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Development of a High-Resolution Coastal Circulation Model for the Ocean Observatory in Lunenburg Bay

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Abstract An advanced ocean observatory has been established in Lunenburg Bay of Nova Scotia, Canada as part of an interdisciplinary research project of marine environmental prediction. The development of a high-resolution coastal circulation model is one of important components of the observatory. The model horizontal resolution is 60 m and the vertical resolution is about 1 m. The coastal circulation model is used to simulate the semi-diurnal tidal circulation and associated nonlinear dynamics with the M_2 forcing specified at the model open boundaries. The model is also used to simulate the storm-induced circulation in the bay during Hurricane Juan in September 2003, with the model forcing to be the combination of tides and remotely generated waves specified at the model open boundaries and wind stress applied at the sea surface. The model results demonstrate strong interactions between the local wind stress, tidal forcing, and remotely generated waves during this period. Comparison of model results with the surface elevation and current observations demonstrates that the coastal circulation model has reasonable skills in simulating the tidal and storm-induced circulation in the bay.

Key Words ocean observatory; coastal circulation model; Hurricane Juan; storm-induced currents; tidal current

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1 Introduction

Ocean sciences are moving from the exploration phase to the understanding and prediction phases, with many advanced ocean observatories established in the world, including Rutgers University Long-term Ecosystem Observatories (LEO) and the Gulf of Maine Ocean Observing System (GOMOOS) in the United States, Liverpool Coastal Observatory (LCO) in the United Kingdom and the Center of Marine Environmental Prediction (CMEP) in Canada. These ocean observatories represent a fundamentally new enabling technology that permits research efforts to examine various processes on space and time scales that were not previously achievable (Jahnke *et al.*, 2002). The real-time physical, biological and chemical observations, together with predictive modelling systems, play an important role in understanding and predicting marine environmental conditions, particularly those during episodic and extreme events.

The CMEP ocean observatory provides a unique opportunity of interdisciplinary collaborations among researchers from Dalhousie University, the Meteorological Service of Canada and the Department of Fisheries and Oceans. The primary goals of the CMEP are 1) to develop an advanced, relocatable, and real-time observation and modeling system for coastal and shelf environments of the Atlantic Canada; and 2) to use this system to test and improve our ability to predict the change on short- to medium-range scales in the coastal and shelf marine environment.

Lunenburg Bay (LB) has been chosen as a test bed for the CMEP observatory. LB is a relatively shallow coastal embayment situated at the south shore of Nova Scotia, and has a surface extension of about 8 km long by 4 km wide, with water depths of less than 30 m. LB is connected to the Scotian Shelf via Mahone Bay to the northeast and Rose Bay to the southwest (Fig. 1). LB is also connected to Upper South Cove (USC) and Lower South Cove (LSC) via a narrow channel known as Corkum's Channel. The narrow channel and the mouth connecting LB and the two coves play a very important role in controlling the tidal circulation in LB and the two coves.

One of the important components of the CMEP is a real-time ocean observing system deployed in LB since 2002. The ocean observing system includes several pressure and temperature (PT) sensors and mooring buoys that measure physical and optical properties of seawaters in LB, a Directional Wave Rider and a Sea-Horse Profiler in the deep water off LB, and stations at Battery Point and Cross Island. The other important

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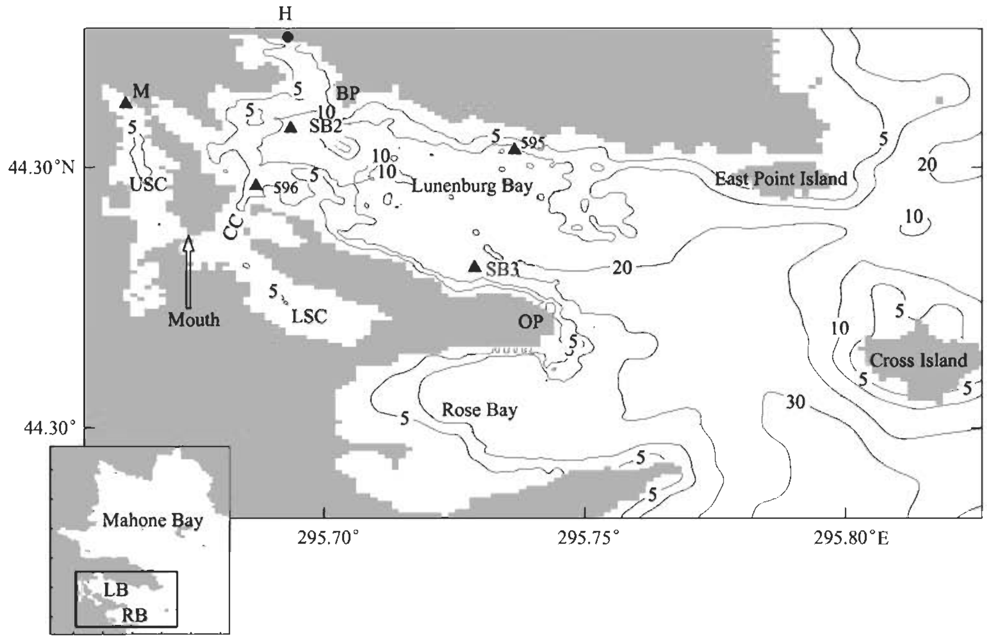

