SPATIAL AND TEMPORAL DYNAMICS OF SUSPENDED PARTICULATE MATTER SURROUNDING FINFISH FARMS ON THE EAST AND WEST COASTS OF CANADA

by

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Submitted in partial fulfilment of the requirements
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To my Mom and Dad for their never-ending support and unconditional love.

“Affirming words from moms and dads are like light switches. Speak a word of affirmation at the right moment in a child's life and it's like lighting up a whole roomful of possibilities.” -- *Gary Smalley*

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Abstract

Achieving optimization of IMTA sites and modeling the efficiency of such a system requires knowledge of the spatiotemporal distribution and variability of TPM surrounding the finfish farms. The objective of this study was to quantify the impact of finfish farms on the surrounding particle field. Platforms equipped with transmissometers, fluorometers and CTD's were towed around the sites while undulating through the water column in a high-resolution 3D spatial survey approach. In addition, combination turbidity and chlorophyll *a* sensors were moored at a variety of locations and depths. Surveys were conducted concurrently with the deployment of current meters. Farms surveyed were found to have little impact on the surrounding suspended particle field (mean effect < 1 mg L^{-1}). Results provided evidence of minimal enhancement from fish farm wastes, primarily in surficial waters (0.5- 2 m depth) immediately adjacent to the cages, and evidence of predominantly tidal driven (M_2) TPM dynamics.

List of Abbreviations and Symbols Used

Abbreviation/Symbol	Definition	Unit
ADV	Acoustic Doppler Velocometer	
ANOVA	Analysis of Variance	
C_p	Beam Attentuation	m^{-1}
CC	Charlie Cove	
CHL*a*	Chlorophyll *a*	$\mu g\ L^{-1}$
cph	Cycles per hour	h^{-1}
CTD	Conductivity-Temperature-Depth Recorder	
df	Degrees of Freedom	
DFO	Fisheries and Oceans Canada	
FCR	Feed Conversion Ratio	
GPS	Geographic Positioning System	
IMTA	Integrated Multi-Trophic Aquaculture	
M_2	Principal Lunar Semi-Diurnal Tides	
NI	Navy Islands	
P_1	Principal Solar Diurnal Tides	
POM	Particulate Organic Matter	
SD	Standard Deviation	
T	Transmittance	%
TPM	Total Particulate Matter	$mg\ L^{-1}$
v.	Version	

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First and foremost, I offer my sincerest gratitude to my supervisors, Drs. Peter Cranford and Jon Grant. I attribute the level of my Masters degree to their encouragement and effort. One simply could not wish for more caring or dedicated supervisors. Peter, I cannot thank you enough for the endless opportunities you have provided for me, and for always looking out for my best interests, both professionally and personally. Jon, I have always valued our open chats and your caring nature. I appreciate the guidance you have given me, and have never taken for granted the understanding and patience you have shown me. Both of you have been motivating, encouraging, and enlightening. You have never judged, nor pushed, when you knew I needed to juggle priorities. Thank you for always believing in my abilities, for making this an incredibly positive experience, and for instilling the professional confidence in me to be a success.

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"At times our own light goes out and is rekindled by a spark from another person. Each of us has cause to think, with deep gratitude, of those who have lighted the flame within us." – Albert Schweitzer

Chapter 1: Introduction

Global finfish aquaculture is developing rapidly (FAO, 2010). The open nature of many culture systems has had impacts on the surrounding environment, including the potential for suspended particulate organic matter (POM) enhancement (Jones and Iwama, 1991; Lefebvre *et al.,* 2000; MacDonald *et al.,* 2011). The finfish aquaculture industry has adopted a number of strategies to reduce wastes from the presence of fecal material and waste feed. Strategies have incorporated improvements in the digestibility of feed (Cheshuk *et al.,* 2003; Islam, 2005; Reid *et al.,* 2008), waste pellet detection (Reid et *al.,* 2008) and the development of dispersal/deposition models (Gowen *et al.,* 1989; Findlay and Watling, 1994; Cromey *et al.,* 2002).

Integrated Multi-Trophic Aquaculture (IMTA) is being viewed as another potential approach to minimizing the finfish farm impact. It is based on the principle of recycling excess organic and inorganic nutrients that are released from the feeding operations of aquaculture activities. IMTA has been utilized for centuries in Asian countries (Li, 1987; Liao, 1992; Chiang, 1993; Qian *et al.,* 1996), and has more recently been developed in Canada, where pilot experiments have been conducted (Chopin *et al.,* 2001).

Research on the potential for bivalve filter-feeders to extract significant quantities of suspended fish farm wastes and consequently, to exhibit enhanced growth has provided conflicting evidence. Some studies have shown growth enhancement from being placed in close proximity where they can use particulate wastes as an additional food supply (Lefebvre *et al.,* 2000; Mazzola and Sarà, 2001; Reid *et al.,* 2008), while others have reported zero or minimal growth enhancement (Taylor *et al.,* 1992; Stirling and Okumus, 1995; Gryska *et al.,* 1996).

The introduction of an IMTA system inclusive of bivalves with the potential to assimilate suspended solid wastes has required new efforts in characterizing the spatial and temporal variability in seston surrounding finfish aquaculture sites. A number of phenomena can impose limitations on the proportion of fish culture solids that could be delivered to a bivalve population, including the amount available compared to natural total particulate matter (TPM) concentrations, and the direction, depth and frequency of particle delivery. There are a few published papers relating to open-water IMTA that have attempted to measure both near- and far-field suspended particle concentrations (Lander *et al.,* 2004; Sarà *et al.,* 2009; MacDonald *et al.,* 2011; Handå *et al.,* 2012). However, the spatial and temporal scope of these studies has been limited by approaches that may not be sufficient to study the fate of particulate wastes in dynamic coastal environments.

The objectives of this thesis are to delimit the magnitude, timing, spatial extent, and dilution/dispersion pathways of suspended particulates at finfish aquaculture sites using high-resolution spatial and temporal surveys. Chapter 2 of this thesis will focus on three-dimensional spatial surveys conducted at two Atlantic salmon farms in the Bay of Fundy region of New Brunswick. Both near-field and far-field survey approaches will be explored at these two sites, which differ from each other based on production size and level of open-water exposure versus shelter. These comparisons will address to what extent the finfish farms are contributing suspended particulates beyond the range of naturally-occurring TPM concentrations, and what factors may affect the variability.

Chapter 2 is intended to provide snapshots on the spatial variability of TPM within the time-scales of estuarine variation. Chapter 3 of this thesis will focus on the collection and analysis of TPM time-series at the same two Atlantic salmon farms in the Bay of Fundy, and a sablefish farm in Kyuquot Sound, British Columbia. A variety of depths and locations will be explored surrounding the sites, which again, differ from each other based on production size and level of shelter, as well as hydrodynamic regime and culture species. These comparisons will provide information on the forcing mechanisms of TPM variability over time at these sites and assess whether the finfish farms contribute excess suspended particulates to the water column on a persistent or intermittent basis. Chapter 3 is intended to bridge the gaps between the spatial snapshots in time that will be examined in Chapter 2, and complete the picture of TPM dynamics at these finfish aquaculture sites. Chapters 2 and 3 are intended as standalone manuscripts for publication in the primary literature. Consequently, there is some repetition among chapters. Lastly, Chapter 4 will summarize the findings of Chapters 2 and 3, recommend areas for future investigations, and provide context for the relevance of findings in these studies to the feasibility of commercial IMTA.

Chapter 2: Atlantic Salmon (*Salmo salar*) Aquaculture Farm Impacts on the Spatial Dynamics of Surrounding Suspended Particulate Matter in the Bay of Fundy Region (New Brunswick)

2.1. Abstract

It has been established worldwide that suspended particulate matter levels may be enhanced by Atlantic salmon farms, due to the presence of fecal material and waste feed. Research on the potential for Integrated Multi-Trophic Aquaculture (IMTA), particularly for bivalve filter-feeders to extract significant quantities of these suspended wastes and, consequently, to exhibit enhanced production from being placed in close proximity to fish cages, has provided conflicting evidence. The difference in findings may indicate the importance of local environmental factors that control waste dispersion. The objective of this study was to quantify the impact of Atlantic salmon farms in the Bay of Fundy on the surrounding particle field by delimiting the magnitude, spatial extent, dilution and dispersion of suspended particulates at these sites. Platforms equipped with transmissometers, fluorometers, and CTDs were towed around two Atlantic salmon farms, in the near- and far-field, while undulating through the water column. *In-situ* calibrations were conducted for estimation of total particulate matter (TPM, mg L^{-1}) and chlorophyll *a* (Chl *a*, μg L^{-1}). Hydrodynamic data was simultaneously collected when instrumentation was available for average current speed and direction. Results provided evidence of low levels (mean effect < 1.5 mg L^{-1}) of suspended particle enhancement from fish-farm wastes, primarily in surficial waters (0.5 to 2 m depth), down-current from both sites. Increased TPM variability in the surface layer immediately down-current from one of the

sites was also found to be a significant result. Given the low levels of apparent TPM enhancement adjacent to the farms, it is difficult to attribute this result to a farm-based source of TPM, or to natural seston patchiness.

2.2. Introduction

Global Atlantic salmon, *Salmo salar*, production reached over 1 million tonnes in 2001. Production in Canada alone neared 100 000 tonnes, making this fish Canada's predominant aquaculture species (FAO, 2010). New Brunswick contributes 30% of Canada's total farmed salmon, second only to British Columbia in terms of production. With 90 active marine site leases, salmon farming is one of New Brunswick's most important economic drivers, generating over $270 million in yearly revenue, as New Brunswick's biggest farm-based export (ACFFA, 2010). Concerns of sustainability are associated with the extent of fish farming throughout the world, and particularly within the Bay of Fundy.

Production of Atlantic salmon is largely derived from coastal culture in floating cages. The open nature of this culture system allows for continuous exchange of water between the cages and the surroundings, which has lead to impacts on the natural environment (Beveridge, 1984; Gowen and Bradbury, 1987; Folke and Kautsky, 1989; Beveridge *et al.,* 1991, 1994; Phillips *et al.,* 1991). Fish cage farms entail the release of large quantities of dissolved and solid biogenic wastes. One of the most conspicuous impacts of open net cage fish farms is caused by the increased particle loading on the seabed in the near-field environment, and consequential organic enrichment impacts on sediment geochemistry and benthos. It has also been established worldwide that suspended particulate organic matter (POM) levels may be enhanced by the farm, due to the presence of fecal material and waste feed (Jones and Iwama, 1991; Lefebvre *et al.,* 2000; MacDonald *et al.,* 2011). However, this is not always the case (Buschmann *et al.,* 1996; Pridmore and Rutherford, 1992) and these conflicting findings suggest that particulate organic loading in the water column and the site-specific effects of fish farm contributions to eutrophication is not fully understood.

The salmon aquaculture industry has adopted a number of strategies to reduce wastes from cage-based farming and its impact on the local environment. Advances have been made over the last two decades to improve the feed conversion ratio (FCR), defined as the weight of dry feed required to produce a unit weight of wet fish (Tucker, 1998), and digestibility of salmon feed. FCRs have declined from 1.7 in 1993 to 1.3 in 2003, ultimately increasing industry efficiency in converting nutrients from fish feed to harvestable biomass (Cheshuk *et al.,* 2003; Islam, 2005; Reid *et al.,* 2008). Early estimates of feed loss were approximately 20% (Beveridge, 1987), but have since been reduced through improved waste pellet detection and feeding control mechanisms (Reid *et al.,* 2008). Feed wastage is now routinely below 5% (Cromey *et al.,* 2002; Perez *et al.,* 2002; Strain and Hargrave, 2005; Stucchi *et al.,* 2005). Dispersal/deposition models have been employed to improve site management by assessing susceptibility to organic enrichment impacts (Gowen *et al.,* 1988; Gowen *et al.,* 1989; Panchang *et al.,* 1993, 1997; Findlay and Watling, 1994; Cromey *et al.,* 2002; Chamberlain and Stucchi, 2007). In addition, emphasis has been placed on the practice of Integrated Multi-Trophic Aquaculture (IMTA) as an ecological engineering tool for reducing effluent impacts.

IMTA involves the co-culture of species from multiple trophic levels, where losses from one species (i.e. outputs) are nutritional inputs for another (Chopin *et al.,* 2001; Troell *et al*., 2003). The practice of IMTA has the potential to maximize energy flow arising from feed loss and minimize the environmental impacts of finfish farming, by following a „niche concept' (Sutherland *et al.,* 2001). IMTA systems can include inorganic extractive species such as seaweeds (removing by-products of finfish excretion and respiration) and organic extractive species such as filter- and deposit- feeders (removing suspended and deposited particulates from waste feed and feces). This practice has been utilized for centuries in Asian countries (Li, 1987; Tian *et al.,* 1987; Liao, 1992; Chan, 1993; Chiang, 1993; Qian *et al.,* 1996). The integration of biofilters, such as mussels, scallops and oysters, at fish farms has been studied in several countries, including Australia, Canada, France, Chile, Spain and the United States (Jones and Iwama, 1991; Taylor *et al.,* 1992; Stirling and Okumus, 1995; Troell and Norberg, 1998; Mazzola and Sarà, 2001; Cheshuk, 2001; Langan, 2004). Research on the potential for bivalve filter-feeders to extract significant quantities of fish farm wastes and consequently, to exhibit enhanced production from being placed in close proximity to fish cages has provided conflicting evidence. Some studies have shown that bivalves are capable of utilizing particulate wastes as an additional food supply, demonstrated by growth enhancement (Lefebvre *et al.,* 2000; Mazzola and Sarà, 2001; Reid *et al.,* 2008). However, other studies have reported zero or minimal growth enhancement when bivalves are cultured in an integrated system (Taylor *et al.,* 1992; Stirling and Okumus, 1995; Gryska *et al.,* 1996). The difference in findings may indicate the importance of local environmental factors that control waste dispersion, which need to be considered in the design of IMTA cultivation methodologies.

In the past, much attention has been paid to sedimentation dynamics at cage sites in an attempt to quantify the increased vertical flux of material. The introduction of an IMTA system design with the potential to assimilate both rapidly settling and suspended fine particulate wastes has required new efforts in characterizing suspended particle transport surrounding finfish aquaculture sites. Ideally, organic extractive species such as bivalves should be placed at optimal locations to capture the maximum cross-sectional area of suspended particulate „plumes’ exiting the fish cages (Reid *et al.,* 2008). The hypothesis of a waste plume typically infers that at some location surrounding the farm, a spatially defined cone of enhanced total suspended particulate matter (TPM) will originate in the water column at the farm and will be continuously and uniformly transported away from the source with the ambient water flow. A decline in excess TPM concentration may be expected with distance from the farm owing to dispersive processes. Whether or not this conceptual suspended particle plume exists at fish aquaculture sites has yet to be determined.

Achieving design optimization of IMTA sites and modeling the efficiency of such a system requires knowledge of the spatial distribution of the enhanced TPM surrounding the farms. There are a few published papers relating to open-water IMTA that have attempted to measure and understand both near-field and far-field suspended particle concentrations (Lander *et al.,* 2004; Sarà *et al.,* 2009; MacDonald *et al.,* 2011; Handå *et al.,* 2012). However, the spatial and temporal scope of these studies has been limited owing to the experimental approach and the discrete water sampling methodologies and technologies employed. These approaches may not be sufficient to meet the challenges of studying the fate of particulate wastes in dynamic coastal environments.

The objective of this study was to quantify the impact of Atlantic salmon farms in the Bay of Fundy on the surrounding particle field by delimiting the magnitude, spatial extent, dilution and dispersion of suspended particulates at these sites. Furthermore, this investigation seeks to determine whether or not the combination of feed and fecal particulate material is transported horizontally in the form of a traditionally viewed „plume'. A high-resolution 3-D spatial survey approach was employed using an undulating towed sensor vehicle, capable of collecting frequent georeferenced measurements in wide-scale spatial surveys and along specific transects to delimit the farm's impact on the surrounding particle field. These survey methods permitted data collection at spatial scales appropriate and meaningful to estuarine variation and the influence of IMTA systems on suspended particle fields.

