NUMERICAL MODELLING OF SEABED DISTURBANCE AND SEDIMENT MOBILITY, WITH APPLICATIONS TO MORPHODYNAMICS ON THE STORM-DOMINATED SABLE ISLAND BANK, SCOTIAN SHELF

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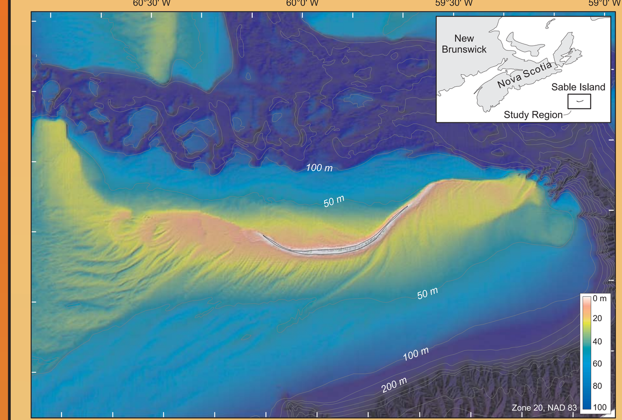
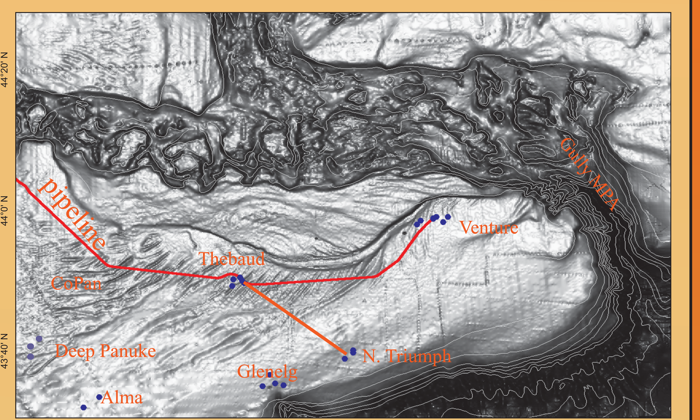
Abstract

Waves, tidal currents, wind-driven and circulation currents, and sediment mobility were modelled for one full year over the storm-dominated Sable Island Bank (SIB), Scotian Shelf. The mean shear velocity of tidal current and that of the wind-driven and circulation current are less than 2 cm/s, but the peak mean wave and combined wave-current shear velocities reach 4 and 4.5 cm/s respectively. Comparison between the model-predicted shear velocity and bedload threshold suggests that the circulation and wind-driven currents cause minimum sediment mobility on SIB. Tidal current and waves can each cause sediment mobility at least once a year over 36% and 71% of the bank area respectively, while the combined wave-current shear can cause sediment mobility over 93% of the bank area. Calculated time percentages of sediment mobility caused by various processes indicate that wave or wave-dominant disturbance is most important and occurs over >50% of the bank area, while mixed disturbance is also significant and occurs over ~ 30% of the bank area. Tide or tide-dominant disturbance occurs over only 10% of the bank area. Several parameters are proposed as universal indices for quantifying seabed disturbance and sediment mobility for coastal and shelf environments. The distribution and mobility of various mid-sized bedforms were correlated with the seabed disturbance parameters. Updated bedform distribution was compared with seabed disturbance predictions to define seven bedform zones on SIB.

INTRODUCTION



Shaded relief bathymetry of Sable Island Bank, Scotian Shelf (Webb and King, 2008).