Fig.1 Major bathymetry features within the model domain of the Lunenburg Bay coastal circulation model. Contours are labeled in meters. Abbreviations are used for Corkum's Channel(CC), Upper South Cove (USC), Lower South Cove (LSC), Oven Point (OP), and Lunenburg Harbour (H). The solid triangles denote the observation locations. Inset shows a large area covering Mahone Bay, Lunenburg Bay (LB) and Rose Bay (RB).

component of the CMEP is the development of a coupled modeling system, of which the key element is a high-resolution three-dimensional coastal circulation model based on the nonlinear free-surface version of CANDIE. The coastal circulation model is coupled to other elements of the modeling system, such as an ocean wave model, an atmospheric circulation model, a coarse-resolution shelf circulation model, and a biological model. In this paper, we discuss the performance of the high-resolution coastal circulation model in simulating the tidal and wind-driven circulation in LB. Readers are referred to Sheng and Wang (2004) and Wang *et al.* (2005)① for a more detailed discussion of numerical studies of the tidal and storm-driven circulation in the bay.

The arrangement of this paper is as follows. The next section briefly discusses the coastal circulation model and external forcing. Section 3 presents numerical results of the tidal circulation and storm-induced circulation during Hurricane Juan. Section 4 discusses the performance of the coastal circulation model by comparing the model-calculated and observed surface elevations and currents at different locations and depths in LB. Section 5 is a summary and conclusion.

2 Coastal Circulation Model and External Forcing

A three-dimensional (3D) coastal circulation model of Lunenburg Bay was developed by Sheng and Wang (2004) based on the nonlinear free-surface version of CANDIE. CANDIE is a three-dimensional z-level model with the 4th order numerics and a better representation of advection terms based on the flux limiter (Sheng *et al.*, 1998). The model horizontal resolution is about 60 m, with 22 z-levels in the vertical. The vertical resolution is about 1 m except for the top z-level of 3.6 m and the last four z-levels of 4.9 m. We follow Smagorinsky (1963) for the horizontal mixing parameterization, and Davies *et al.* (1998) and Csanady (1982) for the vertical mixing parameterization. The vertical eddy viscosity coefficient K is specified in terms of the depth-mean flow and wind stress at the sea surface (Wang *et al.*, 2005):

$$K = K_f + K_s, \tag{1}$$

where K_f denotes the vertical eddy viscosity coefficient due to the depth-mean (tidal) flow and K_s due to surface wind stress. We use the following radiation condition suggested by Davies and Flather (1978) to specify the model open boundary conditions:

$$U = U_t + U_s + \frac{c}{h}(\eta - \eta_t - \eta_s), \tag{2}$$

where (U_t, U_s) and (η_t, η_s) are respectively the prescribed currents (normal to the open boundaries) and sea surface elevations due to tides and remotely generated waves at model open boundaries, and U and η are respectively the model-calculated currents and sea surface elevations. Since there were no direct measurements of U_t and U_s at the model open boundaries, U_t and U_s are set to zero for simplicity (Wang *et al.*,

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① Wang, L., J. Sheng, A. E. Hay, and D. J. Schillinger, 2005. Storm-induced circulation in Lunenburg Bay of Nova Scotia: observations and numerical simulations. *J. Phys. Oceanogr.*, (submitted).

2005). The surface elevations of tides and storm surge at model open boundaries (η_t, η_s) are determined using the simplified incremental approach discussed in Sheng and Wang (2004). The model is run in barotropic mode, with temperature and salinity set to be uniform in time and space. Readers are referred to Sheng and Wang (2004) for a more detailed description of the incremental approach and dynamic equations of the coastal circulation model.

Two numerical experiments are conducted to study the tidal and wind-driven circulation in LB. The model forcing in the first experiment (Exp-I) is the M_2 tidal forcing specified at the model open boundaries in terms of periodic sea surface elevations with an amplitude of 63 cm and a period of 12.42 h. The model forcing in the second experiment (Exp-II) is the combination of realistic tidal forcing, remotely generated waves and surface wind stress during Hurricane Juan in September 2003 (Fig.2). Remotely generated waves and wind stress in Exp-II are calculated based on the oceanographic and meteorological observations at sites SB2, SB3 and Battery Point in LB. Time series of realistic tidal sea surface elevations at model open boundaries in Exp-II is inferred from the tidal sea level prediction at Lunenburg Harbour based on the simplified incremental approach of Sheng and Wang (2004). The tidal sea level prediction at Lunenburg Harbour was produced by the Canadian Hydrographic Service using analysis of more than 60 tidal constituents determined from the historical sea level observations at the harbour.

