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2021

Permanent link: https://doi.org/10.4095/328363

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

Recommended citation
Li, M.Z., Wu, Y., Hannah, C.G., Perrie, W.A., Shen, H., and King, E.L., 2021. Modelling seabed disturbance and sediment mobility on the Canadian Atlantic Shelf; Geological Survey of Canada, Open File 8805, 50 p. https://doi.org/10.4095/328363

Publications in this series have not been edited; they are released as submitted by the author.

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Summary

Ocean surface waves and tidal currents can interact to produce strong seabed shear stress and mobilization of sediments that can significantly impact the seabed stability and benthic habitats on continental shelves. Therefore the knowledge of the magnitude and frequency of seabed disturbance by waves and currents and the resulting mobilisation of sediment on continental shelves is critical for the spatial planning and management of Canada's offshore lands. Modelled waves, tidal current and circulation current data for a 3-year period were used in a combined-flow sediment transport model to simulate the seabed shear stresses and the mobilization of observed sediment grain size on the Canadian Atlantic Shelf. The modelling results are presented and analyzed to derive updated framework of seabed disturbance and sediment mobility on the Atlantic Shelf.

The Atlantic Shelf is affected by strong waves and tidal currents. Maximum mean significant wave height can reach 3.5 m and that of the mean tidal currents up to 1.2 $m \cdot s^{-1}$. Our modeled results indicate that the mean wave and tidal current shear velocities both reach the maximum values of ~4 $cm \cdot s^{-1}$. Our models predict that observed sediments on the Atlantic Shelf can be mobilized by tidal currents at least once during the modelled 3 year period over 30% of the shelf area while storms can mobilize sediments over 35% of the shelf area suggesting slightly stronger sediment mobilization by storms. Further more waves and currents interact to cause enhanced combined wave-current shear velocity >5 $cm \cdot s^{-1}$ that is capable to mobilize sediments over 63% of the shelf area, double that due to either tides or waves.

The spatial variation of the relative importance of waves, tidal current and circulation current in mobilizing sediments was used to classify the Atlantic Shelf into six disturbance types. Wave dominant and tide dominant disturbance types are equally important and both occupy ~25% of the shelf area. Mixed disturbance is insignificant and accounts for only 3% of the shelf area. Universal indices of Seabed Disturbance (SDI) and Sediment Mobility (SMI) were applied to better quantify the exposure of the seabed to oceanographic processes and sediment mobility incorporating both the magnitude and frequency of these processes. The applications of these indices have produced different and probably more adequate quantification of seabed forcing and sediment mobility for many areas on the Atlantic Shelf. The values of SDI and SMI on the Canadian Atlantic Shelf are found to be comparable to those on the Australian shelf. These indices, together with the seabed disturbance type classification scheme, potentially can be used as standard parameters to best quantify seabed disturbance and sediment mobility on other shelves of the world.

1. Introduction

The impacts on the seafloor exerted by waves and currents and the sediment responses to this forcing directly affect the cost and safety of seabed installations for offshore engineering and resource developments (Cacchione and Drake, 1990; Nittrouer and Wright, 1994). Knowledge of seabed disturbance by oceanographic processes and sediment mobility are also required for habitat classification and for understanding the geo-environment control of habitat distribution (e.g. Connor et al., 2004; Hemer, 2006; Kostylev and Hannah, 2007; Harris and Hughes, 2012). Therefore the knowledge framework of the magnitude and frequency of seabed disturbance by waves and currents and the resulting mobilisation of sediment on continental shelves is critical for the planning, management, and sustainable development of the continental shelves of maritime nations. The assessments of seabed disturbance based on seafloor mapping and instrumented lander measurements are limited in space and time. Numerical modelling is the only effective approach for shelf wide systematic prediction of the seabed disturbance and sediment mobility.

Several researchers suggested that about 80% of the world's shelves are dominated by waves, and 17% by tidal currents (Walker, 1984; Swift et al., 1986). However, there have been very few quantitative analyses of the percentage of the world's continental shelves on which sediment mobilization occurs, and of the spatial distribution of dominant sediment transport processes because of the practical difficulties involved in collecting enough data over the shelf. Harris and Coleman (1998) used wave data generated by a global climate model to quantify the mobilisation of fine sand on the earth's continental shelves. The first comprehensive shelf-wide calculation was by Porter-Smith et al. (2004) who used wave climatology data for 1997-2000 and tidal model predictions over a spring-neap cycle to separately assess the relative spatial distribution of wave and tide dominated portions of the Australian continental shelf. Their study found that sediments are mobilised by waves on ~31% of the continental shelf and by tidal currents on ~41% of the shelf. Porter-Smith et al. (2004) only considered the frequency of sediment mobilization and did not include a measure of intensity. Their approach also did not consider the effect of the enhanced combined-flow shear stress due to wave and tidal current interaction which would underestimate the bed stress and sediment mobilization frequency. Hemer (2006) evaluated the exposure of the Australian continental shelf to oceanographic processes by modelling the combined wave and current shear stress for a 8-year period incorporating both the intensity and frequency of this parameter. Three methods of classifying the levels of oceanographic exposure were presented. The approach of Hemer (2006), however, did not compare the combined-flow shear stress with the threshold of sediment transport. Hence the magnitude and frequency of sediment mobilization under combined waves and currents was not specifically predicted.

In Canada, limited efforts have been made to quantify the magnitude and frequency of seabed disturbance, and to use this to understand sediment transport patterns and the distribution and mobility of bedforms for some shelf regions (e.g. Li et al., 2012; Shaw et al., 2014; Li et al., 2015a; Li et al., 2021). In a modelling study of bed shear stress and seabed disturbance on Sable Island Bank on the outer Scotian Shelf, Li et al. (2012) demonstrate that tidal currents alone can cause sediment mobilization over 36% of the bank area while wave action affects 71%. The combined action of waves and tides, however, produces mean shear velocity up to 5 $cm \cdot s^{-1}$, affects 93% of the bank, and mobilizes sediments to water depths as deep as 200 m. Li et al. (2015a) have applied modelled waves, tidal currents, and wind-driven and circulation currents to simulate seabed shear stresses, sediment mobility and sediment transport patterns in the broader Bay of Fundy. Seabed shear in the Bay of Fundy is predominantly due to tides and waves only affect the coastal areas. The strongest mean shear velocity is up to 10 $cm \cdot s^{-1}$ which causes sediment mobilization >30% of the time over most of the bay and as high as 100% of the time in some areas of the bay. Seabed disturbance and sediment mobility indices incorporating both the magnitude and frequency of these parameters are also proposed and applied to quantify the seabed forcing and sediment mobilization in the Bay of Fundy. In an initial Canada-wide effort, wave hindcast data and modelled tidal current data for a 3-year period were used in a combined-flow sediment transport model to simulate the seabed shear stresses and the mobilization of uniform medium sand by waves and tides on the continental shelves of Canada (Li et al., 2021). The Canadian continental shelves are found to be impacted by strong waves and tidal currents that produce mean bed shear velocity > 5 cm·s−1. The modelling study predicts that medium sand can be mobilized by tidal currents over 36% and by waves over 50% of the shelf area of Canada, while the combined shear stresses enhanced by the interaction between waves and tidal current further increase sediment mobilization to over 68% of the shelf area. Quantitative estimates of spatial variation of the relative importance of wave and tidal current disturbances are used to classify the continental shelves of Canada into six disturbance types. Universal Seabed Disturbance (SDI) and Sediment Mobility (SMI) indices are proposed to better quantify the exposure of the seabed to oceanographic processes and sediment mobility incorporating both the magnitude and frequency of these processes. This Canada-wide modelling study thus has established the first national framework of seabed disturbance and sediment mobility on the continental shelves of Canada, and has been applied by Shaw et al. (2014) in the synthesis of processes, landforms, and benthic habitats on the Canadian Atlantic shelf. The major limitations of this initial national study are that important ocean circulation and storm-driven current processes were not included and that uniform medium sand instead of observed grain size data was used. This limited knowledge of seabed disturbance rate will hinder the sustainable resource developments and the effective planning and management of Canada's oceans.

There have been limited applications of seabed disturbance information to the distribution of benthic habitats. Kostylev and Hannah (2007) was the first to develop the benthic habitat map for the Scotian Shelf using a disturbance-scope for growth template and readily available oceanographic data. The characteristic combined-flow shear stress was computed based on near-bed tidal currents empirically extrapolated from modelled depth-averaged tidal current data and the 90th percentile of hindcast significant wave height and period data. Thus the disturbance calculation was not computed using time series data of waves and currents and hence likely skewed to the dominance by the extreme wave parameters. A disturbance parameter was calculated as the ratio of the total combined wave-tide shear velocity to the critical shear velocity for sediment motion. Their disturbance parameter therefor only considers the magnitude of the seabed forcing and does not account for how often the disturbance occurs. Gregr et al. (2016) used a similar approach for a habitat classification for the Canadian Pacific continental shelf.

As a continued effort to advance the finding of Li et al. (2021), various current and wave models have been applied in this study to derive time series data of modelled waves, tidal current, circulation current and storm-driven current on the Atlantic Shelf (See the modelling domain in Figure 1) for the three year period of September 2002 – August 2005. Bathymetry and observed sediment grain size data together with the modelled wave and current data are input in a combined-flow sediment transport model to simulate the wave, tidal, circulation current as well as combined wave-current shear stresses on the Atlantic Shelf. These shear stresses by various processes are then compared with the threshold of bedload motion for observed grain size to quantify the magnitude and frequency of sediment mobilization. The shelf is also classified into sub-regions based on the seabed disturbance rate and the relative impact of tidal, wave, and ocean current processes. The objectives of this report are (1) to present the updated framework of the magnitude and frequency of seabed shear stress and sediment mobilization by waves, tidal currents, circulation currents and combined waves and currents on the Atlantic Shelf of Canada, (2) to derive a classification of the Atlantic Shelf based on the spatial variation of the relative importance of wave, tidal and circulation current disturbance, and (3) to produce the distribution of several universal indices for the quantification of seabed disturbance and sediment mobility on the Atlantic Shelf integrating both the magnitude and frequency of these processes.

2. Methods

This report uses the modelling results derived from a collaborative project undertaken in 2005–2008. The approach in this study is essentially to apply various wave and current models to derive time series data of waves, tidal current, and ocean circulation currents for the period of September 2002 to August 2005 for the Canadian Atlantic shelf. The modelled wave and current data were coupled with bathymetry and grain size data in a sediment transport model to predict bed shear stresses due to various processes. The computed bed shear stresses were then compared with the critical shear stress for the initiation of sediment motion to quantify the magnitude and frequency of sediment mobilization by wave, tide and ocean circulation processes.

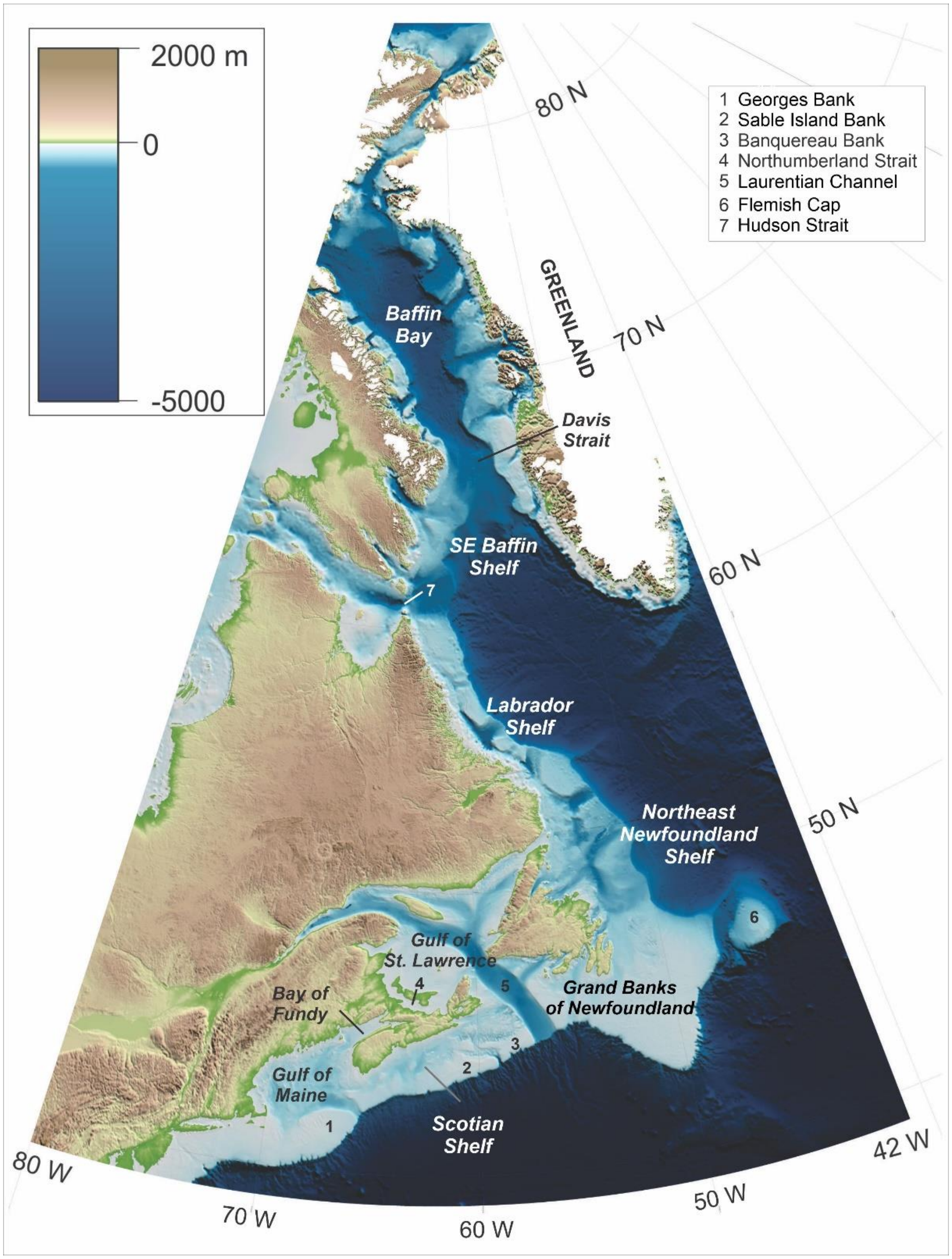


Figure 1 Map of Canadian Atlantic Shelf showing the shaded bathymetry of the modelling domain and geographic locations.

Spatial resolutions are quite different among various wave model, current models, and bathymetry data. To balance the need of spatial resolution and computation time, a common domain of structured rectangular grid was constructed. Wave, current, bathymetry and grain size data were interpolated to this common grid for the shear stresses and sediment mobility calculations. This common domain was defined by 40°N to 82°N and 42°W to 80°W, with a spatial resolution of 0.1° (roughly 10 km). The total sea points are 42,204. Figure 1 shows the modelling domains and key geographic locations.

2.1 Tidal current models and data

The Canadian Department of Fisheries and Oceans (DFO) Webtide models (Dupont et al., 2002) and Oregon State University (OSU) TPXO6.2 global model (Egbert and Erofeeva, 2002) were combined to provide the complete coverage for the Canadian Atlantic shelf modelling domain. The Webtide models are further divided into various regional models. For the Atlantic shelf, several regional models were merged to derive tidal current predictions with the highest spatial resolution and most tidal constituents. The northern one third of the Atlantic shelf region (north of Davis Strait, Fig. 1) was covered by the Arctic regional model and the southern two thirds were covered by the Northwest Atlantic regional model, both with five tidal constituents. The Bay of Fundy and Scotian Shelf were covered by the Scotian Shelf regional model, which has higher spatial resolution and ten tidal constituents (Dupont et al., 2005). The OSU global model with ten constituents was used over small areas where there was no Webtide model coverage. The harmonic constituents available from the various models are listed in Table 1.

The Webtide models provide harmonic constituents on an unstructured triangular grid so that the resolution is coarse (~30 km) on the open shelf and improves to ~200 m in shallow waters and around the coast. The OSU global model is specified on a structured rectangular grid with 0.25° resolution. The tidal constituents from various models were interpolated to the common structured domain of 0.1° resolution used for the shear stress and sediment mobility calculations. Then tidal constituents were combined with the astronomical forcing to predict hourly depth-averaged tidal currents for the three year period of September 2002 to August 2005.
The validation of Webtide models suggests that the surface elevation predictions are accurate to around 0.1 m over most regions. For tidal current predictions, Dupont et al. (2002) report that the M2 current errors for the NW Atlantic regional model are typically 0.05–0.1 $m \cdot s^{-1}$. A detailed description of the Webtide models and model calibration can be found in Dupont et al. (2002, 2005).

2.2 Wave model and data

Wave parameters required for seabed disturbance computation are significant wave height, H_s, spectral peak wave period, T_p, and wave-propagation (towards) direction, W_{dir}. The wave

Table 1 List of tidal constituents for various Webtide regional models and the OSU global tidal model used in this study.

Model	Tidal constituents
Arctic model	M2, N2, S2, K1, O1
Northwest Atlantic	M2, N2, S2, K1, O1
Scotian Shelf	M2, N2, S2, K1, O1, K2, L2, 2N2, Nu2, M4
OSU global	M2, N2, S2, K1, O1, K2, P1, Q1, MF, MM

data parameters used in this study were computed from the DFO WAVEWATCHIII™ model (version 2.22, Tolman, 2002; denoted as WW3 hereafter). The structured WW3 grids consist of a fine grid of 0.2° resolution covering the Atlantic Shelf domain that is nested inside a coarse grid of 1° resolution covering an extended area of the Northwest Atlantic (Figure 2). The wind field used to force the wave model was assembled from three sources, namely the wind data from the Meteorological Service of Canada 50-year wind and wave hindcast data (MSC50; Swail et al., 2006), the operational wind fields for the West North Atlantic prepared by the US National Centers for Environmental Prediction (NCEP NWA), and the North American Regional Reanalysis (NARR) wind data. The wind data over the majority of our Atlantic Shelf modelling domain are from the MSC50 dataset which is further divided into a fine resolution region with 0.1° resolution and hourly intervals and a coarse resolution region with 0.5° resolution and 3-houly intervals. The NCEP NWA wind data of 0.25° resolution and 3-hourly intervals are mainly used over the southeastern corner of the model domain while the NARR wind data with 32 km resolution and 3-hourly intervals essentially cover the eastern edge and top of the Baffin Bay (north of 73°N) of the model domain. The merged wind fields were re-gridded to the wave model grid of 0.2° resolution and used to drive WW3 model to produce 3-hourly significant wave height, peak wave period, and mean wave (propagation to) direction at each grid point for the modelled 3 year period.

