Monitoring the Bras d'Or Lakes: 2009-2012

A. Drozdowski, E. Horne and G. L. Bugden

Coastal Ecosystem Sciences Division
Maritimes Region
Fisheries and Oceans Canada

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

2014

Canadian Technical Report of Fisheries and Aquatic Sciences 3087

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of the Department of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in Aquatic Sciences and Fisheries Abstracts and indexed in the Department's annual index to scientific and technical publications.

Numbers 1 - 456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457 - 714 were issued as Department of the Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page. Out-of-stock reports will be supplied for a fee by commercial agents.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais que ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques du ministère des Pêches et des Océans, c'est-à-dire les scences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications complètes. Le titre exact paraît au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la revue Résumés des sciences aquatiques et halieutiques, et ils sont classés dans l'index annual des publications scientifiques et techniques du Ministère.

Les numéros 1 à 456 de cette série ont été publiés à titre de rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Les rapports techniques sont produits à l'échelon regional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre. Les rapports épuisés seront fournis contre rétribution par des agents commerciaux.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3087

2014

Monitoring the Bras d'Or Lakes: 2009-2012

by

A. Drozdowski, E. Horne and G. L. Bugden

Science Branch
Maritimes Region
Fisheries and Oceans Canada

Bedford Institute of Oceanography
P. O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

Cat. No. Fs97-6/3087E-PDF ISBN 978-1-100-23587-5 ISSN 1488-5379

Correct Citation for this publication:

Drozdowski, A., E. Horne and G. L. Bugden. 2014. Monitoring the Bras d'Or Lakes: 2009-2012. Can. Tech. Rep. Fish. Aquat. Sci. 3087: vi + 24 p.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Drozdowski, A., E. Horne and G. L. Bugden. 2014. Monitoring the Bras d'Or Lakes: 2009-2012. Can. Tech. Rep. Fish. Aquat. Sci. 3087: vi + 24 p.

An overview of the ongoing Bras d'Or Lakes monitoring program and its findings are presented. The Bras d'Or Lakes are Canada's only inland sea, with limited exchange with the North Atlantic. The tide entering through the Big Bras d'Or Channel attenuates rapidly to about 10% of its original range by the time it reaches the interior of the Lakes. A direct consequence of this slow flushing is low oxygen concentration in the deeper parts of the Lakes. The Lakes have shellfish and finfish aquaculture industries, which are subject to the limited oxygen in the region. The Lakes are also home to a large range of plant and animal species that can be adversely affected by oxygen depletion. Many of these species are important to the Aboriginal way of life. In addition to low oxygen, other stressors to plant and animal communities are aquatic invasive species, higher water temperatures, and coastal erosion. The local residents are reporting an increased frequency and magnitude of storm surges which contribute to coastal erosion. The Bedford Institute of Oceanography (in collaboration with the Cape Breton University and the Unama'ki Institute) has been monitoring temperature, water level, currents and optical properties of the Bras d'Or Lakes since 2009. Recently collected data indicates that the deep anoxic layer occasionally invades shallower water regions and has the potential to kill fish and other wildlife. Also of interest is a secondary phytoplankton bloom which occurs in the fall. Observations in Whycocomagh show this region to contain very high concentrations of CDOM (coloured dissolved organic matter), which make it an ideal case study site to design and validate remote sensing algorithms for detecting chlorophyll in high CDOM coastal areas.

RÉSUMÉ

Drozdowski, A., E. Horne and G. L. Bugden. 2014. Monitoring the Bras d'Or Lakes: 2009-2012. Can. Tech. Rep. Fish. Aquat. Sci. 3087: vi + 24 p.

Le présent article fournit un aperçu du programme de surveillance des lacs Bras d'Or en cours et de ses constatations. Les lacs Bras d'Or forment la seule mer intérieure au Canada et ont un accès limité à l'Atlantique Nord. La marée qui pénètre le chenal Big Bras d'Or s'affaiblit rapidement à un pourcentage d'environ 10 % de son amplitude d'origine lorsqu'elle atteint l'intérieur des lacs. Une incidence directe de ce faible débit lent est la faible concentration en oxygène dans les zones plus profondes des lacs. Les lacs accueillent des industries de conchyliculture et de pisciculture, qui sont sujettes à la limite d'oxygène dans la région. Les lacs abritent également un large éventail d'espèces de plantes et d'espèces animales (dont plusieurs sont essentielles au mode de vie des Autochtones), qui souffriront davantage de l'appauvrissement en oxygène. En plus de la faible concentration en oxygène, d'autres agents de stress pour les espèces de plantes et d'animaux sont présents, notamment des espèces aquatiques envahissantes et des températures supérieures à la normale. L'érosion côtière constitue une autre préoccupation. Les résidents du secteur signalent une augmentation de la fréquence et de l'ampleur des ondes de tempête. Depuis 2009, l'Institut océanographique de Bedford (en collaboration avec l'Université de Cap Breton et du Unama'ki Institute) surveille la température, le niveau d'eau, les courants et les propriétés optiques. Les données récemment recueillies indiquent que les couches anoxiques profondes envahissent parfois les zones d'eau moins profonde et peuvent tuer les poissons et la faune. De plus, il est intéressant de mentionner que la prolifération du phytoplancton secondaire se déroule à l'automne. Des constatations à Whycocomagh démontrent que cette région présente la concentration la plus élevée de matières organiques colorées dissoutes jamais mesurée par notre groupe, ce qui fait de cet endroit un parfait emplacement d'étude de cas pour créer et valider des algorithmes de télédétection destinés à la détection de chlorophylle dans les régions côtières présentant ces concentrations élevées.

1. INTRODUCTION

The Bras d'Or Lakes (BDL), located on Cape Breton Island, constitute a remarkably unique and complex estuarine ecosystem and Canada's only inland sea. Composed of 2 major basins, many deep and shallow bays and several narrow channels, the Lakes have limited exchange with the adjacent waters on the Scotian Shelf. There are three connecting channels. By far the largest is through Great Bras d'Or Channel (GBC; see Fig. 1) which is about 500m wide on average and 8-50m deep. The second is called Little Bras d'Or and is located at the end of St. Andrew's channel, and is about a tenth of the size of GBC. The last opening is a set of locks in St. Peter's which have a negligible exchange compared to the other two openings.

The evolution of the Lakes has been greatly shaped by the retreat of ice and large changes in sea level associated with the end of the last ice age ~15 thousand years ago. It appears that the Lakes flipped back and forth between land locked fresh and marine environments as the sea level rose and fell and topography was being shaped (Shaw et al. 2002).

A unique feature of the BDL is wide variability in topography and water properties. The complex system of bays and basins ranging in size of a few 100 meters for Dina's pond to 80 km for the Bras d'Or Lake, are interconnected by narrow channels. The Lakes are relatively shallow on average (~25m) but depth can exceed 50m in many places and reaches 280m in St. Andrew's channel. Typical currents tend to be weak in most places (<5cm/s), but in the narrow channels can be as strong as in the Bay of Fundy, 1-3 m/s range (Petrie and Bugden, 2002). The water is highly stratified in the summer, warm brackish water (20 ^{o}C, 22 psu) on the surface transitioning to cold salty (8 ^{o}C, 26 psu) at about 40 m. In the deep holes, the temperatures can be below 4 Celsius. In the winter, the Lakes partially freeze. The extent of the ice varies greatly from year to year.

The Lakes are home to a large range of plant and animal species. The Lakes are also utilized for a wide range of activities such as fishing, recreational boating and aquaculture industries. Recent concerns in the area involve invasive aquatic species (AIS). Golden Star tunicates are an increasing problem in the Lakes. These tunicates prefer sheltered inshore areas where they form quick growing dense mats which can take over wharfs and other structures and outcompete local species for food, space and light. By growing on infrastructure, this species create fouling issues for aquaculture, boating and other aquatic activities. The invasive green crabs, first observed in Lakes in the 1990s, have largely displaced local rock crab and are a threat to clams and other bi-valves which form the bulk of its diet (Trembley et al. 2006). In addition, the oyster aquaculture industry in the lakes was severely impacted by a parasite called MSX which first appeared in 2002 (Stephenson et al. 2003).

Another concern in the BDL is low oxygen concentrations due to slow flushing. Because the GBC is so narrow compared to the size of the Lakes, the tide (in particular the semi-diurnal) has difficulty entering the Lakes. Gregory et al. 1993 reports 61 days as the average tidal flushing time for the entire lakes. The flushing time for more remote areas such as Whycocomagh and Dundee is expected to be much longer. A consequence of slow flushing is low oxygen concentration in deeper layers. From measurements taken during this study, it is possible to see the low oxygen layer start at a depth of 20m in March in certain locations such as Whycocomagh Bay. The oxygen concentrations of water samples from this layer are some of the lowest oxygen values collected by DFO Maritime Science (including the deep Bedford

Basin). The water from these deep holes has been observed to invade coastal regions and has the potential to impact wild fish stocks and aquaculture sites. For example, a fish kill caused by such an event has already been observed at least once in a fish farm in Whycocmagh in 2012 (Pers. Comm. Robin Stuart, Operations Manager, Atoqwa'su Farms Ltd).

In spite of the small tide there are large changes in the water level around the lakes on the order of 50-75cm resulting from the large scale oceanic and atmospheric factors. These changes are small compared to more exposed coastal areas, but local residents report increase in damage from storm surge in recent times (e.g. Baddeck and West Bay)

The Bras d'Or Lakes have been studied extensively for the several last decades. Parker et al. 2007 present a lengthy ecosystem assessment of the region intended as a background document for integrated management and planning the Bras d'Or watershed. The report reviewed scientific literature and queried staff from relevant government institutions, private sector and First Nation organizations. Information from a Bras d'Or Traditional Ecological Knowledge Workshop has also been included. The report does not identify gaps in sampling of physical parameters but does claim that the deepest waters of the St. Andrew's channel (280m) are well oxygenated. Although we have not yet sampled at this site, based on what has been sampled to date at other sites, the conclusion is dubious and suggest that more data needs to be collected to sufficient understand the situation.