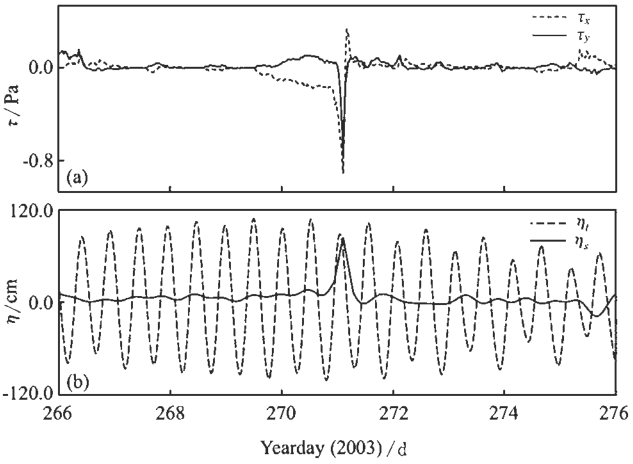

Fig.2 Time series of three types of model external forcing during Hurricane Juan. Upper panel shows the eastward (τ_x) and northward (τ_y) components of surface wind stress in Lunenburg Bay, and lower panel shows surface elevations at model open boundaries to represent tidal forcing (η_t) and remotely generated waves (η_s).

3 Simulated Tidal and Storm-induced Circulation in Lunenburg Bay

3.1 The M_2 Tidal Circulation

We first describe the M_2 tidal circulation in LB based on the model results in Exp-I (Figs.3 and 4). The model results in this experiment generate large differences in M_2 tidal surface elevations between Lunenburg Bay and Upper South Cove (USC) (Fig. 3). The phase difference in tidal surface elevations of M_2 between these two areas is about one hour and forty minutes, which agrees reasonably well to the observed phase difference of one hour and thirty minutes (Thompson *et al.*, 1998). The model-calculated M_2 tidal range in USC is about 67 percent of that in Lunenburg Bay, which also agrees reasonably well to the previous observations. The M_2 tidal circulation is characterized by a jet-like flow through Corkum's Channel that connects western LB to LSC. The model-calculated maximum jet-like flow is about 100 cm s^{-1} near the lowest sea level in LB. As discussed in Sheng and Wang (2004), the jet-like flow is dynamically balanced by non-linear advection, surface pressure gradient, mixing and local acceleration. The Coriolis forcing plays only a minor role in affecting the jet-like flow, which is expected since the barotropic Rossby radius of deformation is much larger than the horizontal scale of the jet flow. The model-calculated tidal flow ellipses of M_2 shown in Fig.4 demonstrate that near-surface tidal current ellipses of M_2 are rectilinear and almost parallel to the local bathymetry. The near-surface current ellipses of M_2 are about 10 cm s^{-1} in Lunenburg Bay and 25 cm s^{-1} in Corkum's Channel and the narrow mouth connecting LSC to USC. The amplitude of the current ellipses of M_2 near the bottom is about 50% smaller than those near the surface due to the significant damping effect of the bottom friction, except for those in Corkum's Channel, USC, LSC and several local areas in Lunenburg Bay where there is only one z-level in the vertical.

3.2 The Storm-induced Circulation During Hurricane Juan

The eastern Canadian seaboard is frequently affected by storms and hurricanes in the fall and winter. In the early morning of September 29 (yearday 271), 2003, for an example, Hurricane Juan made landfall on the south coast of Nova Scotia as a category-2 hurricane in terms of the Saffir-Simpson Scale, with the maximum sustained wind speed of about 158 km h^{-1} (Levinson and Waple, 2004). Hurricane Juan was the most damaging storm to hit Nova Scotia in more than a century and caused significant property damage and loss of several lives in the province.

We next describe the coastal circulation in LB during Hurricane Juan, based on the model results in Exp-II (Fig.5). During this period Hurricane Juan moved northward from the deep waters off the Scotian Shelf and made a landfall at yearday 271.00. As the wind stress in LB increased from 0.36 N m^{-2} (westward) at 00:06 to a maximum value of 1.11 N m^{-2}

