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Surficial sediment stability on Georges Bank, in the Great South Channel and on eastern Nantucket Shoals

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ABSTRACT

Surficial sediment stability was estimated on Georges Bank, in the Great South Channel and on eastern Nantucket Shoals (36,699 km^2) by determining where benthic shear stresses derived from an ocean model matched or exceeded the critical shear stress of the observed surficial sediments. The shear stress resulting from M_2 and S_2 semi-diurnal tides was estimated with the Finite-Volume Community Ocean Model. Mixed-sediment critical shear stress levels were calculated for sediment compositions ranging from sand to boulder-dominated using 67,400 underwater video quadrats sampled from 1999 to 2010. Stresses matched or exceeded the sediment critical levels in 16,926 km^2 (46%) of the study area, and were inversely related to water depth (r^2=69.1%). In depths >50 m (10,953 km^2) all sediments were stable due to weak flow (≤ 0.4 N m^{-2}). In the shallower higher flow areas (>0.4 N m^{-2}, 25,716 km^2) only sediments containing gravel remained stable. The largest stresses occurred on Nantucket Shoals and central and northeastern Georges Bank (≥ 2 N m^{-2}); in these areas only sand with cobbles or sediments dominated by gravel remained stable. Outcrops of these stable sediments were surrounded by highly unstable areas with stresses 2 to 9 times higher than the sediment critical levels. This analysis identifies the locations which likely remain stable even under the high shear stresses typical of Georges Bank, the Great South Channel and eastern Nantucket Shoals. Further, we provide the map products needed to begin investigating the influences of natural sediment disturbance on the spatial and temporal patterns of the benthos including the resilience of stable versus unstable areas to anthropogenic disturbances.

1. Introduction

Sediment stability influences the spatial distributions of benthic organisms in freshwater and marine ecosystems including mussels in the Upper Mississippi River (Morales et al., 2006), and benthic megafaunal community assemblages in the Northwest Atlantic (Kostylev et al., 2005). Unstable sediments can cause direct mortality (e.g., burial by moving sediments), result in increased competition for space (e.g., stable holdfast sites), and impose increased energy demands (e.g., gill clearance in filter feeders) on organisms living at the sediment–water interface (see Gray and Elliot, 2009; Zajac, 1999, 2001, 2008).

East of Cape Cod Massachusetts, USA, lays Nantucket Shoals the Great South Channel and Georges Bank. This area contains an historically productive marine ecosystem which presently yields annual fishery landings worth >0.5 billion US dollars (Backus and Bourne, 1987; Harris and Stokesbury, 2010; Fig. 1). The retreat of the Laurentide ice sheet in the late Pleistocene and subsequent sea level rise ($\sim$140 m) left behind a submerged 13,000 km^2 gravelly glacial moraine stretching from Cape Cod east and north to the outer edge of Georges Bank (Wigley, 1961; Twichell, 1983; Harris and Stokesbury, 2010). Tidal currents over the region are strong and the principal lunar (M_2) and solar (S_2) semi-diurnal tidal constituents account for 80–90% of the kinetic energy annually (Butman, 1987a; Werner et al., 2003). Tidal flows regularly rework the finer sediments (Wigley, 1961; Butman, 1987a), but due to limited information on the spatial distribution of coarser gravel sediments the specific locations of stable and unstable seabed are undefined.

Shear stress is the force per unit area exerted on the seabed by flowing water and is generally given in Newtons m^{-2}. It includes drag caused by and acting on sediment particles (skin friction), bed forms (form drag), and suspended sediments (transport drag, Soulsby, 1997). The skin friction component (τ_{0s}) acts directly on the sediments and is used to calculate their critical shear stress (τ_{cr}), the force required to start the particle moving (Soulsby, 1997). The τ_{cr} levels of mixed sand and gravel sediments have

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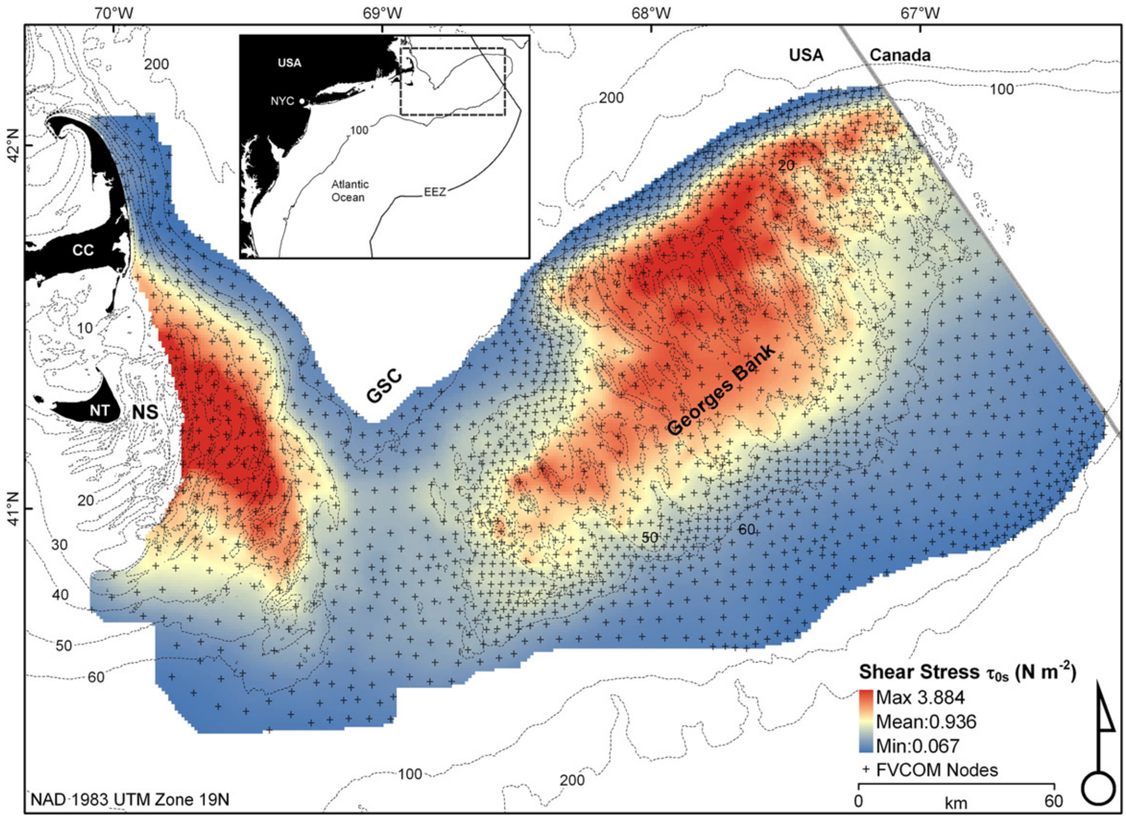

