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Physical processes affecting circulation and hydrography in the Sable Gully of Nova Scotia

Shiliang Shan [a,*], Jinyu Sheng [a], Blair J.W. Greenan [b]

[a] Department of Oceanography, Dalhousie University, 1355 Oxford Street, POB 15000, Halifax, Nova Scotia, Canada B3H 4R2
[b] Ocean and Ecosystem Sciences Division, Bedford Institute of Oceanography, Department of Fisheries and Oceans, Dartmouth, Canada B2Y 4A2

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ABSTRACT

The Sable Gully is the largest submarine canyon along the shelf break off the east coast of North America. The circulation and hydrography in the Gully have significant temporal and spatial variability. This paper presents a numerical study of the three-dimensional circulation and hydrography in the Gully using a multi-nested ocean circulation model. The model is forced by tides, wind stress and surface heat/freshwater fluxes. Model results are in fair agreement with the current and hydrographic observations made in the Gully in 2006 and 2007. A process study is conducted to examine the main physical processes affecting the circulation and hydrography, including tide–topography interaction, wind forcing, and the shelf-scale circulation over the eastern Canadian Shelf. The model results demonstrate that the circulation and hydrography above the canyon rim are influenced significantly by wind, particularly during storm events, while the subsurface flow over the shelf slope is affected by the shelf-scale circulation. There is also significant tide–topography interaction inside the Gully.

1. Introduction

The Sable Gully is the largest submarine canyon along the east coast of North America, with a dimension of over 40 km long and about 10 km wide. The Gully has water depths of over 2000 m near its mouth and it narrows significantly along its sinuous axis toward the head (Fig. 1E). The Gully is located about 40 km east of Sable Island, which is a narrow, crescent-shaped sandbar on the edge of the Scotian Shelf. The eastern and western flanks of the Gully are shallow banks known as Sable and Banquereau Banks, with water depths less than 200 m. The Laurentian Channel is located about 150 km to the east of the Gully, forming a trough of 300–400 m depth and spanning from the Gulf of St. Lawrence to the continental slope. As a hotspot of biodiversity, the Sable Gully was designated as a Marine Protected Area (MPA) in 2004. For an up-to-date report on the ecosystem of the Gully, the reader is referred to Kenchington et al. (under review) and MacIsaac et al. (under review).

Previous studies demonstrated that the circulation over the Sable Gully is influenced by tides, wind forcing and large-scale oceanic circulation over the eastern Canadian shelf. The M_2 and K_1 tidal constituents are the dominant semidiurnal and diurnal tidal constituents in the Gully and other areas of the Scotian Shelf (Dupont et al., 2002). Wind observations from the weather station on Sable Island have demonstrated large seasonal variability in wind speeds and directions, with the predominant wind changing from southwesterly in summer to northwesterly in winter. The shelf-scale ocean currents that affect the circulation over the Gully have three parts: the offshore branch of the equatorward Labrador Current; the outflow from the Gulf of St. Lawrence; and the poleward Slope Water Jet (Csanady and Hamilton, 1988). The offshore branch of the Labrador Current reaches the eastern Scotian Shelf by flowing equatorward around the Tail of Grand Banks and crossing the Laurentian Channel. The low-salinity estuarine water over the western Gulf of St. Lawrence emanates from the Gulf and flows southeastward along the western side of the Laurentian Channel. Part of this low-salinity estuarine water moves onto the eastern Scotian Shelf after passing western Cabot Strait. The rest of the estuarine water follows the Laurentian Channel and joins the Labrador Current at the shelf break. To the south of the Scotian Shelf break, the warm and salty Slope Water Jet flows northeastward. Based on sparse observations and diagnostic models (Petrie et al., 1998; Han et al., 2001; Han and Loder, 2003), the time-mean circulation in the Sable Gully was characterized by a partial cyclonic circulation. A southwestward shelf-break jet occurs outside the mouth of the Gully. On the eastern side of the Gully, a branch of the shelfbreak jet follows the isobaths and turns into the Gully. There is a return flow on the western side of the Gully.