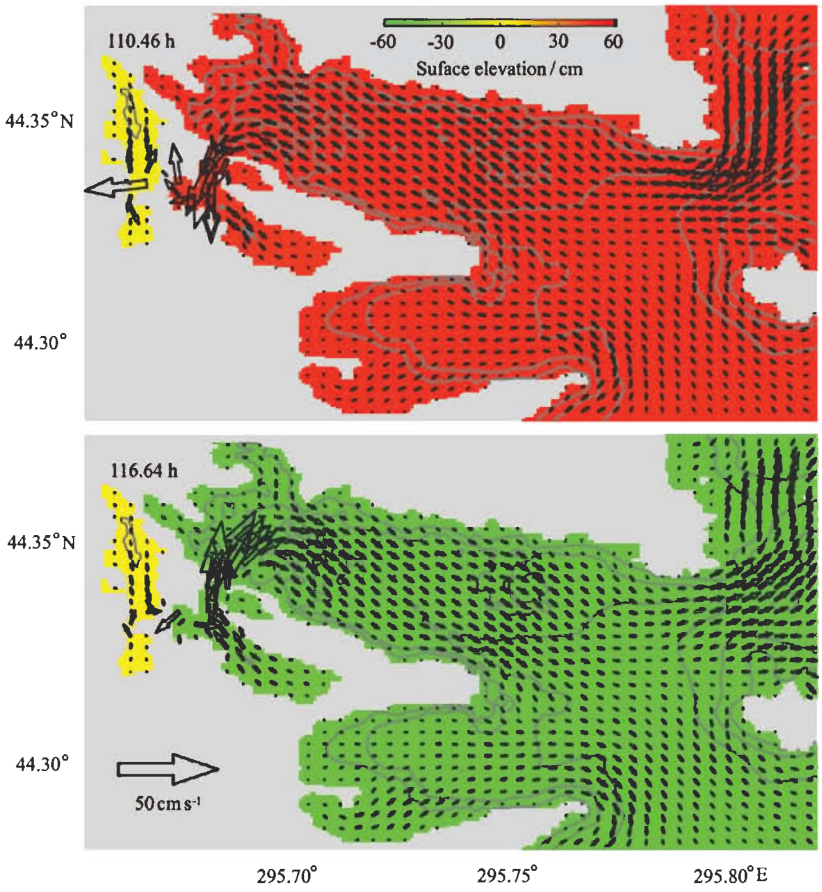

Fig.3 Model-calculated tidal circulation in Lunenburg Bay. Upper Panel shows the near surface currents near the highest sea level. Lower panel shows the currents near the lowest sea level. Colors in two panels represent the sea levels.

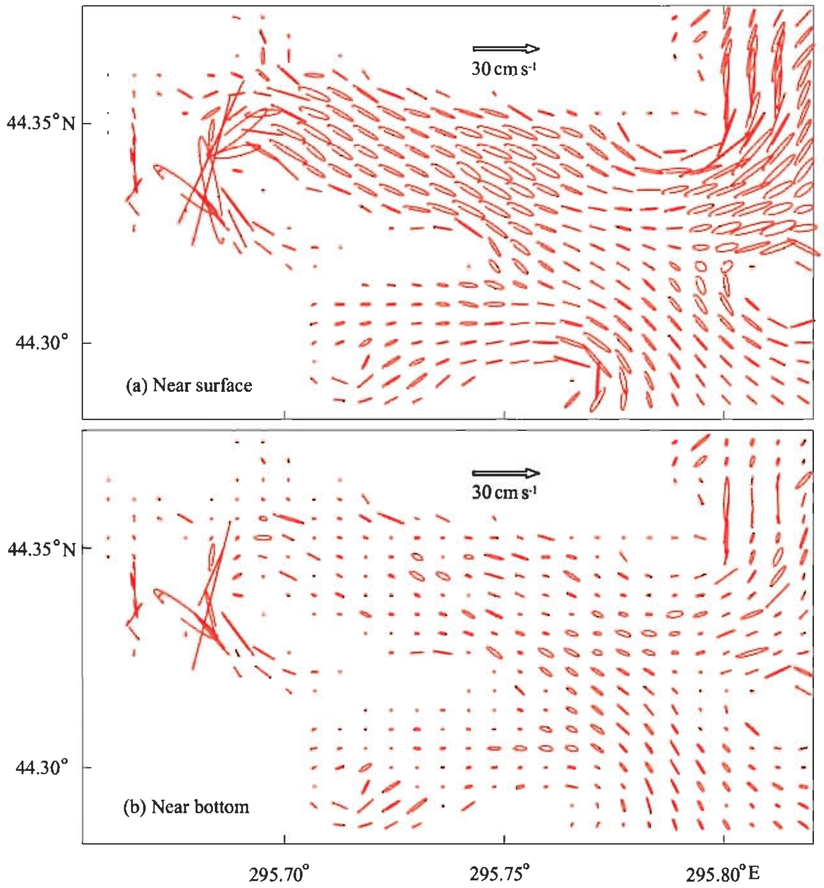

Fig.4 Model-calculated M_2 tidal ellipses near the sea surface (1.8 m) and near the bottom. The ellipses are drawn at every seventh model grid point (adopted from Sheng and Wang (2004)).