WW3 has been used for operational routine forecasts in many areas of the Canadian Atlantic region. Over the years, WW3 has been continually monitored and updated, as new versions have been released by NCEP. In particular, WW3 has been used in a modeling inter-comparison study (Padilla-Hernández et al., 2007; Perrie et al., 2018) focusing on three intense nor'easters that caused extensive coastal damages. Relative to buoy observations along the US Northeast coast and on the Scotian Shelf, the model was shown to have a root mean square (RMS) error of 0.7 m and 2.0 s, and bias of -0.07m and -0.9 s, for significant wave heights and peak periods respectively. These results are comparable to those of other modern wave models, such as an unstructured grid version of WW3 (Roland et al., 2012) and an unstructured version of SWAN (Simulating WAves Nearshore) wave model (Qi et al., 2009).

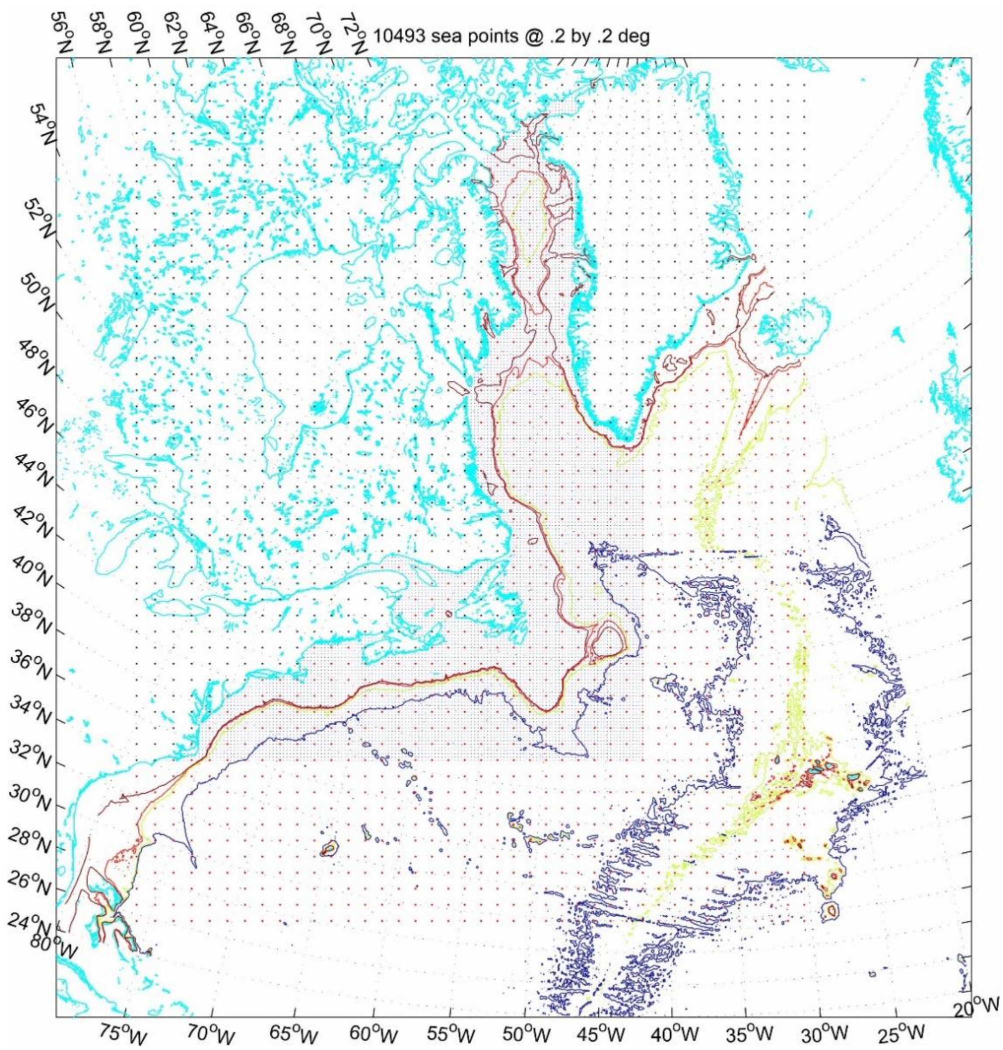


Figure 2 The structured WAVEWATCHIII model grids consisting of a fine grid of 0.2° resolution (blue dots) covering the Atlantic Shelf domain that is nested inside a coarse grid of 1° resolution (red dots) covering an extended area of the Northwest Atlantic. The brown, red, green, and blue lines represent depth contours of 500, 1000, 2000 and 4000 m respectively.

2.3 Ocean circulation model and data

Ocean currents were computed from the Canadian East Coast Ocean Model (CECOM), a 3-D coupled ice-ocean circulation model for the east coast of Canada (Tang et al., 2008). CECOM has been widely applied in studies of sea-ice and circulation of Baffin Bay (Tang et al., 2004), the circulation of eastern Canadian seas (Wu et al., 2012), and circulation and storm-driven currents on the Grand Banks (Tang et al., 2007; Wu et al., 2011; Li et al., 2015b). The model grid has a 0.1° horizontal resolution on a rotated spherical coordinate system. There are 29 generalized σ-coordinate levels in the vertical which enhance vertical resolution in the bottom boundary layer that is important for estimating the shear stress and sediment mobility on the seabed. The ocean component of the model is based on the Princeton Ocean Model (POM) and the ice component is based on a modified Hibler model (Yao et al., 2000). The model was driven by wind stress, barometric pressure, heat and moisture fluxes calculated from 3-hourly NARR (The NCEP North American Regional Reanalysis) atmospheric parameters from the US National Oceanic and Atmospheric Administration (NOAA). Before atmospheric forcing is applied, spinup of the model was made for each month to generate the mean current field. For the spinup runs, the temperature and salinity values are the monthly climatologies computed from an objective analysis of historical data (Tang, 2007). The results of these monthly wind-free spinups were retained as the background "mean circulation" fields that would vary monthly and seasonally through the year. In the output run of the model, the full range of the NARR data including wind stress was used to derive 3 hourly data for the period 1st September 2002 to 31st August 2005. The output variables include 2-D depth averaged velocities (U_{ab}, V_{ab}), sea surface elevation (*elb*), and 3-D velocities (*u, v, w)*. The raw CECOM-generated currents from the the output run are termed "circulation currents" which can be taken as the sum of the instantaneous wind-driven currents and the background mean circulation currents. For the present work, we only use the bottom currents. We compute the bottom circulation current as the average over the bottom 5 meters of the profile.

Extensive efforts have been made to validate CECOM on annual (Wu et al., 2012) and short-term (Wu et al., 2011) time scales. CECOM simulated currents and observed currents at fixed locations and depths in several regions of the eastern Canadian seas were compared using both visual comparison and statistical analysis methods (Wu et al., 2012). The comparison results indicate that the major features of the current fields from observations are reproduced successfully by the model. On shorter time scales, good agreement in both current speed and direction was obtained between the model simulations and current meter measurements during a November 1997 storm over the northeastern Grand Banks (Wu et al., 2011). The mean error for the mean speed predicted at several depths was 7% relative to a mean speed magnitude of 0.16 m s^{-1} and the mean error for the maximum speed was 12% relative to a maximum speed magnitude of 0.36 m s^{-1}. More detailed model description, implementation and verification are given in Tang et al. (2008) and Wu et al. (2012).

2.4 Bathymetry and grain size data

2.4.1 Bathymetry Data

The water column attenuates wave orbital velocity and determines the wave impact on the seafloor. Water depth (bathymetry) is thus an important input for the computation of shear stresses in the bottom boundary layer model. The source for bathymetry data was the Northwest Atlantic (NWATL) data set that was compiled from several sources contributed from various

Canadian, American, and international academia and government agencies (Varma et al., 2008). The NWATL data set therefore was the best bathymetry data presenting the complete coverage of Canadian oceans with the best spatial resolution at the study time. The bathymetry data of the NWATL data set with a much larger domain was sub-sampled to derive the sub-set bathymetry data for Canada with 5 minute resolution defined by the boundaries of 40–90°N and 40–142°W. The Canada 5 minute bathymetry data was further interpolated on to the common structured domain of Atlantic Shelf with 0.1° resolution shown in Figure 1.

2.4.2 Grain size data

Grain size of bottom sediment determines the threshold value for the initiation of sediment transport, and also controls the values of bottom roughness length which in turn affects the computation of seabed shear stresses. Uniform medium sand was used in a previous study (Li et al., 2021) to provide the bench-mark of potential seabed disturbance and sediment mobility on all continental shelves of Canada. Observed grain size data will be used in this study to improve our understanding of bed shear stress and sediment mobility on the Canadian Atlantic Shelf. Different approaches of compilation, cleaning and editing of observed grain size data were taken for different areas of the Atlantic Shelf to make the best use of the available source grain size data. However, the source sample-based grain size data were largely extracted from the GSC Expedition Database (ED; https://ed.gdr.nrcan.gc.ca/index_e.php) in June 2008. Additional data (mainly for the Gulf of Maine) were obtained from U.S. Geological Survey East Coast Sediment Texture Database (Poppe et al., 2014) and USGS usSEABED database (Reid et al., 2005). Some common initial quality control (QC) and cleaning measures were used for the sample-based grain size data for all areas of the Atlantic Shelf. These include:

- samples without size class percentages and mean grain size values were removed;
- samples with the sum of size class percentage less than 90% were not used;
- duplicates with identical latitude and longitude and mean grain diameter were eliminated;
- data from core intervals deeper than 10 cm below sediment surface were not used.

<u>Scotian Shelf and Bay of Fundy region</u>

The gridded rain size for the Scotian Shelf and Bay of Fundy region was based on approximately 7500 sediment samples from the GSC Expedition Database (with data available up to June, 2008) and 18750 samples from the USGS databases (Figure 3a). Part of the USGS grain size data have been used by Hill and Gelati (2017) to study the sediment competency in the Gulf of Maine and Bay of Fundy. Basic QC and editing, as described above, were first applied to the GSC grain size data to eliminate duplicates with identical position and mean grain size and data from core intervals deeper than 10 cm from core surface. The QC'ed and cleaned sample grain size data were interpolated within similar sedimentary facies and the resulting

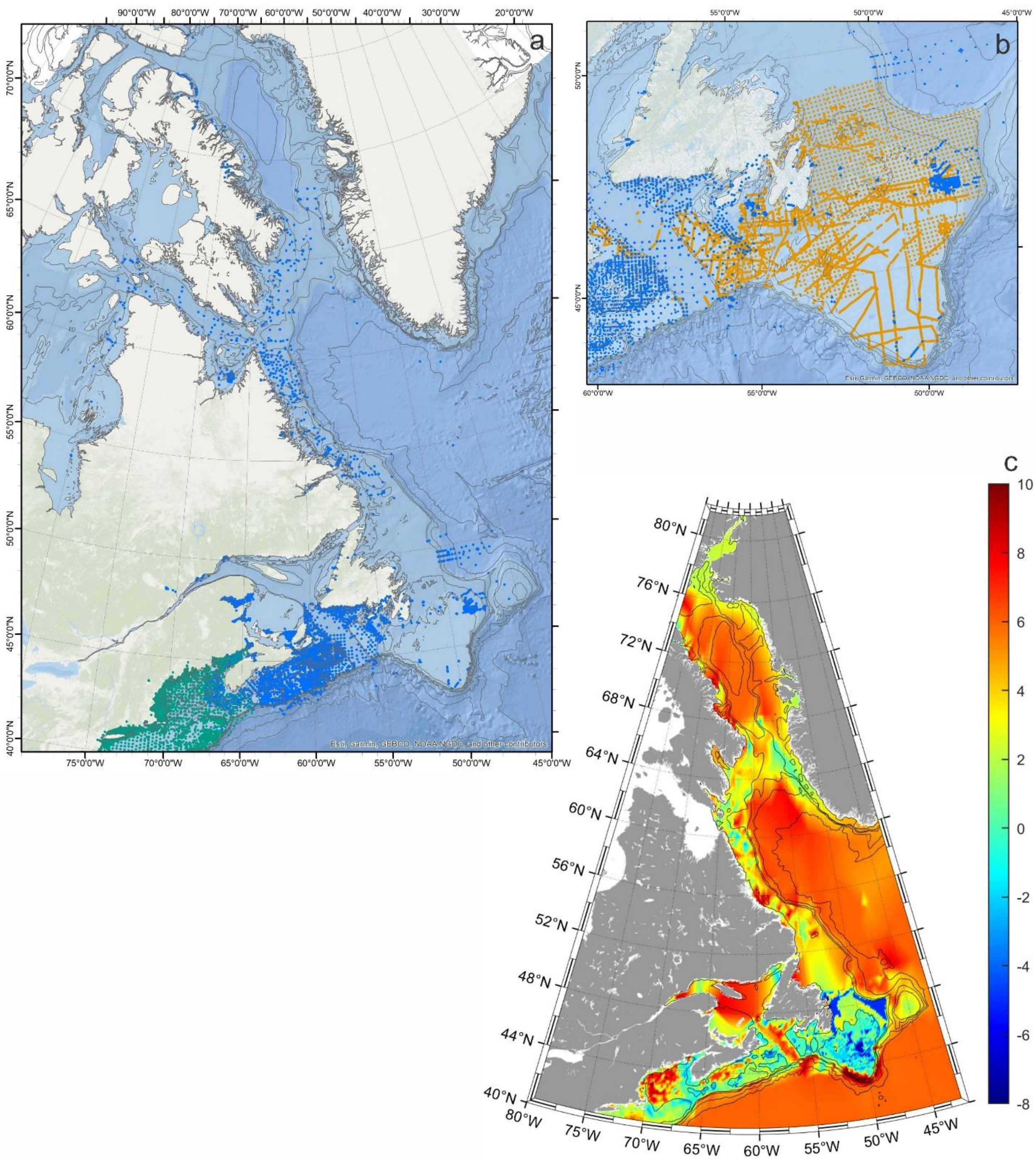


Figure 3 Distribution of (a) sediment samples on the Atlantic Shelf; (b) grain size data deduced from geology and geo-features information on the Grand Banks; and (c) gridded grain size data (in ϕ) with 0.1° resolution on the Atlantic Shelf. Blue dots are data from GSC ED database, green dots are data from the East Coast Sediment Texture Database and usSEABED database of the USGS, and yellow dots are data deduced based on geology and geofeature information on the Grand Banks. Thin grey lines represent depth contours of 100, 200, 500, 1000, 2000 and 3000 m.

interpolations were merged and spatially smoothed (Kostylev and Hannah, 2007). This approach allowed the use of acoustically verified boundaries between sedimentary formations as defined by facies maps while preserving patterns of grain size variability within the formations. The resulting grain size distribution map has previously been used to develop the seabed habitat map for the Scotian Shelf (Kostylev and Hannah, 2007).

<u>The Grand Banks and North Atlantic regions</u>:

In contrast to the adequate coverage of available observed grain size data on the Scotian Shelf, the coverage of observed grain size data on the Grand Banks and Northern Atlantic Shelf is substantially poorer (Figure 3a). Several methods were applied to use as much as possible the available grain size data for these regions. After the initial QC and editing, it was found that a significant number of samples for these regions contain only size class percentages without the mean grain size D values. Samples from these regions with both mean grain size and size class percentage values were used in regressions to derive empirical relationships between mean grain size and percentages of gravel, sand, clay and mud. These empirical relationships were applied to calculate the mean grain size for data that only contain size class percentages. The mean errors of the empirically calculated mean grain size generally range from 1 – 1.5 ϕ (ϕ is related to mean grain D in mm through $\phi = \log_2 D$). In total, there are approximately 3930 observed grain size data for the Grand Banks and north Atlantic region that have original or empirically calculated mean grain size data (shown in Figure 3a).

Coverage of grain size data from samples is limited and unevenly distributed on the Grand Banks. This necessitated deriving the necessary textural information from regional geophysical survey proxies. Interpretation of the surficial geology and geomorphological features from existing sidescan and seismic profile data already existed in a comprehensive geo-database (King et al., 2013). Requiring a gridded grainsize map for our modelling study, we elected to derive grain size proxies from this database. From this geo-database and regional surficial geology maps based on the same data, we surmised sediment types (gravel, sand, silt and clay), and grainsize range at ~2km bins along geophysical survey tracks. For example, presence of surficial till dictated a strong gravel and cobble component with large range in grainsize while a dominantly medium sand was inferred from the presence of low-relief sandwaves, coarse sand or fine gravel from wave-formed ripples, uniform sand across large sand ridges, mud in acoustically stratified basin fill, etc. From these, a mean grainsize ϕ value was assigned and these values were to be used to derive gridded grain size data. This generated ~14528 data points and are presented in Figure 3b. The errors associated with these geology- and geofeature-based grain size data potentially are high. Casual assessments of the interpreted grain size values against sample-based data over areas where seabed samples exist demonstrate qualitative agreements. Nevertheless this approach, together with the limited sample-based data, provides the best information presently available for the Grand Banks.

