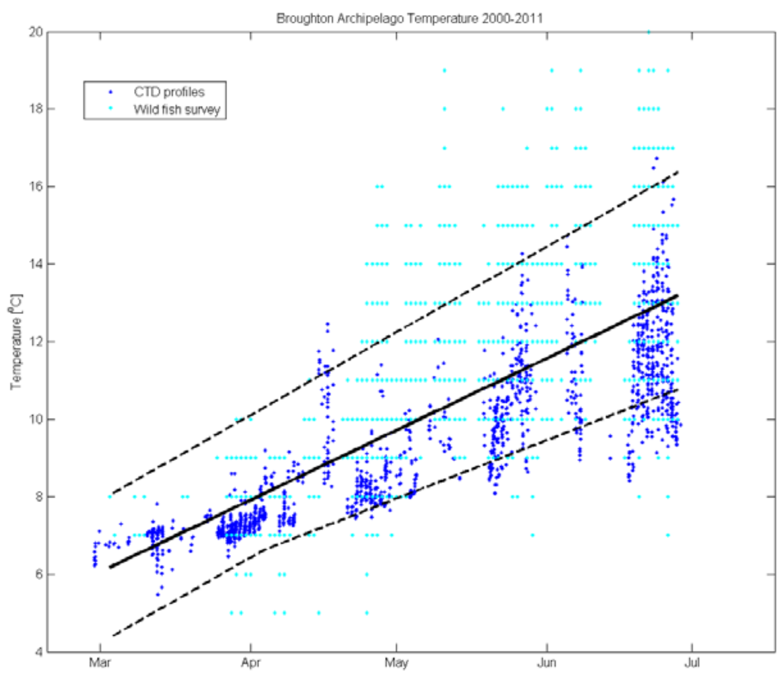

Figure 8. Sea surface temperature data from the Broughton Archipelago during the wild salmon out migration period (March through June). Solid line shows the linear best fit, and region between the dashed lines contains at least 50% of the prediction.

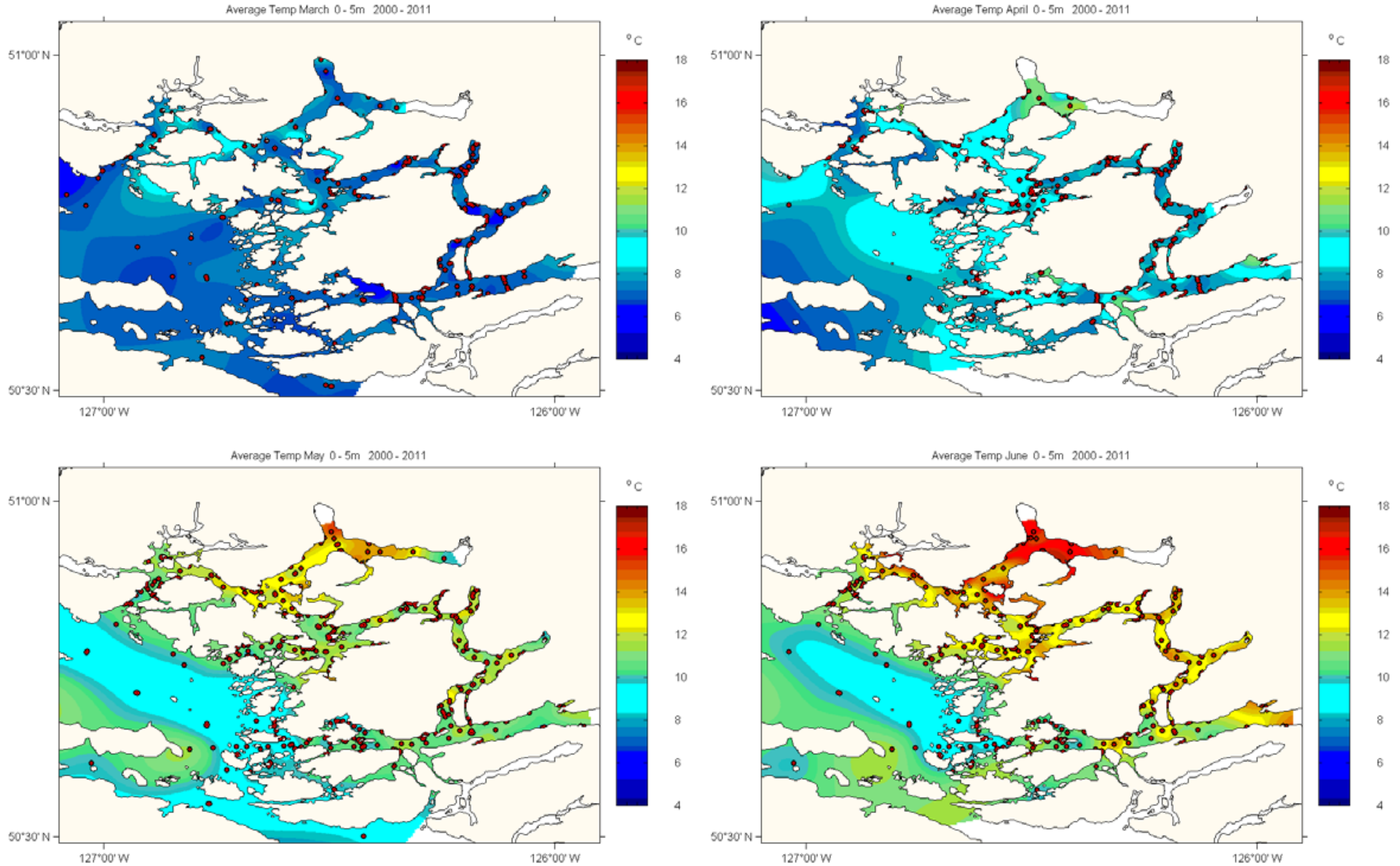

Figure 9. Average sea surface temperature data collected between 2000 and 2011 in the Broughton Archipelago during the wild salmon out migration period (March through June). The location of temperature observations are shown as red dots.

Figure 10 shows the salinity data collected simultaneously with the temperature data discussed above. The greater range of the survey data compared to the CTD data is evident. While the solid line identifying the best linear fit to the data shows a steady decrease in salinity during the out migration period, consistent with the additional fresh water input to the archipelago from river runoff during the spring freshet, there is a continuous presence of saline water throughout the out migration period. Figure 11 shows that this high salinity water is persistent in the western (seaward) regions of the archipelago while the eastern sections experience considerable freshening during the March to June period.

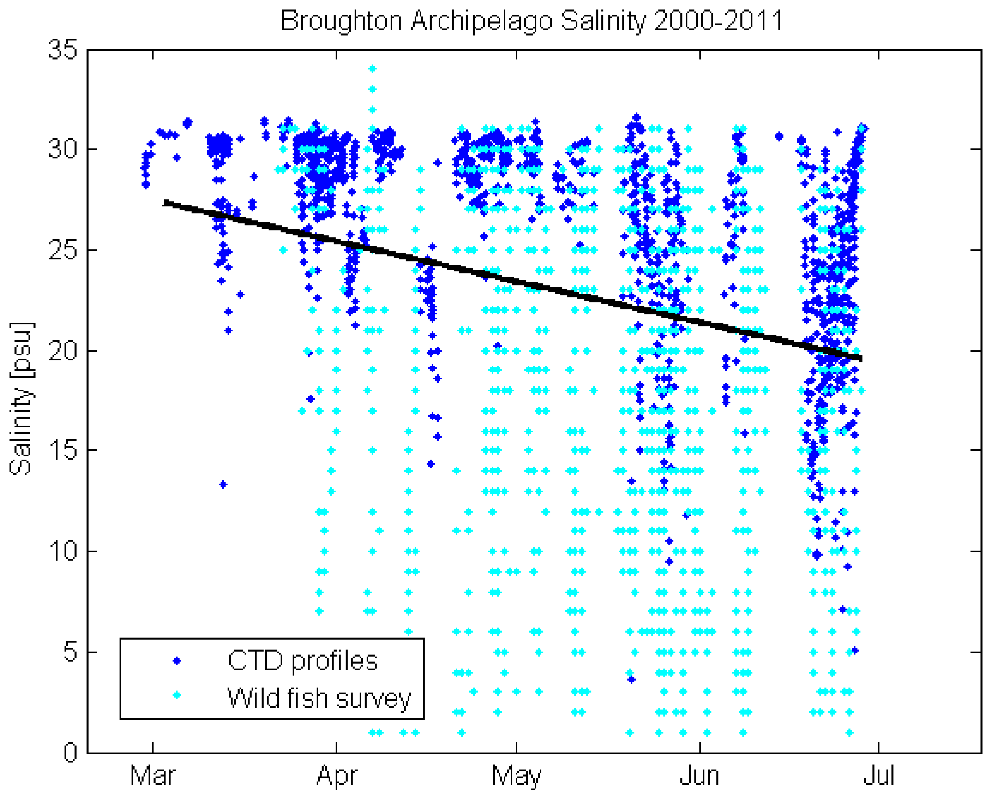

Figure 10. Sea surface salinity data from the Broughton Archipelago during the wild salmon out migration period (March through June). Solid line shows the linear best fit to all the data.

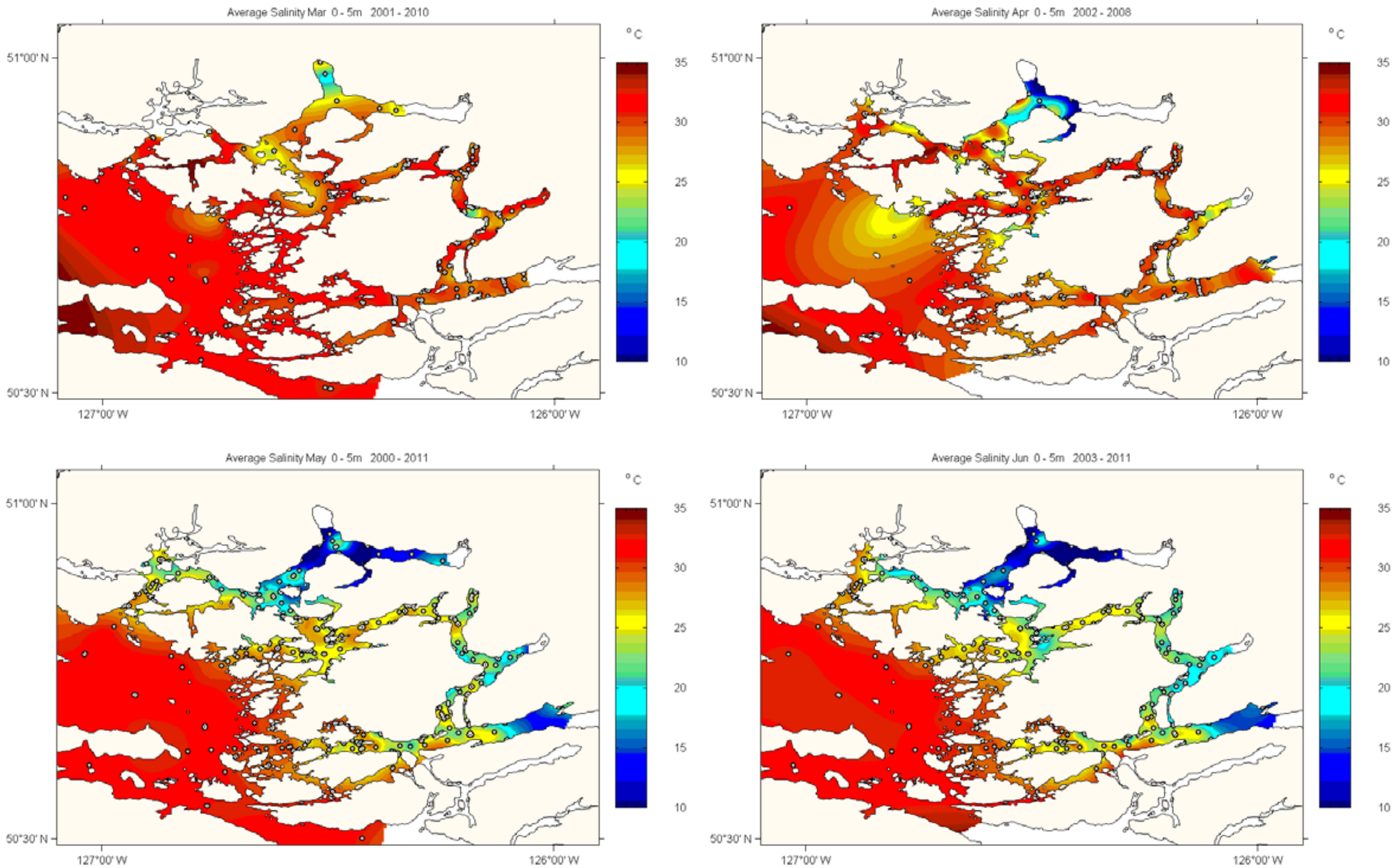

Figure 11. Average sea surface salinity data collected between 2000 and 2011 in the Broughton Archipelago during the wild salmon out migration period (March through June). The location of observations are shown as dots.

Environmental monitoring is carried out at every fish farm site and provides site specific information on oceanographic conditions that influence the production of sea lice. In particular the temperature and salinity measured at the surface, 5 and 10 m depth on a daily basis (Figure 12) provides necessary information to model the production and viability of sea lice eggs. The advection and dispersion of the sea lice larvae and nauplii can then be simulated using hydrodynamic models.

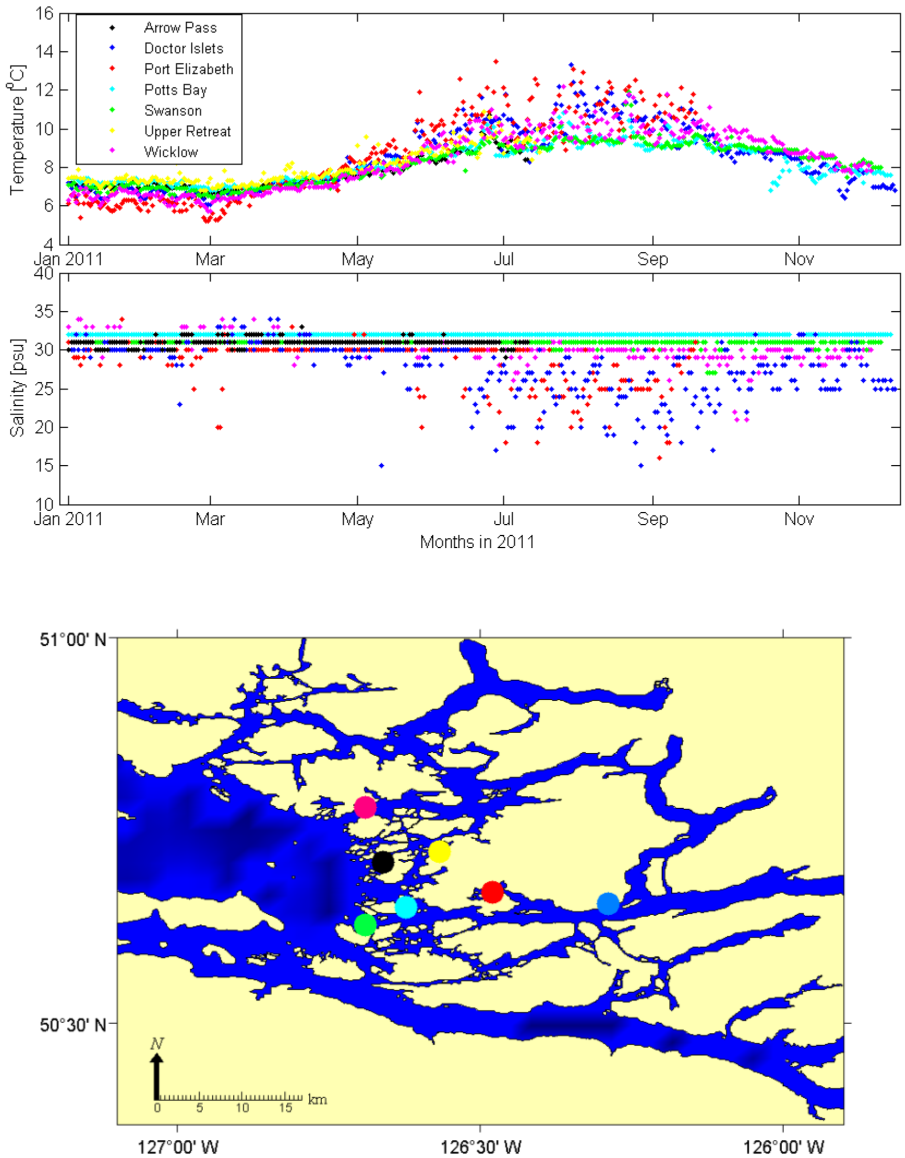

Figure 12. Daily sea surface temperature and salinity observations collected at seven fish farms in 2011. The seasonal temperature cycle is evident at all farms, while the changes in salinity are more site specific and more pronounced the closer the farm location is to the river mouths at the head of the fjords.