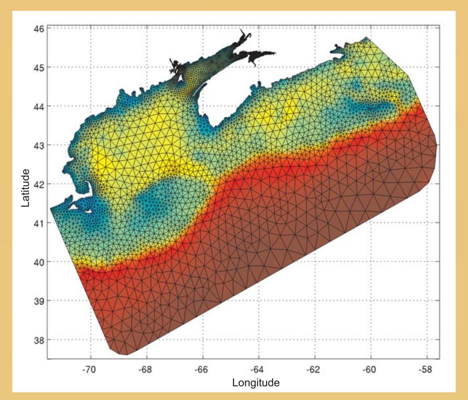


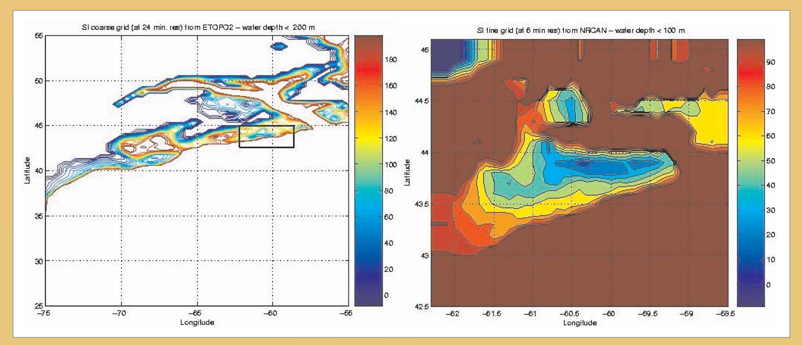
Grey shaded relief bathymetry with gas pipelines and well sites (blue dots).

Study Region:
- Sable Island Bank, approximately 255 km long and up to 115 km wide, is the largest bank located on the outer Scotian Shelf with 40-60 m average depths
- Striking sand ridges and other mid-sized bedforms developed over thick sand sheet of medium to fine sand
- It is an economically and ecologically important area with fishing, shipping, oil and gas, and The Gully MPA
- The knowledge of the impacts on the seafloor by waves and currents and the sediment responses is critical for the cost and safety of seabed installations, and is also required for understanding habitat distribution

Objectives:
- Modelling wave, current and sediment transport based on high-resultion bathymetry and observed grain size to quantify the magnitude and frequency of seabed disturbance
- Understanding the relationship between the seabed disturbance and the distribution and mobility of bedforms

METHOD



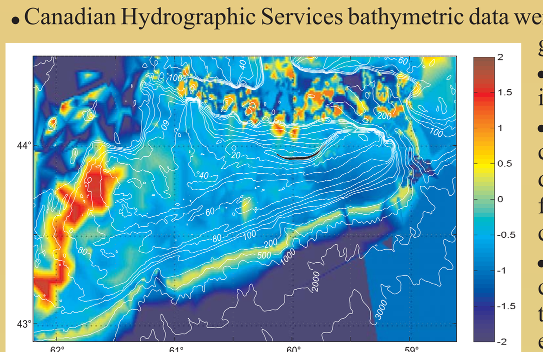


Tidal Current Modeling:
- Tidal currents were predicted from a tidal model for the northwest Atlantic coastal ocean developed by Dupont et al. (2002)
- This finite-element model includes 10 tidal constituents (M2, N2, S2, K1, O1, K2, L2, 2N2, NU2, and M4), with a variable spatial resolution from 2 to 50 km

Wave Modeling:
- The Wave Watch III model (Tolman, 2002) was used for wave predictions.
- The wave model was driven with the USA Navy COAMPS (Coupled Ocean Atmosphere Model Prediction System) wind data and implemented in nested domains of 0.4 and 0.1 degree resolutions

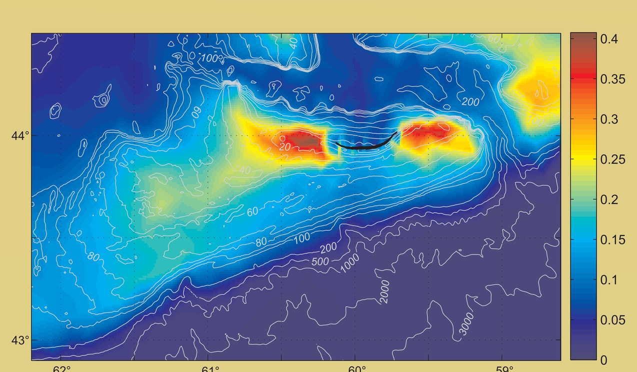
Circulation and Wind-Driven Current Modeling:
- The fields of seasonal mean currents were from the 3D model of Lynch et al. (1992), including forcing by the barotropic and baroclinic pressure gradients implied by hydrographic observations, seasonal mean wind stress and rectification of the M2 tide
- The wind-driven currents were modelled as bottom current responses to the along- and cross-shelf wind speed anomalies according to the 3D model of Lynch et al. (1992)
- The same COAMPS wind data used in wave modelling were also used in the computation of the circulation and wind-driven currents

Seabed Disturbance and Sediment Mobility Computations:
- Canadian Hydrographic Services bathymetric data were compiled to construct a high-resolution (0.01 degree) bathymetry grid for the modelling domain
- GSC seabed sample data were compiled, analyzed, and interpolated to the 0.01 degree grid
- Model-predicted tidal current, circulation and wind-driven currents and wave parameters were linearly interpolated to hourly data over the 0.01 degree common grid, and used in a combined-flow, sediment transport model SEDTRANS (Li and Amos, 2001) to compute the various bed shear stresses
- Model-predicted hourly shear stress at each grid point was compared with the critical shear stress for bedload transport to derive the time percent this critical shear stress was exceeded (threshold exceedance) for the one year period July 2000 to June 2001.