The gridded grain size data for the Atlantic Shelf

The combined sample-based grain size data for the Atlantic Shelf as well as the geology- and geofeature-based grain size data for the Grand Banks have been brought into Matlab for gridding. A bi-linear interpolation scheme was used to derive the interpolated grain size value at each modelling grid point that is the average of the adjacent observed grain size data weighted by the inverse distance of these data to the interpolation point. The map of the initially gridded grain size data showed artefact bands due to interpolation using poor data coverage in areas of the northern Atlantic Shelf. These problems were fixed by inserting points of grain size values based geology and water depth. There are several areas with little or no grain size data coverage. These include Baffin Bay, Northeast Newfoundland Shelf, Flemish Cap, southern Scotian slope, and Gulf of St. Lawrence (Figure 3a). The relationship between depth and grain size from adjacent areas with grain size data coverage was used to fill in hypothetical data for these areas. Finally, all the observed grain size data, the geology- and geofeature-based data on the Grand Banks, and these inserted hypothetical data were gridded again to generate the gridded 'observed' grain size data for the Atlantic shelf region as presented in Figure 3c. Albeit the poor coverage of observed grain size data for several areas, the gridded grain size map suggests that fine-grained sediments (5 – 8 ϕ, silt and clay) are present in the Gulf of Maine, central inner and middle Scotian Shelf, the Laurentian Channel, central to northeastern Gulf of St. Lawrence and the NE Newfoundland Shelf. Coarser sediments (-1 to -5 ϕ, granules to coarse pebbles) notably occur in the Bay of Fundy, on Georges Bank, over western Scotian Shelf and on southeastern Grand Banks. The presence of gravels on the inner shelf off eastern Newfoundland and on the outer northeastern Grand Bank awaits verification of sample data as the gridded grain size distribution for these areas are largely based on geology- and geofeature-based grain size data.

2.5 Computation of shear stresses, seabed disturbance and sediment mobility

The wave model data with 0.2° resolution were interpolated to conform to the Atlantic Shelf common domain of 0.1° resolution. The wave and ocean current data were also interpolated temporally from 3 hourly to hourly to conform with the interval of the tidal current data. The depth-averaged tidal current and the ocean current averaged over the bottom 5 m of the profile were taken respectively as the near-bed tidal and circulation currents at 1 m above bottom (mab). The ocean current averaged over the bottom 5 m above seabed was added vectorialy to the depth-averaged tidal current to derive the total near-bed current for each grid point.

The values of steady currents and the wave oscillatory flows cannot be directly used to assess their relative impact on the seabed because they are often observed or modelled at different heights above bottom, and waves impact the seabed in a much thinner bottom boundary layer than steady currents. For these reasons, current speed and wave parameters (H_s and T_p) are used to compute the various current and wave shear stress τ which can be expressed as shear velocity

u_* (in velocity unit) through the quadratic stress law $\tau = \rho u_*^2$ with ρ being water density. The wave and various current data so described above, together with depth and observed grain size, were used in various algorithms and the combined-flow sediment transport model SEDTRANS (Li and Amos, 2001) to compute the bed shear stresses for tidal current, waves, circulation current, and combined wave-current cases. For steady current cases, the model-predicted hourly tidal current or the circulation current was taken as the mean current at 1 m above bottom, U_{100}, and was used to compute the tidal or circulation current shear velocity from:

$$u_{*cs} = (0.5\ f_c\ U_{100}^2)^{0.5} \qquad (1)$$

where f_c is the steady current friction factor and takes on a value of 0.006 for unrippled sandy seabed (Soulsby, 1983; Dyer, 1986). "s" in u_{*cs} denotes that the shear is the skin-friction shear velocity caused by sediment grain roughness only.

For waves, the interpolated hourly parameters of significant wave height, H_s, and spectral peak wave period, T_p, together with water depth, h, and grain size, D, were used in the linear wave theory to compute the maximum wave orbital velocity u_b and maximum wave orbital excursion amplitude A_b. Wave friction factor f_w was calculated according to Jonsson (1966) as modified by Nielsen (1979):

$$f_w = \exp[5.213(k_b/A_b)^{0.194} - 5.977] \quad \text{for } k_b/A_b > 1.7 \qquad (2a)$$
$$f_w = 0.28 \quad \text{for } k_b/A_b \leq 1.7 \qquad (2b)$$

where k_b is the grain-size related bottom roughness height given by 2.5D. The skin-friction wave shear velocity u_{*ws} was then calculated from:

$$u_{*ws} = (0.5\ f_w\ u_b^2)^{0.5} \qquad (3)$$

Following the method used by Porter-Smith et al. (2004), the wave energy flux (or wave power) P_w integrating the effect of wave height and period was calculated from:

$$P_w = (1/32\pi)\rho g^2 H^2 T \qquad (4)$$

Equation 4 gives the wave energy flux for regular waves with wave height H and period T in deep water conditions. Significant wave height H_s and spectral peak wave period T_p will be used in this study so that the wave energy flux predictions will be comparable with the values for the Australia shelves derived by Porter-Smith et al. (2004).

When tidal currents and waves both affect the seabed, they interact non-linearly to generate an enhanced combined wave-current shear stress (e.g. Grant and Madsen, 1986). A combined-flow sediment transport model SEDTRANS (Li and Amos, 2001) was used in this study to compute the seabed shear velocity due to the combined effect of waves and current. SEDTRANS is a calibrated and widely-used one dimensional computer model that predicts the boundary layer dynamics and sediment transport on continental shelves and in coastal environments for either steady currents or combined wave-current flows (Li and Amos, 2001). The model is based upon the combined wave-current bottom boundary layer theory developed by Grant and Madsen (1986), but also predicts bedforms, and bedload and suspended load transport for both sand and cohesive sediments. Comparisons of measured and modelled bedload transport rates over fine and medium sands showed that the error of the model-predicted sediment transport rate is less than a factor of 5 under complex combined wave and current conditions (Li et al., 1997; Li and Amos, 2001). Calibration of a slightly modified version of SEDTRANS also showed that model-predicted cohesive sediment concentrations are typically within 20% of the measured values using annular flumes in the field (Neumeier et al., 2008). The SEDTRANS model has been applied in a wide range of environments addressing variable scientific issues. These include predictions of bedforms and sediment transport under combined waves and current on the Scotian Shelf and the Grand Banks (Li and Amos, 1998, 1999a,b; Amos et al., 1999; Li et al., 2015b, 2017), modelling sediment erosion and dispersal at a disposal site with mixed sand and cohesive sediments in the Bay of Fundy (Parrott et al., 2002; Li et al., 2009), formation and dynamics of headland-associated sandbanks in English Channel, UK (Bastos et al., 2004) and in Minas Passage, Bay of Fundy (Li et al., 2014), modelling of seabed disturbance and sediment mobility on the Australian shelf (Hemer, 2006) and in the Bay of Fundy (Li et al., 2015a), and the use of modelled seabed disturbance in the development of a benthic habitat map on the Scotian Shelf (Kostylev and Hannah, 2007). For the present study, hourly wave and total current data together with water depth and observed mean grain size were input into SEDTRANS to calculate the combined wave-current shear velocity u_{*cws} through an iterative procedure at each grid point for each hour of the modelled period of 2002 to 2005. Details of the combined-flow bottom boundary layer theory and its iterative computation of the combined wave-current shear velocity u_{*cws} can be found in Grant and Madsen (1986) and Li and Amos (2001).

The observed grain size was used in SEDTRANS to compute the threshold shear velocity for sediment motion u_{*cr} based on the modified Yalin method of Miller et al. (1977) as described by Li and Amos (2001).

$$\log \theta_{cr} = 0.041(\log Y)^2 - 0.356\log Y - 0.977 \quad Y<100 \quad (5a)$$
$$\log \theta_{cr} = 0.132\log Y - 1.804 \quad 100<Y<3000 \quad (5b)$$
$$\theta_{cr} = 0.045 \quad Y>3000 \quad (5c)$$

where θ_{cr} is the critical Shields parameter and Y the Yalin parameter defined as $[(\rho_s-\rho)gD^3/\rho\nu^2]^{0.5}$ with ρ_s as sediment density and ν as kinematic fluid viscosity. The value θ_{cr} can be used in turn to calculate the critical shear stress τ_{cr} from:

$$\tau_{cr} = \theta_{cr}(\rho_s - \rho)gD \qquad (6)$$

and the critical shear velocity u_{*cr} can finally be obtained from the quadratic law $\tau_{cr} = \rho u_{*cr}^2$.

Finally, the hourly skin-friction shear velocity by tidal current, waves, circulation current and combined waves and current as computed above was then compared to the critical shear velocity u_{*cr} to determine if sediment mobilization occurs. The number of times that the threshold value was exceeded by various processes was then summed at each grid point over the modelled 3 year period to produce the threshold exceedance (sediment mobilization frequency) due to tidal current, waves, circulation and combined wave-current for the Canadian Atlantic Shelf.

3. Results

3.1 Waves

Mean significant wave height and spectral peak wave period are shown in Figures 4a and 4b respectively. The strongest waves occur in the open ocean off the Atlantic Shelf where the mean significant wave height values reach 3.5 m and mean wave periods are up to 8 s in these areas while the maximum significant wave heights can reach 15 m (not shown). Wave height progressively decreases from the open ocean, through the shelf, and to the coastal zone. Waves are strongest on the Grand Banks as mean H_s values reach greater than 2.5 m. Values of mean H_s are generally 1–2 m on the Scotian Shelf and on the Newfoundland and Labrador Shelves. Because of sheltering, mean H_s is significantly lower in bays and coastal basins, generally less than 1.2 m in the Bay of Fundy and Gulf of St. Lawrence. Waves are weakest and mean H_s is less than 1 m in Baffin Bay. The low waves in Gulf of St. Lawrence and Baffin Bay are partially attributed to the partial coverage of sea ice in these regions (Li et al., 2021), although this may by modulated by climate change (Wang et al., 2018). Wave periods reach similar values of ~7 s on the Newfoundland shelf and in Baffin Bay, while values are slightly less (6–6.5 s) on the Scotian Shelf (Fig. 4b). Wave periods further reduce to < 5.5 s in the Bay of Fundy and Gulf of St. Lawrence. The spatial distribution of the 95th percentile H_s representing the extreme wave conditions is shown in Fig. 4c. The distribution of the 95th percentile H_s are nearly identical to the mean H_s. However, the values are approximately doubled. E.g. the 95th percentile H_s increases to ~5 m from the mean of 2.5 m over the Grand Banks and to ~4 m from 1–2 m on the Scotian Shelf.

The mean wave power representing the combined effect of wave height and period (from Equation 4) is presented in Fig. 5. The distribution patterns of wave power seem to be better correlated with the distribution of wave height (Fig. 4a) than wave period. The greatest wave energy occurs in the deep waters off the Newfoundland and Labrador shelf where mean wave

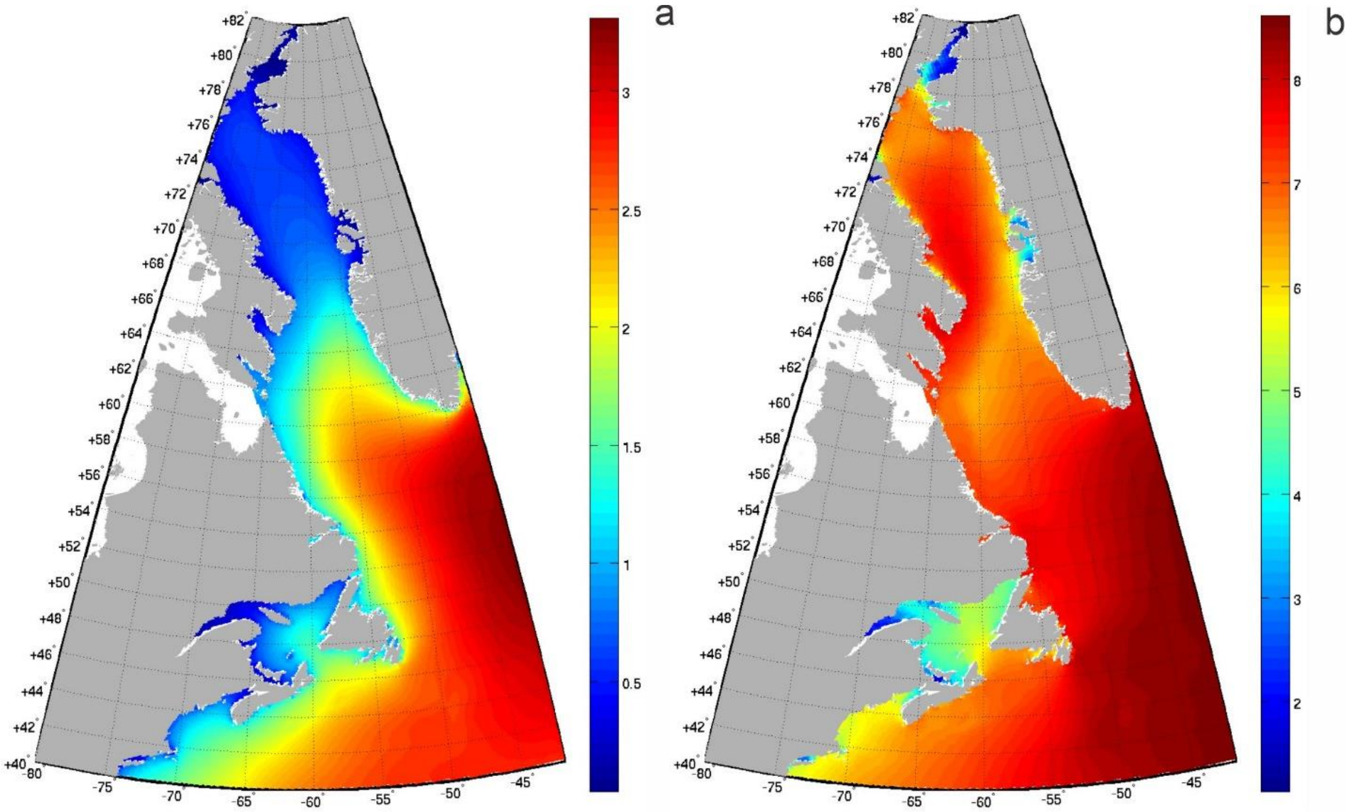


Figure 4 Spatial distribution of (a) mean significant wave height (Hs, m), (b) mean spectral peak wave period (Tp, s) and (c) (next page) 95th percentile significant wave height (m) on the Canadian Atlantic Shelf. Note the different scales in (a) and (c).

power can reach or exceed 90,000 W m^{-2}. On the continental shelves, the greatest wave power occurs on the Grand Banks where the mean wave power is up to ~60,000 W m^{-2}. The mean wave power drastically decreases to 40–50,000 W m^{-2} on the Newfoundland and Labrador shelves and further reduces to 30,000 W m^{-2} on the Scotian Shelf. Due to partial ice coverage (Li et al, 2021), wave energy is the lowest in Baffin Bay with mean wave power of less than 1000 W m^{-2}.

3.2 Currents

3.2.1 Tidal currents

Mean and 95th percentile tidal current speed are respectively presented in Figures 6a and b. The highest mean tidal currents on the Atlantic Shelf are up to 0.8–1.2 $m \cdot s^{-1}$ and occur in Bay of Fundy, on Georges Bank and at the entrance to Hudson Strait on the Southeast Baffin Shelf. Moderately strong tidal currents of 0.5–0.7 $m \cdot s^{-1}$ are found on western Scotian Shelf. Moderate tidal currents of 0.3–0.4 $m \cdot s^{-1}$ are predicted on the banks of the outer Scotian Shelf and in Davis

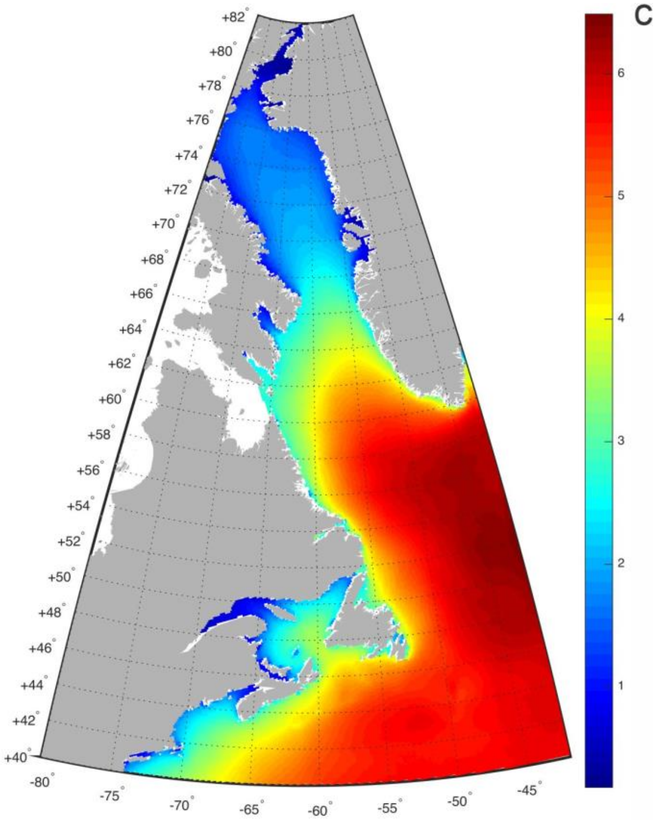


Fig. 4 (continued)

