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Complete List of Authors:	Li, Michael; Bedford Institute of Oceanography , Geological Survey of Canada (Atlantic) Wu, Yongsheng; Bedford Institute of Oceanography, Fisheries and Oceans Canada Hannah, Charles; Institute of Ocean Sciences, Fisheries and Oceans Canada Perrie, William A.; Bedford Institute of Oceanography, Fisheries and Oceans Canada
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**Seabed disturbance and sediment mobility due to tidal current and waves on the
continental shelves of Canada**

Michael Z. Li¹, Yongsheng Wu², Charles G. Hannah³ and Will A. Perrie²

¹Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, Nova Scotia B2Y 4A2, Canada

²Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y
4A2, Canada

³Department of Fisheries and Oceans Canada, Institute of Ocean Sciences, P.O. Box 6000,
Sidney, British Columbia V8L 4B2, Canada

*Corresponding author Michael Z. Li; E-mail: Michael.Li@Canada.ca

Draft

Abstract

Waves and tidal currents can interact to produce strong seabed shear stress and mobilization of sediments on continental shelves. Modelled wave and 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 on the continental shelves of Canada. The modelling results are presented to establish the first national framework of seabed disturbance and sediment mobility on the continental shelves of Canada. Strong waves and tidal currents on the Canadian continental shelves produce mean bed shear velocity $>5 \text{ cm}\cdot\text{s}^{-1}$. Medium sand can be mobilized $>50\%$ of the time over many areas on the shelves. The mobilization by tidal currents occurs over 36% and by waves over 50% of the shelf area, demonstrating that mobilization of sediments is dominated by waves on the Canadian continental shelves. Combined shear stresses due to wave and tidal current interaction further increase sediment mobilization to over 68% of the shelf area.

The spatial variation of the relative importance of wave and tidal disturbances allows classification of the continental shelves into six disturbance types. Innovative Seabed Disturbance (SDI) and Sediment Mobility (SMI) indices are proposed to quantify the seabed exposure to oceanographic processes and sediment mobilization, incorporating both the magnitude and frequency of these processes. The proposed SDI and SMI, together with the disturbance type classification, can be used as standard parameters to best quantify seabed disturbance and sediment mobility on other shelves of the world.

Key words: tidal current and waves; shear stresses; sediment mobilization; seabed disturbance; continental shelves; Canada;

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 is also required for habitat classification, understanding the geo-environment control of benthic habitats, and dredging and pollutant transport near the coast (e.g. Connor et al. 2004; Kostylev 2012; Harris 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 sustainable development and integrated management of the continental shelves of maritime nations. Studies of seabed disturbance, based on surveys and site-specific 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 sediment mobilization on about 80% of the world's shelves is 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. The main limitation has been the practical difficulty 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 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. Thus, mobilisation of sediment on the Australian continental shelf is due more to tides than waves. 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

70 mobilization frequency. Hemer (2006) evaluated the exposure of the Australian continental shelf
71 to oceanographic processes by modelling the combined wave and current shear stress for a 8-
72 year period incorporating both the intensity and frequency of this parameter. Three methods of
73 classifying the oceanographic levels of exposure were presented. The approach of Hemer (2006)
74 did not compare the combined-flow shear stress with the threshold of sediment transport. Hence
75 the magnitude and frequency of sediment mobilization under combined waves and currents was
76 not specifically predicted. The Australian shelf was thus only regionalized based on seabed shear
77 stress intensity and frequency.