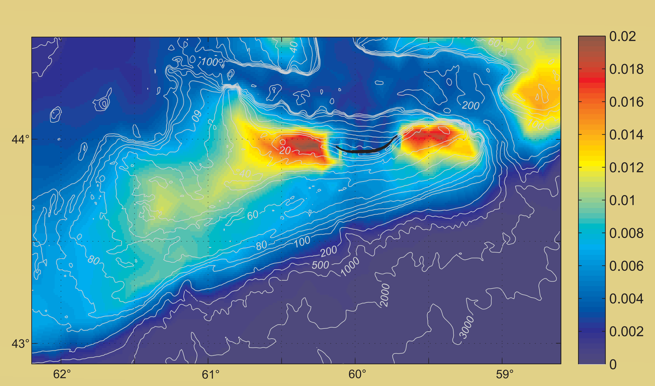


Gridded observed grain size in Log10 mm

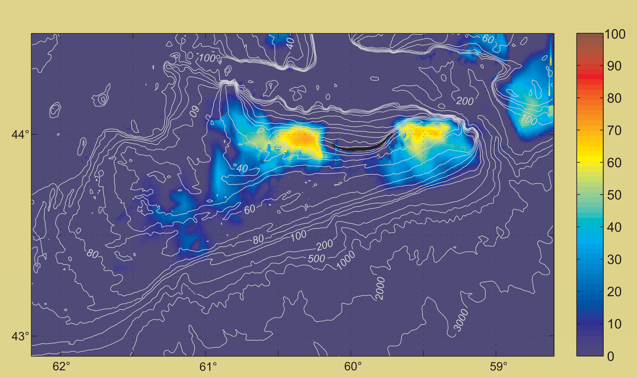
EFFECTS OF TIDAL CURRENT



RMS tidal current (m/s)



Mean tidal current shear velocity (m/s)

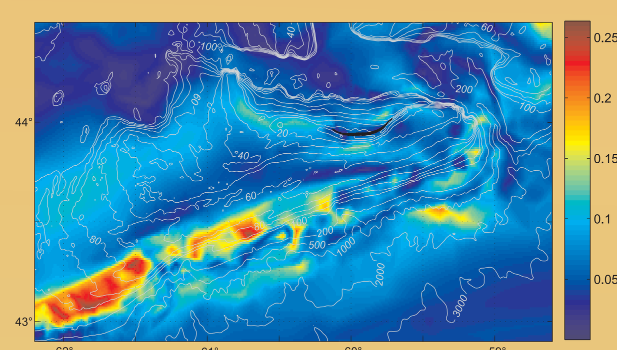


Time percentage of threshold exceedance (%)

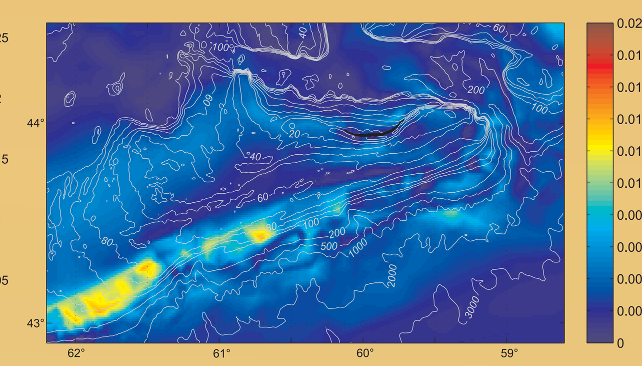
- Maximum RMS tidal current 0.4 m/s
- Maximum mean tidal-current shear velocity 1.8 cm/s
- High values on bank top, decreasing offshore
- Sable Island sheltered tidal current propagation

- Maximum time percentage of threshold exceedance 70%
- Mostly over West Bar and East Bar, the shallowest submarine extensions of the island
- Tidally-driven sediment mobility occurs over 36% of the bank area