It was suggested that the circulation in the Gully plays an important role in the across-shelf exchanges of nutrients, and the enhanced mixing within the canyon helps to sustain the high biological productivity in the Gully Marine Protected Area (Strain and Yeats, 2005). These processes are, however, poorly understood

* Corresponding author. Tel.: +1 902 494 7007; fax: +1 902 494 3877.
E-mail address: sshan@phys.ocean.dal.ca (S. Shan).

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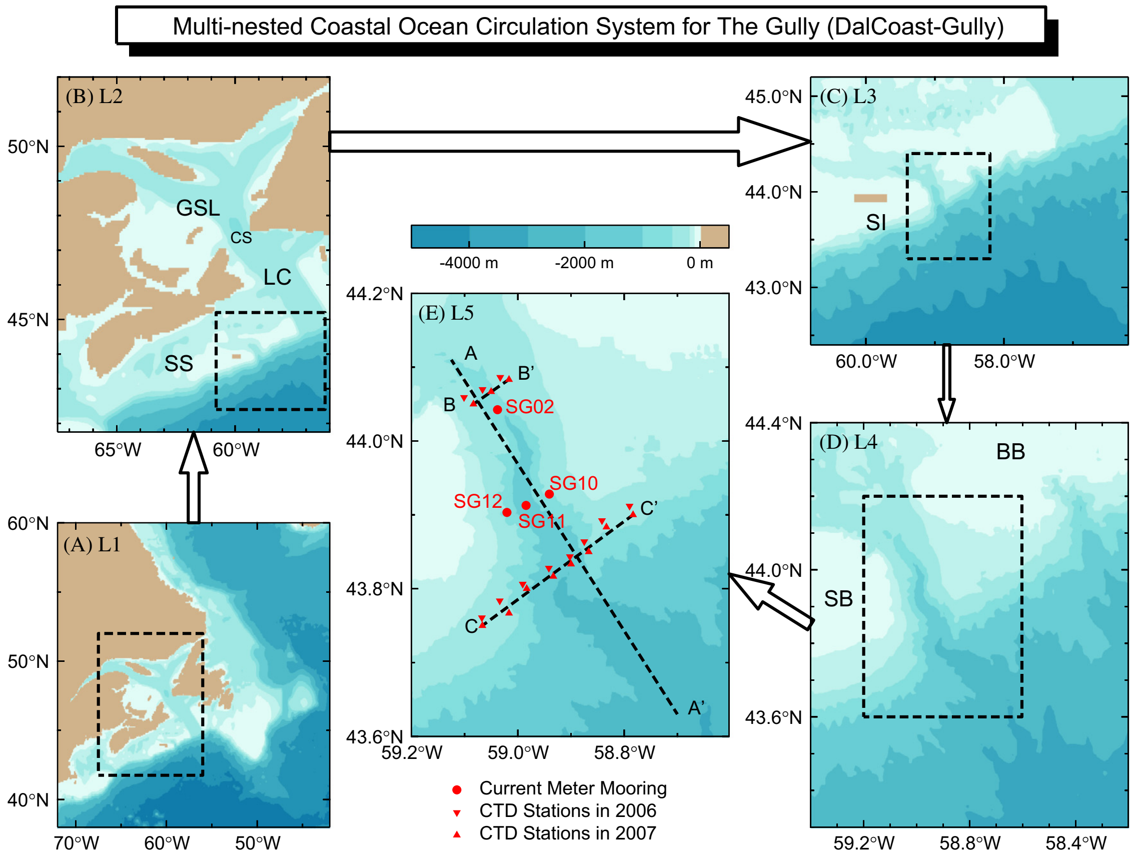

