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Baroclinic dynamics of wind-driven circulation in a stratified bay: A numerical study using models of varying complexity

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ABSTRACT

The baroclinic response of a stratified coastal embayment (Lunenburg Bay of Nova Scotia) to the observed wind forcing is examined using two numerical models. A linear baroclinic model based on the normal mode approach shows skill at reproducing the observed isotherm movements and sub-surface currents during a time of strong stratification in the bay. The linear model also shows that the isotherm movement in Lunenburg Bay is influenced by the wind forcing and propagation of baroclinic Kelvin waves from neighbouring Mahone Bay. The effects of nonlinearity and topography are investigated using a three-dimensional nonlinear coastal circulation model. The nonlinear model results demonstrate that the nonlinear advection terms generate a gyre circulation at the entrance of Lunenburg Bay, and the slope bottom topography at the mouth of the bay strengthens the sub-surface time-mean inflow on the southern side of the bay. A comparison of model-calculated currents in different numerical experiments clearly shows that baroclinicity plays a dominant role in the dynamics of wind-driven circulation in Lunenburg Bay.

1. Introduction

Circulation over eastern Canadian coastal waters is affected by tides, wind and buoyancy forcing associated with heat and fresh water fluxes. The highly irregular coastline and variable bottom topography in the region pose a great challenge that has to be overcome if we are to understand and predict the hydrography and three-dimensional circulation of the region. Lunenburg Bay (LB) of Nova Scotia, Canada (Fig. 1) was therefore chosen as a test site for the development of a prototype modeling and observation network that could be used for marine prediction in the region. Better understanding of the dynamic response of coastal waters to forcing will help improve our ability to accurately model coastal circulation and hydrography. The barotropic dynamics of LB have been extensively studied (Sturley and Bowen, 1996; Thompson et al., 1998; Sheng and Wang, 2004; Wang et al., 2007; Sheng et al., 2008; Mulligan et al., 2008), whereas our understanding of the baroclinic dynamics of LB is still in its infancy (a start has been made in Zhai et al., 2007, 2008). Wang et al. (2007) demonstrated that the barotropic circulation in the bay is significantly affected by local wind. Zhai et al. (2008) showed that the baroclinic circulation and associated high frequency variation (time scales of 1–10 days) of temperature and salinity in the bay are also mainly forced by local wind. The semi-diurnal (M_2) tidal currents also play a role in affecting temperature and salinity distributions in the bay, particularly near Corkum's Channel and in the two connecting coves. In this study, we try to better understand the baroclinic response of LB to wind forcing using a hierarchy of models ranging from a linear baroclinic model, based on the normal mode approach with a flat bottom, to a fully nonlinear model with variable bottom topography.

The baroclinic response of coastal bays and inlets to wind forcing is generally characterized by coastal upwelling/downwelling and baroclinic coastal trapped waves, and can sometimes be approximated by linear baroclinic dynamics. Three types of baroclinic coastal waves were studied in the past, including baroclinic Kelvin waves, baroclinic Poincaré waves and topographic waves. Csanady and Scott (1974) studied baroclinic coastal jets in Lake Ontario using a theoretical model for a two-layer, long and narrow lake. Wang (1975) examined the baroclinic Kelvin waves and topographic Rossby waves in a two-layer water with a slope bottom. Crèpon and Richez (1982) and Crèpon et al. (1984) investigated the effect of capes and bays on the coastal upwelling analytically, and showed that Kelvin waves and Poincaré waves can be generated by the irregular coastline. deYoung et al. (1993b) demonstrated the nonlocal effect of Kelvin wave propagation into Conception Bay from neighbouring Trinity Bay in Newfoundland Canada, and Davidson et al. (2001) further showed that the asymmetric response of Conception Bay to wind forcing is associated with the higher-order baroclinic modes. Gan et al.

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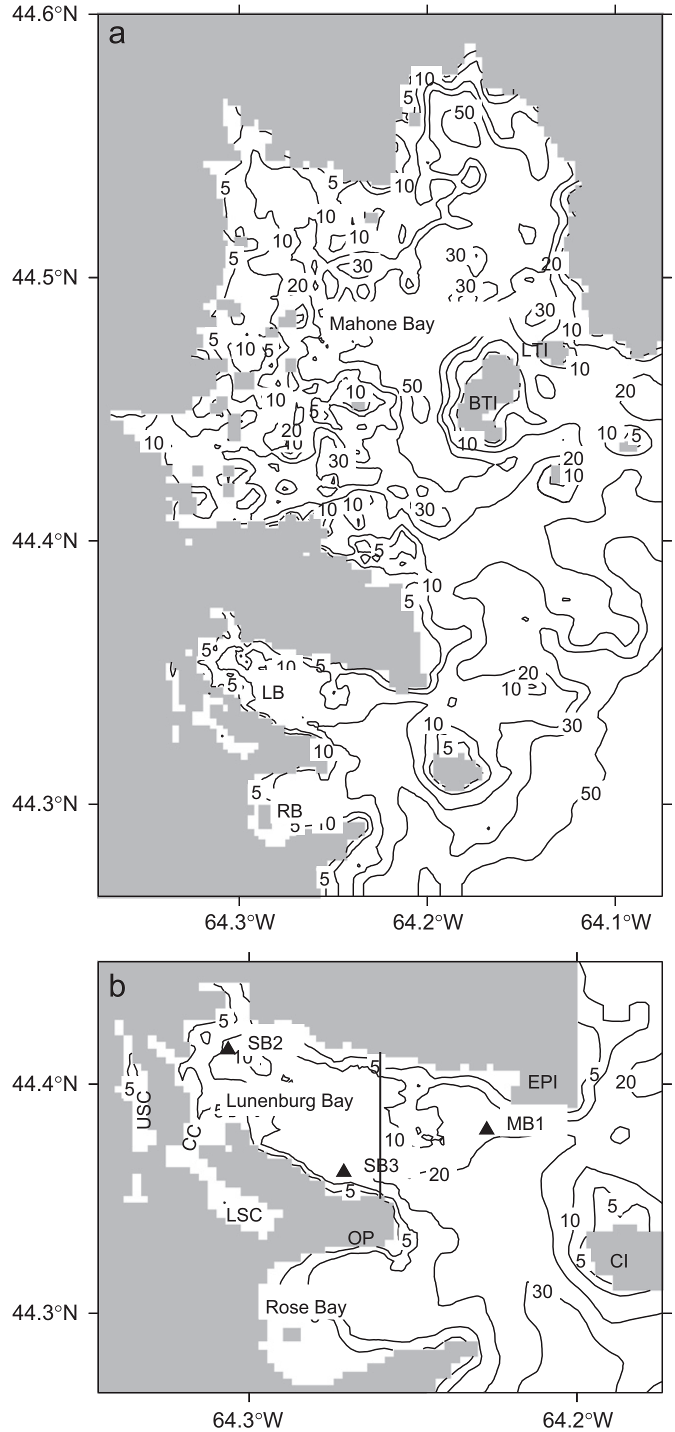