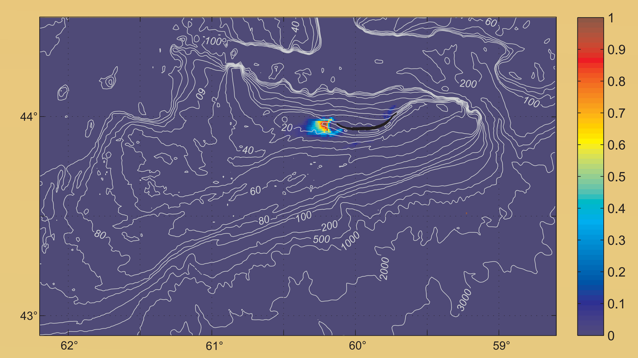
EFFECTS OF CIRCULATION AND WIND-DRIVEN CURRENT



RMS circulation and wind-driven current (m/s).



Mean circulation and wind-driven current shear velocity (m/s)

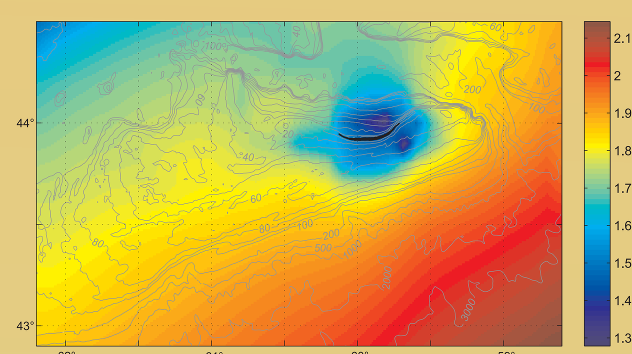


Time percentage of threshold exceedance (%)

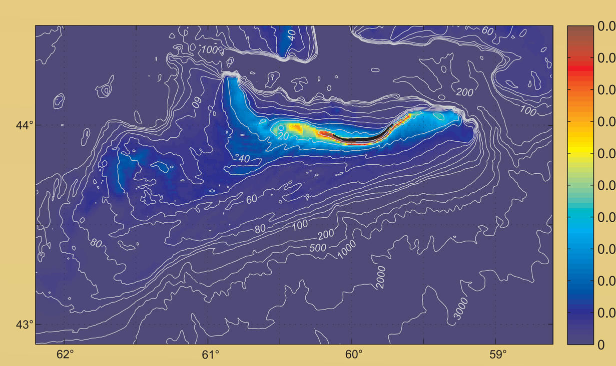
- Relative weak effects: maximum RMS current < 0.2 m/s and shear velocity < 1.4 cm/s
- High values in patches on the outer southwestern Bank, West and East Bars, and south of Sable Island

- Maximum time percentage of threshold exceedance <2%
- Circulation and wind-driven current causes sediment mobility over only a very small area on West Bar

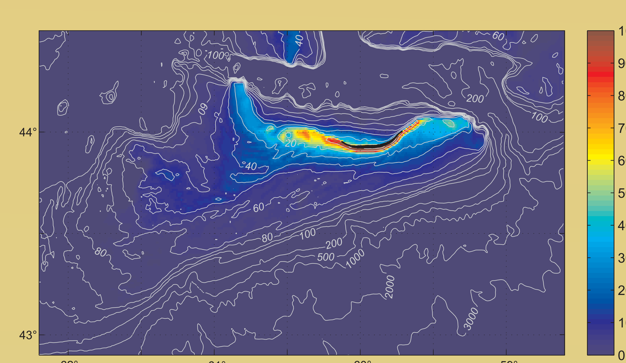
EFFECTS OF WAVES



Mean significant wave height Hs



Mean wave shear velocity (m/s)

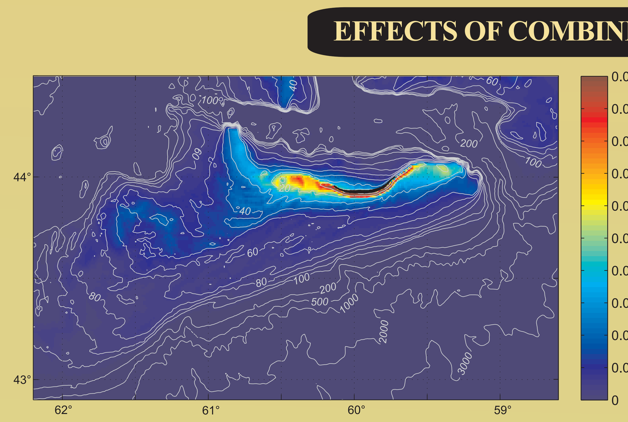


Time percentage of threshold exceedance (%)