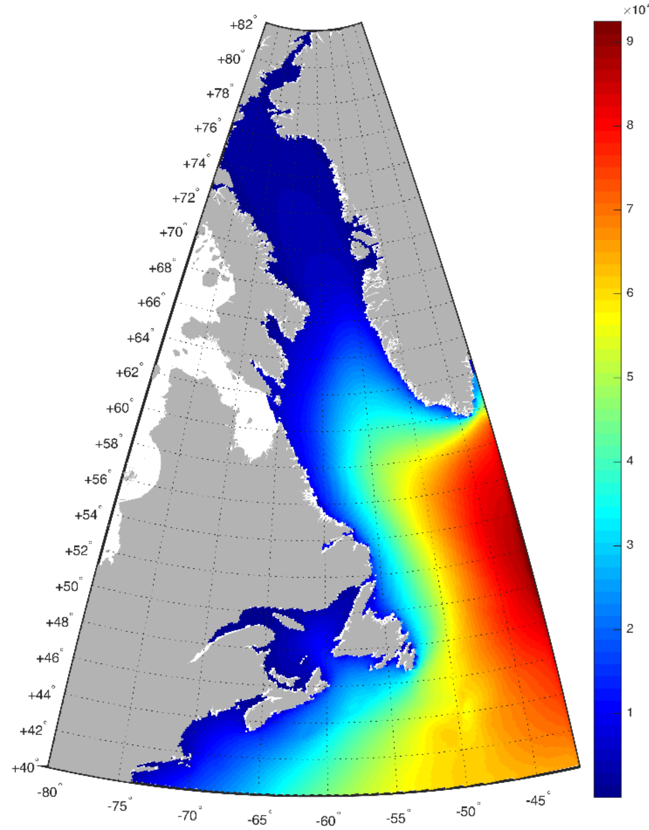
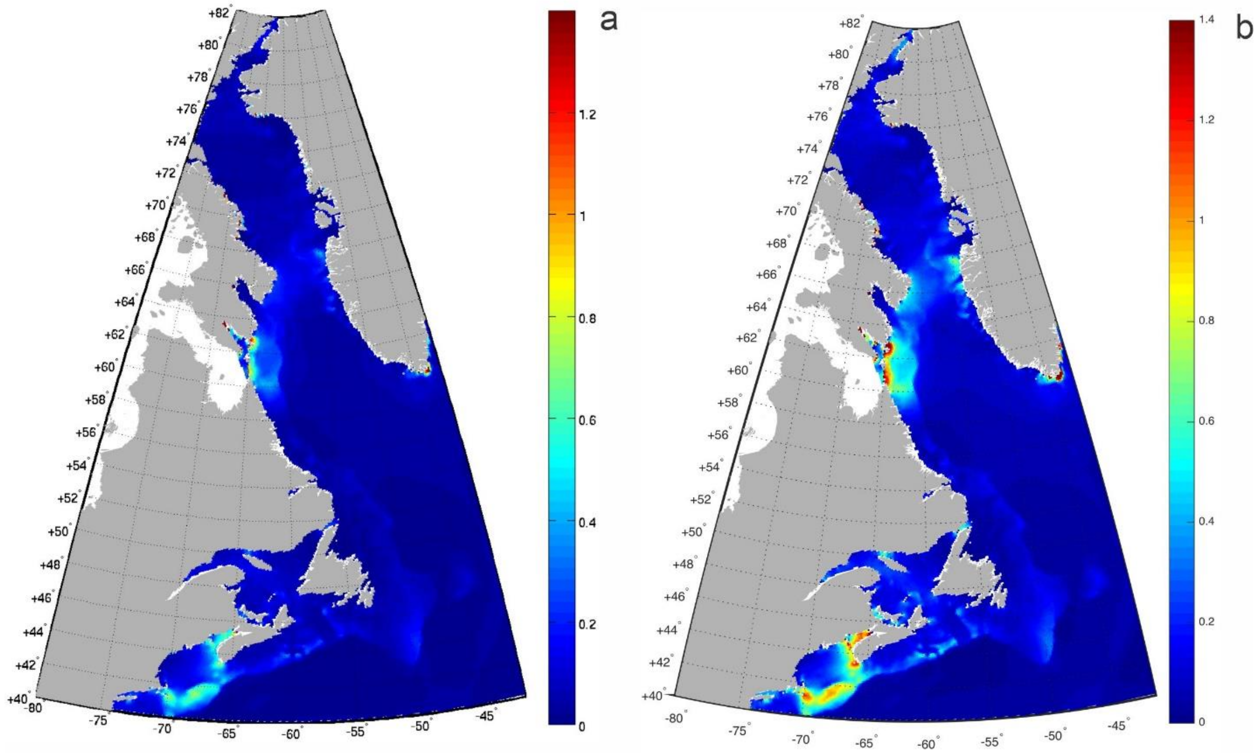


Figure 5 Spatial distribution of mean wave power (Pw, W m^{-2}) on the Atlantic Shelf.

Strait. Low to moderate tidal currents of 0.2–0.3 $m \cdot s^{-1}$ are found on the Grand Banks and in Gulf of St. Lawrence. Low tidal currents of 0.1 $m \cdot s^{-1}$ occur on Flemish Pass and on the banks on the outer Labrador Shelf. The distribution of the 95th percentile tidal current speed is nearly identical to the mean tidal current speed. However the values are on average 30–40% higher largely reflecting the changes of current speed between peak flood/ebb and high/low slack tides and that between neap and spring tides. The increase of the extreme tidal currents is particularly greater in the Bay of Fundy, on western Scotian Shelf and on the Southeast Baffin Shelf.

The high tidal currents in the Bay of Fundy and at the entrance to Hudson Strait, and the moderately high tidal currents on the western Scotian Shelf are attributed to the higher tidal ranges as the mean tidal ranges are 3.6 – 10 m and 2.4 – 3.6 m respectively in these areas (Cornett, 2006). The strong tidal current on Georges Bank with its mean tidal range of merely 1.2 m is probably due to the combination that Georges Bank forms part of the Gulf of Maine-Bay of Fundy tidal resonance system and the bank also causes topographic acceleration of the tidal flow.



Figures 6 Spatial distribution of (a) mean and (b) 95th percentile tidal current speed (m s^{-1}) on the Atlantic Shelf.

3.2.2 Circulation currents

Mean and 95th percentile circulation current speed is respectively presented in Figures 7a and b. Several differences from the distribution of tidal current stand out. Firstly, the magnitude of circulation currents is significantly less than that of the tidal currents and typically is less than 0.2 $m \cdot s^{-1}$. Secondly, moderate to strong tidal currents widely occur in the Bay of Fundy and on other areas on the shelf (Fig. 6a) while circulation currents are minimal in these areas. The moderate circulation flows of 0.2 – 0.3 $m \cdot s^{-1}$ are concentrated in narrow belts along the shelf edge and upper slope on the Atlantic Shelf. The spatial distribution of the 95th percentile circulation current speed in Fig. 7b shows essentially the same patterns as the mean circulation currents. However, the peak values moderately increase to ~0.4 $m \cdot s^{-1}$ particularly off southeastern and southwestern Grand Banks. This lack of significant differences between the mean and extreme values of the circulation current on the Atlantic Shelf are attributed to the fact that the frequency of ocean circulation currents is monthly to yearly and hence its extreme values will not be drastically different from it’s mean magnitudes.

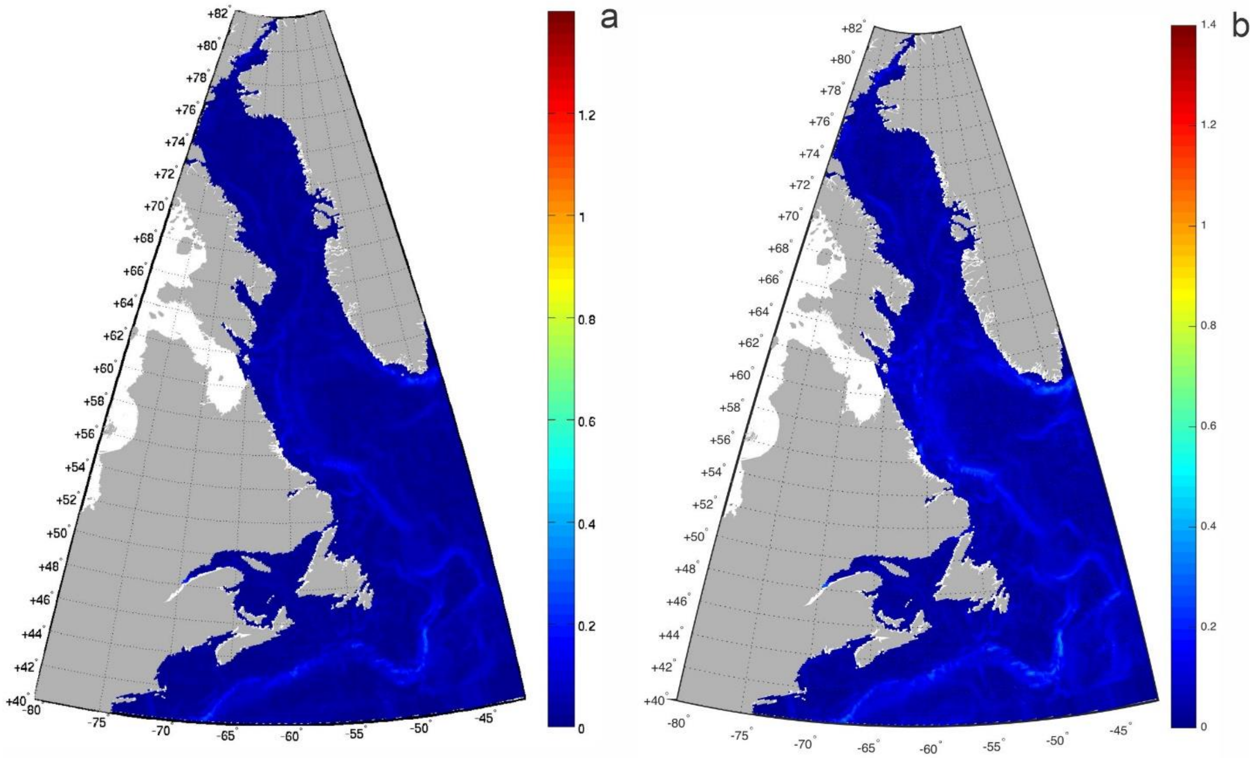


Figure 7 Spatial distribution of (a) mean and (b) 95th percentile circulation current speed (m s^{-1}) on the Atlantic Shelf.

3.2.3 Storm-driven currents and total currents

The CECOM-output circulation currents represent the sum of the instantaneous wind-driven currents and the background mean circulation currents. The mean circulation currents have been vectorialy subtracted from the CECOM-output circulation currents to derive the storm-driven currents. The distribution of the 95th percentile storm-driven currents is presented in Figures 8. The main feature is that winds during storms introduce additional near-bed currents up to ~0.2 $m \cdot s^{-1}$ in magnitude mainly on the shelf, particularly on the Grand Banks, over the banks on the outer Scotian Shelf and on western Scotian Shelf.

The total currents are the vectorial sum of the tidal current and CECOM circulation currents. Mean and 95th percentile total current speed are respectively presented in Figures 9a and b. The highest mean total currents on the Atlantic Shelf are up to 0.8–1.0 $m \cdot s^{-1}$ and occur in Bay of Fundy, on Georges Bank and at the entrance to Hudson Strait on the Southeast Baffin Shelf. Moderately strong currents of ~0.5 $m \cdot s^{-1}$ are found on western Scotian Shelf. Moderate currents of 0.3–0.4 $m \cdot s^{-1}$ are predicted on the banks of the outer Scotian Shelf and in Davis Strait. Areas with the lowest total currents (<~0.1 $m \cdot s^{-1}$) notably include western Gulf of Maine, inner and

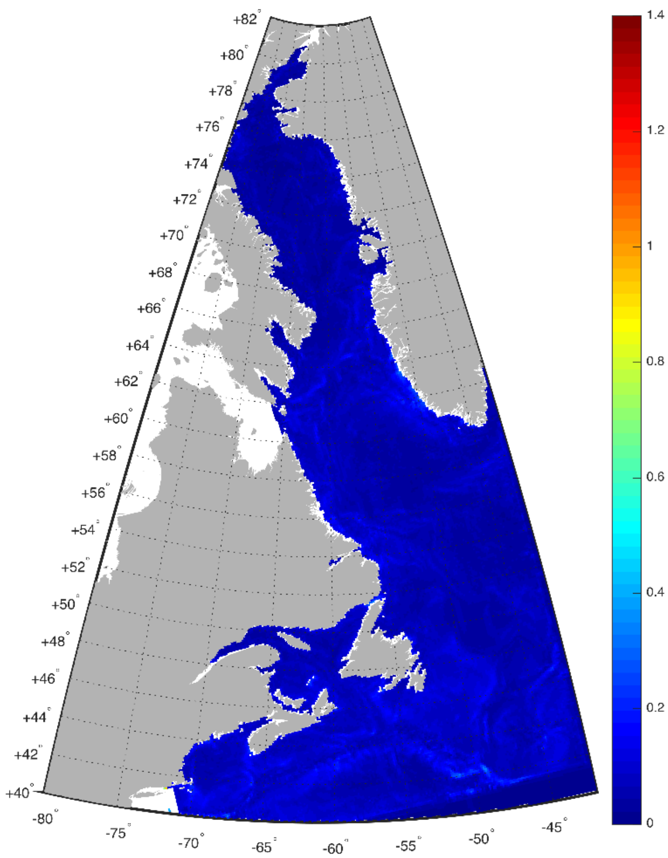


Figure 8 Spatial distribution of the 95th percentile storm-driven current speed (m s^{-1}) on the Atlantic Shelf

mid-Scotian Shelf, Laurentian Channel, southwestern and northeastern Gulf of St. Lawrence, the Northeast Newfoundland Shelf, central and southern Labrador Shelf, and the Baffin Bay. The magnitude and spatial patterns of the total currents are thus quite similar to that of the tidal currents shown in Figure 6. The main difference, however, is that since the total currents include the contribution of the circulation current, Figure 9a also demonstrates the presence of narrow belts of moderate flows of 0.2 $m \cdot s^{-1}$ along the edge and upper slope of the Atlantic Shelf. The 95th percentile total current (Figure 9b) demonstrates nearly identical patterns to the mean total currents. However, the maximum values increased to 1.2 – 1.4 $m \cdot s^{-1}$ in the Bay of Fundy and on the Southeast Baffin Shelf while the moderate currents on the banks of the outer Scotian Shelf and in Davis Strait also increase to 0.5 – 0.6 $m \cdot s^{-1}$. These represent ~50% increases over the mean total currents suggesting the importance of extreme values of the total currents in assessing the intensity and frequency of seabed disturbance.

3.2.4 Magnitude and distribution of various current processes

Comparison of Figures 7a and Figure 8 indicates that circulation and 95th percentile storm-driven currents have similar magnitudes, 0.2–0.3 $m \cdot s^{-1}$. While the effects of storm-driven currents are restricted on the shelf, impact of circulation currents is distributed as perimeters over

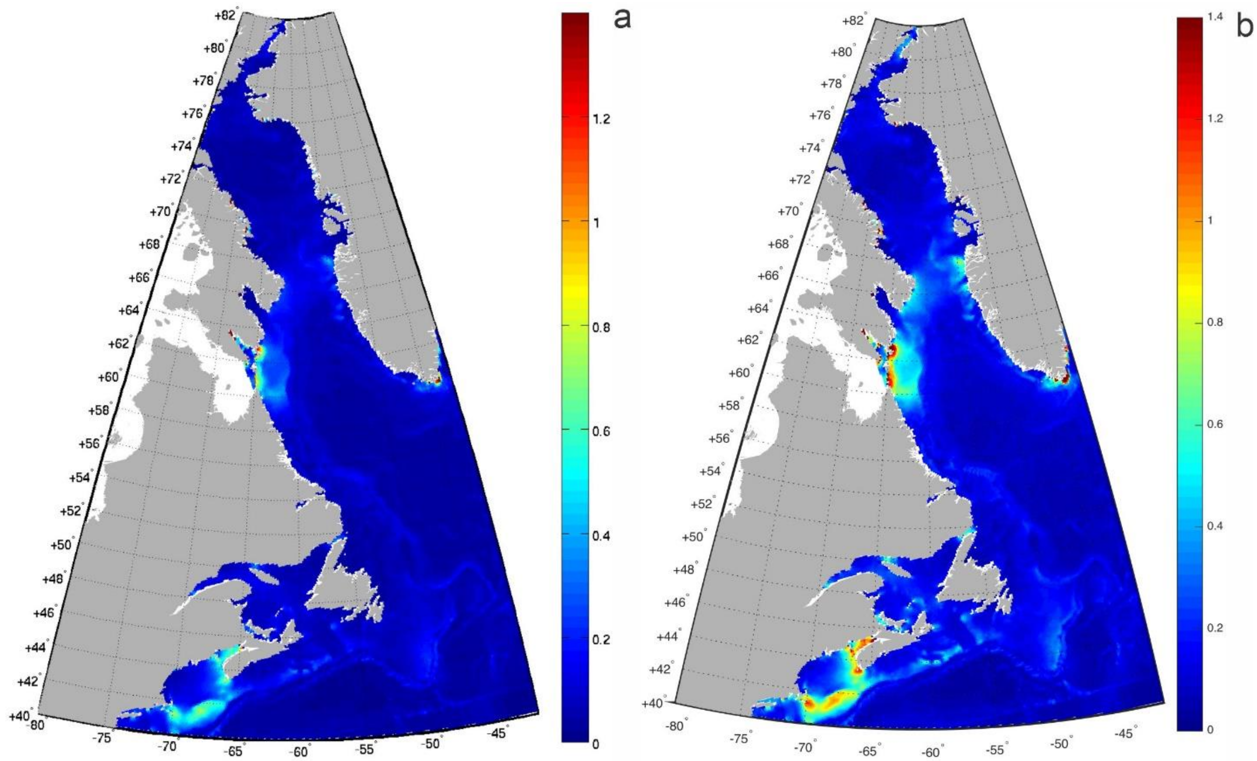


Figure 9 Spatial distribution of (a) Mean and (b) 95th percentile total current speed (m s^{-1}) on the Atlantic Shelf.

the shelf edge and upper slope. Tidal currents (Figures 6a) are significantly greater than the magnitude of either the circulation current or the storm-driven currents as maximum mean tidal current speeds reach ~1 $m \cdot s^{-1}$. Tidal currents also affect the shelf more widely than the storm-driven currents.

With the exception that the total currents (Figure 9a) show moderate flows along the shelf edge and upper slope which is absent in the distribution of tidal currents (Figures 6a), the magnitude and spatial distribution of the mean total currents are essentially the same as that of the mean tidal currents. This compatibility implies that averaged over the modelled 3 years, the vectorial addition of the storm-driven currents causes insignificant changes to the magnitude of the total currents which were used in the computation of the combined wave-current shear stress.