The currents in the Broughton Archipelago are driven by a combination of tides, winds, and fresh water forcing (due to river runoff and direct precipitation), all of which vary considerably in time and space due to the complex bathymetry typical of a fjord environment. In addition, the vertical changes in current are significant because the estuarine circulation forces water seaward at the surface, and in the opposite direction deeper in the water column.

At the head of the fjords in the eastern regions of the archipelago considerable fresh water is introduced as the winter snowfall melts causing a spring freshet which coincides with the period when juvenile salmon migrate to sea. There are over 50 streams and rivers that contribute to the fresh water loading of the archipelago, with the Klinaklini at the head of Knight Inlet being one of the major contributors. Stream flow measured at the Kliniklini River by the Water Survey of Canada is presented in Figure 13 and shows the considerable increase in flow during the out migration period. As a result, the strength of the estuarine flow, the stratification of the water column, and the salinity of the surface layer vary significantly in time and space.

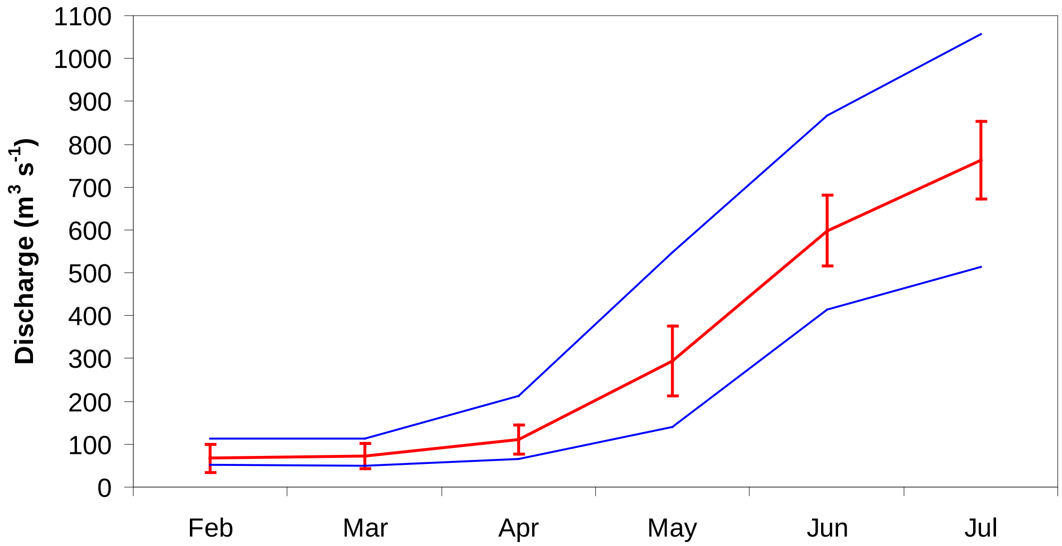

Figure 13. Stream flow data from the Klinaklini River at the head of Knight Inlet. The red line represents the mean discharge flow during 2000 – 2010, with the error bars representing ± standard deviation. The blue curves show the minimum and maximum discharges for each month.

The wind driven component of the circulation is a result of wind stress on the surface of the water, which is then transmitted deeper into the water column. The character of the wind in any given location of the archipelago is a combination of the large scale pressure systems over the BC Coast, as well as the smaller scale sea and land breezes that occur on daily time scales. The Broughton Archipelago is characterised by steep-sided mountains that rise on both sides of relatively narrow and twisting channels. As a result the wind effects are very localised and difficult to relate to Port Hardy, which is the only permanent weather station in the region. A network of nine temporary weather stations has been installed in the area to provide direct observations of the local wind. Analysis is ongoing to establish a reliable relationship between the permanent and temporary weather stations.

Similarly, the use of current meters to observe the speed and direction of the water flow provides detailed information at specific locations during the period of the deployment, but it is difficult to relate this information to the broader circulation patterns of the archipelago.

Knowledge of the currents in three dimensions is necessary to understand how sea lice are transported throughout the archipelago, and knowledge of the temperature and salinity is required to determine the growth rate of the sea lice. Given the location of a fish farm as a source of sea lice, the advection and dispersion of the nauplii during development to the copepodid stage can be used to establish an area of infective influence.

Hydrodynamic models to simulate the physical oceanographic factors that influence sea lice behaviour provide the detail required to represent the complexity of the archipelago. Foreman et al. (2009) have applied a Finite Volume Circulation Ocean Model (FVCOM) to solve the three dimensional hydrodynamic equations for velocity and surface elevation as well as the 3D transport/diffusion equations for salinity and temperature (Figure 14).

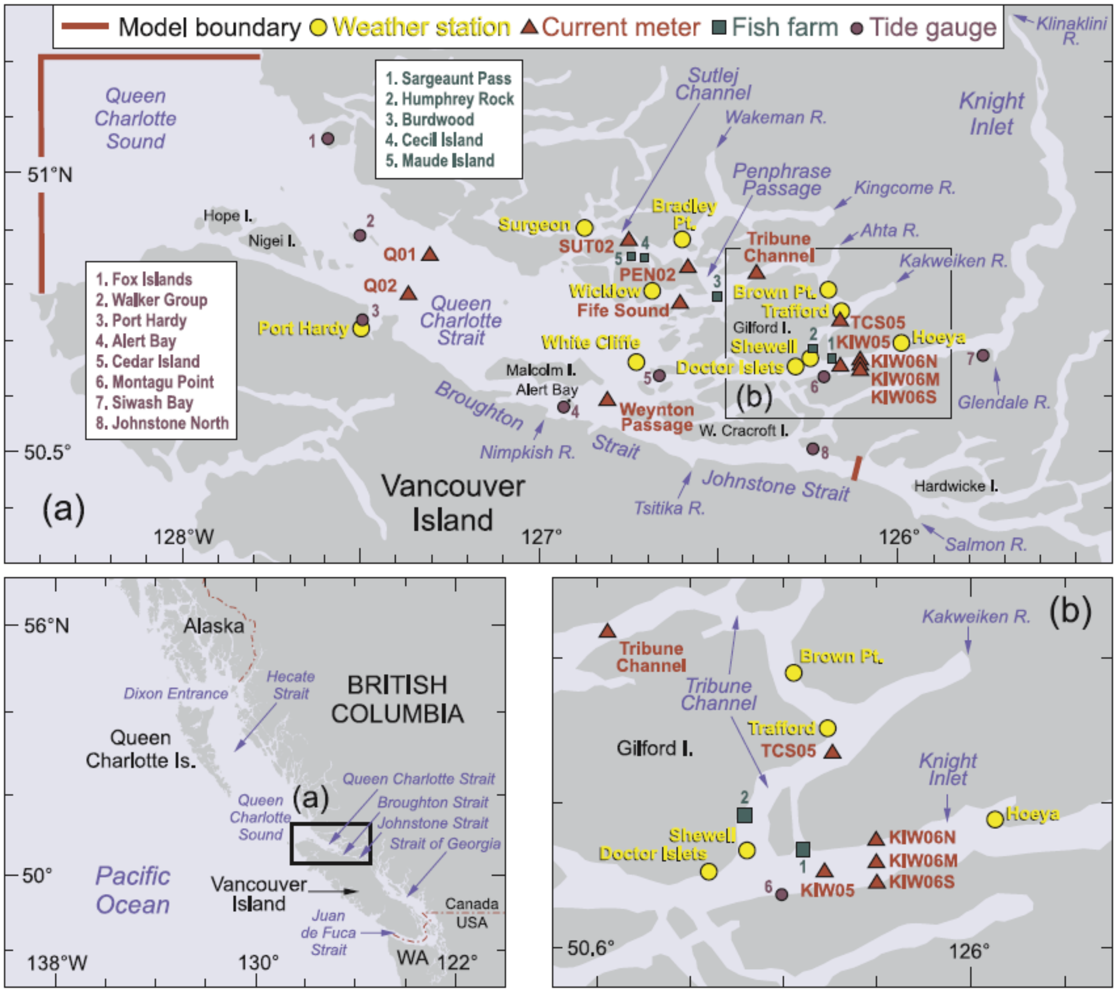

Figure 14. Map of the Broughton Archipelago showing place names, the model domain, weather stations (yellow), current meter (red), tide gauge (purple) and fish farm (green) observations sites used to evaluate a Finite Volume Circulation Ocean Model (FVCOM) from Foreman et al. 2009.

An evaluation of this model for the period 13 March – 3 April, 2008 with current, temperature, and salinity observations shows its capability to simulate, with acceptable accuracy, the physical oceanographic factors needed to develop effective sea lice monitoring and control measures.

Figure 15 shows the results of the model generated M_2 tide, the primary tidal constituent in the Broughton Archipelago. This representation of the tidal velocity can be directly related to the excursion distance (10 cm s^{-1} corresponds to an excursion of about 2.8 km during half a tidal cycle) and demonstrates the spatial variability of the tidal forcing.

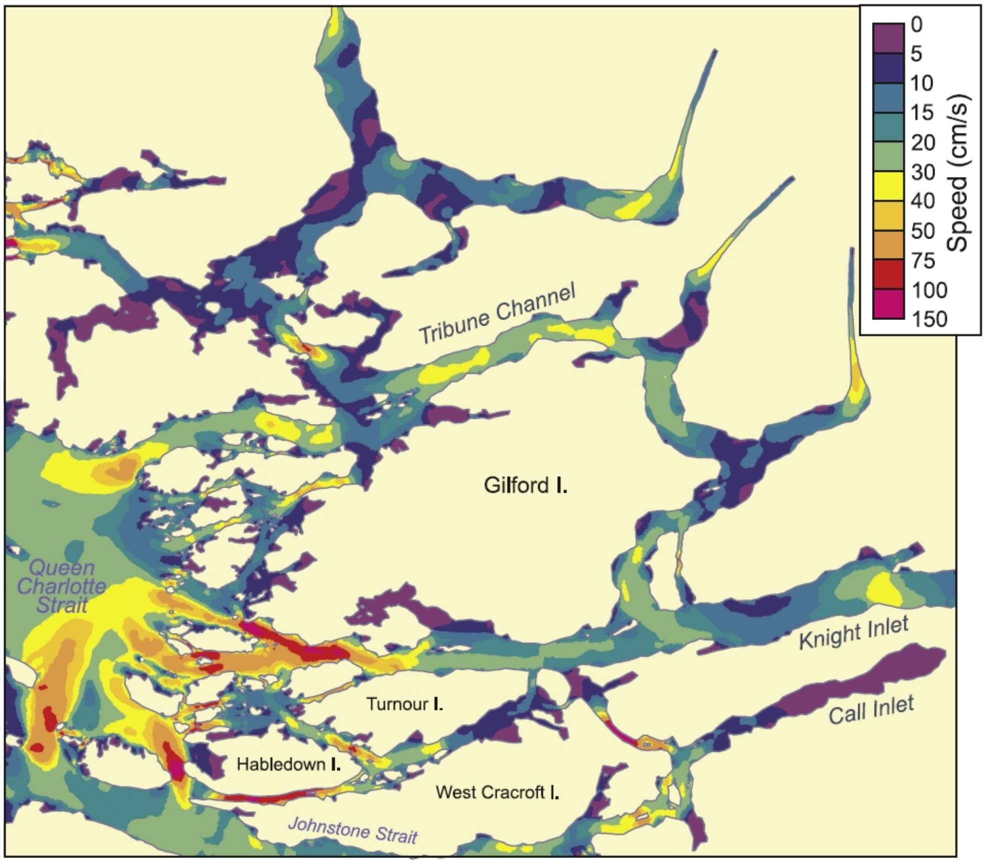

Figure 15. The surface velocity of the M_2 component of the tide derived from a harmonic analysis of the FVCOM model simulation 17 March – 3 April, 2008 (Foreman et al. 2009).

The 3D velocity, temperature and salinity fields generated by this model are being used as input to other models to simulate the development, behaviour, and movement of sea lice. Further refinements to the hydrodynamic forcing, such as better representation of the winds and heat flux, are ongoing. The simulation of other time periods are being undertaken as measured data, required to validate the model output, becomes available.

As data to drive the model (especially winds) becomes available, hydrodynamic models can be used to simulate more oceanographic conditions in the archipelago. At present the results from simulations of March and May of 2008, March to August 2009, and March 2010 are being validated. The velocity, temperature and salinity fields (at one hour intervals) can then be used by trajectory models to identify the pathways of particles (e.g., sea lice) released from specific locations, such as fish farms, and develop matrices of travel times connecting the release points.

Figure 16 shows the Broughton Archipelago segmented into non-overlapping zones based on the wild fish sampling data available in the BAMP database. Using the BAMP database the dynamics of sea lice transmission between the farm and wild salmon populations are being analysed to inform present and future sea lice control management decisions as well as explain the variability seen in sea lice populations over the past ten years (Krkošek et al. 2012).