- Mean Hs ranges from 1.5 to 2 m
- Strong sheltering by Sable Island
- Maximum mean wave shear velocity reaches 5 cm/s
- High values on bank top, decreasing offshore

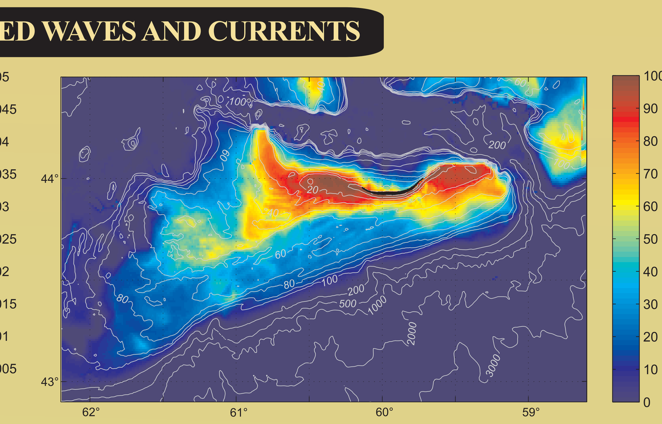
- Maximum threshold-exceedance time percentage 90%
- Mostly in shallow waters around the island
- Exceedance occurs down to 80-90 m depth
- Waves alone cause sediment mobility over 71% of the bank area

EFFECTS OF COMBINED WAVES AND CURRENTS



Mean combined-flow shear velocity (m/s)

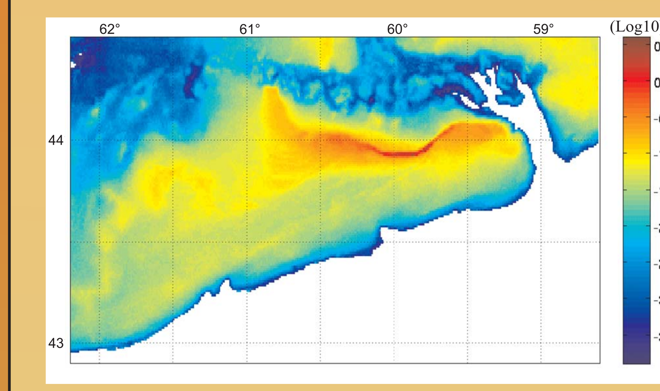
- Maximum mean combined-flow shear velocity 5 cm/s
- High values around East and West Bars, decreasing gradually to < 0.5 cm/s in depths > 100 m



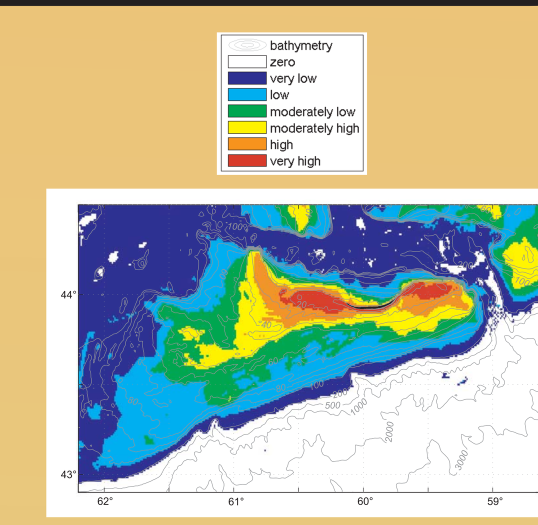
Time percentage of threshold exceedance (%)

- Time percent of threshold exceedance: 90% on bank top, 50% on mid-bank, and <30% on outer bank
- Sediment mobility by combined waves and currents occurs over 93% of the bank area and in depths as deep as 200 m