3.3 Seabed shear stress and sediment mobilization

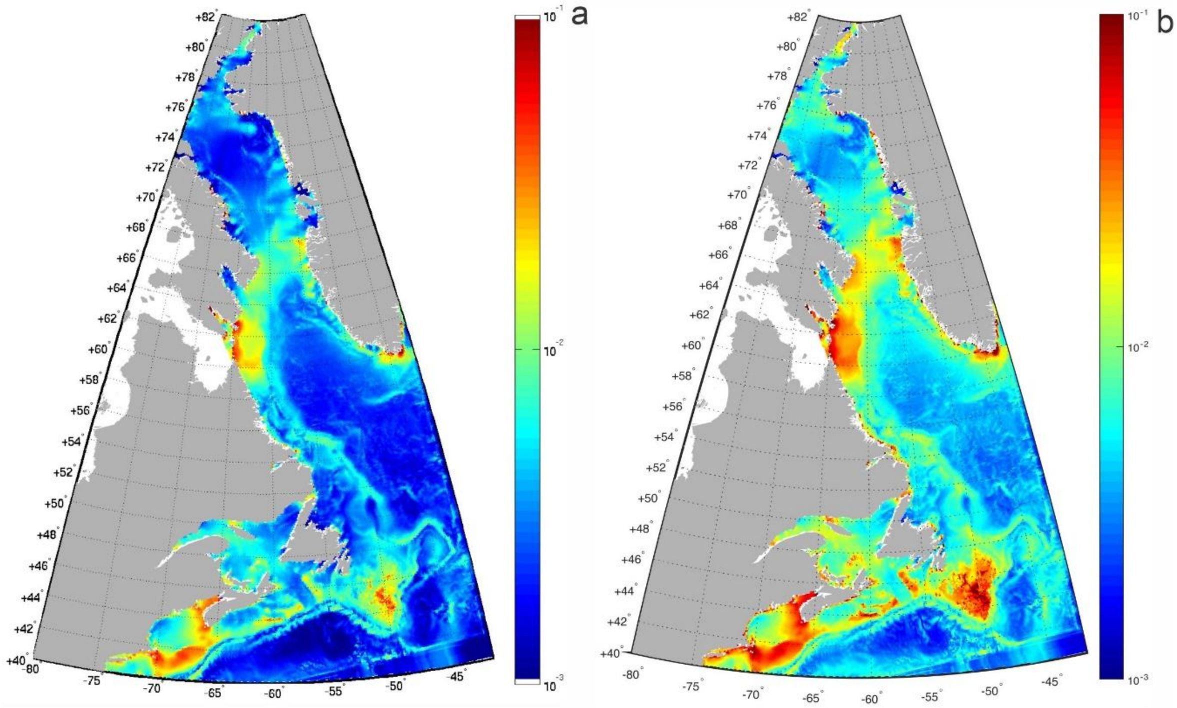
In this section, we first present and describe the distribution of the mean combined wave-current shear velocity to demonstrate the overall spatial patterns of seabed forcing due to the combined effects of tides, waves, and ocean circulation currents. The magnitude and spatial patterns of shear velocities due to individual component processes of tides, waves, and circulation currents will then be presented. Lastly the levels and spatial patterns of sediment mobilization frequency by these component processes as well as by the combined wave-current stress will be analyzed.

3.3.1 Seabed Shear Stresses

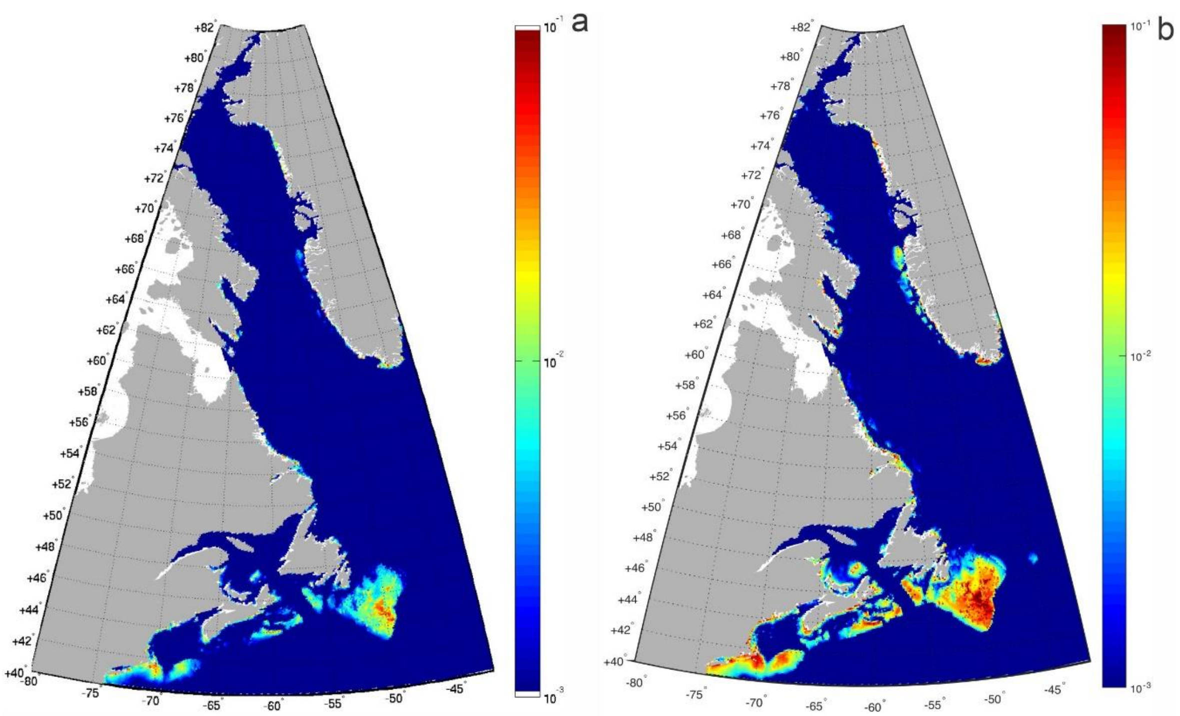
The mean shear velocity due to the combined wave and total current, u_{*cws}, in Fig. 10 represents the overall patterns of seabed forcing from integrating all oceanographic processes i.e. tidal currents, waves and circulation currents. The strongest combined wave-current shear velocity is >5 $cm{\cdot}s^{-1}$ and occurs in the Bay of Fundy, on Georges Bank, on western Scotian Shelf, on central and southeastern Grand Banks, at the entrance to Hudson Strait, and over small patches at top of Sable Island Bank on the outer Scotian Shelf. Moderately high shear velocities of 2–3 $cm{\cdot}s^{-1}$ are found over the banks on the outer Scotian Shelf, on the western and northeastern Grand Banks, in Davis Strait, and over patches of topographic highs in southeastern Gulf of St. Lawrence. Low to moderate shear velocities of 1–2 $cm{\cdot}s^{-1}$ are predicted for central Gulf of Maine, central outer Scotian Shelf, over the remaining areas of the Grand Banks, in patches in the Gulf of St. Lawrence, and as perimeters along the shelf edge and over the upper slope. Notable areas with minimal values of combined shear velocity (<0.5 $cm{\cdot}s^{-1}$) occur in western Gulf of Maine, on inner to middle Scotian Shelf, in Laurentian Channel, in northeastern Gulf of St. Lawrence, on the Northeast Newfoundland Shelf and over most parts of Baffin Bay.

The mean shear velocity due to the individual component processes of waves, tidal current, and circulation current are respectively presented in Figures 11, 12 and 13. The wave impact on the seafloor predominantly depends on the water depths rather than the distribution of wave heights on the ocean surface. Mean wave shear velocity in Fig. 11 demonstrates that the strongest waves in the open ocean (Fig. 4a) do not translate to impact at the seabed due to the deep water depths in these areas. Wave impact on the seabed is generally restricted in shallower waters on the outer shelf banks and along the coasts. The spatial distribution of the mean wave shear velocity (Fig. 11) shows that the strongest wave shear velocity of ~4 $cm{\cdot}s^{-1}$ occurs on the central and southeastern Grand Banks. Moderate wave shear velocities of 2–3 $cm{\cdot}s^{-1}$ are predicted on Georges Bank, on the banks of the outer Scotian Shelf, over a patch in southeastern Gulf of St. Lawrence, and over the remaining areas of the Grand Banks. Low to moderately low wave shear of 0.5–1 $cm{\cdot}s^{-1}$ can be found on middle eastern Scotian Shelf, over a patch in eastern Davis Strait, and along the coasts of the Atlantic Shelf.

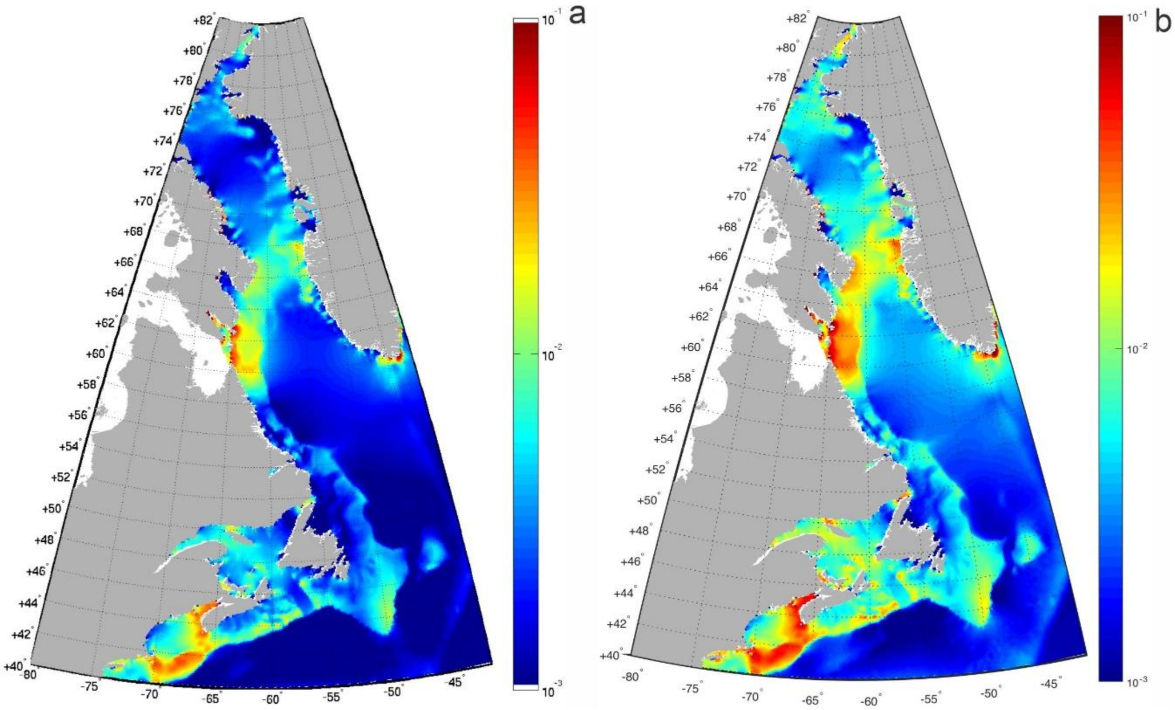
In contrast to the restricted distribution of wave shear stress, the impact of tidal current shear velocity occurs widely on the Atlantic shelf. The patterns of the mean tidal current shear velocity (Fig. 12) are well correlated with that of the mean tidal current speed (Fig. 6a). The highest mean tidal current shear velocity also reaches ~4 $cm{\cdot}s^{-1}$ similar to the peak values of the mean wave



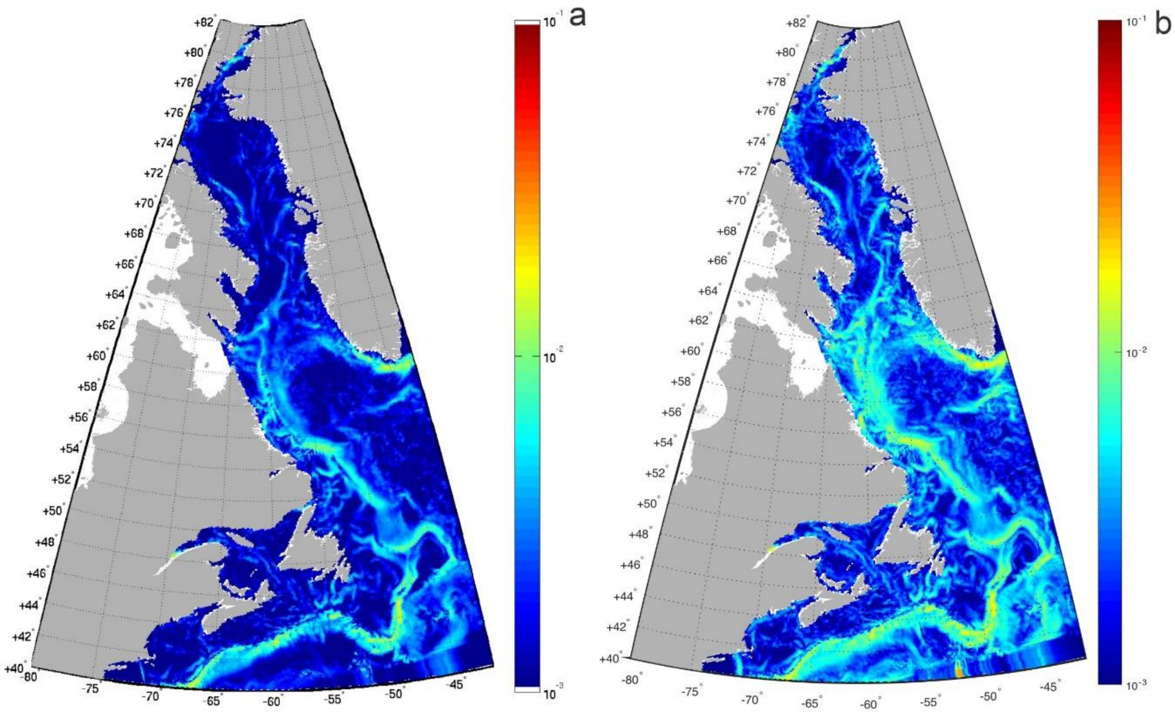
Figures 10 Spatial distribution of (a) mean and (b) 95th percentile combined shear velocity (m s^{-1}) due to wave and total current on the Atlantic Shelf.



Figures 11 Spatial distribution of (a) mean and (b) 95th percentile wave shear velocity (m s^{-1}) on the Atlantic Shelf.



Figures 12 Spatial distribution of (a) mean and (b) 95th percentile tidal current shear velocity (m s^{-1}) on the Atlantic Shelf.



Figures 13 Spatial distribution of (a) mean and (b) 95th percentile circulation current shear velocity (m s^{-1}) on the Atlantic Shelf.

shear velocity. However, the impact of the tidal currents has a much broader distribution as the maximum values of mean tidal shear velocity are found in the Bay of Fundy, on Georges Bank and western Scotian Shelf, and at the entrance to Hudson Strait. Moderate tidal shear velocities of 2–3 $cm \cdot s^{-1}$ also widely occur on the banks of outer Scotian Shelf, on western and southeastern Grand Banks, in patches in the Gulf of St. Lawrence, in Davis Strait, and on northern Labrador Shelf. Low tidal shear velocities of 0.5 – 1 $cm \cdot s^{-1}$ are predicted in central Gulf of Maine, on central outer Scotian Shelf, as a patch on the middle eastern Scotian Shelf, on northeastern Grand Banks, over Flemish Cap, on the banks of the outer Labrador Shelf, and in patches on the Baffin Bay shelves. Tidal shear velocities are minimal (<0.3 – 0.5 $cm \cdot s^{-1}$) in western Gulf of Maine, on inner and middle Scotian Shelf, in the Laurentian Channel, on central and northern Grand Banks, and on the Northeast Newfoundland Shelf.

The shear velocity of the circulation current (Figure 13) demonstrates patterns that are yet different from the wave and tidal current shear velocities. The maximum values of the circulation current shear velocity are much smaller than the wave and tidal current shear velocities and are generally <2 $cm \cdot s^{-1}$. And the distribution of these moderate values is restricted along the perimeters over the shelf edge and upper slope with minimal impact over the vast interior areas of the shelves. The maximum values up to 2 $cm \cdot s^{-1}$ mainly occur on the shelf break and upper slope off southeastern Grand Banks, central Scotian Shelf and Georges Bank. The perimeters of moderate combined wave-current shear velocities along the shelf edge and over the upper slope demonstrated in Fig. 10 are thus dominantly attributed to the impact of the circulation current.

Extreme values of shear stresses from various processes not only represent the potential maximum force exerted on the seabed but also determine if sediment mobilization occurs or not. Therefore the spatial distributions of the 95th percentile combined, wave, tidal current, and circulation current shear velocities are respectively presented in Figures 10b, 11b, 12b and 13b. As storms occur on the intermittent frequency (2 to several days) and are seasonally stronger in the winter, the extreme values of the wave shear velocity represented by the 95th percentile wave shear velocity (Fig. 11b) are greatly different from the mean values averaged over multiple years (Fig. 11a). The maximum values of the 95th percentile values on the SE Grand Banks are nearly double of the mean values increasing from 4–5 $cm \cdot s^{-1}$ to ~10 $cm \cdot s^{-1}$. The mean wave shear velocities of 2–3 $cm \cdot s^{-1}$ on the banks of the outer Scotian Shelf increase to ~5 $cm \cdot s^{-1}$. The impact areas of the 95th percentile wave shear velocity also increase substantially, for instance on Georges Bank and over western Scotian Shelf.

As tidal processes are dominated by the semidiurnal frequency, the 95th percentile tidal current shear velocity (Figure 12b) does not present changes from the mean values as drastically as the wave shear velocity. The distribution patterns of the extreme values are nearly identical to that of the mean values. The maximum tidal current shear velocity only increases from 4 $cm \cdot s^{-1}$ for the mean shear velocity to 5–6 $cm \cdot s^{-1}$ for the 95th percentile values. These moderate increases in the magnitude and spatial impact range should largely come from the variations of the neap-spring cycles at the fortnightly frequency. Circulation currents represent the background mean ocean currents and vary mainly in seasonal and inter-annual cycles. Therefore the comparison of the 95th percentile and mean circulation current shear velocities (Figures 13a, b) indicates that the spatial distribution patterns of the extreme and mean values are nearly the same and that only the magnitude increases moderately from 2 $cm \cdot s^{-1}$ of the mean condition to 3 $cm \cdot s^{-1}$ of the extreme condition.