The first definitive survey of physical oceanography of the lakes was done by the Bedford Institute of Oceanography (BIO) in 1973-74 (Krauel et al. 1975). This study made continuous measurements of water level and currents at multiples sites. Temperature and salinity data at a grid of stations covering the Lakes were observed repeatedly during the study period.

Tidal elevations and currents in the Lakes were modelled by Dupont et al. 2003. They used a 2d finite element model (FEM) and obtained reasonable results. Their work was ported into the tidal prediction software Webtide which is publically available (http://www.bio.gc.ca/science/research-recherche/ocean/webtide/index-eng.php). In addition, their FEM grid formed the starting point of the modelling work undertaken by this study (see Chapter 4d).

Recently, Yang et al. 2007 have developed a 3d circulation model of the BDL based on CANDIE (Sheng et al. 1998) and used it to reconstruct the 3d circulation and temperature-salinity distribution of the Lakes for summer months of 1974. Their results demonstrate that sub-tidal flow is dominated by wind and barometric set-up and to a lesser extent by estuarine circulation driven by the freshwater runoff into the Lakes. The model results reproduced the data for period reasonably well but generally underestimated currents and stratification. The model was also used to study the connectivity of the various parts of the BDL (Yang et al. 2008).

More recently, DFO has been monitoring the Lakes since 2009. The goal of the monitoring program is to assess the health of the ecosystem through the monitoring of physical parameters, in particular: temperature, water level, and water color. These physical parameters will then be linked to possible impacts of stressors such as: anoxia, coastal erosion, rising temperatures and changes in primary production in the Lakes. Water color is tied to the development of an algorithm for the remote sensing of chlorophyll. Once the algorithm is developed primary production in the Lakes can be monitored through satellite observations. Chapter 2 of this report will address will address how this monitoring program fits into DFO science priorities. Chapter 3 will describe the methodology of the monitoring program. In

Chapter 4 a preliminary analysis of the data collected as well as a brief description of the circulation modelling under development will be presented followed by the conclusion of the report in Chapter 5.

2. DFO Priorities

The Bras d'Or Lakes are designated a unique ecosystem by UNESCO Biosphere Reserve program. By conducting research in the Bras d'Or Lakes, the monitoring program described in this report fits into the DFO strategy for Ecosystem-Based-Management. The program has 3 main goals. The first is to improve remote sensing algorithms for chlorophyll and suspended sediment concentrations in the Lakes. This is by far the most economical way to monitor the health of the Lakes in the long term. With this technology in place, the results can be used to provide quick advice to assist DFO in making informed management decisions regarding activities in the Lakes. In addition, once the algorithms are developed they can be ported to similar coastal environments.

The second goal is to enhance the understanding of the circulation and physical properties of the Lakes. This can be best achieved by developing a circulation model for the region which can be calibrated by the collected data. With this tool in place, ecosystem advice such as flushing rates, connectivity, oxygen levels and carrying capacities can be provided on demand. A validated circulation model would be very helpful in environmental assessments of present activities in the Lakes such as fin fish aquaculture in Whycocomagh Bay and the development of the large wharf and marina at Ben Eoin, as well as possible future developments in the area: renewable energy and expanding aquaculture industry.

The third goal of the project is monitoring the impacts of climate change, primarily water levels and temperatures. The circulation model can also aid in forecasting climate change impacts. Once possible impacts are understood, adaptation advice can be provided to clients.

3. METHODS

a. Coastal Stations

To monitor water level and temperature around the Lakes, six coastal stations have been installed around the lakes. Monitoring began in May 2009 with stations at Baddeck, East Bay and Dundee (See map in Fig. 1). Later, stations where added at St. Peters, Whycocomagh and Little Bras d'Or (see Table 1). In addition, the Baddeck station includes 2 land based pressure recorders to provide an atmospheric correction to the water based logger.

The instruments sample pressure and temperature at 20 minute resolution. The loggers are serviced biannually to upload the data. They are attached to the bottom ~2m long PVC pipes with bolts and the pipe itself is screwed into land based wooden structures with the bottom of the pipe ~3/4 submerged. With and experienced crew, the servicing of the stations is done in under ½ hour.

The loggers currently used for the program are Onset Hobo U20. These small and inexpensive (~$600) instruments have a maintenance free absolute pressure sensor and a titanium casing. The water level accuracy is under 0.5 cm and 0.5 ^{o}C, respectively. The instrument has enough memory to collect 21700 combined pressure and temperature measurements, which is enough for a yearlong deployment sampling at about 30 minutes. The data is offloaded with an optical base station. The battery usually last about 5 years.

b. Regular Water Stations

Since 2009, Cape Breton University (CBU) has been contracted to sample at several stations once per month for CTD profiles, hyperspectral light profiles, zooplankton tows and take water samples to analyse for chlorophyll, suspended sediments, CDOM (colored dissolved organic matter), salinity, HPLC and light absorption, for all the ice free months. CBU collaborates with the First Nations of Cape Breton, which enables aboriginal students at the University and staff at the Unama'ki Institute of Natural Resources to engage in the sampling. Optical profiles using a Satlantic hyperspectral probe are gathered at 2 fixed stations during the regular sampling and by an optical buoy (installed by BIO when possible) to measure surface reflectance and ground truth ocean color satellites. This data will help in development of algorithms to accurately measure chlorophyll in the lakes remotely. Remote sensing of chlorophyll would be the most cost effective way to monitor the heath of the Lakes. The timing and duration of blooms will be altered by any pollution entering the Lakes. The Lakes behave optically in a manner that is quite different from the Scotia Shelf and new algorithms need to be developed for the Lakes. This requires on-going collection of optical data.

The small bays and inlets of the Lakes are much harder to sense remotely due to their high values of CDOM. Whycocomagh Bay is far from the open ocean (about 60 km) and connected through several small openings, and as a result is poorly flushed which allows CDOM to build up. This area has the highest CDOM concentrations observed by our group and is a useful testing ground for understanding how CDOM affects reflectance measurements and to develop remote sensing algorithms.

An effort is underway to develop an FVCOM circulation model for the Lakes. This model would be forced and validated by the data collected from this monitoring program. The model would then be used to assess risk to the ecosystem due to poor water quality associated with anoxic events. The model could also be used to forecast the state of the ecosystem after an approaching storm and allow managers and stakeholders to take mitigating action before the storm arrives. Other possible applications of the model include storm surge, spread of invasive species and climate change forecasts.

c. Subsurface Moorings

In addition to the regular coastal and deeper water stations being sampled, the program deploys instrumented subsurface moorings at various locations around the Lakes. These moorings contain more accurate and expensive instruments: ADCP, Seabird CTD and Sediment Trap, and a frame (a.k.a the Quad), instrumented with optical backscatter sensors at 1 and 2 m off the bottom as well as oxygen concentration and a transmissometer Water Quality System. These instruments are in limited availability and are shifted around the Lakes. As of Fall 2012 all the instruments were moored in Whycocomagh Bay. The purpose of these moorings is to provide a richer data set for areas of interest. Whycocomagh is the current focus due to its remote location, high CDOM concentration and presence of an aquaculture site near a deep anoxic hole. Previously the mooring were deployed in East Bay due to its frequent coastal upwelling of deep anoxic water/sediment and the development of the new Ben Eoin Marina.

d. Surface Mooring, Drifters and Other Data

A surface optical buoy is deployed at various locations for a few weeks at a time typically every spring to collect groundtruthing data for the remote sensing component of this program. The bouy measures surface and dowelling irradiance at 1m well as upwelling radiance at 1m and 3m and fluorescence at 1m below the surface respectively. All optical sensors are hyperspectral taking measurements every 2nm from 300-800nm.

Our group is also developing 4 drifters to study circulation. These drifters are barrels outfitted with a GPS and telemetry to email their location. We had a successful test deployment of 2 of these drifters in Whycocomagh Bay in spring 2013. The purpose of these drifters is to help validate the circulation model which is under development.

During the deployment and recovery of moorings, CTD and optical reflectance profiles are typically collected as well as water sample for analysis.

4. RESULTS

This section presents a preliminary analysis of the data. Subsection a and b presents results from selected coastal stations. Section c presents a few examples of the optical profiles collected. Section d describes the state of the circulation model under development. No results from the model are presented. Data from moored instruments are not included. Presentation of the complete data set would be beyond the scope of this report.

a. Water Level

Water level statistics from the coastal stations for summer 2012 are included in Table 2. The South Bar station which is in Sydney Harbour (part of DFO's Long Term Temperature Monitoring Program; LTTMP) is included as reference stations (a proxy for the external forcing into the Lakes). The water level variability (standard deviation; or std) decreases from 0.3 m outside to about .1 m inside the lakes. The total range of elevation recorded for the period was about 55-60 cm inside the Lakes, compared to 1.68m at South Bar.

Low Frequency Variability

Despite the small tide, the water level in the lakes can change by 50-75 cm over a few days. The large water level changes are primarily in response to atmospheric pressure changes and the restricted exchange with the Atlantic. When a low pressure system passes over the region, (time scale on the order of days), the level of the Lakes goes up. Since the systems travel slowly, even with the restricted access to the Atlantic there is enough time to bring the water level in the Lakes to levels outside. After the low pressure system passes, it takes several days for the extra water to leave. Figure 2 illustrates this process for a segment of data collected from October 2012. For demonstration purposes, we also included the Canadian Meteorological Center (model) reanalysis of wind stress from the Sydney Bight area of the Cabot Strait. The pressure lows recorded in by the Baddeck barometer clearly correspond to highs in the lakes (preceded by a few days as the response is delayed due the limited amount of water that can move through GBC). A somewhat different mechanism occurred during the large weather system associated with Hurricane Sandy (Oct 21-30). The initial low pressure (Oct 21) pulls water into the lakes but as the slow moving system progresses, the low gradually transitions to a high. However the level does not fall as expected from previous reasoning, but continues to grow due to very strong winds out of the north which pushed water for several days into the Lakes through the GBC.