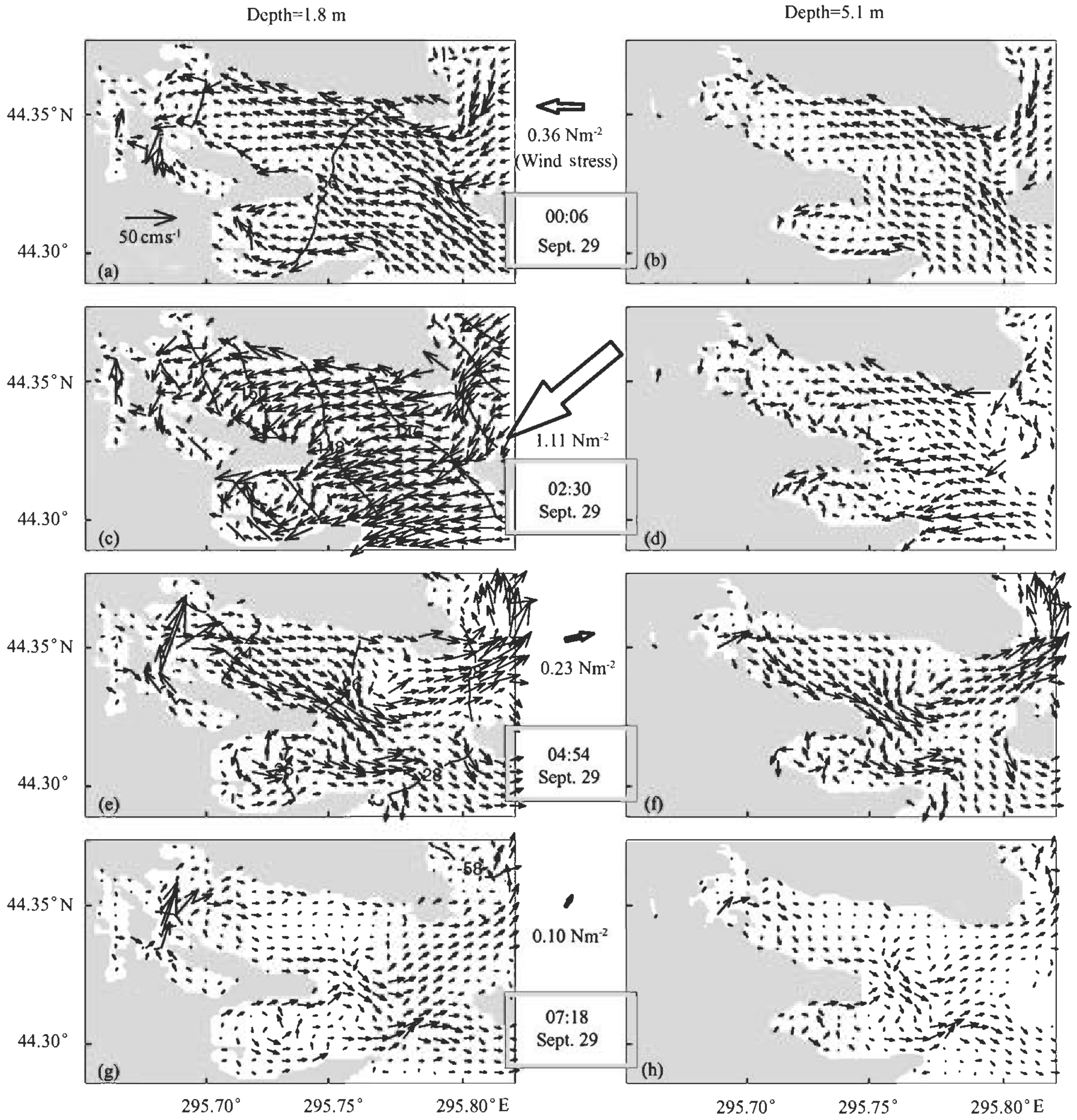

Fig.5 Simulated surface elevations, near-surface (1.8 m) currents and sub-surface (5.1 m) currents at (a, b) 00:06, (c, d) 02:30, (e, f) 04:54, and (g, h) 07:18 (UTC), September 29 (yearday 271), 2003 in the control run. Contour interval for surface elevations is 2 cm. Velocity vectors are plotted at every eighth model grid point (adopted from Wang *et al.* (2005)).

(southwestward) at 02:30, the simulated sea level in LB rises sharply from about 50 cm to 150 cm, and the simulated currents flow into Lunenburg Bay from surface to bottom with an average velocity of about 25–30 cm s^{-1}. After landfall the hurricane moved continually northward from the south coast of Nova Scotia to the Gulf of St. Lawrence and the wind direction in LB changed to the eastward and then northeastward (since LB is located to the left side of the storm track). The wind stress of Hurricane Juan decreased from 0.23 N m^{-2} at 04:54 to 0.10 N m^{-2} at 07:18. During this period the simulated sea level in the bay falls very quickly and the simulated currents turn to the east, with a strong outward jet close to the south shore of LB.

