Mapping Coastal Sections using full 3-D Digital Laser Technology to Monitor Change

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Executive Summary

Traditional approaches to mapping coastal erosion rates have involved the use of decadal timescale aerial photography. This involves the correction of the photos for relief displacement and the perspective lens distortion to construct an orthophoto image which can be used as a map to make measurements. The correction of historical aerial photos can be challenging because of the changes in the land cover and thus control to correct the photo to a map. Additionally, if there is topographic relief between the beach and to top of the bank such as along cliff faces, then using a modern day elevation model to correct for relief displacement is problematic, since the edge of the cliff is typically not is the same location on the older aerial photo as the more current elevation model. Another problem when using this technique of mapping the coastline (geomorphic feature that represents the maximum extent of the ocean on the land scape ie. top of the bank or scarp) on historical photos which allows us to calculate average erosion rate (distance of coastline position change/time separating the aerial photos) which does not accurately reflect the episodic nature of the erosion process. These decadal scale erosion rates do not capture the true process of coastal erosion that is episodic and associated with specific storm surge events causing catastrophic changes rather than being a slow continuous process.

In this study we use repeat ground-based laser scanning techniques to map the changes in the coastline for one winter storm season. Three study sites were chosen to represent the three coastal zones of Nova Scotia: Cape John along the Northumberland Strait, Kingsburg along the Atlantic coast and Mavillette along the Bay of Fundy coast. At each site, typical sections of the coast representing dunes, glacial till banks, and bedrock banks were scanned in the 2010 and 2011. In the case of Cape John, on the Northumberland Strait, where multiple laser scans were conducted from June 2010 to January 2011, a severe storm impacted the coastline in late December 2010. As part of another project, a coastal monitoring system was setup at this site which consisted of measuring water levels (tide gauge), local weather conditions using a weather station deployed at the coast, and a time-lapse camera system to document the conditions of the coast. The results for Cape John indicate storms in Sept. and Nov. 2010 with water levels up to 1.4

m above mean sea-level (MSL) had the effect of eroding the foot of the mud (glacial till) bank and reducing the depth of sand on the beach by 10-20 cm. The storm of Dec. 21 eroded the glacial bank to an elevation level of 4.5 – 5 m. The tide gauge indicate a 1.5 m storm surge with total a water level measure at 2.21 m MSL while the elevation of the wrack line (debris left behind inland from the storm) measured by GPS was 2.38 m MSL. The repeat laser scans before and after the storm were used to measure the volume of sediment that was removed from the along a 150 m section of the coastline which was 780 m^3. Additional material was removed after the bank slumped in the spring and smaller storm surges removed the slumped material from the base of the bank.

The other two sites at Kingsburg and Mavillette were not impacted to the same degree as Cape John by winter storms in the 2010-2011season. With sea-levels rising and the possibility of storms becoming more intense and more frequent in the future, the results of this study allow us to relate the effects of a specific storm event to changes of the coastline. This has the advantage of being able to relate the number and intensity of storm events when making predictions of erosion into the future considering climate change. Although the scaling up of the results at Cape John have not been applied to similar areas along the Northumberland Strait, this is possible if detailed mapping of the materials comprising the coastline were available. For example, maps indicating if the base of the bank is comprised of sand, or glacial till (mud in the case of many areas along the Northumberland Strait) or bedrock would allow us to apply the rates measured at Cape John to larger sections of the coast where the geological materials and orientation of the coastline are similar. Investigations of the effect of the Dec. 2010 storm along the coast from Pugwash to Tidnish (NS-NB boarder on the Northumberland Strait) have indicated similar erosion and coastal flooding as observed at Cape John. The coastal monitoring system was ideal to measure the local atmospheric forcing conditions and local water level conditions during storm surge events to better relate the storm intensity to the changes in the coastline. The time-lapse photography is especially useful since many of the worst storms that impact the coastline occur in the winter when it is often dangerous and not practical to visit the coast under such conditions. This type of monitoring system could be applied to the other two sites and additional annual laser scanning surveys conducted if funding were available. Not only are these studies valuable for improving our scientific understanding of coastal process, they can also be used to help educate the public and policy makers on the threats of erosion and coastal flooding along the coast. They also provide the basis to allow us to better predict possible future impacts of storm surges with increased sea-level rise and possible increases in storm intensity and frequency.

1. Introduction

The past approaches to assessing coastal erosion have been to exploit aerial photography that is typically acquired on a decadal time scale. The air photos are scanned and used with ground control, often in the form of GIS layers, e.g. roads, buildings, and a digital elevation model, to correct for the perspective viewing angle and relief displacement, to produce a digital orthophoto. The orthophotos are interpreted for coastline position, often defined by a break in vegetation or the location of the scarp of a bank or cliff edge. The coastline position is then compared between the orthophoto dates (decadal) to determine the rates of erosion (m/year). This essentially produces broad time-averaged estimates of erosion along the coast. Sediment volumes are typically not directly calculated from this approach. Sediment budget includes source and depositional areas and are important to consider when predicting future changes to the coastline in light of climate change and sea-level rise.

Erosion of the coast is dependent on storm water level conditions, local wind direction (waves), local bathymetry, relief and orientation of the coastline and the composition of the bank material (bedrock, glacial till - mud bank, or dune). Often in Maritime Canada we experience our most intense storm damage along the coast including flooding and erosion in the winter (Feb. 1976 Groundhog Day storm, Jan 21, 2000 storm – highest storm surge on record, Jan 2, 2010 - Port Elgin, NB, Dec. 6, 21, 28 northern coasts along the Northumberland Strait). Erosive processes in the winter, especially on glacial till banks, often cut the foot of the bank making the slope steeper to near vertical and in the spring during the thaw cycle and increased soil moisture from run-off, the bank will slump. With this episodic nature of the erosion process, often the scarp or top of bank does not recede until the next season when the slumped material has been washed away from subsequent high water events.

In this project we used a ground based laser scanner (lidar) to scan 3 representative coastal areas of NS (Northumberland Strait, Bay of Fundy, Bay of Fundy) (Table 1, Fig. 1)). At each of the sites there are typical geomorphologic coastal features including dunes, glacial till banks, and bedrock cliffs. These sites will be monitored every year of the RAC project, and hopefully beyond 2012 if resources are available, to assess the erosion rates and document the effects of specific storm events.

Table 1 Coastal study sites for detailed change detection using ground-based laser scanning.

Coastal Water Body	**Specific study site**
Northumberland Strait	Cape John, Meg's Cove
Gulf of Maine - Bay of Fundy	Mavillette Beach
Atlantic Ocean	Kingsburg – Hirtle's Beach

Figure 1 Location of the coastal laser scanning sites denoted with the black boxes. Source of map data Google Maps.

This approach will allow measurements of coastline change between the episodic processes of coastal erosion and better relate the changes to specific storms. This will improve our understanding of the process and the threat of climate change and erosion for each type of coastal morphology.

We planned to scan the same section every year (spring and fall) to map the changes and calculate the volume of sediment removed, or accreted, along the coast. In the case of Cape John which was severely affected by the Dec. 21, 2010 storm surge, we surveyed it in Jan. 2011 to document the change. We anticipate doing the remaining spring surveys in April or May, 2011. In addition to the laser scanning surveying, we tracked the weather and specific storm events that affect the coastal sections. This allows us to determine the wind & wave direction of a particular storm event.

2. Methods

We have utilized the Optech ILRIS ground based lidar scanning unit owned by the Applied Geomatics Research Group (AGRG). The system allows us to capture the full three dimensional aspects of the coastal section. It is an eye-safe laser that has a 40 degree by 40 degree field of view (Fig. 2). The scans have a spatial resolution on the order of a point every 1-5 cm in spacing and a vertical precision of 2-5 cm.

Figure 2 Typical ILRIS setup along the coast. The yellow shaded area is a cartoon to represent the 40 degree by 40 degree field of view.

The ILRIS does not directly georeference the laser scans. In order to geocode the lidar point cloud, we place a minimum of 4 targets within each scene and use RTK GPS to measure their locations (Fig. 3).

Figure 3 Example of a georeferencing target and GPS positional measurement (precise of 2 cm in Z).

The targets are then located in the point cloud and (Fig. 4) and used as control points with the GPS coordinates. A first order polynomial transformation is used to convert the point cloud data to UTM NAD83 zone 20 horizontal coordinates and the elevations are referenced to CGVD28.

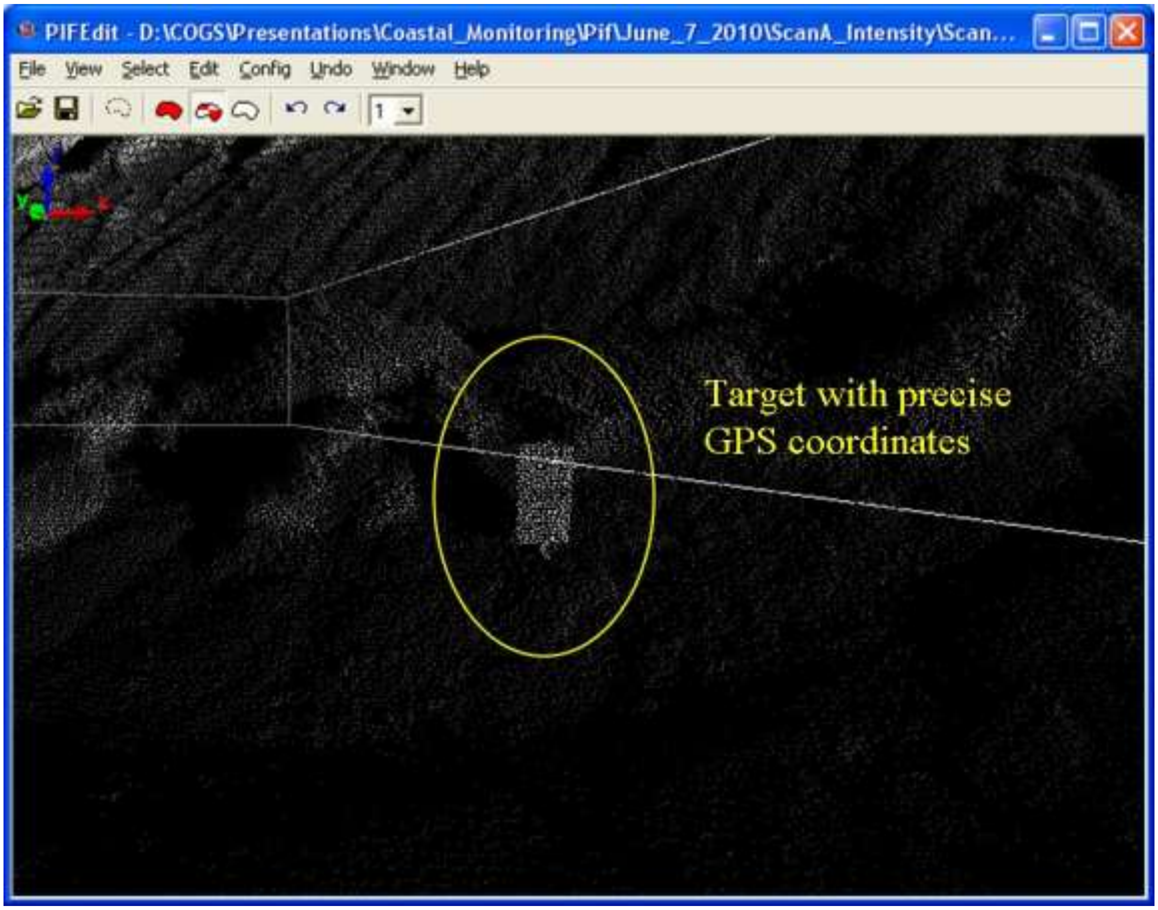

Figure 4 Lidar point cloud along the coast with a target highlighted.

The ILRIS records the range (distance) to the targets in the scene and also records the intensity of the backscattered energy of the laser pulse. This is referred to as the intensity of the lidar pulse. A medium quality camera is aligned with the laser field of view and acquires an image for each scan. Thus the lidar point cloud can be visualized based in the intensity as greyscale or can be viewed using the camera RGB values (Fig. 5).

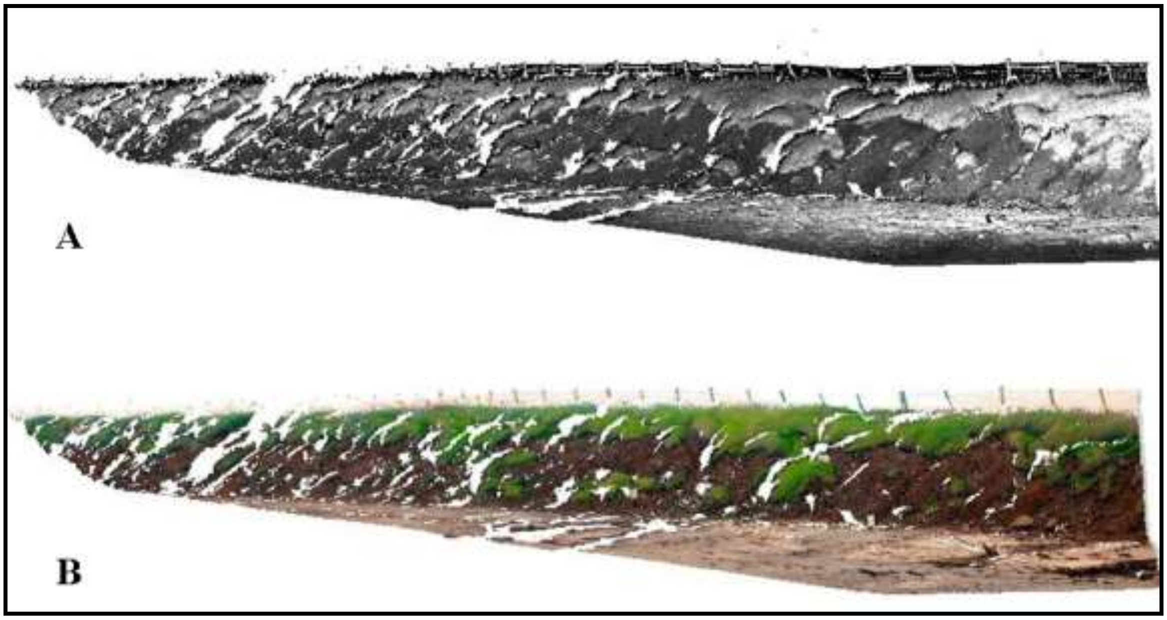

Figure 5 Example of lidar point clouds. A) Shades of grey relate to the intensity, lighter tones denote grass and darker tones are mud. B) The same point cloud with the camera RGB values (green grass and red-brown mud). The white slivers are areas of missing data as a result of shadows.

Due to a slight misalignment and the limited resolution of the camera, compared to the laser point density, there is an offset in the RGB colour codes and the laser points. As a result we always use the intensity image to assign the ground control points to the point cloud for geocoding.

Once the lidar point clouds were georeferenced, detailed elevation grids can be made and used for change detection and visualization. All of the ground-based scanning sites have been flown with airborne lidar. Airborne lidar typically has a ground point spacing every 0.5 – 1 m and usually does not sample the steeper slopes adequately to capture their detail. However, the wide area coverage of airborne lidar makes it ideal to merge with the detailed ground-based lidar for steep sloped coastlines (Fig. 6).

The three study sites were all visited in the fall of 2010 and scans were acquired. In the case of Cape John several scans were acquired through June, July, Oct., Dec. and Jan. to measure the gradual and catastrophic change associated with the Dec. 21, 2010 storm. The coastal sections at Kingsburg and Mavillette were both scanned in the fall of 2010 and the summer of 2011.

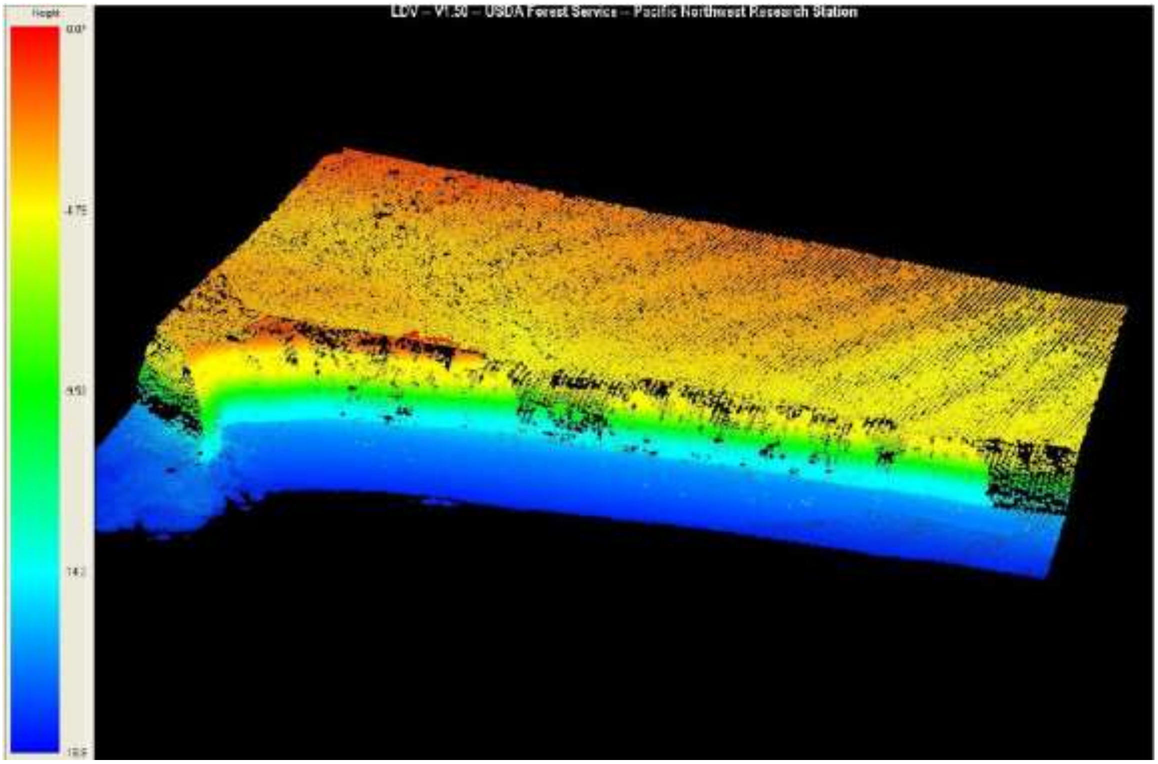

Figure 6 Example of airborne lidar points (sparse spacing – appears as scanlines) merged with geocoded ground-based lidar point (dense spacing – appears as solid) for the cliff area of Cape John. Elevations in the case are still referenced to the GRS80 ellipsoid and have not been converted to orthometric height above CGVD28 yet.

In order to track specific storm events, the local weather information for each site was investigated. The weather underground website was used to extract daily weather records for the nearest station to the study sites. The historic weather data were downloaded from the internet for the following sites:

Cape John used Caribou Point CWBK

http://www.wunderground.com/history/airport/CWBK/2011/4/3/DailyHistory.html?req_city=Pictou&req_state=NS&req_statename=Nova+Scotia

Kingsburg used Lunenburg CXLB

http://www.wunderground.com/history/airport/CXLB/2011/4/3/DailyHistory.html?req_city=Lunenburg&req_state=NS&req_statename=Nova+Scotia

Mavillette used Brier Island, CWVU

http://www.wunderground.com/history/airport/CWVU/2010/10/2/DailyHistory.html?req_city=Brier+Island&req_state=NS&req_statename=Nova+Scotia

The monthly phase of the moon was also downloaded as this influences the height of the tidal water level and the threat of coast flooding from storm surge events. The water levels are highest at the new moon phase (waning crescent) or full moon phase as a result of the combined gravitational attraction of the sun and moon.

In addition to the daily weather records downloaded monthly for the three sites, AGRG deployed a weather station and time-lapse camera system at Cape John as part of another study. The weather station was deployed at Cape John at the top of the glacial till bank in late October, 2010. AGRG also deployed a water level and barometric sensor in late August, 2010 at Skinners Cove, approximately 10 km east of the Meg's Cove site on Cape John. The barometric sensor is used to compensate for changes in atmospheric pressure that affect the measurements of the water levels based on changes in pressure.

The coastal sections were scanned from different azimuth angles to minimize the shadow effects of active laser scanning. In shadow areas no laser returns are recorded which results in no data being available for surface modelling and thus change detection. Although the multiple scanning angles reduced the number of shadows, minor data gaps in the point cloud still existed. As a result of there being data gaps, the Inverse Distance Weighting (IDW) interpolation method was used to construct the elevation grids (DEMs) from the point clouds. The Triangular Irregular Network (TIN) method, which is usually employed with the airborne lidar data point clouds, would have introduced too many artefacts in the areas of data gaps. The DEMs were constructed for the glacial till bank section for each survey date. During the surveys, RTK GPS points were collected to compare and validate the lidar point clouds and DEM surfaces. The RTK GPS elevations along transects were compared to the DEM models for accuracy assessment. The DEM grids produced from the lidar point clouds for Cape John were analyzed for change detection using two methods: 1) subtraction of one DEM grid from another (for example June 2010 DEM – Jan. 2011 DEM); and 2) by examining a series of profiles running perpendicular to the coastline. These methods of change detection are complimentary. The grid subtraction method allows for the calculation of the volume of material that has changed and the spatial location of the changes, while the profile method allows for detailed inspection of how the coastline relief and shape has changed over time and is simpler to interpret for the non-specialist.

3. Results

The daily weather data for the months of Oct. 2010 to July 2011 for each of the three sites (Cape John, Mavillette, and Kingsburg) is located in Appendix A, B, and C respectively. The phase of the moon during this past storm season highlights dates where tidal water levels were high based on astronomical conditions (new moon and waning crescent and full moon) (Fig. 7).

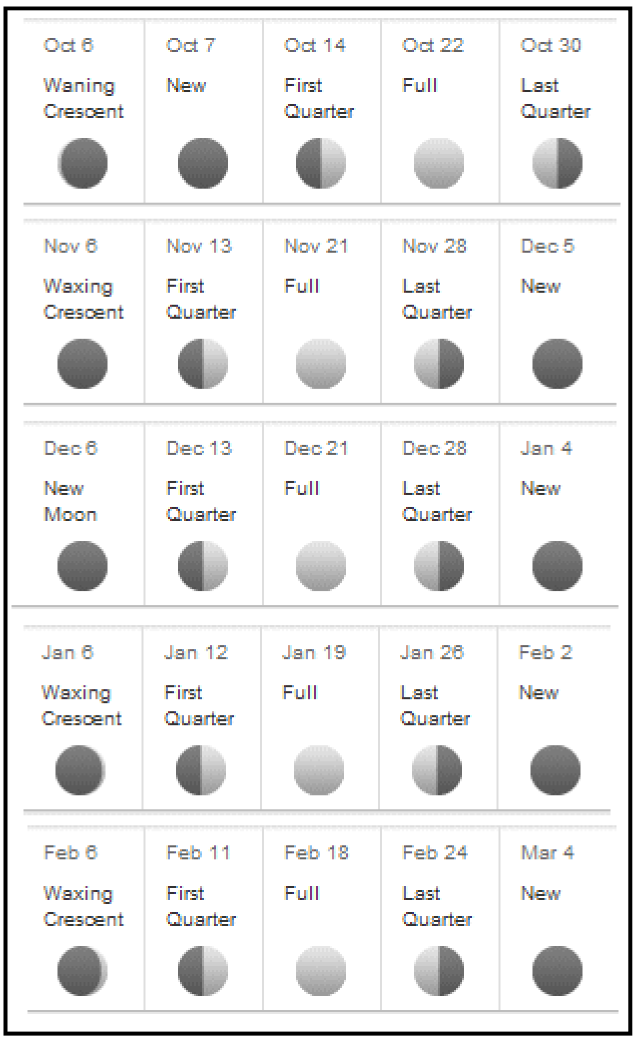

Figure 7 Phases of the moon for Oct. 2010 through to Feb. 2011.

3.1 Cape John

Three distinct geomorphic sections of the coast were scanned at Cape John; 1) the bedrock cliff forming the eastern point of the cover (purple swath main map), 2) the glacial till bank and armour stone section (3 swaths inset map), and 3) a sand dune (blue swath inset map) (Fig. 8).

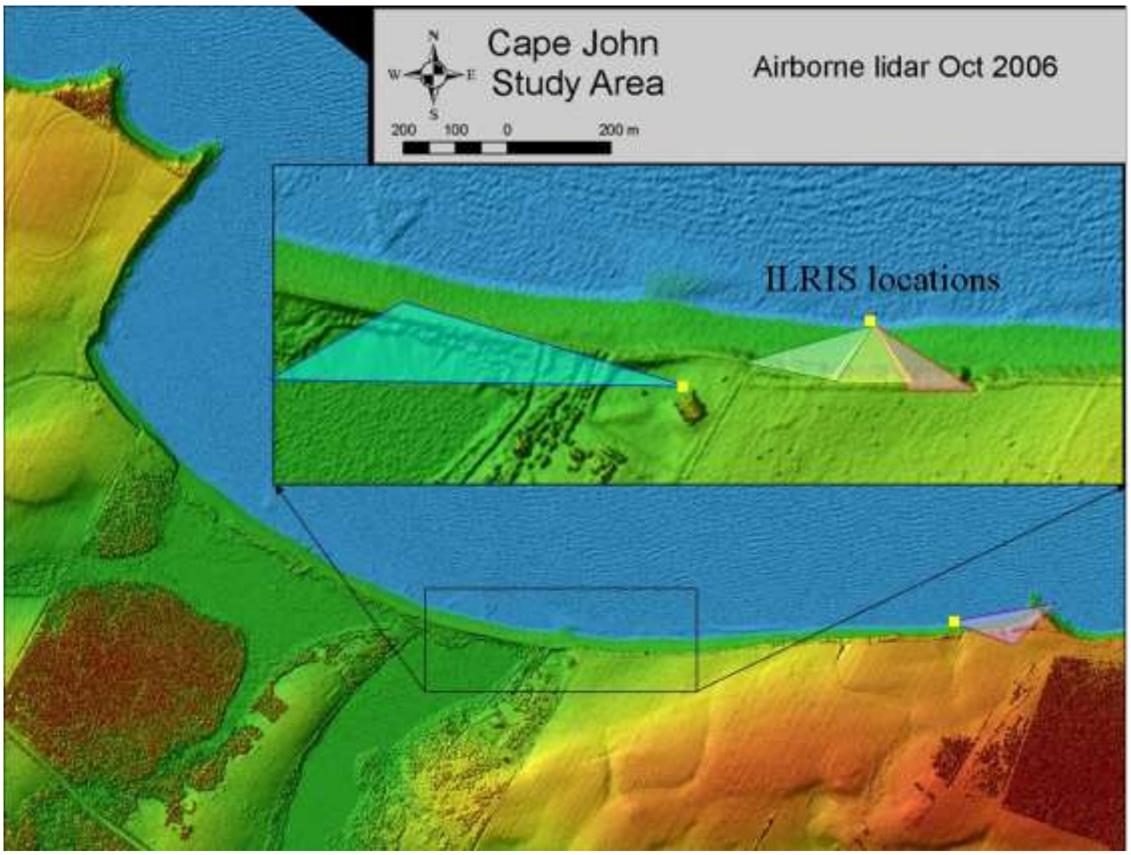

Figure 8 Cape John (Northumberland Strait) scanning locations. The yellow dot represents the scanner and the triangles represent the swath (approximately). Note the scan location of the eastern point with a cliff coastline within the large map.

Of the three geomorphic type areas scanned, the glacial till bank coastline is best suited for this type of survey method. The sand dune only has a metre of relief at best and is thus difficult to scan at beach level and placing georeferencing targets is problematic for the cliff area (Fig. 9). As in many coastal sections of Nova Scotia, the glacial till bank represents the transition from a dune in the center of the embayment to a bedrock cliff defining the point of the embayment. The glacial till bank at this site includes natural material as well as a section of armour stone for shoreline stabilization.

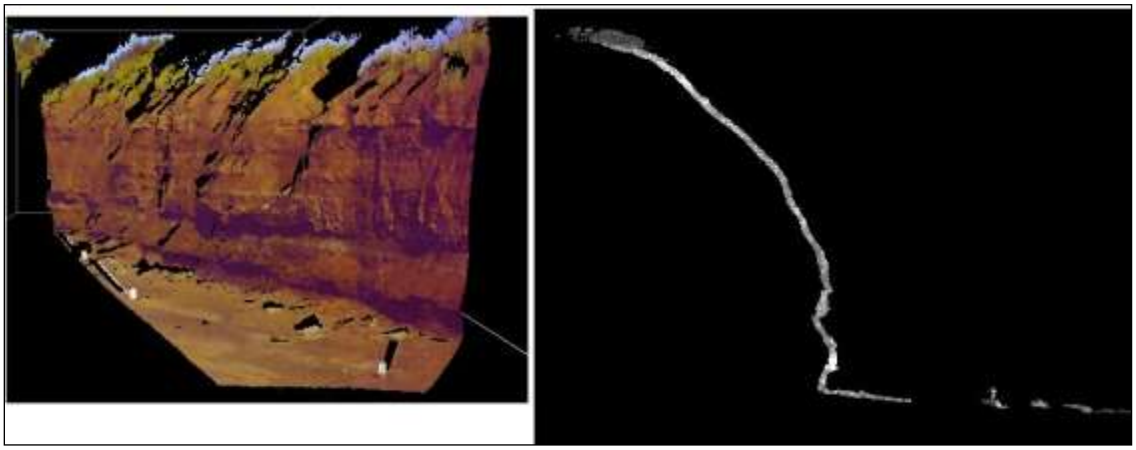

Figure 9 The left image is a RGB scan of a cliff coastline at Cape John where the different sedimentary rock layers are visible. The white rectangles and black shadows are targets placed on the beach. The right image is a cross-section view with the greyscale intensity. Note the vegetation at the top of the cliff and the overhang in the rocks.

The glacial till bank section was expected to have the most significant change in terms of potential from surface runoff and storm surge events and was therefore scanned several times to monitor systematic and catastrophic change. If there is dense vegetation, the laser pulse may not to penetrate to the ground surface and thus will bias the surface model and results of the analysis. The surveys were conducted from June through to Jan. under a variety of conditions (Table 2).

Table 2 Dates of laser scanning for Cape John study site, glacial till bank.

Date of scan of glacial till bank section	**Condition of vegetation (grass) & cover**
June 7, 8, 2010	Brown to Lush Green, 5 cm
July 24, 2010	Lush, 5-10 cm
Oct. 6, 2010	Lush, 5-10 cm
Dec. 16, 2010	Brown, Dead 5 cm

Jan. 4, 2011	Sod eroded from bank, Snow 3-5 cm

The individual geocoded scans from different vantage points were integrated and DEM grids constructed for each date (Table 2). The DEM grids were constructed with 20 cm grid cells using the IDW interpolation method (Figs. 10-14).

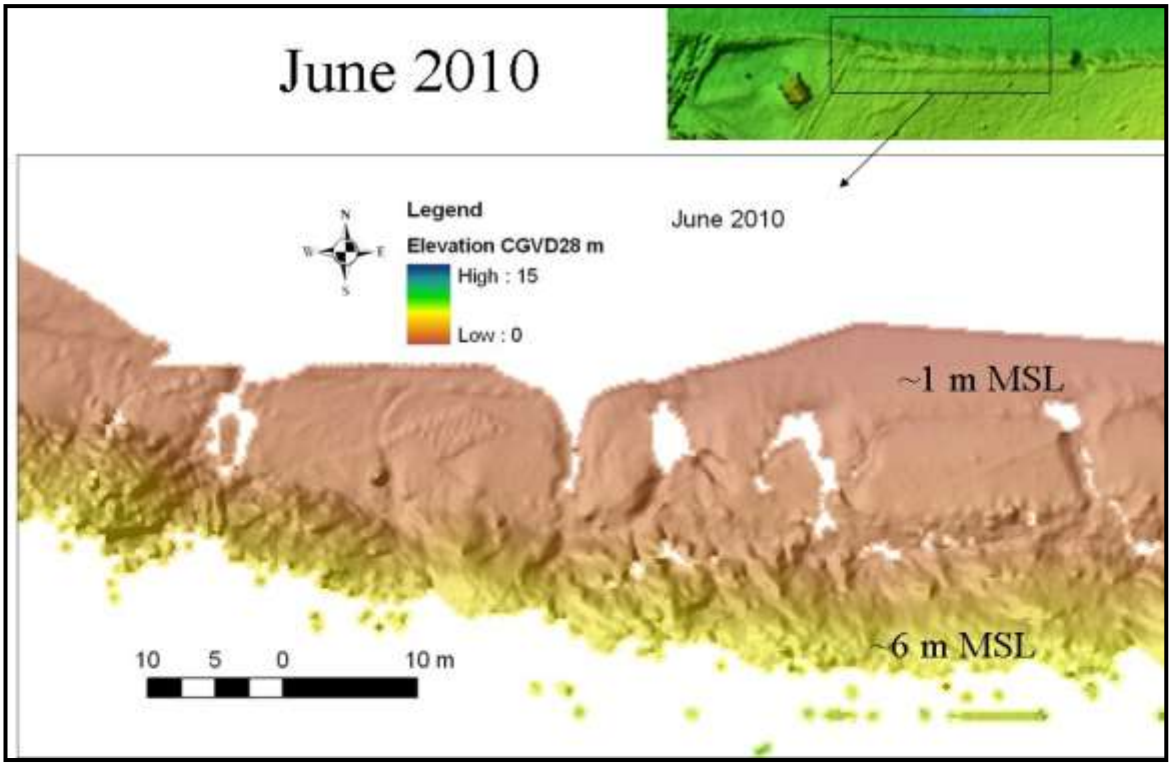

Figure 10 June DEM colour shade relief map from ILRIS point cloud (20 cm grid cells).