2.3. Methods

2.3.1. Study Sites

Field studies were conducted at two separate Atlantic salmon farms in the macrotidal Quoddy region of the Bay of Fundy, the main fish culture area in eastern Canada. There are approximately 90 culture sites in this region, although not all are occupied simultaneously. The Navy Islands site (Passamaquoddy Bay, 45^o 01.846' N, 67^o 00.160' W) is larger in production size with 15 net pens, while Charlie Cove (L'Etête Passage, 45^o 01.845' N, 66^o 52.002' W) has 8 pens (Fig. 2.1).

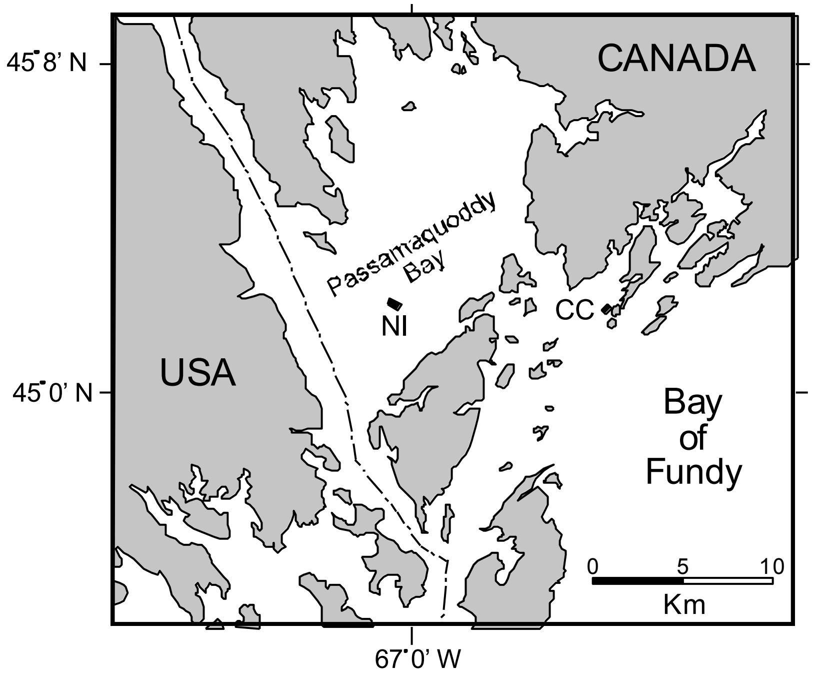

Figure 2.1. Location of study sites in the of Bay of Fundy, New Brunswick, Canada. The Navy Islands (NI) and Charlie Cove (CC) fish farms are represented by black rectangles.

Both sites contained mature fish in their final season of growth. Fish stocking levels are not available but each cage is known to contain between 30,000 to 50,000 fish, meaning a minimum of 450,000 and 240,000 fish on site at Navy Islands and Charlie Cove, respectively. Both sites are 23 m in depth and subject to strong tidal currents and mixing owing to the 6 m average tidal range (Trites and Garrett, 1983; Thompson *et al.,* 2002).

2.3.2. Particle-Sensing Instrumentation

The general complexity in TPM dynamics in coastal waters (i.e. high spatial and temporal variability) presents challenges in detection and mapping of any TPM enhancement from aquaculture wastes. To address these challenges, two different sensor packages were used. The first is referred to as BIO-Acrobat, a computer controlled undulating vehicle (Acrobat LTV-50, Sea Sciences Inc., Arlington, Mass., USA), used as a platform for obtaining high-resolution georeferenced data with attached environmental sensors. For this study, BIO-Acrobat was equipped specifically as a particle-survey tool. The sensor payload consisted of a CTD sensor (AML Oceanographic MicroCTS, Sidney, Canada), a chlorophyll *a* (chl *a*) fluorometer (Seapoint Sensors, Inc., Kingston, NH, USA) and a transmissometer with a 25 cm optical path length (c-Rover CRV5, WET Labs, Philomath, OR, USA). For all surveys, BIO-Acrobat was programmed to automatically undulate from 0.5 m below the surface to 10 m depth using real-time water depth (boat transponder) and vehicle depth (BIO-Acrobat pressure sensor) information. The instruments were powered from the surface by 12 V lead-acid batteries and all measurements were made at a sampling frequency of 2 Hz. Tow speed was maintained at approximately 2 m sec^{-1} during synoptic surveys and the sensor data stream was combined on board the tow vessel with simultaneous GPS reading using Windmill 7 data acquisition and visualization software (Windmill Software Ltd., Manchester, UK). The BIO-Acrobat surveys were designed to consider the possibility of both near- and far-field (up to approximately 200 m from the farm) impacts on TPM distributions surrounding the farms. Regions within the survey domain that were up-current from the farm are considered to represent natural (reference) conditions.

The second survey tool used in this investigation is the BIO-Wasp, consisting of the same sensor payload taken from the BIO-Acrobat, with the exception of a Cyclops chlorophyll *a* fluorometer (Turner Designs Inc., Sunnyvale, CA, USA) instead of the Seapoint. BIO-Wasp is smaller and lighter than BIO-Acrobat, and the sensors are encased in a protective streamlined jacket (polyethylene sheet) designed to allow water flow past them while preventing snagging from ropes. This package operated manually, either by continuous towing along a transect at slow speed while rapidly lowering and raising the instrument (parts of Charlie Cove site containing numerous mooring ropes), or by employing a stop-and-go method that allowed it to sink to the desired depth prior to being returned to the surface as the boat moved forward along a given transect (Navy Islands site). This transect sampling approach provided detailed coverage of the entire water column between 0.5 m and up to 25 m depth. The BIO-Wasp surveys were designed for high-resolution comparative surveys of TPM concentration at different distances from the farms, and at varying tidal stages.

2.3.3. Field Surveys

All fieldwork at the Navy Islands site was conducted in 2010. A wide-scale BIO-Acrobat survey was performed in summer, on 16 June 2010, while three transect surveys were performed with BIO-Wasp in late autumn, on the 16th and 30th of November 2010, and 1st of December 2010. All fieldwork at the Charlie Cove site was conducted in the summer of 2011. Two wide-scale BIO-Acrobat surveys were performed on 5th and 6th of July 2011, while one BIO-Wasp transect survey was conducted on 7 July 2011. The trajectories of the three BIO-Acrobat surveys (one at Navy Islands and two at Charlie Cove) are summarized in Figure 2.2.

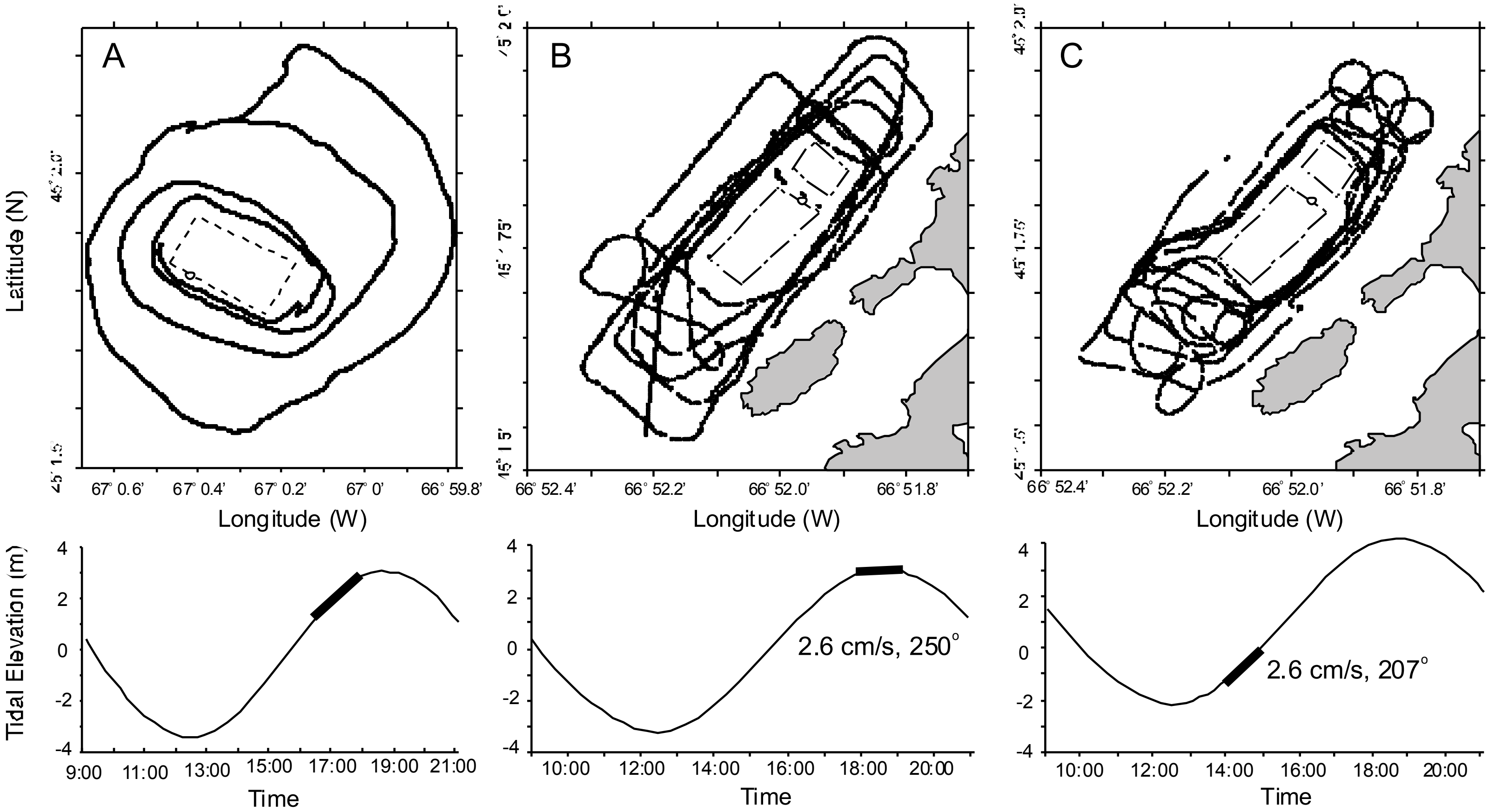

Figure 2.2. GPS tracks (top) and corresponding tidal elevation (m) conditions (bottom) during BIO-Acrobat surveys conducted at A) Navy Islands on 16 June, 2010, B) Charlie Cove on 5 July, 2011 and C) Charlie Cove on 6 July, 2011. Gaps in towpath are due to the removal of surface data above 0.5 m depth (see text). Farm boundaries are depicted by dashed lines on the above plots, while black bars highlight survey time (GMT) on the bottom plots. The northern section of the Charlie Cove farm (plots B and C) contained cultured macroalgae. Average current speeds and direction obtained from current meters (locations represented by open circles) are given for each survey time period, where available.

Surveys at Navy Islands and Charlie Cove were conducted between 0.5 to 10 m and 0.5 to 5 m depth, respectively. Inner boundaries of each survey were determined by farm activities, such as changing of nets, feeding, and/or harvesting, and associated equipment (buoys, ropes and vessels), while outer boundaries were either determined by the surrounding coastal morphology, or the capacity to complete the full survey in less than two hours. This survey time limitation was decided based on a compromise between the need to collect far-field data and the possibility that longer surveys can be affected by temporal variations in TPM resulting from the tide.

Four separate transect surveys (three at Navy Islands and one at Charlie Cove) were conducted using the BIO-Wasp (Fig. 2.3), performed on opposing sides of each farm across the prevailing current direction on ebb/flood tides and at various distances from the center of each farm. One survey focused on measuring particles entering the farm on consecutive ebb and flood tides (Fig. 2.3b) to examine tidal cycle differences in natural seston conditions.

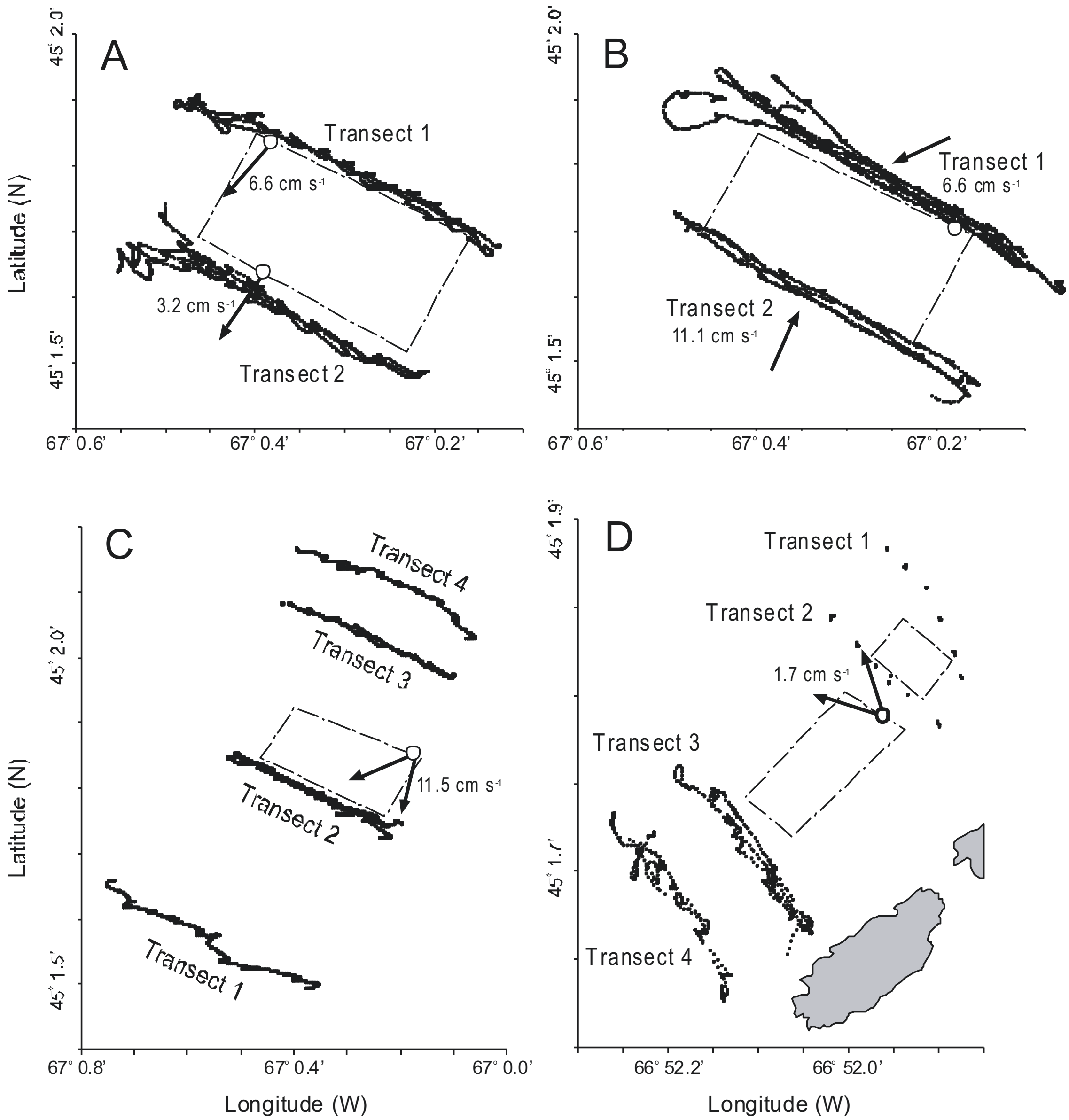

Figure 2.3. GPS tracks of transects conducted during BIO-Wasp surveys at Navy Islands on 16 November, 2010 (Plot A), 30 November, 2010 (B), and 1 December, 2010 (C), and at Charlie Cove on 7 July, 2011 (D). Dashed lines depict farm boundaries. Average current speeds and range of direction (illustrated by solid arrows) obtained from current meters (locations represented by open circles) are given for each survey time period.