We conducted two additional numerical experiments by forcing the model with the tidal forcing and wind forcing separately (Wang *et al.*)①. The comparison of model results between these two additional experiments and Exp-Ⅱ demonstrates that the local wind stress plays an important role in generating currents and a minor role in affecting the sea level during Hurricane Juan. On the other hand, the tidal forcing and remotely generated waves make significant contribution to the total surface elevation during the same period.

To examine the nonlinear dynamics in the bay, we compare the model results in Exp-Ⅱ (nonlinear case) with those produced by a linear model, which includes a linear free surface in the continuity equation and linear bottom friction (with the linear bottom friction

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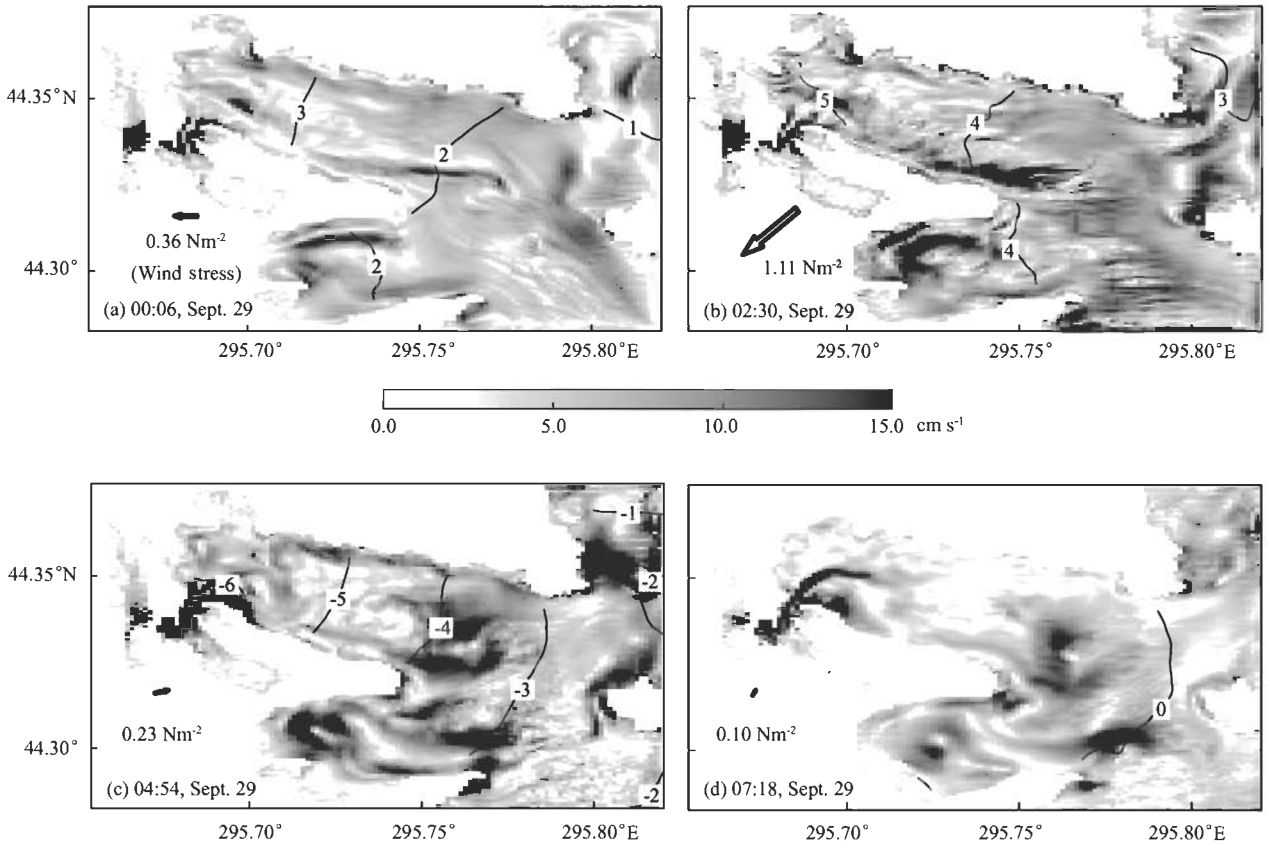

Fig.6 Differences in model-calculated surface elevations (contour lines in cm) and magnitude of currents (represented by grey scale image in unit of cm s^{-1}) between the nonlinear and linear models.

coefficient set to 0.01 cm s^{-1}) and excludes nonlinear advection terms in the momentum equations. The differences in model-calculated surface elevations and currents between the linear and nonlinear cases indicate that the storm-induced circulation in LB has significant nonlinear characteristics during Hurricane Juan. Fig.6 shows the differences in surface elevations and currents between the linear and nonlinear cases. The maximum difference in surface elevations is about -6 cm, occurring at 04:54 near the entrance of Corkum's Channel in western Lunenburg. The nonlinear dynamics still play an important role in the coastal circulation in LB at 04:54 (Fig.6c) and start to decay in Lunenburg Bay, but remain strong in Corkum's Channel at 07:18 (Fig.6d). The analysis of model results indicates that the quadratic bottom friction plays a dominant role in generating the nonlinear dynamics in LB during Hurricane Juan.