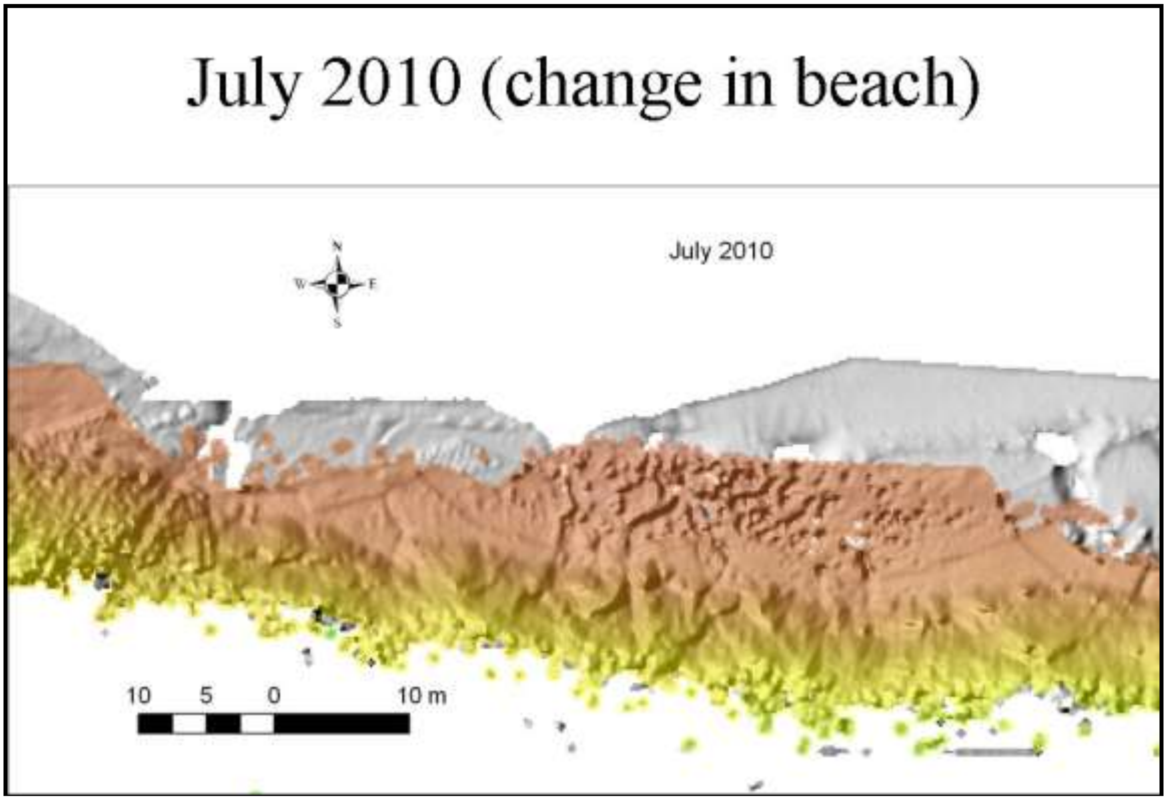

Figure 11 July DEM colour shade relief map from ILRIS point cloud (20 cm grid cells).

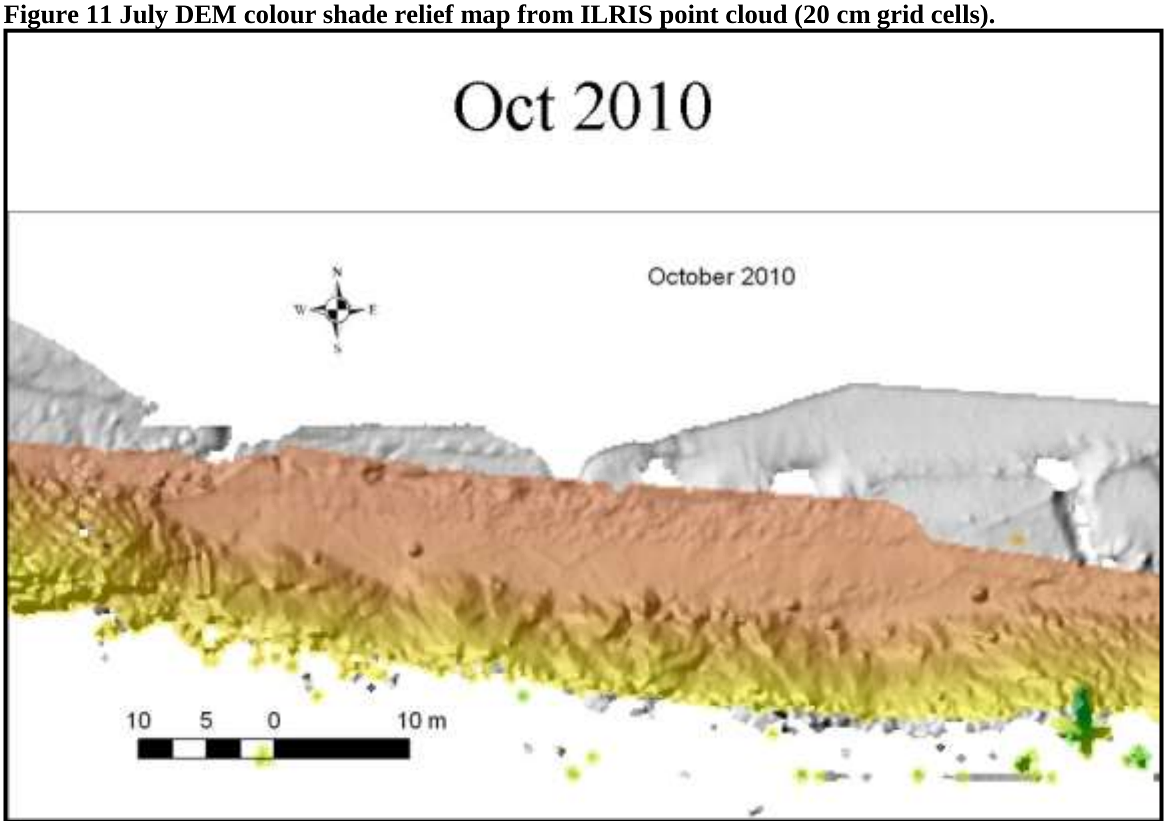

Figure 12 October DEM colour shade relief map from ILRIS point cloud (20 cm grid cells).

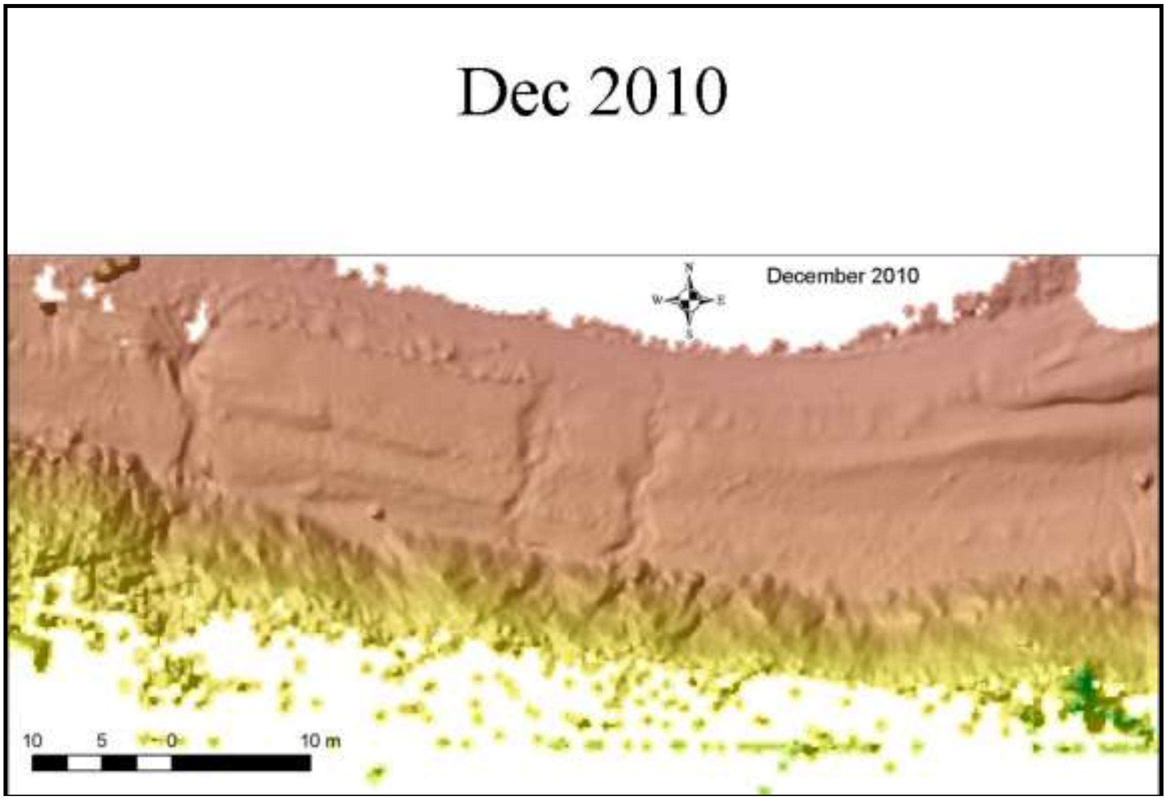

Figure 13 Dec 2010 colour shade relief map from ILRIS point cloud (20 cm grid cells).

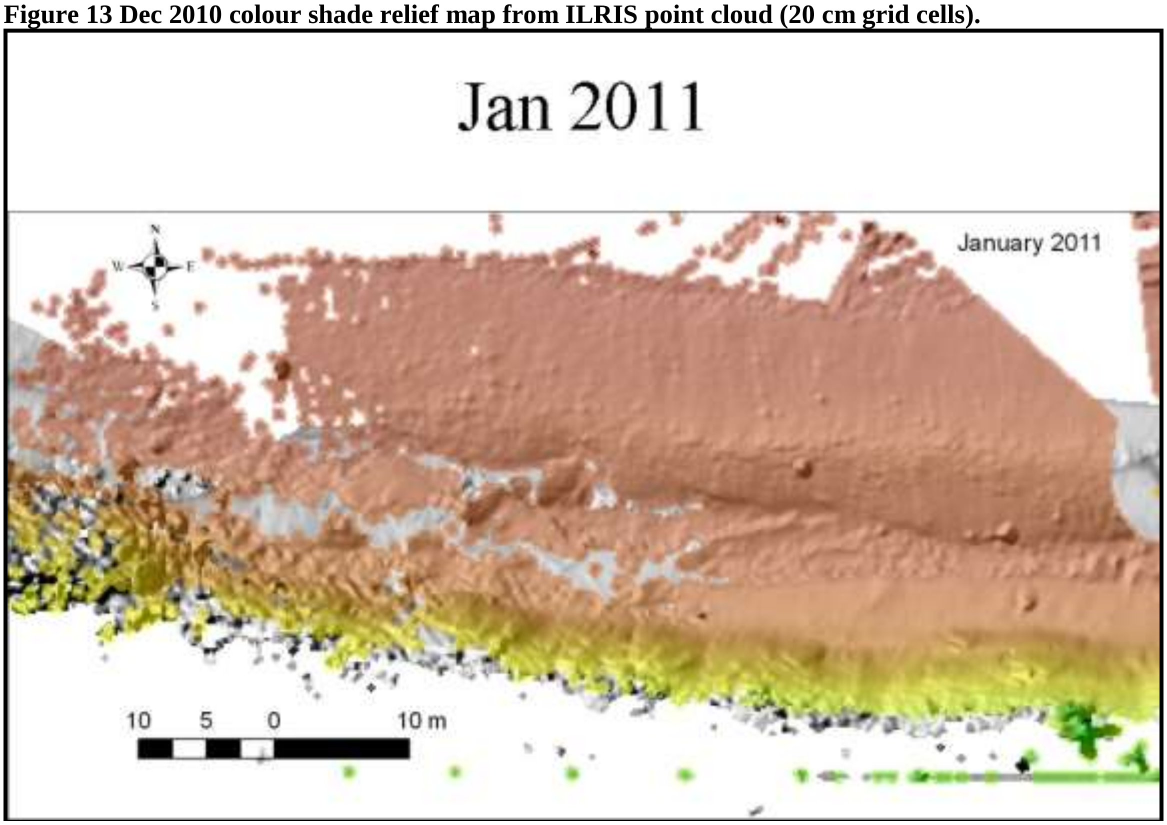

Figure 14 January DEM colour shade relief map from ILRIS point cloud (20 cm grid cells).

The DEMs were compared to GPS transects to determine their accuracy. The Dec. 16 GPS transect elevations were compared to the DEMs from June, October, December, 2010 and January, 2011 (Fig. 15). The Dec. GPS points match the Dec. DEM quite well, with the exception of the foot of the bank, where the DEM is too high. All of the DEMs are higher than the GPS elevations at the top of the bank. The error at the bottom of the bank could be a result of a slight shadow or dense clumps of sod and grass on the bank. The error at the top of the bank where the DEMs are too high is attributed to dense grass vegetation and the scanning geometry. The scans were acquired with the ILRIS positioned on the beach, thus at the top of the bank, the bias affect of vegetation would be at a maximum as a result of the local incidence angle of the laser pulses. The differences in profiles between Dec. and Jan. on figure 15 shows the significant amount of material that was removed from the bank and is associated with erosion during the Dec. 21, 2010 storm surge.

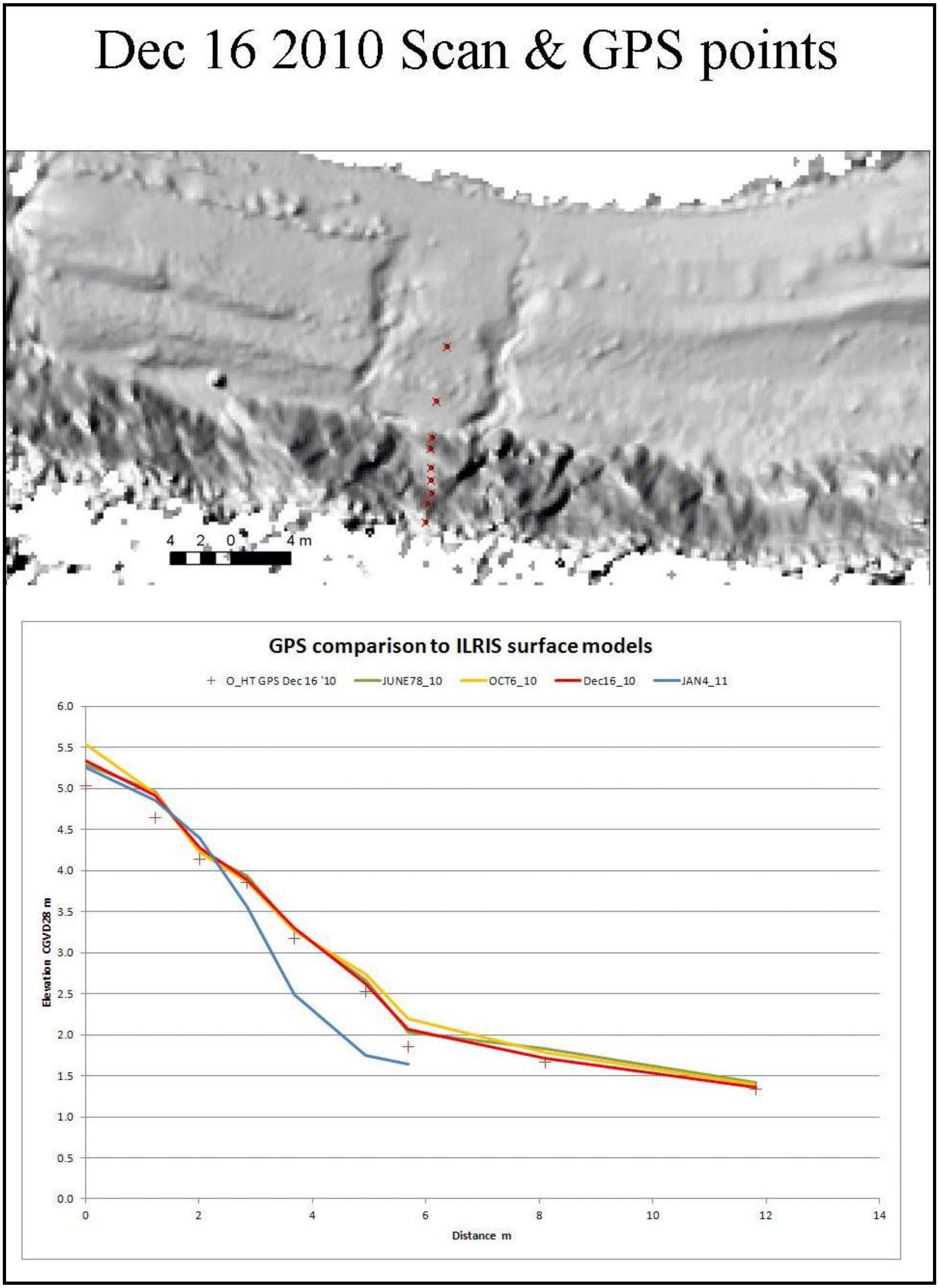

Figure 15 December 2010 shaded relief DEM with GPS (red x) transect locations (top). Profile of GPS elevations (+) and DEM surfaces (lines).

There were several smaller storm events leading up to the most significant storm on Dec. 21, 2010. The AGRG water level and barometric sensor was deployed in late August, 2010 at Skinners Cove and captured several high water events (Fig. 16). To our knowledge no other water level measurements were made along the Nova Scotia coast of the Northumberland Strait during this time. The nearest tide gauge on the south side of the Strait is at Shediac, NB. Pictou had a gauge for several years but was decommissioned in 1996 by CHS. AGRG deployed a weather station and time-lapse camera system at the study site. Unfortunately the time-lapse camera system leaked and was damaged and only recorded events from late Aug. to Oct., 2010.

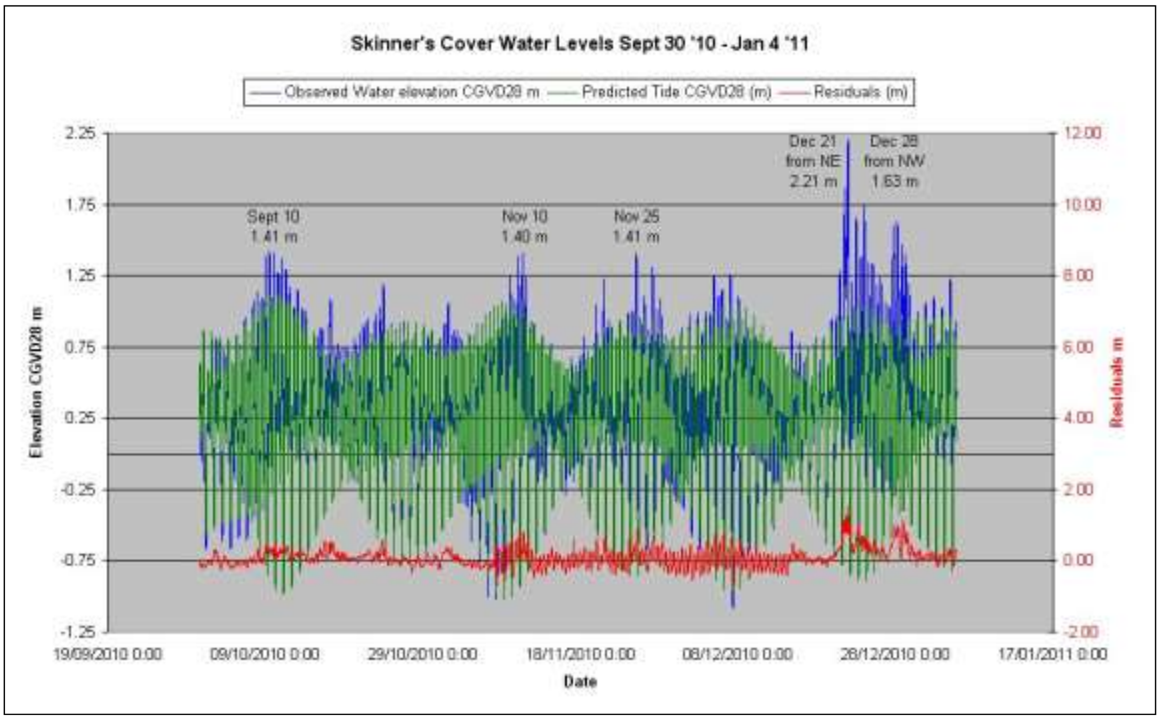

Figure 16 Skinners Cove tide gauge record. The data were recorded every 30 minutes. Note the extreme high-water associated with the Dec. 21, 2010 storm surge, then followed by Dec. 28th.

The Sept. 10 high-water event was captured with the time-lapse camera system (Fig. 17). This high-water event in combination with the storm surges of Nov. 10 and 25th have caused erosion of the beach sand and removal of some of the glacial till material at the foot of the bank (Fig. 18).

Figure 17 Example from the time-lapse camera system. Top photo is normal "spring" high tide. Bottom photo is the storm surge from Sept. 10, 2010 (1. 41 m).

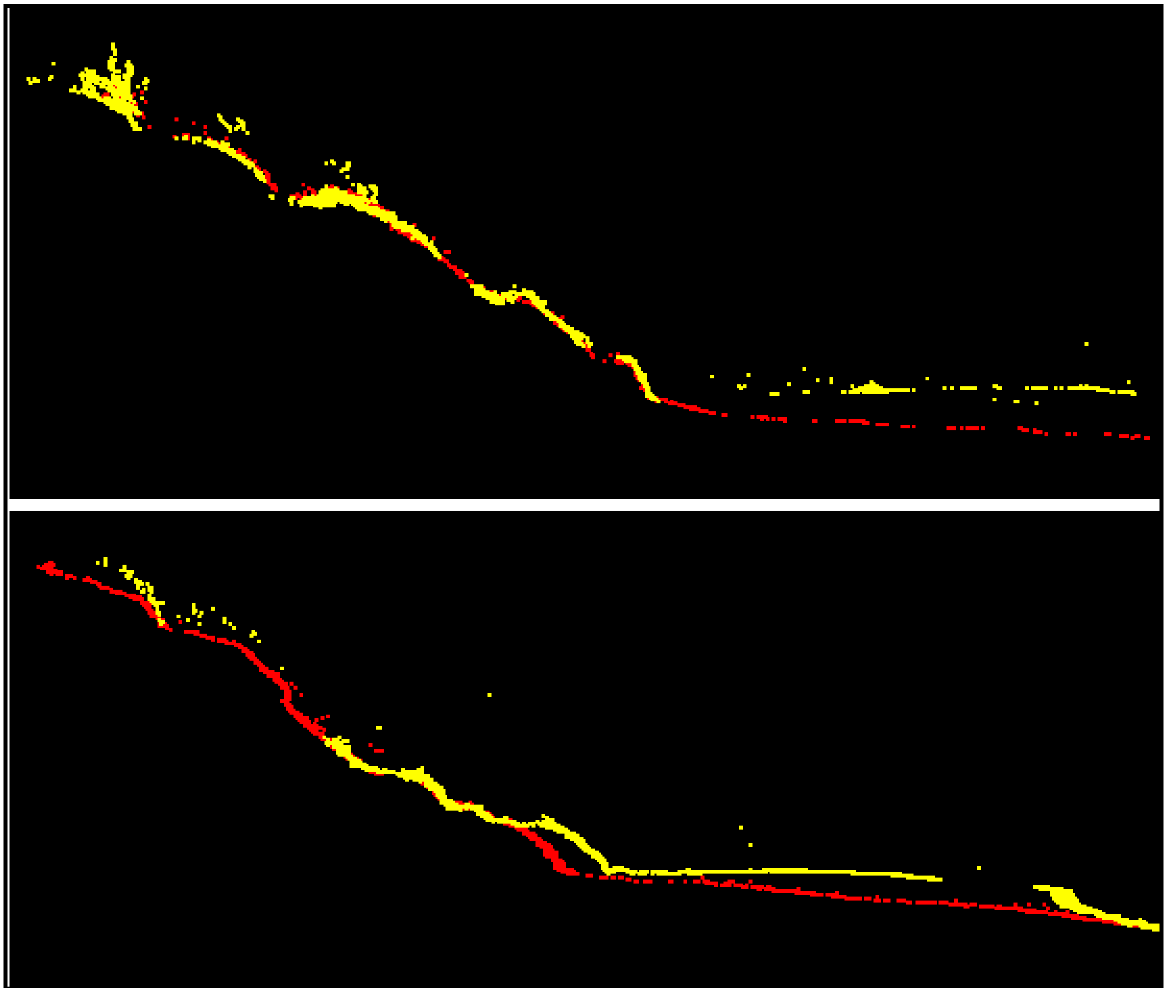

Figure 18 Comparison of point cloud profiles from June (yellow) and December (red) scans. The top image shows more vegetation present along the bank and the beach at a higher level in June than Dec. The lower image shows erosion of the foot of the bank and a lowering of the beach between June and Dec. The relief along the Y-axis is approximately 6 m and the distance on the X- axis is approximately 20 m.

The changes observed in the lidar scans (Fig. 18) are attributed to the storm surge events of Sept. 10, Nov. 10 and 25 and possibly Dec. 6, although the water did not exceed 1.25 m for the last event based on the tide gauge data (Fig. 16).

Data from the AGRG weather station from Dec. 1, 2010 - Jan. 4, 2011 is presented (Fig. 19). The most significant storm surge occurred on Dec. 21 (2.21 m Fig.16) and was then followed a week later on Dec. 28th (1.63 m Fig. 16) by another high-water event. The daily weather records for the months of Oct. 2010 through to Feb. 2011 for Cape John are presented in Appendix A.

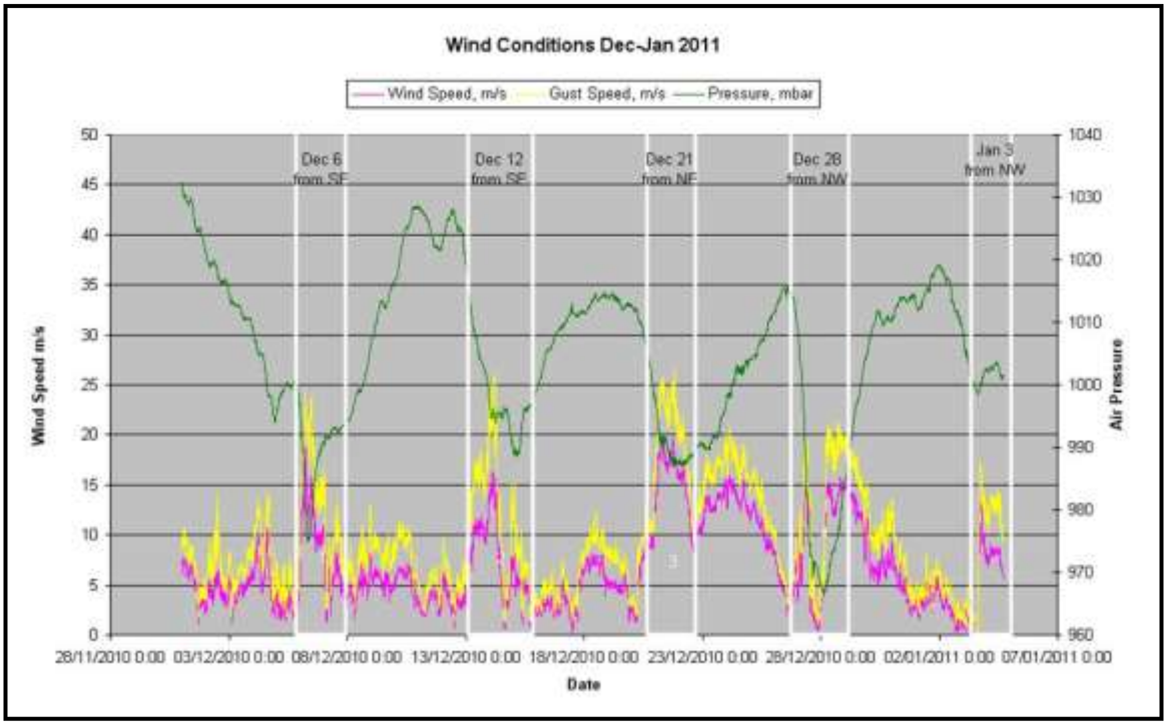

Figure 19 Cape John weather station record for wind speed & gusts and atmospheric pressure. The two variables that drive storm surges. The dates of significant storms and wind direction are plotted between the white markers. The data were recorded every 15 minutes.

The Dec. 21 storm devastated coastal regions all along the Northumberland Strait with flooding and significant erosion. The sand was totally removed from the beach and the sand dune destroyed at Cape John (Fig. 20).

Figure 20 Erosion of the sand from the beach and destruction of the dune from the Dec. 21, 2010 storm surge event.

The glacial till bank was severely eroded and steepened significantly as a result of the high-water and wave action. Several markers that had been placed into the bank to monitor creep and slumping and were removed (Fig. 21). As can be observed in Figure 21, all of the clumps of sod have been removed from the bank during the storm. The sand has been removed from the beach and only bedrock and larger stones remain. Unfortunately snow followed the Dec. 21 storm event prior to us being able to visit the site and collect GPS and another ILRIS scan. The depth of snow was approximately 5 cm and was not drifted when the post storm ILRIS scan was acquired on Jan. 4, 2011. GPS locations of the high-water wrack line were collected along with some beach elevations. The beach is very resilient however, as sand had been deposited back onto the beach, although not at the levels observed prior to the storm. The lidar point clouds and DEMs were used to analyze the change in the glacial till bank by examining profiles and differences in the DEM surfaces. The difference between the June, 2010 DEM and Jan., 2011 DEM shows a significant amount of change (Fig. 22). The difference DEM has been used to calculate the amount of sediment that has been removed. Along a coastal section 150 m in length, approximately 1081 cubic metres of material was removed from June 2010 to January 2011. Although we have observed erosion of the beach and at the foot of the bank from July to Dec., the most significant erosion was during the Dec. 21 storm. Profiles of the lidar DEMs for June, Oct. 2010 and Jan. 2011 for two locations (Fig. 22) are plotted in order to observe the steepening of the bank slope after the storm (Fig. 23).

In order to better quantify the effects of the Dec. 21 and possibly the 28th storms, similar analysis was carried out between the Dec. 16 DEM and the Jan. 4 DEM and between point clouds (Fig. 24). The colour shaded relief difference map (Dec. DEM – Jan. DEM) shows the distinct change in the terrain as a result of the erosion and deposition associated with Dec. 21 and 28th storms. A profile has been extracted based on the difference map (Fig. 24) in an area showing data coverage from both dates (Dec. and Jan.). The profile shows the vertical limit of erosion is close to the 4.75 m mark, where material below was removed (Fig. 25). The beach immediately adjacent to the bank was also scoured and eroded down by approximately 0.5 m, while more seaward on the beach, sediment has been deposited raising the beach up 0.25-0.5 m in elevation (Figs.