A further source of water level variability is in direct response to the low frequency variability in the Cabot Strait which is influenced by larger oceanic variability between the Gulf of Saint Lawrence and the North Atlantic as well as the Saint Lawrence River run off and flow through the Strait of Belle Isle. These systems dominate the low frequency variability of water level in the Lakes.

The low pass filtered series of elevation collected at East Bay is shown in Fig. 3. The record is peppered with spikes where the water level jumps by about 20-50 cm above or below mean sea level which are superimposed over what appears to be a seasonal cycle with amplitude of about 20 cm. The seasonal cycle peaks in around Nov-Dec time frame, the timing of which is likely to be linked to larger scale oceanographic variability in GSL but more analysis needs to be done to be certain. In addition, there is more variability centered during the winter season compared to the summer and is expected due to the increase in the frequency of storms during winter. In the 4 years that data were collected, the high water (surge) events were more intense (up to 55 cm), compared to the low water events (down to -0.35 cm). This is demonstrated with water level distribution histogram (Fig. 4). The analysis was performed on the un-averaged 20 min. data in order to include the full effect the tides and other high frequency forcing. The distributions are fairly tight and symmetric but there is slight skew with large (+-0.2-0.3m) events which are twice as common for high water then low. In addition, water levels < -.3 m was not observed but levels > 0.3 m were observed in all stations except Baddeck. Another feature of the distribution is that while the extreme high water events are more intense and frequent, the common events (+/- 0-0.1 m) are skewed towards low water level.

To highlight seasonal and interannual variation, Fig. 5 shows the elevation histogram for the available years from East Bay. The main feature is the difference between the summer and winter seasons. The winter data is much broader and has more large and extreme events. However, not all years are the same. For example winter data (Oct 11 – May 12) is comparable to summer data (May 12 – Nov 12). Whereas Nov 10-May 11 is distinctly broader and has many more extreme events (exceeding +/- 0.3m): 5%, compared to the next highest Jul09-Nov09 (at 3%) followed by May11-Oct11 at 0.8 %. The Nov 10-May 11 winter is the most extreme in terms of water level and a high level of erosion might have taken place during this period. In fact during this period our installation from East Bay became detached from a bridge post and was found on the seafloor nearby.

High Frequency Variability

The tide is dominated by M2, but the amplitude attenuates rapidly from 36cm at South bar to ~4cm inside the Lakes (an order of magnitude smaller). The diurnals do not attenuate as much due to their longer wave length (i.e. longer periods are more effective in propagating the narrow GBC) going from about 7 to 1.5 cm, a fivefold decrease. Once inside the lakes, however, the tide does not attenuate any further but is delayed as seen from the differences in phase (the tide arrives in East Bay 1/6 of tidal period ~2 h after Baddeck as it traverses the Grand Narrows and Bras d’Or Lake (Table 2).

Figure 6a show the power spectra of the data collected from East Bay. The tides and low frequency variability were removed with a 1 day linear FIR (finite impulse response) phase filter. There is a dominant peak at around 12.5 day^{-1} (~2 h period). This frequency corresponds well to the lowest natural seiche mode of the Bras d'Or Lake (Big Lake) approximated as a rectangular basin 60 km by 25 km and 23 m deep (dimensions capture the aspect ratio and volume of this basin). The amount of energy in this mode is about an order of magnitude smaller than the tide but the amplitude varies and can be as big as 10 cm (as big as the tide). Moreover the same peak is observed in 2012 in Dundee and St. Peters but not in the stations external to this basin (Fig 6b). The external stations (Whycocomagh, Baddeck and Little Bras d'Or) have their own dominant mode of 20 day^{-1} (1.2 h period). This frequency corresponds to the lowest natural seiche mode of the North Lake approximated as a rectangular basin 42 km by 12 km and 40 m deep. Whycocomagh is expected to have a period of about 36 day^{-1} (40 min. period; taken as 12 x 5 km basin with mean depth of 10m) this is just at our detection threshold of our present sampling (20 min.). However, from Fig. 6b we see a peak at 28 day^{-1} (50 min. period). We believe that this is the seiche mode for Whycocomagh which the basic calculation underestimates. It is important to understand that the basic calculation is very crude and only meant to give the order of magnitude for the seiche frequency. A numerical model would have to be used to get a more precise answer. A similar situation occurs in St. Peter's Bay where the theory predicts 28 day^{-1} (51 min. period) but data shows a peak at 24 day^{-1} (1 h period) . The recorders would have to sample faster to resolve the seiche modes of the smaller bays and higher order modes for the big bays.

b. Temperature

Low Frequency Variability

The temperature record from East Bay is shown in Figure 7. A 30-day running mean was applied to allow seasonal cycle to stand out (top) and show anomaly (bottom). The seasonal cycle from year to year shows little variation peaking in August at 20-23 ^oC and dropping to 0-2 ^oC in February. The anomaly for the record shows a lot more variability. Fig. 8 shows the anomaly for all stations in summer 2012. Large temperature drops of 5-15^oC can be found throughout the records. There are also large differences between the stations. For example, Baddeck is fairly uneventful compared to East Bay. Fig. 9 shows the 30 day running mean averaged temperature for all stations in summer 2012. It shows that there can be up to a 5 ^oC difference in the spring and summer seasons before cooling in the fall converges the temperatures. East Bay and Little Bras d'Or are the warmest. This is not surprising, as due to their isolation they have a chance to warm up before their heat diffuses into the Bras d'Or Lake and Cabot Strait. One might expect Whycocomagh to be the warmest as this is perhaps the most isolated bay in the Lakes. However, it is only the 3rd warmest. East Bay has a dip in early June which is not seen in the other stations. The dip corresponds to large negative anomaly around the same time (near day 150, Fig 8). The fact that this occurred only in East Bay suggest a large upwelling of deep cold water in the area. Dundee has the lowest temperatures likely caused by its exposure the cooler waters of Bras d'Or Lake.

Table 3 shows temperature statistics for East Bay. The variability is much higher in the summer (std: 4-5 ^oC) compared to the winter (std: 2-3 ^oC). The minimum summer temperatures (another indicator of high variability) dip down to 4.3 in the May12-Nov12 period. Table 4 shows temperature statistics for the various stations in 2012. East Bay has the highest variability of all the stations. Minimum temperature is recorded from Dundee at 3.5 ^oC while the highest is

26.8 ^{o}C at Lt. Bras d'Or. It's worth pointing out that the variability in the Lakes (both std and min/max difference) is higher than in the reference stations at South Bar, indicating that the variability is a local effect unique to the Bras d'Or Lakes.

High Frequency Variability

Figure 10 shows the power spectra of temperature anomaly at East Bay. The dominant forcing frequencies are the tides and the seiche of Bras d'Or Lake (~2 h period). Figure 11 shows the spectra of all stations for summer 2012. East Bay is an order of magnitude more energetic then the other statation and is the only station where temperature variability is significantly affected by the seiche mode and tides. At this point it is difficult to explain the unique spectra at East Bay. The station is a located near deep topographic features which hold cold water even in the middle of summer but this features is also present in Little Bras d'Or, Dundee and Whycocomagh.

Extreme Temperature Drops

Motivated by presence of large temperature drops in the middle of summer as seen in Fig 7 and 8, temperature anomaly distributions are presented in Fig. 12 and 13. East Bay and Little Bras d'Or clearly have a skew towards large negative anomalies that is not present at all in St. Peter's, Baddeck and South Bar. For East Bay, the skew occurs only in summer and varies from year to year, 2009 being a year with many large swings while 2011 a relatively quiet one. Overall the probability for one of these events is about 1%. The presence of large temperature drops in the summer is indicative of upwelling of deep cold layers which are likely to anoxic. More work needs to be done to understand the precise mechanism responsible for these events.

c. Color

Monitoring the optical properties of the water is a good way to access the heath of the Lakes and is also vital to ground truth satellite remote sensing. Satellites measure surface reflectance. This is the ratio of upwelling radiance to downwelling irradiance. Fig 14 shows four reflectance spectra from Bras d'Or Lake (Red), Whycocomagh (Blue) and Bedford Basin (Black) and offshore (Green). Since reflectance is a ratio it should be independent of incoming radiation. You can see from the plot that the four areas have much different magnitude and shape of their surface reflectance spectra. The shape of the spectra is influenced by chlorophyll content, sediment content and CDOM (colored dissolved organic matter). Bedford Basin has more chlorophyll than any of the other areas so it has the biggest peak. The offshore has much less CDOM (which attenuates blue light strongly) than the others so has more signal in the blue end of the spectra (405 nm). Whycocomagh has the highest CDOM concentration so has the lowest signal in the blue end of the spectra. The effects of CDOM on the optical properties of the water can also be seen by looking at the extinction coefficient K_d. If I(z) is the intensity of light at depth z then

$$I(z) = I_0 \exp(-K_d z) ,$$

where I_0 is the intensity of light at the surface. K_d has dimensions of m^{-1}. The inverse of K_d is a measure of how deep light penetrates in the water. In Fig. 15, profiles of K_d for a wavelength of 405 nm (in the blue end of the spectra) are shown for the same four areas shown in Fig 14.

Notice that K_d for the offshore is around 0.1 or smaller which means that light penetrates 10's of meters in the water whereas in Whycocomagh it is nearly 1 which means that light only penetrates 1 m into the water. This will have dramatic implications for any biological life in the water.

Since ocean color algorithms calculate the ratio of the reflectance spectrum at different wavelengths to calculate chlorophyll or sediment concentration, the same algorithm will not work in all four areas. Most of the algorithms we have now were developed for the offshore which we can see from Fig 14 and 15 has a much different optical signature than does the inshore. There are also large differences between different inshore locations due to their differences in chlorophyll, sediment and CDOM concentrations. Therefore a special algorithm will need to be developed for the Bras d'Or Lakes and these optical measurements are crucial for its development.

d. Circulation Model

An effort is underway to develop an FVCOM circulation model for the Lakes. Fig. 16 shows the model grid adapted from Dupont et al. 2003. The grid covers the entire BDL area. St. Ann's and Sydney Harbour and part of the Sydney Bight are included in the model. This was done in order to move the open boundary of the model away from the area of interest, as the solution near the open boundary is generally questionable. The two smaller openings into the BDL are neglected. The model was implemented with FVCOM version 3.14 (Chen et al. 2003) and forced on the open boundary (Cabot Strait) with the tidal solution of Dupont et al 2003. The model reproduced the results of Dupont et al. 2003 very well. The strength of FVCOM is that being a finite element model it can resolve small bays and the coastline as required while minimizing resolution where less needed. The inset of Fig. 16 shows the resolution in Whycocomagh Bay where grid spacing goes down to about 20 m. The spacing in the middle of Lakes is a few hundred meters and up to kilometers in the Cabot Strait.