4 Assessment of Model Performance

We assess the model performance by comparing the model-calculated and observed surface elevations and currents in the first two weeks of September in 1991 and 2003. During these two periods, the tidal forcing is dominant and wind forcing is relatively weak. Readers are referred to Sheng and Wang (2004) for a more detailed discussion. The model calibration indicates that the coastal circulation model produces very well the observed surface elevations and reasonably well the observed currents in the study region (Sheng and Wang, 2004). During Hurricane Juan the observing system deployed in Lunenburg Bay provided valuable information that can be used in the model validation. We assess the model performance by comparing the simulated surface elevations and currents with the observations at different depths for nine days in LB. Hurricane Juan affected the study region during the middle of this 9-d period. An index of γ^2 defined as a variance of the model errors normalized by the observed variance is used to quantify the model performance. If the model results are exactly the same as the observations γ^2 should be zero and the model reproduces the observations perfectly. Otherwise, a larger γ^2 indicates that the model cannot produce satisfactory observations. Both simulated and observed surface elevations at four locations (SB2, SB3, Lunenburg Harbor and USC) are highly comparable and γ^2 is 0.001 at SB2 and SB3, 0.003 at Lunenburg Harbor and 0.03 at USC (Fig.7). We also compare model-calculated and observed eastward and northward components of currents at three depths of sites SB2 and SB3. Before and after the hurricane event the model-calculated eastward component of currents are in good agreement with observations when tides are dominant (Fig.8a–8f). During Hurricane Juan the model still

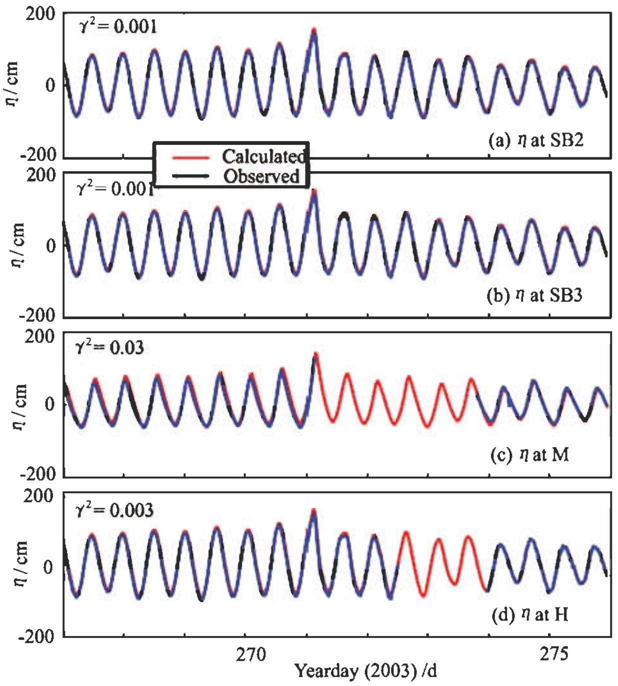

Fig.7 Time series of observed and simulated sea surface elevations at sites (a) SB2, (b) SB3, (c) M in Upper South Cove, and (d) H in Lunenburg Bay.

captures the peak signals of currents with the right phase, but overestimates the magnitude of eastward component of currents at SB2 and underestimates that at SB3. The values of γ^2 are 0.67−0.95 at SB2 and 0.21–0.34 at SB3. By contrast, the model reproduces less well the observed northward component of currents at sites SB2 and SB3. The values of γ^2 are 0.71–1.20 at SB2 and 0.41−0.61 at SB3.

In summary, the coastal circulation model reproduces less well the observed currents than the observed surface elevations in the study region, which can be explained by the following two reasons. First, coastal currents are more sensitive to the local topography than surface elevations. Any discrepancy of topographies between model and site may cause the significant difference of currents. In other words, any circulation with scales less than 60 m could not be simulated properly by the coastal circulation model. Second, the barotropic model is used in the present study by ignoring the baroclinic effect in the study region. The latest study using a baroclinic coastal circulation model demonstrates the significant influence of the baroclinic dynamics in LB (not shown in the paper).