Figure 21 Erosion of the glacial till bank by the Dec. 21, 2010 storm surge event at Cape John. The pole for the time-lapse camera system and weather station are common in each photo which was taken looking east.

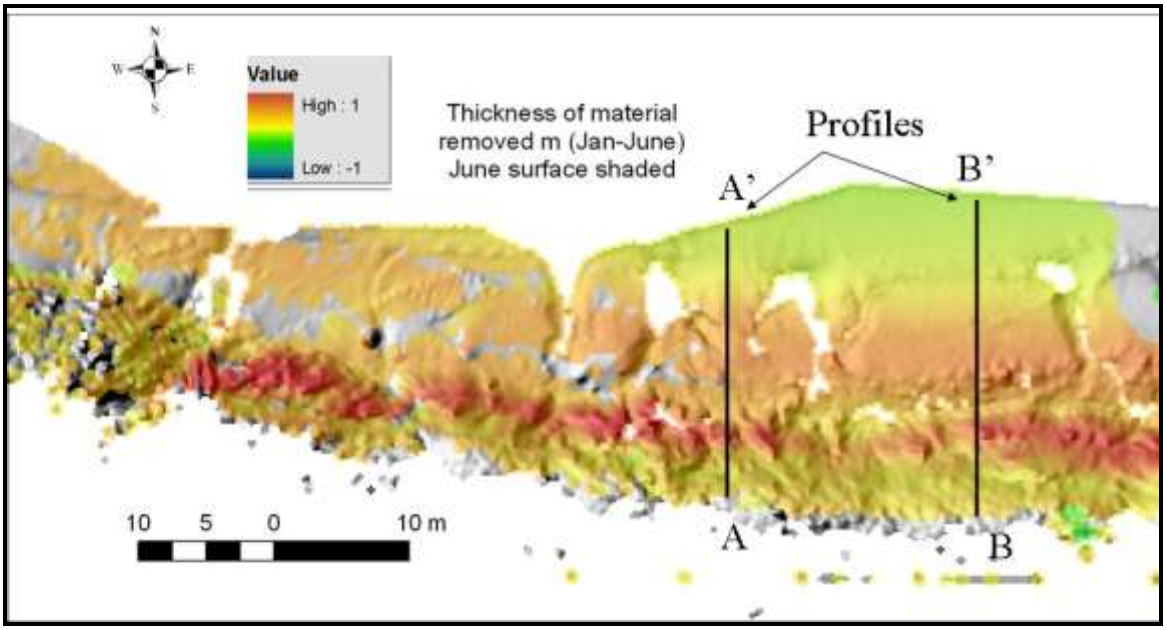

Figure 22 DEM difference colour shaded relief map between June, 2010 and January, 2011. The red areas denote the most significant erosion. Note the location of profiles A-A' and B-B',

23-25). The total volume of sediment removed along a 150 m section of the coast was 771 cubic metres by analyzing the Dec. and Jan. grids. Therefore according to our calculations, 310 cubic metres of material had been removed between June and Dec. In addition to examining the lidar derived DEM surfaces in maps and profiles, the georeferenced point clouds have been examined to observe the changes from Dec. to Jan.. For each profile of the point cloud, the width of the profile is approximately 1 m. Four profiles are presented that have been extracted from the point clouds from west to east. In the first profile the point cloud is symbolized by the greyscale intensity. The lighter tones on the upper point cloud represent pieces of sod that were present along the bank in Dec (Fig 25 top image). The remaining point clouds are colour coded based on their date, with the Dec. scan in green and the Jan. scan in red (Fig. 25 middle and lower images). The same general pattern is present with the bank being eroded at the 4-5 m elevation and the adjacent beach scoured with deposition farther seaward on the beach (Fig. 25). However, some subtle details are evident in the point cloud profiles that are not identified in the DEM profiles. For example, two terraced steps appear to be present in the bank of the Jan. 2011 scans (Fig. 25). The upper terrace may represent the dominant level of erosion and material above this was undercut and was subsequently removed by continued wave

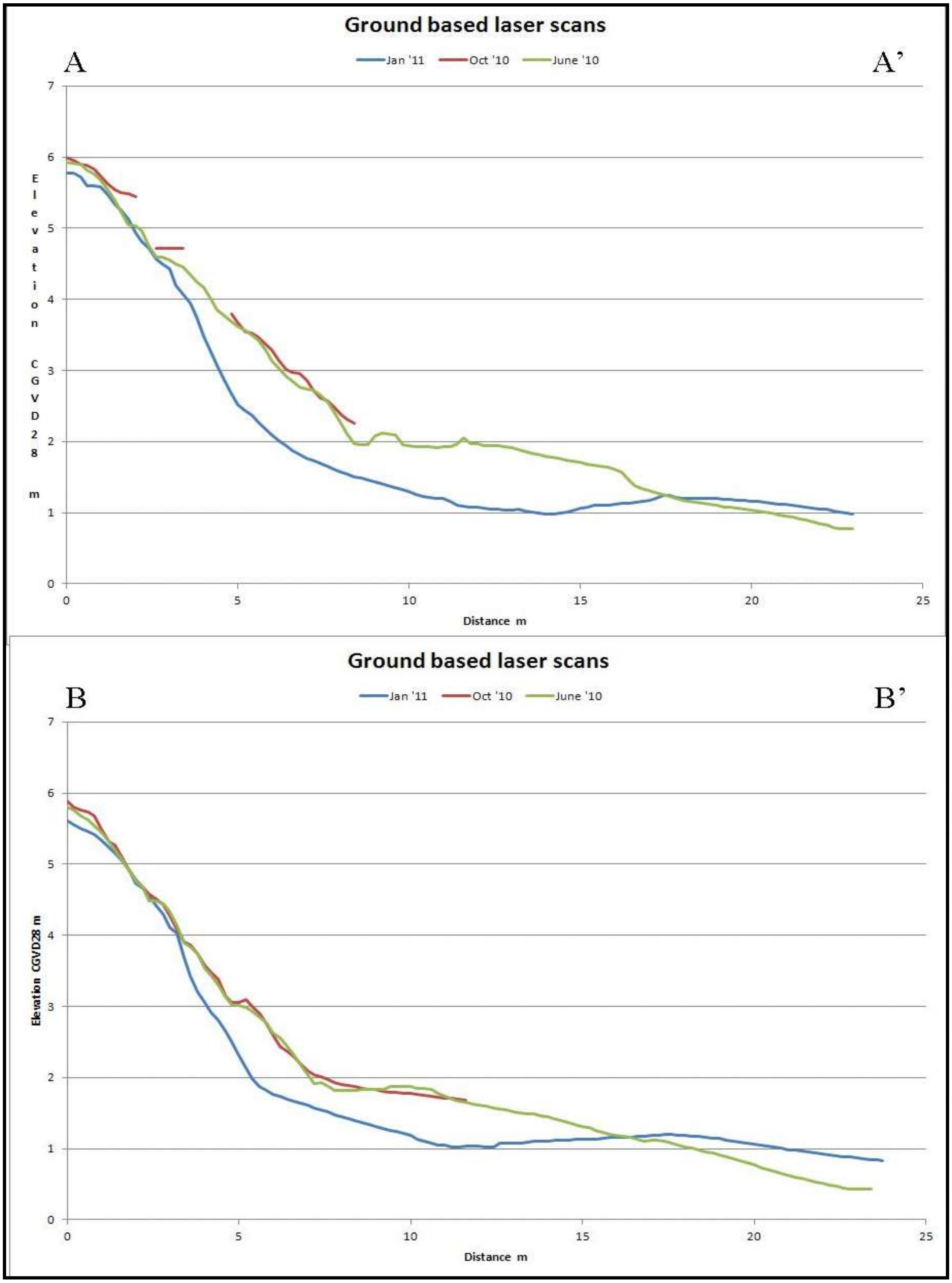

Figure 23 Profiles of DEM surfaces for A-A' and B'B' (Fig. 22). The bank appears to have been eroded to the 4.5 m elevation based on the profiles.

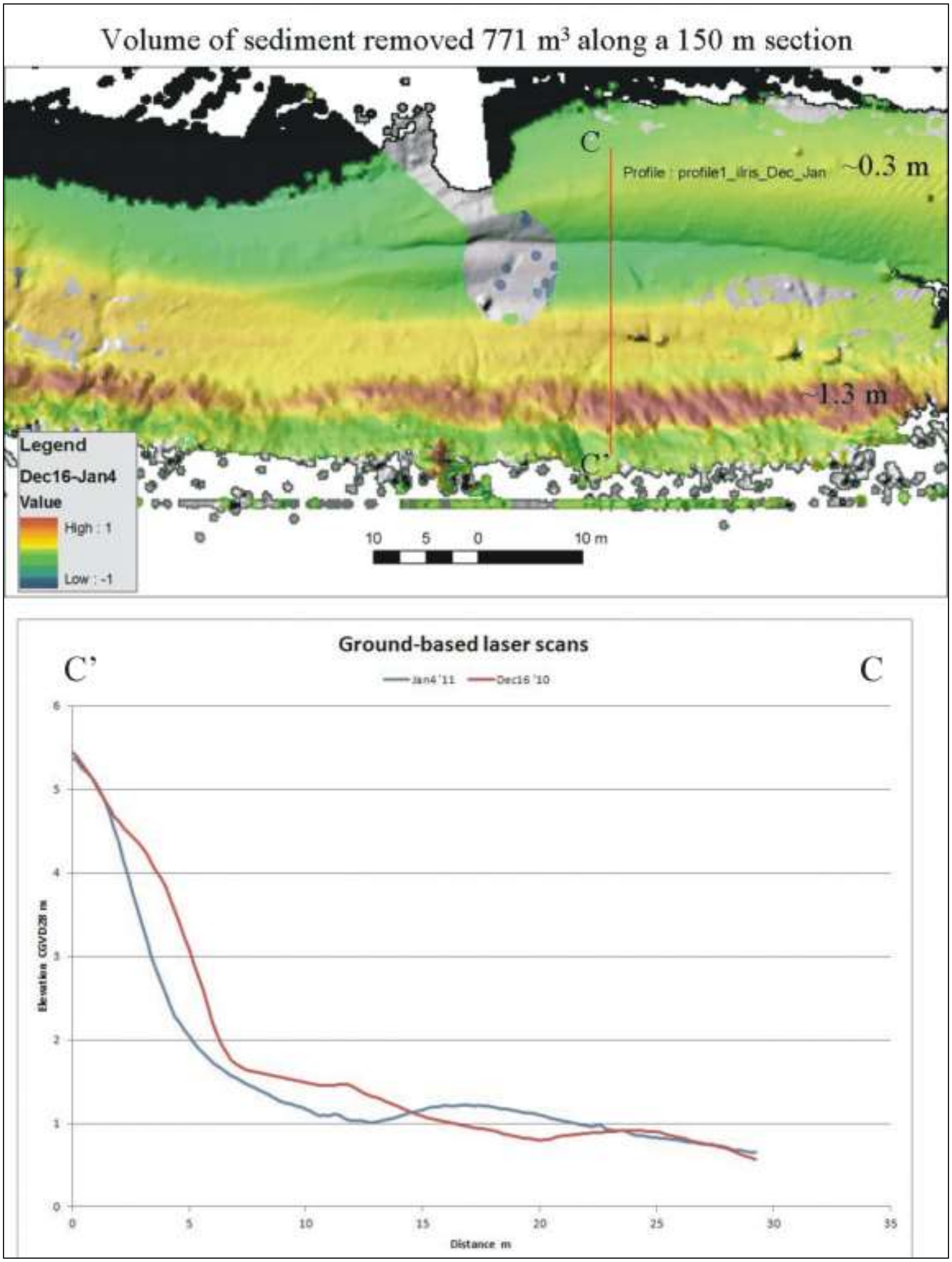

Figure 24 Top image is the colour shaded relief difference grid between Dec. and Jan. with profile location C'-C. The lower image is the profile of C'-C, showing the elevation of the bank from the Dec. 16, 2010 DEM and Jan. 4, 2011 DEM.

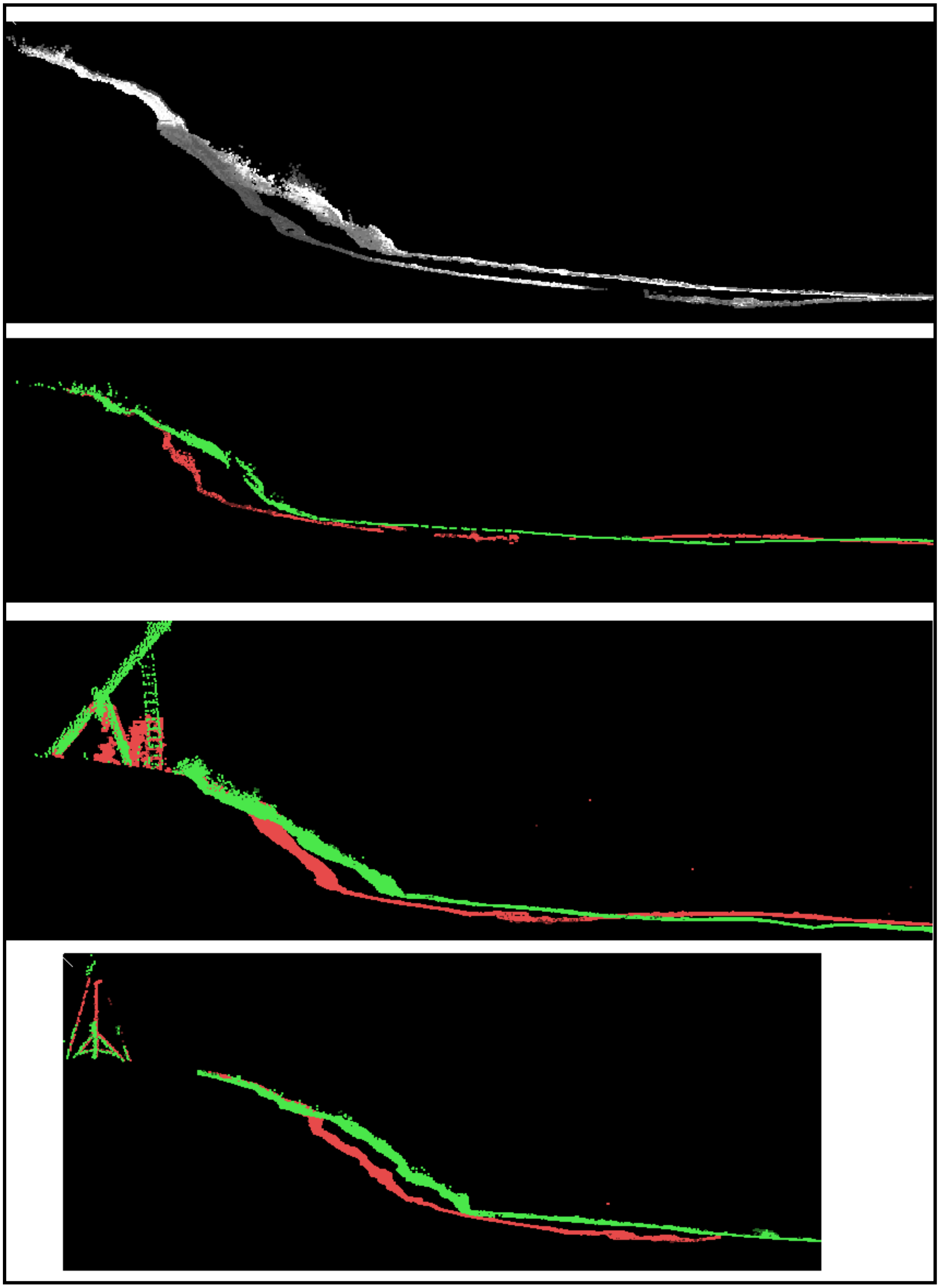

Figure 25 Lidar point cloud profiles of Dec. 2010 and Jan. 2011 scans. The upper image shows the lidar intensity of the scans. In the remaining images green points are from Dec. and red points are from Jan. The time lapse pole and ladder are present in the third image and the weather station is

present in the lower image. Note the two terrace levels present in the lower 3 images for Jan. scan. Images are approximately 6m on Y-axis and 20-25 m on the X-axis.

action. The lower terrace may reflect the high-water erosion level of the Dec. 28 storm which reached 1.63 m based on the tide gauge record (Fig. 16). In addition to the water level being recorded with the tide gauge at Skinner's Cove, which sampled every 30 minutes and does not account for waves, the wrack line of debris was surveyed with RTK GPS after the Dec 21 storm. The flood limit determined from the tide gauge and an airborne lidar DEM were compared to the wrack line GPS locations (Fig. 26). The tide gauge water-level was 2.21 and the wrack line GPS elevation was 2.38 (Fig. 26). The measurements are within 20 cm in the vertical of one another and are in close agreement on the map. This storm caused sever damage throughout all the Maritime Provinces whose coastlines faced north in the Gulf of St. Lawrence.

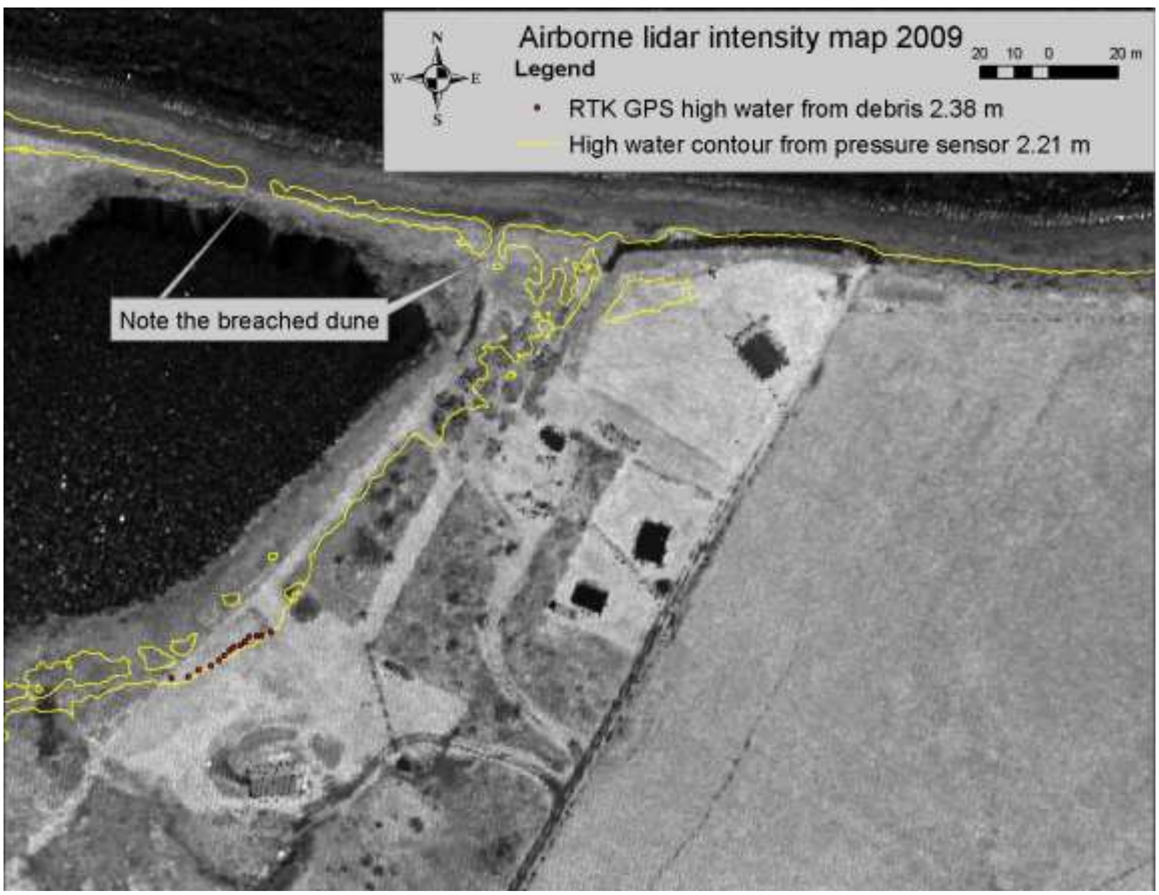

Figure 26 Airborne lidar intensity image with the flood limit (yellow line) as defined by the tide gauge water level measurement (2.21 m) and the wrack line location (red dots) (2.38 m).

4.2 Mavillette Beach

The Bay of Fundy – Gulf of Maine study site is located at Mavillette Beach area and was scanned on Oct. 20-21, 2010. This site was part of the Geological Survey of Canada (GSC) coastal monitoring network (Fig. 27). Unfortunately, funding for this activity has been reduced and the site is no longer monitored. Four sections of the coast were scanned with the AGRG ILRIS system (Fig. 28).

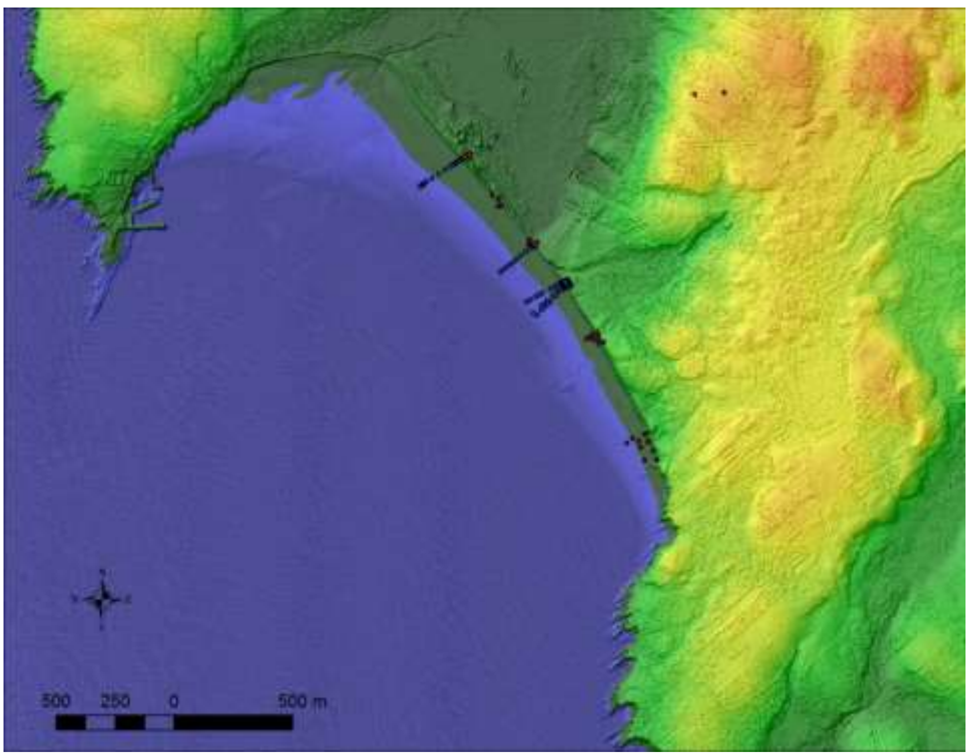

Figure 27 GSC monitoring sites (blue dots) and georeferencing targets (red dots) for AGRG coastline laser scans.

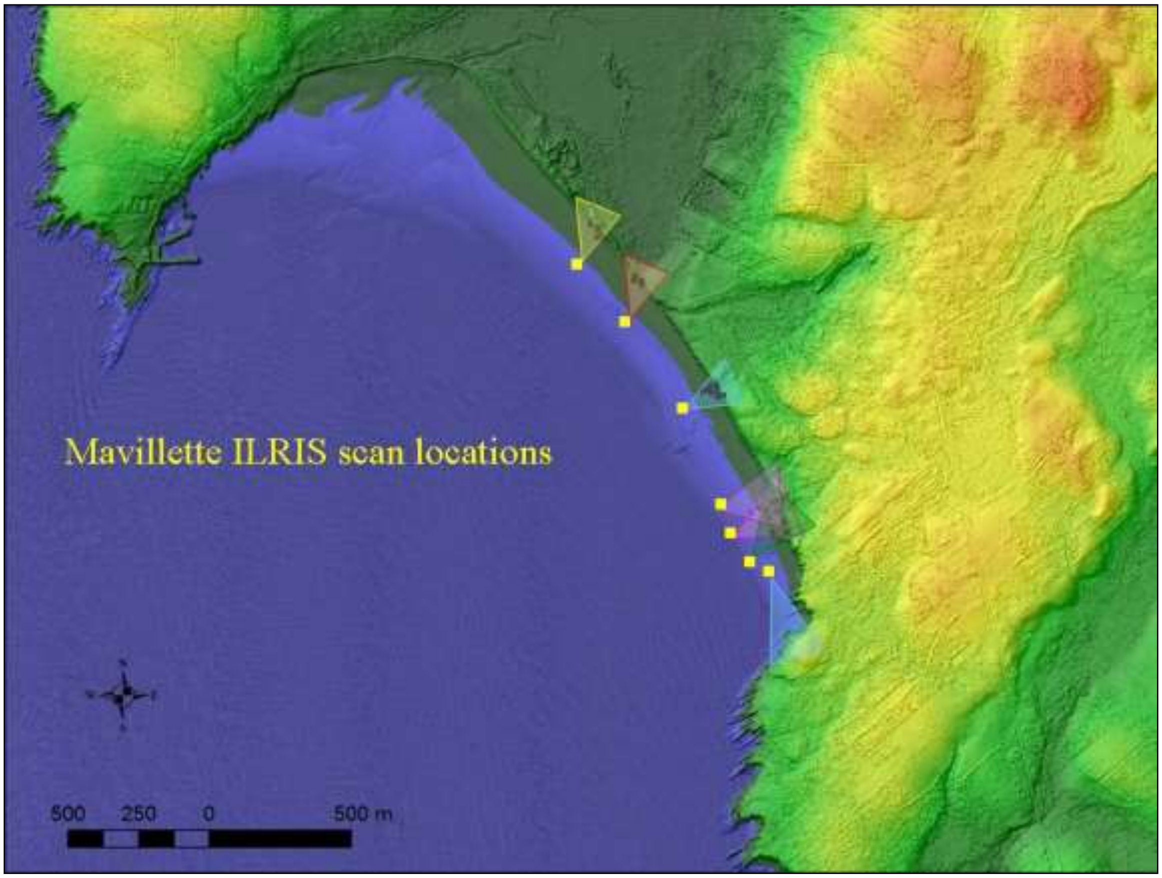

Figure 28 Mavillette beach 2010 laser scan locations.

The tidal height variation at Mavillette is significant and with low tide, the ILRIS can be placed at a larger distance orthogonal to the coastline, thus minimizing shadows cause by gullies, for the scan setups (Fig. 29). When the tide is high, there is very little room to setup the instrument above the water line and would require scanning at an oblique angle to the coastline as has been done in the previous survey areas.

Figure 29 Tidal water level variations at Mavillette beach. The top photo is looking southeast from the beach entrance at high tide. The lower photo is looking northwest towards to beach entrance at low tide.

This site consists of geomorphic units; 1) a large sand dune, 2) glacial till bank, and 3) a bedrock cliff. The sand dune scan is represented in Figure 30.

Figure 30 Laser scan of the sand dune system at Mavillette

The glacial till is very different in composition compared to that occurring at Cape John. The Cape John till is very clay rich and red in colour. The Mavillette till is grey in colour and has less clay content (Fig. 31). The till appears to have a significant amount of calcium carbonate cement and is very hard when dry and consists of more clasts than the fine grained matrix. The glacial till scans are represented in Figure 32. Similar to Cape John, grass sod occurs on top of the till bank and in some areas has slumped and occurs on the bank slope (Fig. 31, 32). The slumped green sod on the bank (Fig. 31) appears bright on the lidar intensity point cloud (Fig. 32). The dipping layers within the conglomerate that underlies the glacial till sheets are apparent on the photo and laser scan (Figs. 31, 32).

Figure 30 Photo of ILRIS setup for scanning the glacial till bank. Scan represented in Fig. 32 of this area.

The land cover on top of the glacial till section transitions of a cleared grass field to shrubs and eventually to forested land as one moves southeast along the coast. The land cover on top of the cliff is visible on the scan which captures the transition from a glacial till bank to bedrock (Fig. 33).

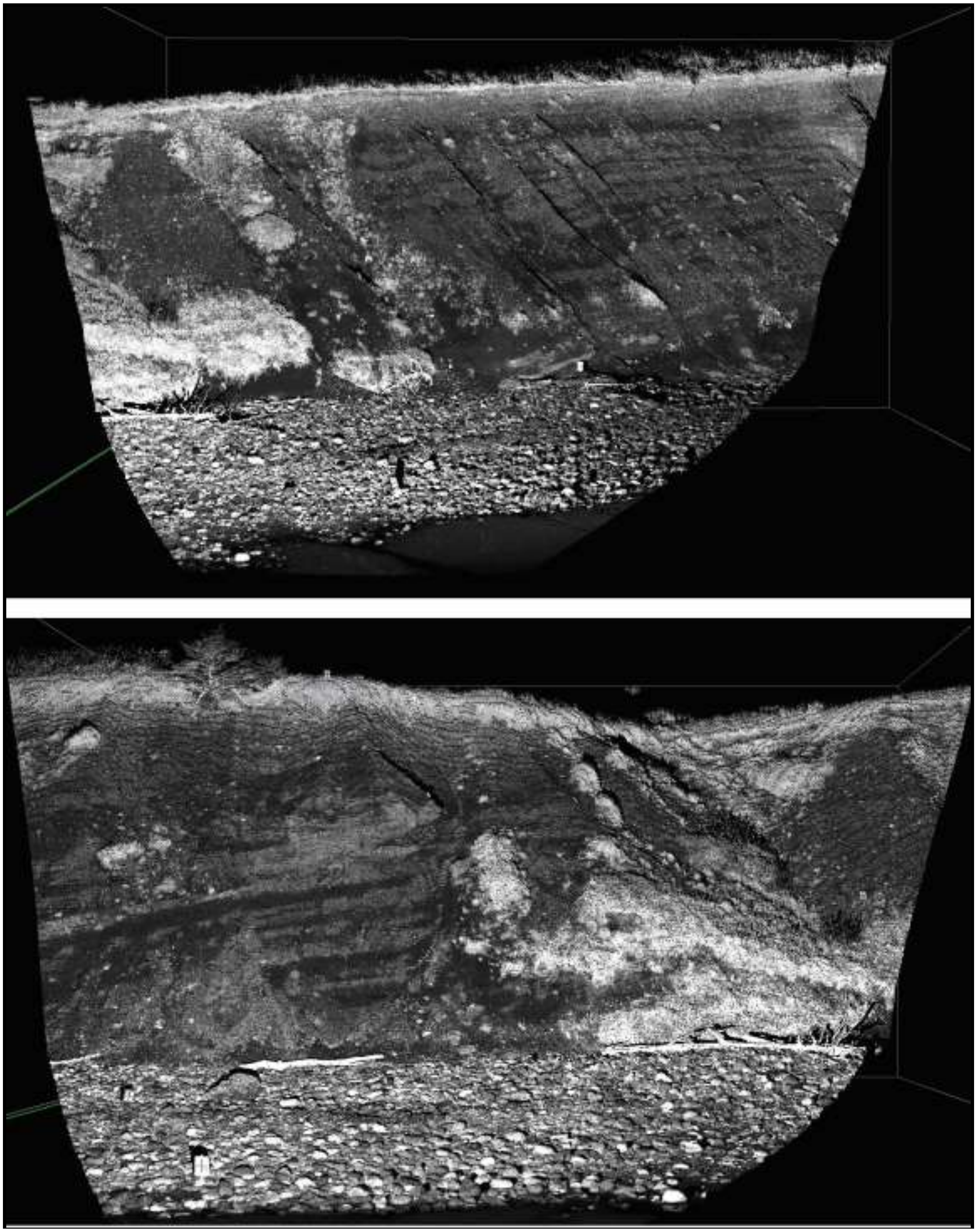

Figure 31 Laser scans of the glacial till bank at Mavillette Beach. The drift wood log on the left of the top image is visible on the lower image on the right. The light toned areas consist of grass vegetation. Darker bands in the bank are a result of different materials and moisture content. The driftwood tree at the base of the bank is visible in both scans.

