



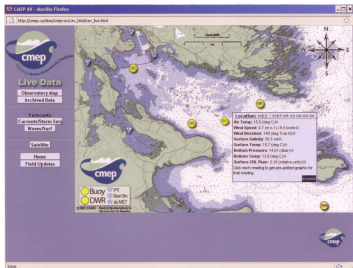
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Lunenburg Bay Observatory web page
La page web de l'observatoire de la baie de Lunenburg

The Lunenburg Bay Project

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Abstract: The Lunenburg Bay Project concluded in March 2008, having attained its primary goal: the development of Canada's first real-time interdisciplinary ocean-atmosphere observation and forecast system. After five years of successful operation, and through the combined efforts of biological and physical oceanographers and atmospheric scientists from academia, government and industry, the project has significantly advanced the state-of-the-art in marine environmental prediction. The project achieved many of the original objectives of implementing and adapting operational atmosphere, ocean and wave models to conditions of Atlantic Canada, as well as developing observational techniques suitable for adaptation in the next generations of ocean observing systems on a global basis. Improved numerical models for describing and forecasting coastal ocean biological conditions have also been developed, which will be useful for further research and development. Together, these advances will contribute to the detection and prediction of marine conditions including severe cyclonic events in coastal environments and have the potential to make Canada a world leader in real-time ocean analysis and forecasting.

Résumé: [Traduit par la rédaction] Le projet de la baie de Lunenburg, terminé au mois de mars 2008, a atteint son but primaire: soit l'élaboration d'un système canadien interdisciplinaire de prévision et d'observation océan-atmosphère en temps réel. Après cinq années de développement couronné de succès et suite aux efforts combinés des océanographes biologiste et physicien et des scientifiques de l'atmosphère en provenance du milieu universitaire, des gouvernements et de l'industrie, le projet a avancé de façon significative et est à la fine pointe en ce qui concerne la prévision environnementale marine. Ce projet a réalisé plusieurs objectifs initiaux dans l'exécution et l'adaptation de modèles opérationnelles pour l'atmosphère, l'océan et les vagues aux conditions du Canada atlantique. De plus, le projet a développé des techniques d'observation appropriées pour l'adaptation aux futures générations de systèmes d'observation marine sur une base globale. On a aussi développé des modèles numériques perfectionnés pour la description et la prévision des conditions biologiques de la côte océanique, ce qui sera utile pour le futur dans la recherche et développement. Toutes ces réalisations vont contribuer à la détection et la prévision des conditions marines incluant les phénomènes cycloniques sévères dans les milieux côtiers et auront la possibilité de faire du Canada un leader mondial dans la prévision et l'analyse marine en temps réel.

Introduction

The Lunenburg Bay Project, initiated in 2002 with funding from the Canada Foundation for Innovation (CFI) and the Province of Nova Scotia, and supported since 2003 by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), is a reflection of longstanding and ongoing cooperation among Dalhousie University, Fisheries and Oceans Canada (DFO), Environment Canada (EC) and private industry.

The primary goal of this project was development of a real-time interdisciplinary prediction capability for the coastal regions of Atlantic Canada, using data assimilative and coupled models guided directly by observations from oceanographic and meteorological instrument arrays. The project included strong commitments to observations and modelling, supported by fundamental research. It was a collaborative effort, beginning in 2003 with 12 principal investigators and 13 subprojects, with additional project elements for data and project management. With the addition of a remote sensing add-on in 2005 and modest

reprofiling for a two-year extension, the network ultimately comprised 11 research elements led by 15 investigators, and support elements for field operations, data services and project management.

The primary objectives were:

- To develop an advanced, relocatable, real-time observation and modelling system for coastal and inner shelf environments;
- To use this system to test and improve our ability to predict change on short to medium range time-scales (e.g., days to weeks) in the coastal marine environment.