Attempts were made to survey during a variety of tidal stages; however, events such as farm activities, weather conditions and periodic equipment malfunction provided limitations to some preferred survey periods.

A variety of available current meters were deployed during most BIO-Acrobat and BIO-Wasp surveys to obtain information on current speeds and directions. An Argonault-ADV (SonTek/YSI, Yellow Springs, USA) was deployed at 5-m depth during the 16 November 2010 BIO-Wasp survey. All surveys conducted at Charlie Cove gathered current information using an Infinity-EM current meter (JFE Advantec Co., Ltd, Hyogo, Japan) moored at 1.8-m depth. Current meter positions during BIO-Acrobat and BIO-Wasp surveys are depicted in Figs. 2.2 and 2.3, respectively.

2.3.4. Instrument Calibrations

In-situ calibration was conducted for the Seapoint fluorometer using seawater samples collected beside the BIO-Acrobat with a 2 L Kemmerer sampler. Water samples stored in pre-rinsed 1 L Nalgene bottles were filtered through pre-washed GC-50 filters (Advantec, 25-mm glass fibre) and kept frozen (-20 ^{o}C) in the dark until analysis. The chlorophyll *a* content of particles collected on the filters was determined by the fluorometric technique of Holm-Hansen *et al.* (1965). The Cyclops fluorometer was also calibrated under field conditions by comparing water column vertical profiles obtained with both the Cyclops and a previously calibrated WETStar fluorometer (Wet Labs). Regression analysis of measured chlorophyll *a* (μg L^{-1}) versus chlorophyll *a* fluorescence (mV) for the Seapoint and Cyclops instruments provided calibration equations of $Chl\ a = 5.01 \times mV + 0.970$ (n = 46; $r^2 = 0.93$) and $Chl\ a = 6.44 \times mV + 0.033$ (n = 443; $r^2 = 0.89$), respectively.

BIO-Acrobat and BIO-Wasp surveys used the same cRover transmissometer (25-cm path length) for estimating TPM concentration (mg L^{-1}). *In-situ* calibration was conducted using water samples (n = 101) collected at the same depth as cRover and stored in the same manner described above. Water samples were filtered through pre-rinsed and pre-weighed GC-50 filters (Advantec, 25 mm) and rinsed with ammonium formate to remove salt. Filters were then dried at 60^{o}C and weighed to determine TPM concentration (mg L^{-1}). Percent transmittance (T) for each TPM sample was calculated by dividing the sample reading by the zero reading (3.96 mV for filtered seawater) and multiplying by 100. Beam attenuation (C_p) was then calculated using the equation:

$$C_p = [\ln(1/T)] / L$$

where L is the instrument path length (0.25 m). The results of TPM gravimetric analysis (mg L^{-1}) for field and lab samples were compared to instrument C_p measurements using regression analysis. Therefore, $TPM = 2.97 \times mV + 1.56$ ($r^2 = 0.85$) was used for estimation of TPM (mg L^{-1}) from the cRover output.

2.3.5. Data Analysis

Data collected from all BIO-Acrobat and BIO-Wasp surveys were initially processed to remove measurements taken above 0.5 m depth and gross outliers. The excluded surface data largely included periods when the instruments were on, or above, the surface, but also included air bubble effects on TPM measurements from waves and boat propellers. The outlier data amounted to just a few points per survey that likely resulted from interference from large floating detritus such as macroflora.

2.3.6. Spatial Patterns in Suspended Particulate Matter– BIO-Acrobat Surveys

Vertical profile plots and contour maps of TPM concentrations were used to summarize and observe spatial patterns in the large BIO-Acrobat data sets for each survey. Contouring of data from selected depth intervals (depth ranges showing limited depth variability in TPM) was conducted using ordinary kriging in Surfer 9 (Golden Software, Inc., USA). The BIO-Acrobat survey data showed very limited spatial variation in TPM at depths greater than 2 m depth and this ultimately led to the following focus of data analysis on the upper 0.5 to 2 m depth range for each survey. Interpretation of contour plots can be subjective, particularly where adjacent tow tracks have greatest separation. Therefore, to further investigate the possibility of farm-derived enhancement of TPM, the data were subdivided into several geographic areas so that regional difference in average TPM concentration can be compared relative to the location of the farm. First, all data within the 0.5 to 2 m depth range was plotted as classed post maps using *ArcMap 10*. These plots were then used to select geographic swaths through the farm and on either side of the farm within the survey field. The data swaths were designed to be of equal latitude and longitude range (within each survey), and oriented in the direction of the predominant ebb/flood tide. Data within each swath were further divided into boxes (regions) representing different distances from the center of the box to the center of the farm. Distances considered to be „down-current' of the farm (according to the predominant tidal flow measured during the survey) were assigned positive integers, while those located „up-current' were assigned negative integers. Kilometer distances were calculated from geographic coordinates (Michels, 1997). Average TPM concentrations within all regional data sub-sets were calculated and compared.

2.3.7. Spatial Patterns in Surface TPM – BIO-Wasp Surveys

Data collected during each BIO-Wasp transect survey was divided into four depth ranges; 0.5 to 5 m, 5 to 10 m, 10 to 15 m, and 15 to 20 m. Quantitative differences between transects within each of these depth layers was tested separately by one-way ANOVA (SPSS Ver.17) with Transect as the fixed factor. Prior to analysis, transect variances were assessed for homogeneity (Levene's test). Within-treatment normality was not assessed given the very large sample sizes and the robustness of ANOVAs to non-normal distributions (Underwood, 1981; Cheshuk *et al.*, 2003). Heterogeneous variances were indicated for all surveys and multiple transformations failed to stabilize these variances. Therefore, the hypothesis of no spatial (transect) effect on mean TPM was assessed using Welch's ANOVA. As is common with high-resolution spatial surveys, significant autocorrelations within the survey data showed that the TPM measurements were spatially dependent (detected using Systat Ver. 10 software). The undulating sampling approach between two set depths also resulted in a persistent autocorrelation cycle with distance between measurements. Consequently, correction approaches, such as estimating the effective sample size, would not be able to remedy this problem (Dale and Fortin, 2009). A simple solution that accounts for spatial autocorrelation and provides some assurance that any significant results detected are indeed significant is to adjust α to a lower value (Dale and Zbigniewicz, 1997; Dale and Fortin, 2002). Given the very large sample sizes obtained in this study, reducing α to the highly conservative value of 0.005 will have little impact on the statistical power of the ANOVAs. In cases of a significant ANOVA result for a site having more than two transects, post-hoc tests were used to further explore differences between transect means (Games-Howell test for unequal variances).

2.4. Results

2.4.1. General TPM and Chlorophyll a *Characteristics*

Vertical profiles of TPM concentrations from the BIO-Acrobat surveys are shown in Figure 2.4. Similar results were observed for the BIO-Wasp surveys and the data are not shown. TPM concentrations were predominantly in the range of 3 to 4 mg L^{-1} at both the Navy Islands and Charlie Cove sites during all surveys. In all cases, at least 98% of the TPM values were $\leq$ 11 mg L^{-1} (Fig. 2.4). There was little variation in TPM below 2 m depth where at least 99% of the TPM values were $\leq$ 4 mg L^{-1}. Elevated concentrations at both sites were present mainly within the top 0.5 to 2 m of the water column. Maximum surface concentrations during all survey periods and sites were primarily below 12 mg L^{-1} although some values as high as 25 mg L^{-1} were measured at Navy Islands. Across all the spatial and transect surveys at both sites, chlorophyll *a* did not exhibit similarly elevated surface concentrations (Fig. 2.4 for Navy Islands; data not shown for Charlie Cove), and the depth distributions of chlorophyll *a* were not similar to that of TPM at either site.

2.4.2. Spatial Patterns in Surface TPM – BIO-Acrobat Surveys

Contour maps of TPM concentrations within the upper 2 m of the water column for the two BIO-Acrobat surveys at Charlie Cove are displayed in Figure 2.5.

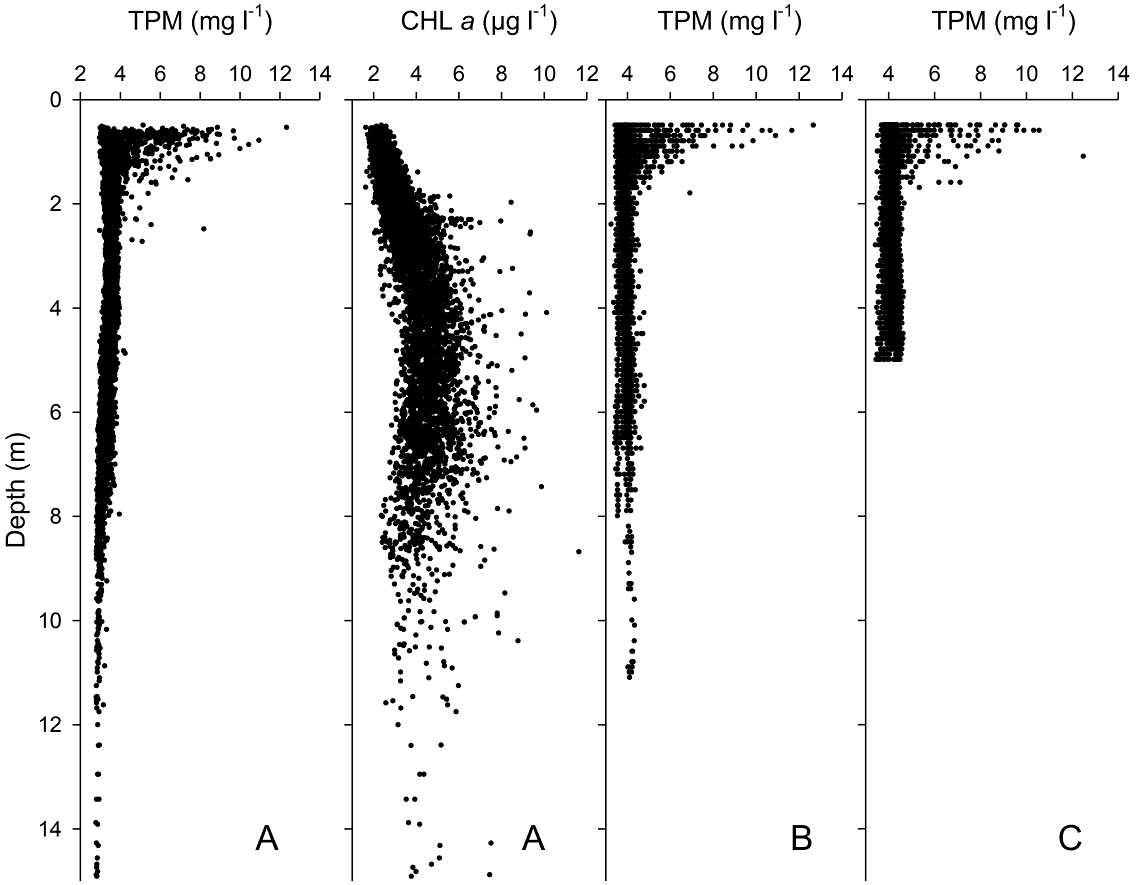

Figure 2.4. Depth (m) distribution patterns of TPM (mg L^{-1}) and chlorophyll *a* (CHL; µg L^{-1}) during BIO-Acrobat surveys at Navy Islands on 16 June, 2010 (A) and at Charlie Cove on 5 July, 2011 (B) and 6 July, 2011 (C). Chlorophyll *a* data are not available for Charlie Cove BIO-Acrobat surveys due to equipment malfunction.

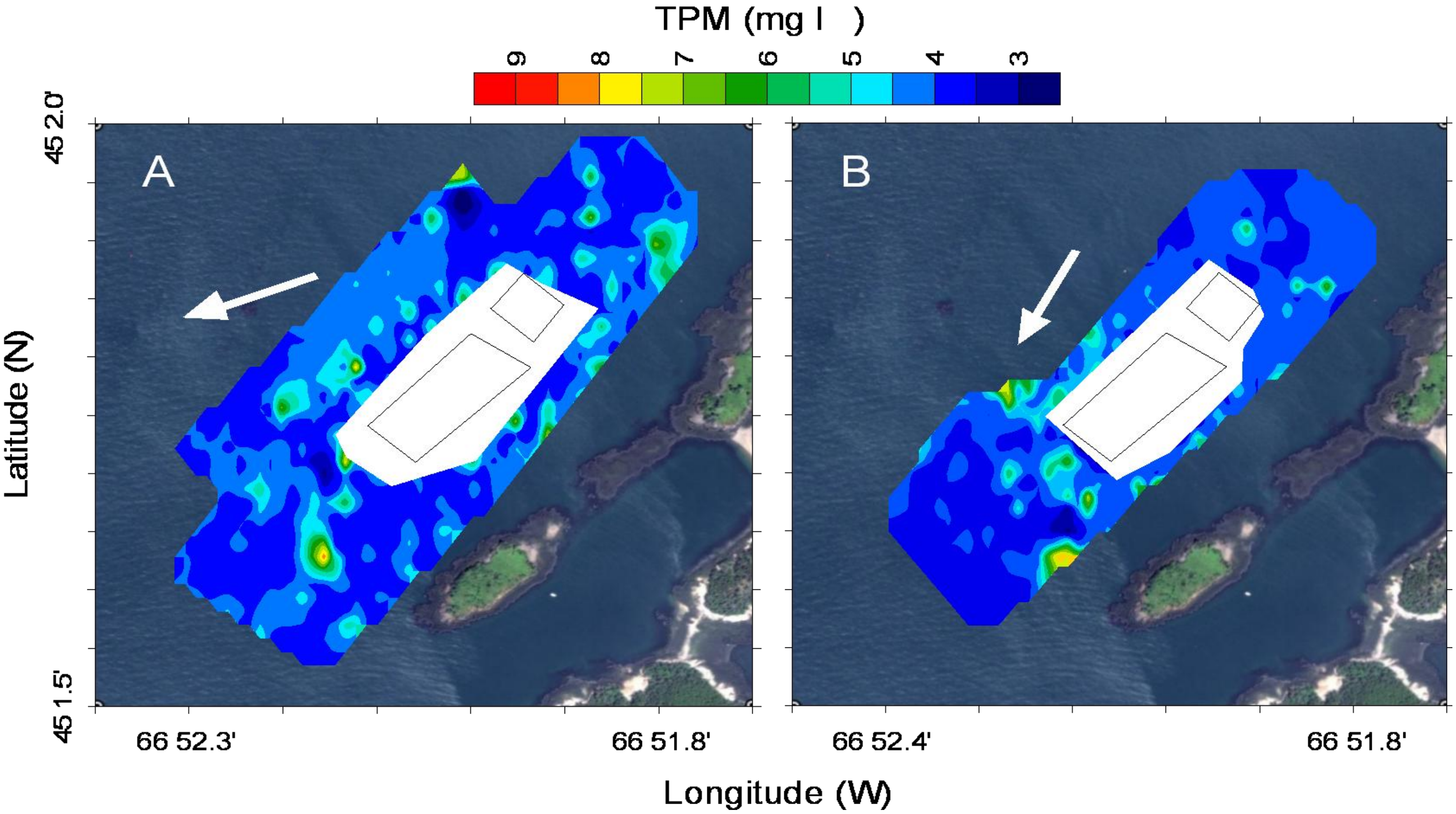

Figure 2.5. Colour-scaled contour plots of TPM (mg L^{-1}) at Charlie Cove based on data collected between 0.5 and 2 m depth on 5 July, 2011 (A) and 6 July, 2011 (B). Arrows indicate the predominant current flow direction during each survey period. The instrument tow tracks are shown in Figure 2b and c.

The contour maps of TPM concentrations at Charlie Cove on 5 and 6 July, 2011 showed that the elevated levels observed in the surface layer (Fig. 2.4) were randomly distributed in patches, with slight indications of higher down-current TPM concentrations, relative to the farm (Fig. 2.5a, 2.5b). This hypothesis was further examined below. A contour plot is not shown for the Navy Islands survey on 16 June 2010 due to the relatively large distance between some tow tracks (i.e. potentially excessive extrapolation of data).