The patterns of the 95th percentile combined wave and current shear velocity (Fig. 10b) reflect the effect of the spatial variation of the relative impact of tides and storms. For areas where wave impact is dominant, the values of the 95th percentile combined shear velocity increase by a factor of 2 from the mean values. For instance, the combined shear velocity increases from the mean values of 5 $cm \cdot s^{-1}$ to maximum values of 10 $cm \cdot s^{-1}$ on the SE Grand Banks and the values increase from 2–3 $cm \cdot s^{-1}$ to 6 $cm \cdot s^{-1}$ over the banks of the outer Scotian Shelf. For areas dominated by tidal processes such as the Bay of Fundy, Georges Bank, and the entrance to Hudson Strait, the changes are more moderate. The values increase from ~4 $cm \cdot s^{-1}$ of the mean values to ~6 $cm \cdot s^{-1}$ of the 95th percentile for these areas. Although the spatial patterns of the 95th percentile combined shear velocity are similar to that of the mean, the spatial extent of the impact of the 95th percentile values increases substantially. This is particularly apparent over the Gulf of Maine-western Scotian Shelf, on the banks of the outer Scotian Shelf, and on the Labrador Shelf.

3.3.2 Sediment Mobilization Frequency

<u>Waves and storm processes</u>

The percentage of time that waves alone cause mobilization of observed grain sizes on the Atlantic Shelf is presented in Figure 14. The map of wave sediment mobilization frequency shows overall patterns very similar to that of the mean wave shear velocity of Figure 11a. The highest wave mobilization frequency, up to 30–50% of the time, occurs on Sable Island Bank on the outer Scotian Shelf. Moderate frequency of wave mobilization of 10–30% is found over the Banquereau Bank on the outer Scotian Shelf, on the SE Grand Banks, over the topographic highs in southeastern Gulf of St. Lawrence and along the coast of Labrador Shelf. Low to moderate mobilization frequency up to 10% occurs on Georges Bank, on western Grand Banks, on NE Grand Banks and over eastern Davis Strait. Low wave mobilization frequency of 1–3% is predicted on southwestern and northern Grand Banks and at the top of Flemish Cap.

The percentage of shelf area over which various processes exceed the threshold of sediment motion can be used to quantify the relative importance of component processes in the mobilization of observed sediments on the Atlantic Shelf. The shelf break often occurs in water

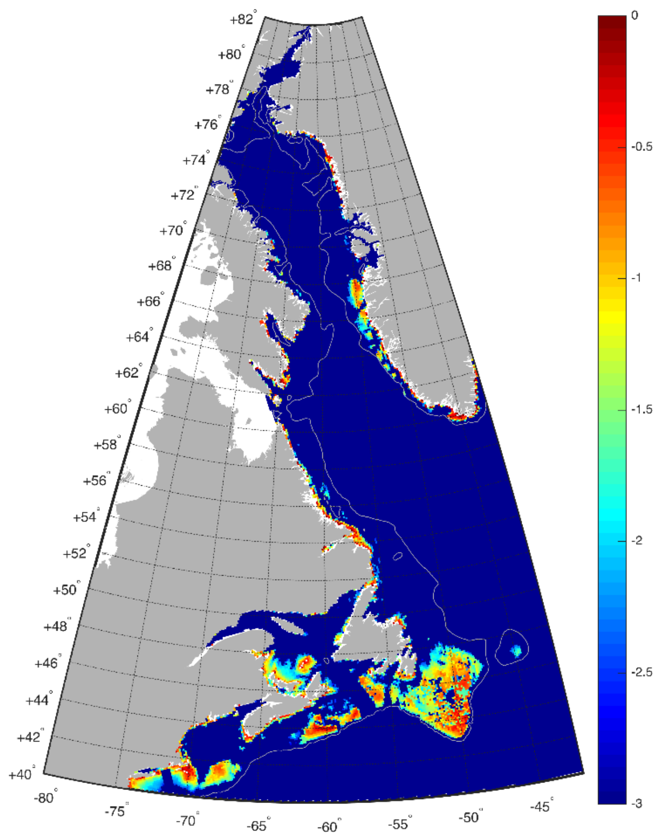


Figure 14 Spatial distribution of mobilization frequency (% of time) of observed sediments by waves on the Atlantic Shelf averaged over the period of 2002 – 2005.

depths down to 300–500 m over significant parts of the Atlantic Shelf (Piper, 1991). The depth range of 10 – 500 m is thus used to define the total area of the Atlantic Shelf at ~1.88 million km^2. The wave threshold exceedance data have been used to compute the area and the percentage of shelf area over which waves exceed the threshold of sediment motion at least once over the modelled 3 year period. These statistics are listed in Table 2. Figure 14 together with Table 2 demonstrate that waves are capable of mobilizing sediments at least once over 30.2% of the Atlantic Shelf area. In association with the large wave heights, winter storms will also generate moderate near-bed wind-driven currents as presented in Fig. 8. The combined shear velocity due to the interaction of waves and the storm-driven currents could be used for an evaluation of sediment mobilization by the total effects of storm processes (waves plus storm-driven currents) on the Atlantic Shelf. This shear velocity due to the combined effect of waves and storm-driven currents has been used to compute the threshold exceedance by storms (Table 2). It is estimated that storms can mobilize sediments at least once over 34.9% of the Atlantic Shelf area indicating that inclusion of storm-driven currents cause moderate increase from sediment mobilization by waves alone.

As a function of the combined effect of the maximum significant wave height H_s, associated peak wave period T_p and the spatial distribution of observed grain size, the maximum depth that waves are capable of mobilizing sediment is down to ~175 m on the Atlantic shelf. This occurs on the Flemish Cap over fine sand under waves with maximum H_s of 13 m, associated T_p of 14.5 s, and southwesterly propagation direction.

Table 2 Area and percentage of total shelf area of threshold exceedance of observed grain sizes by the processes of tides, waves, storms, circulation current and combined waves and current on the Canadian Atlantic Shelf.

Processes	Total shelf area (km^2)	Area (km^2)	% of shelf area
	1,884,768		
Tide		555,738	29.5
Wave		569,362	30.2
Storm		647,073	34.9
Circulation		4,979	0.3
Combine wave-current		1,192,870	63.3

<u>Tidal Currents</u>

The percentage of time that the tidal current alone causes mobilization of observed sediments on the Atlantic Shelf is presented in Figure 15. It is immediately clear that sediment mobilization by tidal currents, particularly at higher intensity, occurs more widely and reaches higher frequency than that by waves. The highest frequency is up to 100% of the time and occurs in the Bay of Fundy, on Georges Bank, on western Scotian Shelf, on SE Baffin Shelf near the entrance to Hudson Strait, and over eastern Davis Strait. High mobilization frequency of 50–70% of the time occurs on the banks on the outer Scotian Shelf, in Northumberland Strait and in the remaining areas of Davis Strait. Moderate sediment mobilization by tidal currents of 10–30% of the time occurs over patches in the Gulf of St. Lawrence. Tidal current alone causes little or no sediment mobilization in the Gulf of Maine, on the inner and middle Scotian Shelf, on the Grand Banks, on Northeast Newfoundland Shelf, on the central and southern Labrador Shelf and in Baffin Bay. The percentage of shelf area over which tidal currents exceed the threshold of sediment motion at least once over the modelled 3 year period is 29.5% (Table 2), just slightly smaller than the waves.

There is a fair correlation between the distribution of tidal sediment mobilization and tidal current shear velocity (Figure 12). Areas of highest mobilization frequency are also areas with strongest tidal current shear velocity, e.g. the Bay of Fundy, Georges Bank and SE Baffin Shelf. The distribution of grain size also affects the patterns of the sediment mobilization by tides. The banks on the outer Scotian Shelf and SE Grand Banks have similar magnitudes of tidal shear

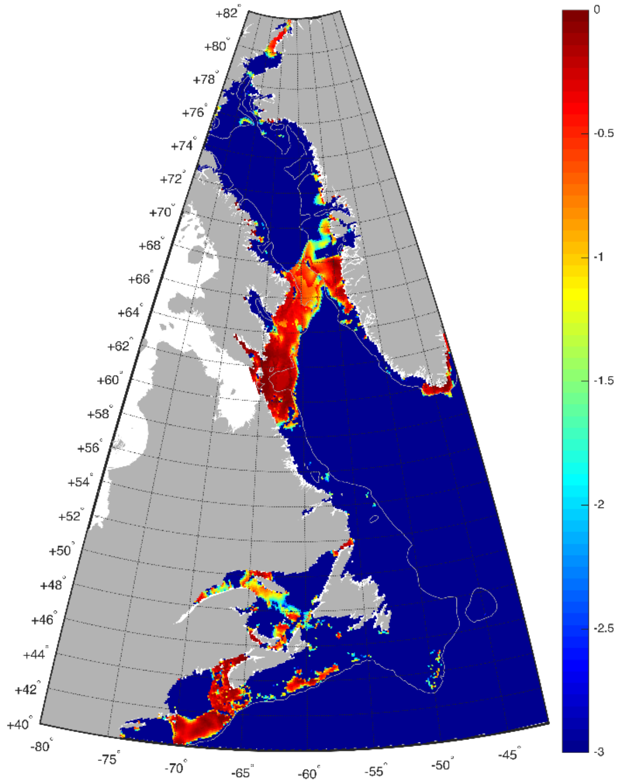


Figure 15 Spatial distribution of mobilization frequency (% of time) of observed sediments by tidal currents on the Atlantic Shelf averaged over the period of 2002 – 2005.

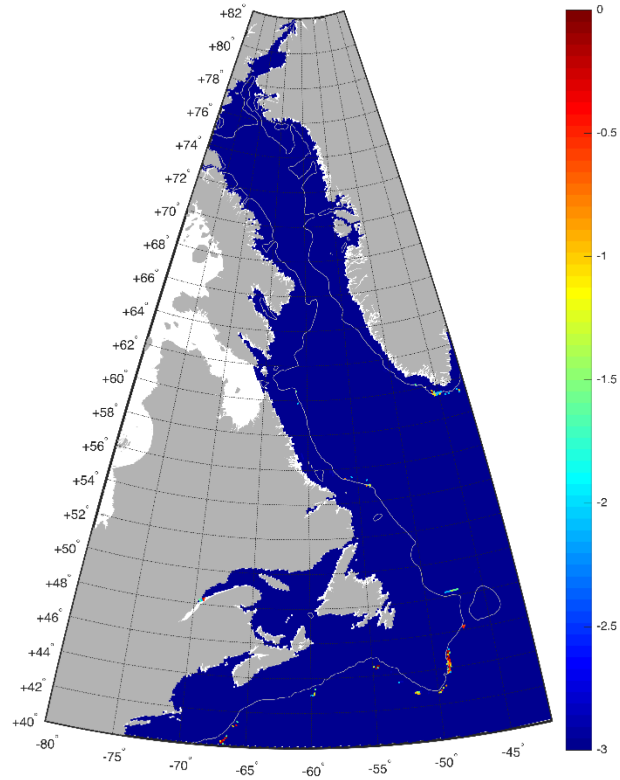


Figure 16 Spatial distribution of mobilization frequency (% of time) of observed sediments by circulation currents on the Atlantic Shelf averaged over the period of 2002 – 2005.

velocity (Figure 12). However, the sediments on the outer shelf banks are dominantly sandy while that on the SE Grand Banks are gravelly (Figure 3c). Therefore high tidal mobilization (50–70%) occurs on the outer shelf banks while tidal currents cause little mobilization of the gravelly sediments on the SE Grand Banks (Figure 15). Comparison of sediment mobilization frequency by tides (Figure 15) with that by waves (Figure 14) suggests that the areas dominated by tides and by waves tend to be mutually exclusive. Sediment mobilization by waves predominantly occurs on the Grand Banks where tides cause little sediment mobilization. Tidal currents mobilize sediments strongly in the Bay of Fundy, on western Scotian Shelf, on SE Baffin Shelf and in Davis Strait which are areas where waves do not cause mobilization of sediments.

<u>Circulation current</u>

The percentage of time of mobilization of observed sediments by circulation current on the Atlantic Shelf is shown in Figure 16. The spatial pattern is strongly dependent on the distribution of the circulation current shear velocity presented in Figure 13a. The mobilization of sediments occurs as sporadic spots or patches along the narrow perimeters over the shelf edge and upper slope. The maximum frequency values could reach up to 80% of the time due to the year-round present of the mean circulation currents. Shelf area wise sediment mobilization by circulation current is insignificant on the Atlantic Shelf as the percentage of shelf area over which circulation currents exceed the threshold of sediment motion at least once over the modelled 3 year period is only 0.3% (Table 2).

Combined waves and current

The percentage of time that the combined wave-current shear stress causes mobilization of observed sediments on the Atlantic Shelf is presented in Figure 17. The highest mobilization frequency of ~100% of the time occurs in the Bay of Fundy, on Georges Bank and SW Scotian Shelf, at the top of SIB, on SE Baffin Shelf near the entrance to Hudson Strait, and over eastern Davis Strait. High mobilization frequency of 50 – 70% is found over the remaining areas of the banks on the outer Scotian Shelf and in the Northumberland Strait. Moderately high frequency of 30–50% occurs in patches of topographic highs in the Gulf of St. Lawrence, along the coasts of Labrador Shelf and over the remaining areas of Davis Strait. The SE Grand Banks and western central and southwestern Gulf of St. Lawrence show moderate mobilization of 10–30% of the time. Low mobilization of 1–10% of the time is predicted on central outer Scotian Shelf, on southwestern and northern Grand Banks, on Flemish Cap, and over the banks on the outer Labrador Shelf. Low to moderate sediment mobilization is also found along the shelf edge and upper slope around the Grand Banks largely attributed to the influence of the Labrador Currents. The combined wave-current shear is minimal and causes no sediment mobilization in the Gulf of Maine, on the inner and middle Scotian Shelf, in the Laurentian Channel, over the northeastern Gulf of St. Lawrence, on the Northeast Newfoundland Shelf, and on the shelves around Baffin Bay.

The distribution of the sediment mobilization frequency in Figure 17 demonstrates close correlation with the magnitude of the combined wave-current shear velocity shown in Figure 10a. High mobilization frequency on the banks on the outer Scotian Shelf and moderate mobilization on the western and SE Grand Banks are respectively in agreement with the moderately high shear velocities over these areas. Spatial variation of observed grain size, however, causes substantial difference in the distribution of the sediment mobilization frequency than that of shear velocity. The SE Grand Banks has the highest shear stress similar to the values in the Bay of Fundy and on Georges Bank (Figure 10a). Sediments on the SE Grand Banks, however, are fine to medium pebbles (-2 to -4 ϕ; Figure 3c) which are much coarser than the very coarse sand and granules (0 to -1 ϕ) in the Bay of Fundy and on Georges Bank. This difference in grain size determines that sediment mobilization frequency on the SE Grand Banks

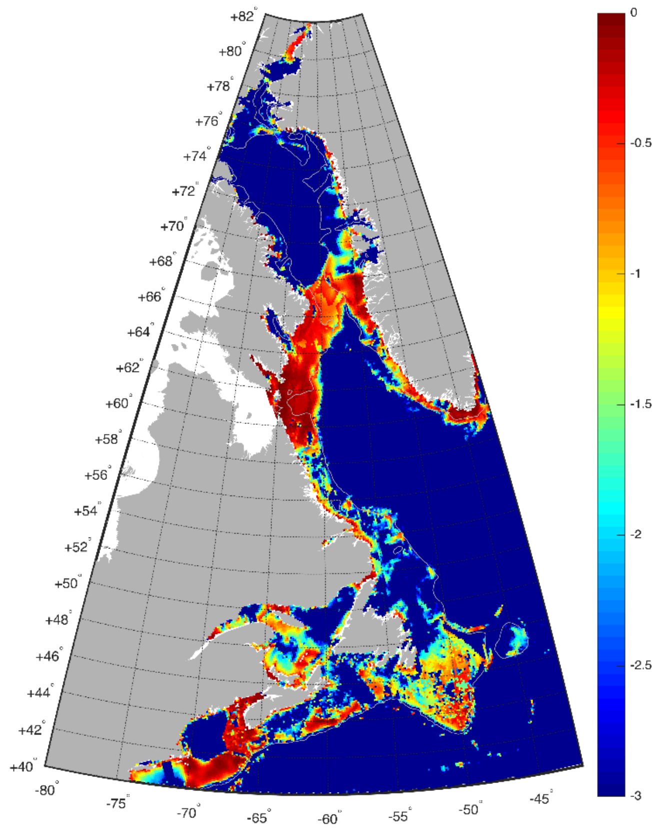


Figure 17 Spatial distribution of mobilization frequency (% of time) of observed sediments by the combined wave and currents on the Atlantic Shelf averaged over the period of 2002 – 2005.

is much lower than that in the Bay of Fundy and on Georges Bank. Sediments on Sable Island Bank (SIB) are dominantly fine to medium sand while gravelly sediments are dominant on Georges Bank and western Scotian Shelf. Although combined shear velocities on Georges Bank and western Scotian Shelf reach 4–5 $cm \cdot s^{-1}$ and that on SIB only reach 2–3 $cm \cdot s^{-1}$, the finer grain sizes on SIB results in high mobilization frequency that is similar to the levels on Georges Bank and western Scotian Shelf.

The estimates of areas and % of shelf area over which observed sediments are mobilized at least once by the combined wave-current shear velocity are also listed in Table 2. The non-linear interaction of waves and currents results in higher shear stress values and broader impact on the seabed (Figure 10a) than either waves alone (Figure 11a) or tides alone (Figure 12a) cases. Thus the combined wave-current shear velocity can mobilize observed sediments over 63% of the Atlantic Shelf area. This is double the shelf area percentage of threshold exceedance by either waves or tides (Table 2).