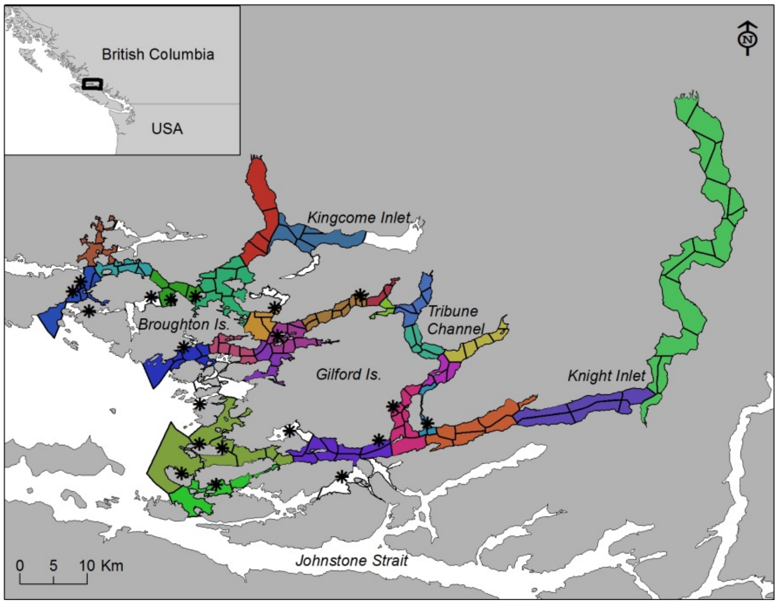

Figure 16. The spatial units of the Broughton Archipelago statistical model used to structure the data for the multivariable analysis. The coloured sub-regions are used where data are sparse. The locations of fish farms that were active during the study are also shown as black asterisks.

EAST COAST- SOUTH COAST OF NEWFOUNDLAND AND LABRADOR

Bay d'Espoir is a long fjord-like estuary with a hydroelectric generating facility located at the head of the bay. This facility is a main source of freshwater runoff into the bay, thus influencing the salinity and the temperature of the surface water. This influence can be seen as far as the mouth of the bay. Figure 17a illustrates the typical distribution of salinity at 1 m depth along Bay d'Espoir in early summer. Salinity ranges from 0 psu (freshwater) at the head of the bay to values around 25 psu near the mouth (brackish with higher open ocean saline water content). Vertical stratification can be strong during seasons of high runoff, and mixing occurs in the vertical to a depth of not more than 10-15 m. Below this depth, the water mass consists of mainly ocean water with salinity above 30 psu.

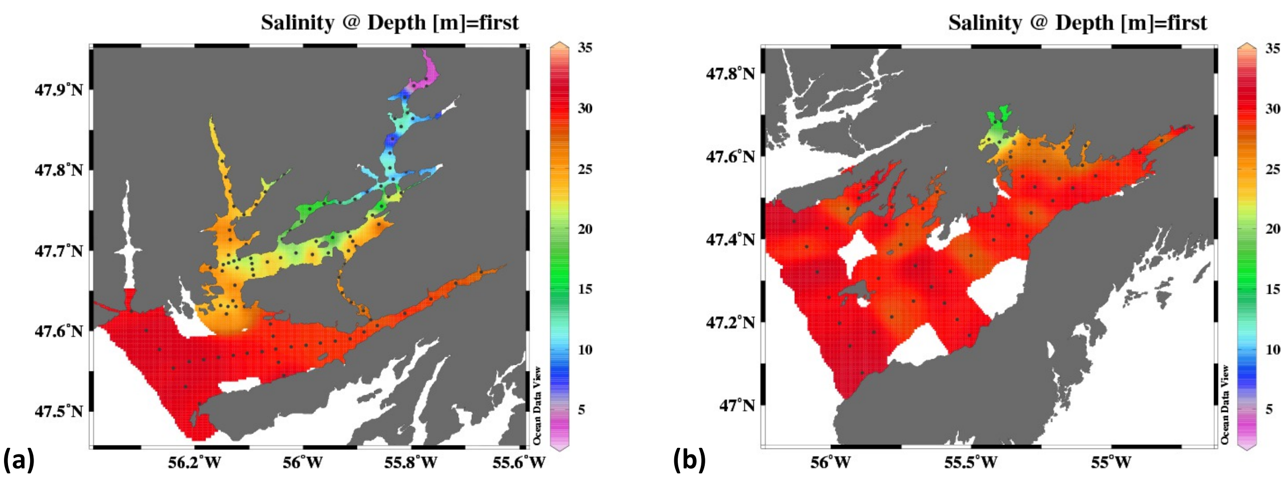

Figure 17. Distribution of salinity at 1 m depth in (a) Bay d'Espoir and Hermitage Bay for June 2009 and in (b) Fortune Bay for May 2011.

Surface salinity values can be very low during the summer season (Figure 18) with the lowest salinity found toward the head of the bay. Lower freshwater runoff keeps the surface water with higher salinity during winter season.

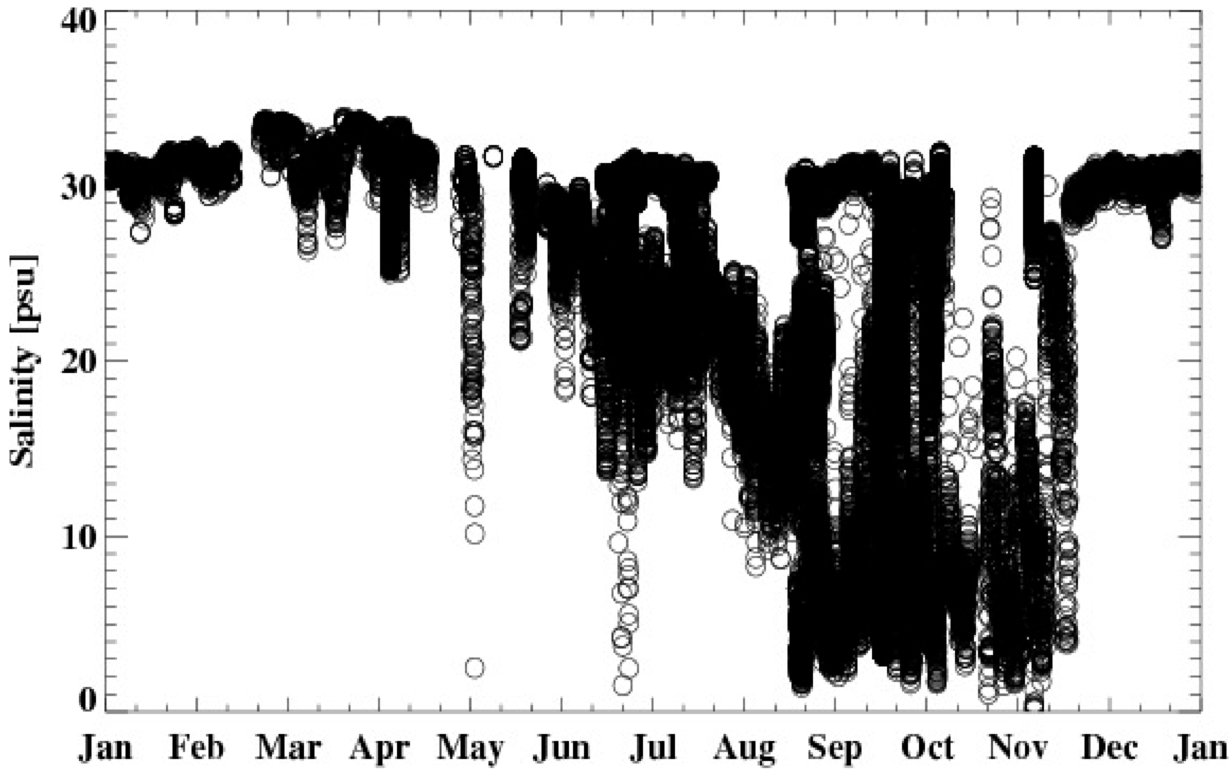

Figure 18. Annual cycle of salinity in the surface layer, 0 - 4 m, for Bay d'Espoir. Data source: historical and more recent measurements.

The annual cycle of temperature in Bay d'Espoir within the surface layer (0-4 m) is shown in Figure 19 as obtained from historical and more recent measurements taken at different locations within the bay. The minimum temperature is observed in winter season with values as low as -1.3° C during some years. The temperature is typically below 5°C from mid-December to mid-April. Surface water temperature is highest in summer; reaching above 21°C in some years. Short term variability can take place as a result of rapid mixing with water from below.

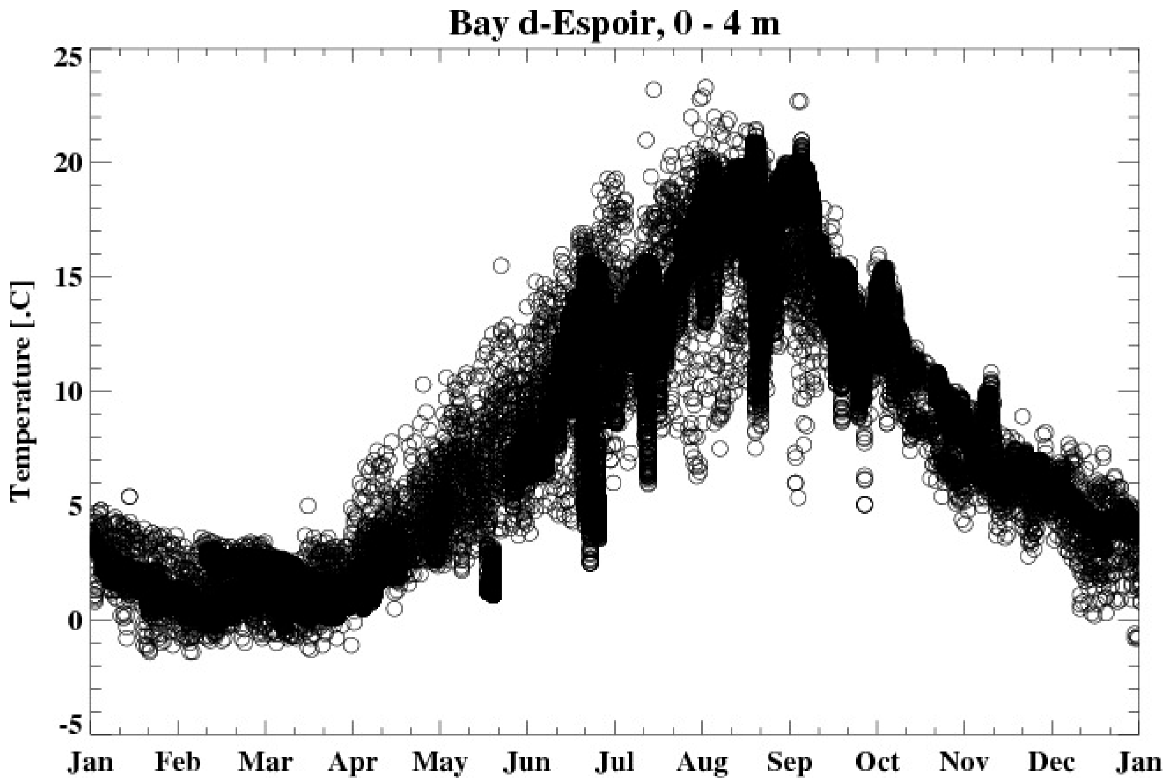

Figure 19. Annual cycle of temperature in the surface layer, 0 - 4 m, for Bay d'Espoir. Data source: historical and more recent measurements.

In terms of ocean currents, there are various factors which drive the circulation, the main influences being tide, wind, thermohaline circulation, and the difference in sea level between the head and the mouth of the bay. The latter is related to atmospheric pressure in the Region. In Bay d'Espoir, the contribution of tide to the water currents at different depths is small. Surface drifter experiments conducted in the bay showed that the mean surface currents during non-stormy weather range between 0.08 to 0.26 m s^{-1} except at the mouth where mean currents were higher (>0.36 m s^{-1}) (Ratsimandresy et al. 2012). The surface circulation is complex and driven by a combination of various factors including tides and winds. As such, surface currents as high as 1.1 m s^{-1} have been observed. Despite the presence of freshwater at the surface, its influence on the surface circulation is reported to be negligible.

Fortune Bay is also a fjord-like estuary, with a larger width. It connects to a smaller bay, Belle Bay, at the north. In the present work, the system Fortune Bay – Belle Bay will be referred to as Fortune Bay. Figure 17b illustrates the geographic distribution of salinity at 1 m depth for the bay observed in late spring 2011. In this bay, freshwater from river runoff is also present, mainly at the head of Belle Bay, although the measured minimum salinity shows that faster mixing with ocean water takes place. The horizontal extent of the freshwater does not reach as far as in Bay d'Espoir. Vertical mixing of freshwater with open ocean water is also present and gradually decreases down to a depth of 10 to 15 m.

Surface water temperature in Fortune Bay presents a similar annual cycle as in Bay d'Espoir but with a lower maximum temperature in summer (Figure 20) and shows less short-term temperature variability within the surface layer during the summer period. Temperature within the surface layer is typically lower than 5°C between mid-December to mid-April.

As in Bay d'Espoir, currents in Fortune Bay present a very low tidal contribution. Surface and subsurface drifter experiments carried out in summer 2010 in Fortune Bay show a general counter-clockwise circulation. Under non-stormy weather conditions, an average current speed of the order of 0.14 m s^{-1} has been observed.

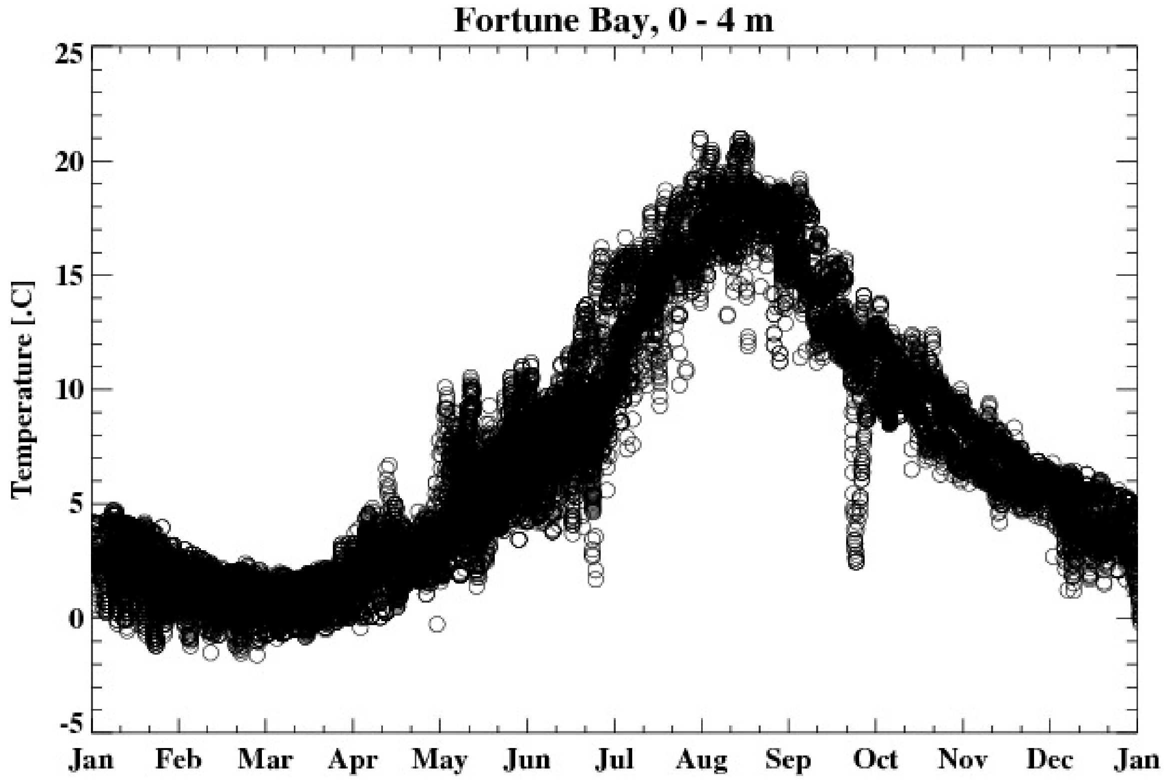

Figure 20. Annual cycle of temperature in the surface layer, 0 - 4 m, for Fortune Bay. Data source: historical and more recent measurements.