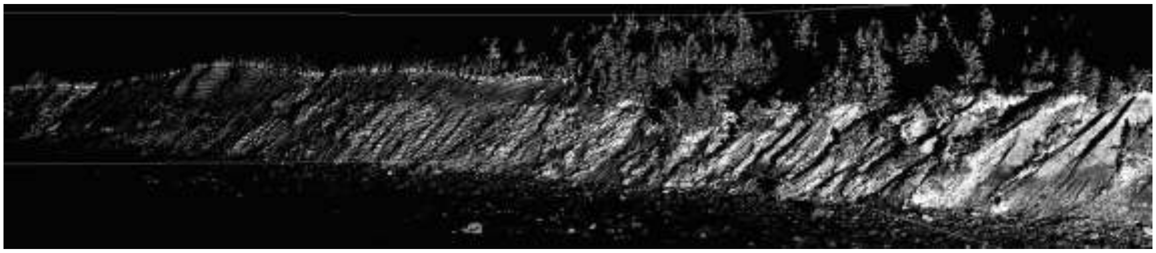

Figure 32 Transition of glacial till bank top cover type. Cleared grass field in the north (left in scan) and forest covered in the south (right in scan) of the section.

The glacial till cover transitions into the bedrock cliff morphology as one moves southeast along the embayment. The bedrock sections consist of areas where the till veneer holding the tree cover has slumped and is partially covering the bank. The high tide line covers much of the outcrop and the metasedimentary rocks are slate which is quite dark (Fig. 34). The low reflectivity of the bedrock result in dark intensities of the lidar returns (Fig. 35 top image).

Figure 33 Photo of slumped trees in the glacial till and exposed bedrock at the foot of the bank. The bedrock is very dark as a result of the composition of the slate and tidal inundation.

As one moves farther southeast along the embayment, a promontory is formed by the bedrock cliff of the coastline. The bedrock cliffs are exposed along this section of the coast and consist of deformed metasedimentary rocks of the Meguma Group (Fig. 35 lower image). Glacial till sits on the bedrock cliff and the bank forms a shallower slope (Fig. 36). The boundary between the bedrock and glacial till shows up as a bright strip in the intensity scans (Fig. 35 lower image).

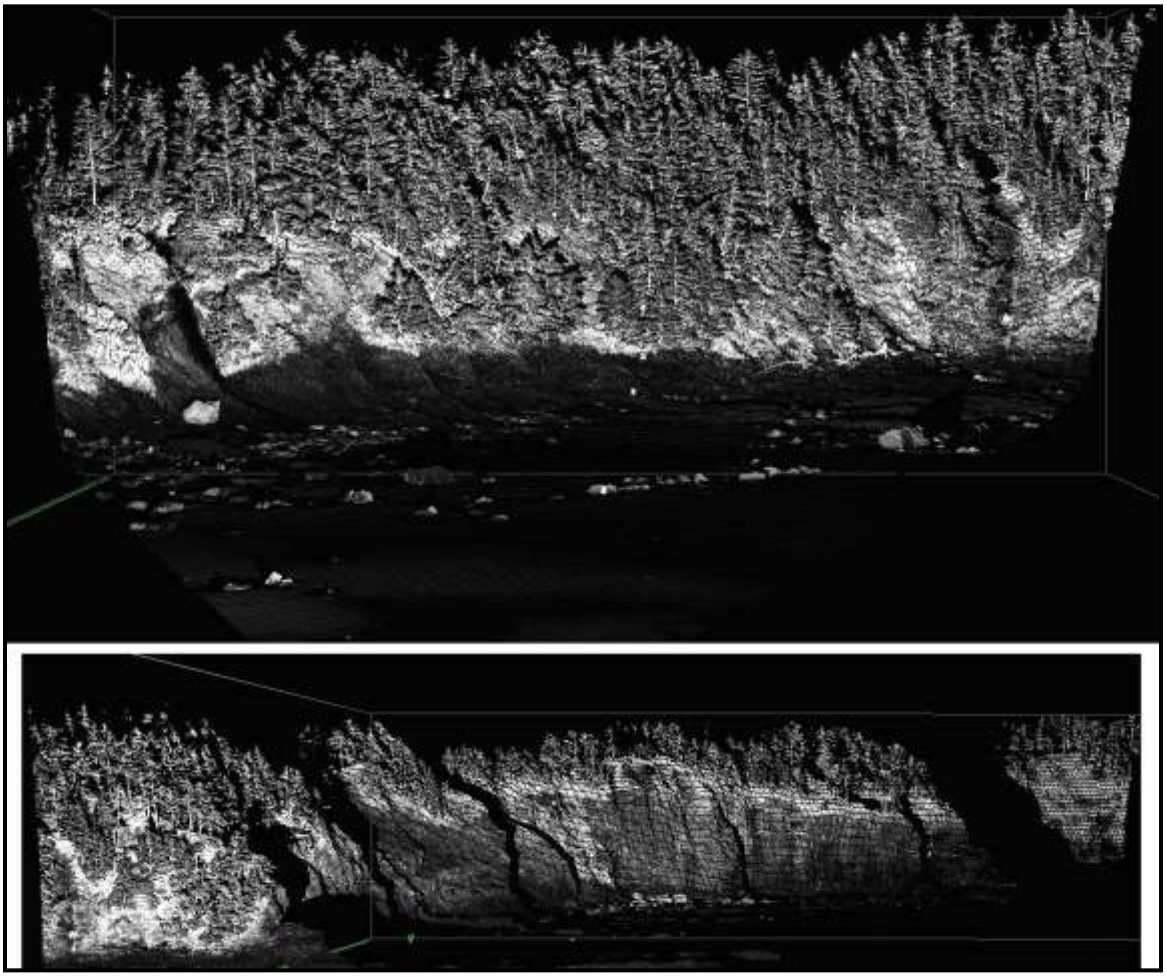

Figure 34 Laser scans of the bedrock section at Mavillette. The top image is a scan consisting of tree cover that has slumped over the bank and the dark area at the base on the bank is the exposed dark bedrock. The lower image is a scan consisting of an exposed bedrock cliff.

The bedrock forms a steep cliff coastline with the glacial till forming a shallower sloped bank above the bedrock. The rocks in the areas are highly deformed and metamorphosed, thus making them very resistant to erosion.

Figure 35 Photo of the bedrock cliff that forms a promontory. The glacial till sits on top of the bedrock and forms a shallower sloped bank than the bedrock cliff. The rocks are highly deformed and resistant to erosion.

Table 3 Dates of laser scanning for the Mavillette study area.

Date Acquisition	**Number of Scan**
October 20, 2010	3
October 21, 2010	8
July 28, 2011	20

The area was re-surveyed on July 28, 2011 at low tide. The dune, glacial till bank and bedrock cliff features were all scanned during this day. There were several people on the beach at this time of year which made acquiring scans more challenging. The scans were geocoded and cross-sections were generated between the point clouds acquired in 2010 and 2011. Three cross-sections are presented: one for the dune system, one for the glacial till bank, and one for the bedrock area (Fig. 36). Grids were also constructed from the two datasets and compared.

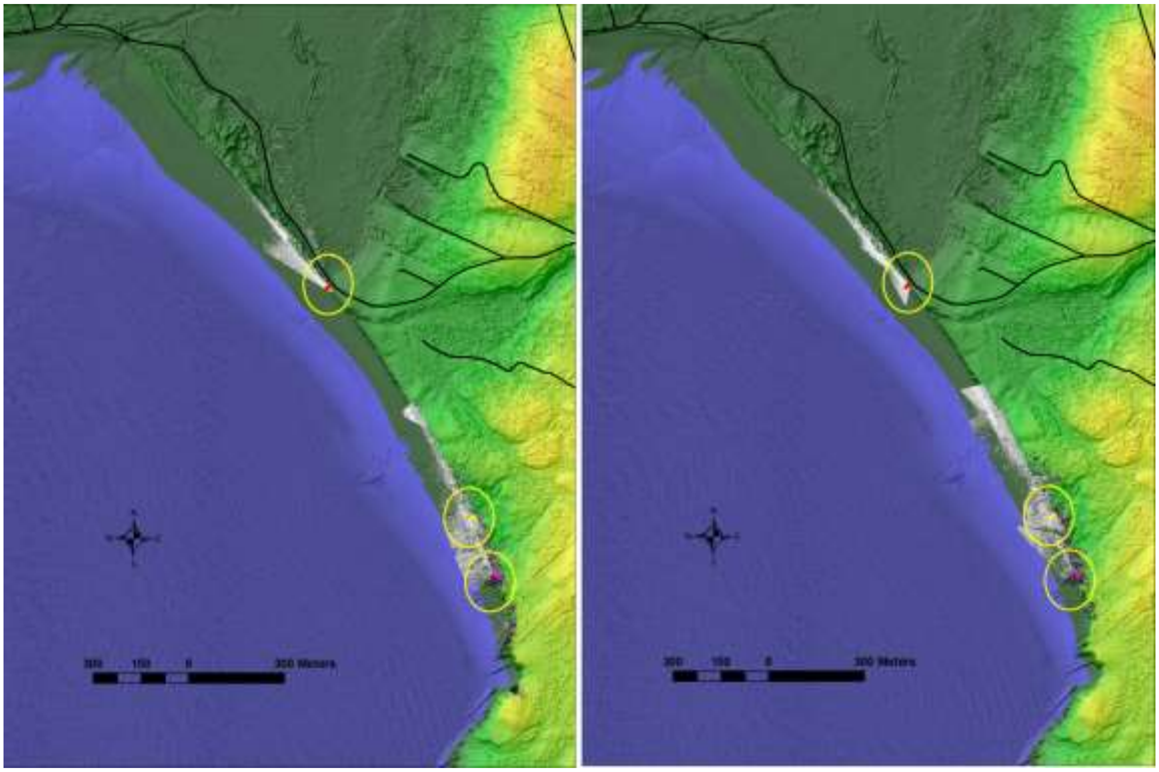

Figure 36 Airborne lidar colour shaded relief map of Mavillette with 2010 scans (left grey scale) and 2011 scans (right grey scale). Cross-section for the dune is at the north (red line with yellow ellsipse), glacial till area (central yellow line with yellow ellipse), and becrok in the south (purple line with yellow ellipse).

The comparison of the point clouds for the dune area indicates that the beach has lowered between 2010 (red profile Fig. 37) and 2011 (green profile Fig. 37). The amount of change is not that significant considering the low relief of the coast in this area.

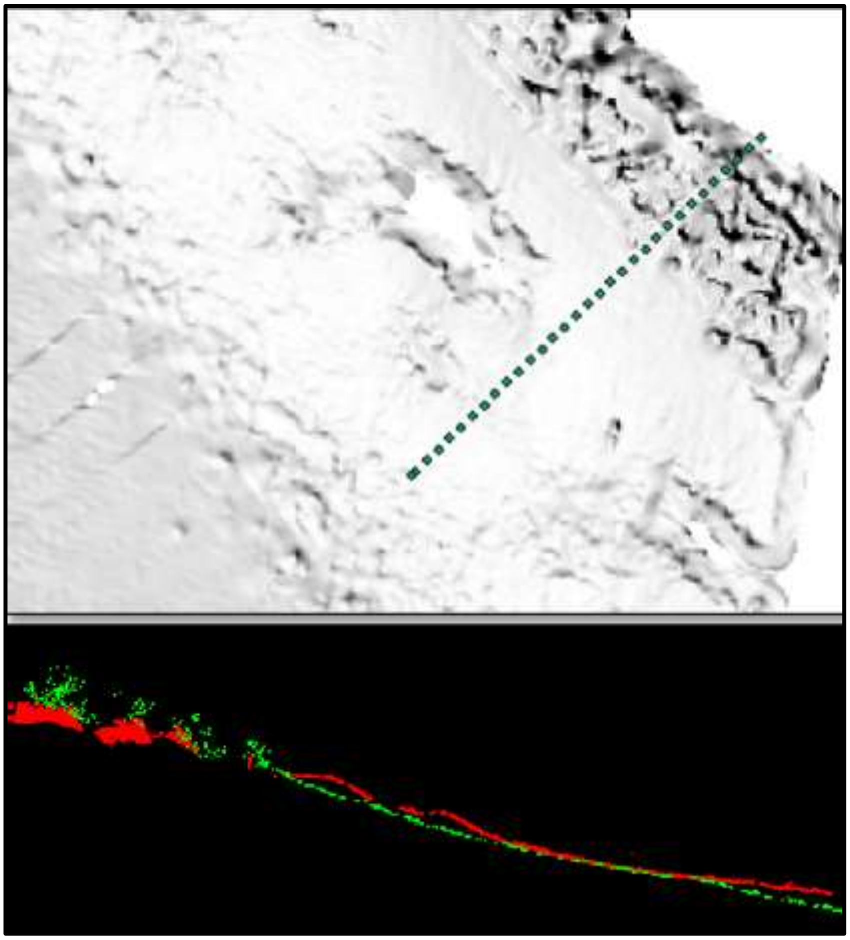

Figure 37 Gentle slope and vegetation of the dune at Mavillette. Top image is the shaded relief DEM and the lower image is a cross-section of the point cloud from 2010 (red) and 2011 (green).

The comparison of the point clouds for the glacial till area indicates that the lower section of the bank has lost material between 2010 (red profile Fig. 38) and 2011 (green profile Fig. 38). It appears that the scans may have a slight offset in their georeferencing in this area based on the apparent offset of the overhang at the top of the bank, therefore adding more uncertainty to the actual real change between 2010 and 2011.

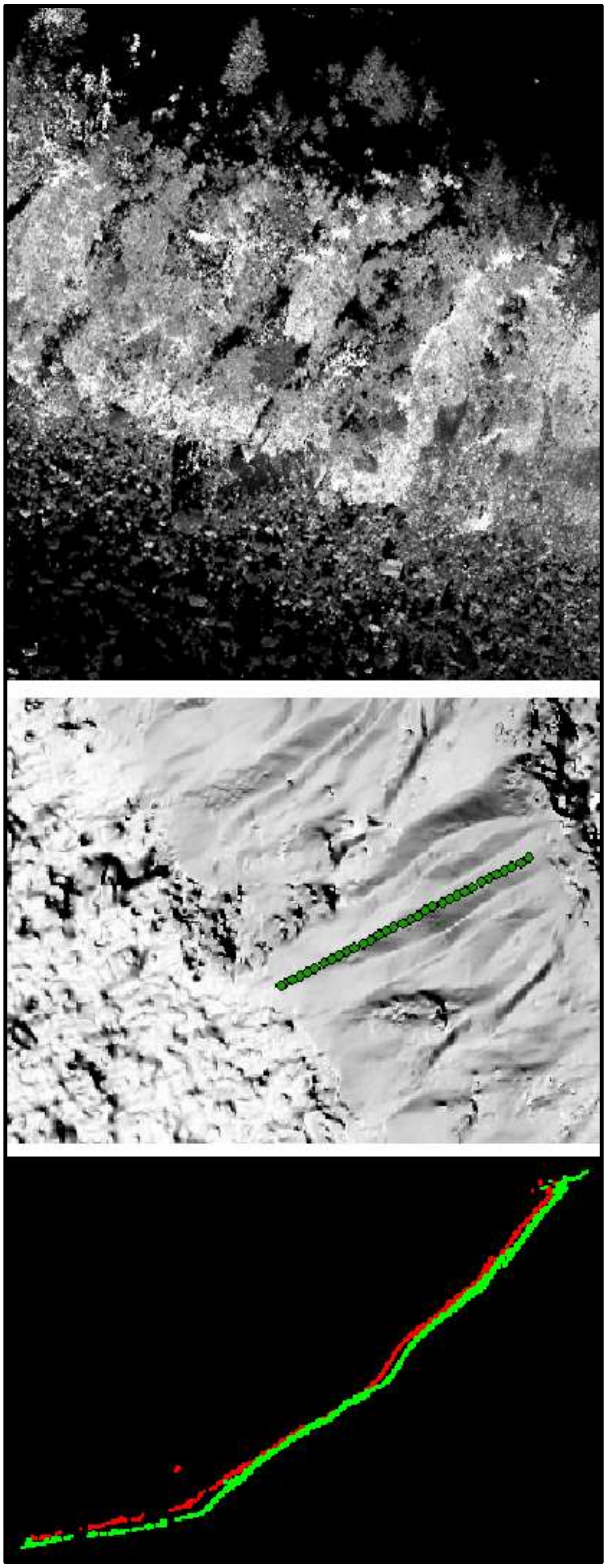

Figure 38 Glacial till bank at Mavillette. Top image is the point cloud intensity image, middle image is the shaded relief DEM, and bottom is a cross-section of the point cloud in 2010 (red) and 2011 (green).

The comparison of the point clouds for the bedrock headland area indicates no change between 2010 (red profile Fig. 39) and 2011 (green profile Fig. 39).

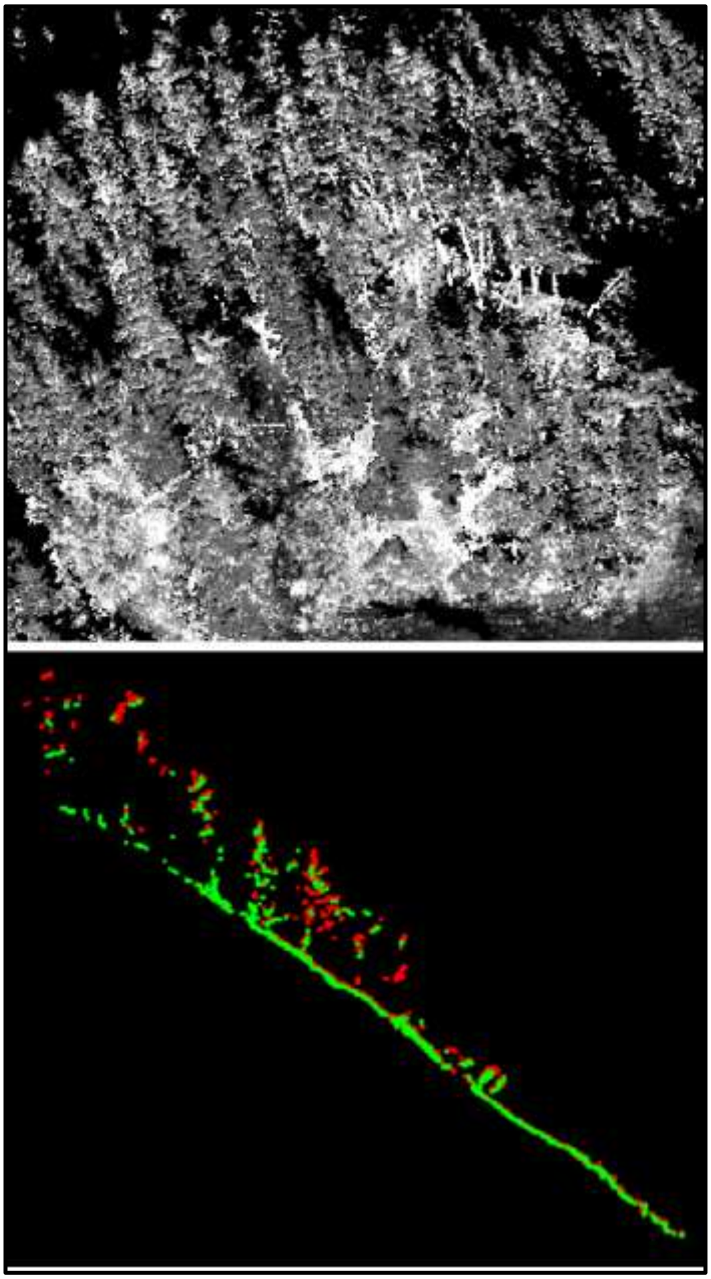

Figure 39 Steep tree covered bank with glacial till on the slope and a bedrock the base. Top image is the point cloud intensity image, bottom is a cross-section of the point cloud in 2010 (red) and 2011 (green).

The closest tide gauge to Mavillette on the same coast is at Yarmouth. The Department of Fisheries and Oceans has the tide gauge water levels on line and have compared the observed levels to predicted levels to calculate residual, which would represent storm surge events (Fig. 40) (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/sl-pm/index-eng.asp). Although there were some storm surges in late 2010 and early 2011 (Nov. 2010-Jan. 2011), so significant winter storms appear to have impacted this section of coast.

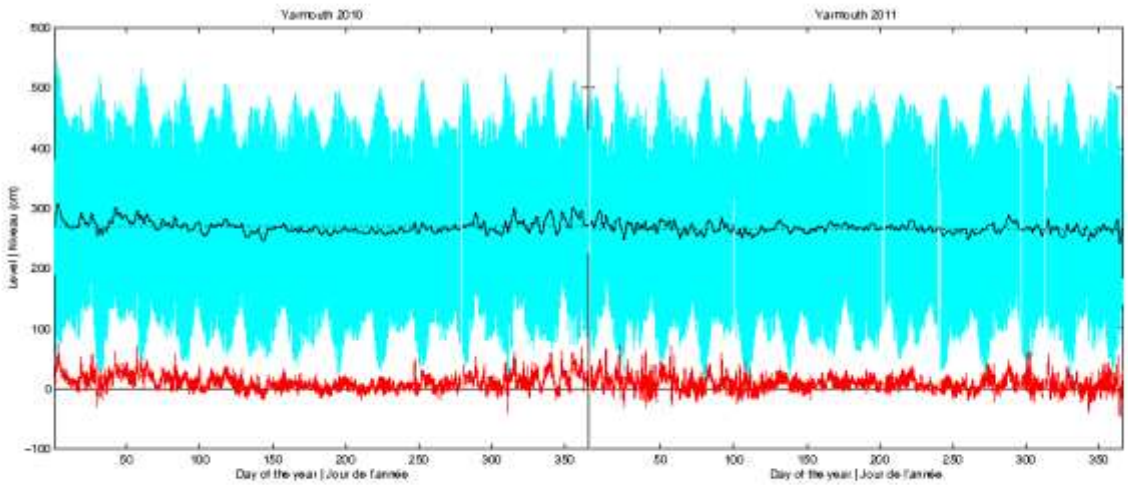

Figure 40 Tide gauge water level record from Yarmouth (2010-2011). Blue line is water level (cm) above chart datum, red line is the residual (e.g. storm surge), black line 4 day average. The X-axis are Julian days of the year (1-365). Source DFO.

4.3 Hirtles Beach, Kingsburg

The Atlantic Ocean study site is located at Hirtles Beach at Kingsburg. The geomorphic features at this site consist of a large eroding drumlin that dominates the coastline. There is a gravel dune system that protects ponds located landward of them, directly west of the drumlin. A low bedrock cliff is present east of the drumlin and forms the point of the embayment. The glacial till of the drumlin is a combination of the Lawrencetown till, similar to that at Cape John, although it has more clastic material, and a grey till that appears to have a significant amount of calcium cement making the till very hard when dry. The large eroding drumlin is another GSC coastal monitoring site that is no longer systematically measured (Fig. 41). This site has also been mapped by researchers at AGRG and GeoNet Technologies as part of a Coast Decision Support System AIF project.

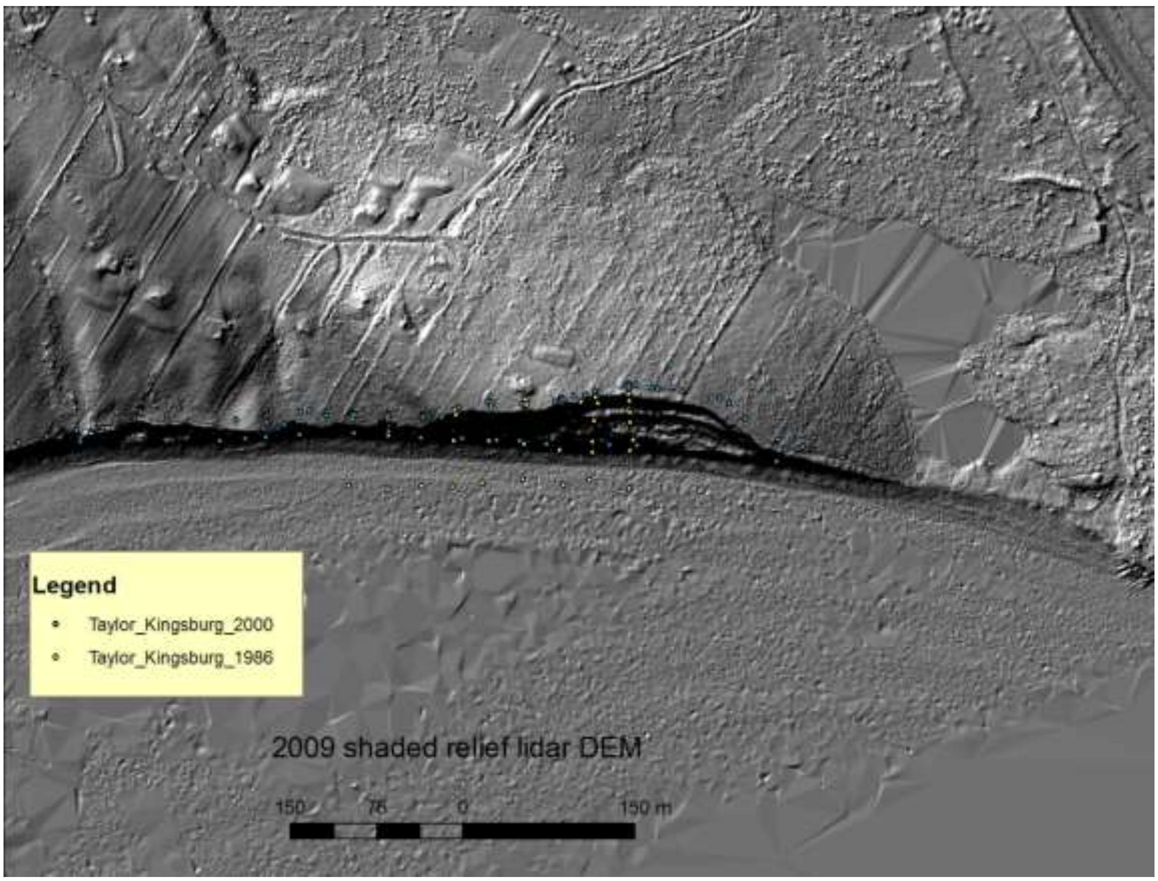

Figure 41 Shaded relief airborne lidar DEM with GSC measurements (1986 and 2000) from the coastal monitoring network.

As part of the AIF project, several historic airphotos were orthorectified and the coastline interpreted and digitized in order to analyze erosion rates. The orthophotos and interpreted coastlines go back to 1931, 1945, 1955, 1972, 1986 and 2001 (Fig. 42). As is typical with this type of approach the measurements have a decadal temporal scale.

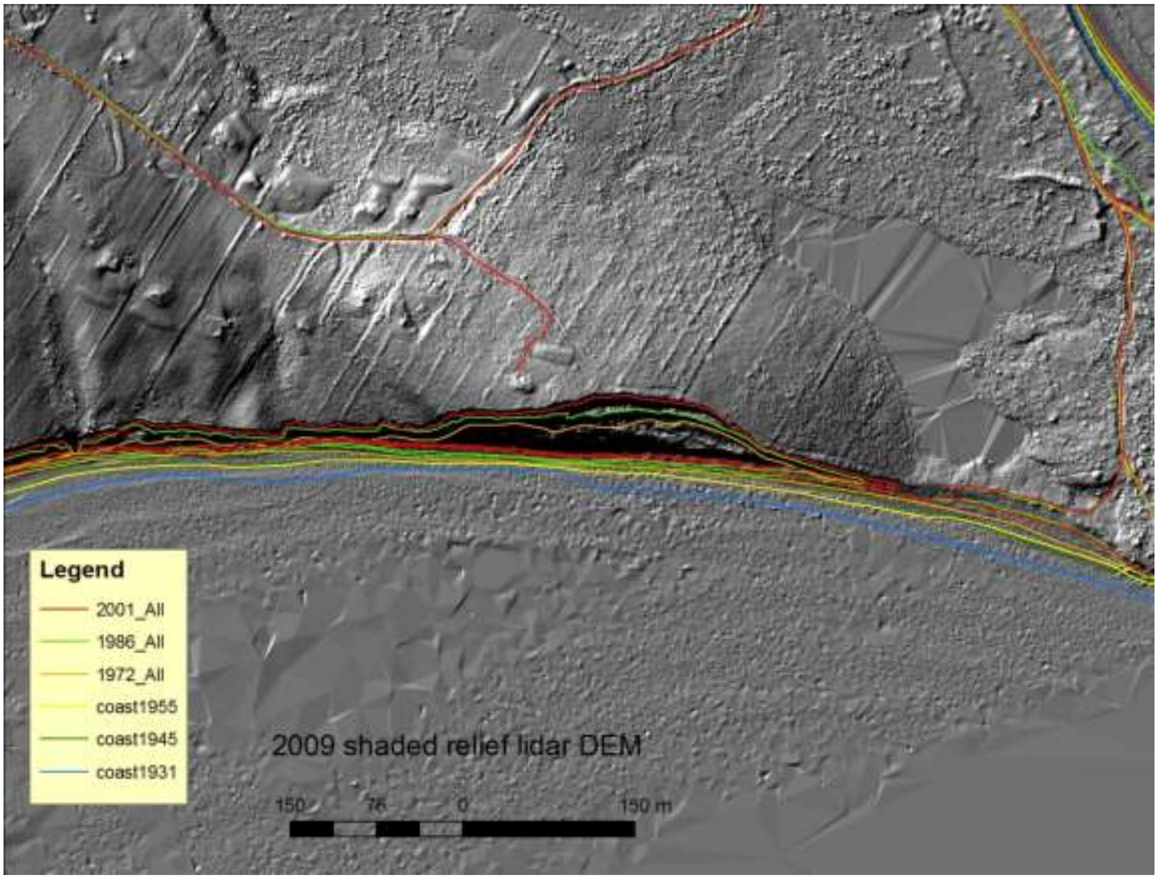

Figure 42 Hirtles beach historical coastlines from orthophotos. Coastlines are plotted over a shaded relief airborne lidar DEM from 2009. Data courtesy of GeoNet Technologies Inc.

The drumlin face is exposed to the open ocean and is actively eroding. The current relief of the coastline is terraced as different sections of the bank have failed and slumped to form the terraces. The bank consists of exposed glacial till on the steep slopes and grass and shrub cover on the terraced sections with shallow slopes (Fig. 43). The historic airphotos indicate the area was used for grazing by animals until the 1990s. Today, there are several houses in the area including a house on top of the drumlin. The exposed drumlin face is very large, ca. 150-200 m in length, making it challenging to scan from the beach with the limited exposed intertidal zone. As a result, the area was scanned in opposite directions and at oblique angles to minimize the shadows (Fig. 44). In order to acquire the large exposure of the eroding drumlin, a broad scan was acquired at a long distance (Fig. 44).

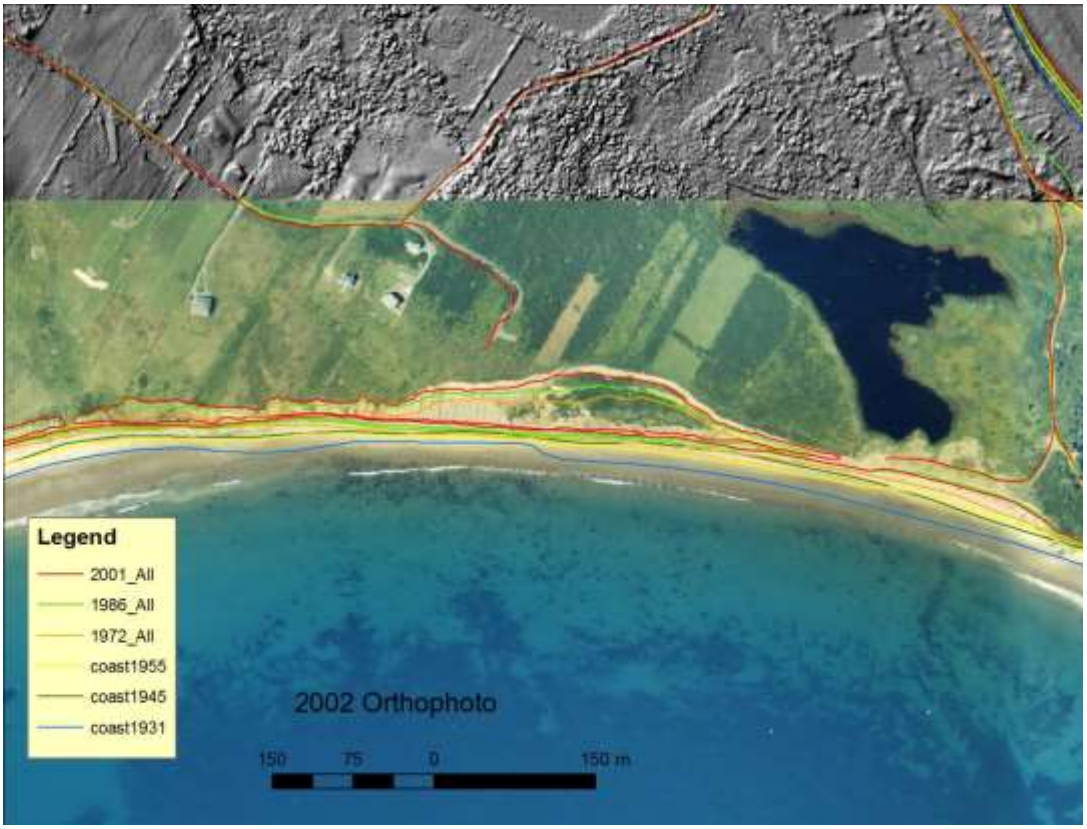

Figure 43 2002 orthophoto with historic coastlines along the eroding drumlin face at Hirtles Beach.