The network also committed to studying coastal dynamics including: (1) the role of wind-wave forcing on the circulation within relatively shallow bays during storm events; and (2) the dynamics of the flow in tidal channels, the associated ebb tide jet, and their effects on mass and momentum

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mixing in Lunenburg Bay. The research was by its nature innovative and at the cutting edge: we committed to developing an integrated, interdisciplinary observation and modelling system that reported data and forecasts to users in near-real time. This was a first for Canada, and one of the first in the world. The work involved conducting scientific research, finding technical solutions, and coordinating operational efforts to:

- deploy and maintain a comprehensive coastal ocean observatory and data management system;
- integrate and constantly improve an interdisciplinary environmental modelling system that spanned atmosphere and ocean, treating winds, waves, currents and hydrography, as well as relevant aspects of marine chemistry and biology;
- develop and validate procedures for using novel optical data streams to describe biological variability in coastal waters;
- describe key dynamical processes to improve mechanistic understanding and to promote development of the next generation forecast systems; and
- present data and results to users in new ways, using the internet and other forms of communication.

The project terminated in March, 2008. Its web site is <http://cmep.ca/>, where the live data feature is replaced by a retrospective simulation of the web site ("Time Machine") as it appeared for any day of its operation, as chosen by the user.

The Integrated Observation and Forecast System

The Marine Environmental Prediction System Lunenburg Bay (MEPS-Bay) observatory included three major components, each including many elements:

1. *Observing Component:* A real-time observation system was deployed in Lunenburg Bay, a typical coastal inlet. Three radio-telemetering moorings and a shore-based meteorological station provided real-time observations of atmospheric forcing and variability in the physical and optical properties of the Bay. The moorings included meteorological instruments and oceanographic sensors to monitor the water temperature, salinity, velocity, surface waves, bottom stress and sea level. Newly developed optical sensors recorded the colour and clarity of the water, which were related to the amount of plant life, suspended sediment and coloured dissolved organic matter in the water. An array of temperature recorders was deployed on one of the moorings to give sub-metre scale measurements in the vertical. At other locations around the Bay, bottom pressure sensors measured sea level and acoustic current meters measured velocity and surface waves. Directional wave measurements were also conducted outside the Bay using a pitch-and-roll buoy. Meteorological sensing

systems included a standard weather observing station (XLB) that was established at Battery Point and continues as a project legacy, a weather station with additional visibility sensor for fog on nearby Cross Island, and a wind profiler and radio acoustic sounding system that observed winds and temperature in the marine atmospheric boundary layer from a location near Battery Point. Supplementary specialized microphysical instrumentation for fog measurements produced rich data sets during June 2006 and June 2007 as part of Environment Canada's Fog Remote Sensing and Modelling (FRAM) field experiment. The project also included a Shelf element which provided offshore measurements of temperature, salinity, fluorescence, irradiance and the partial pressure of carbon dioxide in seawater. The direct observations were complemented by a remote sensing program to provide images of sea surface temperature and chlorophyll from ocean colour, archived and also presented as a layer on Google Earth, as well as coastal vector winds from satellite scatterometers.

2. *Communications Component:* Instrument systems were in wireless contact with a base station at Battery Point, which relayed data to an internet connection at the Fisheries Museum of the Atlantic and on to Dalhousie University. Communications were two-way, and instruments could be controlled remotely. Communications with offshore instruments utilized the Iridium satellite network.
3. *Modelling and Analysis Component:* Considerable effort was devoted to the development of state-of-the-art atmosphere, ocean and waves models and data management including presentation, web-based visualization and archiving. Data include measured variables as well as the output of a variety of models in the interdisciplinary modelling system, as described in our Results and Achievements section.

Over the course of the project, elements of the observation and forecast system were integrated and then tested during a demonstration project in 2007 as described below.