In order to understand the complex hydrography and water circulation in the south coast of Newfoundland, a hydrodynamic model based on the Finite Volume Coastal Ocean Model (FVCOM) is being developed using the best available realistic wind and tidal forcing. Validation of the model output is ongoing. Preliminary results have shown how sea level height is well explained by tidal phenomenon. Further analysis of these results will help in the evaluation of the role of the other forcing fields (e.g., wind) in generating water circulation in the bay. This result, combined with a particle tracking model, is the base of a transport study of sea lice with the possibility of predicting different environmental conditions, including extreme ones.

EAST COAST- MARITIMES REGION

Bathymetry

Salmon farms in the Maritimes Region are mostly situated in relatively shallow (<~20 m), near-shore waters in areas with relatively flat or gently sloping bottoms. Maps of the depth contours along with statistical summaries of the water depths within most inlets within the Region have been published by Gregory et al. (1993). In southwestern New Brunswick (Figure 21) the average depth within approved farm leases ranges from 5-40 m, with an overall average of 14 m (depths below normal lowest tide, based on Canadian Hydrographic Service data). In Nova Scotia, farm sites are mainly in waters less than 18 m in depth (Figure 22), although two new farms near the mouth of St. Mary's Bay are located at depths of approximately 50 m.

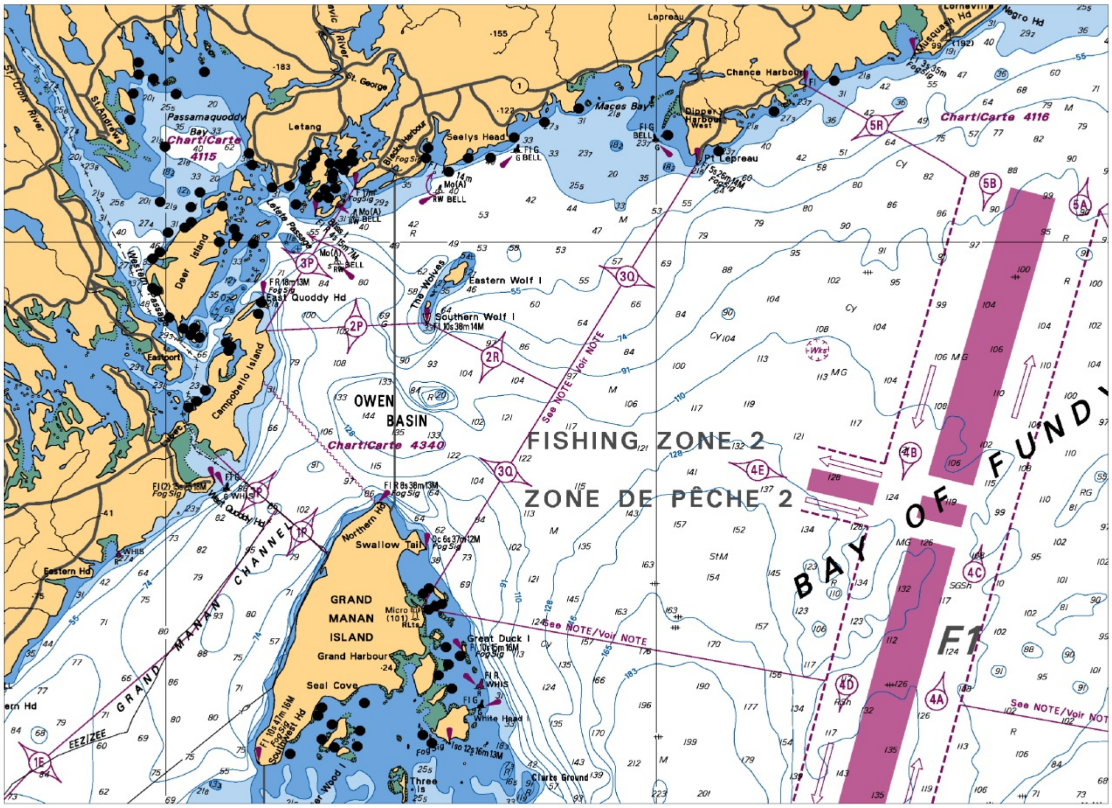

Figure 21. Approved salmon farm leases in southwestern New Brunswick as of 2012 (black dots). The background chart is Canadian Hydrographic Service chart 4011 (Approaches to Bay of Fundy). Depths are in metres. The dark blue areas are depths less than 18 metres and the light blue areas are less than 36 metres.

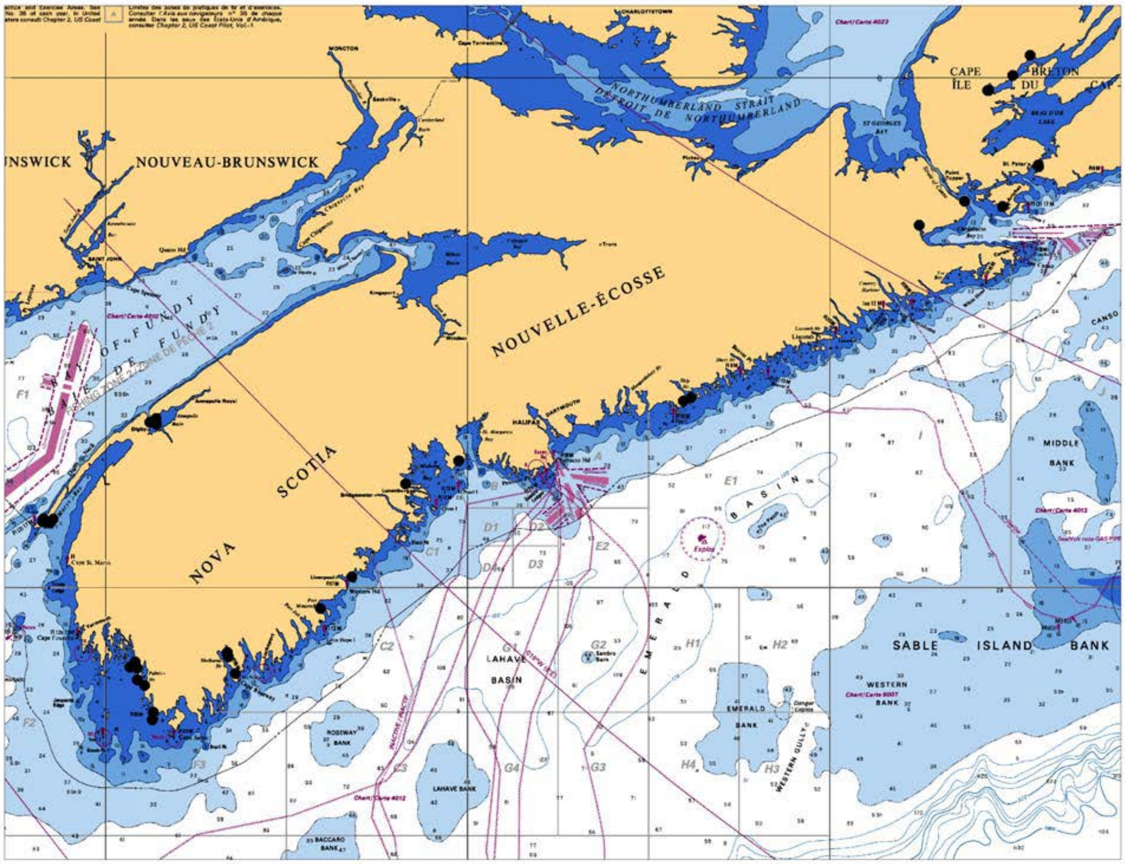

Figure 22. Map showing approved salmon farm leases in Nova Scotia, as of 2012 (black dots). The background chart is Canadian Hydrographic Service chart 4003 (Cape Breton to Cape Cod). Note that depths are in fathoms and the depth contours correspond to 10 (darkest blue), 20 and 50 (lightest blue) fathoms or 18, 37 and 92 metres, respectively.

Temperature

The large scale spatial and seasonal pattern of coastal water temperature in the Maritimes Region is illustrated by satellite derived estimates of sea surface temperature (SST; Figure 23). The images show bi-weekly composites of SST for each season; i.e., the last two weeks of February, May, August and November 2010 (the middle of each annual quarter). The images show that the region is generally cool (<~5^{o}C) during the winter months, and as spring and summer progress the area experiences a west to east warming to near 20^{o}C in the summer along much of the south shore of Nova Scotia and about 15^{o}C in the Bay of Fundy. The cooler temperatures in the Bay of Fundy and southwest Nova Scotia area are due to vigorous tidal mixing and upwelling processes. In the fall, the pattern reverses and water temperatures begin to reduce.

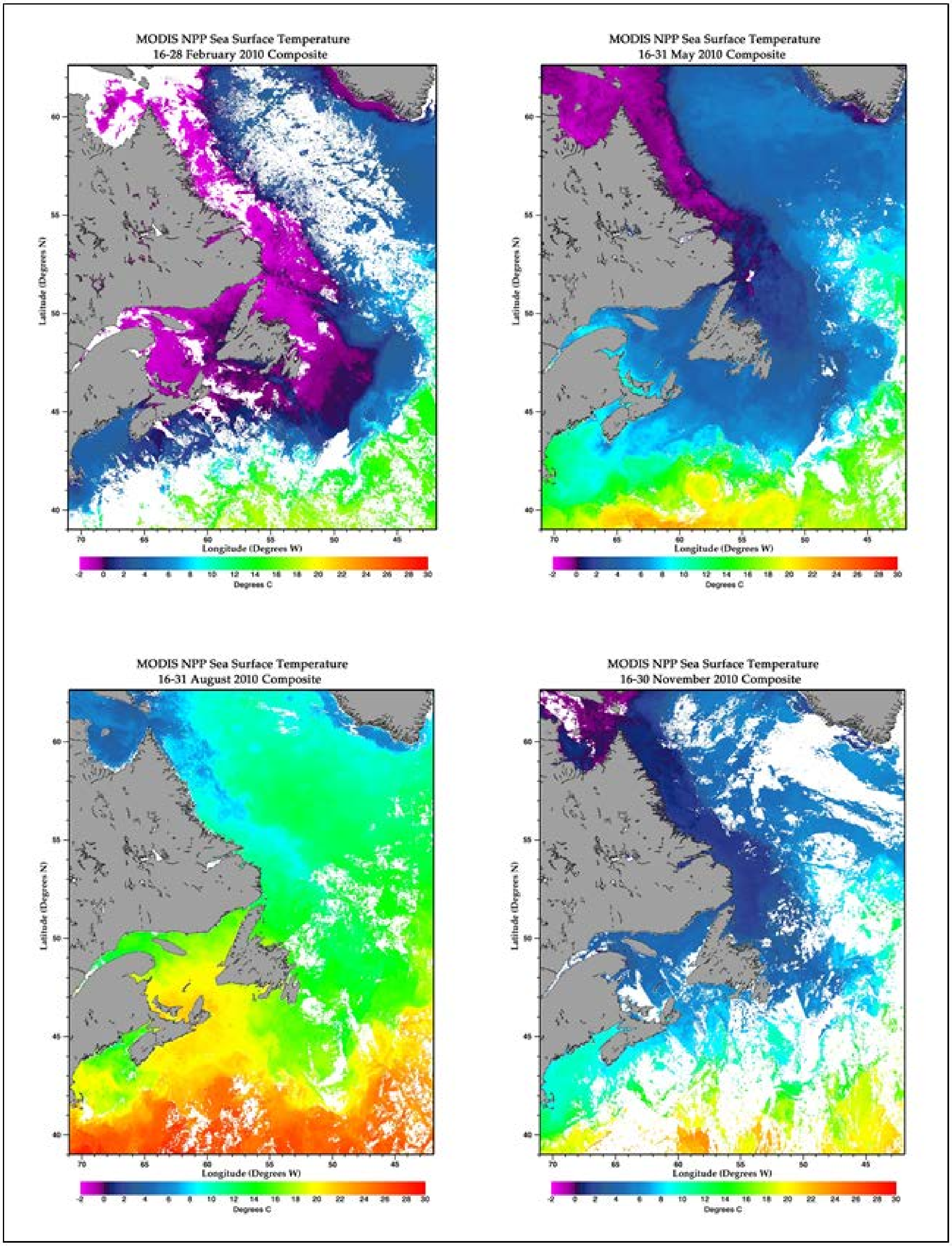

*Figure 23. Bi-weekly composites of satellite derived (MODIS) sea surface temperature for Atlantic Canada selected to represent annual quarters. Each pixel represents an area of about 1.5 x 1.5 km and an average of all data available for the two week period indicated on each panel. The composites were retrieved from the Bedford Institute of Oceanography's web site (*BIO Website for Operational Remote Sensing, Semi-Monthly Composites*).*

The satellite images mostly represent offshore water temperatures and do not show the details of water temperatures within the very near coastal zone where salmon aquaculture occurs. Temperatures for the near-shore are more accurately represented by data from in-situ temperature monitoring. This type of data has been collected within the Maritimes Region since the early 1900s. Initially the data were limited in space and time and were mainly collected from the southwest New Brunswick area because of the presence of the St. Andrews Biological Station. In the late 1970's temperature time series began to be collected from throughout the coastal regions of New Brunswick and Nova Scotia using moored temperature recorders (Petrie and Jordan 1993, Gregory 2004). Much of these data are contained within the DFO Maritimes Region's Coastal Time Series Database (CTS) and access to statistical summaries of this data is available online from the following web address: Oceanographic Databases.

A brief overview of the data holdings is provided by Gregory (2004). The data have been collected by mechanical and electronic temperature recorders. The recorders used during the 1970-80s were largely mechanical and had accuracies of 0.5 - 1°C. More recent recorders are electronic digital instruments and have accuracies of approximately 0.1 - 0.2°C (Gregory 2004). The vast majority of the data have been collected since 1980. A description of the statistical data analyses approach is given on the web site and in Petrie and Jordon (1993) and Gregory (2004). In brief, the data have been analyzed by selecting all of the data collected from the bottom at depths less than 12 m and at locations believed to be representative of areas greater in extent than the specific recording location. The data have then been grouped within specified geographic areas and combined into a single time series for each area. Temperature conditions within micro-environments are therefore not represented in the summaries. Monthly minima, maxima, means, standard deviations, means ± 1 standard deviation and ranges have then been calculated from each time series. A summary of the data available up until 1990 has been given by Petrie and Jordan (1993).

The summary presented here is based on data available in the database as of 28 July 2012, a considerably larger data set than that available to Petrie and Jordan (1993).

The locations of the temperature monitoring sites are shown in Figure 24 along with the boundaries defining geographic regions into which the data have been grouped. These areas correspond with management defined fishing areas. The data have not been extracted and binned into different areas specific to aquaculture for this report.