A more detailed investigation is underway to include the stratification and low frequency elevation variability. To implement temperature and salinity as active tracers, a higher resolution grid is required which resolves the regions of steep topography with greater precision. New grids of East Bay and Whycocomagh are under development. Once this is completed the model would be forced and validated by the data collected from this monitoring program. The model would then be used gain understanding of the observed anoxic events and other ecosystem based applications.

5. CONCLUSION

The Bras d'Or Lakes Monitoring Program has been collecting oceanographic data since 2009. The program is monitoring a unique and sensitive ecosystem and building collaborations with Cape Breton University and First Nation Unama'ki scientists. The area is exposed to pressures such as oxygen depletion, increased storm surge and invasive species. Monitoring improves knowledge and understanding of the impacts of these pressures on the ecosystem. Our data so far shows that deeper regions of the Lakes are poorly flushed and periodically bring up cold anoxic water into shallow regions. This is particularly true in East Bay and Little Narrows but also to a lesser extend in East Bay (Dundee) and Whycocomagh. The mechanism for this process is still not well understood but is believed to be a result of the coupling between external atmospheric/ocean forcing and the internal seiche and tidal modes. An ocean circulation model is under development to help shed light on this phenomenon. Whycocomagh is a particularly interesting area because of its extreme isolation and new aquaculture sites under development which will further deplete the oxygen. This is also an ideal site for developing/ground truthing of remote sensing algorithms for chlorophyll detection in the nearshore due to its very high concentrations of CDOM.

ACKNOWLEDGMENTS

Excellent support for the preparation, deployment and recovery of the moorings was provided by Shawn Roach (HES). The authors would like to thank Bruce Hatcher (CBU) who is collaborator in this study. Many thanks to Herb Vandermeulen (CESD), Dave Hebert (OESD) and Eddy Kennedy (HES) for reviewing the draft of this report.

REFERENCES

Chen, C. H. Liu, R. C. Beardsley: 2003. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. *J. Atm. &Oceanic Tech*., ***20,*** 159-186.

Dupont, F., B. Petrie., and J Chaffey: 2003. Modelling the Bras d'Or BdOL. Canadian Technical Report of Hydrography and Ocean Sciences, 999, viii+53p.

Krauel, D.P.: 1975. The physical oceanography of the Bras d'Or BdOL 1972-1974. Dartmouth, NS, Canada: Bedford Institute of Oceanography, Fisheries and Marine Science Technical Report No. 570, 357 p.

Parker, M., M. Westhead, P. Doherty and J. Naug. 2007. Ecosystem Overview and Assessment Report for the Bras d'Or Lakes, Nova Scotia. Can. Manuscr. Rep. Fish. Aquat. Sci. 2789: xxii + 223 pp.

Petrie, B. and G. Bugden: 2002. The physical oceanography of the Bras d'Or Lakes. Proc. N.S. Inst. Sci. 42 (1): 9-36.

Shaw, J., D.J.W. Piper and R.B. Taylor: 2002. The geology of the Bras d'Or Lakes, Nova Scotia. Proc. N.S. Inst. Sci. 42 (1): 127-147.

Stephenson, M. F, S. E McGladdery, M. Maillet, A. Veniot and G Meyer: 2003. First reported occurrence of MSX in Canada. Journal of Shellfish Research, **22:** 355.

Yang, B., J. Sheng, B. G. Hatcher, and B. Petrie: 2007. Numerical study of circulation and temperature-salinity distribution in the Bras d'Or Lakes. *Ocean Dynamics*, **57**, 245-268.

Yang, B., J. Sheng, B. G. Hatcher: 2008. Modeling Circulation and Hydrodynamic Connectivity in Bras d'Or Lakes using Nested-Grid Approach. *Journal of Coastal Research*, 57-70

TABLES

Table 1 Years covered by coastal stations

T & Z coverage	2009	2010	2011	2012	2013
Baddeck	x	X	x	X	x
East Bay	x	X	x	X	x
Dundee	x	X	x	X	x
St. Peter's			x	X	x
Little Bras d'Or			x	x	x
Whycocomagh			x	x	x

Table 2 Summary water level statistics from summer 2012. Mean Depth is the depth of the instrument relative to sea level. Std is the standard deviation. The 5 dominant tidal components are included. Phases are referenced to GMT.

Summer 2012 Water Level	South Bar	Baddeck	Whycoco-magh	Lt._Bras d'Or	St. Peter's	Dundee	East Bay
Mean Depth (m)	2.08	1.39	1.65	0.71	2.03	1.35	1.17
Std (m)	0.31	0.09	0.09	0.09	0.1	0.1	0.09
Min (m)	-0.85	-0.26	-0.27	-0.23	-0.3	-0.28	-0.26
Max (m)	0.83	0.27	0.3	0.32	0.32	0.32	0.33
count	15358	14184	14054	14042	13970	13973	14037
M2 amp (cm)	36.63	3.73	4.66	3.45	4.69	4.74	4.5
M2 pha (^{o})	265.51	337.66	355.92	326.92	35.81	37.18	39.16
S2 amp (cm)	10.37	0.89	1.07	0.84	1.03	1.11	1.04
S2 pha (^{o})	307.51	15.23	31.21	7.91	76.38	76.94	76.46
N2 amp (cm)	7.54	0.73	0.92	0.73	0.88	0.89	0.82
N2 pha (^{o})	245.72	316.21	333.85	308.61	12.1	13.61	14.25
K1 amp (cm)	6.93	1.3	1.41	1.19	1.52	1.54	1.51
K1 pha (^{o})	282.55	357.53	2.4	358.24	21.83	23.55	29.6
O1 amp (cm)	7.92	1.57	1.67	1.53	1.68	1.64	1.71
O1 pha (^{o})	247.68	321.86	329.69	322.09	347.54	346.24	346.3
Tot.Tidal std (m)	0.29	0.03	0.04	0.03	0.04	0.04	0.04
%VarRemoved	0.89	0.13	0.17	0.11	0.15	0.16	0.16

Table 3 Temperature statistics from East Bay. All temperatures in Celsius.

Temper-ature	May09-Jul09	Jul09-Nov09	Nov09-May10	May10-Nov10	Nov10-May11	May11-Oct11	Oct11-May12	May12-Nov12
Mean	15.08	17.52	3.59	17.61	4.21	15.7	4.41	16.8
Std	3.19	4.99	2.71	4.58	3.24	4.17	3.27	5.19
Min	4.42	7.78	-0.89	7.58	-0.55	3.89	-0.44	4.31
Max	23.2	25.51	10.26	26.59	13.85	22.81	13.56	26.2
Count	5831	10081	12983	11940	14140	11593	12970	14037

Table 4 Temperature at all statistics from Summer 2012. All temperatures in Celsius.

Temper-ature	St. Peters	Dundee	Whycoc-omagh	Baddeck	Little Bras d'Or	East Bay	South Bar
Mean	16.3	14.76	16.88	16.37	17.96	16.8	16.47
Std	4.51	4.65	4.49	4.63	4.7	5.19	3.92
Min	5.96	3.47	4.31	4.52	6.78	4.31	7.88
Max	23.97	23.87	25.22	24.93	26.78	26.2	24.06
Count	13970	13973	14054	14184	14042	14037	15358

FIGURES

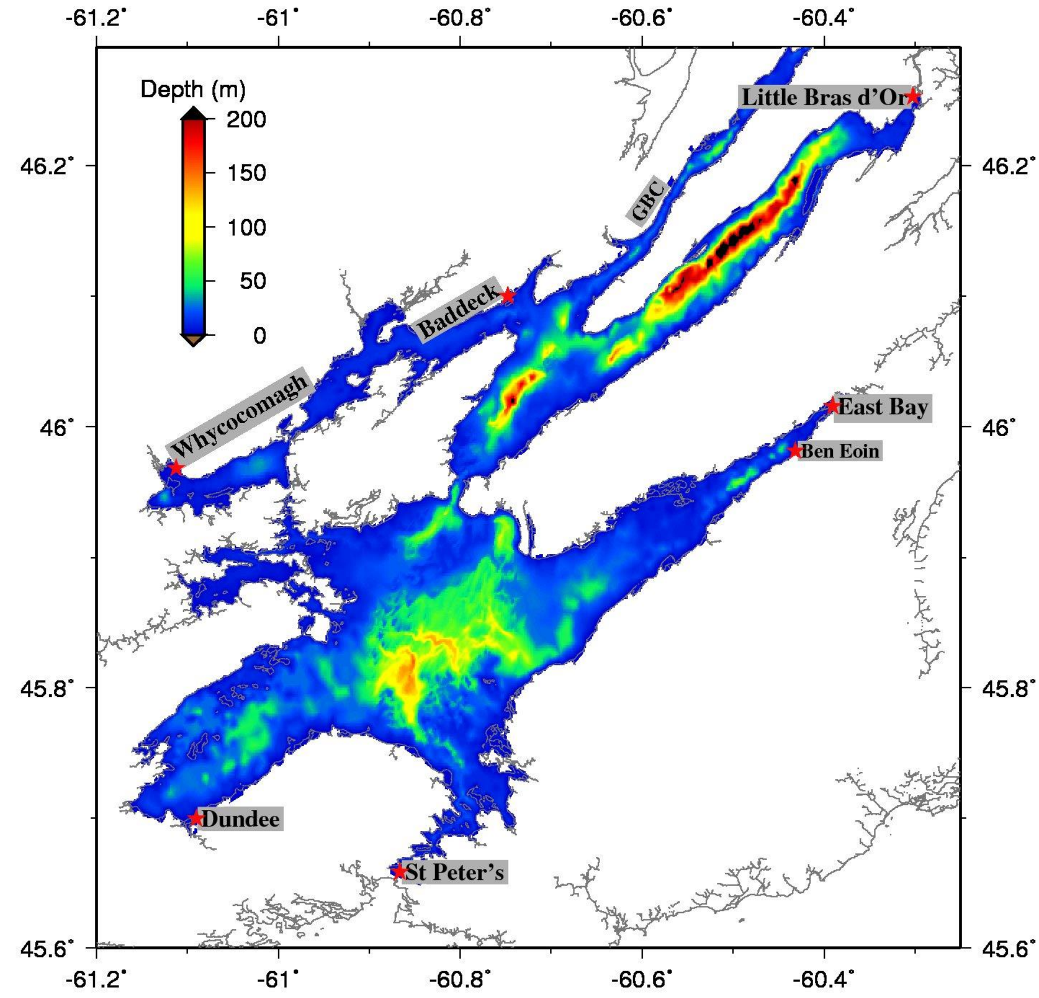

Figure 1 Map of the Bras d'Or Lakes showing locations of coastal stations and other points of interest. Bathymetry is color coded.