Challenges

Despite the technical complexity of the project, and the need to deploy instrument systems in a sometimes harsh coastal environment, the system was successfully developed, then operated for years with few significant delays or interruptions (buoys were hauled out during winter because of ice conditions). There were some failures or losses of instrumentation, including the SeaHorse profiling system in 2003 and 2004, and a radiometer and fluorometer in 2007 (victims of a careless boater). Due to weather and predictable wear and tear, some observing system elements were out of service for periods of time, awaiting repair. Most repairs were completed quickly, and sometimes achieved remotely because real-time information from sensors was provided to a highly-qualified technical team that responded quickly and dependably. The principal

investigators developed a strong appreciation for the level of dedication and commitment – both in terms of people and financial resources – required to keep an observing system operational for years on end. We also found out that a system of this complexity requires effective management at all levels — requiring teamwork among technically-proficient personnel. With support from CFCAS and partners in government, the Lunenburg Project developed this management capability.

Results and Achievements

During its five years, the network met the vast majority of its many milestones, mostly associated with individual project elements. More fundamentally, we achieved our ambitious primary goal, the development of a real-time interdisciplinary prediction capability for a coastal region, using data assimilative and coupled models guided directly by observations from oceanographic and meteorological instrument arrays. Specifically:

- The Lunenburg Project generated interdisciplinary forecasts of weather, waves, currents, other ocean conditions and ocean biology — all in near-real time.
- Forecast models from different disciplines were coupled, for example to describe the influences of weather on waves and ocean circulation or the influence of currents on the distributions of phytoplankton.
- High-resolution local models were nested within larger scale models to comprise a regional forecast system.
- Data from the real-time observing system were assimilated — that is, used directly to test and adjust forecasts to improve their accuracy.
- All of this was supported by an interdisciplinary coastal ocean observatory unparalleled in Canada, feeding data in real time to a web-based system that included Google Earth access to data and forecasts, reports to cell phones, and easy downloading of graphics and data.

Also, the Lunenburg Bay Project achieved more than had been originally planned by the addition of 1) a remote sensing component that furnished satellite imagery and data for presentation and synoptic analysis, 2) an enhanced coastal dynamics research element and 3) a shelf processes component that deployed autonomous measurement systems on the Nova Scotia shelf to provide key information on physical and biogeochemical processes in the waters that strongly influence Lunenburg Bay.

Because interdisciplinary observation-based forecasting of ocean processes is in its infancy, there is still much work that needs to be done. Indeed, we succeeded in developing a capability that had not been in the grasp of Canadian science. However, the system that we developed reached only the earliest stages of what could ultimately evolve into an operational capability for monitoring and predicting change in Canadian coastal waters for the protection of

coastal communities, ecosystems, and resources, while managing recreational and commercial use.

The following summaries of project elements focus on high-level results that have been, or are ready to be, taken up by user groups for policy development and operational improvements.

Interdisciplinary Modelling System. The Lunenburg Bay interdisciplinary modelling system consists of various multidisciplinary numerical models and an atmospheric model. The atmospheric model is Environment Canada's GEM-LAM, a nested limited area version of the Global Environmental Multiscale (GEM) Model. The ocean circulation model is a five-level nested-grid coastal ocean prediction system known as NCOPS-LB (Figure 1, Yang and Sheng, 2008), which includes DALCOAST3 for the three-dimensional shelf circulation over the Scotian Shelf and the Gulf of St. Lawrence and a z-level ocean model known as CANDIE for circulation over coastal waters and nearby shelf areas. Wave models include a fine-resolution shallow-water SWAN model, nested within coarser-grid, basin-scale WaveWatch 3 (WW3). Ecosystem models include the Biology module and the Diagnostic Bay model. In all, there are 4 nested wave model grids and 5 nested ocean model grids. This system provided the core modelling capability for many of the sub-projects and the Demonstration Project described below.

Coastal Ocean Observatory. Observing system operations made up the backbone of the Lunenburg research project. By deploying the observing system for 6 to 8 months every year over the last 5 years, this project element provided quality data both above and below sea-level to nested atmospheric and oceanographic models to support the novel interdisciplinary forecast capabilities of the Lunenburg Bay Project. This capability is a legacy of the project, and it shows that Canadians can conduct near real-time interdisciplinary coastal observations and forecasts, if and when they decide to do so.