The annual cycle in the near-shore shallow water temperature statistics is shown in Figure 25 for each of the geographic regions. The temperature time series are dominated by a seasonal cycle in which temperatures are typically lowest (means < 2°C) during the winter months (February, March) and highest (means > 12°C) during the late summer and early fall months (August, September; Figure 23). The monthly standard deviations of temperature show limited seasonality (Figure 23). The monthly ranges of temperature are several multiples larger than the standard deviations and with the exceptions of 4Xr and 4Xq, the ranges vary seasonally, being smallest during the winter and largest during the summer (Figure 26). The extremes in temperatures range from -2.4 to 24.3°C whereas the monthly mean temperatures range from -0.9 to 17.3°C.

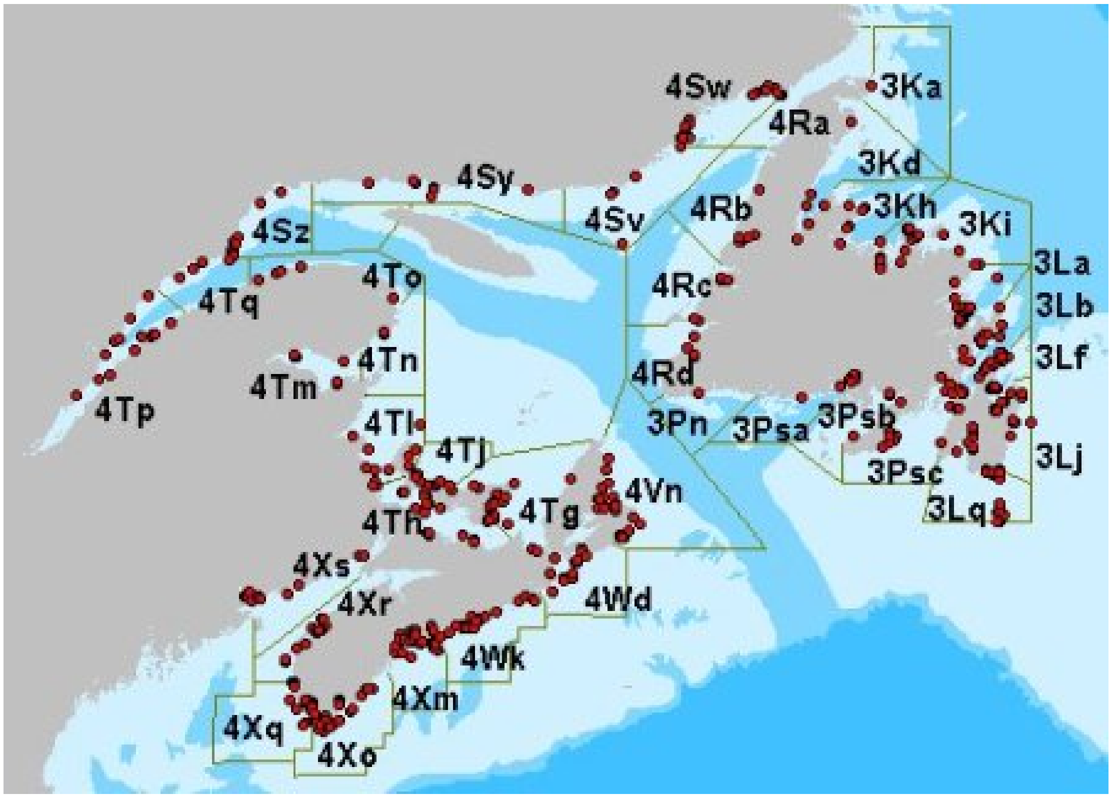

Figure 24. Map showing the locations (red dots) of coastal temperature monitoring time series throughout Atlantic Canada. The figure is a copy of that appearing on the DFO web site (Coastal temperature monitoring in Atlantic Canada) on 28 July 2012. The polygons, and the labels associated with them, indicate the geographic regions for which summary data can be extracted from the coastal temperature database. The regions correspond to fisheries regions and were used by Petrie and Jordan (1993) and Gregory (2004) in their descriptions of the database and temperature statistics.

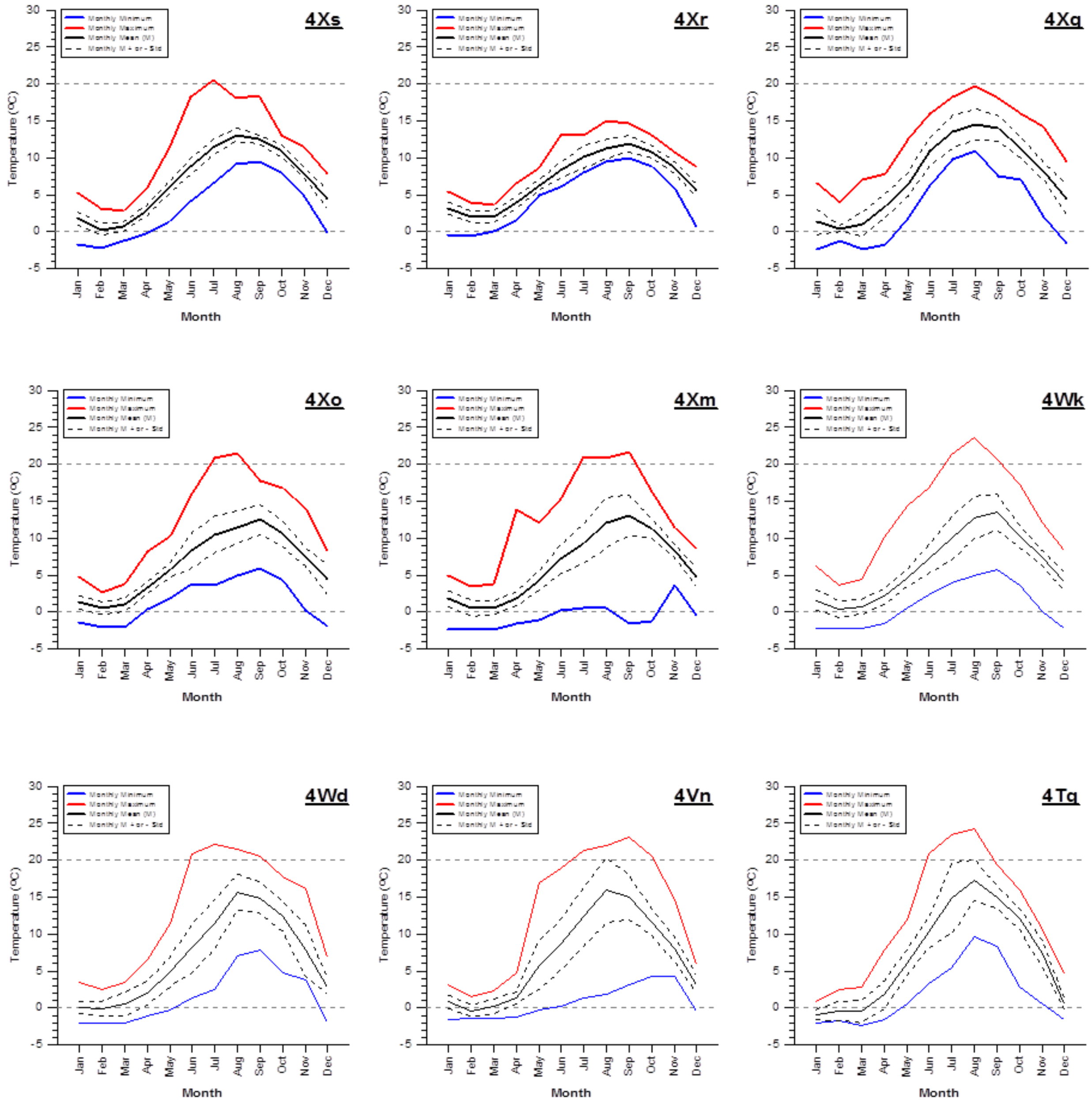

Figure 25. Monthly variation in near surface (upper 12 m) water temperature statistics (minimum, maximum, mean, mean ± 1 standard deviation) within the coastal regions indicated in Figure 22. The statistics are based on the output from the DFO web site on 28 July 2012 (Oceanographic Databases).

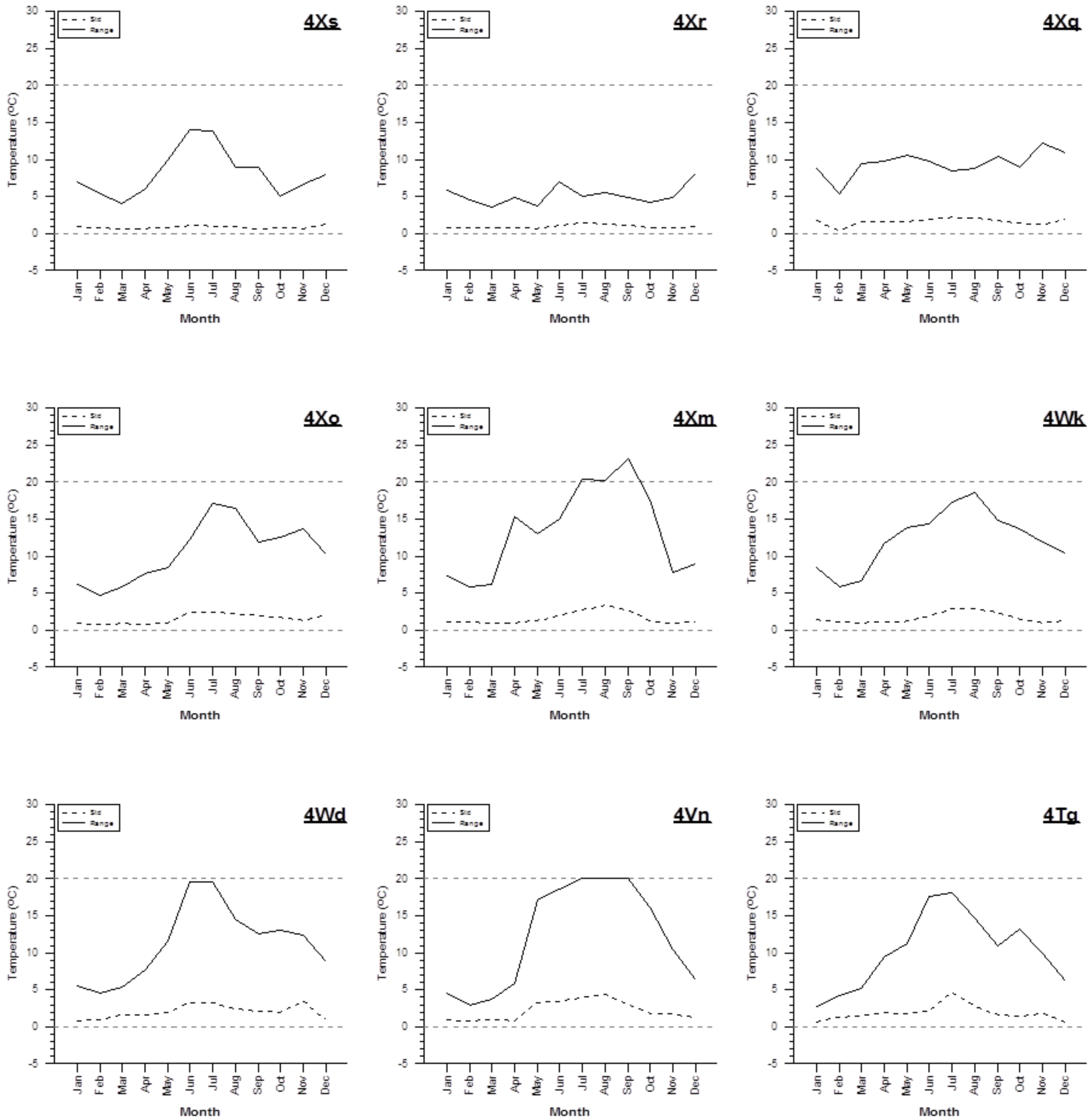

Figure 26. Monthly variation in near surface (upper 12 m) water temperature statistics (standard deviation and range) within the coastal regions indicated in Figure 22. The statistics are based on the output obtained from the DFO web site on 28 July 2012 ([Oceanographic Databases](#)).

The spatial variation in temperature statistics is shown in Figure 27. The maximum monthly mean temperature increases by about 5°C from west to east, i.e., from the Bay of Fundy to eastern Nova Scotia (Cape Breton) and the minimum monthly mean decreases by about 2°C from west to east. The minimum monthly mean remains reasonably constant throughout the region, whereas the monthly maximum increases from west to east. The range in the monthly means and the range in the monthly extremes (i.e., maximum minus the minimum observed temperature) increases from west to east, with the ranges being smallest in the Bay of Fundy (4Xs, 4Xr) and largest in the northern Cape Breton area (4Tg). These patterns reflect the moderating influence of the tidal mixing that occurs within the Bay of Fundy area and the influence of the St. Lawrence River outflow on the eastern areas. The temperatures in the Maritimes Region suggest that the duration of the free swimming pre-infective sea lice phase (naupliis I & II and copepodids), as estimated using the development rate relationships developed by Stien et al. (2005), ranges from about 2 to 10 days (Table 1).

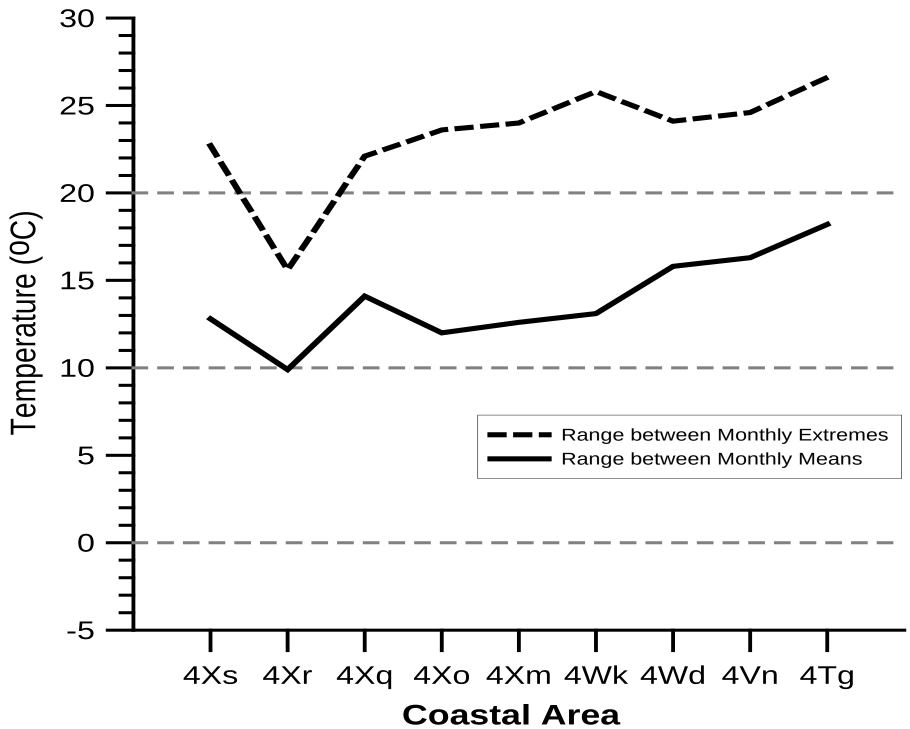

Figure 27. Annual ranges in near surface (upper 12 m) water temperatures within the coastal regions indicated in Figure 22. The total range, or the range between monthly extremes, was calculated as the maximum minus the minimum recorded values for each geographic area. The range between monthly means was calculated as the maximum monthly mean minus the minimum monthly mean. The ranges were calculated from data retrieved from the DFO web site on 28 July (Oceanographic Databases).