Fig. 1. Model domains of (a) Mahone Bay (MB), Lunenburg Bay (LB) and Rose Bay (RB), and (b) Lunenburg Bay and Rose Bay. Abbreviations used: Big Tancook Island (BTI), Little Tancook Island (LTI), Upper South Cove (USC), Lower South Cove (LSC), East Point Island (EPI), Cross Island (CI) and Corkum's Channel (CC). The solid triangles in (b) denote mooring buoys. Model results along the transect due north from Ovens Point (OP) in (b) are discussed in Sections 3 and 4.

(1997) investigated the impact of the baroclinic Gaspé Current on the circulation in the Baie des Chaleurs of the Gulf of St. Lawrence, Canada.

In this paper, we first demonstrate that a simple linear baroclinic model based on the normal mode approach (hereafter the multi-mode model, McCreary, 1981a) is able to capture the main physical processes necessary to understand the baroclinic circulation and upwelling and downwelling in the bay. The main advantage of the normal mode approach is that the governing equations for the mode coefficients and vertical normal modes are separated and that the baroclinic response is easily illustrated (Gill, 1982). We then use the nonlinear coastal circulation model described by Zhai et al. (2008) to examine the nonlinear and topographic effects. The arrangement of the paper is as follows. In Section 2, the main features of the observations relevant to this study are briefly discussed together with some thoughts on the relevant dynamics. In Section 3, the multi-mode model is applied to LB and Mahone Bay (MB) with a flat bottom to investigate the remote effect of propagation of baroclinic Kelvin waves from MB to LB. In Section 4 the fully nonlinear and three-dimensional coastal circulation model described in Zhai et al. (2008) is used to investigate the influence of topography and nonlinearity neglected in the linear multi-mode model. Results are discussed, and conclusions are made in Section 5.

2. Observations and dynamical considerations in LB

Three moorings (shown in Fig. 1) were deployed at sites SB2, SB3 and MB1 in LB to acquire observations of wind vectors, hydrography and currents (see Zhai et al., 2007, for the details). August 13 (day 224) to September 7 (day 249) in 2003 is chosen as the study period. This was a period with strong vertical stratification in LB, during which the baroclinicity plays an important role in the coastal circulation in the bay. The wind stress calculated from the observed wind speed at the mooring SB3 as well as observed temperatures at different depths at SB3, SB2 and MB1 during this period are shown in Fig. 2. The bulk formula suggested by Large and Pond (1981) is used in converting the observed wind velocity to wind stress. Mean wind stress during this period is about 0.18 dyn cm^{-2}, and points in the direction of $\sim 22^\circ$ measured anti-clockwise from east. The standard deviation of the wind stress is greater than the mean with a magnitude of 0.42 dyn cm^{-2}, 68% of which is associated with the major axis (64.2° measured anti-clockwise from east and pointing northward across the bay), and the remaining variance is associated with the minor axis. Multiple regression analysis indicates that the variability of observed temperatures at the three mooring sites (shown in Fig. 1) can be partially explained by the past history (within 12 h) of wind forcing during the period (Zhai et al., 2007). The observed temperatures at fixed depths can be used to estimate the vertical motion of the isotherm. The decrease (increase) in temperatures at different depths at the three moorings is associated with the upward (downward) movement of the isotherm. From day 233 (August 21) to day 238 when the wind stress changed from northeastward (across-bay) to southeastward (along bay), the observed temperatures at the three mooring locations decreased first due to the upwelling induced by Ekman divergence, and then gradually increased due to downwelling (Fig. 2). We show in the next section that this downwelling event is mainly associated with the propagation of baroclinic Kelvin waves from MB to LB.

Previous studies demonstrated that the strong stratification in LB in August and early September of 2003 was mainly maintained by the heat and fresh water input at the sea surface and the wind-induced upwelling of the relatively cold and saline near-bottom waters (Zhai et al., 2007, 2008). Based on the area-averaged density profile (Fig. 3a) made by the CTD surveys on September 6, 2003, which is representative during the study period, the first four baroclinic vertical modes (Fig. 3c) are calculated from the buoyancy frequency $N^2 = -(g/\rho_0)(\partial\sigma_t/\partial z)$, where $g = 9.8\,\mathrm{m\,s^{-2}}$, $\rho_0 = 1024\,\mathrm{kg\,m^{-3}}$ and σ_t is the in situ density (see Eq. (A.2) in