TPM levels averaged across selected regions within the Navy Islands surveyed area displayed no apparent directional or distance trends, relative to the farm location, in seston enhancement (Fig. 2.6). For both the 5 and 6 July, 2011 surveys at Charlie Cove, average TPM levels „down-current' of the site tended to be slightly higher (< 0.5 mg L^{-1} enhancement) and more variable in the region closest to the farm (Figs. 2.7 and 2.8). Natural patchiness in mean TPM concentration is indicated by difference in mean TPM levels for different regions in the up-current side of the farm (Fig. 2.6 to 2.8).

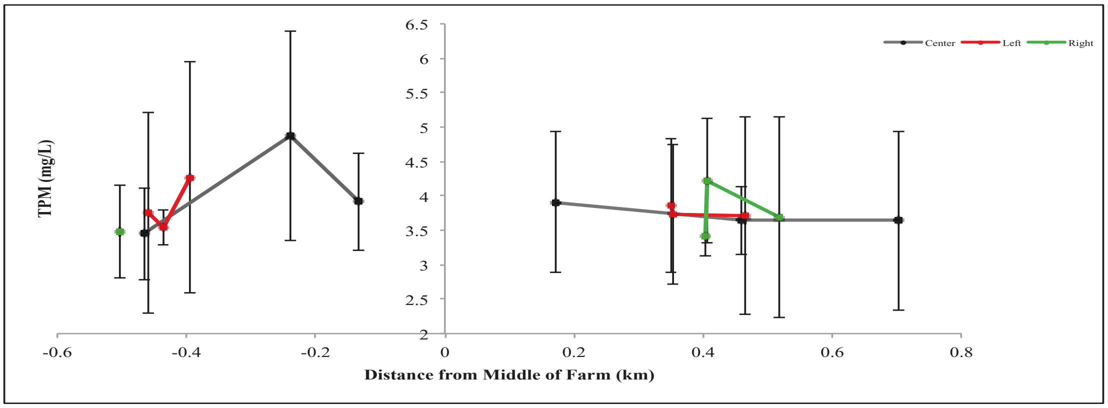

Figure 2.6. Mean TPM (mg L^{-1}, 0.5 to 2 m depth) for regional data subsets located at selected distances (km) and directions from the center of the Navy Islands site on 16 June, 2010. Distances considered „down-current' and „up-current' of the farm were assigned positive and negative integers, respectively. ±SD bars are shown.

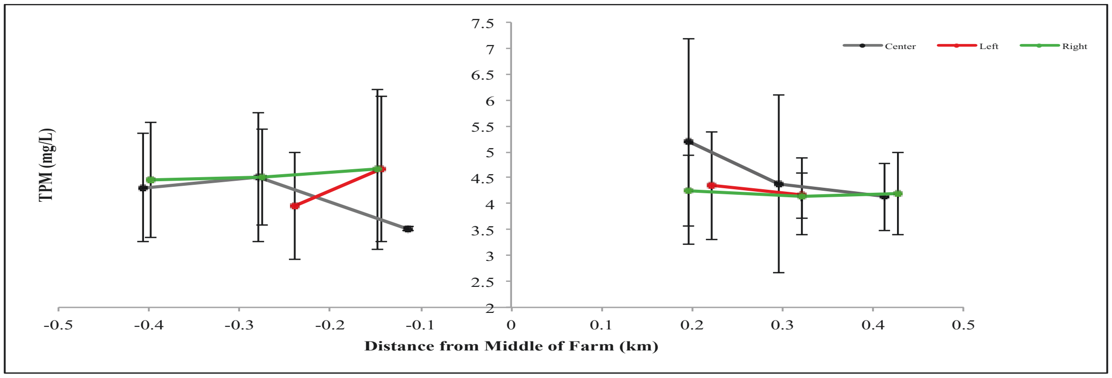

Figure 2.7. Same as for Figure 2.6 except data are from the Charlie Cove site on 5 July 2011.

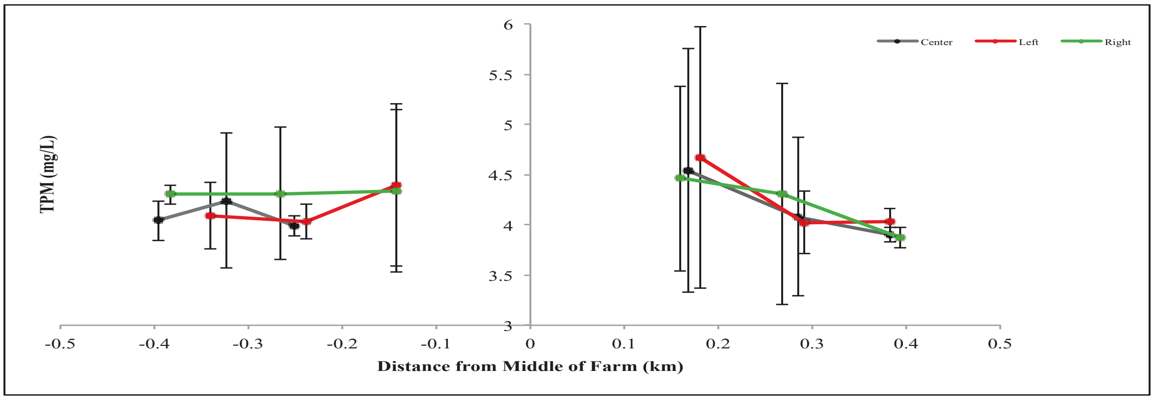

Figure 2.8. Same as for Figure 2.6 and 2.7 except data are from the Charlie Cove site on 6 July 2011.

2.4.3. Spatial Patterns in Surface TPM – BIO-Wasp Transect Surveys

The results of one-way Welch ANOVA comparisons between transects (Fig. 2.3) of mean TPM levels within different depth intervals are given in Tables 2.1 to 2.3. Significantly higher TPM was found in the 0.5 to 5 m depth range along Transect 2, as compared to Transect 1, at Navy Islands on both 16 November and 30 November, 2010 (Table 2.1; $p < 0.001$). The former comparison showed higher TPM concentrations exiting the farm (1 mg l^{-1}) in the surface layer, while the latter showed a greater amount of TPM entering the farm on the flood tide than on the ebb (< 0.8 mg l^{-1}; Table 2.1). Significant differences in TPM were also detected in the 15 to 20 m depth range at Navy Islands, with higher TPM along Transect 1 on 16 November 2010 and along Transect 2 on 30 November 2010 (Table 2.1; $p < 0.001$).

Welch test results for surveys conducted with four transects on 1 December 2010 at Navy Islands (Fig, 2.3c; Table 2.2) and 7 July 2011 at Charlie Cove (Fig, 2.3d; Table 2.3) indicate significant differences between transects within most of the depth ranges ($p < 0.001$ for all comparisons except within the surface layer on 7 July at Charlie Cove). In all comparisons, the mean difference between transects was less than 1.5 mg L^{-1} with only small mean differences in TPM (< 0.4 mg L^{-1}) calculated for depths greater than 5 m. Significant differences were generally unrelated to water flow directionality from the farm, highlighting the naturally patchy nature of TPM surrounding these sites. For example, post-hoc tests from Navy Islands on 1 December 2010 indicated that Transect 1 was significantly higher (22.6% increase) in TPM than all other transects in the 0.5 to 5-m depth range, but that Transect 2 was significantly lower in TPM than Transect 1 and 4 in the 5 to 10-m depth range.

Table 2.1. Welch ANOVA test results of mean TPM concentrations (mg L^{-1}) between Transect 1 and Transect 2 (Fig. 3a and b) within the indicated depth ranges at Navy Islands on 16 November and 30 November 2010. .

	Welch Test (assumes unequal variance)					
Depth Interval	Hypothesis	Statistic	*df1*	*df2*	*p*	*Mean Difference (mg L^{-1})*
Navy Island – 16 November 2010						
0.5 – 5 m	T1=T2	12.914	1	1332	< 0.001*	- 0.960
5 – 10 m	T1=T2	3.121	1	675	0.078	0.006
10 – 15 m	T1=T2	3.658	1	713	0.056	0.035
15 – 20 m	T1=T2	112.53	1	697	< 0.001*	0.091
Navy Island – 30 November 2010						
0.5 – 5 m	T1=T2	20.453	1	755	< 0.001*	- 0.844
5 – 10 m	T1=T2	0.212	1	675	0.645	- 0.019
10 – 15 m	T1=T2	5.724	1	556	0.017	- 0.199
15 – 20 m	T1=T2	23.078	1	1283	< 0.001*	- 0.051

** Significant at the $p < 0.005$ level*

Table 2.2. Welch ANOVA and post-hoc test results of mean TPM concentration (mg L^{-1}) between Transects 1, 2, 3 and 4 (Fig. 3c) within the indicated depth ranges at Navy Islands on 1 December, 2010.

	Welch Test (all transects)					***Post hoc* Transect Comparisons**		
Depth interval	Hypothesis	Statistic	*df1*	*df2*	*p*	Mean Difference (mg L^{-1})	SE	*p*
0.5 – 5 m	T1=T2=T3=T4	13.737	3	628	< 0.001*			
	T1=T2					1.11	0.226	< 0.001*
	T1=T3					1.45	0.231	< 0.001*
	T1=T4					1.37	0.254	< 0.001*
	T2=T3					0.33	0.137	0.072
	T2=T4					0.26	0.172	0.429
	T3=T4					-0.07	0.179	0.978
5 – 10 m	T1=T2=T3=T4	7.779	3	335	< 0.001*			
	T1=T2					0.025	0.005	< 0.001*
	T1=T3					-0.09	0.092	0.749
	T1=T4					0.003	0.005	0.965
	T2=T3					-0.117	0.092	0.548
	T2=T4					-0.022	0.006	0.004*
	T3=T4					0.09	0.09	0.733
10 – 15 m	T1=T2=T3=T4	20.809	3	286	< 0.001*			
	T1=T2					0.047	0.007	< 0.001*
	T1=T3					0.031	0.008	0.001*
	T1=T4					0.016	0.009	0.315
	T2=T3					-0.016	0.004	< 0.001*
	T2=T4					-0.031	0.006	< 0.001*
	T3=T4					-0.015	0.007	0.131
15 – 20 m	T1=T2=T3=T4	79.623	3	734	< 0.001*			
	T1=T2					0.072	0.009	< 0.001*
	T1=T3					0.048	0.009	< 0.001*
	T1=T4					-0.099	0.013	< 0.001*
	T2=T3					-0.024	0.007	0.004*
	T2=T4					-0.171	0.012	< 0.001*
	T3=T4					-0.147	0.012	< 0.001*

* *Significant at the* $p < 0.005$ *level*

Table 2.3. Welch ANOVA and post-hoc test results of mean TPM concentrations (mg L^{-1}) between Transects 1, 2, 3 and 4 (Fig. 3d) within the indicated depth ranges at Charlie Cove on 7 July, 2011.

		Welch Test (all transects)				***Post hoc* Transect Comparisons**		
Depth interval	Hypothesis	Statistic	*df1*	*df2*	*p*	Mean Difference (mg L^{-1})	SE	*p*
	Charlie Cove – 7 July 2011							
0.5 – 5 m	T1=T2=T3=T4	3.507	3	124	0.017			
	T1=T2					0.854		
	T1=T3					1.433		
	T1=T4					1.210		
	T2=T3					0.579		
	T2=T4					0.355		
	T3=T4					-0.224		
5 – 10 m	T1=T2=T3=T4	21.725	3	155	< 0.001*			
	T1=T2					0.182	0.041	< 0.001*
	T1=T3					0.284	0.037	< 0.001*
	T1=T4					0.206	0.039	< 0.001*
	T2=T3					0.102	0.028	0.002*
	T2=T4					0.024	0.031	0.861
	T3=T4					-0.077	0.024	0.009*
10 – 15 m	T1=T2=T3=T4	19.575	3	152	< 0.001*			
	T1=T2					0.092	0.051	0.286
	T1=T3					0.213	0.045	< 0.001*
	T1=T4					0.140	0.046	0.016
	T2=T3					0.122	0.027	< 0.001*
	T2=T4					0.048	0.028	0.306
	T3=T4					-0.073	0.013	< 0.001*
15 – 20 m	T1=T2=T3=T4	26.018	3	151	< 0.001*			
	T1=T2					0.115	0.071	0.379
	T1=T3					0.326	0.065	< 0.001*
	T1=T4					0.321	0.065	< 0.001*
	T2=T3					0.212	0.029	< 0.001*
	T2=T4					0.206	0.028	< 0.001*
	T3=T4					-0.005	0.005	0.735

* Significant at the p < 0.005 level

2.5. Discussion

2.5.1. Suspended Particle Enhancement from Salmon Farming in the Bay of Fundy?

This study provided evidence of low levels (mean effect < 1.5 mg L^{-1}) of suspended particle enhancement from fish-farm wastes, primarily in surficial waters (0.5 to 2 m depth), down-current from two salmon farms in the Bay of Fundy. Spatial surveys with the undulating towed-vehicle indicated a small increase in mean TPM (< 1.0 mg L^{-1} mean effect) and increased TPM variability in the surface layer immediately down-current from the Charlie Cove farm site (Figs. 2.7 and 2.8). The cross-current transect data similarly provided a basis for concluding that significant increases in TPM levels occasionally occurred in the surface layer exiting both farms, with a mean increase of less than 1.5 mg L^{-1} (Tables 2.1 to 2.3). Given the low levels of apparent TPM enhancement adjacent to the farms, it is difficult to attribute this result to a farm-based source of particulate matter or to natural seston patchiness. Note that seston concentrations were occasionally higher on the up-current side (moving towards the farm; Fig. 2.6) and that natural seston conditions varied on ebb and flood tide (Table 2.1).

Enhanced primary production in the vicinity of the farm is an unlikely cause of seston enhancement considering the results of other studies investigating fish culture-phytoplankton interactions and the time-scales involved for phytoplankton turnover (Gowen *et al.,* 1988; Wildish *et al.,* 1993; Stirling and Okumus, 1995; Cheshuk *et al.,* 2003). Elevated TPM levels were not accompanied by increased chlorophyll *a* levels (Fig. 2.3) and this suggests that the increased particulate matter found in the surface layer surrounding the farms during this investigation was of different origin, and perhaps evident of farm-derived enhancement.

Potential farm-derived, non-algal TPM would include feed fines and faecal wastes, as reviewed in the Introduction. It has been suggested that there are many mechanisms by which „fines’ can be produced at a fish farm, creating an environment that could be enhanced with suspended particulates. The use of automated feeding methods, as used at these sites, can create a dusty by-product known as „feed fines’ (Cheshuk *et al.,* 2003; Kullman *et al.,* 2009; Reid *et al.,* 2010). It has also been suggested that some fecal material may exit a net-pen system as fine particulate matter rather than as whole pellets, due to factors such as the high digestibility of fish feed and aggressive fish swimming activity (Troell and Norberg, 1998). Furthermore, even larger suspended waste particles are expected to become smaller over time by way of natural destructive forces such as biodegradation and water turbulence (Ismond, 1993; Summerfelt, 1999; Brinker and Rösch, 2005). Biodegradation may be heightened within a net-cage fish farm due to the activities of bio-fouling biota such as microbes. Turbulence is of particular importance in particle transport and dispersion. Localized turbulence is generated by the fish and cage structure, and a high degree of regional diffusivity occurs naturally in the tidally-energetic Bay of Fundy. Although the past focus on particle dynamics at fish farms has been on sedimentation processes (Brown *et al.,* 1987; Gowen and Bradbury, 1987; Gowen *et al.,* 1988; Wildish *et al,* 1990; Findlay *et al.,* 1995; Brooks *et al.,* 2002), a source of smaller particles suspended in the upper water column appears to exist, even under these turbulent and energetic conditions.