Salinity

As mentioned above, most of the coastal bays within the Maritimes Region have freshwater inputs, although most of the inputs are relatively small. The exceptions are the outflow from the Saint John River and the St. Lawrence River via the Gulf of St. Lawrence. The Saint John River outflow is the dominant single source of freshwater into the Bay of Fundy-Gulf of Maine system whereas the Gulf of St. Lawrence outflow is the dominant flow affecting eastern Nova Scotia.

Unfortunately, unlike temperature, salinity has not been monitored nearly as extensively in the inshore areas of the Maritimes. Hence, data from the two fixed hydrographic monitoring stations within the region are presented in an effort to give a flavour for the seasonal variations in salinity. The stations are Prince 5 located off swNB in the mouth of the Bay of Fundy and Halifax Station 2, located off the mouth of Halifax harbour on the Atlantic coast of Nova Scotia. At both stations the salinity usually remains above 30 psu (Figure 28).

At the Prince 5 station, the salinities undergo a seasonal cycle with the minimum occurring in April or May and the seasonal maximum occurring in October-November. This coincides with the cycle in the freshwater outflow from the Saint John River. The salinities nearer to shore show a similar pattern but with seasonal lows often dropping to slightly below 30 psu.

In contrast, the salinities at Halifax Station 2, have an annual minimum in the fall and a broad maximum from February through August. This pattern is related to the freshwater flow from the St. Lawrence River and the delayed seasonal minimum is due to the time needed for the freshwater to travel from the St. Lawrence to the Scotian Shelf.

Although the Prince 5 and Station 2 data give a general indication of the salinity regime within a few kilometres of the coast , the very near-surface waters in the near-shore farming areas may sometimes drop below 30 psu, typically to values in the mid to high 20 psu range (e.g., Krauel 1969; Keizer et al. 1996, Robinson et al. 1996).

In general, the salinities throughout the Maritimes Region are high enough that they probably have relatively little effect on sea lice survival on most of the salmon farms.

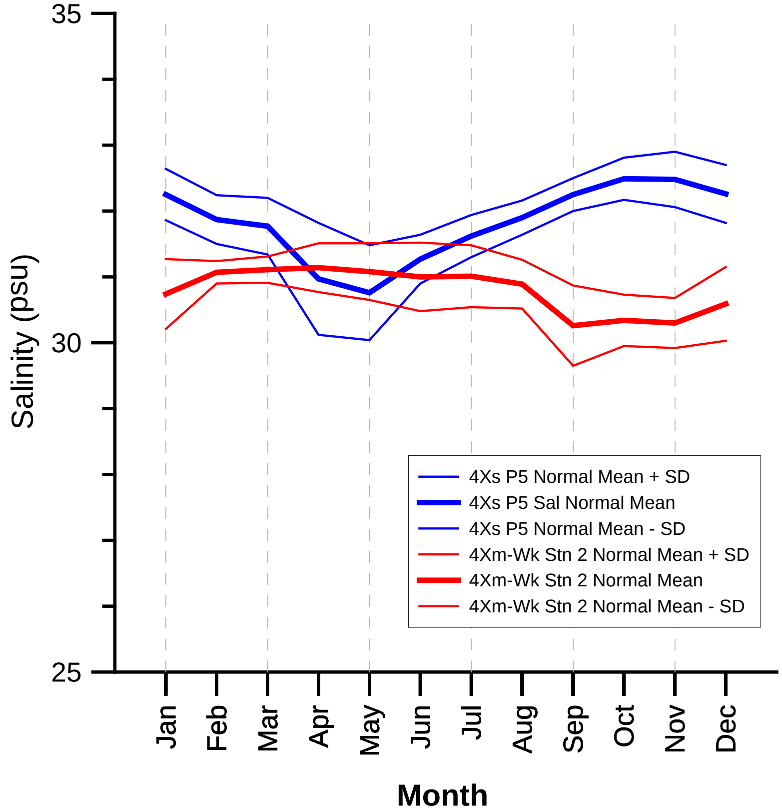

Figure 28. Monthly salinity climatology at the Prince 5 and Station 2 hydrographic stations located off southwest New Brunswick and Halifax Nova Scotia, respectively. The heavy solid lines are the 30 year (1971-2000) climatological normals (means) and the thin solid lines are the means ± 1 standard deviation. The data were obtained from Hydrographic Data.

Stratification

The water column in the offshore coastal waters of the Maritimes Region is vertically well mixed in some areas and seasonally stratified in other areas, with the geographic location of the well mixed areas being determined to a large extent by the degree of tidal mixing (Garrett et al.1978). In the inshore areas where fish farming is practiced, the water column is quite often well mixed vertically, although weak vertical stratification does occur seasonally in some areas.

Figure 29 shows an example of one of the stratified farming areas within swNB and Figure 30 shows a profile for a location within Nova Scotia. Figure 29 shows vertical profiles of water temperature, salinity and density for four periods of the year from a location within the

Passamaquoddy Bay area of swNB. The profiles indicate the presence of weak thermoclines, haloclines and pycnoclines between the sea surface and about 5 to 10 m. During the winter and summer the vertical gradients are smallest with differences in near-surface to near- bottom temperature, salinity and density being of order 0.5^{o}C, 0.2 psu and 0.1 σ_t, respectively. During the spring and fall, the vertical gradients are a bit stronger with differences in temperature, salinity and density being of order 1^{o}C, 2-3 psu and 1-2 σ_t.

Figure 30 shows vertical profiles of water temperature, salinity and density for the summer period from a location within Shelburne Harbour on the Atlantic coast of Nova Scotia. The profiles indicate the presence of weak thermoclines, haloclines and pycnoclines between the sea surface and about 5 m. The vertical gradients in near-surface to near bottom temperature, salinity and density being of order 6^{o}C, 0.2 psu and 1 σ_t.

Water Currents

The large scale water flow within the Maritimes Region is from east to west (Hannah et al. 2001, Han and Loder 2003; and references therein). Water from the Gulf of St. Lawrence flows from Cape Breton on the east, toward Yarmouth in the west. The magnitude of this Scotian Current flow varies seasonally in relation to the outflow from the Gulf of St. Lawrence. Tidal forces cause an upwelling off Yarmouth and drive the mean flow into the Bay of Fundy. This eastward flow proceeds along the Nova Scotia shore of the Bay of Fundy until about midway into the bay where the flow begins to cross over to the New Brunswick side. On the New Brunswick side the flow is toward the west and out of the Bay of Fundy into the Gulf of Maine.

The general characteristics of all of the major inlets and bays within the Region have been estimated by Gregory et al. (1993). These characteristics include summaries of bathymetry, tidal heights, freshwater inputs and estimated tidal currents and flushing rates. The tidal currents and flushing rates were based on simple tidal prism considerations, with flushing times generally being on the order of 1 - 10 tidal cycles (Gregory et al. 1993).

Along the eastern areas of Nova Scotia, areas 4Tg, 4Vn, 4Wd and 4Wk, the tides are relatively weak (amplitude order 1 m), tidal currents are estimated to be of order 0.1 m s^{-1} and wind, freshwater and offshore pressure driven forces have a significant influence on currents. In contrast, the tides and currents within the bays along the entrance to and within the Bay of Fundy (areas 4Xs, 4Xr and 4Xq) are dominated by tidal motions. The tidal amplitude in these areas is several meters (4 - 10 m) and typical tidal currents are of order 0.1 - 0.5 m s^{-1}. Tidal currents in some of the narrow channels within the coastal areas of the Bay of Fundy can exceed several meters per second. These geographic differences in driving forces are reflected in time series of current speeds. For example, current time series from the swNB area show reasonably regular periodicity in the current speeds due to the dominance of the tides whereas current meter records from the southeastern coast of Nova Scotia show a more irregular pattern (Figure 31).

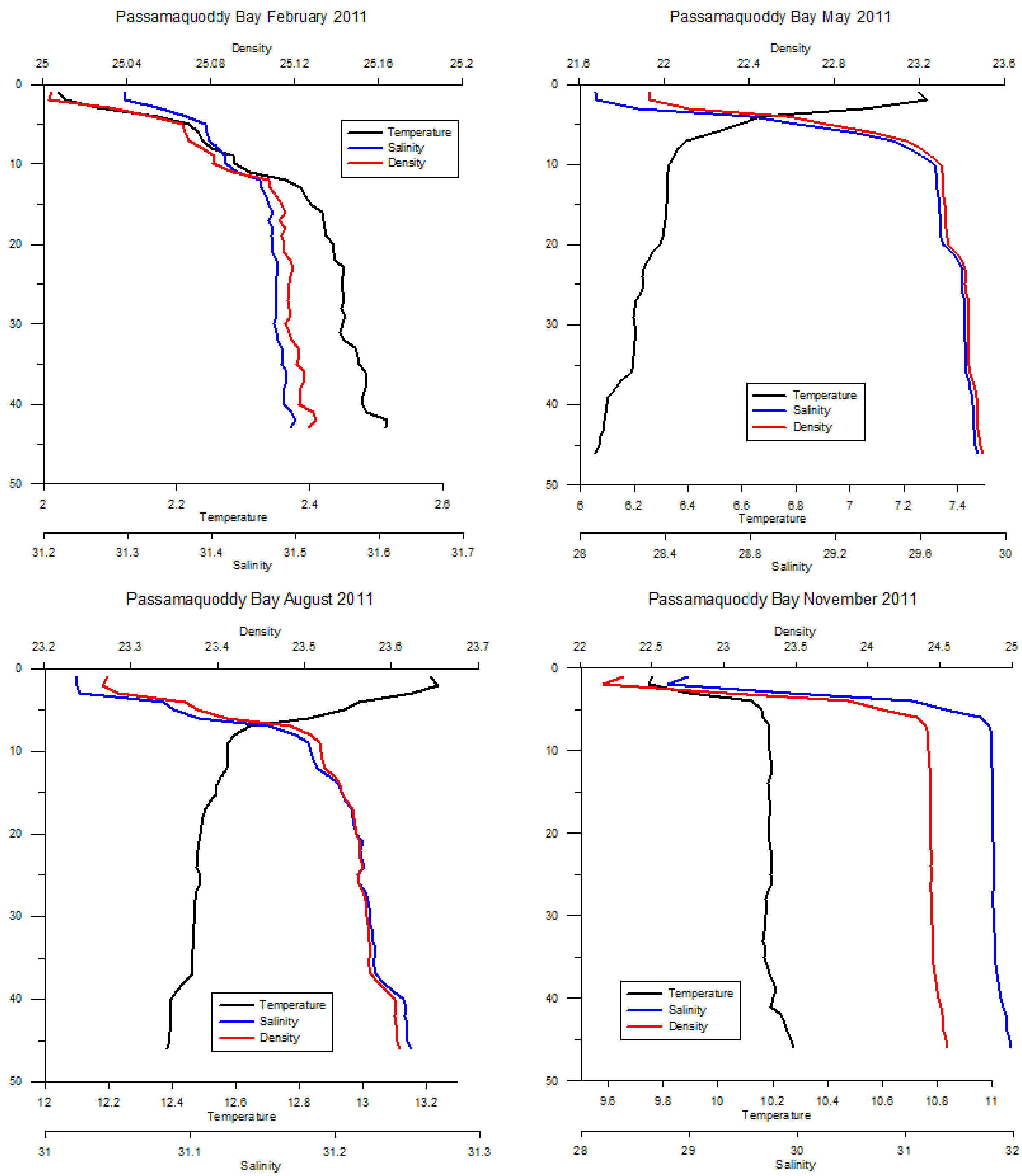

Figure 29. Vertical profiles of water temperature, salinity and density at a location within Passamaquoddy Bay, swNB. Note the scales differ between panels.

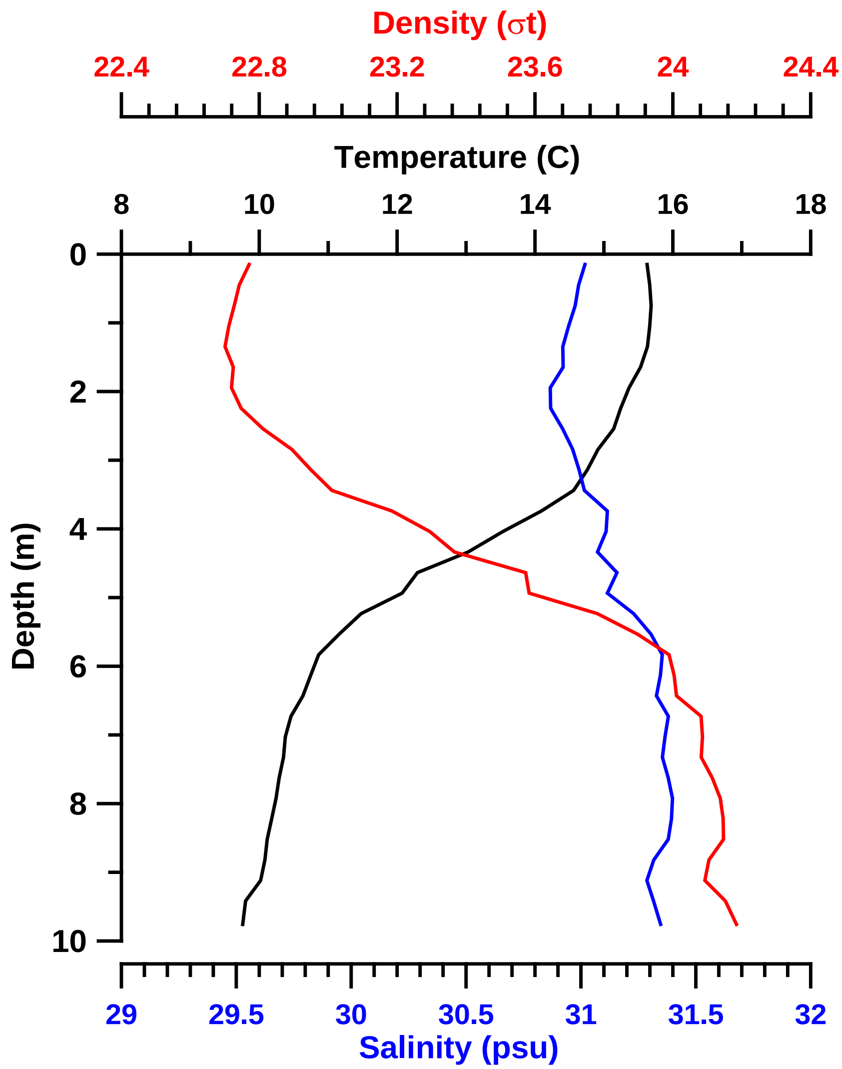

Figure 30. Vertical profiles of water temperature, salinity and density at a location within Shelburne Harbour, Nova Scotia.