Fundamental Research on Coastal Dynamics. One of the principal goals of this element was to investigate the limits of predictability during intense forcing conditions, and specifically the role of surface gravity wave forcing. We demonstrated conclusively that wave forcing is equally important as the wind forcing during storms in driving circulations over the exposed, relatively shallow bays typical of Nova Scotia's Atlantic coastline. Since wave-forcing is typically not included in the present generation of coastal circulation models, predictions made using these models will consequently be inaccurate. Thus, our work indicates that improved forecasts of currents along the coast during storm conditions require the use of models which incorporate surface gravity wave forcing, a surface gravity wave module, and two-way coupling between waves and currents. With regard to operational requirements and policy development, we note that predictions during storm conditions are needed for a variety of operational requirements including search-and-rescue and oil spill

response operations; further, the need for forecasts is often greatest when the conditions are the worst: that is, when the waves are highest. We note that there is at present no model in the nation which has the required capability. Results from this project element are available for development of new Canadian models. There are efforts under way internationally to develop and improve the necessary models, the Delft3d Community Model Development Program being one example, the Community Sediment Transport Model development project in the US being another. The latter is an open source project, and one in which Canada has some involvement.

During the development of the sophisticated nested-grid coastal circulation prediction system for Lunenburg Bay (NCOPS-LB), various components of the system were used in the study of circulation and variability during storms in Lunenburg Bay (Wang et al., 2007), the dispersion and hydrodynamic connectivity of surface waters associated with tidal and wind-driven currents in the Bay (Sheng et al., 2008), and synoptic variability of circulation and hydrography in the Bay affected by the generation and propagation of baroclinic waves (Zhai et al., 2008). Efforts were also made in developing a computationally efficient scheme to assimilate hydrographic observations at moorings in the Bay to a three-dimensional coastal circulation model (Zhai and Sheng, 2008).

Automated Optical Assessment of Biological Variability. We provided validated optical data from the moorings, requiring a great deal of analysis, programming and reprocessing. The legacy data set from Lunenburg now includes the best available continuous estimates of biological variability in the Bay (Huot et al., 2007). This has served as a resource for modelling and will continue to be used in research on bio-optical properties of coastal waters and new approaches to modelling. The data are particularly valuable because they are accompanied by an extensive set of in-situ validation measurements from the field sampling program.

Our analysis of the strengths and limitations of passive optical observations has led to significant advances in the understanding of variability in the optical properties of coastal waters and our ability to detect biological variability. One legacy is the next generation of ocean observatories being developed by our industrial partner, Satlantic. Their LOBO systems rely more on active optical measurements (e.g., fluorometers), which we now know how to interpret more accurately. Ultimately we will combine active and passive measurements to develop even more robust observation strategies. This activity will be associated with planned deployments of the SeaHorse profiling system on the Nova Scotia Shelf, and another legacy of the Lunenburg Project, the Bedford Basin Ocean Monitoring Buoy (BBOMB), being deployed in Halifax.

Integrated Interdisciplinary Observation-Forecast System. Much of the project was devoted to developing individual components of the observation and prediction capability, but as it proceeded, these were joined into an integrated observation, data assimilation, forecasting and verification system that was implemented in a demonstration project that started in June 2007 and continued into the fall. The essential elements included atmosphere, ocean, wave and biology models in a (one-way) coupled system, assimilating Lunenburg Bay data, evaluating skill, and presented on the Lunenburg Bay project web site. During the demonstration period there were interactions with meteorologists at the EC National Laboratory for Marine and Coastal Meteorology in collaboration with the Atlantic Storm Prediction Centre (ASPC), and real-time access to observations, analyses and forecasts through the Lunenburg Bay Project website for evaluation by the ASPC, DFO and other users.