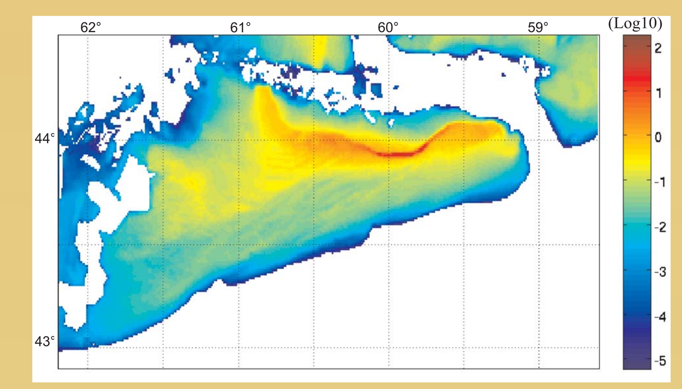
TOWARD UNIVERSAL INDICES OF SEABED DISTURBANCE AND SEDIMENT MOBILITY



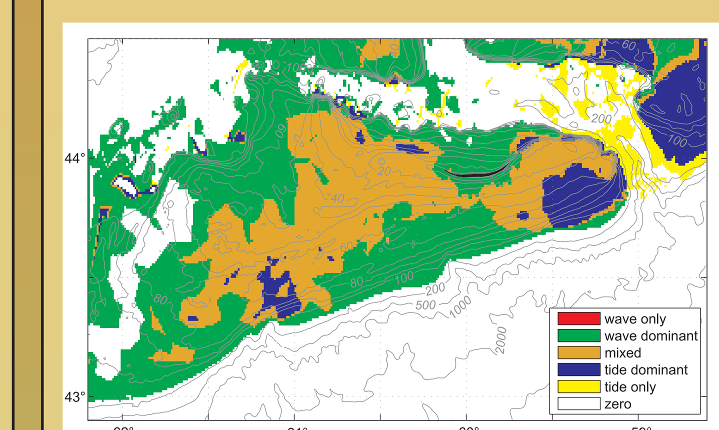
Seabed Disturbance Index (SDI)
- Defined as the maximum value of $(\tau_{cws})^{1.5}$ P: τ_{cws}, combined-flow shear stress; P, probability distribution of τ_{cws}
- Quantifies the level of exposure of the seabed to waves and currents considering both the magnitude and frequency of the bed shear stress
- Ranges from 10^{-4} to 4 with a mean of 0.04 on SIB, while SDI ranges from 1.9×10^{-4} to 1.3 on the Australia shelf (Hemer, 2006)



Mobility Frequency Index (MFI)
- Defined as time% of threshold exceedance due to combined-flow shear stress
- Shows concentric pattern surrounding Sable Island: very high (>90%) or high (70-90%) on bank top in depths<30 m; moderate (30-70%) in depths of 30 to 60 m; and low (10-30%) or very low (<10%) in depths > 60 m



Sediment Mobility Index (SMI)
- Defined as (τ_{cws}/τ_{cr}) x time% of threshold exceedance; (τ_{cws}/τ_{cr}), the mean normalized shear stress for times when sediment mobilization occurs, and τ_{cr}, the threshold shear stress
- A non-dimensional index that indicates the level of sediment mobility integrating both magnitude and frequency
- SMI ranges from 10^{-5} to 180 with a mean of 0.16 on SIB
- SMI values > 10 on bank top suggest strong sediment mobility with mobilization occurring in >90% of the time and shear velocity reaching 4-4.5 cm/s during mobilization events
- SMI values of ~0.2 on the mid-bank indicate moderate sediment mobility with mobilization occurring over about 50% of the time and shear velocity at 1-1.5 cm/s during mobilization events



Disturbance Classifications:
- wave dominant: wave exceedance >3 times of tide
- tide dominant: tide exceedance > 3 times of wave

Disturbance Type Classification
- Defined by relative time% of threshold exceedance caused by various processes
- Wave disturbance most important, >50% of bank area, mid- and outer-bank
- Mixed disturbance also important, 30% of bank area, central core enclosed by wave-only or wave-dominant disturbance
- Tide disturbance less important, < 10% of bank area, in The Gully and on SE bank

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LOCATION MAP

Available from
Geological Survey of Canada
615 Booth Street
Ottawa, Ontario K1A 0E8