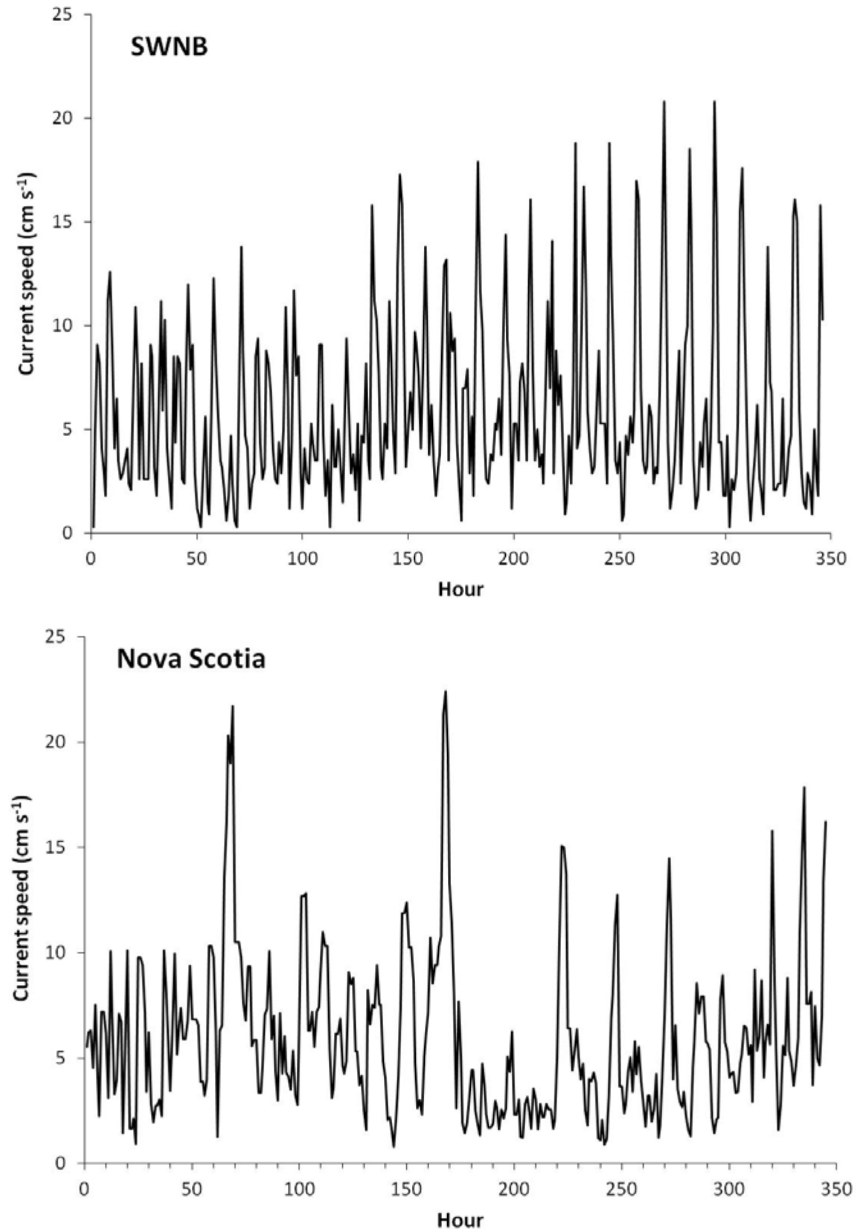

Figure 31. Time series showing a two-week period of current speed recorded at a salmon farm site in the tidally dominated swNB (top) area and at a farm site in a less tidally active area of Nova Scotia (bottom).

Detailed specific characteristics of water currents within the bays and inlets are not well known in most cases. Empirical observations are absent or sparse from most of the inlets and numerical circulation models of one sort or another have been developed for only a few inlets (Lunenburg Bay, Halifax Harbour, Ship Harbour and swNB). An example of output from the swNB model is shown in Figure 32. Models are now being worked on for several of the bays (e.g., St. Mary's Bay and Shelburne Harbour) supporting salmon aquaculture.

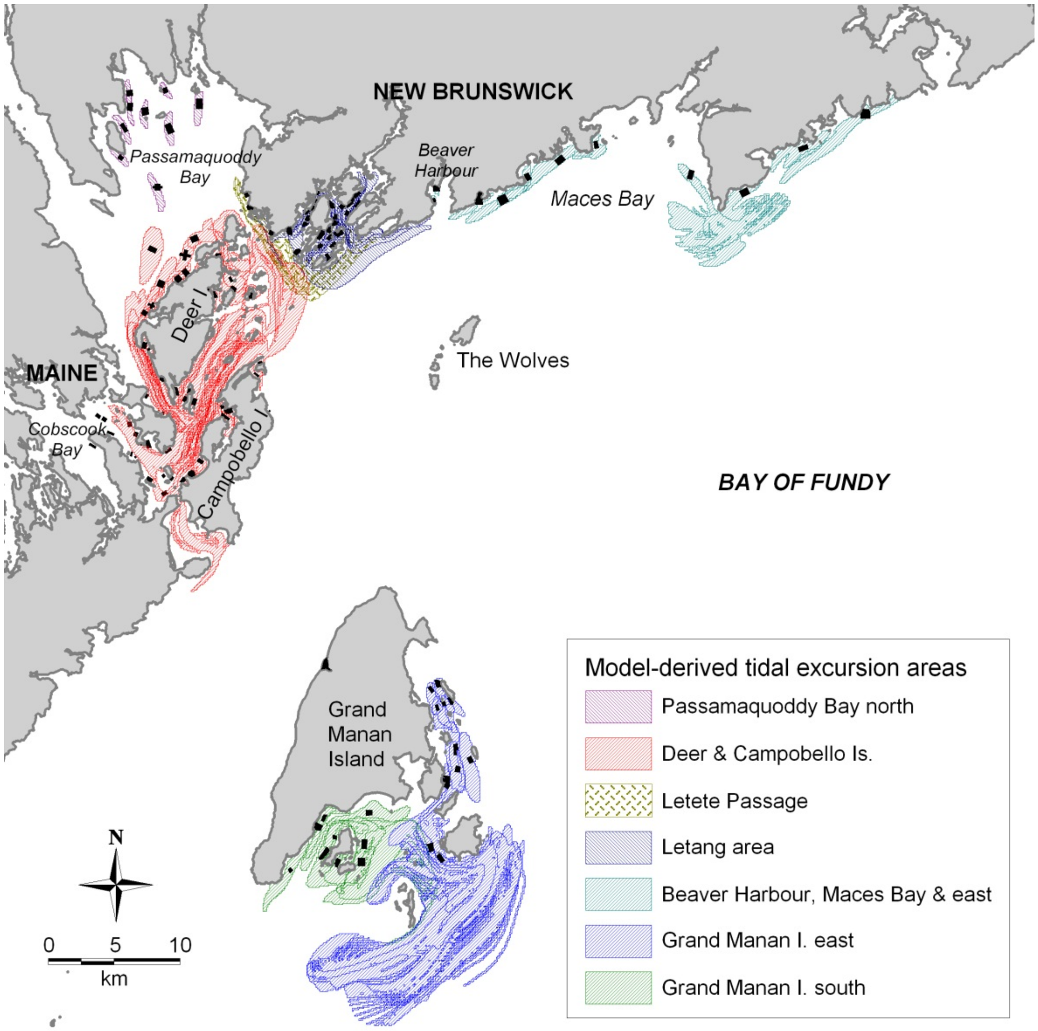

Figure 32. Tidal excursion areas estimated for salmon farms in the southwest New Brunswick area, area 4Xs, of the Bay of Fundy. This figure is based on outputs described in Page et al. (2005), Greenberg et al. (2005), and Chang et al. (2005 a,b,c, 2006 a,b, 2007).

Despite the general lack of available current meter records from the farming areas and farm sites, some records do exist and descriptive statistics of current speeds generated from some of these records are shown in Figure 33. The currents have been measured with Acoustic Doppler Current Meter technology. For the most part the duration of each current meter record is about 30 days, although some records are longer. The number of salmon farms in Nova Scotia is much fewer than in southwest New Brunswick and hence the number of current meter records available from Nova Scotia farms is considerably less than for New Brunswick. In all geographic areas the minimum current is below 2 cm s^{-1}. The mean and median current speeds range between about 5 and 50 cm s^{-1} with the majority of the mean and median speeds being between 5 and 25 cm s^{-1}. In contrast, the maximum speeds range between about 20 and 200 cm s^{-1}, with the majority of the maxima being between 20 and 60 cm s^{-1}. Mean and median speeds greater than 25 cm s^{-1} and maximum speeds greater than 70 cm s^{-1} occur at only a few sites and these are in the tidally dominated 4Xs and 4Xr geographic areas.

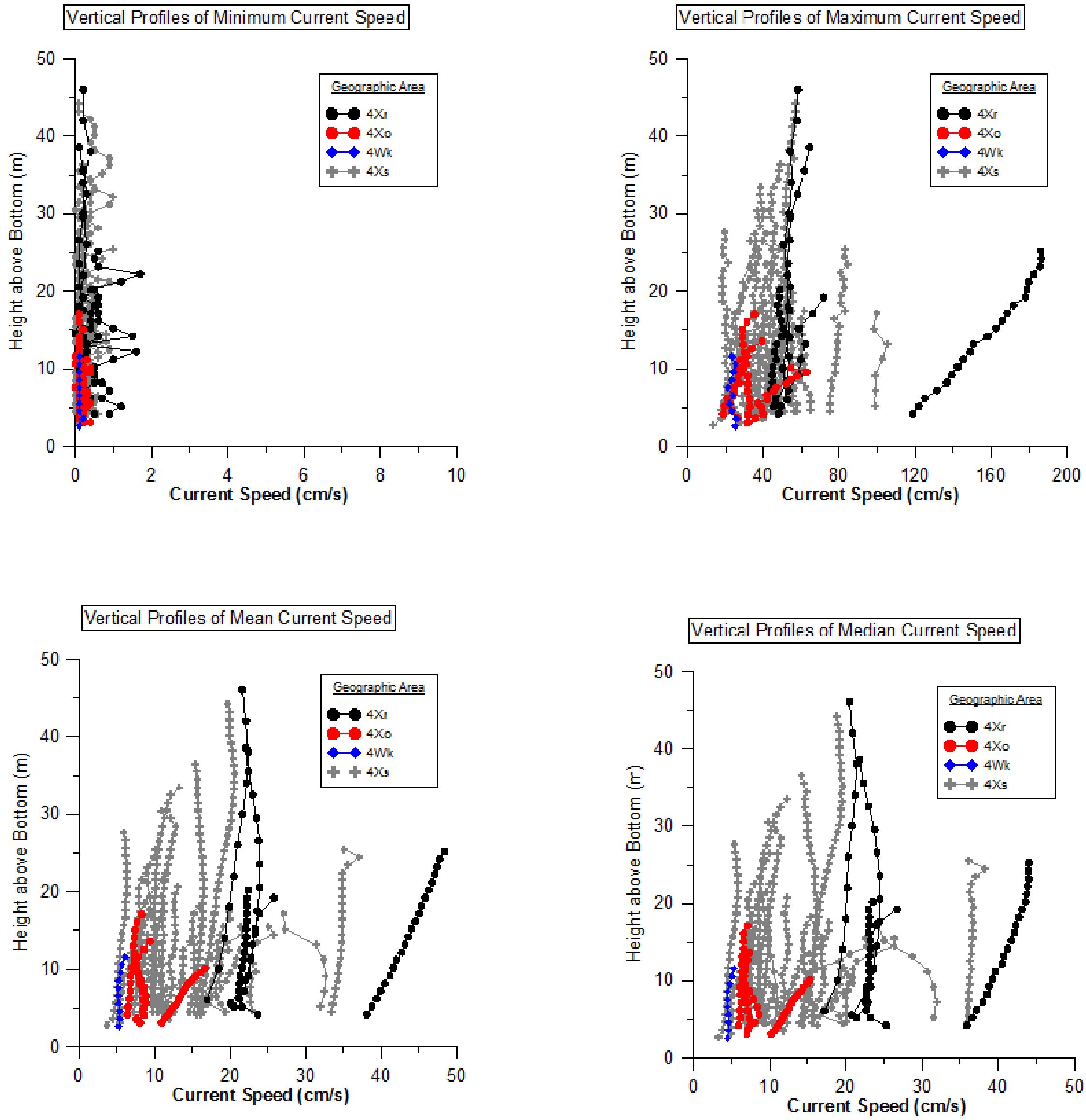

Figure 33. Vertical profiles of water current speed statistics at salmon farms located within the major salmon farming areas of the Maritimes Region.

The above current speeds can be used to crudely estimate a travel distance for the free swimming pre-infective stages of sea lice, nauplier I & II and copepodid stages. For each estimate the duration of the pre-infective stages was estimated from the indicated temperature assuming the stage duration as a function of temperature relationship reported by Stien et al. (2005). The distance travelled was estimated as a simple product of water velocity times the stage duration for a range of constant water current speeds.

Table 1 shows the estimates of distance travelled for a range of water temperature and current speed values. The distances at a typical temperature of 10^{o}C and mean current speeds of 10-20 cm s^{-1} ranged from 10 to 124 kilometres. These distances suggest that water transport of the infective stages of sea lice between clusters of salmon farms within the Maritimes Region may not be a regular occurrence since the distance between clusters is usually greater than 100 km by sea (Figure 21). However, the estimated travel distances far exceed the nearest neighbour distance between farms within each of the farm clusters, particularly within the swNB area of the Maritimes Region (Chang et al. 2011).

Table 1: Estimates of distance (km) travelled by free swimming pre-infective stages (nauplius I and II and copepidid) of sea lice assuming a range of current speeds and water temperatures. The duration of the free swimming pre-infective stage was estimated using the relationship reported by Stien et al. (2005).

Temperature (^{o}C)	Duration of Free Swimming Stages (days)	Current Speed (cm s^{-1})					
		5	**10**	**15**	**20**	**30**	**40**
5	9.6	41.3	82.7	124.0	165.3	248.0	330.6
10	3.6	15.7	31.3	47.0	62.7	94.0	125.4
15	1.9	8.2	16.4	24.5	32.7	49.1	65.4
20	1.2	5.0	10.0	15.0	20.0	30.1	40.1

This latter point is further illustrated by the fact that the travel distances greatly exceed the tidal (12.4 h) excursion distances estimated for each of the salmon farms in swNB (Figure 32). Excursion plumes in this area were estimated using a particle tracking model driven by currents generated by a Quoddy finite element 3D circulation model implemented for the area (Page et al. 2005; Greenberg et al. 2005; Chang et al. 2005 a,b,c; Chang et al. 2006 a,b; Chang et al. 2007). This model assumed particles remained near the sea surface and drifted passively with the current. These relatively short duration excursions are sufficient to indicate that a considerable potential exists for exchange of sea lice between salmon farms in the swNB area. Excursions and dispersal associated with the several day durations of pre-infective sea lice stages further enhances the potential for exchange.

In addition to the above features, exposure to surface gravity waves, and hence wave generated currents, can be significant in some areas, and at some farms. Significant wave heights are of order 3 m and extreme heights are of order 10 m in the more exposed locations (Trites and Garrett, 1983). To date only a few farm sites are located in these exposed areas because of the difficulties in maintaining and operating farms in such conditions but technologies are slowly being developed and implemented that will help overcome these difficulties. However, at the present time little information is available to quantitatively describe these characteristics at farm sites.

KEY FINDINGS

PACIFIC COAST

1- There are concentrations of salmon farms in several regions on the Pacific Coast including the inlets along the west coast of Vancouver Island, the Discovery Islands and the Broughton Archipelago. The Broughton Archipelago has been the focus of most of the research into the control of sea lice.