The results of the present study are not meant to suggest that heavier particulates do not exist at all surrounding these sites. At Navy Islands, TPM concentrations at 6 to 13 m depths were occasionally, albeit very infrequently, detected at levels upwards of 20 mg

L^{-1}. Moreover, the overall lack of suspended TPM enhancement surrounding the farms found in this investigation likely highlights a stronger downward vector component to the waste stream. This vertical particle flux is prominent in aquaculture waste dispersal models such as DEPOMOD (Cromey *et al.,* 2002). It could be predicted that there will be some intact feed and/or fecal pellets that may stay undisturbed and sink to the bottom. More importantly, processes such as turbulence and bio-fouling may also work in the opposite way to what was discussed above, fostering an environment that increases aggregation of suspended solids. Periods of higher turbulence, such as that generated by fish activity alone, have been thought to increase the chance of collisions between particles, leading to increased flocculation. This is especially true for organic particles and in areas where microbial colonization is abundant, as may be the case surrounding these sites. The production of extracellular polymers and polysaccharides by microbes strongly favours the adhesion of smaller particles to form larger ones (Brinker and Rösch, 2005). For these reasons, it is to be expected that the majority of particulate matter would not be fine enough to remain suspended in the surface of the water column.

It is important to note that higher levels of seston enhancement were found in the surface of the water column at Navy Islands compared to Charlie Cove, with maximum TPM concentrations reaching 26 mg L^{-1} at Navy Islands, and only 11 mg L^{-1} at Charlie Cove. This could be due in part to differences in fish stocking densities and the overall production scale between the two farms. Navy Islands has twice the number of net pens (15 cages) relative to Charlie Cove (8 cages). A larger scale farm means more feed delivery, waste production, and most importantly overall biomass (Cheshuk *et al.,* 2003). Brinker and Rösch (2005) showed that higher fish biomass (kg m^{-3}), as present at Navy

Islands, can significantly reduce particle size due to factors such as increased turbulent swimming activity, and consequently generate a larger amount of smaller particles that remain suspended in the surface layer. This suggests that overall production scale is of importance when considering the extent of impact a fish farm has on the surrounding particle field.

2.5.2. Spatial Trends – Is There Directionality?

Although higher levels of TPM were found in the surface of the water column at Navy Islands relative to Charlie Cove (Fig. 2.4), mapping of the particle field surrounding Navy Islands did not display any distinct regions of TPM enhancement (Fig. 2.6), and certainly did not allude to a traditionally viewed ‘plume’. If a fish farm has the potential to significantly enhance the particulate matter in the near-field environment, it may be expected that the area „down-current’ of the farm (depending on the tidal state during the time of survey) would experience increased TPM concentrations due to forcing by advective processes. Perhaps one of the most significant findings of this study was the significantly higher TPM within Transect 2 at the Navy Islands farm on 16 November, 2010 (Table 2.1). Tidal state during the time of survey meant that Transect 2 was located along the side of the farm that would be expected to show elevated TPM, with waste particles from the farm moving from Transect 1 towards Transect 2 (Fig. 2.3A). The close location of Transect 2 to the farm boundaries left little room for dilution to occur before being detected during sampling. This was the strongest evidence of a potential farm-derived particulate „pulse’ throughout this investigation, albeit a small one (<1 mg l^{-1}; Table 2.1).

This study also shows that the predictive directionality of farm waste spreading certainly does not always exist. For example, a BIO-Acrobat survey at Charlie Cove showed that even though a slight increase of 0.5 mg L^{-1} may exist „down-current' of the farm, the concentrations are within the same range of variability in TPM on the „up-current' side of the farm (4.0 – 4.5 mg L^{-1}). These findings are in agreement with those of Cheshuk *et al.* (2003) who concluded that wastes from cages are dispersed in all directions due to cyclic shifts in current flow. The common fish farm is typically oriented with the largest dimension in the main current direction (Løland, 1993) although this was not the case at the Charlie Cove farm. It may seem logical that water flow surrounding these sites would be dominated by the highly-energetic tides of the Bay of Fundy in a strongly advective manner. However, dispersive processes within fish farms should certainly not be underestimated. Net cages present at fish farms are porous and highly flexible; characteristics which can strongly govern the flow pattern both within and around the fish farm (Løland, 1993). The influence of farm structure, in conjunction with fish behaviour and other daily farm activities, fosters an environment of highly complex and unpredictable flow patterns. Currents measured near the surface at Charlie Cove appear to be highly modified by farm structures. The ebb-tide current direction measured during the transect survey (Fig. 2.3d) was predominantly towards the southwest, but flows measured in close proximity of the net pens were directed to the northwest.

Surveys conducted to compare TPM at different distances from each farm did not show significantly higher seston concentrations closer to the farm than at a distance from the farm. In fact, at Navy Islands on 1 December 2010, the transect farthest away from the farm (Transect 1, Fig. 2.3C) had a mean TPM that was 22.6% greater than the rest of the survey. Although „down-current' from the farm during the time of survey, the question remains as to why the transect on the same side but up against the farm boundaries (Transect 2) did not show any enhancement. Moreover, transects conducted at Navy Islands on 30 November 2010 (Fig. 2.3B) indicated significant differences in TPM in the sources of water flowing into the farm, depending on tidal stage. All of the contradicting observations discussed above highlight the reality of a far more intricate system than ideally envisioned of a slowly dispersing plume of nutrients radiating away from these aquaculture sites in a uniform manner.

2.5.3. Temporal Variability - A Persistent or Pulsing Source?

The level of enhancement found both at depth and in the surface was variable over time not only between sites, as discussed above, but even within sites. When background concentrations were consistent at 3 to 4 mg L^{-1}, *maximum* elevated concentrations ranged from 6 to 26 mg L^{-1} in the surface layer and 6 to 20 mg L^{-1} at depth (when present). TPM surrounding these sites is subject to the same factors of natural variability driven by tides, weather events and seasons. In the tidal inlet of Passamaquoddy Bay in particular, tides alone can have significant impacts on seston levels, with concentrations being at a minimum by the end of a flood tide (as oceanic waters are advected into the inlet) and at a maximum by the end of an ebb tide (Dowd, 2003).

Moreover, TPM at these sites is also subjected to additional farm factors such as feeding cycles, machinery work and net cleaning which may also have significant effects on the local particulate matter. Troell and Norberg (1998) calculated that farm waste production could increase suspended solids concentrations anywhere from 3- to 30-fold. Indications of both natural and potentially farm-induced variability over time were found in this study given the relatively high standard deviations that were calculated for average TPM concentrations at locations within (farm-induced) and outside (natural) of farm boundaries (Figs 2.7 and 2.8). .

Suspended particulate matter is a highly dynamic variable and in this study, replication of particle enhancement results between sampling dates was not found. TPM above ambient concentrations was only occasionally found at depth. Troell and Norberg (1998) referred to an „enriched pulse' of nutrients as more likely than a continuously present plume due to the nature of periodic feeding and probable mass release of feces at some time after feeding. These findings suggest that a particle source may exist, but in an intermittent manner, and that timing of sampling could be very important in the search for this particle „pulse'.

2.5.4. The Feasibility of IMTA

When considering the feasibility of an efficient IMTA system, it is of primary importance to determine whether or not an additional suspended food source is even being supplied by the farm in order contribute to the enhanced growth of another commercial species, such as bivalves. This research shows that intermittent farm-derived enhancement may exist, but in no consistently preferred spatial orientation. Although being located in a tidal inlet of the Bay of Fundy where advective processes would be assumed to dominate, the diffusive properties of these sites (as discussed above) cannot be ignored. The unpredictable leakiness, which occurs as a result, makes it difficult for educated placement of bivalves that would optimally intercept the suspended particulates exiting the fish cages.

In agreement with previous studies examining co-culture of finfish and bivalves (Brown *et al.,* 1987; Gowen and Bradbury, 1987; Coyne *et al.,* 1994; Findlay *et al.,* 1995; Cheshuk *et al.,* 2003), the surveys showed limited horizontal displacement of increased seston levels away from the farm. It has been suggested that under low-to-moderate current conditions, bivalves would need to be cultured well within 50-m of the fish cages (Cheshuk *et al.,* 2003). In this study, the strongest farm-derived signal in this investigation was detected immediately adjacent to the fish cages. For an IMTA system to be located in the highly energetic Bay of Fundy, it may mean co-culture within very constrained boundaries. This significantly restricts the area for bivalve culture that would be beneficial to their growth. Bivalve culture in areas beyond this more productive region may be necessary to reach a population filtration capacity that can effectively reduce particulate wastes from the farm. Limited areas for optimal placement could mean significant consequences for commercial scale farming production of a bivalve species within an IMTA system.

Varying levels of seston enhancement were found mainly in the surface of the water column throughout this study, but they must be interpreted in the context of local ambient particulate concentrations. Transects conducted approximately 200 m from the farm showed that 20% increase above the surrounding mean TPM can occur naturally in Passamaquoddy Bay. Therefore, an increase in particulate matter > 20% would be required to suggest that these fish farms are having a notable impact on local particle load. In this investigation, results showed > 20% enhancement near the farm only once, indicating that the farm impact is rarely above and beyond naturally existing particle concentrations. Similar results were found by Cheshuk *et al.* (2003) where the level of enrichment was not outside the natural range, supporting the argument that waste production from these farms is likely too low and/or too easily dispersed to significantly elevate food concentrations to beneficial levels.

2.5.5. Conclusions

This study suggests that fish farms may intermittently release minor levels of suspended particulate matter, primarily in the upper 2 m of the water column. The hypothetical „plume' that is often referred to in relation to the movement of solid aquaculture wastes was not detected at the farms studied in Passamaquoddy Bay. Moreover, contributions of potential farm-derived suspended solids rarely reached levels outside of the natural range of concentrations existing in this region. However, the findings of this study are contrary to what has been found in some others. MacDonald *et al.* (2011) did find that farm sites in Passamaquoddy Bay exhibited significantly higher TPM levels than reference sites. Moreover, others have recommended bivalve culture at depths greater than 5 m to intercept what was found to be a large fraction of solid waste emissions from the cages (Cheshuk *et al.,* 2003). The conflicting outcomes highlight the site-specific nature of this topic of study and the critical need for more information.

These results do not provide evidence of enhanced particle sources for adjacent suspension feeders in IMTA culture. However, they apply only to specific locations in highly dispersive Fundy environments. Other trophic levels of IMTA systems, such as sea plants, may derive significant growth benefits from the dissolved waste component of finfish aquaculture (Buschmann *et al.,* 2001; Chopin *et al.,* 2001; Neori *et al.,* 2004). Further exploration of the potential of IMTA remains important as a means of increasing aquaculture sustainability, but it must be tailored to the magnitude of waste streams and their potential to be exploited.

Chapter 3: Temporal Dynamics of Suspended Particulate Matter Surrounding Atlantic Salmon (*Salmo salar*) and Sablefish (*Anoplopoma fimbria*) Farms in the Bay of Fundy, New Brunswick and Kyuquot Sound, British Columbia

3.1. Abstract

Coastal marine environments are subject to extreme variability in dissolved and particulate matter, influenced by several factors such as tides, primary production, winds and sediment resuspension. The addition of fish farm activity adds another challenge to understanding this complex water column. Moreover, the introduction of an IMTA system inclusive of bivalves with the potential to assimilate suspended solid wastes has required new efforts in characterizing the temporal variability in seston surrounding finfish aquaculture sites. The objective of this study was to further quantify the spatiotemporal variations in turbidity and chlorophyll, in order to understand how they are affected by wastes from Atlantic salmon and Sablefish farms in the Bay of Fundy and Kyuquot Sound, respectively. Two combination turbidity and chlorophyll *a* sensors were moored at various depths or locations adjacent to the sites, in line with the suspected predominant flow direction. Laboratory calibrations, confirmed by field inter-calibration, were conducted for estimation of total particulate matter (TPM, mg L^{-1}) and chlorophyll a (Chl *a*, μg L^{-1}). Hydrodynamic data was simultaneously collected when instrumentation was available for current speed and direction. Low level differences (mean effect <1 mg L^{-1}) in suspended particulate matter were found at various locations over time. Doubling of TPM concentrations was found to occur at one of the sites; however, these peaks generally correspond with onset of flood tide and flow of natural reference waters into the site. Therefore, results provided evidence of predominantly tidal-driven TPM patterns.

3.2. Introduction

Global aquaculture is developing rapidly and is the fastest growing food-producing sector, with nearly half of the world's seafood supply now sourced from aquaculture (FAO, 2010). The open nature of many culture systems allows for continuous exchange of water between the cages and surroundings (Beveridge, 1984; Gowen and Bradbury, 1987; Folke and Kautsky, 1989; Beveridge *et al.,* 1991, 1994; Phillips *et al.,* 1991). Cage aquaculture can release a considerable amount of biogenic waste such as organic matter and inorganic nutrients that are generated in the production process (Troell and Norberg, 1998; Cheshuk *et al.,* 2003; Vassallo *et al.,* 2006; Redmond *et al.,* 2010). The rapid expansion of cage aquaculture has raised a general concern about increasing amounts of solid and dissolved nutrients released to the aquatic environment (Perez 2002; Whitmarsh *et al.,* 2006; Redmond *et al.,* 2010).

One of the most conspicuous impacts of open net cage fish farms is the increased particle loading on the seafloor in the near-field environment, and consequential impacts on sediment geochemistry and benthos. It has also been established worldwide that nutrient loading to the water column can occur, whereby suspended particulate organic matter (POM) levels may be enhanced by the farm (Jones and Iwama, 1991; Lefebvre *et al.,* 2000; MacDonald *et al.,* 2011). Large faeces particles and uneaten feed may sink rapidly and accumulate in sediments on the seafloor (Cromey *et al.,* 2002; Olsen *et al*., 2008; Nickell *et al.,* 2009), while smaller particles of waste can remain in suspension. However, this is not always the case (Buschmann *et al.,* 1996; Pridmore and Rutherford, 1992), and the conflicting findings suggest that particulate loading on the water column is not well substantiated, when considering fish farm contributions to eutrophication.

A main challenge facing aquaculture today is sustaining a continued increase in fish production while minimizing the impact on the environment (Suguira *et al.,* 2006, Navarrete-Mier *et al*., 2010). Advances have been made over the last two decades to improve the feed conversion ratio (FCR) and digestibility of many fish feeds. For example, salmon feed FCR's have gone from 1.7 in 1993 to 1.3 in 2003 (Cheshuk *et al.,* 2003; Islam, 2005; Reid *et al.,* 2008), and feed wastage is now routinely below 5% (Cromey *et al.,* 2002; Perez *et al.,* 2002; Strain and Hargrave, 2005; Stucchi *et al.,* 2005). Dispersal/deposition models have been employed to assess site susceptibility to organic enrichment impacts (Cromey *et al.,* 2002; Reid et al., 2008). In addition, emphasis has been placed on the practice of Integrated Multi-Trophic Aquaculture (IMTA) as a means for reducing effluent impacts.

IMTA involves the co-culture of species from multiple trophic levels, where losses from one species are nutritional inputs for another (Chopin *et al.,* 2001; Troell *et al.,* 2003). IMTA systems can include inorganic extractive species such as seaweeds (removing by-products of finfish excretory and respiratory metabolism) and organic extractive species such as filter and deposit feeders (removing suspended and deposited particulates from waste feed and feces). IMTA has been practiced for centuries in Asia (Li, 1987; Fang *et al.,* 1996; Qian *et al.,* 1996). For instance, cultivation of scallops, kelp and abalone in the marine IMTA system of Sungo Bay, China, has been commercially successful at industrial scales (Fang *et al.,* 1996; Troell *et al.,* 2009). IMTA has more recently been explored in Canada, Scotland and Australia, where several pilot experiments have been conducted (Stirling and Okumus, 1995; Cheshuk *et al.,* 2003; Chopin *et al.,* 2001).