Distribution of Data and Forecasts to the Public and to Researchers. The CMEP-Access / Visualization system developed many innovative capabilities for distributing data and forecasts to the public and to researchers, including a capable web site with easy procedures for graphing and downloading data, real-time displays of environmental measurements through Google Earth, and cell phone access. As planned, our data distribution system moved beyond accessing, processing, presenting and archiving data from the observatory, by providing visualized forecast model output on the website (www.cmeop.ca, Figure 2). Several data products, including remote sensing imagery, were provided as layers on Google Earth. The models include the Scotian Shelf and Lunenburg Bay waves model forecast from DFO and the nested-grid coastal circulation prediction system for Lunenburg Bay (NCOPS-LB, see Figure 1). Both the ocean and wave models were very successful at presenting “now-cast” conditions inside Lunenburg Bay (Mulligan et al., 2008); A Ph.D. student, Ryan Mulligan, was able to use our flexible data system to upload his model results to the web site.

Real-time data, accessible on the CMEP web site and on PDA devices, proved to be a valuable asset for observing systems since they provide current environmental conditions as well as status information for the equipment. This has been an invaluable tool for the field operations team in charge of the maintenance of the observing system. During the open house in the town of Lunenburg (entitled “The Underwater Weather”) in September 2007 and during numerous Dalhousie and Bedford Institute of Oceanography open house events, we were able to display our website and our Google Earth graphical interface to the enthusiastic young school crowd. To the public, the observing system in Lunenburg was the visible tip of an information iceberg. Fish harvesters, boaters, surfers, divers, coastal residents and regional students logged on to visit the buoy sites and view the latest conditions. The lobster harvesters of the Lunenburg region always had a keen interest in bottom temperatures as it determined the presence of the resource.

Nested-grid Coastal Ocean Prediction System (NCOPS-LB)