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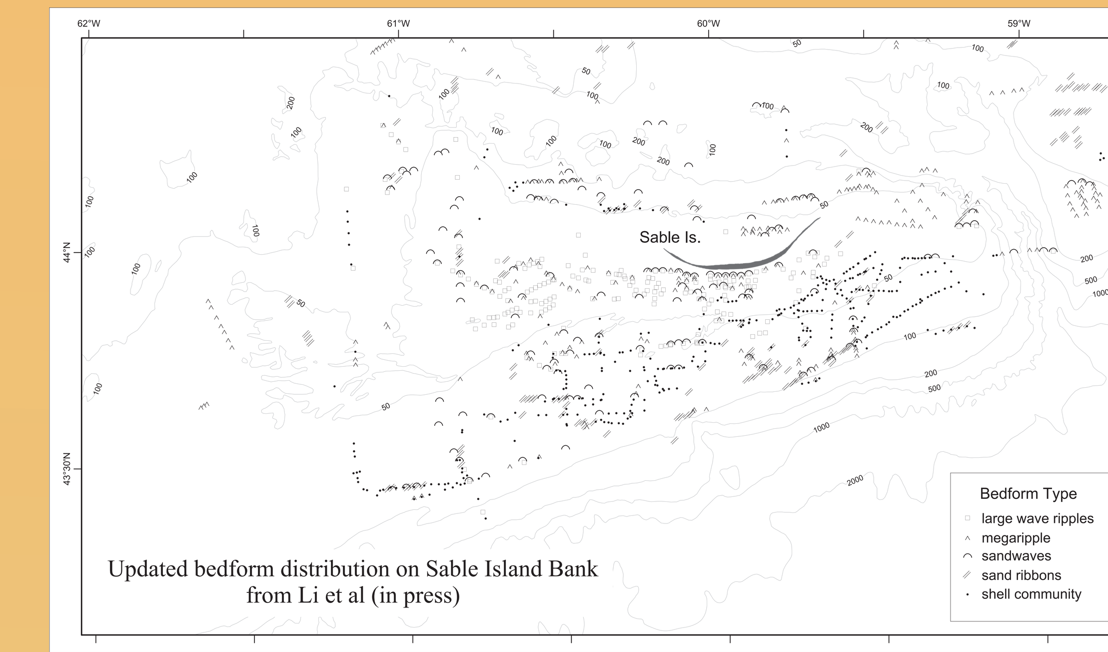
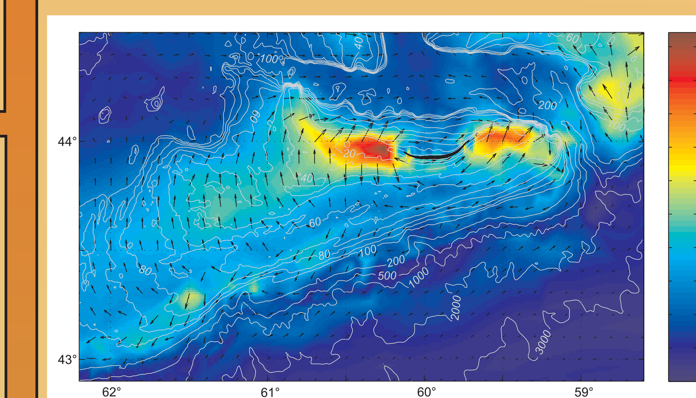
IMPLICATIONS TO BEDFORM MORPHODYNAMICS

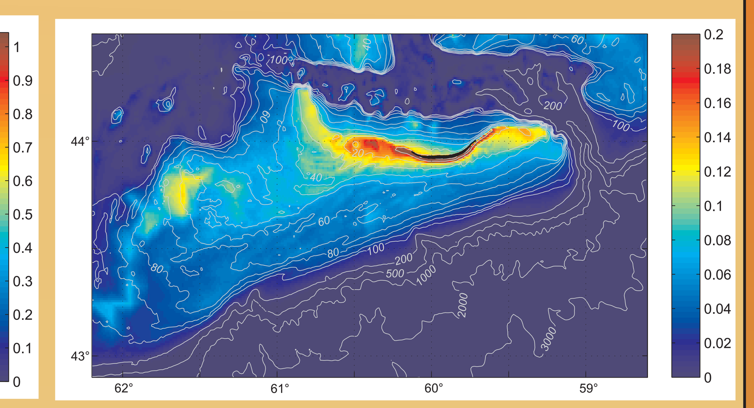


Updated bedform distribution on Sable Island Bank from Li et al (in press)