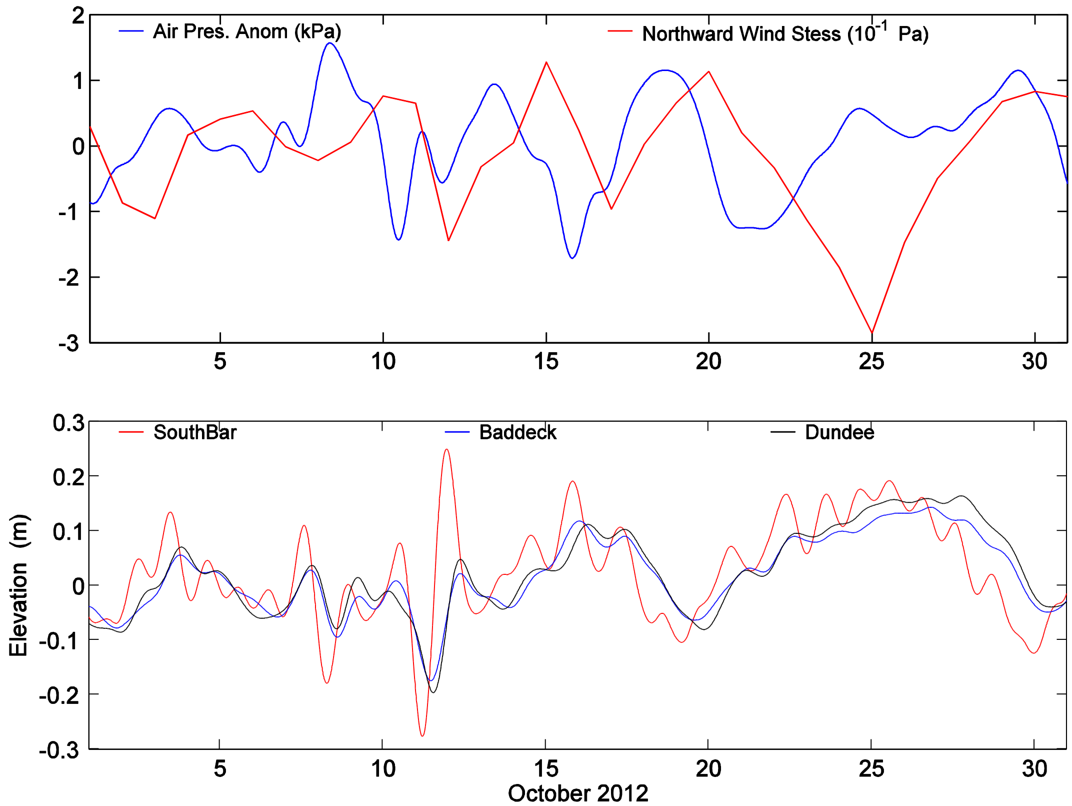

Figure 2 Data segments from October 2012. Top: barometric pressure anomaly (kPa) from Baddeck and north wind stress (10^{-1} Pa) from Cabot Strait. Bottom: water level from South Bar, Baddeck and Dundee.

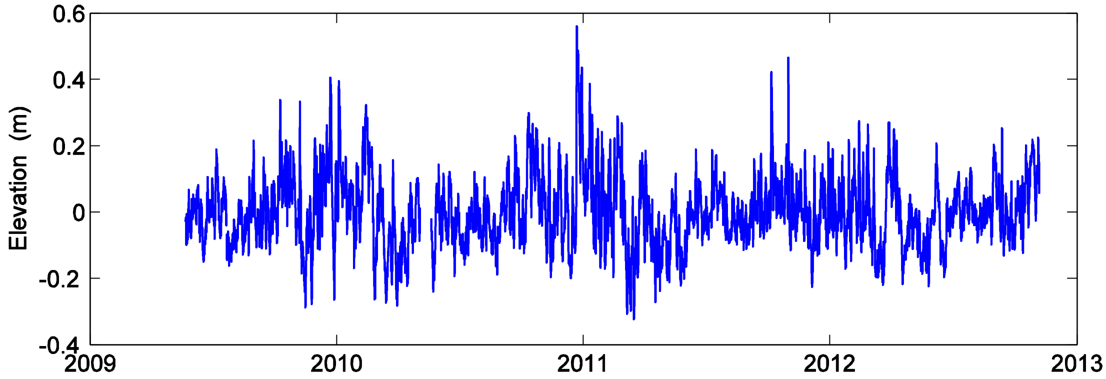

Figure 3 Water elevation at East Bay. Data was 1-day low-pass filtered.

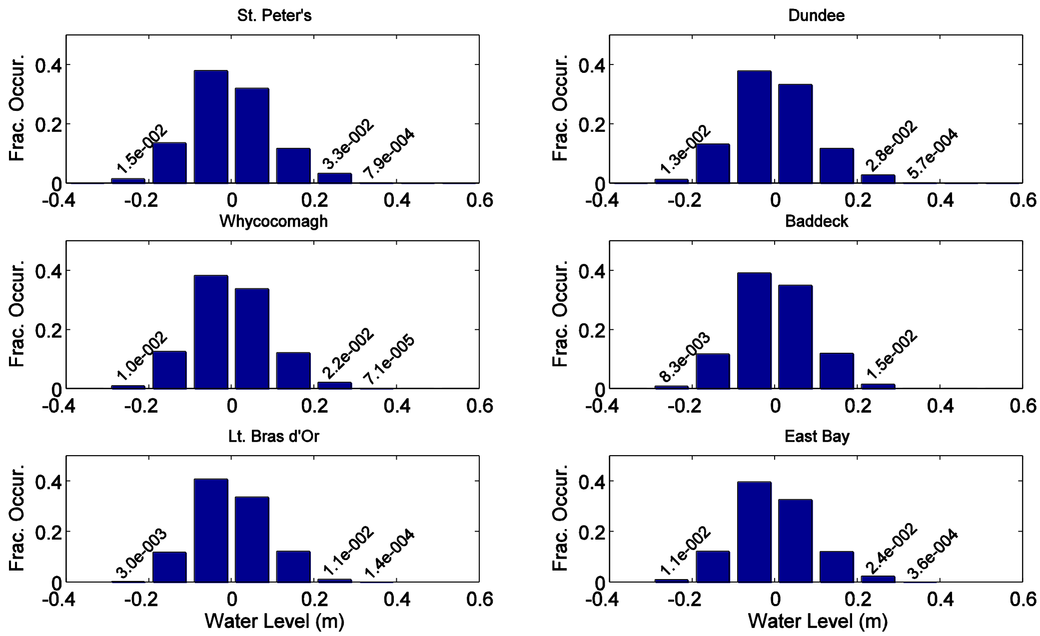

Figure 4 Water level histograms from the coastal stations (Summer 2012).

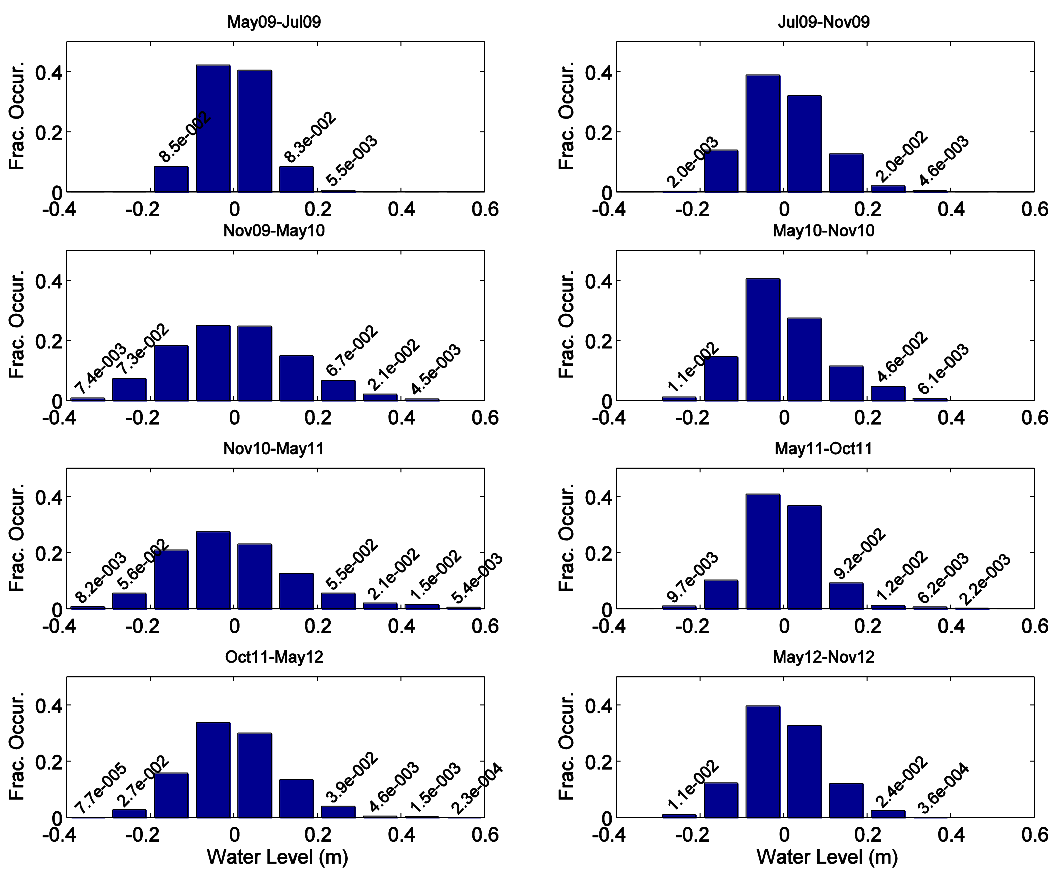

Figure 5 Water level histograms for consecutive deployment periods from the East Bay coastal station.