4. Discussion

4.1 Implication to surficial geology and habitat classification

The nature and distribution of sediments on the continental shelves are determined by a number of factors including sea level change, sediment supply, geomorphology, biology (e.g. through bioturbation and materials from primary production), as well as shelf energy regime. Modelled seabed shear stress and sediment mobilization from this study can be compared with the surficial geology on the Atlantic Shelf to gain insight on how seabed disturbance correlates with sediments and grain size distribution on a continental shelf scale. The combined wave-current shear velocity (Fig. 10a) is the highest in the Bay of Fundy, on Georges Bank, western Scotian Shelf, and on southeastern Grand Banks. These energetic regimes would imply that fine sediments would be winnowed away leaving coarse-grained lags in these areas. Indeed the observed grain sizes (Fig. 3c) over these areas are in the range of -1 to -5 ϕ (granules to coarse pebbles). In contrast, quiescent conditions of low shear stress are predicted for the Gulf of Maine, central inner and middle Scotian Shelf, the Laurentian Channel and the NE Newfoundland Shelf. The low energy conditions over these areas favour the deposition of very fine sand to fine silt (4 – 7 ϕ) as shown in Fig. 3c. The correlation between the distribution of shear stress and mapped grain size is also corroborated by the distribution of surficial geology as Li et al. (2021) demonstrated the presence of glacial till and gravelly sand respectively in the Bay of Fundy and on Georges Bank and western Scotian Shelf, and the dominance of fine-grained LaHave Clay (a postglacial mud formation; Fader et al., 1977) in low-energy areas of the Gulf of Maine, inner and middle Scotian Shelf, and the Laurentian Channel.

Kostylev and Hannah (2007) produced the benthic habitat map for the Scotian Shelf using a disturbance - scope for growth template that was derived from oceanographic property parameters, mean near-bed tidal currents, and the 90th percentile of the significant wave height and period from a 42-year wave hindcast data. Li et al. (2021) have compared preliminary Canada-wide seabed disturbance modelling results against the results of Kostylev and Hannah (2007) to illustrate that considerably different patterns of seabed disturbance can be achieved from the use of time series wave and tidal current data. The seabed disturbance and sediment mobility modelling results of the present study are further improved from Li et al. (2021) because of the use of observed grain size and the inclusion of additional storm-driven and ocean circulation current processes. Thus the updated modelling results from the present study are compared with Kostylev and Hannah (2007) to better demonstrate the similarity and differences between these studies and what improvements have been made. The disturbance and scope for growth maps for the Scotian Shelf and the eastern Gulf of Maine of Kostylev and Hannah (2007; reproduced in Figure 18) show a broad-scale, east-west gradient of increasing scope for growth while the disturbance produces a complex spatial pattern which generally shows stronger disturbance on the outer-shelf banks on eastern Scotian Shelf and low to moderate disturbance in

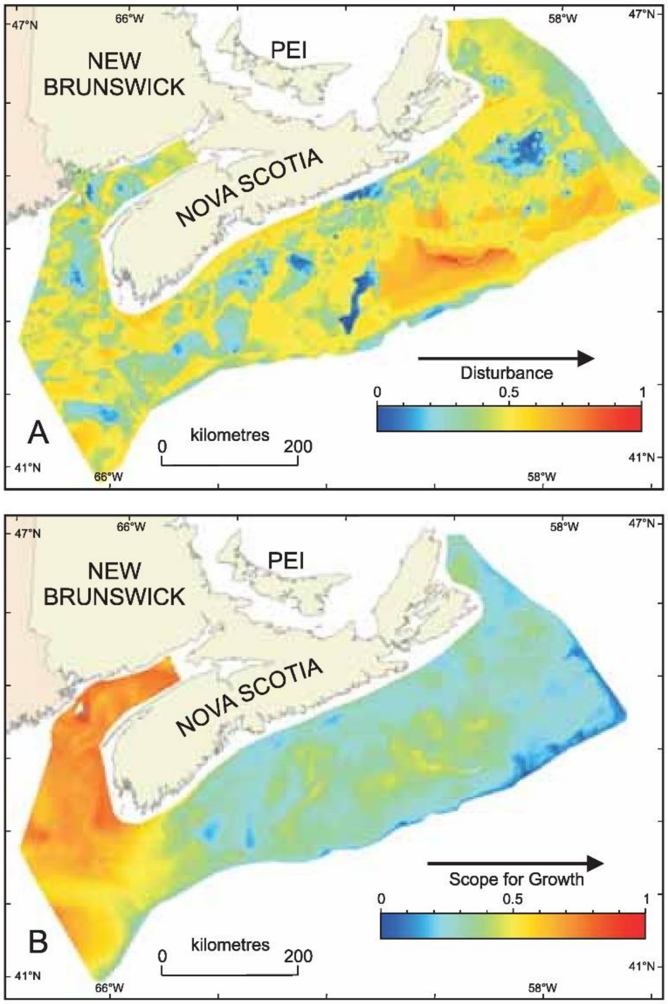


Figure 18 Maps of (a) the natural disturbance axis and (b) the scope for growth axis of the habitat template model for the Scotian Shelf developed by Kostylev and Hannah (2007).

the Bay of Fundy and on parts of Georges Bank and western Scotian Shelf. The maps of combined wave-current shear stress (Fig. 10a) and sediment mobilization frequency (SMF) (Fig. 17; approximately equivalent to the disturbance map of Kostylev and Hannah, 2007) of our study, however, show that while moderately high shear stress and SMF are predicted on the outer shelf banks on eastern Scotian Shelf, the highest shear stress and seabed disturbance actually occur in the Bay of Fundy and on Georges Bank and western Scotian Shelf. These differences are attributed to the use of extreme wave parameters versus mean tidal currents in Kostylev and Hannah (2007) which resulted in skewed emphasis on waves and hence highest shear stress on the outer shelf banks where waves are significantly stronger (Fig. 4a). Following established approaches of international studies (Porter Smith et al., 2004; Hemer, 2006), our study used time series data of tidal current and waves and thus equal-weighted effects for waves and tidal currents. Therefor the relationship between the distribution of benthic habitat types and the physical environment such as presented for the Scotian Shelf in Kostylev and Hannah (2007) should be re-interpreted based on the updated modelled seabed shear stress and sediment mobilization of the present study.

4.2 Disturbance type classification and statistics

The percentage of shelf area over which various processes exceed the threshold of sediment motion has been used in Section 3.3.2 to quantify the relative importance of component processes in the mobilization of observed sediments on the Atlantic Shelf. For uniform medium sand, Li et al. (2021) show that the Atlantic shelf is dominated by wave mobilization as waves can mobilize medium sand over 49% of the shelf area and tidal mobilization only occurs over 34% of the shelf area on the Atlantic Shelf. With the more realistic observed grain size, the present study demonstrates that shelf areas of sediment mobilization by waves and tides are nearly the same on the Atlantic Shelf (Table 2).

As demonstrated by Porter-Smith et al. (2004) and Li et al. (2015a, 2021), continental shelves can also be classified into disturbance types (i.e. regionalisation) based on quantitative estimates of the spatial variation of the relative importance of threshold exceedance by wave, tide and circulation current. Considering the relative importance of these processes, five disturbance types are defined: (1) unaffected: time% of mobilization by individual wave, tide, and circulation process is all 0; (2) wave dominant: time% of exceedance by wave is at least 3 times that either by tide or circulation current; (3) tide dominant: time% of exceedance by tide is at least 3 times of wave or circulation current; (4) circulation dominant: time% of mobilization by circulation current is at least 3 times of wave or tidal current; (5) mixed disturbance: cases that do not fall into neither of the above four types. The spatial distribution of the seabed disturbance types is presented in Figure 19 and the statistics of the areas and percentages of shelf areas for the five disturbance types are given in Table 3.

Tide dominant type mainly occurs in the Bay of Fundy, on Georges Bank, on western Scotian Shelf, in Northumberland Strait, over central and western Gulf of St. Lawrence, on the SE Baffin Shelf and over Davis Strait accounting for 24.6% of the shelf area. Wave dominant category predominantly occurs on the Grand Banks, along the coasts of Scotian Shelf and Gulf of Maine, over southwestern Gulf of St. Lawrence and on the inner shelf and outer shelf banks on the Labrador Shelf. Wave dominant disturbance type occupies 24.7% of the shelf area (Table 3), nearly the same as the tide dominant type. Mixed disturbance accounts for only 3.2% of the shelf area and primarily occurs on the banks of the outer Scotian Shelf. Circulation dominant disturbance type is even less significant (only 0.1% of the shelf area) and mainly occurs as narrow bands along the upper slope off the Grand Banks influenced by the Labrador Currents.

Waves, tides and circulation processes alone cause zero sediment mobilization (unaffected type) over nearly half of the Atlantic Shelf (Table 3). Fig. 19 demonstrates that mixed disturbance types predominantly occur as cores on the banks of the outer Scotian Shelf and these cores are typically surrounded by the wave dominant and tide dominant disturbance types on the central and eastern Scotian Shelf. These patterns contribute to establishing a west-east trend from the tide dominant disturbance over the Bay of Fundy and western Scotian Shelf, through the

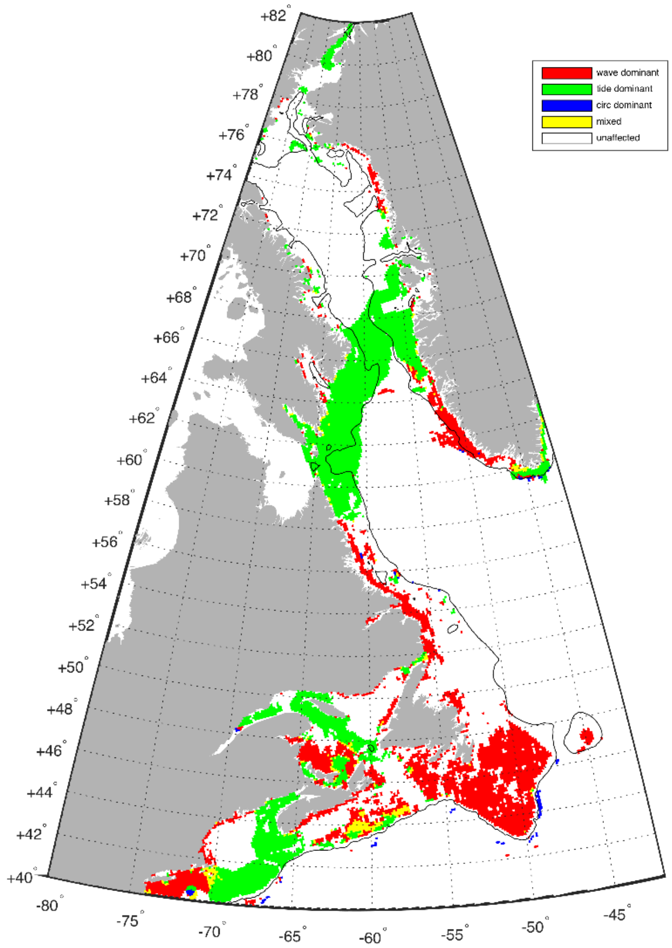


Figure 19 Spatial distribution of seabed disturbance types on the Canadian Atlantic Shelf.

Table 3 Area and percentage of total shelf area of various disturbance types on the Canadian Atlantic Shelf.

Disturbance Types	Total shelf area (km^2)	Area (km^2)	% of shelf area
	1,884,768		
Tide dominant		463,540	24.6
Wave dominant		464,813	24.7
Circulation dominant		1,571	0.1
Mixed disturbance		59,779	3.2
Unaffected		893,461	47.4

mixed disturbance on central and eastern Scotian Shelf, to the predominantly wave dominant disturbance on the Grand Banks.

4.3 Universal indices of seabed disturbance and sediment mobility

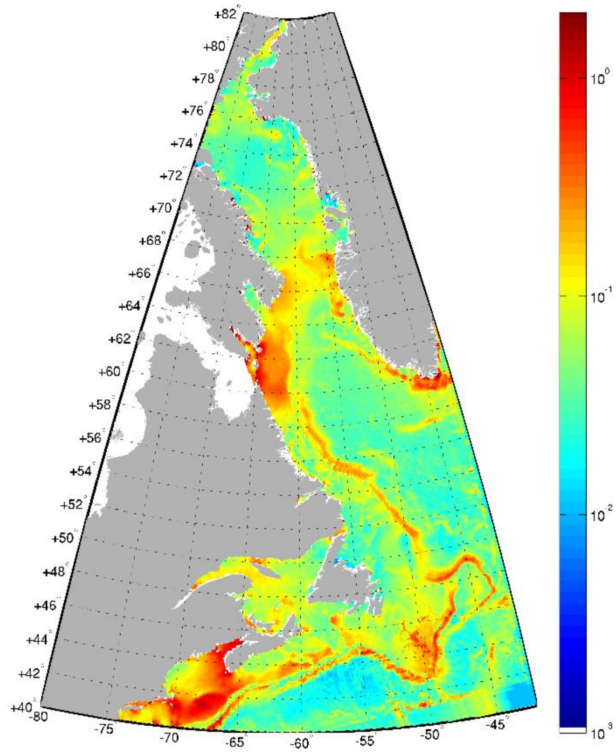
The effectiveness of the oceanographic processes to impact the seabed and to shape benthic habitats depends on both the magnitude of the shear stresses from these processes, and the frequency with which they occur. The mean combined wave-current shear velocity of Fig. 10a quantifies only the magnitude of the bed shear stress and does not reflect the effect of how often shear stresses with various magnitudes occur. For instance, extreme storms tend to produce very high values of shear stress and hence the greatest instantaneous impact on the benthic community. However, these storms occur rarely and last only days and their impact is greatly reduced when the mean bed shear stress is averaged over one or several years. In contrast, the threshold exceedance map of Fig. 17 demonstrates how often the combined wave-current shear stress causes mobilization of sediment on the Atlantic Shelf, but ignores the effect of how strong the mobilization is. Consequently, indices that incorporate both the magnitude and frequency of these processes are needed to better quantify the exposure of the seabed to oceanographic processes and sediment mobilization on continental shelves.

Hemer (2006) proposes three schemes that quantify both the frequency and magnitude of combined-flow bed shear stresses for the regionalization of the Australian continental shelves. However, these schemes only quantify the magnitude and frequency of the combined-flow shear stress. The magnitude and frequency of sediment mobilization was not evaluated. Indices for seabed disturbance and sediment mobility considering both the magnitude and frequency have been defined and estimated at regional scales for Sable Island Bank, Scotian Shelf (Li et al., 2009) and for the Bay of Fundy (Li et al., 2015a). More recently, Li et al. (2021) have applied similarly defined indices to quantify the seabed shear stresses and sediment mobilization on the continental shelves of Canada, although the estimates are for uniform medium sand sediments and do not account for the effects of circulation and storm-induced currents. Following these previous studies, the two 'universal indices' are applied here to quantify the level of seabed exposure to a full range of oceanographic processes and the levels of mobilization of observed sediments on the Canadian Atlantic Shelf. The Seabed Disturbance Index (SDI) is adopted from Hemer (2006) and is defined as the maximum value of $\tau_{cws}^{1.5}$ P. Here τ_{cws} is the skin-friction combined wave-current shear stress (= ρu_{*cws}^2) and $\tau_{cws}^{1.5}$ represents the work done by the combined-flow shear stress to disturb the seabed, and P is the percent time for which a given stress is achieved. So the product $\tau_{cws}^{1.5}$ P quantifies the level of exposure of the seabed to oceanographic processes, considering both the magnitude and frequency of the combined-flow bed shear stress regardless if sediment mobilization occurs or not. The second parameter is called Sediment Mobility Index (SMI) which is defined as the normalized shear stress (τ_{cws}/τ_{cr}) multiplied by time% of threshold exceedance (i.e. SMF of Fig. 17). The time% of threshold exceedance is the time percent the combined-flow shear stress τ_{cws} exceeds the critical shear stress τ_{cr} for sediment transport initiation. τ_{cws}/τ_{cr} is the mean ratio of τ_{cws} over τ_{cr} for times when

τ_{cr} is exceeded. Thus SMI serves as a non-dimensional index that quantifies the level of sediment mobility integrating both the magnitude and frequency of the sediment mobilization process.

The seabed disturbance index (SDI) map of Figure 20 shows that the strongest seabed disturbance up to 1.5 occurs in the Bay of Fundy, on Georges Bank and western Scotian Shelf, and on SE Baffin Shelf off Hudson Strait. Moderately high disturbance of 0.4–0.6 is found on the banks of outer Scotian Shelf, on the southeastern Grand Banks, in Davis Strait, and over the narrow bands along the shelf edge and upper slope. Weak disturbance of ~0.1 or less is predicted for western Gulf of Maine, on inner and middle Scotian Shelf, in Laurentian Channel, on the Northeast Newfoundland Shelf and over most parts of Baffin Bay. Significant changes can be recognized when SDI map in Fig. 20 is compared with Fig. 10a where only the magnitude of combined wave-current shear velocity is used to quantify seabed disturbance. According to Fig. 10a, seabed disturbance will be classified as the strongest on both Georges Bank and the central and southeastern Grand Banks as the combined wave-current shear velocity reaches >5 $cm \cdot s^{-1}$ in both areas. Since Georges Bank is dominated by high-frequency tidal energy while the Grand Banks is dominated by low-frequency storms, the values of SDI will categorize Georges Bank as high disturbance area while the disturbance on the Grand Banks is characterized as moderately high. The use of SDI also changed significantly the interpretation of seabed disturbance over the narrow perimeter along the shelf edge and over the upper slope. If only the magnitude of shear stress is considered (Fig. 10a), SE Grand Banks and the banks on the outer Scotian Shelf would be classified as areas of high and moderately high disturbance while disturbance would be low to moderate along the shelf edge and upper slope where shear velocities only reach 1–2 $cm \cdot s^{-1}$. The interpretation based on SDI, however, would classify the perimeter along the shelf edge and upper slope in the same moderately high category as SE Grand Banks and the banks on the outer Scotian Shelf due to the year-round presence of the low to moderate shear stress along the shelf edge and upper slope.