Fig. 1. Map of τ_{0s} and FVCOM nodes (N=1809). The inset shows the location of the study area (dashed box) relative to the east coast of the USA, New York City (NYC) and the Exclusive Economic Zone (EEZ). The Great South Channel (GSC), Nantucket Shoals (NS), Cape Cod, MA (CC) and Nantucket, MA (NT) and the 10–60 m, 100 m and 200 m isobaths are also shown.

been modeled, and validated with direct observations, in rivers and streams (Komar, 1987; Lorang and Haurer, 2003).

Our aim was to identify the stable sediments on Georges Bank, the adjacent Great South Channel, and the eastern part of Nantucket Shoals. Sediment was deemed to be "stable" when model-derived shear stresses from frequent and regularly occurring semi-diurnal lunar and solar tides did not exceed the sediment's critical level. We calculated a sediment stability index ($\xi=\tau_{0s}/\tau_{cr}$) using τ_{0s} predictions from the Finite-Volume Community Ocean Model (FVCOM, Chen et al., 2003, 2006; Cowles, 2008a) and τ_{cr} based on the sediment compositions observed in 67,400 video quadrat samples (Harris and Stokesbury, 2010). We hypothesized (1) that shear stresses would exceed the critical sediment thresholds in most of the study area, but (2) that there were outcrops of gravel sediments that remained stable even under very large stresses.

2. Methods

2.1. Estimating shear stress (τ_{0s})

Estimates of the shear stresses were made at 1809 locations in the study area using a regional tidal database application of the FVCOM (Fig. 1, Chen et al., 2011). FVCOM is an open source Fortran90 software package for simulating ocean processes in coastal regions. It was developed in the Marine Ecosystem Dynamics Modeling Laboratory at the University of Massachusetts Dartmouth, Department of Fisheries Oceanography (http://fvcom.smast.umassd.edu/FVCOM). The model computes a solution of the hydrostatic primitive equations on an unstructured triangular grid using a finite-volume flux formulation (for details see Chen et al., 2003, 2006; Cowles, 2008a).

The FVCOM Gulf of Maine tidal model extends from the Scotian Shelf south to the New England Shelf and encompasses all of Nantucket Shoals, the Great South Channel and Georges Bank (Chen et al., 2011). The model employs 45 vertical layers, and in the study area the horizontal resolution ranges from 0.5 km to 2.0 km (Fig. 1). The model sea surface elevation is forced at the open boundary using eight regional tidal harmonics (M_2, N_2, S_2, K_1, K_2, O_2, P_1,Q_1) derived from the Egbert and Erofeeva (2002) 1/6° tidal database. The model is integrated for two months and the flowfield is archived at hourly intervals. Model-computed currents and sea level are decomposed into tidal constituents using a least squares harmonic method (Foreman, 1977). The FVCOM Gulf of Maine tidal model was validated through comparison with tidal current observations from 130 stations and tidal elevation measurements at 98 sites (Chen et al., 2011).

Mean maximum bi-weekly benthic boundary shear stresses were estimated using the sum of the M_2 and S_2 constituents of the tidal currents. The logarithmic law of the wall formulation with a depth dependent seabed roughness (Bradshaw and Huang, 1995; for equations see Chen et al., 2003 and Cowles et al., 2008b) was used to derive the stress from the bottom tidal velocities.

2.2. Estimating critical shear stress (τ_{cr})

The critical shear stress levels (τ_{cr}) were calculated following Lorang and Hauer (2003).

$$\tau_{cr}=\theta_{cr}g(\rho_s-\rho){d_{50}}^{1-a}{d_{\max}}^{a} \tag{1}$$

where θ_{cr} is the adjusted Shield's parameter=0.045 (Komar, 1987), g is acceleration due to gravity=9.81 m s^{-2}, ρ_s is sediment grain