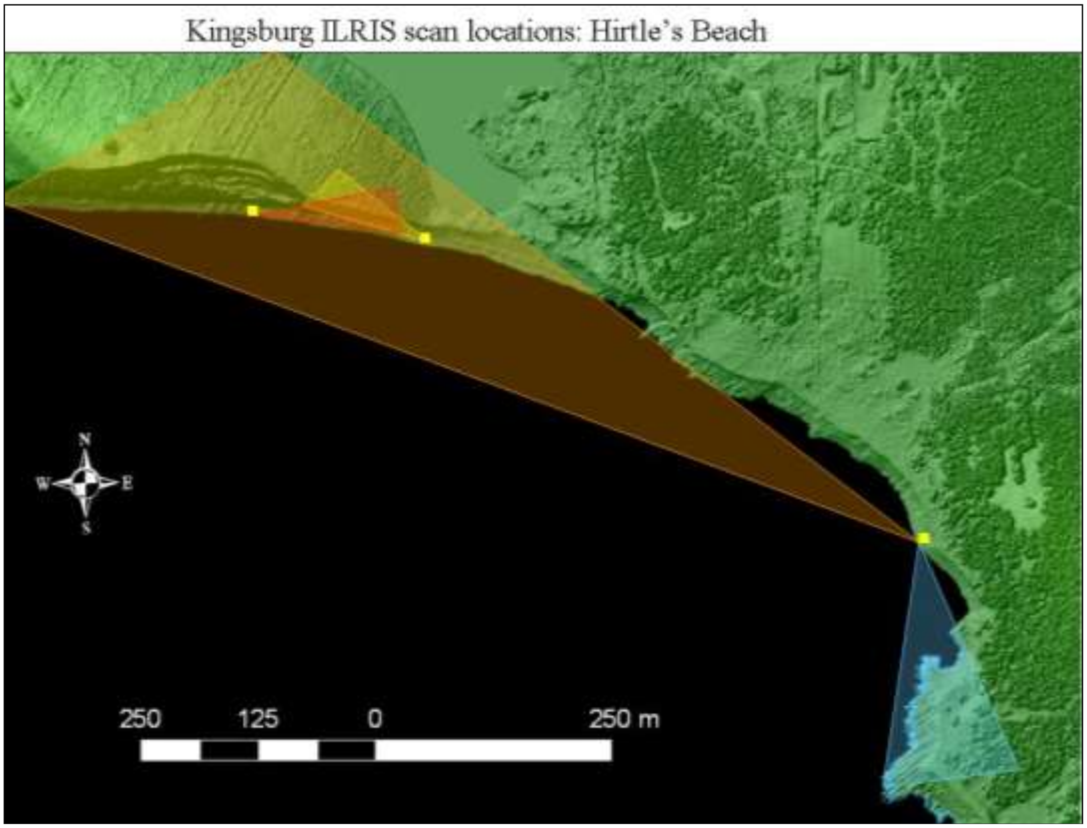

Figure 44 Kingsburg laser scan locations over a colour shade relief airborne lidar DEM.

Scans of the eroding drumlin east of the major slumping area were completed and from opposite angle to compensate for shadows (Figs. 45-46).

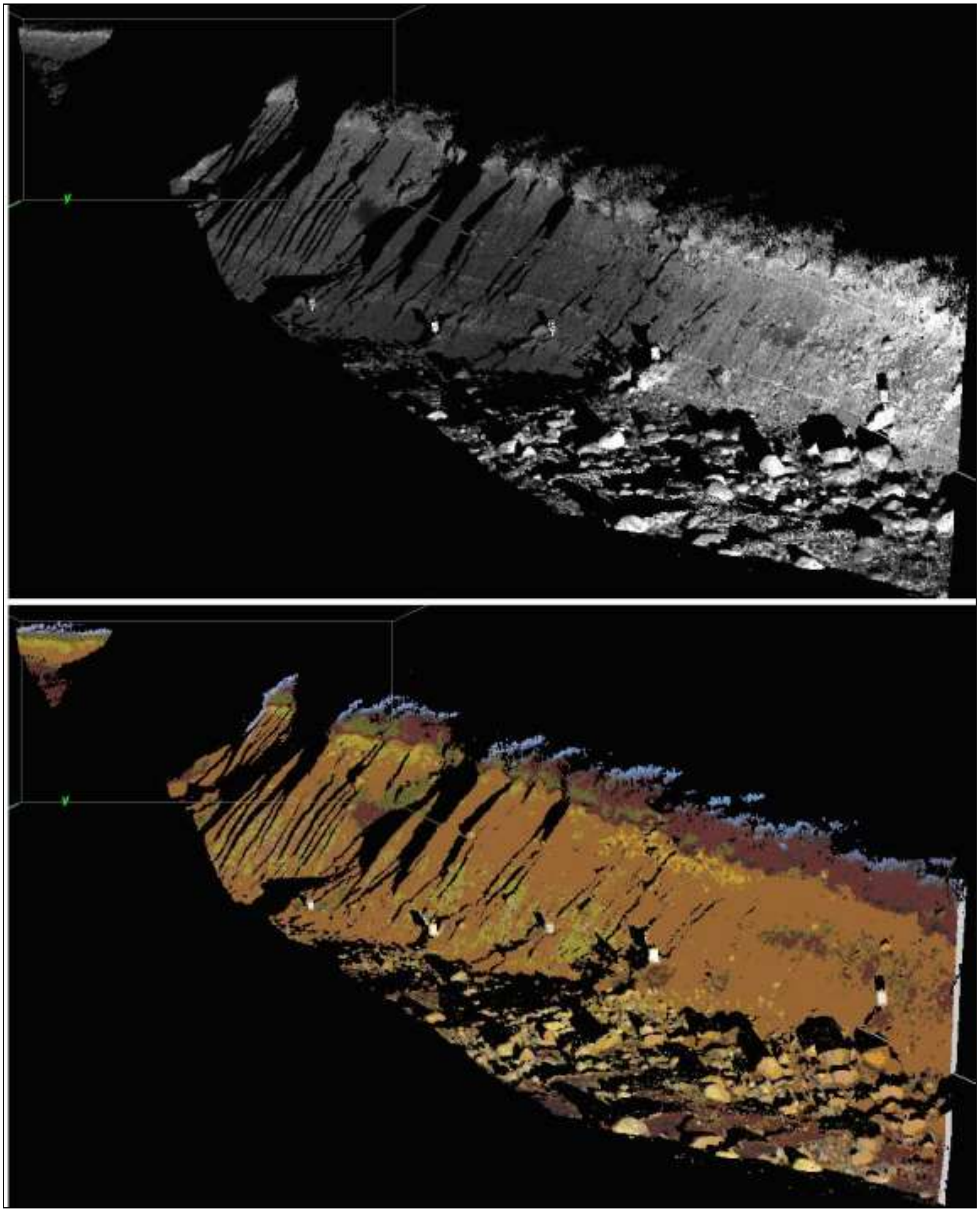

Figure 45 Laser scan of the glacial till bank at Kingsburg, Hirtles Beach. Top image is lidar intensity and the lower image is the RGB point cloud. Scan is towards the west, the white rectangles are georeferencing targets.

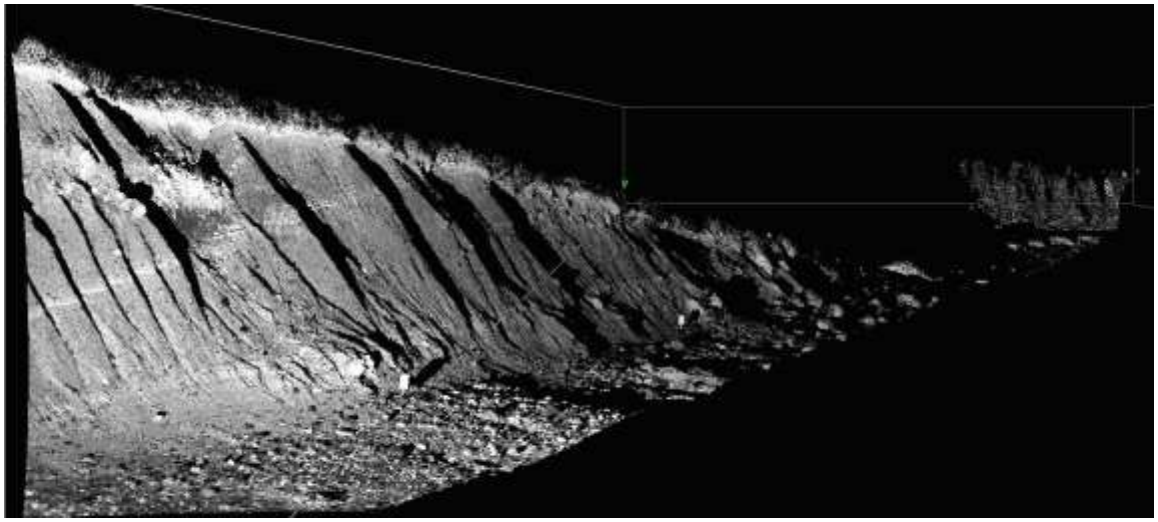

Figure 46 Glacial till bank at Hirtles beach, lidar intensity looking east.

The glacial till is comprised of different materials. There are actually two layers of till present in the exposed costal section of the drumlin (Fig. 47).

Figure 47 Photo of glacial till adjacent to the eroding drumlin at Hirtles Beach. Notice the layers within the till (grey to dark brown).

The low relief bedrock platform was also scanned (Fig. 48). The relief here is very small, only 2-3 m in elevation and has low reflectivity (lidar intensity). The bedrock consists of

Meguma Group metasedimentary rocks which are very dark in colour as a result of its composition and tidal inundation, thus do not reflect the laser pulses with much intensity (Fig. 48).

Figure 48 Low relief bedrock point laser scan at Kingsburg.

Table 4 Dates of laser scanning for the Kingsburg study area.

Date Acquisition	Number of Scan
October 13, 2010	5
July 13, 2011	8
July 14, 2011	6

The area was re-scanned on July 13 and 14th in 2011. Additional coverage of the large rotational lumping section of the drumlin was targeted during these surveys. The weather at this site is very challenging for laser scanning. Several attempts were made in 2010 to acquire scans with only one successful day on Oct. 13, 2010 (Fig. 49). As a result the gravel dune-bar system was not surveyed in 2010. Similarly, in 2011 several attempts were made and although scans were acquired on July 13 and 14, there were periods of showers that affected the scans (Fig. 49).

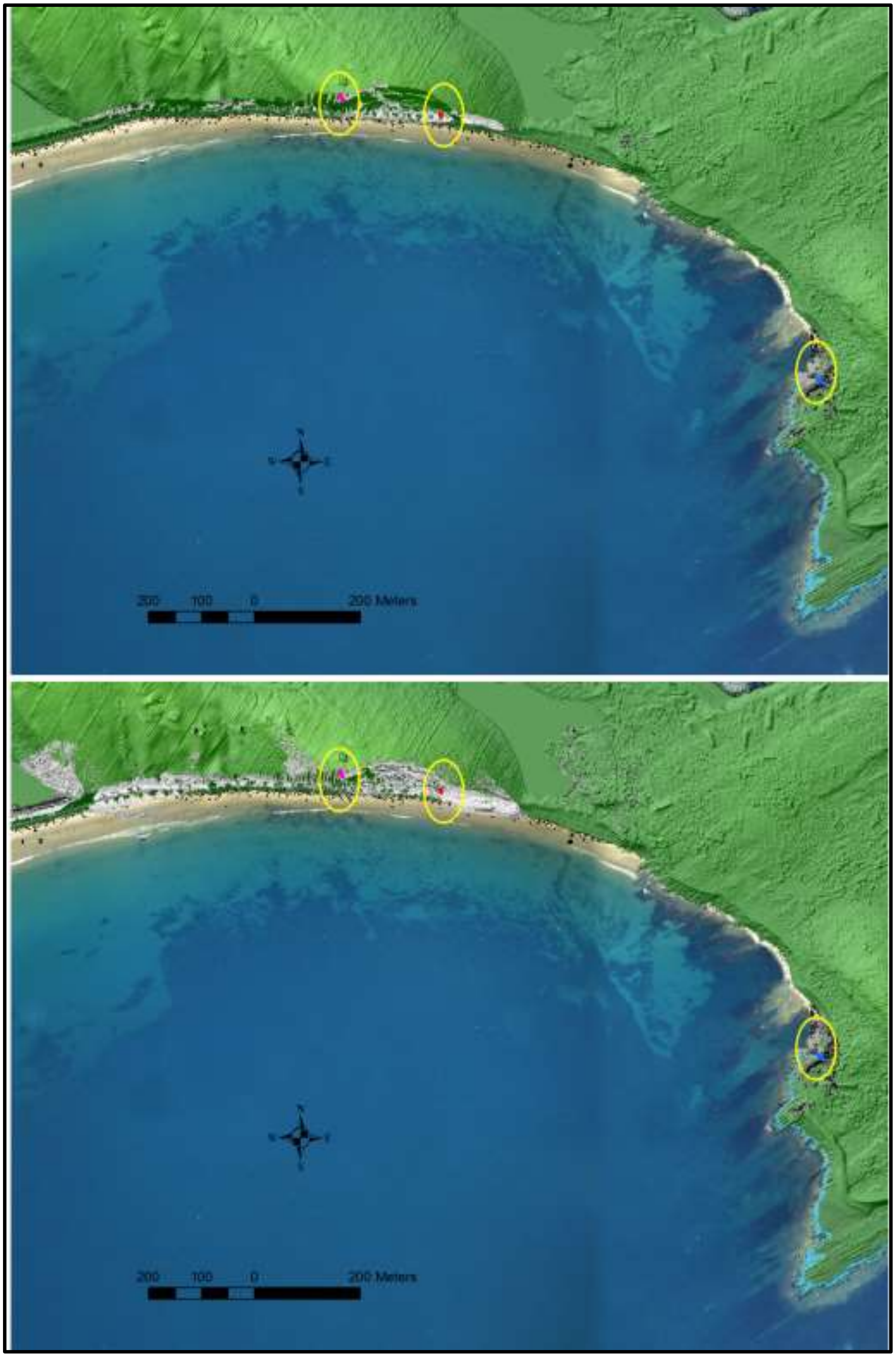

Figure 49 Airborne lidar colour shaded relief map of the land and a 2002 airphoto for the offshore area with 2010 scans (grey scale) and cross-section locations for comparison between 2010 and 2011 (grey scale lower map) locations highlighted with yellow ellipses.

The gravel dune-bar system was acquired in 2011 for the area in front of Hirtles Pond (west edge of the lower map grey scale scan Fig. 49). As mentioned a larger section of the eroding drumlin face was scanned on July 13 and 14th in 2011 (Fig. 50).

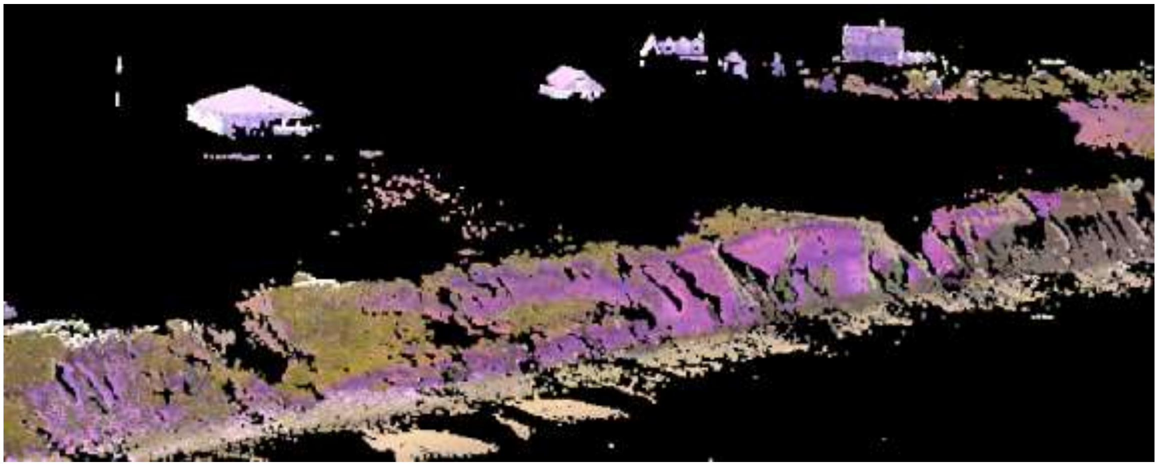

Figure 50 Hirtles Beach scans with ILRIS photo overlaid of the drumlin glacial till bank, and 2011. The ILRIS camera is of poor quality and limited exposure settings, thus giving the appearance of purple cliffs when in fact the glacial till is a grey colour.

Where the lidar point clouds acquired in 2010 overlapped with those acquired in 2011, cross-sections were extracted for comparison of the bank position. The first cross-section is for the upper section of the bank west of the large rotational lumping section of the drumlin (left most yellow ellipse, Fig. 49) (Fig. 51).

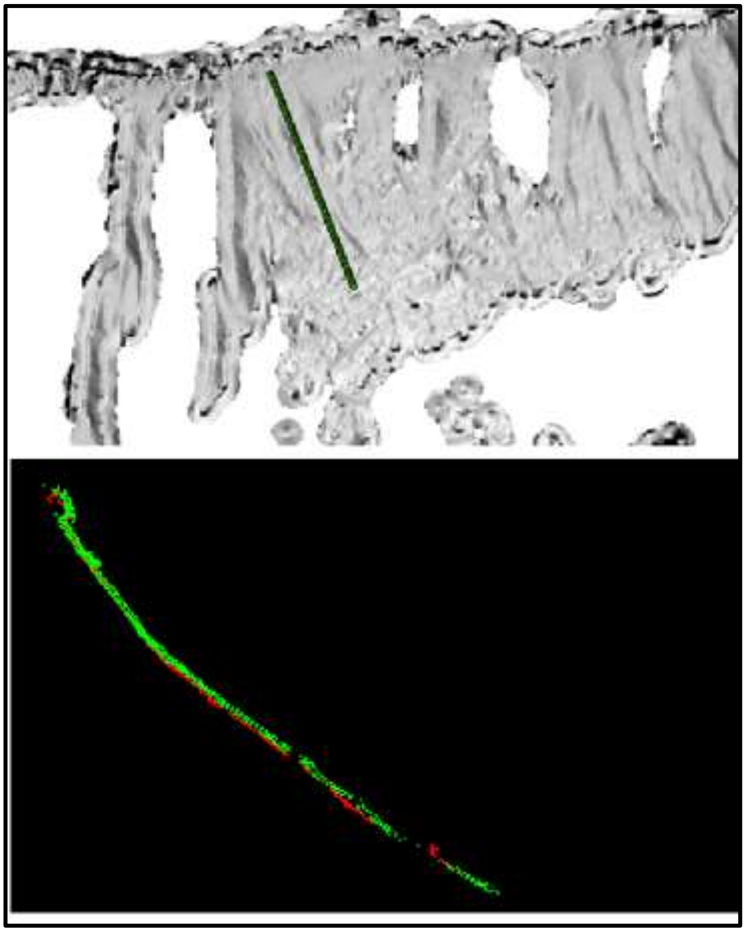

Figure 51 Hirtle's Beach upper section of the moderate sloping glacial till bank. The top image is a shaded relief DEM, lower image is a cross-section of the point cloud from 2010 (red) and 2011 (green).

Based on figure 51 it does not appear that there has been any significant change in the bank location between 2010 and 2011. The second cross-section is for the upper section of the bank east of the large rotational lumping section of the drumlin (central yellow ellipse Fig. 49) (Fig. 52).

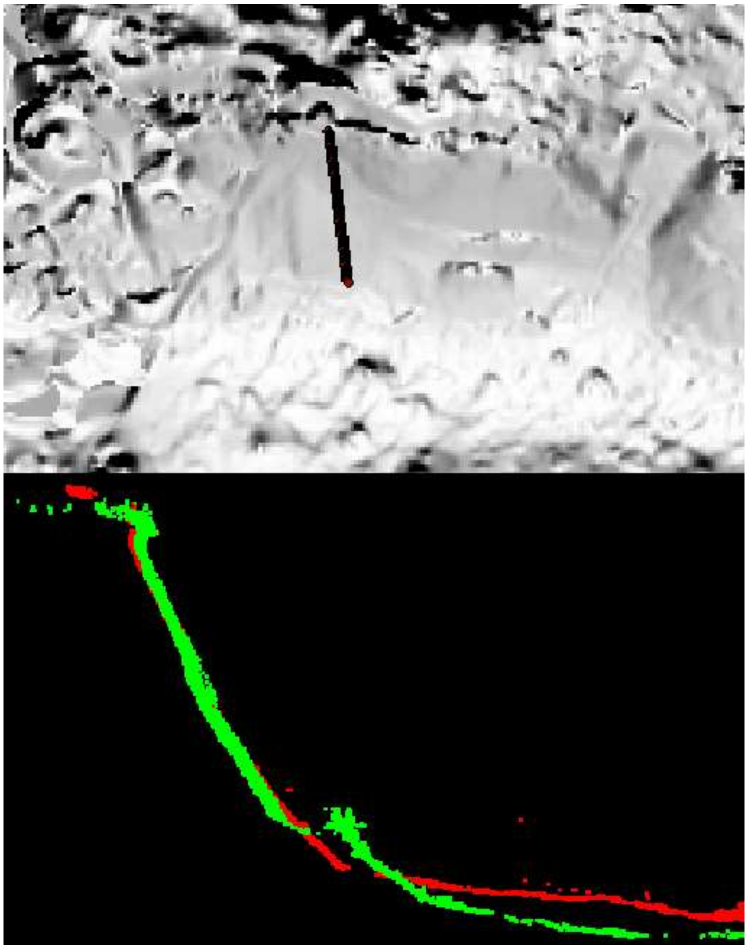

Figure 52 Hirtles Beach steep high relief face of the drumlin, top image is the shaded relief DEM, lower image is a cross-section of the lidar points clouds from 2010 (red) and 2011 (green).

Based on figure 52 it appears that there has been significant change in the bank location between 2010 and 2011. It appears that the bank has lowered from 2010 (red) to 2011 (green) as well a section of terrain with vegetation has been emplaced in 2011 that was not there in 2010 (Fig. 52). This is probably a section of the bank that has slumped into this position from above. The third cross-section is for the low relief bedrock headland (eastern yellow ellipse Fig. 49) (Fig. 53).

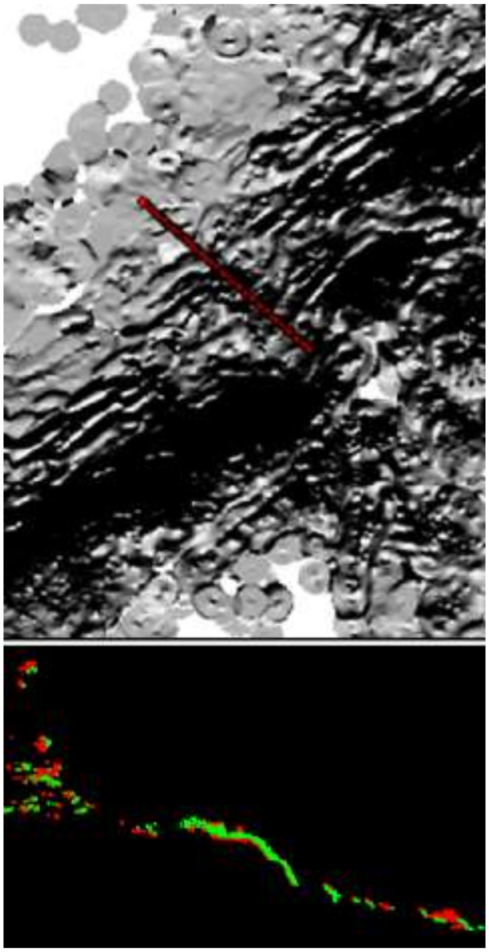

Figure 53 The top image is the 2011 shaded relief DEM map of the bedrock outcrop. Lower image is point cloud cross section of 2010 (red) and 2011 (green) lidar scans.

Based on the lidar point clouds there does not appear to be any significant change between 2010 and 2011 for this area (Fig. 52).

The closest tide gauge to Kingsburg on the same coast is at Halifax. The Department of Fisheries and Oceans has the tide gauge water levels on line and have compared the observed levels to predicted levels to calculate residual, which would represent storm surge events (Fig. 54) (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/sl-pm/index-eng.asp). Although there were some storm surges in late 2010 and early 2011 (Nov. 2010-Jan. 2011), so significant winter storms appear to have impacted this section of coast.

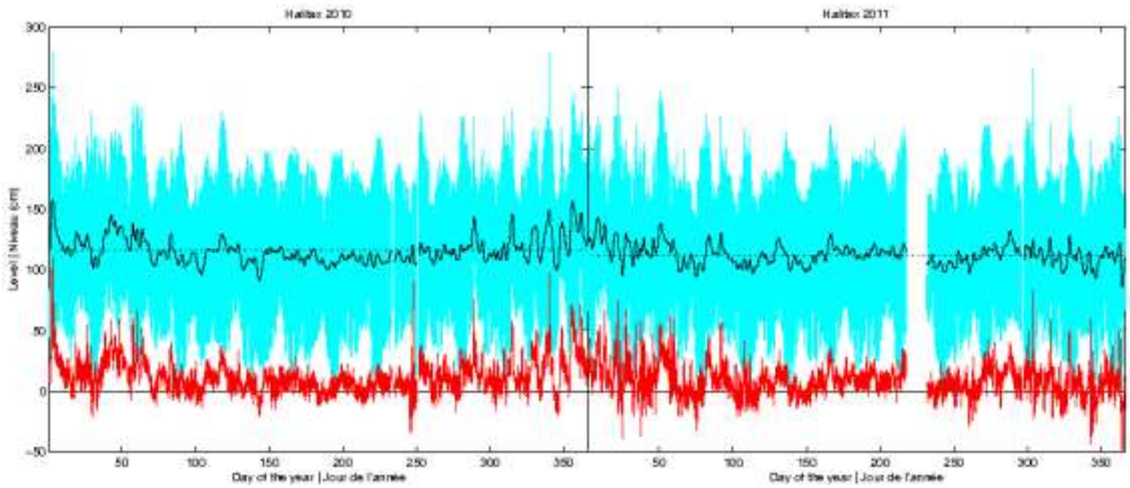

Figure 54 Tide gauge water level record from Yarmouth (2010-2011). Blue line is water level (cm) above chart datum, red line is the residual (e.g. storm surge), black line 4 day average. The X-axis are Julian days of the year (1-365). Source DFO

5. Conclusions and Recommendations

All three study sites on the Nova Scotia coast were successfully scanned in 2010 and 2011. All of the sites have been covered with airborne lidar. The Atlantic and Bay of Fundy sites are previous Geological Survey of Canada coastal monitoring sites. The Atlantic and Northumberland Strait sites have had previous coastline erosions studies completed based on historical orthophoto analysis.

In the case of Cape John, where multiple laser scans were conducted from June to December, a severe storm impacted the coastline in late December and it was scanned in Jan. 2011 to capture the immediate effects of the storm on the coastline. Based on the various data collected at Cape John; multiple laser scans, water level information, local weather station data collected every 15 minutes, and daily weather variables for the months of Oct. 2010 to Feb 2011, the storms and associated storm damage have been related. The storm history of the area was documented. The methodology of analyzing multi-lidar scan to measure the detailed change along the coastline was successfully developed. The methodology for surveying the coastline and measuring the detailed change was presented for Cape John. The other two sites have only had the initials scans completed but are scheduled for the spring scans in 2011. The weather information for the Northumberland Strait, Atlantic and Bay of Fundy sites has been processed and is presented in the appendices.

The results for Cape John indicate storms in Sept. and Nov. 2010 with water levels up to 1.4 m CGVD28 had the effect of eroding the foot of the till bank and reducing the depth of sand on the beach by 10-20 cm. The storm of Dec. 21 eroded the glacial bank to an elevation level of 4.5 – 5 m. The tide gauge water level measured 2.21 m CGVD28 while the elevation of the wrack line measured by RTK GPS was 2.38 m CGVD28. The differences are probably related to the effects of wave action (height and direction) of the storm surge to cause the flooding and erosion. The volume of material removed from the bank as a result of the Dec. 21 storm was 780m^3 along a 150 m section of the coast.

Additional laser scans were acquired for the other two sites in 2011. Based on the comparisons of the point clouds and surface models these other two sites did not experience significant erosion through the winter of 2010-2011. Although erosion at Mavillette was not as significant as at Cape John, the analysis did reveal some sites of erosion of the glacial till bank and changes in the beach slope near the dune system. Similarly, changes in the bank were also observed in the Kingsburg area along the eroding drumlin face. In all locations the bedrock coastlines did not change.

The results of this study have demonstrated how this approach can be used to relate changes in the coast (erosion) to specific storm events. This was clearly demonstrated for Cape John where the volume of material removed was attributed to the Dec. 21, 2010 storm and to a lesser degree the Dec. 28, 2010 storm surge. These results can be extrapolated and applied along the Northumberland Strait if we had adequate and reliable mapping of material comprising the coastline. Specifically if we had details of the material at the base of the bank ie. Glacial till, sand, or bedrock. If this information existed, one could determine coastlines that were exposed to the northeast wind and wave action and calculate the amount of material eroded along a large section of the province. This approach would be feasible if the composition of the glacial till was similar throughout the study area. As discussed earlier, the composition of the glacial till is different for three study sites along the three coasts of the province, thus local erosion rates should be calculated and applied to specific till types. Additional information to provide a synoptic view of coastal erosion can be obtained from the MERIS satellite platform that has spectral bands designed to map suspended material in the water. Scientists at DFO in the Bedford Institute of Oceanography have qualitatively demonstrated this in the Northumberland Strait near the Confederation Bridge. These types of regional information products could supplement the detailed analysis conducted in this study to more accurately scale the results up to the regional level.

Ideally funding would be available to maintain the annual scanning of these sites and the deployment of a coastal monitoring system at Mavillette and Kingsburg similar to what has been established at Cape John. This consists of a weather station, time lapse camera focused on the coastline and a water level sensor (tide gauge). As seen in this study the nearest weather station to Mavillette was Brier Island and the nearest tide gauge was at Yarmouth. In Kingsburg the nearest weather station was at Lunenburg and the nearest tide guage was at Halifax. As Hurricane Juan demonstrated, a storm system can have localized effects that are limited to 10s of kilometres of coastline, and thus having local monitoring of the atmospheric forcing conditions and local water level conditions allows one to better relate the storm intensity to the changes in the coastline. The time-lapse photography is especially useful since many of the worst storms that impact the coastline occur in the winter when it is often dangerous and not practical to visit the coast under such conditions. These detailed results could then be coupled with satellite observations of the region to highlight the degree of sediment in the coastal waters to assist in determining the spatial extent and patter of erosion for larger areas. With better coastline material mapping, the combination of information from this detailed quantitative study and the qualitative information from satellite observations could facilitate regional mapping and predictions of coastal erosion and vulnerability.

6. Acknowledgements

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Appendix A, Caribou Point monthly weather graphs Oct. 2010-July 2011

Daily weather data for Caribou Point, nearest location to Cape John and Meg's Cove, Oct. 2010 - July 2011.