The spatial distribution of sediment mobility index (SMI) on the Atlantic Shelf is shown in Figure 21. High mobility of 1–2 occurs in the Bay of Fundy, on Georges Bank and western Scotian Shelf, at the top of Sable Island Bank, and at entrance to Hudson Strait. Moderately high sediment mobility of 0.5–1 is found on the banks of the outer Scotian Shelf, on southeastern Grand Banks, and in eastern Davis Strait. Moderate mobility of 0.1 – 0.5 is predicted on western, central and northeastern areas of the Grand Banks, in Northumberland Strait, in southeastern Gulf of St. Lawrence, along the coast of Labrador Shelf, and in the remaining areas of Davis Strait. Low mobility of 0.1 or less occurs on outer eastern Scotian Shelf, on the remaining areas of the Grand Banks, in central and southwestern Gulf of St. Lawrence, on the banks of the outer Labrador Shelf. Zero or minimal sediment mobility is predicted for the Gulf of Maine, inner and middle Scotian Shelf, the Laurentian Channel, the northeastern Gulf of St. Lawrence, Northeast Newfoundland Shelf, and the shelves around Baffin Bay. The sediment mobility index map of Fig. 21 demonstrates significant differences from the threshold exceedance map shown in Fig. 17



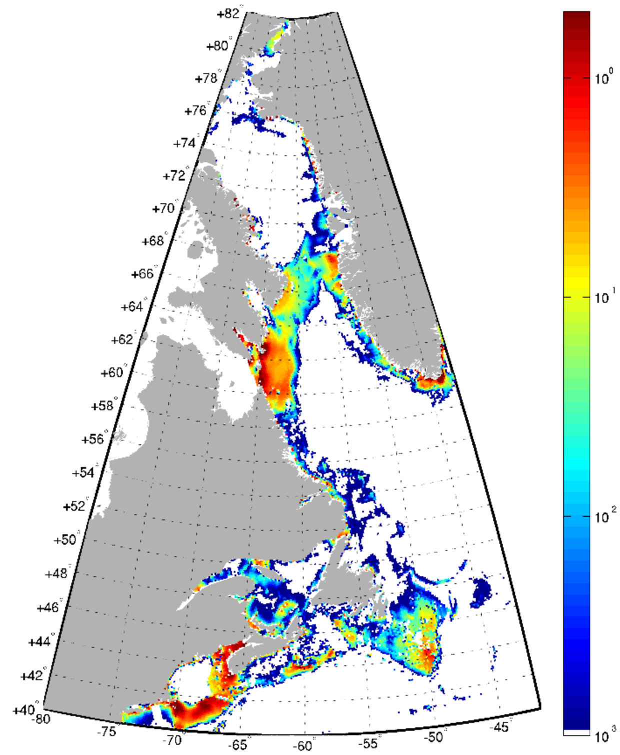


Figure 20 Spatial distribution of Seabed Disturbance Index (SDI) on the Canadian Atlantic Shelf. See text for definition of SDI.

Figure 21 Spatial distribution of Sediment Mobility Index (SMI) on the Canadian Atlantic Shelf. See text for definition of SMI.

which only considers the mobilization frequency not the magnitude. For instance, western Scotian Shelf and eastern Davis Strait are both classified as areas of high mobility (Fig.17) if only mobilization frequency is considered. The map of mean shear velocity (Fig. 10a), however, shows high combined wave-current shear velocity of 5 $cm \cdot s^{-1}$ on western Scotian Shelf and only moderate value of 2 – 3 $cm \cdot s^{-1}$ for the eastern Davis Strait area. Therefor the SMI values calculated using both the magnitude and frequency of sediment mobilization would classify that sediment mobility is high on western Scotian Shelf but moderately high for the eastern Davis Strait area (Fig. 21) even though sediment mobilization frequency values are the same for these areas.

The values of seabed disturbance index range from 0 – 1.5 and the sediment mobility index is from 0 – 2 on the Atlantic Shelf. Similar ranges of values have been found for uniform medium sand for other shelves of Canada (Li et al., 2021). SDI on the Australia shelf ranges from 0 to 1.3 (Hemer, 2006). The values of SMI are not available for the Australia shelf but they should be in the range of 0–2 based on the magnitude of SDI. The magnitudes of these indices therefore are comparable for the Canadian and Australia continental shelves attesting the robustness of these indices. In addition to the conformity of the values of these indices on the Australia and Canadian continental shelves, the proposed SDI and SMI parameters also quantify the seabed exposure and sediment mobilization incorporating both the magnitude and frequency of the processes. These indices, together with the seabed disturbance type classification scheme (shown in Fig. 19), potentially can be used as standard parameters to best quantify seabed disturbance and sediment mobility on other shelves of the world.

4.4 Advances from previous studies and future efforts

Knowledge on the seabed disturbance and sediment mobilization on the Canadian continental shelves has been achieved progressively through various studies in the last decade. The information of derived parameters, type of grain size data, geographic regions, source data (i.e. oceanographic processes) and computation methods for these previous studies is summarized in Table 4.

In developing the benthic habitat map for the Scotian Shelf, Kostylev and Hannah (2007) estimated the disturbance as the ratio of total combined wave-current shear velocity, u_{*cw} (including the effect of bedforms and presence of wave boundary layer), over the critical shear velocity, u_{*cr}, of observed grain size on the Scotian Shelf. This ratio is a proxy of the magnitude of sediment mobilization. However it was based on averaged near-bed tidal current and 90th percentile of significant wave height and period, not truly calculated using time series wave and current data. Their disturbance parameter only considers the magnitude of the seabed forcing and does not include the effect of the disturbance frequency. Only wave and tidal processes are considered and processes of ocean circulation current and wind-driven currents in storms are not addressed. The first study addressing the effect of the full range of oceanographic processes was undertaken by Li et al. (2015a) who used modelled time series data of waves, tidal currents, wind-driven and circulation currents to predict seabed shear stresses and sediment mobility for observed grain size in the Bay of Fundy. Li et al. (2015a) also classified seabed disturbance types and proposed and applied seabed disturbance and sediment mobility indices to quantify the seabed forcing and sediment mobilization incorporating both the magnitude and frequency of these parameters. Although the study of Li et al. (2015a) models the seabed disturbance and sediment mobility with consideration of the full range of oceanographic processes, it is focused on the Bay of Fundy region and does not represent a shelf-scale study. In an initial Canada-wide effort, Li et al. (2021) uses wave hindcast data and modelled depth-averaged tidal current data for a 3-year period to simulate the seabed shear stresses and the mobilization of uniform medium sand by waves and tides on all continental shelves of Canada. The study also undertakes the regionalization of seabed disturbance type based on the relative importance of wave and tidal current disturbances and applies the SDI and SMI indices to quantify the seabed exposure to oceanographic processes and sediment mobility incorporating both the magnitude and frequency of these processes. This Canada-wide modelling study thus has established the first national

Table 4 Summary of derived parameters, grain size data, geographic region, source data (oceanographic processes) and computation method of key Canadian seabed disturbance studies.

Studies	Parameters, grain size and region	Source data and calculation method
Kostylev and Hannah (2007)	Total shear velocity u_{*cw}; disturbance defined as ratio of u_{*cw} over critical shear velocity u_{*cr}; Observed grain size; Scotian Shelf	Total u_{*cw} calculated from RMS near-bed tidal current extrapolated from 2D model and 90th percentile of wave height and period of a 42 year hindcast data; Not based on time series data of current and wave.
Li et al. (2015)	Skin-friction seabed shear stresses, sediment mobilization frequency, disturbance type classification, seabed disturbance index and sediment mobility index; observed grain size; Bay of Fundy region	Time series data of wave height and period and depth-averaged tidal current, circulation current, and storm-induced current
Li et al. (2020)	Skin-friction seabed shear stresses, sediment mobilization frequency, disturbance type classification, seabed disturbance index and sediment mobility index; uniform medium sand; All continental shelves of Canada	Time series data of depth-averaged tidal current, and wave height and period; ocean circulation current and storm-induced current not included
Li et al., this study	Skin-friction seabed shear stresses, sediment mobilization frequency, disturbance type classification, seabed disturbance index and sediment mobility index; observed grain size; Canadian Atlantic Shelf	Time series data of depth-averaged tidal current, wave height and period; near-bed circulation current and storm-induced current

framework of seabed disturbance and sediment mobility on all three continental shelves of Canada. The major limitations of this Canada-wide study are that important ocean circulation and storm-driven current processes were not included and that uniform medium sand instead of observed grain size data was used. The present study represents the most up-to-date and comprehensive shelf-scale study of seabed disturbance and sediment mobilization as it uses time series data of depth-averaged tidal current, modelled significant wave height and period, near-bed circulation current and storm-induced current to simulate seabed shear stresses, sediment mobilization frequency, disturbance type classification, seabed disturbance index and sediment mobility index of observed grain sizes on the Canadian Atlantic Shelf

Section 4.1 has demonstrated that the disturbance estimates by Kostylev and Hannah (2007) based on mean magnitude of tidal current and extreme wave parameters depict stronger disturbance on the outer-shelf banks on eastern Scotian Shelf and low to moderate disturbance in the Bay of Fundy and on parts of Georges Bank and western Scotian Shelf. The bed shear stress and sediment mobilization frequency of the present study using time series wave and current data, however, show significantly different patterns. The highest shear stress and seabed disturbance occur in the Bay of Fundy and on Georges Bank and western Scotian Shelf while these parameters are only moderately high on the banks of the outer Scotian Shelf.

One of the major improvements of this study from the initial Canada-wide modelling study of Li et al. (2021) is the inclusion of circulation current and storm-induced current so that a full range of oceanographic processes are considered. The most immediate improvement by the inclusion of circulation and storm-induced currents are the presence of moderate shear velocity along the perimeters over the shelf edge and upper slope (Fig. 10a of this study versus Fig. 11 of Li et al., 2021) attributed to the effect of the circulation current. The second significant change is the increased magnitude of bed shear stress over storm-dominated areas on the Atlantic Shelf that can be attributed to the addition of storm-induced currents. The impact from this is particularly strong on the southeastern Grand Banks where the maximum combined wave-current shear velocity increased from ~2 $cm \cdot s^{-1}$ without the storm-induced currents to > 5 $cm \cdot s^{-1}$ with the storm-induced currents included. Moderate increase of the shear stress is also found on Sable Island Bank where the maximum mean combined wave-current shear velocity increased from 2–3 $cm \cdot s^{-1}$ to ~4 $cm \cdot s^{-1}$. Without the effect of storm-induced currents, waves and tides are equally import in mobilizing sediments on the Atlantic Shelf (~30% of the time for both processes; Table 2). When storm-induced currents are considered, the interaction between waves and storm-induced currents can mobilize sediments for 35% of the time making storm disturbance slightly stronger than tides on the Atlantic Shelf.

The inclusion of circulation current process and the use of observed grain size also substantially improve the modelled sediment mobilization frequency (SMF). The inclusion of circulation current causes additional low to moderate sediment mobilization in narrow bands along the shelf edge and upper slope (Fig. 17 of this study versus Fig. 12 of Li et al., 2021). For uniform medium sand, Li et al. (2021) estimate that the SMF reach up to 50% of the time on the southeastern Grand Banks and SMF greater than 30% occurs broadly over the entire Grand Banks (Fig. 12 of Li et al., 2021). The gridded grain size data of Fig. 3c shows that the sediments on the central to SE Grand Banks are largely medium to coarse pebbles although the detailed distribution of texture can be complex (e.g. Miller et al., 1990). The map of sediment mobilization frequency for observed grain size (Fig. 17) demonstrates that sediment mobilization frequency only reach moderate level of 30% on southeastern Grand Banks and that the SMF values are predominantly < 10% over most parts of the Grand Banks. The sediments in Davis Strait and on northern SE Baffin Shelf are dominantly 3 – 4 ϕ (very fine sand) and much finer than medium sand. Therefore the modelled sediment mobilization frequencies of this study (Fig. 17) are higher and occur more widely than that based on uniform medium sand (Fig. 12 of Li et al., 2021).

The use of observed grain size in the calculation of sediment mobilization frequency also results in substantial changes to the percentages of shelf areas of sediment mobilization by waves, tides and combined waves and tides leading to different characterization of the relative importance of wave and tide disturbances. For uniform medium sand, the percentages of shelf area of sediment mobilization by tides, waves and combined wave-tide are respectively 34.6%, 49.2% and 66.8% (Li et al., 2021). These percentage values for observed grain size decrease to 29.5%, 30.2% and 63.3% respectively (Table 2). The percentages of shelf area of threshold exceedance by tides and waves calculated for uniform medium sand would suggest that the Atlantic Shelf is wave-dominant. These values calculated for observed grain size (Table 2), however, would define that sediment mobilization on the Atlantic Shelf is equally affected by tides and waves.

In developing the initial Canada-wide framework of seabed disturbance and sediment mobility, Li et al. (2021) have identified several areas for improvement in future modelling studies. The present study has made progresses by including ocean circulation currents and storm-induced currents and using observed grain size for the Canadian Atlantic Shelf. Although near-bed circulation and storm-induced currents were used in the present study, tidal currents were still depth-averaged and will over-estimate the seabed forcing of tidal currents. Future seabed disturbance modelling should utilize near-bed tidal currents from 3-D current models to more adequately predict the effect of tidal currents. There are poor or no coverage of observed grain size data in areas of the north Atlantic Shelf, on the Northeast Newfoundland Shelf, and on the Grand Banks. Efforts should be made to collect seabed samples over these areas and the improved grain size data integrating all possibly available sample data should be used in future modelling studies. Energetic events such as temperate storms and cyclones or hurricanes occur on time scales of days to years. Seabed disturbance modelling needs to model over a period long enough to adequately quantify the contribution of these processes. Seabed disturbance modelling studies have progressively increased the modelling durations to 8 – 11 years (Hemer, 2006;

Harris and Hughes, 2012). Future modelling studies in Canada need to make efforts to model seabed stresses and sediment mobilization for longer time durations. Stratification of water column on the continental shelf can substantially modify the vertical structure of the tidal currents due to the generation of internal tides over steep topography. This is known to be important in Queen Charlotte Sound (e.g. Cummins and Oey, 1997). Tidal currents are also observed to be amplified and cause episodic erosion and transport of sediments in canyons and on the shelf break on Scotian Shelf (Li et al., 2019). Future seabed disturbance modelling should consider to include the internal tides in the modelled oceanographic processes.

5. Conclusions

Various current and wave models have been applied in this study to simulate waves, tidal current, circulation current and storm-driven current on the Atlantic Shelf of Canada for a three year period of 2002 – 2005. The modelled wave and current data were then input in a combined-flow sediment transport model to produce an updated framework of the magnitude and frequency of bed shear stresses and mobilization of observed sediments due to waves, tides, circulation current and combined waves and currents on the Canadian Atlantic Shelf. The present study has advanced previous shelf-scale modelling studies by utility of modelled wave data, inclusion of important ocean circulation and storm-driven current processes, and the estimates of shear stress and sediment mobilization using observed grain size data.

(1) The Atlantic Shelf is affected by strong waves and tidal currents. Maximum mean significant wave heights can reach 3.5 m and mean wave periods are up to 8 s in the open ocean off the Atlantic Shelf. Mean tidal currents can reach 0.8 – 1.2 $m \cdot s^{-1}$ in coastal bays and on banks on the shelf. Moderate circulation currents with speed of 0.2 $m \cdot s^{-1}$ occur as narrow belts along the shelf edge and upper slope on the Atlantic Shelf. Storms introduce additional near-bed currents up to ~0.2 $m \cdot s^{-1}$ that are restricted in the interior of the shelf.

(2) Our modeled results indicate that the mean wave and tidal current shear velocities both reach the maximum values of ~4 $cm \cdot s^{-1}$. However, high wave impact is restricted to the southeastern Grand Banks while high values of tidal current shear stress occur widely in coastal bays and on the open shelf. When processes are considered independently, our modelling results suggest that tidal currents are capable to mobilize sediments at least once during the modelled 3 year period over 30% of the shelf area while storms can cause sediment mobility over 35% of the shelf area suggesting slightly stronger effect of storms. Interaction between waves and currents can produce enhanced combined wave-current shear velocity >5 $cm \cdot s^{-1}$ that is capable to mobilize sediments over 63% of the shelf area, double that due to either tides or waves.

(3) The spatial variation of the relative importance of waves, tidal current and circulation current in mobilizing sediments was used to classify the Atlantic Shelf into six disturbance types. Wave

dominant and tide dominant disturbance types are found equally important and both occupy ~25% of the shelf area. Mixed disturbance is insignificant and accounts for only 3% of the shelf area.

(4) The universal Seabed Disturbance Index (SDI) and Sediment Mobility Index (SMI) have been applied to quantify the seabed exposure to physical processes and sediment mobilization on the Atlantic Shelf accounting for the effect of both the magnitude and frequency of these processes. The applications of these indices have produced different and probably more adequate quantification of seabed forcing and sediment mobility for some areas on the Atlantic Shelf. The values of SDI and SMI on the Canadian Atlantic Shelf are found to be comparable to those on the Australian shelf attesting the robustness and universal applicability of these indices. These indices, together with the seabed disturbance type classification scheme, potentially can be used as standard parameters to best quantify seabed disturbance and sediment mobility on other shelves of the world.

Acknowledgement

We would like to thank Vladimir Kostylev and Richard Pickrill for their contribution in the development of this research project as part of the Geoscience for Ocean Management (GOM) Program of the Geological Survey of Canada. We thank Robert Prescott for his significant contribution in the initial processing of the various modelling results. We are thankful to Charles Tang for his initial contribution to circulation current modelling, Bash Toulany for wave data reduction and to Jason Chaffey for help with providing the tidal current data. We are grateful to Paul Hill of Dalhousie University for making available the compiled GSC and USGS grain size data for the Bay of Fundy and Gulf of Maine region. We also would like to thank John Shaw for help with the study area map and Paul Fraser for help with the land and ocean base map and depth contours used in figures of this study. Internal review by John Shaw substantially improved the quality of this report. This research was supported by the Geological Survey of Canada GOM Program.

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