78
79 In Canada, limited efforts have been made to quantify the magnitude and frequency of seabed
80 disturbance, and to use this to understand sediment transport patterns and the distribution and
81 mobility of bedforms for some shelf regions (e.g. Li et al. 2012; Shaw et al. 2014; Li et al. 2015).
82 The modelling study of bed shear stress and seabed disturbance on Sable Island Bank (SIB;
83 Figure 1; Supplementary Fig. S1) on the outer Scotian Shelf (Li et al. 2012) demonstrates that
84 tidal currents alone can cause sediment mobilization over 36% of the bank area while wave
85 action affects 71%. The combined action of waves and tides, however, produces mean shear
86 velocity up to $5 \text{ cm} \cdot \text{s}^{-1}$, affects 93% of the bank, and mobilizes sediments to water depths as
87 deep as 200 m. Classification of seabed disturbance types based on the relative time percentage
88 of threshold exceedance by various processes shows that wave-dominant and mixed wave-tide
89 disturbance types are predominant and occur respectively over >50% and 30% area of SIB. Li et
90 al. (2015) used modelled waves, tidal currents, and wind-driven and circulation currents to
91 predict seabed shear stresses, sediment mobility and sediment transport patterns in the broader
92 Bay of Fundy (BoF; Fig. 1). Seabed shear in the BoF is mostly due to tides, and wave effects are
93 only important in coastal areas. While predominant waves are from the southwest both on SIB
94 and in the BoF, mean wave heights on the open SIB are 3 times higher than the sheltered BoF
95 explaining the much lower effect of waves in the BoF. The strongest mean shear velocity is up to
96 $10 \text{ cm} \cdot \text{s}^{-1}$ which causes sediment mobilization >30% of the time over most of the bay and as
97 high as 100% of the time in some areas of the bay. Li et al. (2015) proposed seabed disturbance
98 and sediment mobility indices incorporating both the magnitude and the frequency of these
99 parameters and applied these to quantify the seabed forcing and sediment mobilization in the
100 BoF. As part of a synthesis of processes, glacial history and landforms, sediment mobility, and

benthic habitats of the Canadian Atlantic shelf (Shaw et al. 2014), model predictions of waves, tidal currents, and wind-driven and circulation currents, as well as bed shear stresses, over a 3-year period were used to shed light on the mobilization of medium sand and the spatial pattern of seabed disturbance types on the Atlantic shelf. The highest sediment mobilization frequency of nearly 100% of the time occurs in the BoF, on Georges Bank, and on the northern Labrador Shelf under the tide-dominant condition. Sediment is also frequently mobilized on the Scotian Shelf and on the Grand Banks, the former being dominated by wave-dominant and mixed disturbances, and the latter dominated by wave-dominant disturbance. Kostylev and Hannah (2007) produced the benthic habitat map for Scotian Shelf (Fig. 1) 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 2-dimensional tidal model predictions and the 90th percentile of the significant wave height and period from a 42-year wave hindcast dataset. Thus the disturbance calculation was not computed using time-series data of waves and currents over a selected period of time and hence was dominated 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 the transport of observed sediment grain size over the study area. Their disturbance parameter only considers the magnitude of the seabed forcing and neglects how often the disturbance occurs. Also the total shear velocity was used in the calculation of the disturbance, not the skin-friction component that alone should be responsible for sediment mobilization. Gregr et al. (2016) used a similar approach for a habitat classification for the Canadian Pacific continental shelf.

In the present study, wave hindcast data and model-predicted tidal current data for a 3-year period were used in a combined-flow sediment transport model to predict the wave, tidal current and combined wave-current shear stresses for the Canadian continental shelves. These shear stresses were compared with the threshold shear stress for medium sand (approximately the averaged grain sizes on the Canadian Atlantic Shelf) to quantify the magnitude and frequency of sediment mobilization. The aims of this study are (1) to present the first national framework of the magnitude and frequency of seabed forcing and sediment mobilization by waves, tidal currents, and combined waves and tide on the continental shelves of Canada, (2) to derive a classification of Canadian continental shelves based on the spatial variation of the relative

importance of wave and tidal disturbance, and (3) to propose several universal indices for shelf-scale quantification of seabed disturbance and potential sediment mobility, integrating both the magnitude and frequency of these processes.

1.1 Origins and relict-active nature of sediments

The origin of sediments on the Canadian continental shelves is useful to understanding the distribution of sediment types, and the relict or active nature and sorting of the sediments are additional evidence for sediment mobility. This section provides overviews of the knowledge of sediment origin, relict and active nature, and sorting (where applicable) for each shelf of Canada.