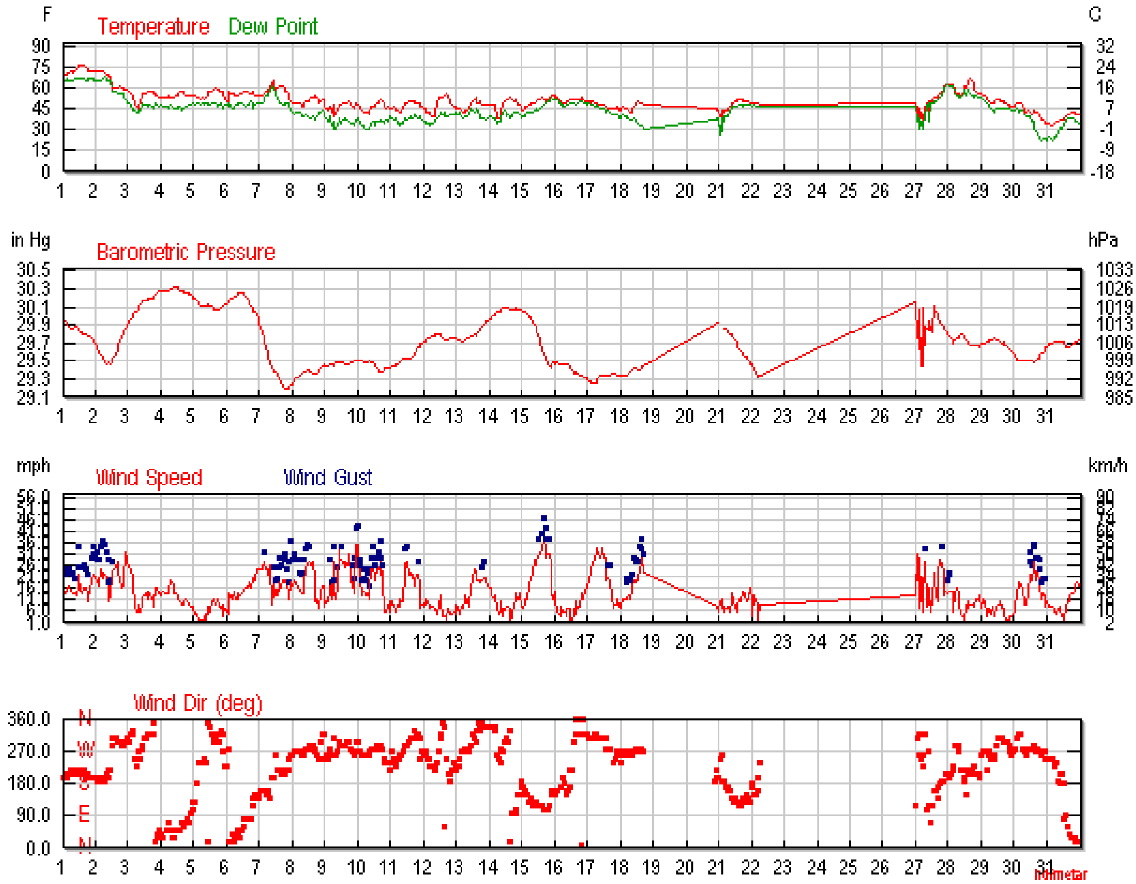

Figure 55 Oct 2010 weather for Caribou Point.

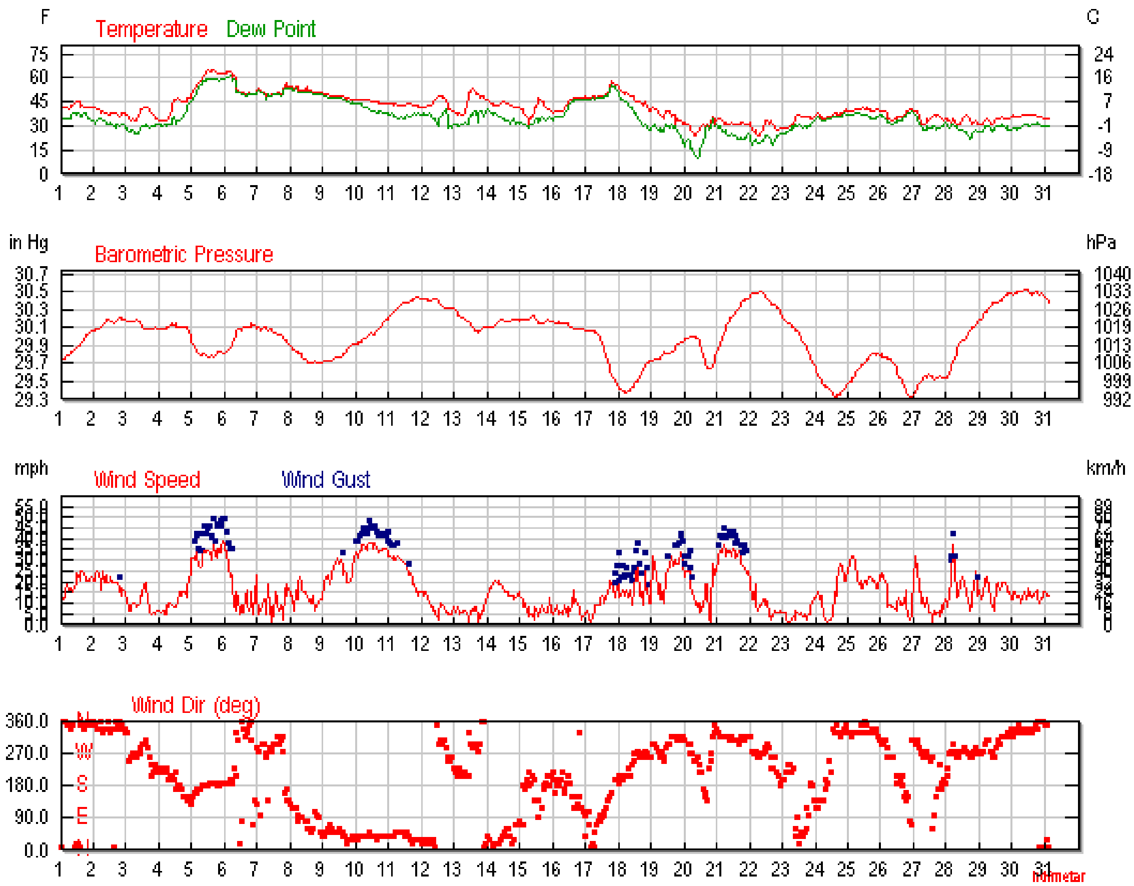

Figure 56 Nov. 2010 weather for Caribou Point.

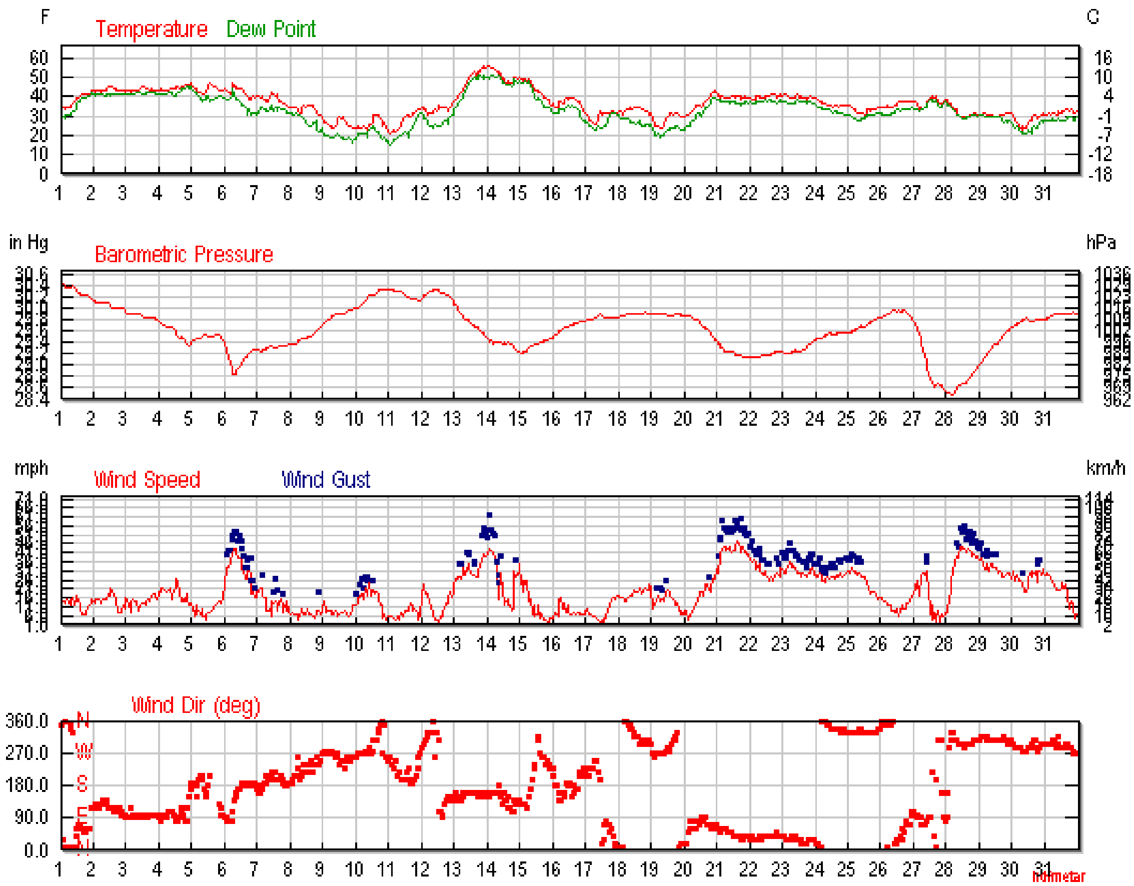

Figure 57 Dec 2010 weather for Caribou Point.

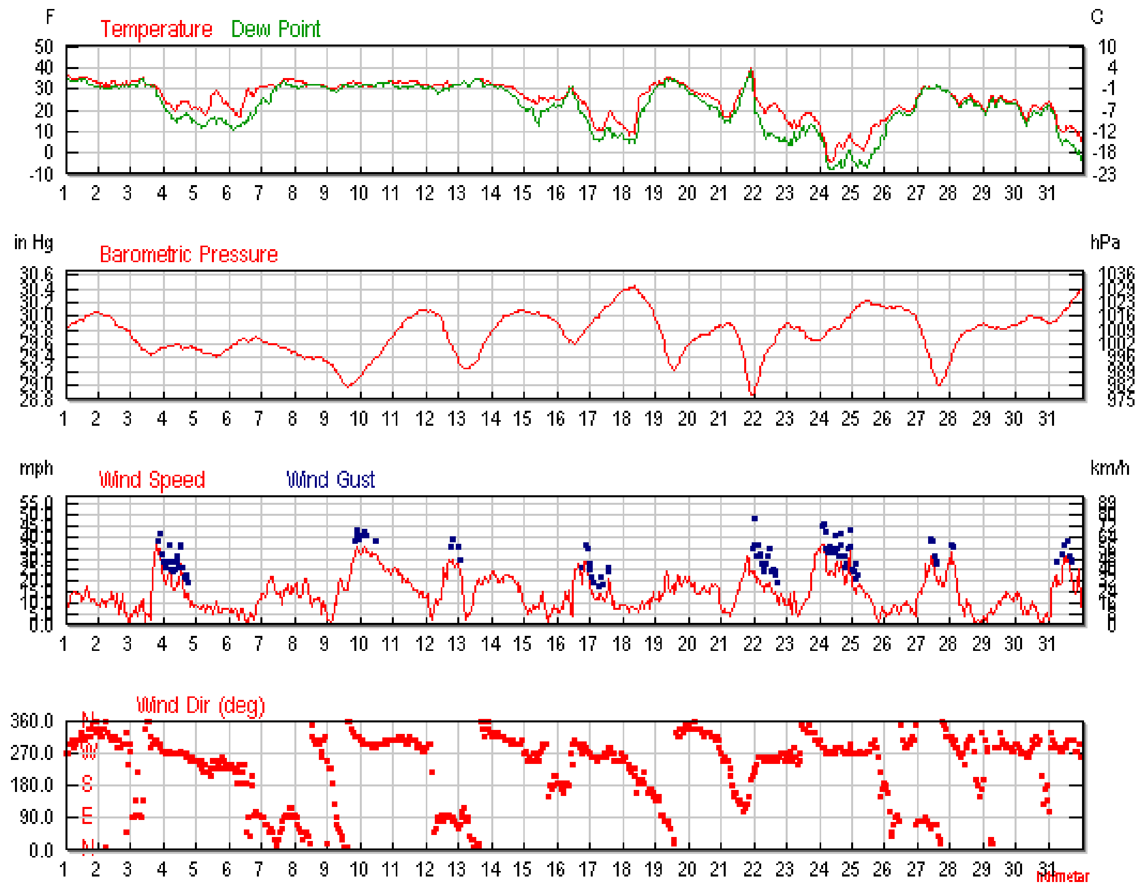

Figure 58 Jan 2011 weather for Caribou Point.

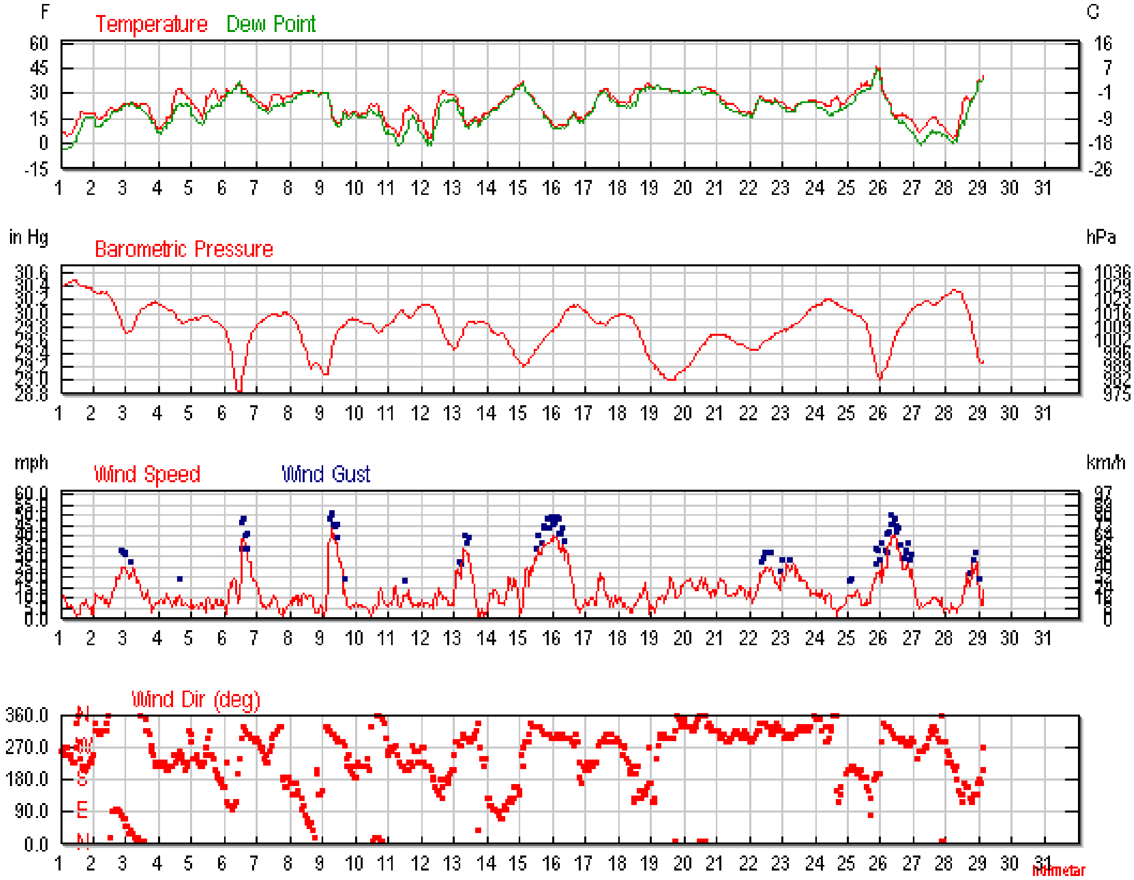

Figure 59 Feb 2011 weather for Caribou Point.

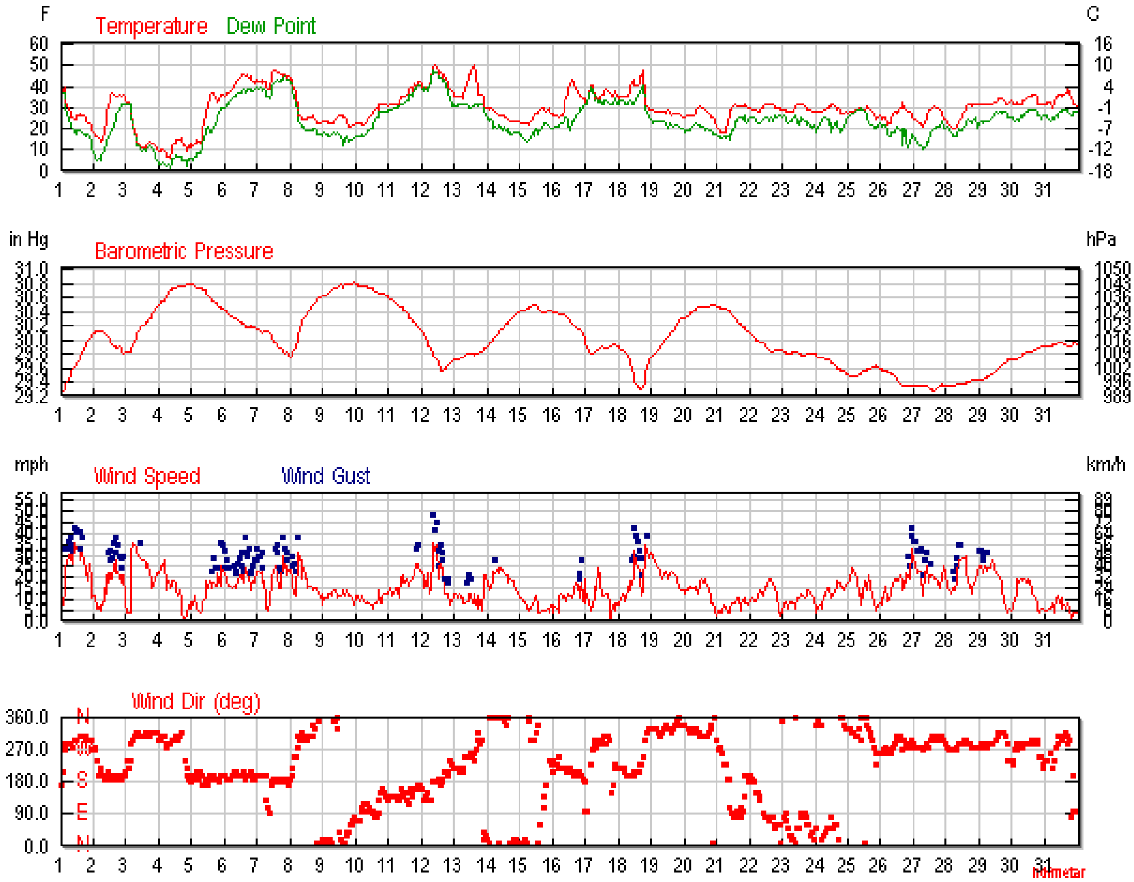

Figure 60 Mar 2011 weather for Caribou Point.

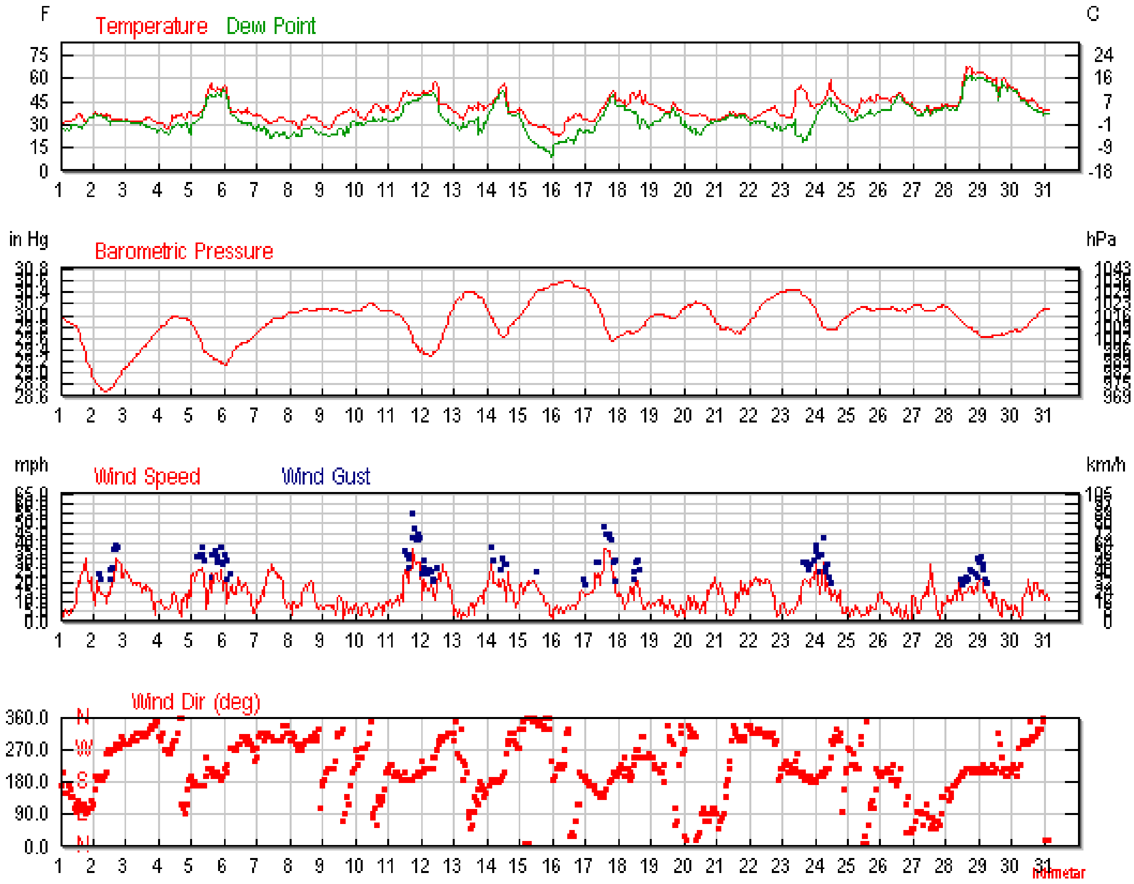

Figure 61 April 2011 weather for Caribou Point.

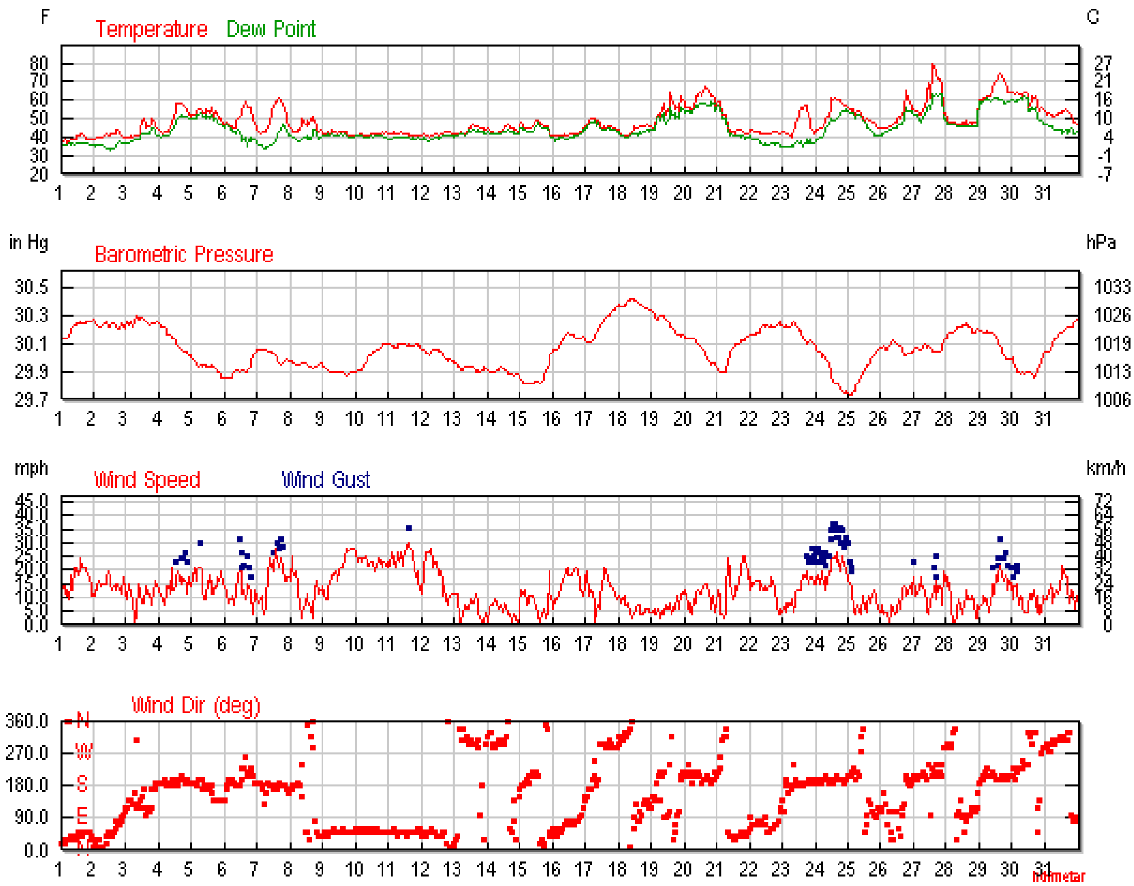

Figure 62 May 2011 weather for Caribou Point.

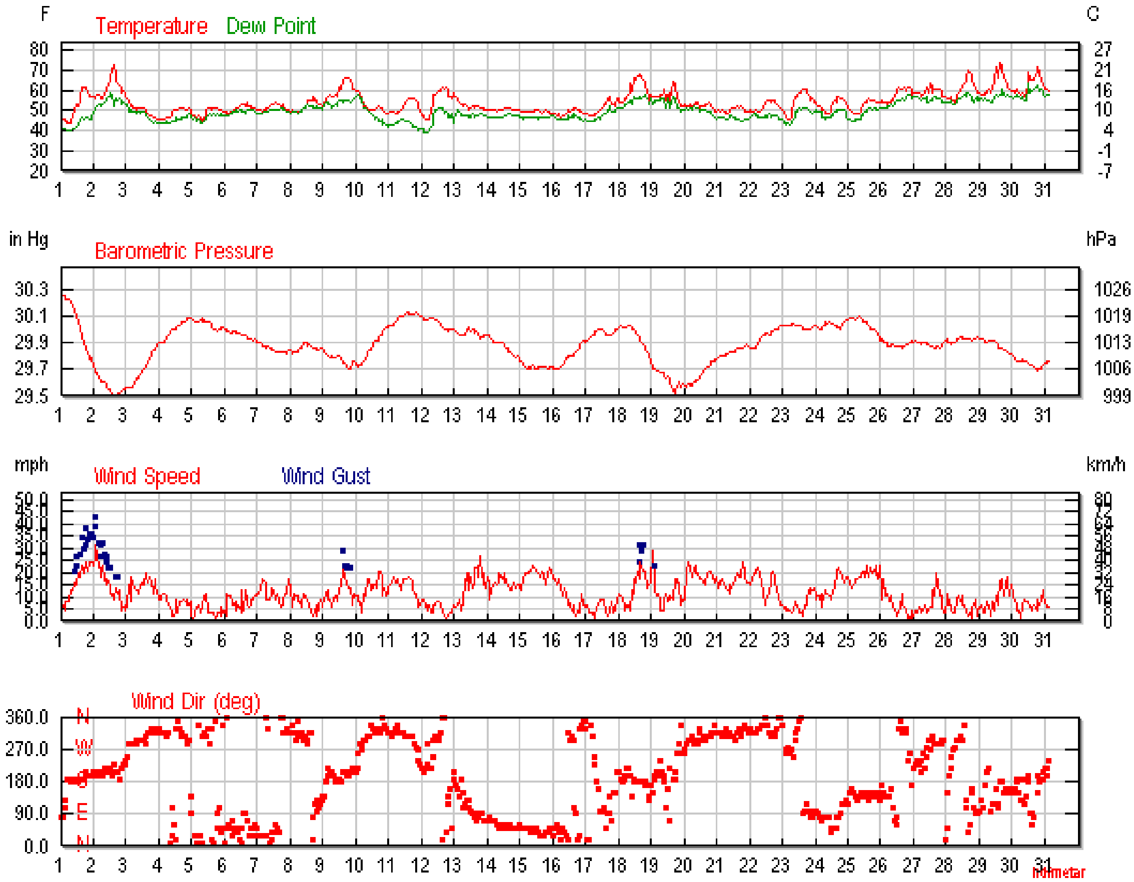

Figure 63 June 2011 weather for Caribou Point.

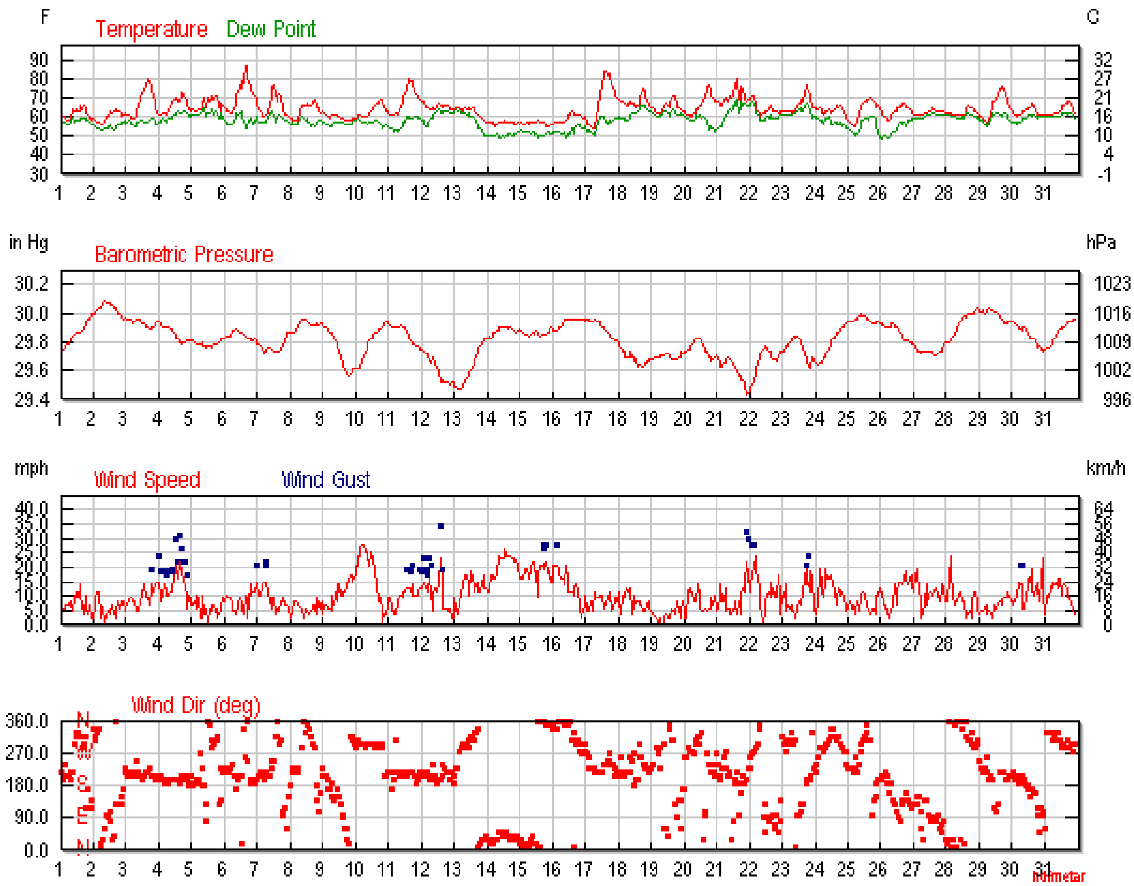

Figure 64 July 2011 weather for Caribou Point.

Appendix B Brier Island monthly weather graphs Oct. 2010-July 2011

Daily weather data for Brier Island, nearest location to Mavillette Beach,, Oct. 2010 - July 2011.