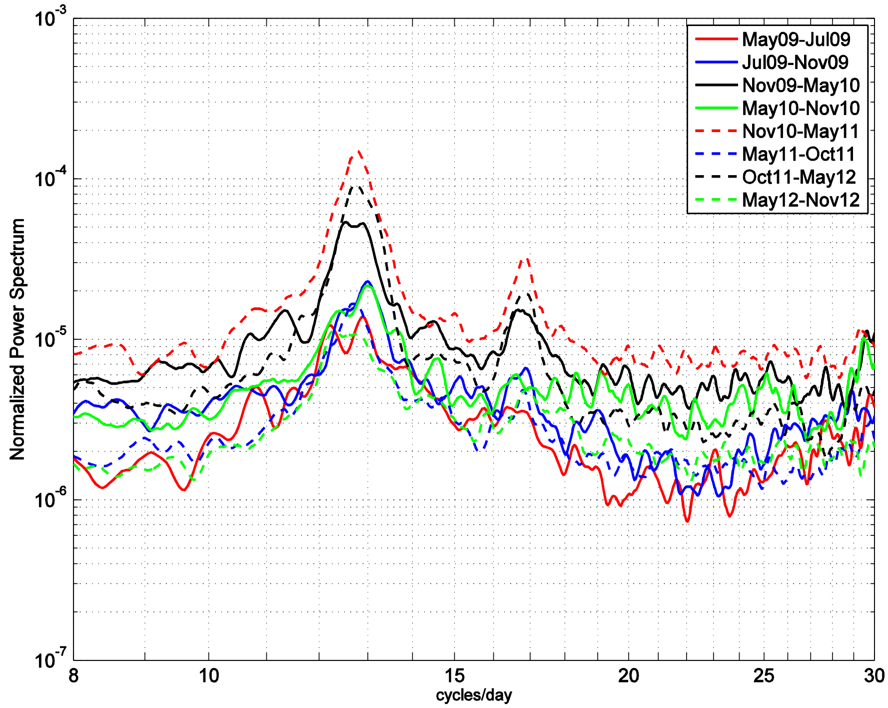

Figure 6a Normalized high frequency power spectra of water level from East Bay for consecutive deployment periods .

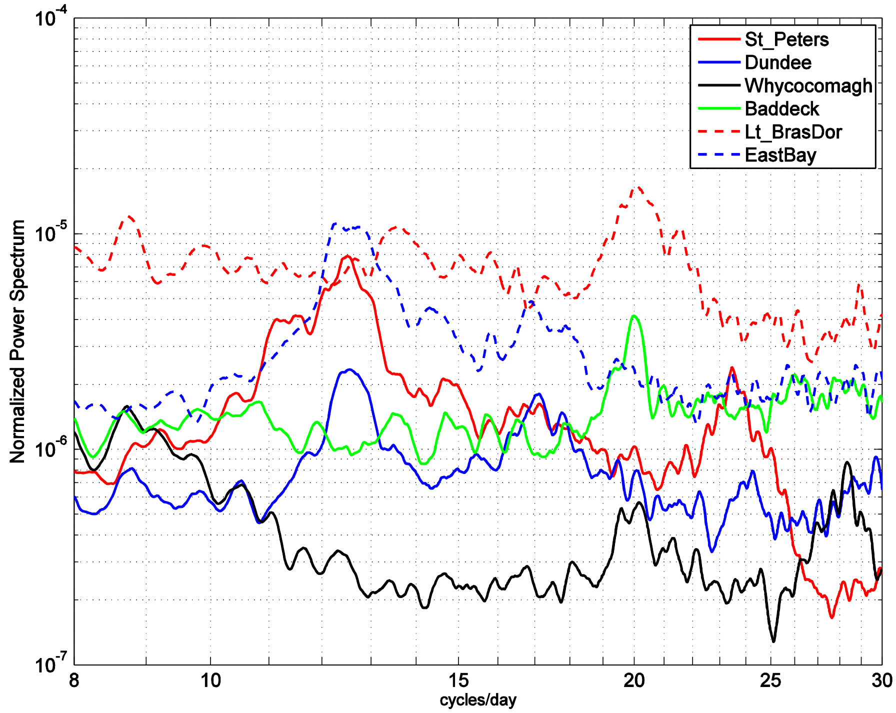

Figure 6b Normalized high frequency power spectra of water level from coastal stations for summer 2012.

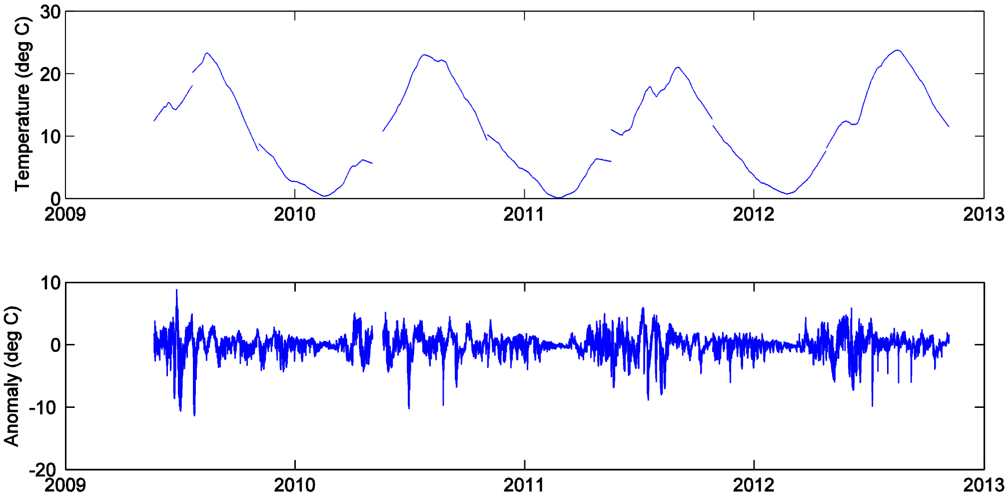

Figure 7 Temperature and Temperature anomaly from the East Bay coastal station. A 30 day running mean was applied (top). Anomaly (bottom) was based on the running mean.

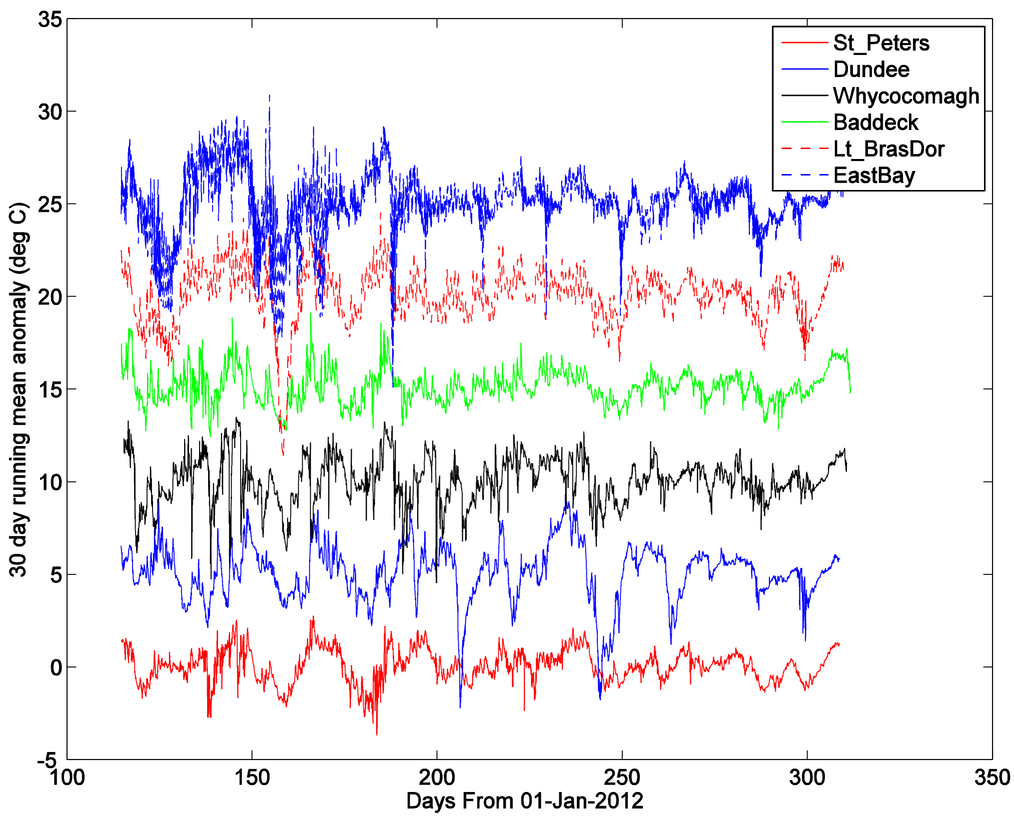

Figure 8 Temperature Anomaly for summer 2012 across the region. Anomaly was based on 30-day running mean.