Studies have shown conflicting evidence regarding the potential for bivalves to benefit from being placed in close proximity to fish cages, and consequently, to extract significant quantities of fish farm wastes. Some research has shown that bivalves are capable of utilizing particulate wastes as an additional food supply (Lefebvre *et al.,* 2000; Mazzola and Sarà, 2001; Reid *et al.,* 2008; MacDonald *et al.,* 2011), by displaying growth enhancement. However, other studies have reported minimal, growth enhancement of bivalves cultured in an integrated system (Taylor *et al.,* 1992; Stirling and Okumus, 1995; Gryska *et al.,* 1996). The difference in findings may indicate that local environmental factors controlling natural seston variability and fish farm waste dispersion pathways are important in IMTA systems.

Coastal marine environments are subject to extreme variability in dissolved and particulate matter, influenced by several factors such as tides, winds, primary production, grazing and sediment resuspension (Velegrakis *et al.,* 1999; Shi, 2010). Suspension feeding bivalves are thus exposed to fluctuations in food quality and quantity as a result of changes in seston, which occur over time scales ranging from hours to months or years. Considerable efforts have been invested into understanding the behaviour of different environmental characteristics of the water column and how they may affect aquaculture productivity.

Food supply has been at the core of many bivalve aquaculture studies, because food quantity and/or quality are often related to indices of bivalve growth, and food is usually supplied in limited amounts within a bivalve farm. The introduction of bivalves as part of an IMTA system has the potential to make use of the POM provided through fish feces and feed waste as an additional bivalve food supply. However, several factors affecting seston concentrations could limit the availability and delivery of food in an IMTA system. These factors include biological processes, such as photosynthesis, growth and grazing, operating on a smaller scale and physical processes, such as tides, estuarine circulation and wind, operating on a larger scale. It is paramount to recognize this complex combination of different temporal and spatial scales, and understand the importance of timing between different forcing agents.

The physical basis for most aquaculture studies is coastal hydrodynamics, including the influence of wind and tides on circulation, given that water circulation allows the exchange of particles and nutrients between open ocean and bays while flushing out food-depleted waters and wastes. The introduction of an IMTA system inclusive of bivalves with the potential to assimilate suspended solid wastes has required new efforts in characterizing the temporal variability in seston surrounding finfish aquaculture sites.

Previous work has utilized high-resolution 3-D spatial surveys to delimit the fish farm's impact on the surrounding particle field (Brager *et al.,* unpublished). This work examined the spatial distribution pathways of seston surrounding finfish sites; however, the spatial focus meant taking snapshots in time of a highly dynamic variable. Therefore, this investigation will employ the use of sensor moorings, as well as current meters for hydrodynamic data, at a variety of depths at finfish farms to further quantify the spatiotemporal variations of turbidity and chlorophyll, in order to understand how they are affected by fish aquaculture. This information is vital to the evaluation of the potential for efficient nutrient recovery for the bivalve-component of IMTA systems.

3.3. Methods

3.3.1. Study Sites

Time-series data from moored in situ particle sensors was collected on both the east and west coasts of Canada. On the east coast, field studies were conducted at two Atlantic salmon farms in the macrotidal Passamaquoddy Bay region of the Bay of Fundy, Navy Islands (Passamaquoddy Bay, 45^{o} 01' 49.46'' N, 67^{o} 00' 11.24'' W) and Charlie Cove (L'Etête Passage, 45^{o} 01' 46.58'' N, 66^{o} 52' 01.11'' W). On the west coast, data were collected at a site culturing mainly *Anoplopoma fimbria* (black cod) in the mesotidal area of Kyuquot Sound on the Northwest coast of Vancouver Island (50^{o} 02' 48.52'' N, 127^{o} 17' 45.87'' W). The Navy Islands site is larger in production size with 15 net pens, while Charlie Cove and Kyuquot Sound had 8 and 4 stocked pens at the time of sampling, respectively. Both sites on the east coast (Navy Islands and Charlie Cove) are 23-m in depth, and subject to strong tidal currents and mixing owing to the 6-m average diurnal tidal range (Trites and Garrett, 1983; Thompson *et al.,* 2002). Kyuquot Sound is approximately 28-m in depth, and subject to a 3-m average semi-diurnal tidal range.

3.3.2. Particle-Sensing Instrumentation

Two combination optical back scatter and fluorometer sensors with internal batteries for autonomous recording (FLNTUSB ECOMeter, WET Labs, Philomath, OR, USA) were used in this investigation. Sampling rates were set consistently at 1 Hz; however number of samples collected and length of dormancy period were set for the ECOMeters depending on intended duration of sampling period. At Navy Islands, Charlie Cove and Kyuquot Sound, instruments were programmed for 10 samples (i.e. a 10-second burst at 1 sec^{-1}) every 2 minutes (16 – 18 November 2010), 10 minutes (5 – 15 July 2011), and 1 minute (24 – 28 July 2011), respectively.

3.3.3. Mooring Deployments

Arrangement of moorings for each site was variable depending on tidal characteristics, farm structure, and available instrumentation. At Navy Islands, two separate moorings were deployed at 5-m depth and hung from the fish cages themselves, on opposite sides of the farm in the predominant current flow direction. Two ADV current meters were also attached to the same instrument frames. In contrast, one single-point mooring was deployed at both Charlie Cove and Kyuquot sound, with both ECOMeters at different depths. At Charlie Cove, a mooring was deployed directly outside of the farm compensator buoys at one end of the site. The mooring consisted of an ECOMeter at 5-m and 15-m. Current meters were also attached at each depth (Infinity current meter at 1.5-m and ADV at 15-m). At Kyuquot sound, the mooring was deployed directly off of the fish cage containing the largest number of fish, with an ECOMeter at 1- and 20-m depth, and an Infinity current meter at 19-m. The mooring was located in line with the suspected predominant flow direction from the net-pen.

3.3.4. Instrument Calibrations

WET Labs ECOMeters were calibrated in the laboratory using chlorophyll (CHLa, μg L^{-1}) and total particulate matter (TPM, mg L^{-1}) standards (n=14) prepared by suspending known concentrations of algal cells (mixed flagellates) or fine sediment (natural clay/silt mixture pre-sieved through a 64 μm mesh) in seawater. TPM and CHLa concentrations in all standards were determined using routine gravimetric and fluorometric procedures, respectively. A field sensor inter-calibration was also conducted to confirm the accuracy of CHLa and TPM measurements made with the laboratory calibrated ECOMeters. Both instruments were programmed to record data at 2-sec intervals and then attached to a Seabird CTD sensor package containing a WET Labs C-Rover transmissometer (25 cm path length), and a WET Labs WETStar fluorometer. These latter sensors were previously calibrated from extensive in-situ sampling. The WETStar fluorometer readings were highly correlated with CHLa concentrations in discrete samples of seston collected on Whatman GF/C filters and extracted in 90% acetone ($r^2 = 0.899$, $n = 80$). The C-Rover transmissometer counts were similarly calibrated against gravimetrically determined TPM concentrations in water samples ($r^2 = 0.848$, $n = 100$). The combined instrument package was used to conduct random water column profiles so that results from the different sensors could be compared. Laboratory calibrations for the WET Labs ECO turbidity sensors were confirmed for use under field conditions by this inter-calibration. However, the laboratory calibration for the CHLa sensors provided results that were markedly different from those obtained by the WETStar fluorometer. Consequently, the ECO sensor counts were calibrated against simultaneous CHLa measurements made with the WETStar fluorometer. Calibration equations used in this study are $TPM = 0.0043 \times counts + 0.8284$ ($r^2 = 0.99$) and $Chl\ a = 0.0191 \times counts - 0.4512$ ($r^2 = 0.90$), and $TPM = 0.0046 \times counts + 0.9296$ ($r^2 = 0.99$) and $Chl\ a = 0.0193 \times counts - 0.7107$ ($r^2 = 0.94$) for Wetlabs ECO instrument serial numbers 2017 and 2018, respectively.

3.3.5. Data Analysis

TPM (mg L^{-1}) and CHLa (µg L^{-1}) data for each site were averaged to obtain one sample per 10-sec sample burst. Due to high sampling frequency and the consequent likelihood of variable noise, data was also smoothed using a 10-sample moving average. DFO Webtide was used to make tidal elevation (m) predictions for both the east and west coast sites. Spectral analyses on TPM time-series were performed in MATLAB. All TPM data were linearly detrended and subsequently run through the *periodogram* function. Cyclic periodicities were obtained from peak frequencies ($hour^{-1}$) in the periodogram plots. Polar plots of current speed and direction, as well as TPM and direction, were constructed using SigmaPlot (v. 12.0) for visualization of the distribution of currents and TPM in space.

3.4. Results

3.4.1. Spatial Variations in TPM Concentration

Spatial variations in TPM concentration over time were studied at the Navy Islands site with the deployment of two instruments on either side of the farm in the predominant current direction. Time series of TPM and CHLa collected at 5-m depth every two minutes on the inner- and outer-bay side of the farm have been smoothed using a 10 sample moving average and presented in Figure 3.1.

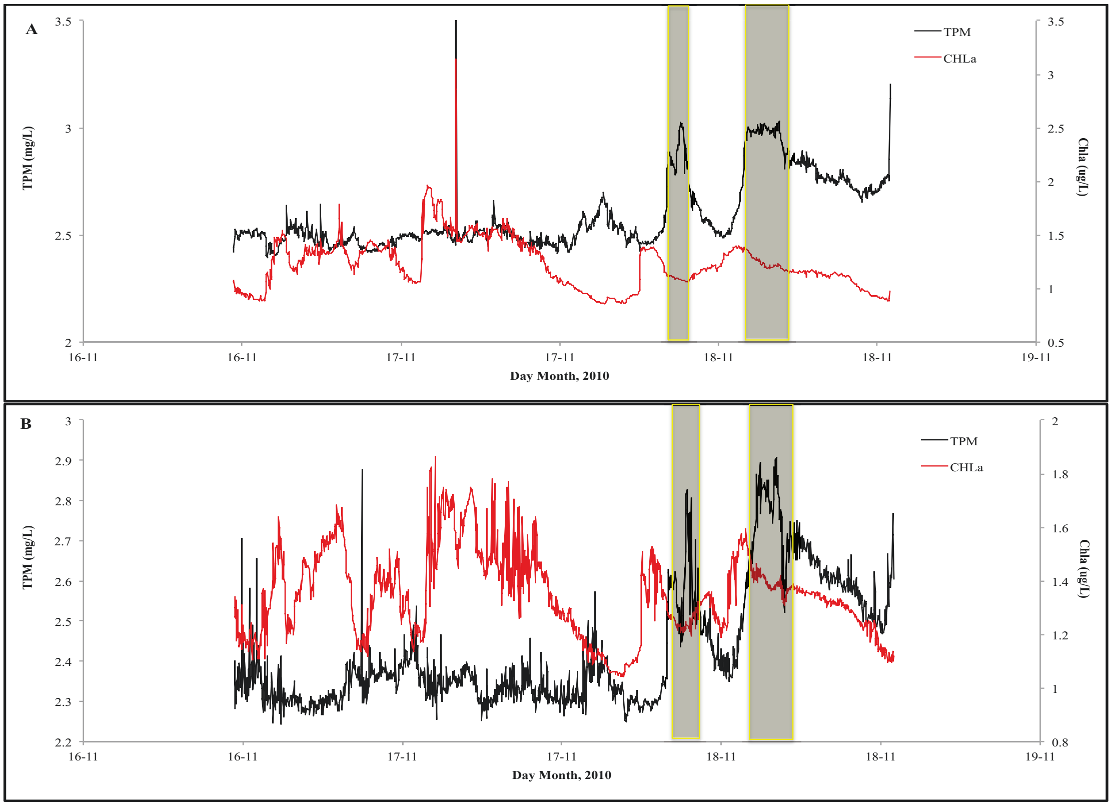

Figure 3.1. TPM (mg L^{-1}) and CHL*a* (µg L^{-1}) concentrations logged every two minutes at Navy Islands from 16 November to 18 November 2010. Data shown here were collected at 5-m depth on the A) "inner"- and B) "outer"-bay sides of the farm. Each instrument was located within 3-m of a net-pen. Data has been smoothed using a 10-sample moving average. Yellow highlighting represents a distinct TPM increase and co-occurring CHLa decrease.

TPM concentrations on the inner-bay side (mean = 2.6 mg L^{-1}) were slightly higher on a consistent basis than the outer-bay side (mean = 2.4 mg L^{-1}). However, this difference is within the standard error of estimate provided by the regression equations used to calculate TPM. An upward trend in TPM was observed on both sides of the farm starting on 17 November 2010 at approximately 20:00h. Identical peaks in TPM occurred for both instruments (Fig. 3.1) on 17 November 2010, lasting approximately 1 hour (20:07 – 21:01h), and again on 18 November 2010 for approximately 2 hours (02:04 – 04:06h), but did not occur in CHLa (Fig. 3.1). However, these individual peaks only represented TPM increases above mean values of roughly 0.5 mg L^{-1}. There was no indication in these data of an allocthonous source of particulate material exiting the salmon farm at 5 m depth during the sampling period.

3.4.2. Depth Variations in TPM Concentration

Depth variations in TPM concentration over time were studied with the deployment of instruments at 5-m and 15-m and 1-m and 20-m depth at the Charlie Cove and Kyuquot Sound sites, respectively. Time series of TPM and CHL*a* collected every 10 minutes at Charlie Cove and every minute at Kyuquot Sound have been smoothed using a 10 sample moving average and presented in Figures 3.2 and 3.3, correspondingly.

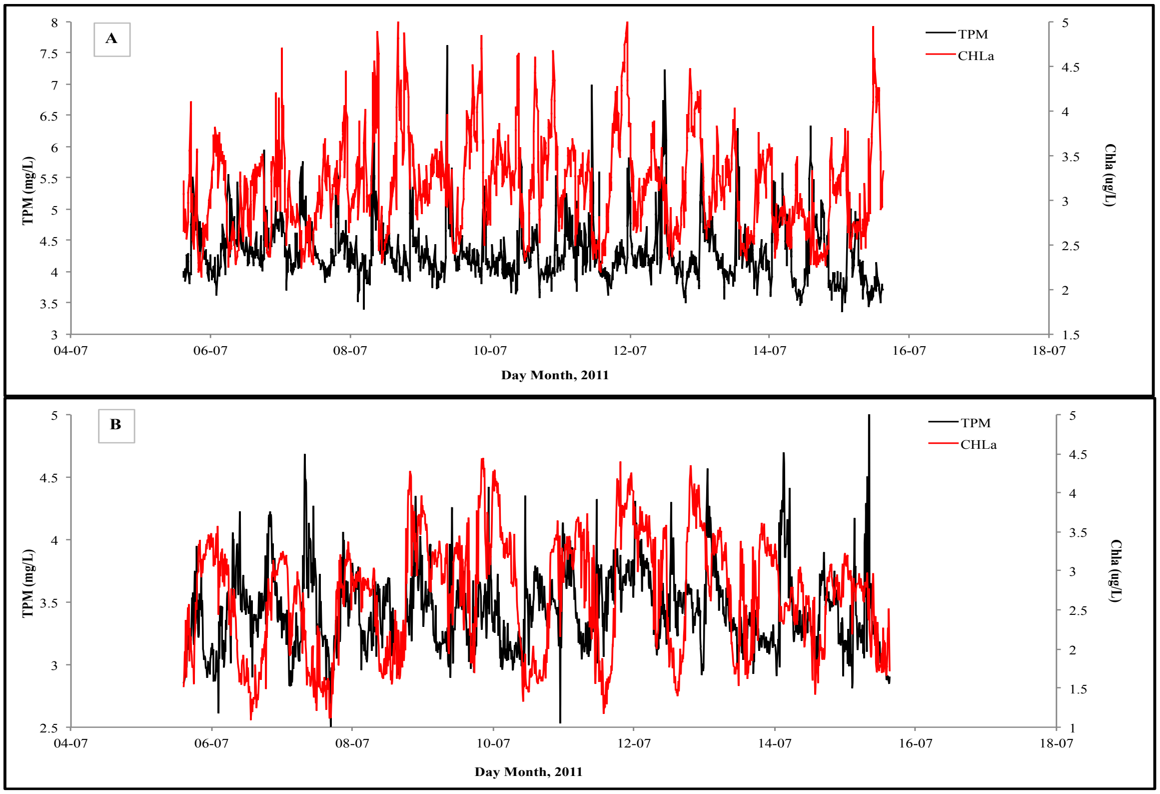

Figure 3.2. TPM (mg L^{-1}) and CHLa (μg L^{-1}) concentrations logged every 10 minutes at Charlie Cove from 5 July to 15 July 2011. Data were collected at A) 15-m and B) 5-m depth at a single location near the farm. Data has been smoothed using a 10-sample moving average.