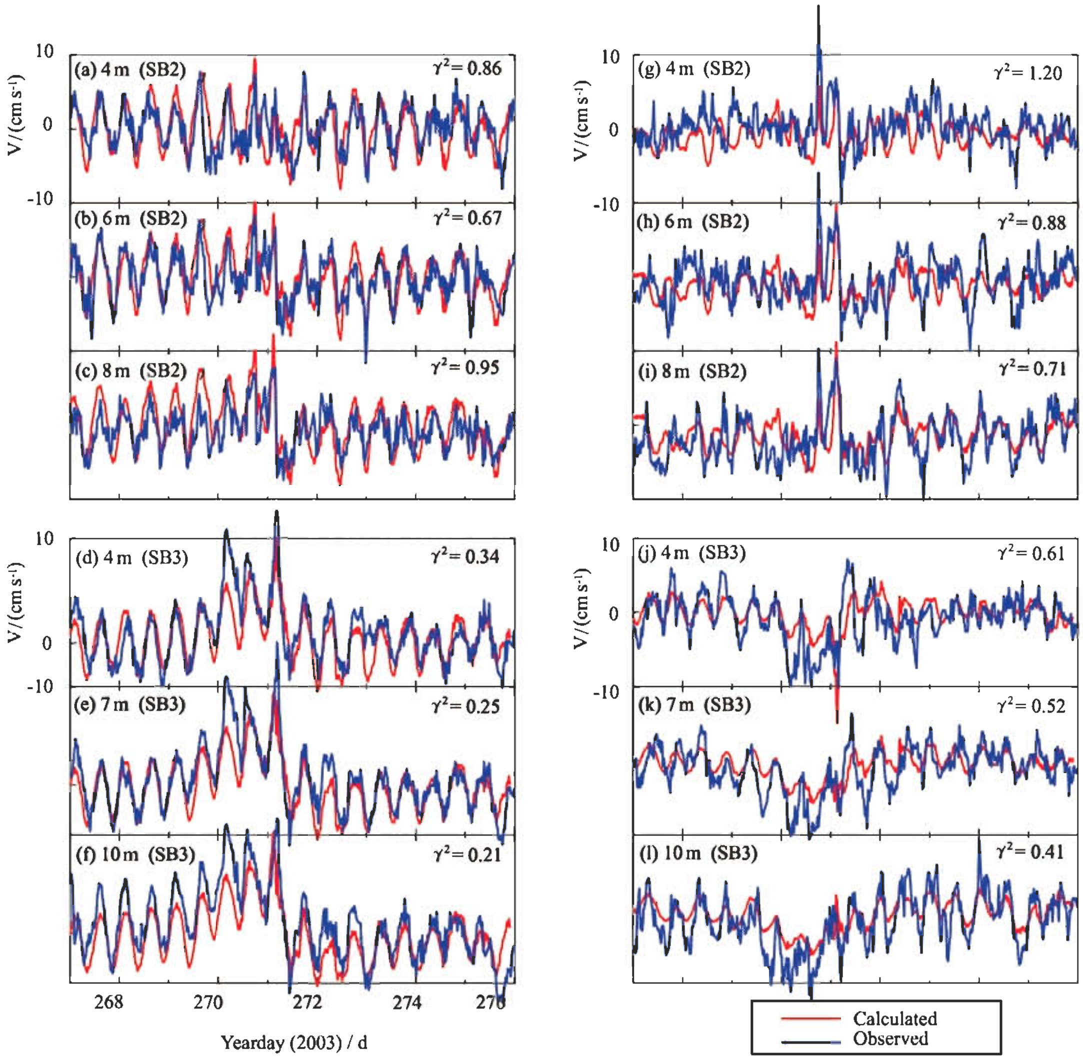

Fig.8 Time series of eastward and northward components of observed and simulated currents at depths 4, 6, and 8 m at site SB2, and those at depths 4, 7, and 10 m at site SB3.

5 Summary and Conclusion

An advanced ocean observatory has been established in Lunenburg Bay (LB) of Nova Scotia. A three-dimensional coastal circulation model was developed for the observatory. In this study, the coastal circulation model was used to study the tide-induced and storm-induced circulation in LB (Sheng and Wang, 2004; Wang *et al.*, 2005). The model-calculated M_2 tidal circulation demonstrates the significant nonlinear characteristics such as a jet-like flow through Corkum's Channel, and the significant differences in the phase and amplitude of surface elevations between Upper South Cove and Lunenburg Bay. The simulated M_2 tidal currents are rectilinear and almost tangential to the local bathymetry. Corkum's Channel and the narrow mouth connecting western Lunenburg Bay to Upper South Cove are two important hydraulic controls which generate significant nonlinear dynamics in the study region. The model results demonstrate the important effects of tides and remotely generated waves on surface elevation, and wind stress on currents during Hurricane Juan. The model results also demonstrate that the nonlinear dynamics are due mainly to the quadratic bottom friction during Hurricane Juan. Assessment of model performance demonstrates that the model has reasonable skills in reproducing the observed surface elevations and currents in the study region.

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