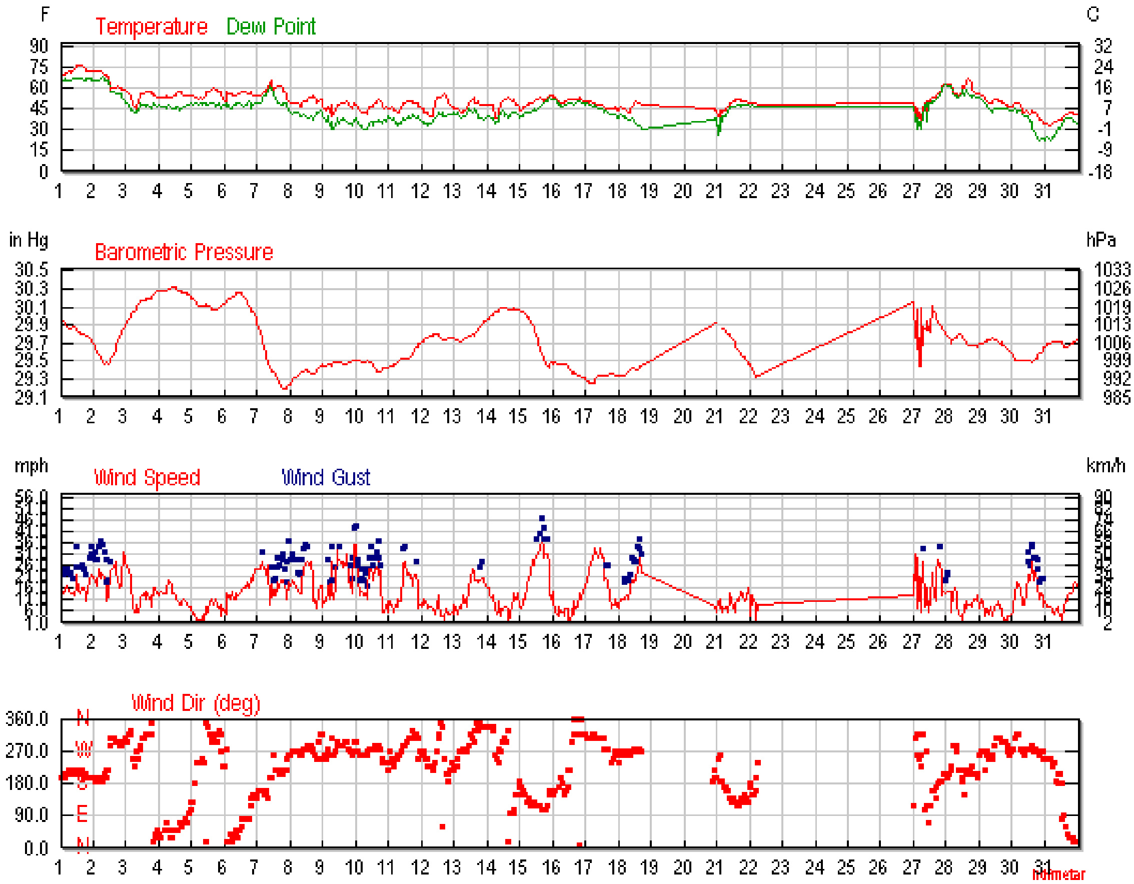

Figure 65 Oct 2010 weather for Brier Island.

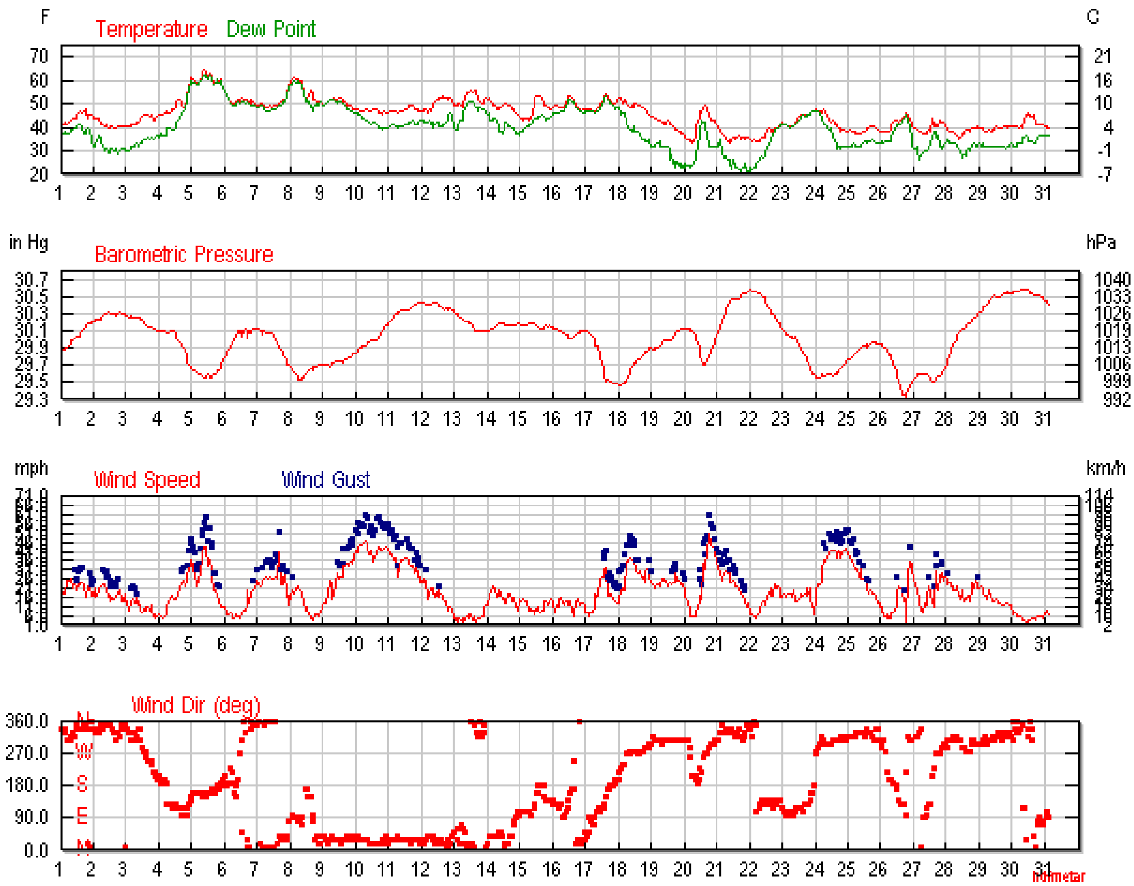

Figure 66 Nov. 2010 weather for Brier Island.

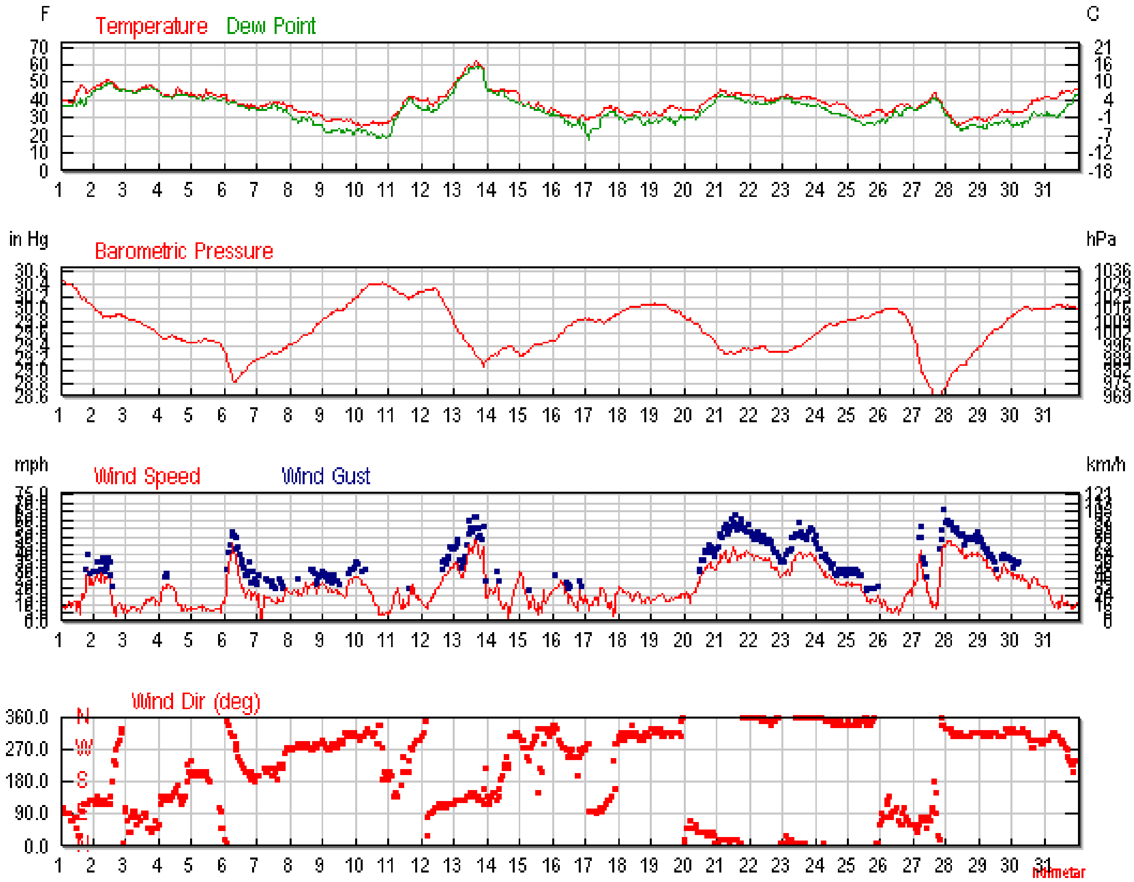

Figure 67 Dec. 2010 weather for Brier Island.

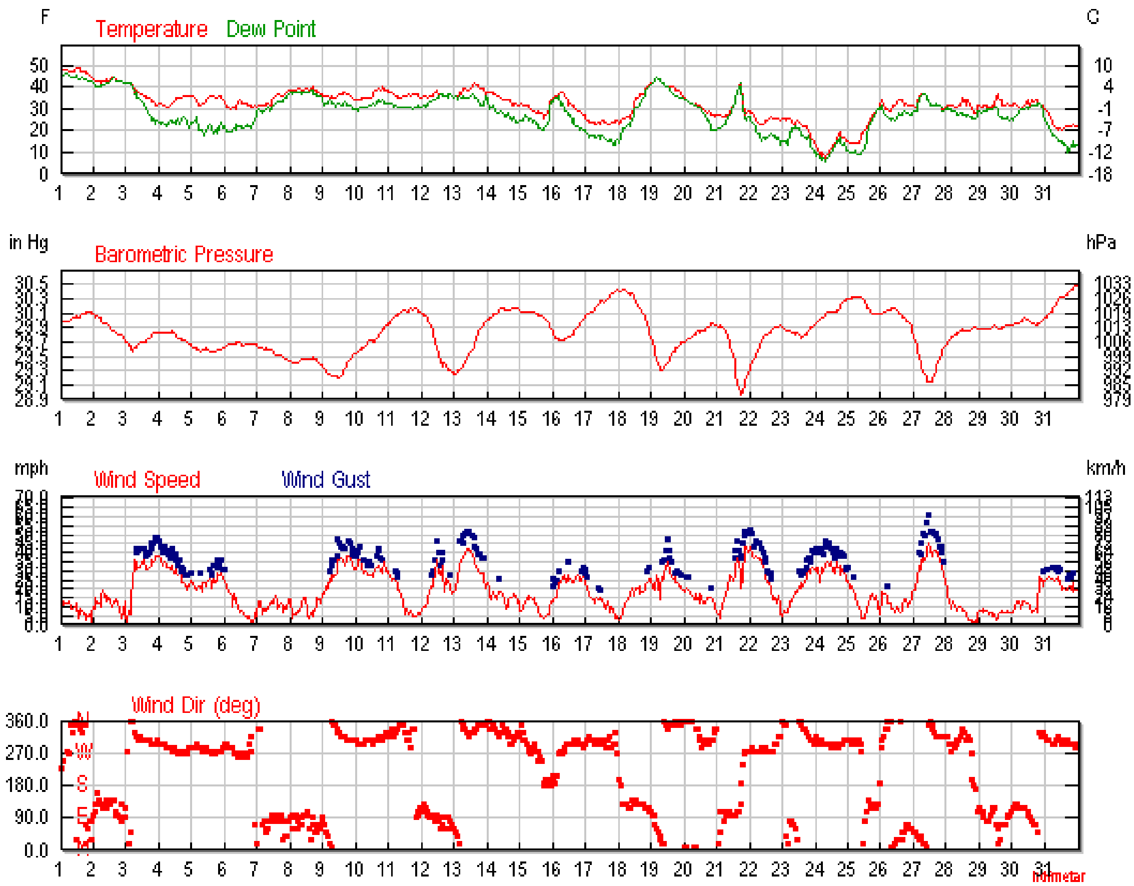

Figure 68 Jan. 2011 weather for Brier Island.

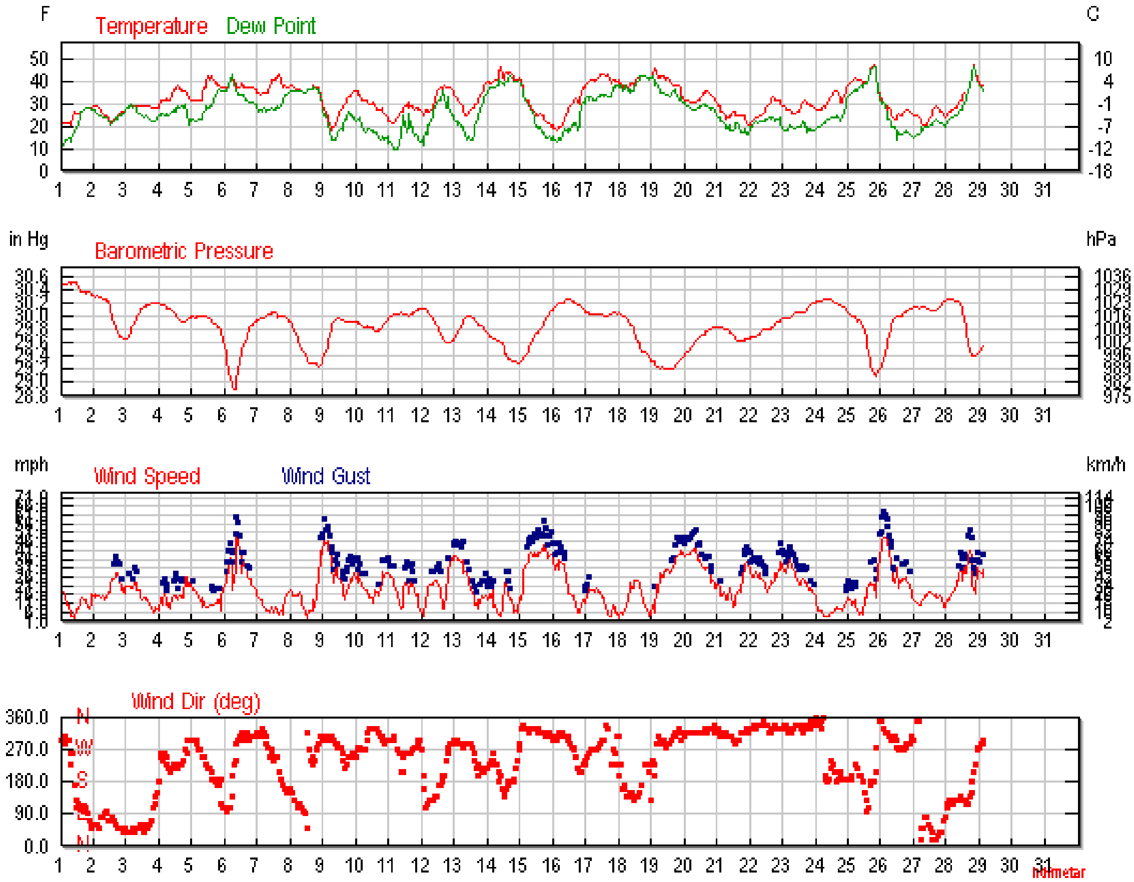

Figure 69 Feb. 2011 weather for Brier Island.

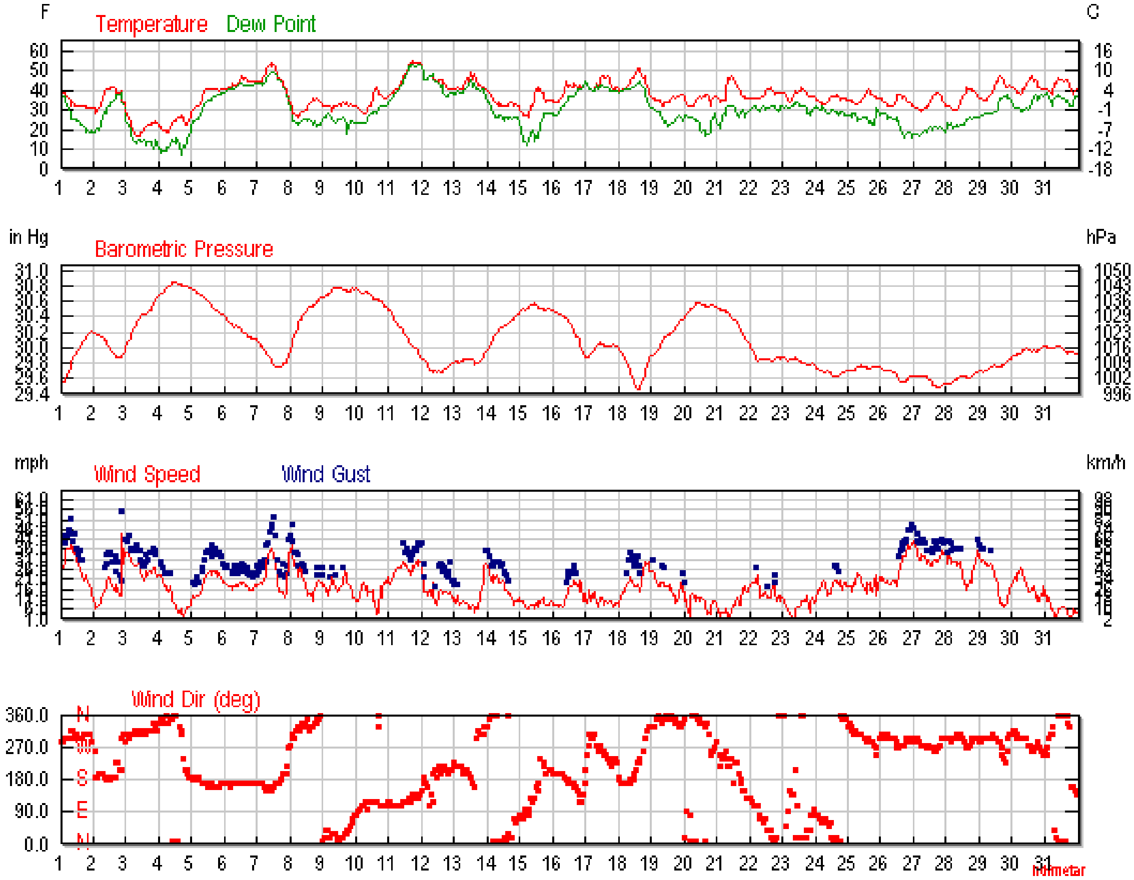

Figure 70 Mar 2011 weather for Brier Island.

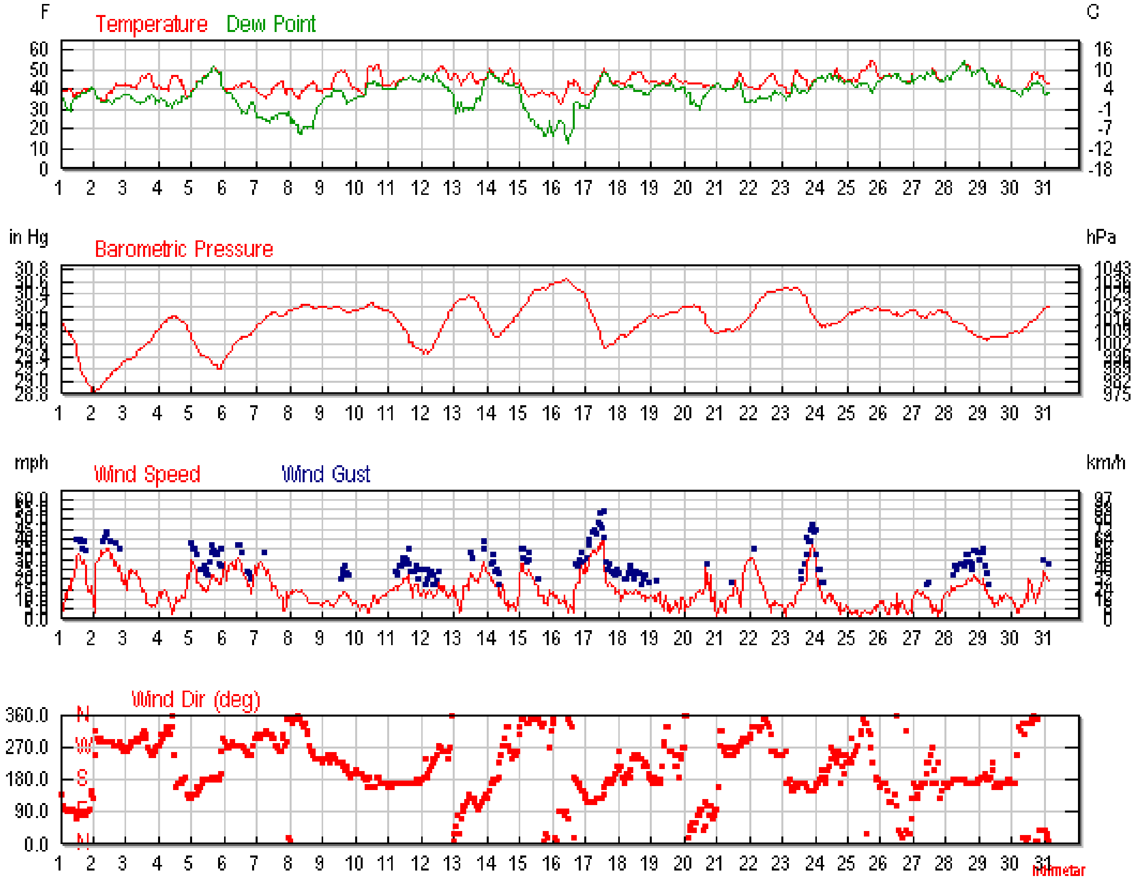

Figure 71 April 2011 weather for Brier Island.

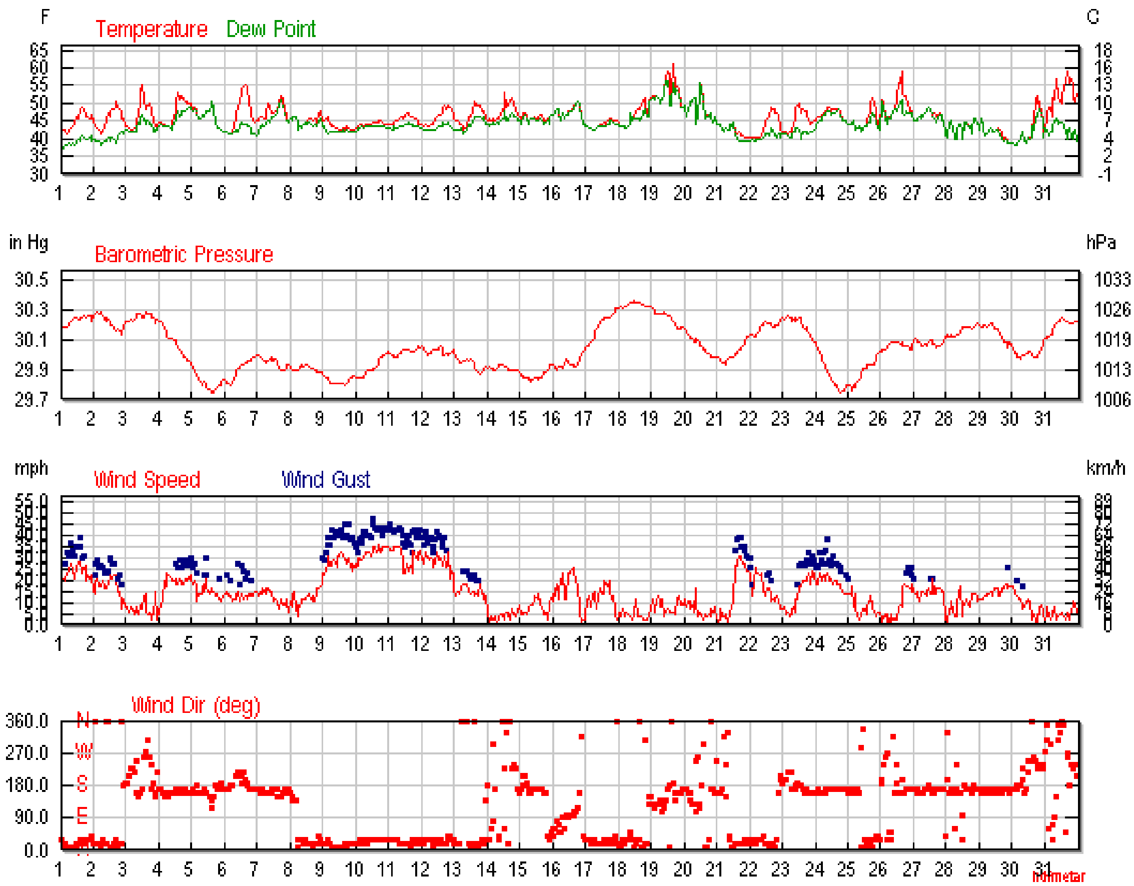

Figure 72 May 2011 weather for Brier Island.

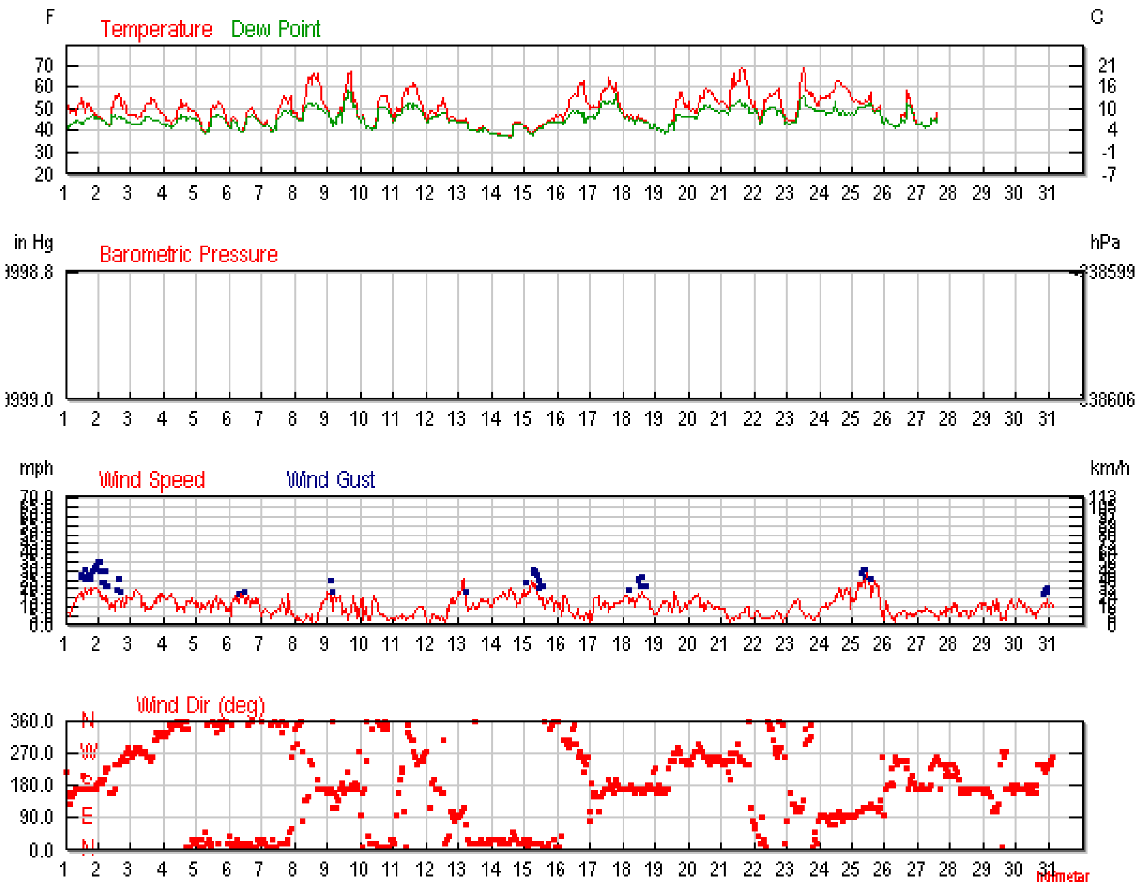

Figure 73 June 2011 weather for Brier Island.

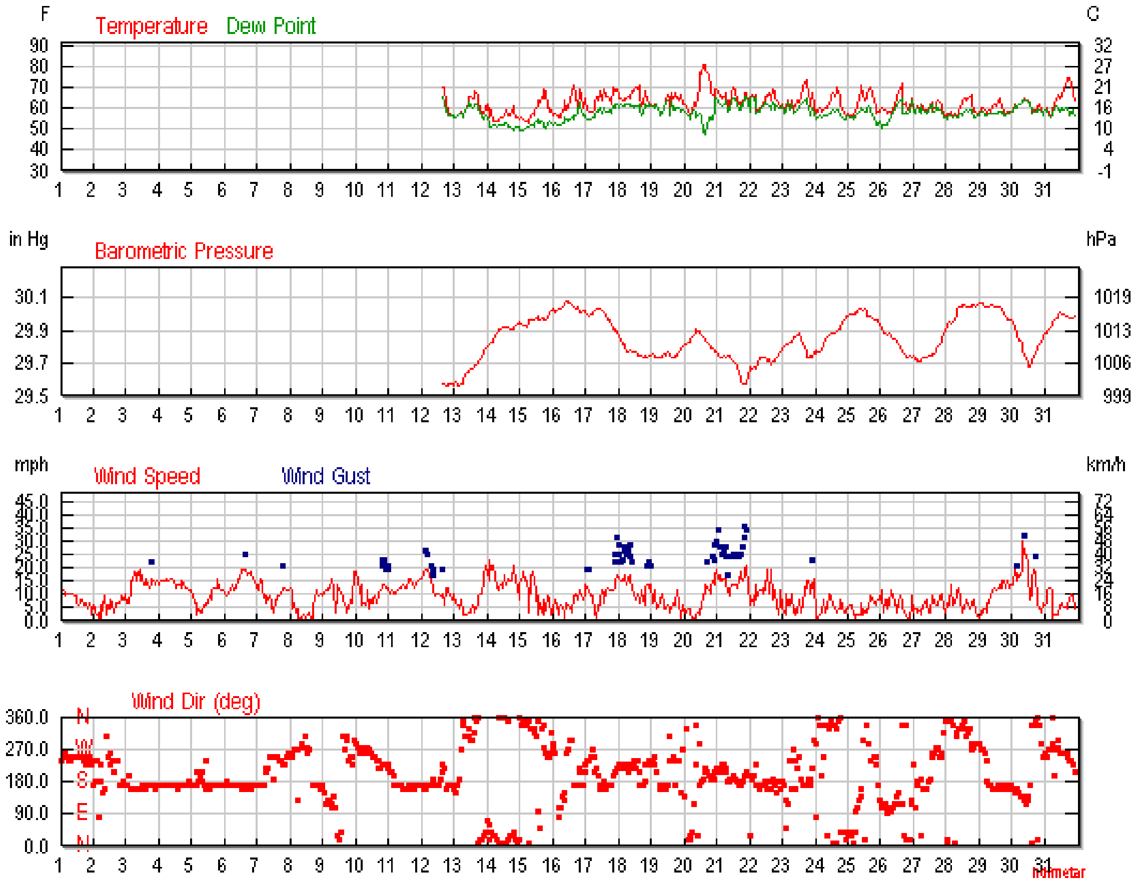

Figure 74 July 2011 weather for Brier Island.