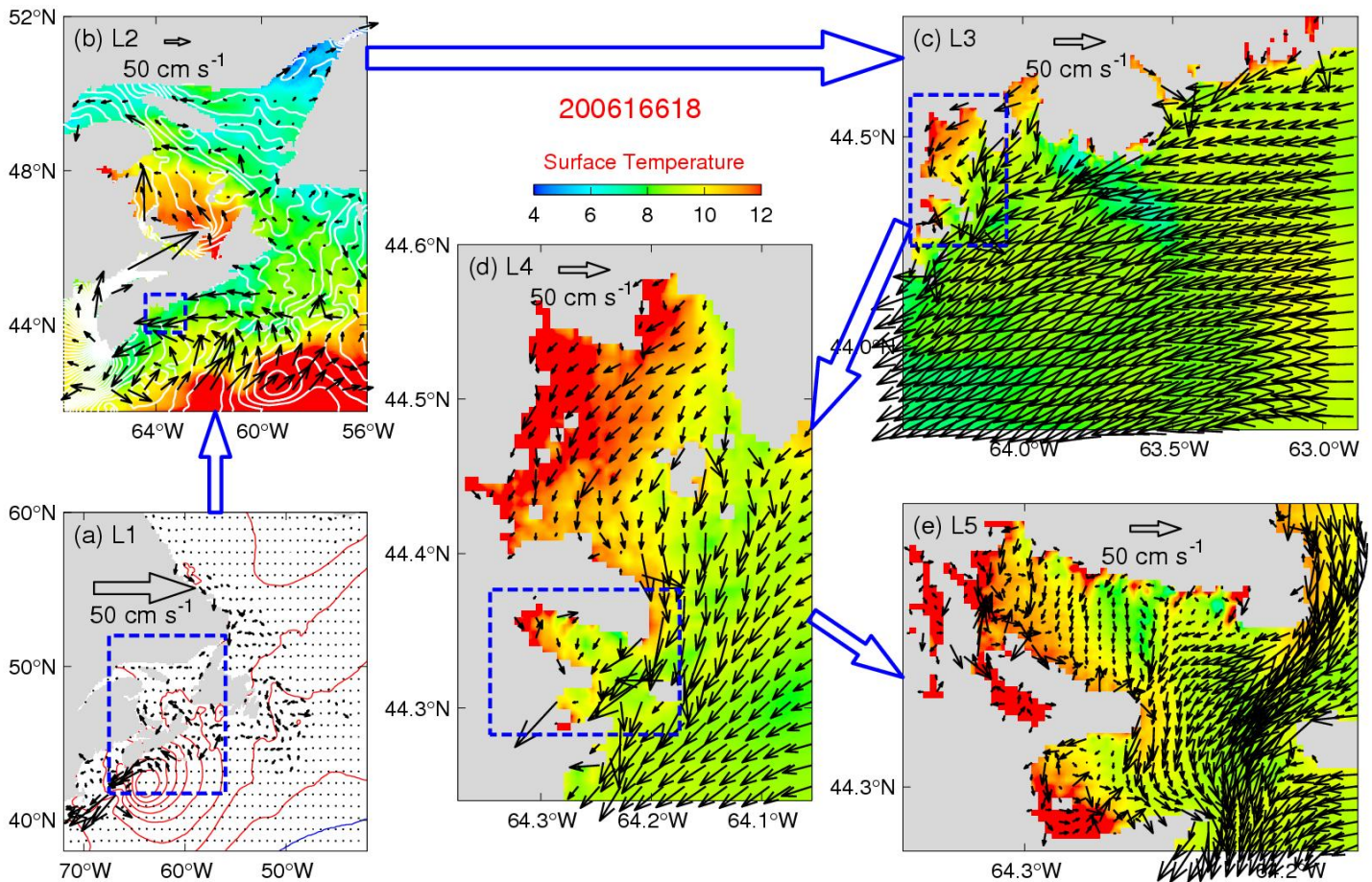


Figure 1. Model results at 1800 June 15 (day 166.75) of 2006 during tropical storm Alberto produced by the nested-grid coastal circulation model (NCOPS-LB, Yang and Sheng, 2008). The centre of the storm at this time was located over the central Scotian Shelf. (a) Simulated depth-mean currents (black arrows) and total surface elevations (red/blue contours for positive/negative values with the contour interval of 5 cm) produced by sub-model L1; (b) surface currents (black arrows) and sea surface temperatures (images) produced by sub-model L2; and (c-e) near-surface (1.5 m) currents and temperature produced by sub-models L3-L5 of the NCOPS-LB in the control run. For clarity, velocity vectors are plotted at every (a) 9th, (b) 10th, (c) 4th, (d) 3rd, and (e) 2nd model grid point.

Data originated from different sources, mainly from the field operations (research buoys, meteorological sensors and discrete field sampling), remote sensing and from model output, spreading across various levels of complexity from raw formats to processed and quality controlled formats. Efforts have been initiated to make the complete datasets and associated metadata available to the general public in co-operation with the Department of Fisheries and Oceans (DFO - ISDM).

This project has made many advances in data management, data visualization and archiving, providing a blueprint for future work in ocean monitoring and forecasting. One of the first tangible outcomes is the utilization of the Lunenburg Project data system as the foundation for a new Dalhousie - DFO collaborative ocean observatory project, the Bedford Basin Ocean Monitoring Buoy (<http://cmep.ca/>). This system utilizes a remodelled Lunenburg buoy deployed in Bedford Basin, a site which

has 40 years of observations by the Bedford Institute of Oceanography. A new, real-time interdisciplinary observation capability is being established at a fraction of the cost of a new ocean observatory, solely because we can use the hardware, expertise and data systems from the Lunenburg Project.

Training of personnel. One of the most important measurable outputs generated by this project element is the training of highly-qualified personnel. The observatory was a test bed for meteorological and oceanographic instruments and their integration; consequently the expertise acquired by the personnel was of much value beyond their training in the operation of individual sensors. The team was often composed of students, interns, young technicians and volunteers. The Lunenburg ocean observatory has without a doubt served as a great learning platform that inspired many to continue working or studying in the field of oceanography.