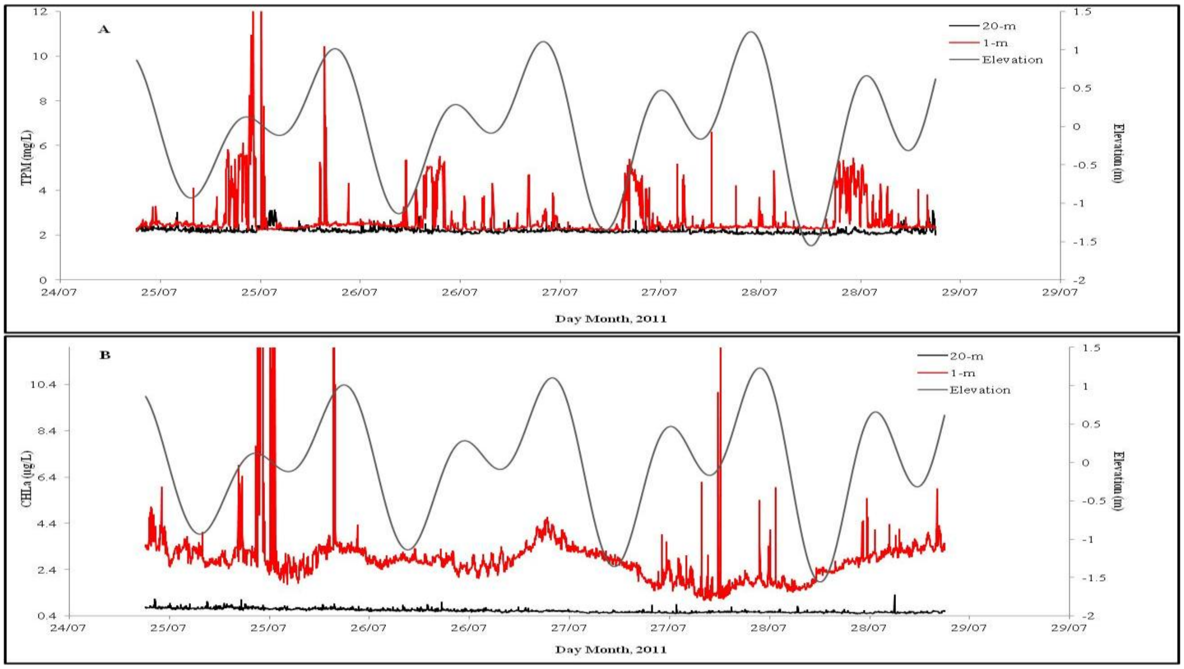

Figure 3.3. TPM (A, mg L^{-1}) and CHLa (B, µg L^{-1}) concentrations logged every minute at Kyuquot Sound from 24 July to 28 July 2011 collected at 20- and 1-m depths at a single location near the farm. Data has been smoothed using a 10-sample moving average. Corresponding tidal elevation (m) predictions from DFO WebTide are displayed as well.

Differences in TPM over time were seen depending on depth at both sites. Consistently higher TPM concentrations were present at 15-m (mean = 4.3 mg L^{-1}), as compared to 5-m (mean = 3.4 mg L^{-1}), at Charlie Cove. A cyclic trend is represented in both TPM and CHLa at Charlie Cove at 5- and 15-m depth, though the variables are not always in sync. At Kyuquot Sound, TPM concentrations present at 1-m often doubled from approximately 2.5 mg L^{-1} to 5.0 mg L^{-1}. These peaks generally corresponded with the onset of flood tide, as displayed in Fig. 3.3a, however, were not reflected in the CHL*a* data (Fig. 3.3b), nor present in TPM patterns at 20-m depth (Fig. 3.3a). TPM at 20-m depth remained constant at approximately 2.3 mg L^{-1}. A distinct peak, representative of a 0.7 mg L^{-1} increase, occurred on 25 July 2011, lasting for roughly 1 hour. Current meter data collected suggest that the TPM increase occurred while current speeds were less than 0.5 cm s^{-1}.

3.4.3. Periodicity in TPM Concentration

Periodograms for TPM at the Navy Islands farm on the inner- and outer-bay (Fig. 3.4a) sides were calculated to identify any intrinsic periodic signals in the time-series data. TPM on the outer-bay side shows the highest magnitude of frequency at approximately 0.08 cycles per hour (cph) or 12.5 hours. The periodogram for the inner-bay shows TPM was not dominated by the same 12.5 hour tidal cycle. The highest peak occurred at a frequency of approximately 0.014 cph, or 71.4 hours, but still at a very low/negligible magnitude. Periodograms for TPM at Charlie Cove at 5- and 15-m depth (Fig. 3.4b) both have peaks at approximately 0.08 cph (12.5 hours), in agreement with predicted tidal harmonics. Periodograms for TPM at Kyqouot Sound at 1- and 20-m (Fig. 3.4c) depth both displayed peaks at the 0.08 cph frequency (12.5 hours), however of significantly less magnitude at 20-m than 1-m. TPM at 1-m also had a significant peak at approximately 0.042 cph, representative of a 24 hour cycle. At 20-m, the highest peak occurred at a frequency of 0.067 cph, or approximately 15 hours, however at a very low magnitude.

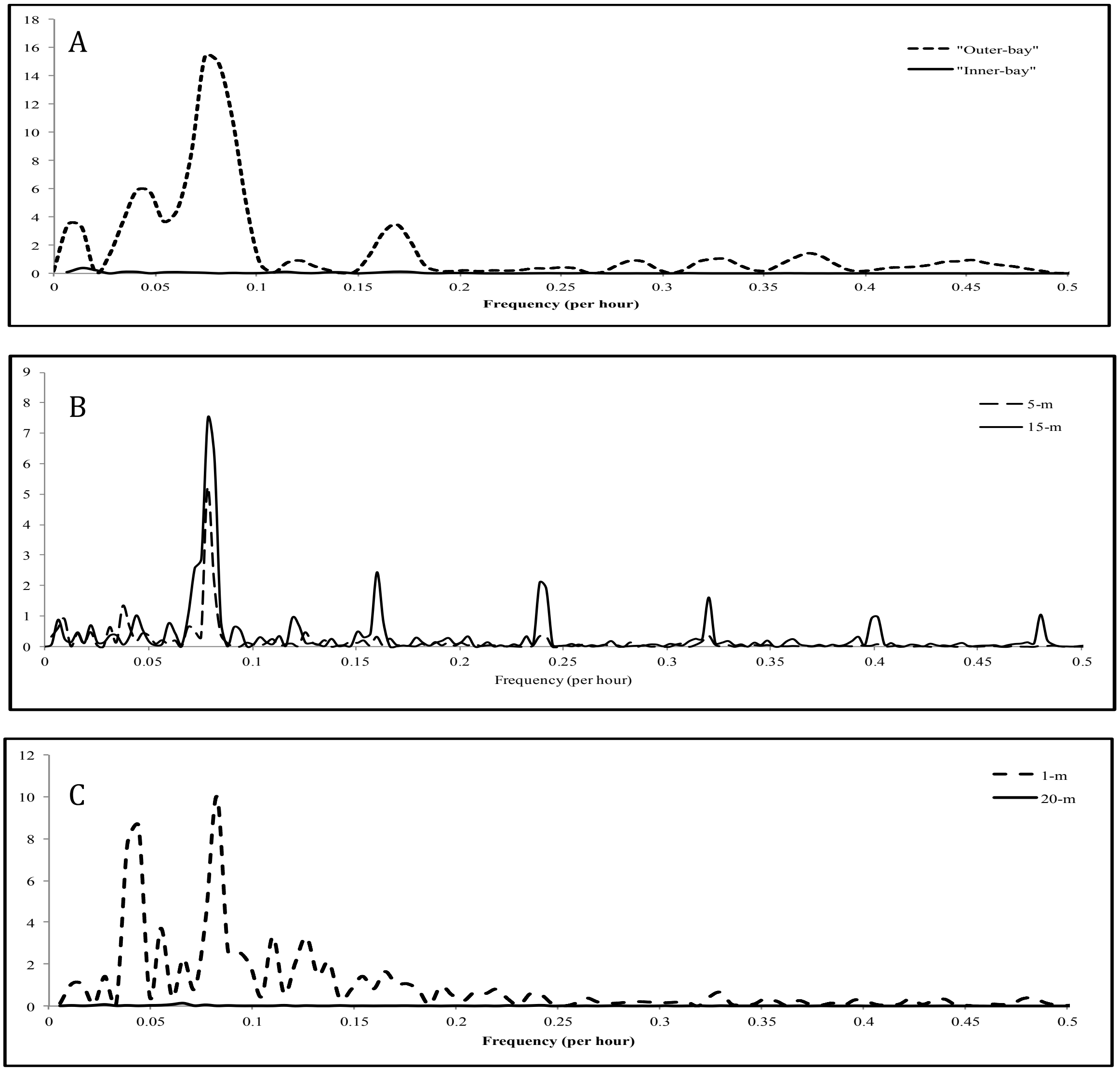

Figure 3.4. Periodogram displaying frequency (hour $^{-1}$) peaks in TPM at A) Navy Islands from 16 – 18 November 2010 on the inner- and outer-bay sides of the farm, B) Charlie Cove from 5 – 15 July 2011 at 5- and 15-m depth at one location near the farm and C) Kyuquot Sound from 24 – 28 July 2011 at 1- and 20-m depth at one location near the farm.

3.4.4. Directionality in TPM Concentration

Current speeds and directions measured at 5-m depth at Navy Islands are presented in Fig. 3.5. Current directions that would suggest water has passed through the farm, and therefore could potentially be influenced by the farm, have been highlighted. Current speeds were approximately the same on both the inner- and outer-bay side of the farm, with the majority of data collected being < 40 cm s^{-1} (Fig. 3.5a, 3.5b). Current speed rosettes indicate slightly higher speeds coming from the direction of the farm than for waters flowing towards the farm (Fig. 3.5a, 3.5b). TPM concentrations corresponding to different current directions are displayed in Fig. 3.5c and 3.5d. On the outer-bay side of the farm, more data points of higher TPM concentrations were found in the reference waters flowing towards the farm, than in the water having already moved through the farm (Fig. 3.5c). On the inner-bay side, however, TPM was consistent around 3.0 mg L^{-1} across all directions (Fig. 3.5d).

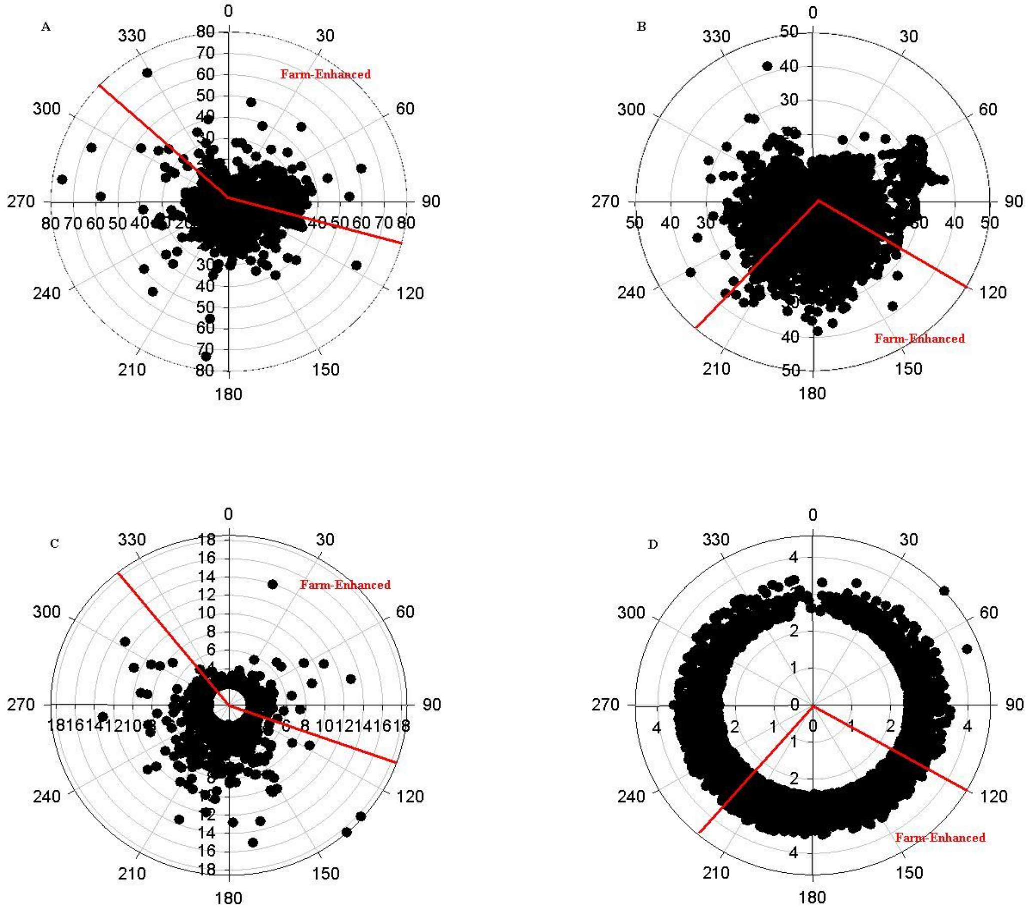

Figure 3.5. Polar plots of time-integrated current directions and A) outer-bay current speeds (cm s^{-1}), B) inner-bay current speeds (cm s^{-1}), C) outer-bay TPM (mg L^{-1}) and D) inner-bay TPM (mg L^{-1}) at the Navy Islands salmon farm from 16 to 18 November 2010 . Red lines represent the range of flow directions of water coming from the farm (i.e. potentially „farm-enhanced').

Current speed and direction data from 5-m depth at the single Charlie Cove farm mooring indicates that a larger fraction of the data were collected from reference waters flowing towards the farm, than in the direction of water which has already moved through the farm. Directional data also displays slightly higher current speeds in reference waters with most data falling within 15 cm s^{-1}, in comparison to most farm waters falling within 10 cm s^{-1} (Fig. 3.6a). Directional TPM data does not suggest higher concentrations in water which may have passed through the farm, as compared to reference waters, at neither 5- nor 15-m depth, but rather is consistent at ~ 3.4 mg L^{-1} and 4.3 mg L^{-1}, respectively (Fig. 3.6b and 3.6c). Current speed and direction data from Kyuquot Sound taken at 20-m depth at one location indicates a directionality preference, with higher current speeds in the directions which include that of water coming from the direction of farm (Fig. 3.7a). A directional enhancement in TPM concentration also exists in water flowing from the direction of the farm. At 20-m depth, concentrations are slightly higher in those directions in comparison to reference waters flowing towards the farm (Fig. 3.7b); however, at 1-m depth concentrations are 2 to 3 times higher in those directions, than in comparison to what would be flowing into the farm (Fig. 3.7c).