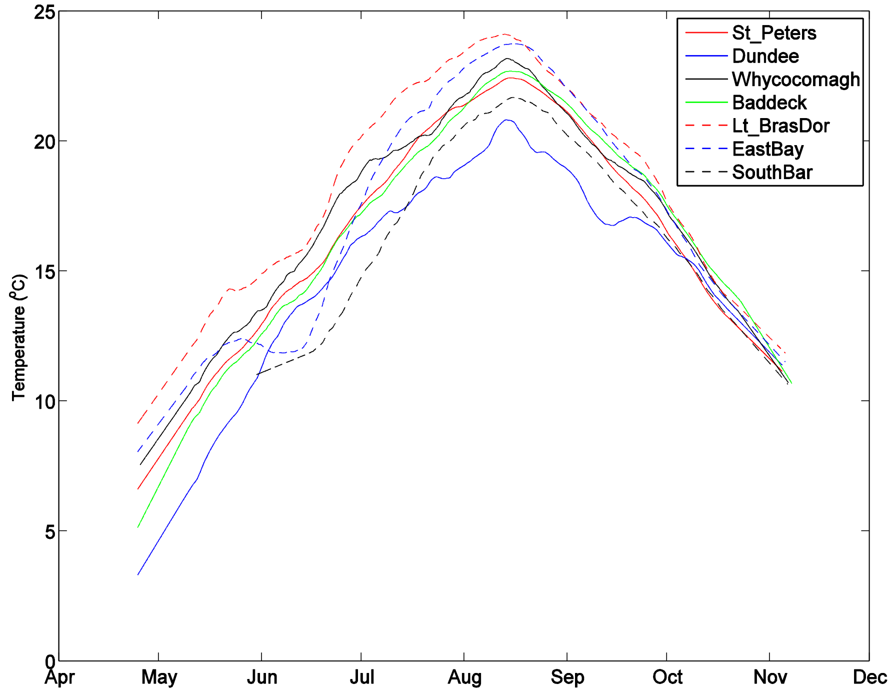

Figure 9 Temperate for summer 2012 across the Lakes. A 30 day running mean was applied. South Bar reference station included.

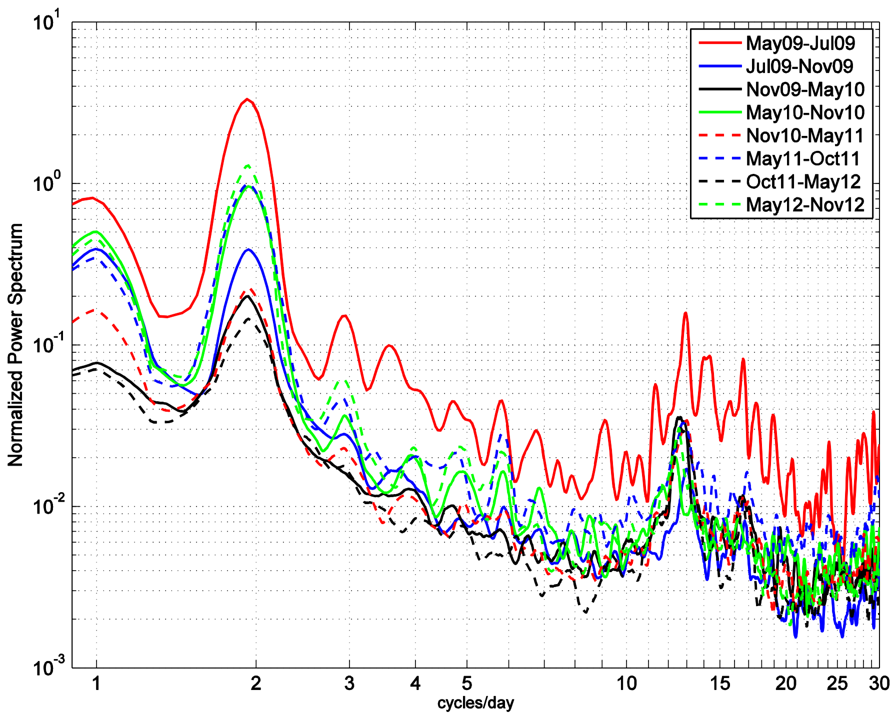

Figure 10 Power spectra of East Bay temperature anomaly for various periods. Anomaly based on 30-day running mean.

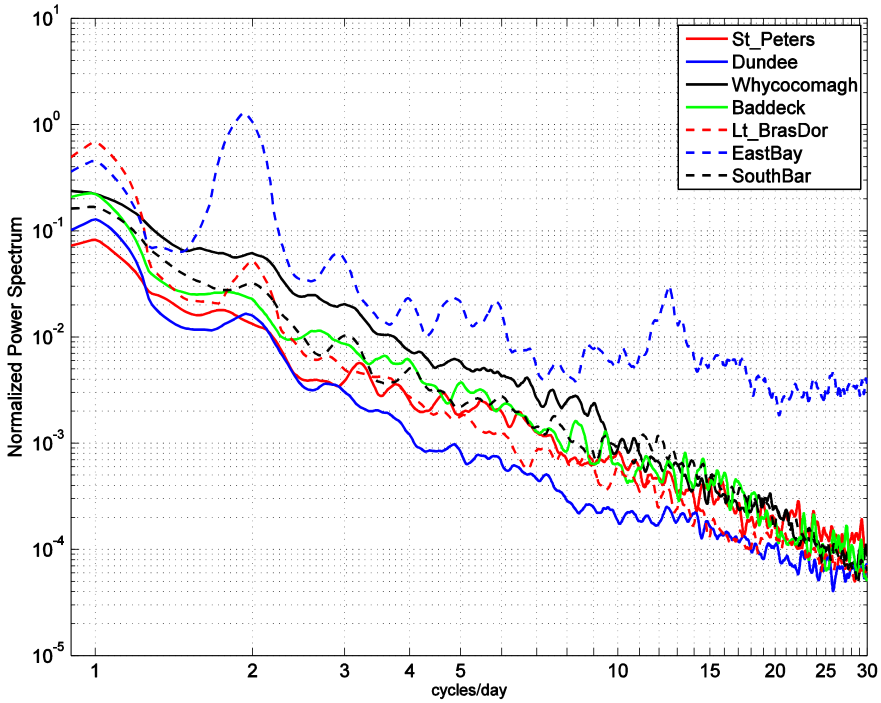

Figure 11 Power Spectra of summer 2012 temperature anomalies from all stations. Anomaly based on 30-day running mean.

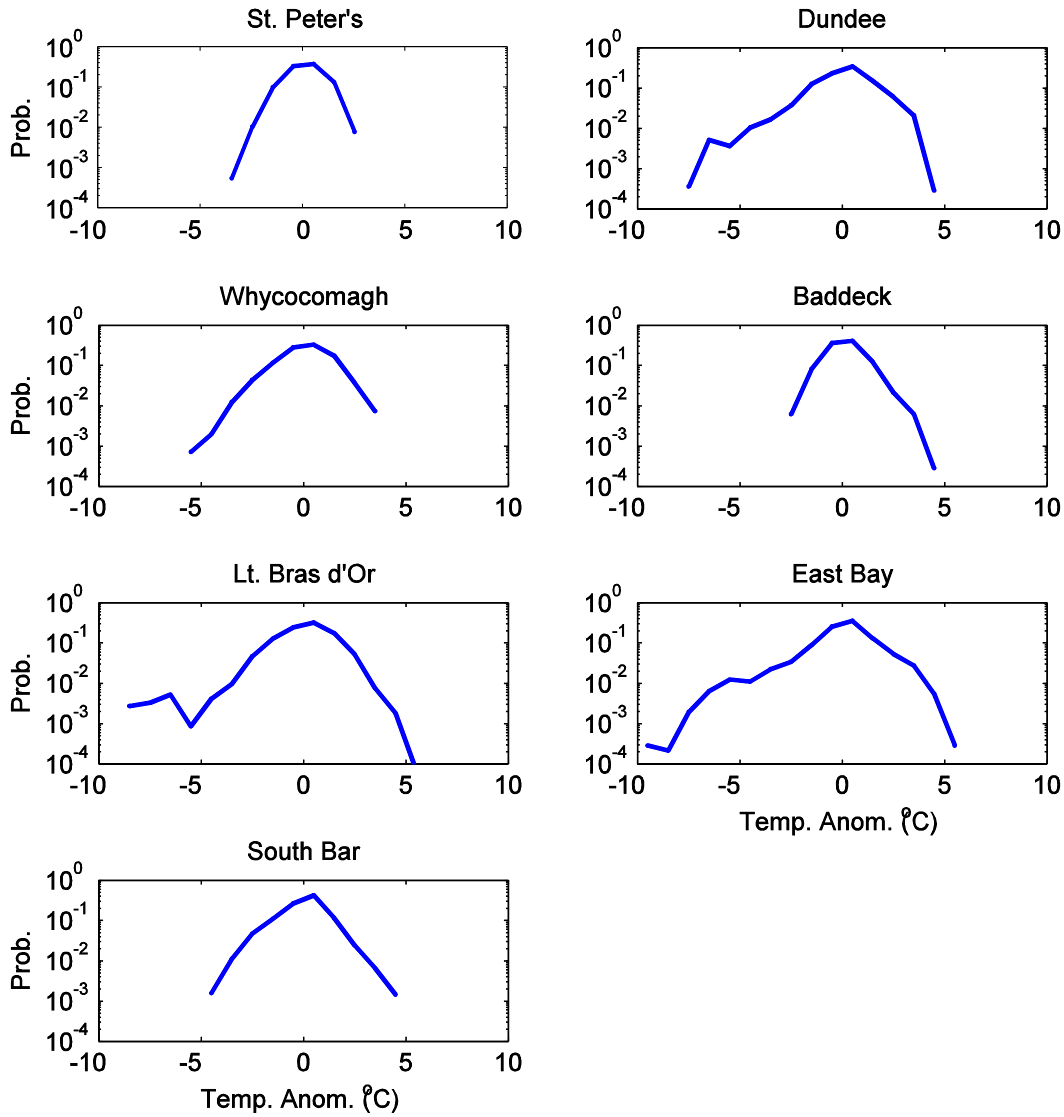

Figure 12 Temperature anomaly distribution for all stations from Summer 2012. Note the log scale on y-axis.