Fig. 1. Major topographic features and domains of the five-level multi-nested modelling system for the Sable Gully and adjacent waters. Submodels (A) L1 and (B) L2 are based on DalCoast (Thompson et al., 2007), with horizontal resolutions of (1/12)° and (1/16)°, respectively. Submodels (C) L3, (D) L4 and (E) L5 are based on CANDIE (Sheng et al., 1998), with horizontal resolutions of ~2 km, ~1 km and ~500 m, respectively. The one arc-minute global relief dataset (ETOPO1, http://www.ngdc.noaa.gov/mgg/global/global.html) was used for the bathymetry of L3. Bathymetry of submodels L4 and L5 is based on the multibeam observations. Red dots in (E), indicate positions of four current moorings: SG02, SG10, SG11 and SG12; the dashed lines represent three transects along the longitudinal axis of the Sable Gully (AA'); and across the head (BB') and mouth (CC') of the Gully. Triangles in (E) denote CTD (conductivity, temperature, and depth) stations on the transects. Land is masked in tan colour. Scotian Shelf (SS), Gulf of St. Lawrence (GSL), Laurentian Channel (LC) and Cabot Strait (CS) are marked in (B). Sable Island (SI) is marked in (C). Sable Bank (SB) and Banquereau Bank (BB) are marked in (D). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

due to relatively sparse observations available in the Gully. Limited modelling efforts have been made to understand the circulation pattern in the Gully. de Margerie and Lank (1986) demonstrated relatively strong tidal currents over shallow banks and relatively weak tidal currents in deep waters of the Gully using a two-dimensional (2D) tidal model. Swart et al. (2011) examined the tidal currents based on mooring observations and employed a simple idealized 1.5-layer, linear model to examine the amplification of tidal currents in the Gully. They suggested that the observed strong diurnal currents in the Gully are amplified by resonance. Hannah et al. (2001) studied the seasonal circulation on the Western and Central Scotian Shelf based on a short-term prognostic refinement of seasonal mean observational ocean state using a finite element model and found a seasonally varying partial cyclonic circulation over the Gully, with onshore flow on its eastern side in spring, summer and fall. Han et al. (2001) developed a diagnostic ocean circulation model for the eastern Scotian Shelf to examine the three-dimensional (3D) tidal currents and seasonal mean circulation. The diagnostic model (in which model temperature and salinity are prescribed) had a resolution of ~2 km for the Gully with 61 vertical levels, and was integrated only for 6–8 M_2 cycles. Simulations of the 3D circulation and hydrography using a prognostic model (in which model temperature and salinity are allowed to evolve with model flow field) have not been made for the Gully. The Sable Gully's complex topography and unique physical attributes pose a great challenge for numerical modelling over the Gully and adjacent waters. The main objectives of this study are, therefore, to simulate the 3D circulation and hydrography and examine the main physical processes over the Sable Gully using a multi-nested ocean circulation model with realistic topography and a suite of forcing functions.

This paper is organized as follows. A multi-nested ocean circulation model for the Sable Gully is described in Section 2. The model performance is assessed in Section 3 by comparing model results with oceanographic observations. The major physical processes affecting the circulation and hydrography in the Gully and adjacent waters are discussed in Section 4 based on model results in different experiments. The results of this study are summarized in the final section.

2. Multi-nested circulation model

The ocean circulation model used in this study was modified from the circulation modelling system developed previously for two coastal waters along the Nova Scotia coast: Lunenburg Bay (DalCoast-LB, Yang and Sheng, 2008) and Halifax Harbour (DalCoast-HFX, Shan et al., 2011). Both DalCoast-LB and DalCoast-HFX were extensively validated against observations. In this study, the three inner-most submodels of DalCoast-HFX are reallocated to the Sable Gully and adjacent waters for covering the core of the Gully Marine Protected Area. The inner-most submodel of the Gully is modified to have a finer resolution in the vertical to accommodate the steep bathymetry and unique attributes of the