Upon termination of our project, potential users in Canada did not immediately initiate programs of interdisciplinary marine environmental prediction in the coastal zone, but government laboratories have hired several of our personnel to contribute to their marine modelling efforts. Other students and staff are working on oceanographic and atmospheric projects in Canada and abroad. These researchers, steeped in their Network experience, represent a core contribution to Canada's next generation of ocean and atmosphere modellers and observing system specialists. The training of highly-qualified personnel and advances in novel interdisciplinary modelling are tangible and significant contributions to operational improvements and policy development as government priorities require marine environmental prediction.

Benefits to industry. Companies involved in the making of the various components of the observing system have learned a great deal from this long term monitoring experiment. The constant stress on the components provided important benchmark values that can be used for future product development. We have shared some of the Lunenburg data with Vaisala Inc. on their meteorological sensor, which innovates by having no moving parts. Our interaction and collaboration with Satlantic Inc., based in Halifax, enabled improvements for many of their sensors and the designs of their monitoring buoys. Their next generation monitoring systems, including the Land / Ocean Biogeochemical Observatories (LOBO), have many innovations that are rooted in learning from Lunenburg Bay, and represent a legacy of our project.

Conclusion

Many changes occurring in the ocean and atmosphere have profound effects on our society. A few examples of these include sea level rise, coastal flooding, storm track changes, droughts and harmful algal blooms. Some of these changes are expressed as short-term events related to long-term trends in the climate of the Canadian maritime region. At present, we do not fully understand the magnitude of these changes, their causes and their consequences, which can make it difficult to prepare for and adapt to future change adequately.

Ocean and atmosphere observations are collected at global, national, regional and local scales and impact many facets of our daily lives. At the regional and local scales, the Lunenburg Bay Project has provided significant advances to the oceanographic and atmospheric research community in Canada and globally through the development of new observational and modelling techniques. One of the key benefits of this project has been the training of the next generation of scientists and technical staff who are now capable of applying their knowledge in academia, government organizations and the private sector.

No single agency or organization in Canada has the capacity or resources to implement fully a national interdisciplinary atmosphere-ocean observing system. The demonstration of a successful collaboration in the Lunenburg Bay Project among universities, government agencies and the private sector could provide important lessons as the community moves forward in the development of the next generation of observing systems.

Acknowledgments

This project was a joint effort of more than 100 researchers, technicians, programmers, engineers, postdoctoral fellows, graduate students, summer students and volunteers (listed on our web site, <http://cmep.ca/>), including many from government agencies who participated with personal enthusiasm mirroring that of their university colleagues, making the project a true partnership. The authors sincerely appreciate the contributions of the Lunenburg Project team members, who — through their dedication, talent and hard work — were essential to the success of this effort. We also acknowledge encouragement and support from DFO, EC and Dalhousie University, coordinated through the Centre for Marine Environmental Prediction Advisory Board, and critical management contributions from Jim Elliott and Raymond St-Pierre. Members of the Canadian Foundation for Climate and Atmospheric Sciences provided excellent guidance throughout.