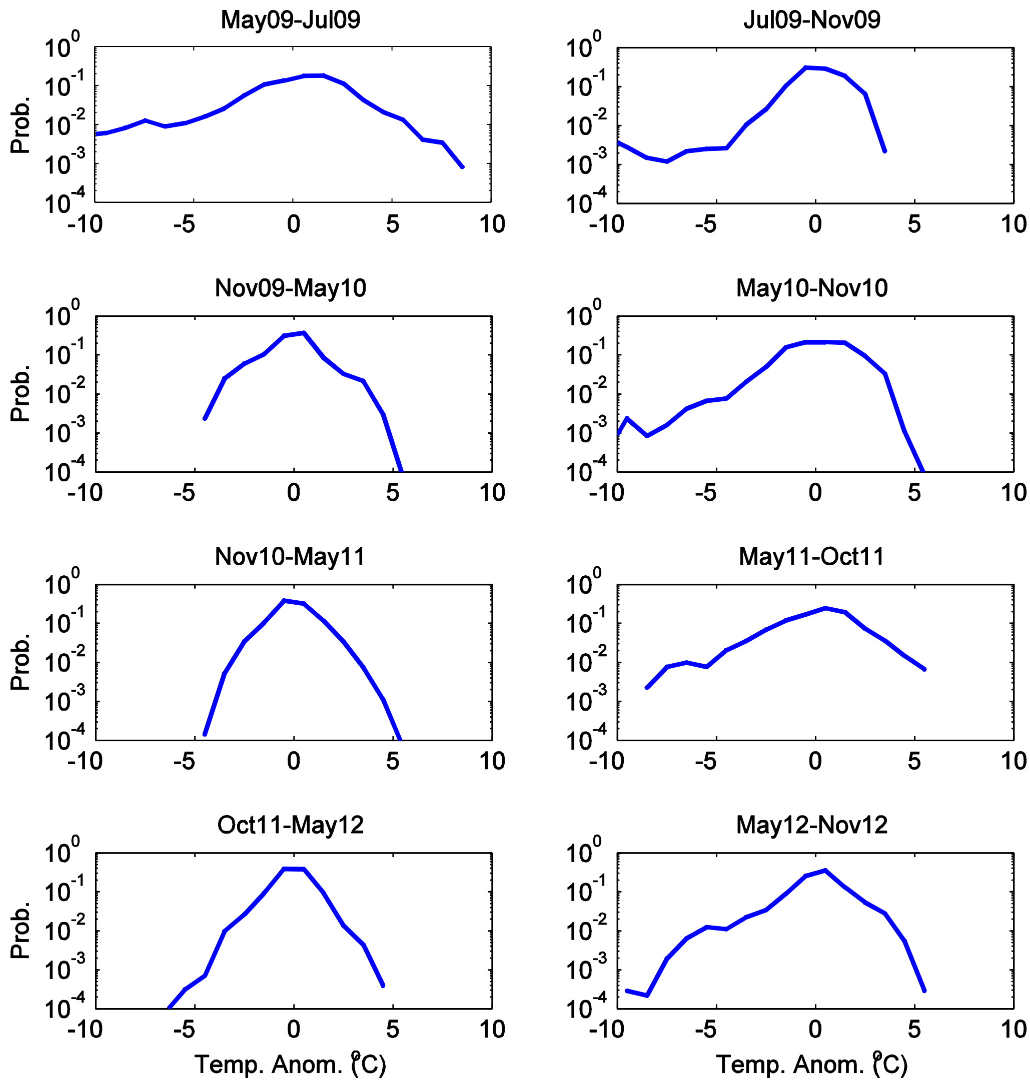

Figure 13 Temperature anomaly distribution from East Bay for consecutive deployment periods. Note the log scale on y-axis.

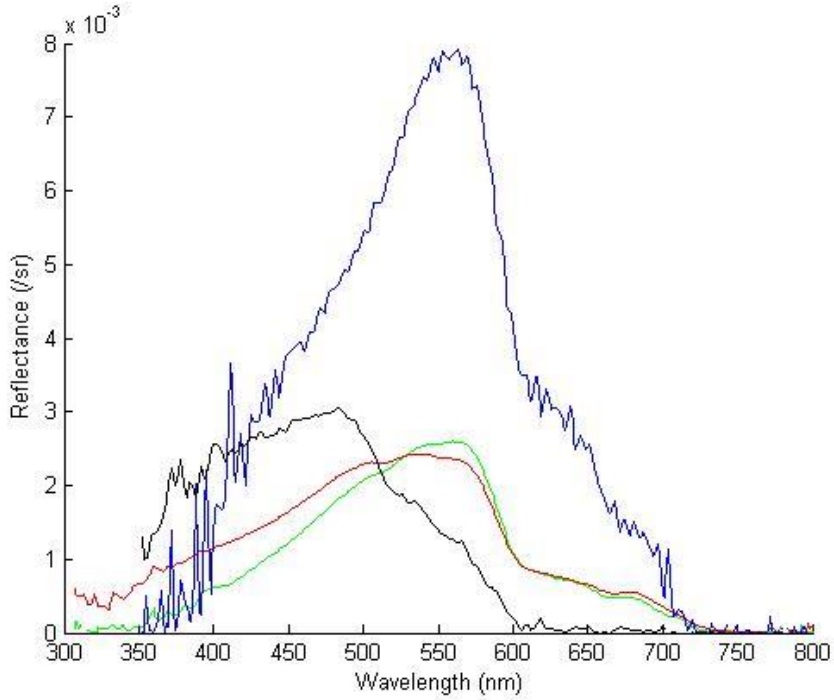

Figure 14 Reflectance Spectra. (Red= Bras d'Or Lake, Blue = Whycocomagh Bay, Black = Bedford Basin, Green = offshore)

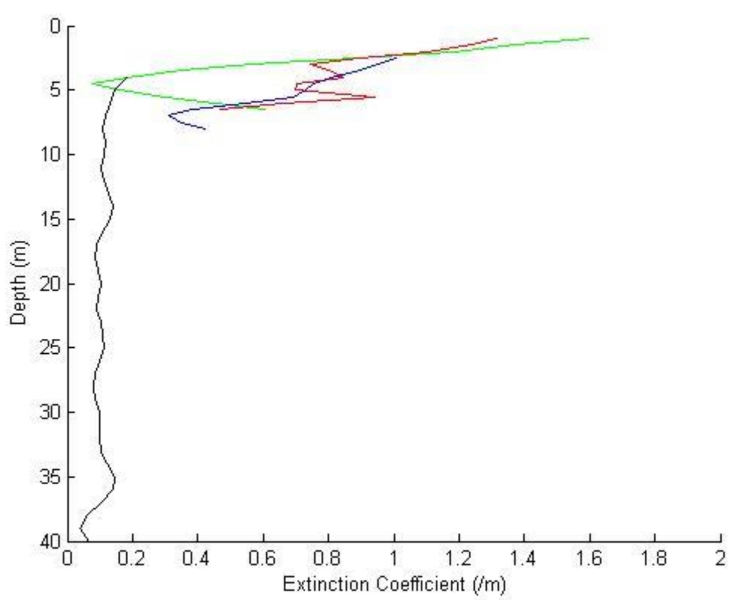

Figure 15 Extinction Coefficient Kd (Red= Bras d'Or Lake, Blue = Whycocomagh, Black = Bedford Basin, Green = offshore)

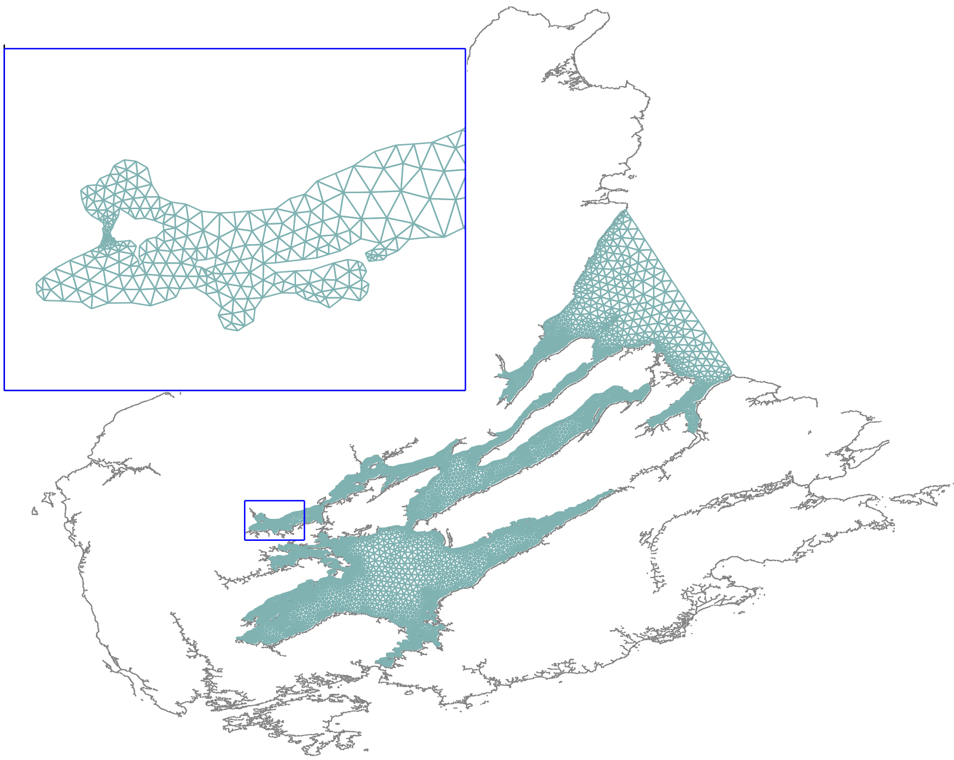

Figure 16 FVCOM model grid. Downscaled to Whycocomagh Bay (inset).