Appendix C Lunenburg monthly weather graphs Oct. 2010-July 2011

Daily weather data for Lunenburg, nearest location to Kingsburg and Hirtle's Beach, Oct. 2010 - Feb. 2011.

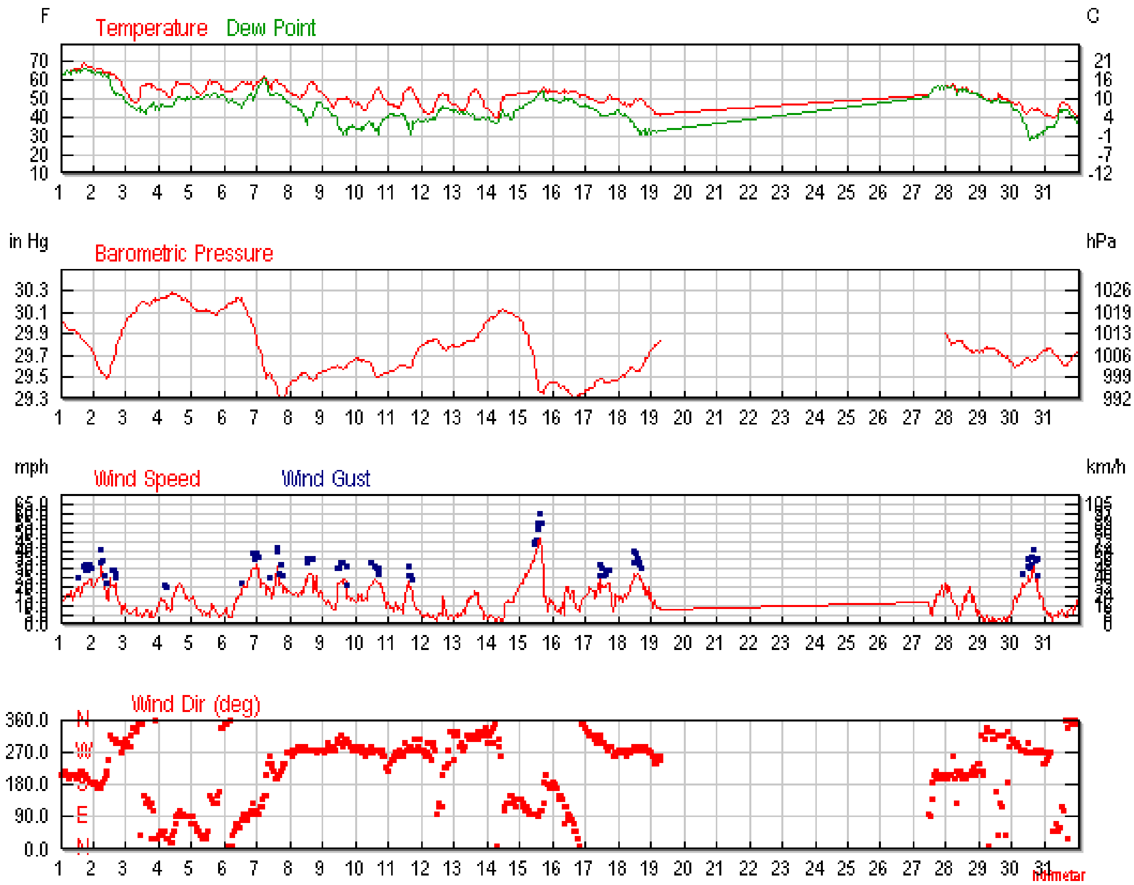

Figure 75 Oct. 2010 weather for Lunenburg.

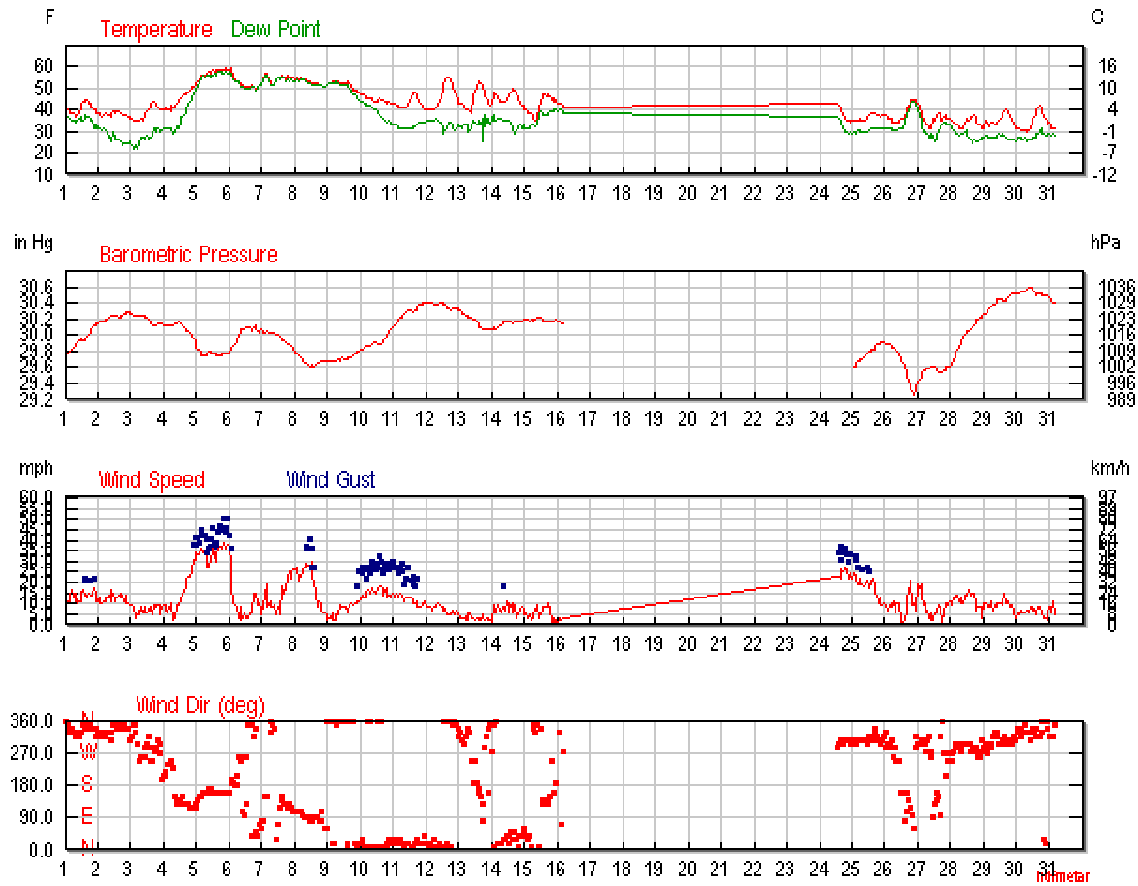

Figure 76 Nov. 2010 weather for Lunenburg.

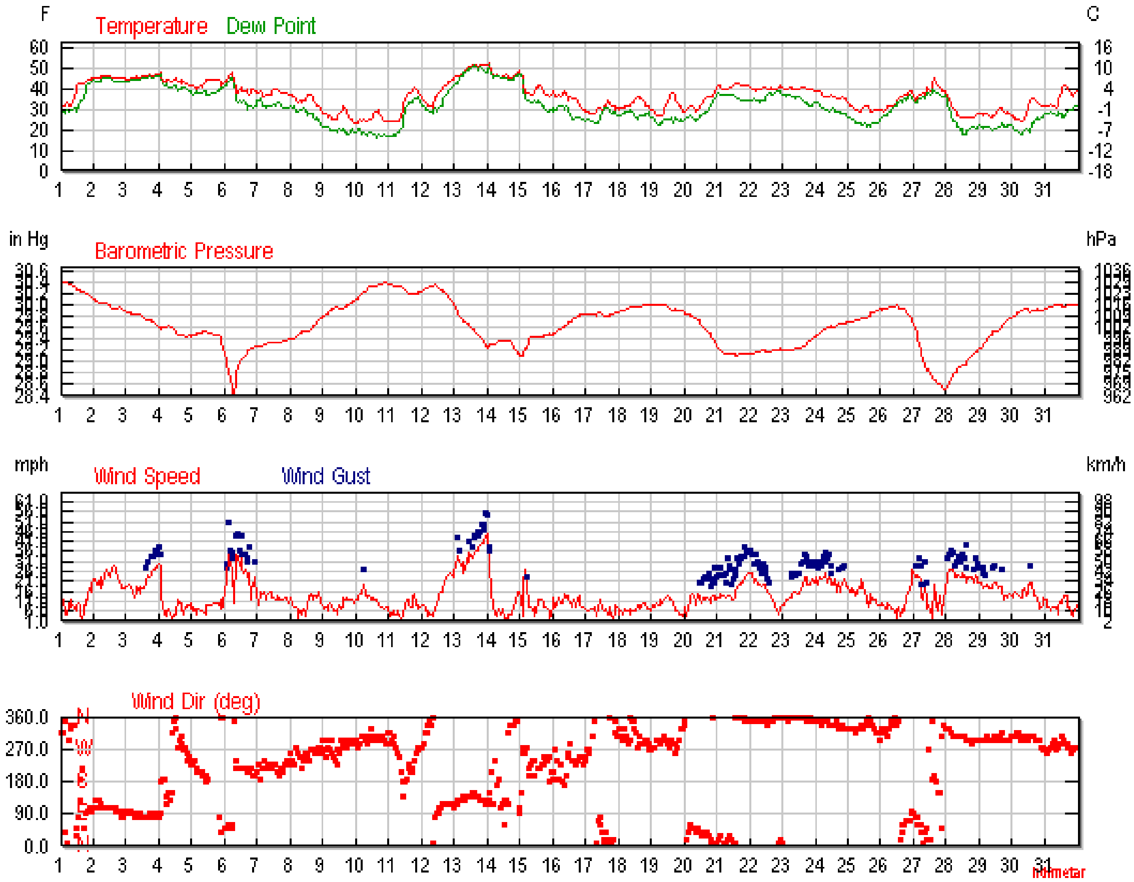

Figure 77 Dec. 2010 weather for Lunenburg.

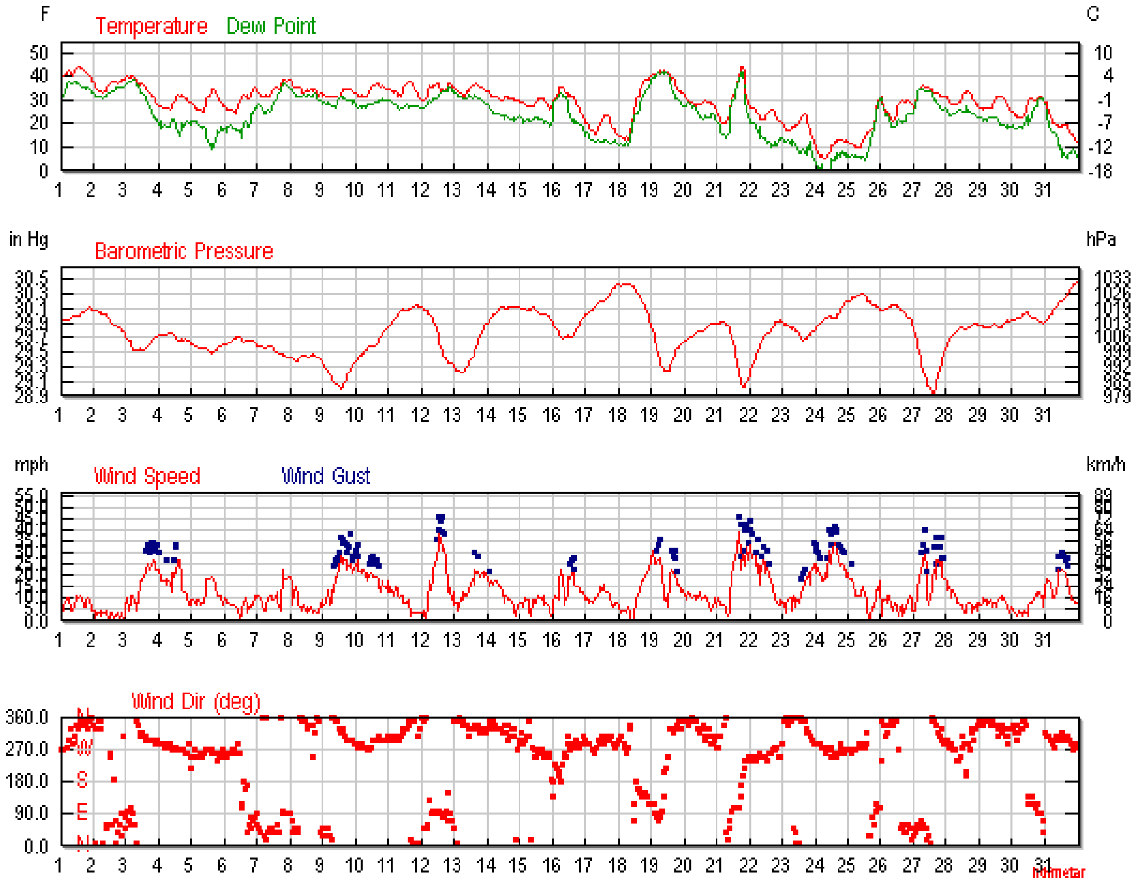

Figure 78 Jan. 2011 weather for Lunenburg.

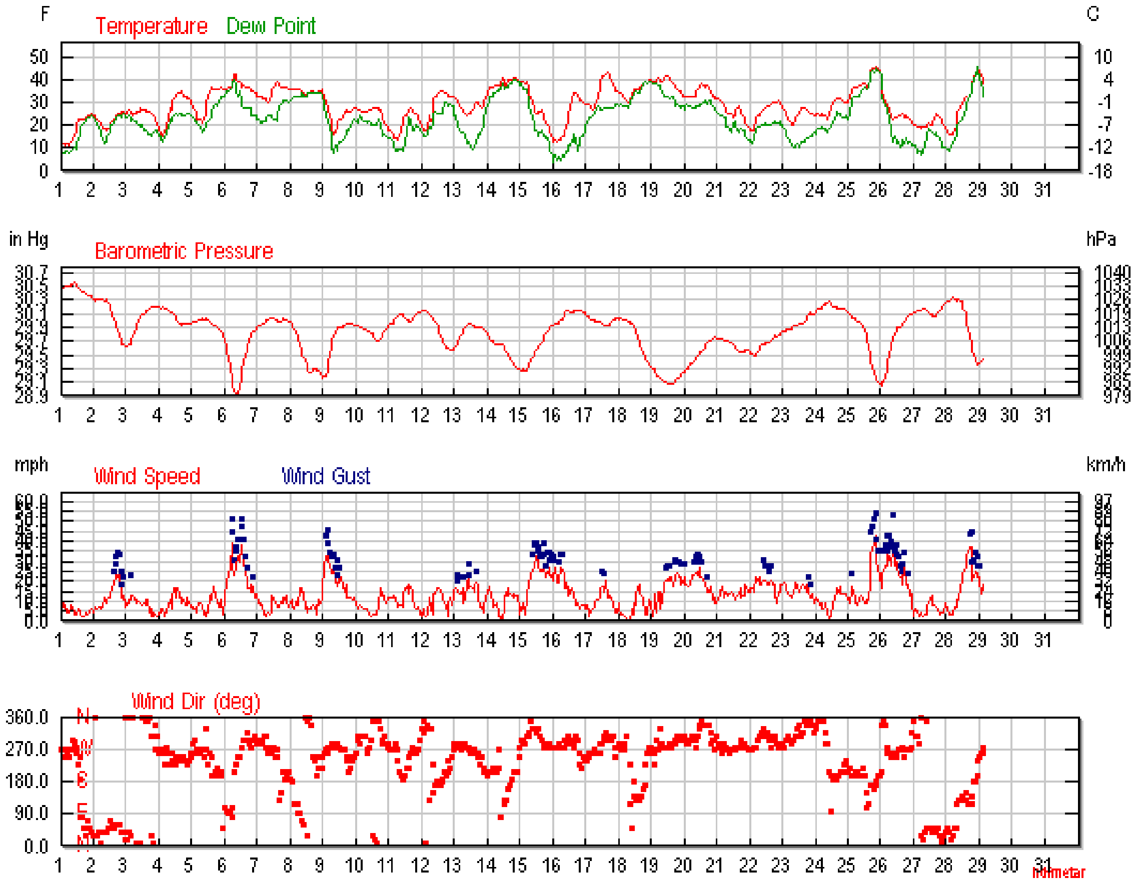

Figure 79 Feb. 2011 weather for Lunenburg.

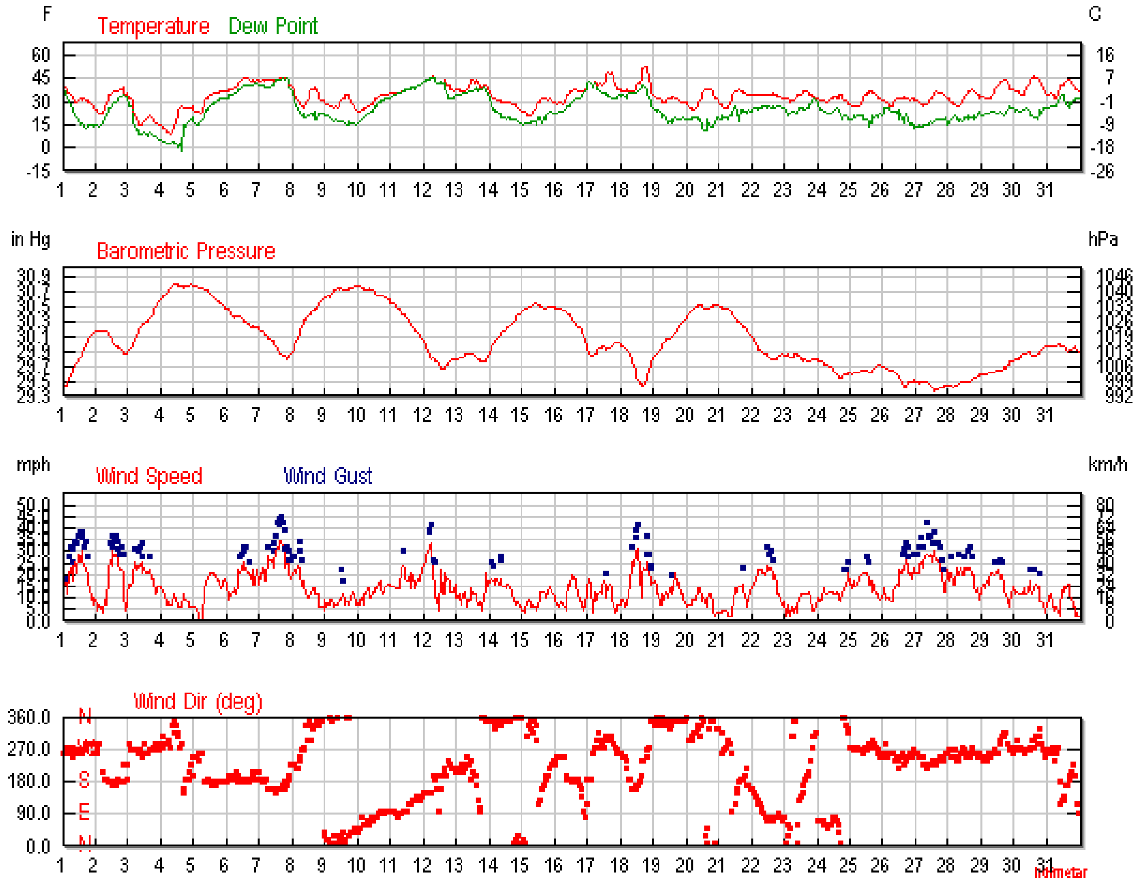

Figure 80 Mar 2011 weather for Lunenburg.

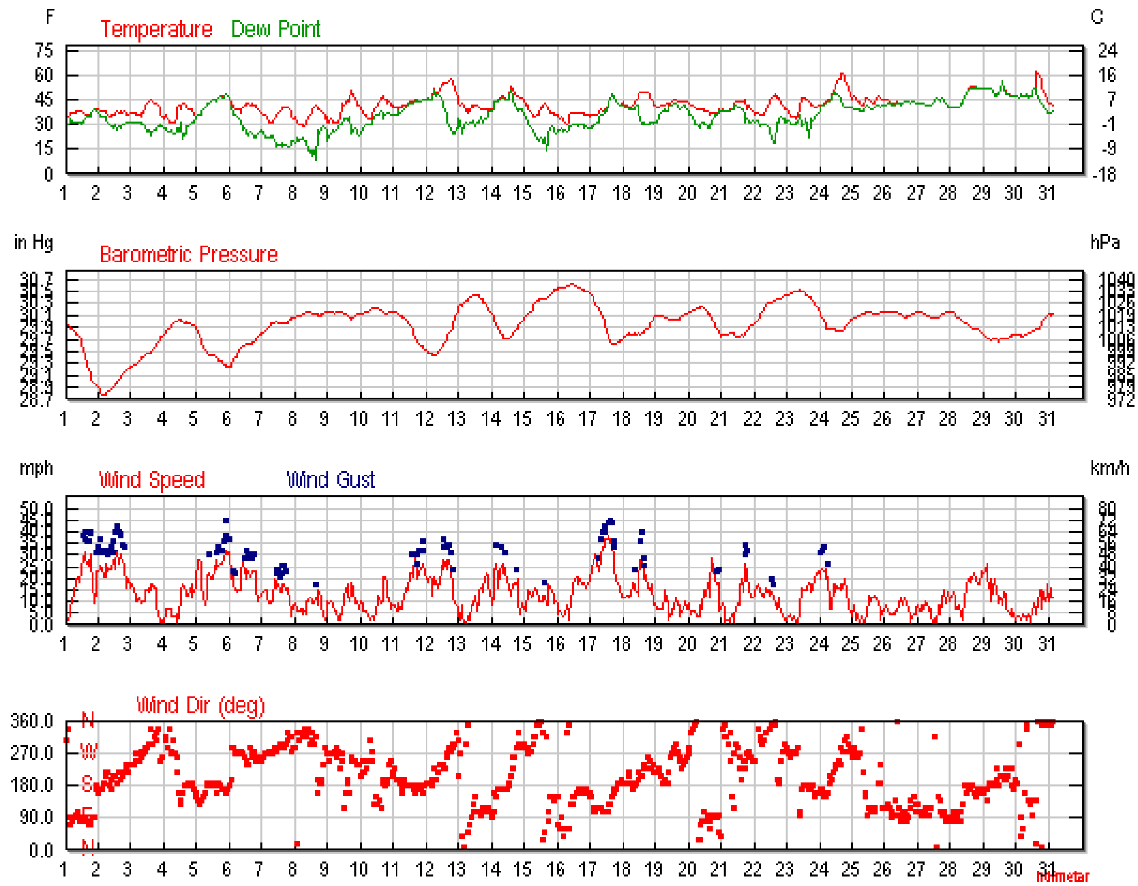

Figure 81 April 2011 weather for Lunenburg.

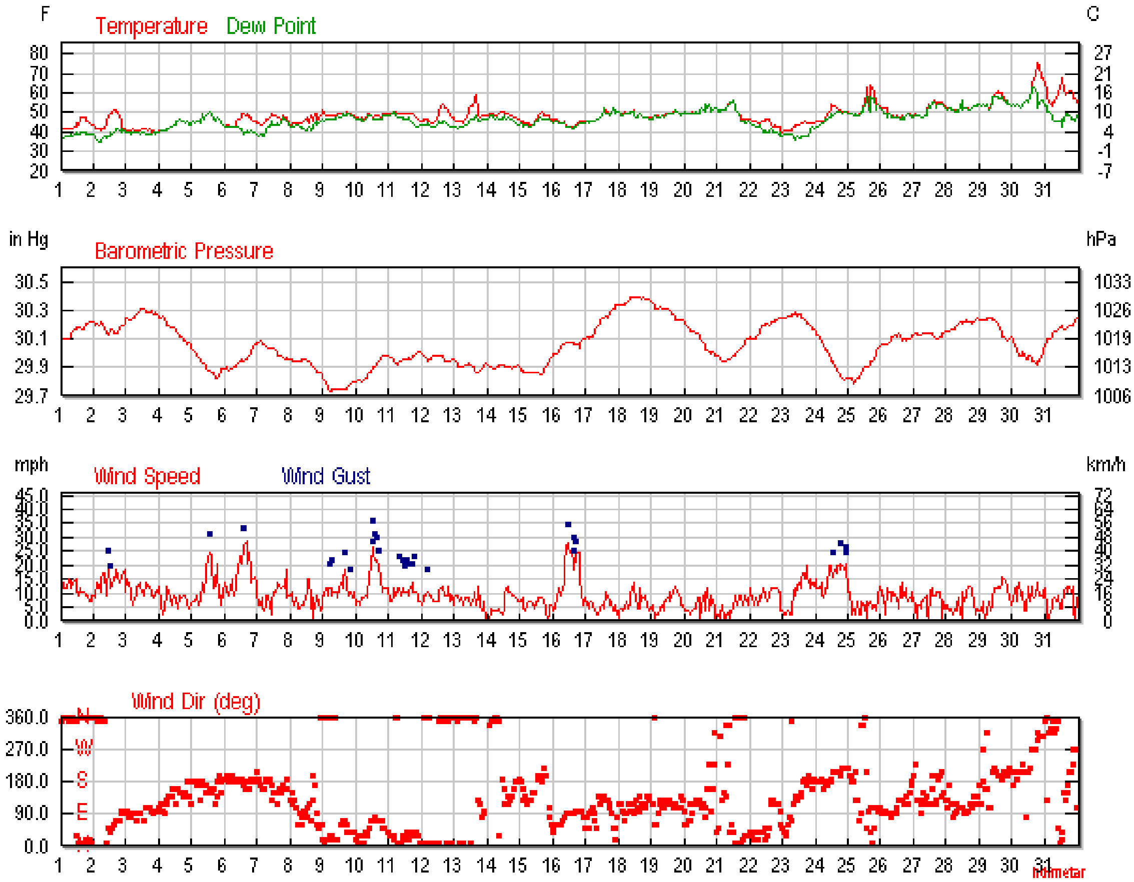

Figure 82 May 2011 weather for Lunenburg.

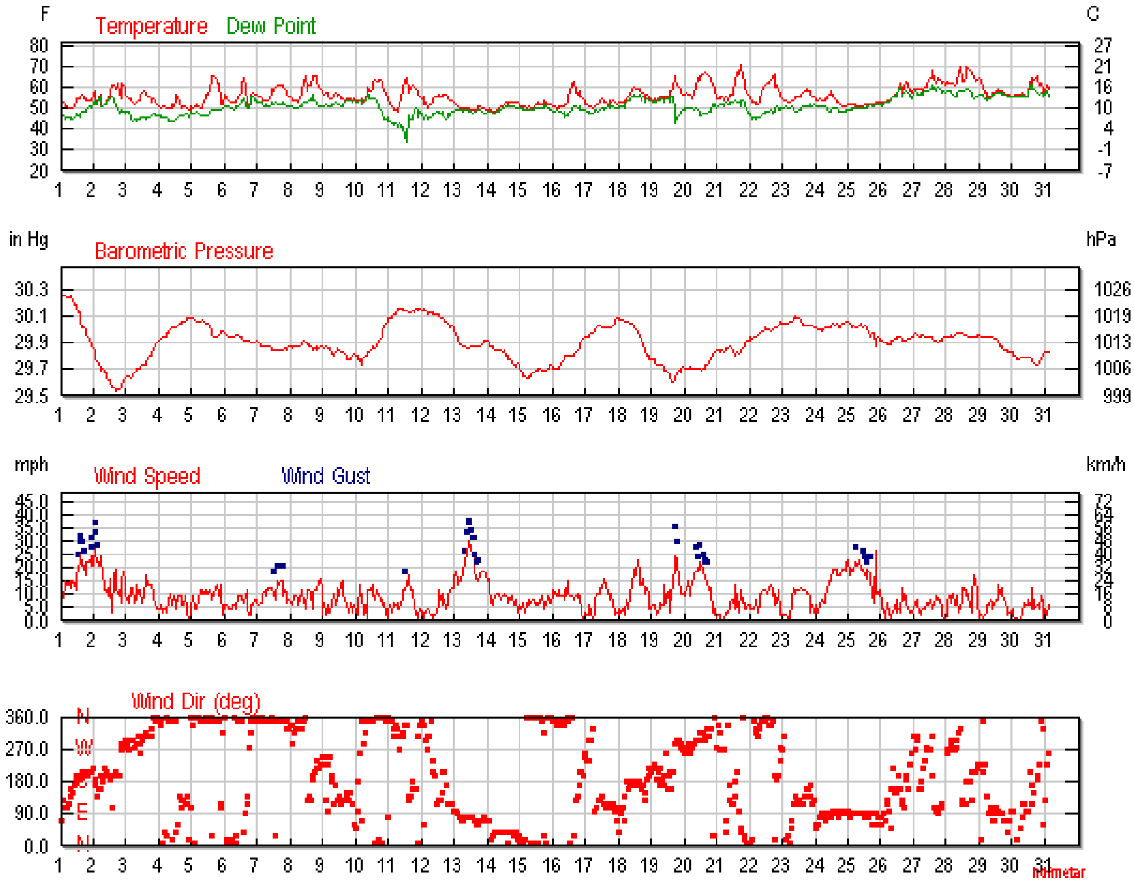

Figure 83 June 2011 weather for Lunenburg.

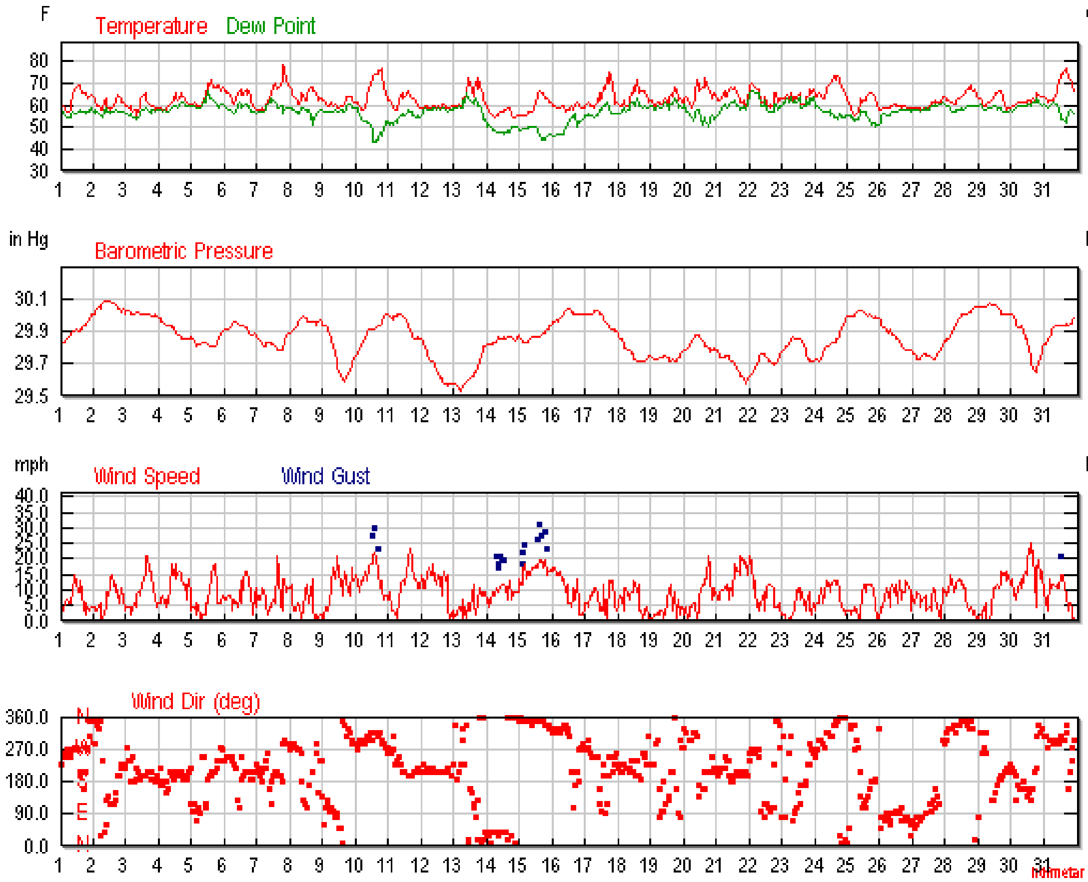

Figure 84 July 2011 weather for Lunenburg.