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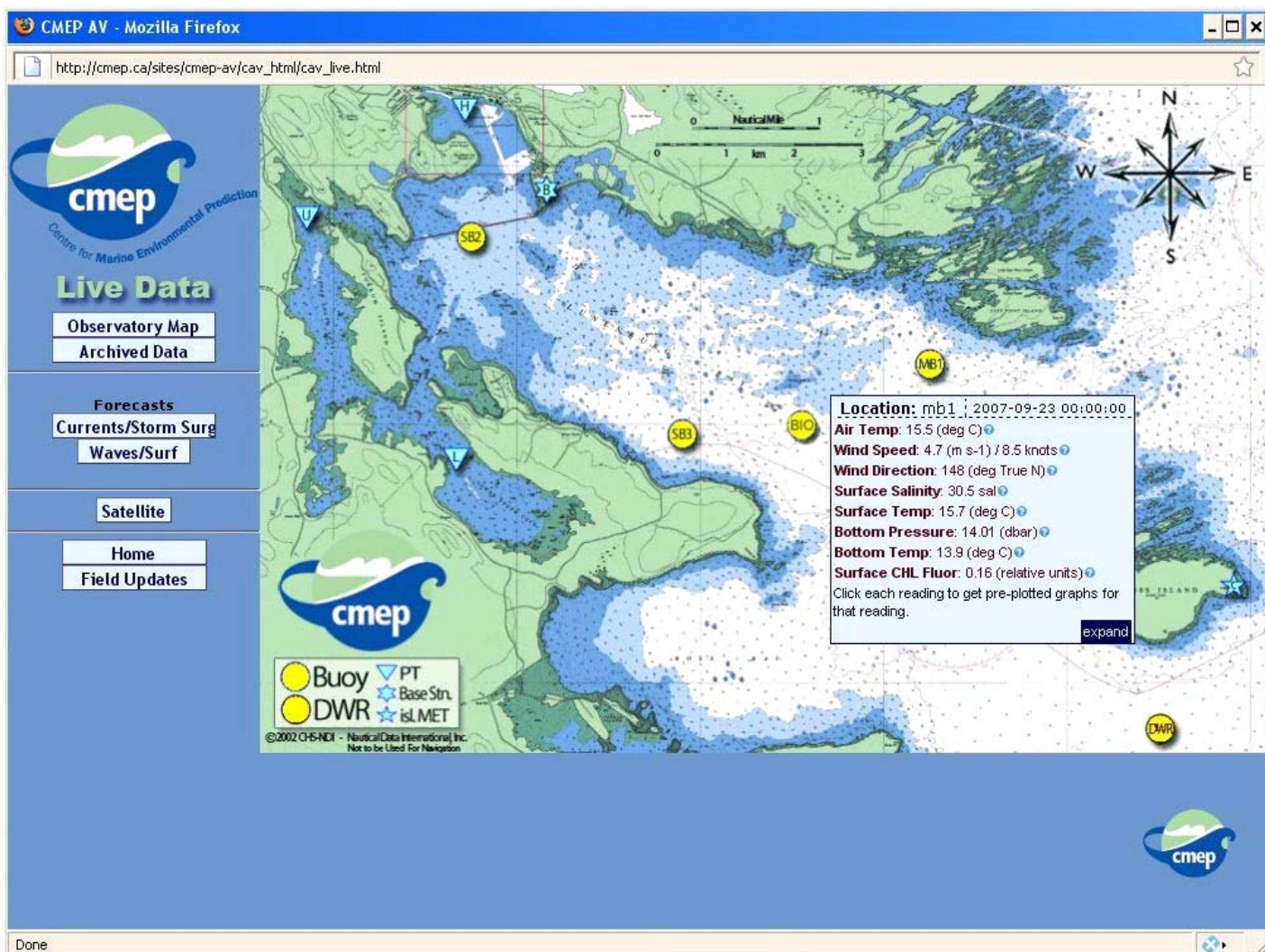


Figure 2: Lunenburg Bay Observatory web page which allowed users to access real-time meteorological and oceanographic data. Instrumentation type is indicated by the legend in the lower left of the image.

Institutional Partners

- Environment Canada <http://www.msc-smc.ec.gc.ca/>
- Department of Fisheries and Oceans <http://www.mar.dfo-mpo.gc.ca/e/homepg.htm>
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Community Partners

- Town of Lunenburg <http://www.town.lunenburg.ns.ca/>
- High Liner Foods <http://www.highlinerfoods.com/>
- Bluenose Coastal Action Foundation http://www.coastalaction.org/index_home.html
- The Rumrunner Inn <http://www.rumrunnerinn.com/>

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