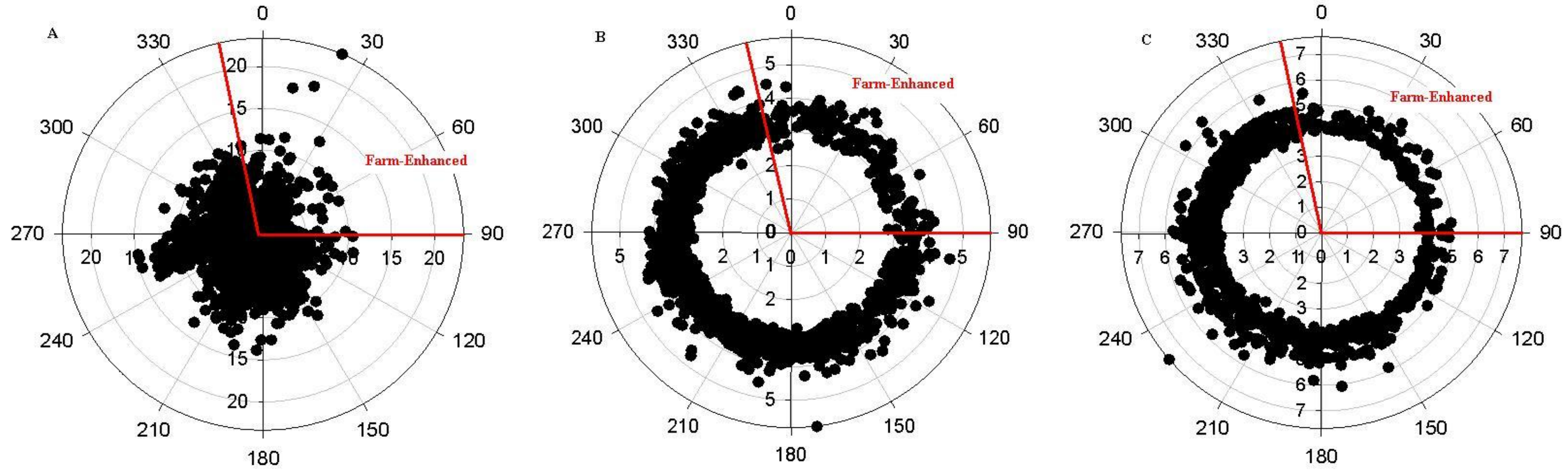

Figure 3.6. Polar plots of time-integrated directions and A) 5-m depth current speeds (cm s^{-1}), B) 5-m depth TPM (mg L^{-1}) and C) 15-m depth TPM (mg L^{-1}) at Charlie Cove. Red lines represent the flow directions of water coming from the farm (i.e. potentially „farm-enhanced').

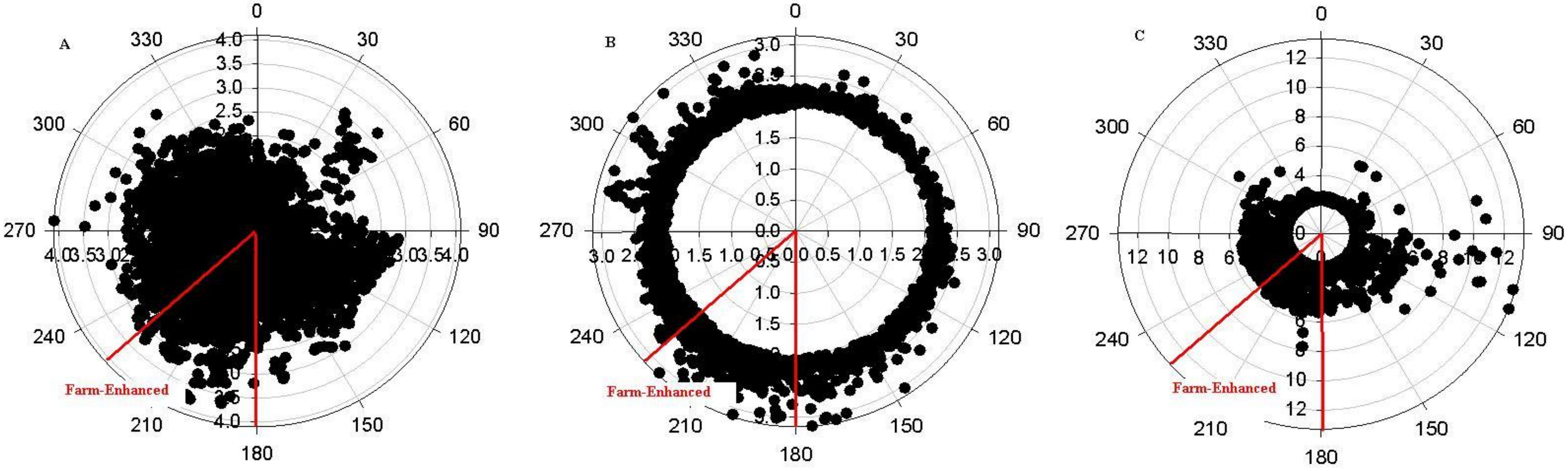

Figure 3.7. Polar plots of time-integrated directions and A) 20-m depth current speeds (cm s^{-1}), B) 20-m depth TPM (mg L^{-1}) and C) 1-m depth TPM (mg L^{-1}) at Kyuquot Sound. Red lines represent the flow directions of water coming from the farm (i.e. potentially „farm-enhanced').

3.5. Discussion

Previous studies have not directly examined whether or not suspended particulate matter loading from a fish farm has any persistent impact over time on the naturally-occurring variability of seston in estuarine/coastal systems. This study provided evidence of the dynamic nature of TPM surrounding two fish aquaculture sites in the Bay of Fundy, and one in Kyuquot Sound. Periodogram results were strongly indicative of predominantly tidal driven TPM patterns (Fig. 3.4). Other characteristics in the time-series of TPM concentrations such as differences between the inner and outer bay sides of the Navy Islands site (mean effect < 0.5 mg L^{-1}), depth variations present at all sites, and infrequent peaks in concentration over time (lasting approximately 1 to 2 hours each) are suggestive of highly variable TPM concentrations over tidal time scales.

Frequency peaks corresponding to periodicities in conjunction with M_2 principal lunar semi-diurnal tides were the most common amongst all time-series data collected in this investigation. Kyuquot Sound data also indicated a strong 24-hour cycle at 1-m depth, which is likely due to P1 principal solar diurnal tides. In tidally-driven environments, in particular, variability of TPM concentration at tidal frequencies has been shown to be present and well-documented as a source of short-term variability (Cloern *et al.,* 1989; Velegrakis *et al.,* 1997; McCandliss *et al.,* 2002). Therefore, the dominant lower frequency oscillations present in the results of this study were to be expected, particularly in the macrotidal region of the Bay of Fundy.

In regions controlled primarily by the tides, the spatial and short-term temporal variations in suspended particulate matter concentrations have been described as associated with horizontal advection and vertical exchanges of material (Velegrakis *et al.,* 1997).

Previous studies have identified horizontal displacement of TPM due to tidal excursion induced by flood and ebb flows, often resulting in concentration gradients (Weeks *et al.,*1993; Velegrakis *et al.,* 1997). In the tidal inlet of Passamaquoddy Bay in particular, tides alone can have significant impacts on seston levels, with concentrations being at a maximum by the end of a flood tide (as oceanic waters are advected into the inlet) and at a maximum by the end of an ebb tide (Dowd, 2003). This could potentially provide explanations for some of the major temporal fluctuations seen here. The doubling of surficial TPM concentrations (1-m depth) present in the time-series record collected at Kyuquot Sound is correlated with flood tide periods. This suggests that relatively large amounts of suspended material moved past the mooring every flood tide for the duration of sampling. However, the predominant flood flow direction means that water flowing past the mooring had not already been through the farm. Therefore, this would suggest that the recurring increases in surficial TPM concentrations that occurred at the Kyuquot Sound site over the four-day period of observation were not farm-derived.

One must be cautious when comparing temporal changes alone in the absence of information about spatial gradients (see preceding paper, Brager *et al.,* unpublished). The temporal focus of that investigation meant taking spatial snapshots over time of a variable that has been shown to have a largely patchy distribution (Brager *et al.,* unpublished). The limited availability of instruments for the collection of data meant that assumptions were made regarding predominant current flows through the farm for the most ideal sampling design to intercept and detect any farm-derived increases in TPM.

Although it may seem logical that water flow surrounding these sites would be dominated by the tides in a strongly advective manner, dispersive processes within these fish farms should certainly not be underestimated. Net cages present at fish farms are porous and highly flexible; characteristics that can strongly govern the flow pattern both within and around the fish farm (Løland, 1993). These impacts were demonstrated by the results of this investigation. Directional data from Charlie Cove showed a farm „shading-effect' at 5-m depth (Fig. 3.6a), meaning that water coming from the farm may have been hindered and was not passing the instrument mooring as often as reference water from directions other than the farm. Flow reduction also appeared to occur through Charlie Cove from approximately 15 to 10 cm s^{-1}. Physical cage structures and implications for water and particle exchange have been assessed and discussed in previous studies (Cromey and Black, 2005; Stucchi *et al.,* 2005; Troell *et al.,* 2009).

The impacts of net-pens on tidal flow can be significant, but flow alteration does not always necessarily mean flow reduction. At both Navy Islands and Kyuquot Sound, current speeds were actually slightly higher in water coming from the direction of the pens as compared to reference waters flowing in. Flows surrounding these sites are influenced by farm structure, daily farm activities and fish behaviour, fostering an environment of highly complex and unpredictable flow patterns. At the stocking densities present at these sites, it may seem logical that fish swimming activity alone could create a number of small-scale eddies around the cages and cause localized increased flow. Atlantic salmon can be seen swimming in the surface waters at an aquaculture site, while sablefish are known to circle the bottom of the nets and only come up to feed (Cross, personal communication). This fish swimming behaviour may help to explain the increases in current speed seen at 5-m depth at Navy Islands and 20-m depth at Kyuquot Sound.

Although tidal advection has often been characterized as the predominant mechanism for short-term variability of TPM, other mechanisms (e.g. river sources, terrestrial inputs, storms, anthropogenic impacts) may contribute to TPM variability observed at the tidal time scale. The presence of finfish aquaculture sites has been shown to impact surrounding particle fields, including contributing to higher concentrations of local suspended particulate matter at the Charlie Cove site studied here (MacDonald *et al.,* 2011). Data previously collected at Charlie Cove by MacDonald *et al.* (2011), however, was collected with a few discrete samples over a short period of time. The extensive nature of the data collected during this investigation only showed higher concentrations of TPM coming from the farm at Kyuquot Sound at 20-m depth, and shows no consistency in this otherwise (Figs. 3.5 – 3.7). For instance, there were no differences in the TPM concentrations of water flowing into or out of the Charlie Cove site. Furthermore, other data highlighted higher concentrations of particulate matter in reference waters (i.e. due to naturally-occurring seston) than in „farm-impacted' waters at both Navy Islands and Kyuquot Sound.

Fish farm activity adds another challenge to understanding an already complex water column, with the potential addition of small suspended or slow-sinking organic particulates generated from feed waste or faeces to the environment. Given that feed wastage rates likely contributing to the majority of suspended fines are now routinely below 5% (Cromey *et al.,* 2002; Perez *et al.,* 2002; Strain and Hargrave, 2005; Stucchi *et al.,* 2005), it could be predicted that little would be detected during this investigation in the way of additional suspended matter. Organic deposition, from mainly faeces, below a salmon farm is estimated to be approximately 2,800 kg per day, and therefore, it is not unreasonable to assume that the majority of particles sink rapidly to the seafloor (Handå *et al.,* 2012).

The preceding paper (Brager *et al.,* unpublished) suggests that a particle source may exist, but in an intermittent manner, and that timing of sampling could be very important in the search for this particle „pulse', hence the motivation behind this study. Troell and Norberg (1998) referred to an „enriched pulse' of nutrients as more likely than a continuous plume due to the nature of periodic feeding and probable mass release of feces at some time after feeding. Non-recurring intermittent peaks in TPM occurred only a few times over the duration of this investigation. At Navy Islands, two short-lasting (~ 1-2 hours) increases in TPM (mean effect < 0.5 mg L^{-1}) were recorded at 5-m depth. Although it is possible, given the close proximity of the fish cages to the mooring, that these increases could potentially be derived from suspended farm wastes, it is also possible that these increases were caused by storm activity that took place in the days following 18 November 2010. Storm winds would have been increasing on 17 November and 18 November 2010, creating wind driven surface currents and turbid water masses. Another instance of a peak in TPM occurred at Kyuquot Sound at 20-m depth, also lasting approximately 1 hour. This could potentially be heavier farm-derived particulates (i.e. fish feces) leaking out the bottom of the net pen while current speeds are low (< 0.5

cm s^{-1}). However, the accumulation of particulates does not exist once current speeds increase, and the waste is rapidly advected away from the site.

The partitioning of suspended particulate matter temporal variability among the potential array of forcing mechanisms is difficult and no consistent generalizations have emerged concerning the magnitude or primary source(s) of short-term variability in estuaries. However, this investigation concludes that TPM surrounding open-water fish farm sites is largely driven by hydrodynamics, with the farm having little impact above the naturally-occurring range in *suspended* particle concentrations. This is in agreement with previous long-term monitoring studies highlighting the importance of physical influences on TPM variability, such as wave activity and tidal currents (McCandliss et al., 2002).

When considering the feasibility of an efficient IMTA system, it is of primary importance to determine whether or not the farm is even supplying an additional food source in order to contribute to the enhanced growth of another commercial species, such as bivalves, and its temporal consistency. This research shows that short-lived, intermittent farm-derived enhancement may exist, but in no consistent manner and of little magnitude outside of naturally-existing seston concentrations. However, the potential of the IMTA concept to increase global food production and efficiency warrants further exploration into the mechanisms by which particulate wastes can be recycled under the complexities of open water conditions.

Chapter 4: Conclusion

This thesis documents low levels of suspended particle enhancement from fish-farm wastes. Spatial surveys indicated small increases (< 1.5 mg L^{-1}) in mean TPM, primarily in surficial waters (0.5 to 2 m depth), and increased TPM variability immediately down-current from the fish farms. Given the low levels of apparent TPM enhancement adjacent to the farms, rarely outside of the range of naturally-existing particle concentrations, and that seston concentrations were occasionally higher in natural waters (i.e. not farm-impacted), it is difficult to attribute any increases in TPM concentrations to a farm-based source. Moreover, findings were strongly indicative of predominantly tidal driven TPM patterns.

One must be cautious when comparing solely spatial or temporal changes in the absence of information about the other. The initial spatial surveys of this investigation suggested that a particle source may exist, but in an intermittent manner, and that the timing of sampling could be very important in the search for this particle „pulse'. However, the latter temporal surveys of this investigation provided evidence that these farm-derived pulses do not exist, and that naturally-occurring tidal phenomena play the predominant role in TPM variability, even at finfish aquaculture sites. The complementary nature of Chapters 2 and 3 presented in this thesis provide an in-depth picture of the state of spatial and temporal TPM variability at finfish farms.

The topic of an „ideally-envisioned' plume of particles emanating away from finfish aquaculture farms is often discussed in the context of bivalve-finfish IMTA, when considering where to optimally place bivalves in order to intercept the particulates. However, mapping of the particle field surrounding the sites in this investigation did not display any distinct regions of TPM enhancement, but rather a highly patchy distribution. This is likely due to the fact that advective processes are not the only forces surrounding these complex environments, and dispersive processes should not be underestimated. Farm structure and even fish swimming activity, all contribute to flow reduction and/or flow alteration around these sites.

These results do not provide evidence of enhanced particle sources for adjacent suspended feeders in IMTA culture. However, they apply only to specific locations. Moreover, other trophic levels of IMTA systems, such as sea plants, may derive significant growth benefits from the dissolved waste component of finfish aquaculture. Adopting the IMTA philosophy for aquaculture production in Canada could result in a number of costs and benefits to the industry. In some cases, costs may include: increased nutrient loading and complexity in infrastructure. Benefits may include: proactive method for dealing with nutrient loading and increased revenue streams.

However, the findings of this thesis mean that the co-culture of bivalves and finfish could come at more of a cost. The limited horizontal displacement of any form of increased seston levels would significantly restrict the area for bivalve culture that would be beneficial to their growth. Co-culture within very constrained boundaries for optimal placement could mean significant consequences for commercial scale farming production of a bivalve species within an IMTA system.

Nevertheless, the potential of the IMTA concept to increase aquaculture sustainability in Canada and increase global food production and efficiency warrants further exploration into the mechanisms by which particulate wastes can be recycled and utilized under the open-water conditions that affect the magnitude of waste streams and their potential to be exploited.

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