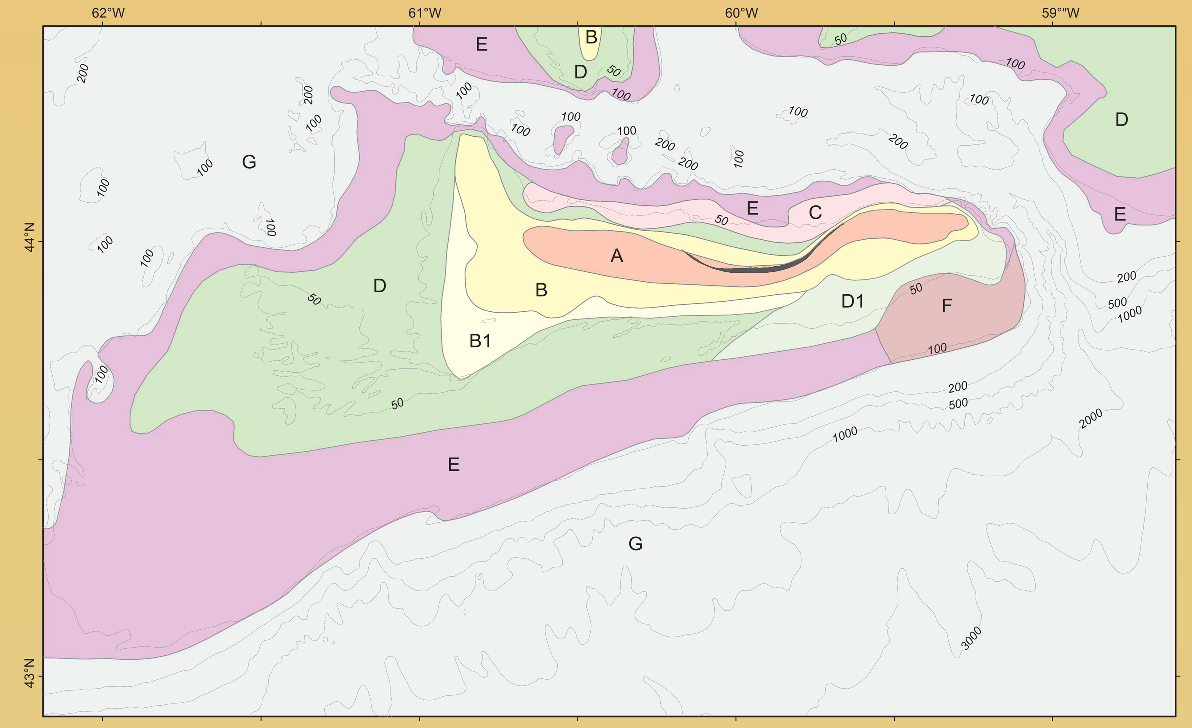
Vector of maximum total current speed (m/s)

- Megaripples cluster around the shoals of West and East Bars and in sand ridge fields
- These coincide with areas of high total currents. Total current speeds exceed the threshold for megaripple formation
- Total currents are thus responsible for the formation of megaripples in these locations



Maximum wave shear velocity (m/s)

- Large wave ripples occur mainly on top of the bank but can occur in depths up to 100 m
- Maximum wave shear velocity in depths < 100 m is generally > 2 cm/s, the threshold for large-wave ripple formation over medium and coarse sand
- This suggests the limit of large wave ripple distribution partially controlled by the storms of 1 to 2 year return intervals



Bedform Zones

Zone	Description
A	High energy; nearshore influenced by breaking waves; upper-plane beds, large wave ripples, megaripples and sand waves on shoreface sand ridges
B	Moderately high energy; nearshore and inner shelf; shoreface connected sand ridges with superimposed megaripples, large wave ripples, sand waves
B1	Intermediate energy; inner shelf; Bedforms same as B but much lower abundance of large wave ripples
C	Intermediate energy with strong current effects; mid-shelf; sand waves, specks, megaripples, and some sand ribbons over offshore sand ridges
D	Intermediate energy; mid-shelf; sand waves, specks, and megaripples superimposed on less-active offshore sand ridges
D1	Intermediate energy; mid-shelf; stronger current effect and higher abundance of sand ribbons and specks than D
E	Moderately low energy; mid- and outer-shelf; specks, sand waves, megaripples and sand ribbons; Highest abundance of sand ribbons
F	Moderately-low to intermediate energy under current-dominant disturbance; shelf; specks on otherwise featureless seabed
G	Quiescent or very low energy; shelf edge and slope; featureless seabed with trawl marks

Bedform Zones on SIB:
- Bedform distribution is compared with seabed disturbance predictions to define 7 bedform zones
- Each zone has distinguished combination of bedform types, energy level, and relative effects of waves and tidal current (Li et al. in press)

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