2- Sea surface temperatures vary seasonally and by region (from just above freezing to 18^{o}C), and are suitable for all life stages of sea lice.

3- Sea surface salinity varies by season and location due to the influx of fresh water from direct precipitation and snowmelt.

- On the west coast of Vancouver Island winter precipitation is greatest and surface water salinity is lowest during this time (November to February). In the fjords of the Broughton Archipelago and other areas that are influenced by snowmelt from the watersheds of the Coast Mountain Range, the low salinity season is from April to July.

4- Energy from tides, waves and winds is present in all areas to drive the vertical and horizontal movement of water. Vertical and horizontal density differences also contribute to the current regime.

- There is considerable spatial variability in the relative contributions of these forces. The rough coastline topography can cause small scale intensification or sheltering of these forces. This may result in significant changes in local stratification and rates of advection over space scales of a few kilometres and time frames of hours.

EAST COAST- SOUTH COAST OF NEWFOUNDLAND

1- The aquaculture activities in the south coast of Newfoundland are mainly concentrated in Bay d'Espoir, Fortune Bay, and Hermitage Bay, with further expansion anticipated.

2- Each of these three salmon farming areas have quite different oceanographic characteristics in terms of their temperature, salinity and currents.

3- Surface salinity varies by season and location within the bay. The presence of freshwater is more important in Bay d'Espoir (0 – 25 psu) than in the other bays.

- Vertical stratification can be strong during seasons of high run-off, but not below 10-15 m. Below this depth the water mass salinity remains at 30 psu.
- Salinities appear to be very high in the winter months and lower in the summer months due to river run-off.

4- Surface temperatures range from as low as -1.3^{o}C in the winter up to 21^{o}C in the summer months.

- Typical temperatures are below 5^{o}C from mid-December to mid-April.

5- Short term variability, with a time scale of hours to days, have been observed during summer and fall. The variation of surface salinity can be more than 20 psu and that of surface temperature, more than 10^{o}C.

6- Mean surface currents range between 0.08 - 0.26 m s^{-1} except during times of severe storms or at the head of the bay (0.36 m s^{-1}).

7- Surface circulation is complex and driven by a number of forces (tides, winds, etc.).

EAST COAST- MARITIMES REGION

1- Commercial salmon aquaculture occurs predominantly in the Bay of Fundy; however there is significant expansion into southern Nova Scotia anticipated.

2- Inshore water temperatures within the Maritimes Region range from -2.4 to 24.3^{o}C.

- In the east the temperatures sometimes exceed the preferred range limits for Atlantic Salmon.

3- Salinities within the farming areas of the region are generally above 30 psu or are in the high 20s.

4- Farms in the Maritimes region are generally located in relatively shallow and gently sloping bottoms, with water depths of about 20 m.

5- Current speeds at farms in the region range from almost zero, to over 100 cm $s^{-1.}$

- Mean current speeds are typically less than 25 cm s^{-1}.

6- The duration of the dispersal stages of the sea lice, nauplii and copepodids, ranges from about 1 to 10 days based on average temperatures and the temperature duration relationship of Stien et al. (2005).

7- The transport distances of pre-infective sea lice stages is on the order of 10 - 100 kilometres suggesting that farms within bays or nearby bays may exchange sea lice whereas farms in bays separated by distances greater than 100 km may have only limited sea lice exchange.

ALL REGIONS

Bathymetry

- The bathymetric and topographic complexity of many of the salmon farming regions in Canada make it advisable to adopt a region specific approach to sea lice management.
- Bathymetric data are a necessary input to hydrodynamic models used to simulate sea lice dispersal.

Salinity

- Salinity plays a key role in the movement of water and the viability of sea lice. In BC and NL, freshwater influences are of greater importance than in NS, NB, where salinity rarely falls below 28 psu.
- Salinity varies seasonally and spatially.

Stratification

- The degree of stratification and vertical mixing varies temporally and spatially in all regions and have potentially significant implications for control and management, especially with respect to the use of therapeutants.

Currents

- Data on currents are required both at the farm site and throughout the region to validate hydrodynamic and particle tracking models.

AREAS OF UNCERTAINTY

1- Environmental conditions during stormy conditions and seasons are less understood, in large part because it is relatively difficult to obtain in-situ observations during stormy weather.

- Of particular concern are the storms that occur during the summer/fall seasons when the temperature conditions are favourable for sea lice growth. Although storms occur during the winter season the water temperatures are relatively low and sea lice development is hindered.

2- Simple estimates of transport distances for the infective stages of sea lice range from 10 - 100 km. These assume constant water temperatures and current velocities over the duration of the pelagic, pre-infective sea lice stages and that the sea lice remain within these conditions. More refined estimates of transport distances require that sea lice behaviour and the spatial and temporal variations in the temperatures and velocities be taken into consideration.

3- The environmental conditions in the existing salmon farming areas will change in the future to some degree, especially in the context of climate change. For example climate change is expected to:

- Increase the frequency and severity of storms and hence increase wave heights and vertical mixing on an “event” scale.
- Shrink mountain glaciers and snow packs and hence reduce freshwater runoff from these sources. This may influence water stratification and the areas suitable for sea lice survival.
- Increase sea levels which may in turn change tidal dynamics, water currents and mixing.
- Increase water temperatures and hence accelerate sea lice development rates and increase the duration of the sea lice favourable “season”.
- Increase the acidification of coastal waters which may influence sea lice physiology.

4- The temperature, salinity and water flow information produced by numerical models requires field truthing to reduce the uncertainties associated with management decisions to control sea lice.

5- Field monitoring of sea lice on wild fish contributes to a reduction in the uncertainty that models and management strategies are effective.

ADVICE AND RECOMMENDATIONS FOR FUTURE RESEARCH

1- More oceanographic data are needed at the specific locations of the salmon farms and this needs to be related to the broader scale oceanographic context in the area of interest.

2- More information is needed to relate the influence of water velocities and sea lice behaviour on sea lice transport and dispersal.

3- Consideration should be given to identifying the influence of other environmental factors that may impact sea lice biology, such as dissolved oxygen and pH.

4- Sea lice monitoring data should be used to test predictions of sea lice life stage duration.

5- Currents and flushing rates at the farm scale should be characterized using field data and corresponding model simulations.

6- Investigate the relative importance of physical oceanography factors in the context of influencing control and management strategies for sea lice.

7- Coupled physical-biological models need further development, validation, and application. The models are a useful tool for helping to develop enhanced understanding of sea lice dynamics in spatially and temporally varying environments. However, they need to be further developed, tested, and validated from both physical and biological perspectives. A particularly weak component of these models is sea lice behaviour; how it varies in relation to different environmental conditions and how it influences the development and dispersal of the various sea lice stages.

8- Collaboration among different bodies (Industries, Province, Universities, DFO) involved in sea lice control should be highly encouraged with the objectives of quick response when taking any measures.

SPECIFIC CONNECTIONS TO THE TERMS OF REFERENCE

The following section summarizes some thoughts on how knowledge of the oceanography in the sea lice areas relates to specific questions (objective numbers) in the CSAS Terms of Reference. Since the physical oceanographic factors differ to some degree among the regions of Canada, the TOR questions will be addressed from specific regional perspectives, i.e., Pacific Coast, East Coast-Newfoundland and East Coast-Maritimes.

POPULATION ECOLOGY AND EPIDEMIOLOGY OF SEA LICE IN CANADIAN WATERS

Question 1: Role of other sea lice hosts (wild salmonid and non-salmonid) as reservoirs and other factors influencing sea lice dynamics near or on farms.

Pacific Coast

Wild salmon migrating in the fall to their spawning streams are known to host sea lice. As they proceed into the fresher water of the spawning areas it is expected that this exposure to low salinity water results in motile sea lice abandoning their wild hosts to seek other hosts in more saline conditions. In these circumstances stocked fish farms in areas where the salinity is greater than 25 psu provide a likely target for sea lice.

The March to July period is the time frame when the out-migrating wild juvenile salmon population is sympatric with farm-source sea lice. This time period coincides with significant changes in temperature and salinity due to seasonal warming and increased fresh water from snow melt. Awareness of environmental conditions is important to both the rate at which sea lice will advance through their life cycle and the efficacy of the chemotherapeutants used at the fish farms.

East Coast - Newfoundland

Given the differences in salinity among the bays in the south coast of Newfoundland, and within the same bay itself, its effect on controlling the sea lice development and mortality will differ. The heads of the bays tend to show certain degrees of lower salinity, while towards the mouth, salinity is generally higher, reaching values closer to that of the open ocean.

East Coast - Maritimes

Salmon farms within the Maritimes Region tend to be located in relatively shallow water and at the mouth of estuaries or along the open ocean coast. As a consequence, the physical environmental conditions of most influence are temperature, current and waves. For most farms the influence of freshwater outflows is dampened somewhat by estuarine mixing processes before it reaches farms sites. However, there are a few exceptions and these farms are subjected to wider variations in salinity and temperature. Several farms in Nova Scotia have the potential to experience rapid changes in temperature, on the order of ten degrees Celsius, due to water mass exchange processes. Several farms are challenged by exposure to strong currents and relatively high wave amplitudes and a few farms are challenged by exposure to the challenge of drifting shore fast ice.

From a biological perspective most of the Maritimes Region farms are potentially in the migration pathways of wild Atlantic Salmon and the status of these salmon stocks is threatened.

From a farm distribution perspective, many of the farms, particularly in southwest New Brunswick, are in very close geographic proximity to each other and hence the potential for exchange of sea lice between farms is high and the need for coordination of sea lice management activities between farms is paramount.

MONITORING FOR SEA LICE ON FARMED AND WILD SALMON IN WESTERN AND EASTERN CANADA AND ADVICE ON SOUND METHODOLOGIES

Pacific Coast

The daily temperature and salinity, measured from the surface to a depth of 15 m, at fish farms is a necessary component of understanding the environmental conditions important to the control of sea lice. These observations require an accuracy of 0.1^{o}C for temperature and 0.1 psu for salinity. This information is useful for both on-farm and regional management programs to control sea lice.

East Coast - Newfoundland

In the south coast of Newfoundland, observations have shown that environmental conditions can change in a very short time with surface salinity variation of more than 20 psu and surface temperature variation of more than 10^{o}C. These events can have time scales of hours to days. When monitoring farms for sea lice, this short-term variability should be captured with relatively high frequency measurement (maximum of few hours). This is a necessity especially in summer and fall when the variation in environmental conditions is more frequent and the temperature of the surface water is within the range favorable to sea lice growth and survival. An accuracy of 0.1^{o}C for temperature and 0.1 psu for salinity is recommended in order to collect valuable environmental data.

East Coast - Maritimes

In the southwest New Brunswick area fish farms are very close together and many of the farms are hydrographically connected such that drift time scales between farms are on the order of minutes to hours. Hence, interpretation of sea lice counts on individual farms needs to take into consideration the possibility of sea lice infestations from adjacent farms. These infestations may not just be through pre-infection transport and dispersal; they may also be from later stages if these have been knocked off by sea lice control measures or harvesting processes.

Interpretation of development rates, monitoring of environmental conditions and forecasting of sea lice development also needs to take into consideration that temperatures at some farms can vary by several degrees during each tidal cycle.

Question 6: Program design for wild fish sea lice monitoring, including: frequency of sampling, out-migrations, in-migrations, sampling location, timing, environmental factors to be considered, sea lice dynamics, and other considerations (e.g., species differences, at-risk status of wild stocks of interest, etc.).

Pacific Coast

Any monitoring of wild fish will benefit from the simultaneous collection of relevant environmental data. At a minimum there is a need to collect sea surface temperature and salinity to an accuracy of 0.1^{o}C and 0.1 psu, respectively. For sites that are monitored on a regular basis, additional physical features should be recorded including: flow variability due to tides, the proximity and flow rate of adjacent streams, and changes in foreshore characteristics.

East Coast - Newfoundland

The timing of the wild fish migration (out-migration of smolt and returning adult salmon) occur mainly between early spring and mid-summer (Dempson et al. 2001, 2011). During this period of the year, monitoring of sea lice as well as physical parameters such as temperature, salinity, and currents is critical and helps in carrying out coupled biology-hydrodynamical and statistical modeling exercises involving sea lice dynamics. A minimum accuracy of 0.1^{o}C for temperature and 0.1 psu for salinity is recommended for the data to be usable in modeling exercises.

East Coast - Maritimes

Most of the Maritimes Region salmon farms are to some degree within the migration pathways of wild Atlantic Salmon and the status of these salmon stocks is threatened. Hence, there is a potential for wild-cultured salmon interaction involving sea lice. Unfortunately, the low abundance of the wild salmon limits the ability to sample the wild populations. It also increases the need to sample the cultured salmon and to implement effective sea lice control strategies.

NON-CHEMICAL MEASURES OF CONTROL AND PREVENTION

Question 8: Scientific advice on factors that influence the effectiveness of fallowing as a means of sea lice control, including fallowing time required, scale of fallow (e.g., farm-scale versus bay-scale), and other factors required to interrupt sea lice population dynamics on farms to decrease next year’s load, etc.

Question 9: The effect of farm density and stocking density on sea lice population dynamics at different scales (i.e., individual pens, individual farms, within a bay or area).

Pacific Coast

The use of hydrodynamic models at a regional scale, i.e., within a management area such as the Broughton Archipelago or the Discovery Islands, provides a means of simulating the combined effects of water flow, temperature, and salinity on the operational management of fish farms. Suitable model runs can inform farm siting, fallowing and stocking options, and treatment and harvesting practices at a range of temporal and spatial scales. The validity of these models to represent the physical environment continues to be tested, and the uncertainties in the model output will remain an important consideration in decisions regarding the management of sea lice.

East Coast - Newfoundland

Given the high number of active sites and the frequent and sometimes high variability in environmental conditions in the south coast of Newfoundland, a circulation and sea lice dispersion model could play a major role in providing advice on spatial and temporal farm-fallowing decisions. The model can be used to simulate different possible scenarios of sea lice dispersion from individual farms and its footprint under different environmental conditions. This should bring valuable information in developing an efficient and effective sea lice management strategy.

East Coast - Maritimes

In southwest New Brunswick, farms within designated aquaculture bay management areas are fallowed for two to four months or longer before restocking. This fallowing is part of the area’s Aquaculture Bay Management Area strategy. Unfortunately, most of the fallowing occurs during the winter months when sea lice activity is temperature limited. Fallowing during the spring-summer-fall periods may be more effective from a sea lice control perspective. Also, in southwest New Brunswick the close proximity of farms to each other and the potentially large dispersal distances of sea lice, means the effectiveness of farm fallowing may be limited due to re-infection from active sea lice shedding from infected farms within the sea lice transport and dispersal zones.

In the southwest New Brunswick area farms are relatively close together, within 100's of metres to a kilometre or so of a neighbouring farm. As a consequence the farms are extensively connected via hydrographic processes and the potential for sea lice exchange between farms is high as is the need for coordinated sea lice control measures. A reduction in farm density may therefore have the potential to improve sea lice control capability and reduce the intensity and geographic extent of sea lice outbreaks. Development and implementation of a coordinated sea lice monitoring and physical-biological modeling initiative that can identify farms with high sea lice counts and predict the potential consequence of this situation to other farms, may help develop and direct an efficient and effective sea lice management strategy.

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