In a review of seabed geology of the Canadian Atlantic shelf, Piper (1991) indicated that the principal modern source of sediment to the northern shelves is ice rafting and iceberg-scour reworking of Quaternary sediments. Southern shelves receive sediment through erosion of Quaternary sediments; only small amounts of fine-grained sediment derived from coastal erosion and rivers escape from the coastal zone. During the Holocene sea-level rise, glacio-marine sediments on the shelf seabed above a depth of about 120 m were reworked by a winnowing process: the finer fractions were entrained, transported from the banks and deposited in adjacent deeper basins, while the coarser materials remained as a veneer of sand and gravel on the banks and were worked into various bedforms by the modern oceanographic processes (Fader et al. 1977; Amos & King 1984; King and Fader, 1986; Butman 1987; Twichell et al. 1987; Amos and Judge 1991; Li and King, 2007; Li et al., 2012; Shaw et al., 2014). Surficial sediment texture on the Atlantic Shelf thus shows widespread occurrence of gravel, generally poor sorting, better sorted sands on shallow banks, and mud in shelf basins (Keen and Williams, 1990; Piper, 1991). Shaw et al. (2014) characterize the sediments on the Atlantic Shelf as 50% modern and 50% relict.

The sediment origins and surficial geology on the Pacific Shelf have been reviewed by Bornhold and Barrie (1991). In the Strait of Georgia (Fig. 1), an abundant supply of glacial outwash deposits particularly along the western margin of the strait has resulted in broad areas of nearshore gravelly and sandy platforms and the extensive development of longshore drift

features (Clague and Bornnold, 1980). Elongate basins in central Strait of Georgia can attain depths of more than 300 m in which muds derived principally from the Fraser River (in southern Strait of Georgia) presently accumulate. Virtually all of the sediment load of the Fraser River remains trapped within the strait. The Fraser River delta occupies much of the southeastern part of the Strait and is characterized by broad sand and mud flats. Sediments on the Vancouver Island shelf are relict almost everywhere owing to the trapping of modern sediments in coastal fiords and in the Strait of Georgia. Nearshore sediments consist mainly of gravels and boulders and become finer offshore such that muds are slowly accumulating in depths greater than 100 m. Medium to coarse sand bedforms that developed over an armoured lag of pebbles and cobbles are present in many areas on the mid- and inner shelf. High wave and current energies and efficient sediment trapping in coastal fiords have resulted in low rates of accumulation. Holocene muds and muddy sands are generally less than 0.3 m thick and have accumulated only on the outer shelf. Sediments in Queen Charlotte Sound at water depths shallower than 100 m are composed of sand and gravel; mud is completely absent. The bank tops display a patchy distribution of immobile gravel and zones of mobile wave- and current-rippled sand (Luternauer, 1986). Both storm swells and strong tidal currents leave their impact on bank sediments to water depths of at least 130 m. Muddy sediment is restricted to water depths generally greater than 160 m, particularly in the deeper parts of major troughs. Hecate Strait, between the Haida Gwaii and the mainland, consists of a prominent southward-opening trough along the east side of the Strait bounded by banks on the west. The trough below 200 m is filled by silts. The banks are covered by discontinuous sands and gravels of variable calcareous content. The bank edges typically display megaripples, sand waves, sand and gravel ridges, indicative of active sediment transport. Surficial sediments have not been studied in Dixon Entrance area except in inshore areas off northern Graham Island.

The Canadian Beaufort Sea is characterized by the rich sediment supply from the Mackenzie River and sea-ice coverage for 9 months per year which likely results in a near shut-down of significant sediment transport on the shelf (Hill et al., 1991; Carson et al., 1998). The Beaufort Shelf is underlain by a thick succession of interbedded Pleistocene outwash sand and marine mud (Blasco et al., 1990). The shelf has undergone a marine transgression during the Holocene which has resulted in a veneer of Holocene marine mud covering most of the shelf (Hill et al.,

1991). Relict sand and gravel, however, crop out on the seabed west of Mackenzie Trough and on the most easterly portion of the shelf (Pelletier, 1975). Analysis of bottom currents and wave impact (Fissel and Birch, 1984; Hill et al., 1991) suggests that strong waves combined with strong coastal currents result in frequent resuspension and transport of bottom sediments in the nearshore and on the inner shelf. Although energy is low on the middle to outer shelf, resuspension of fine sediments and their advection to the shelf edge should be expected during downwelling-favorable wind conditions (Osborne and Forest, 2016; Li et al., 2020). The essentially low energy regime on the middle to outer shelf favours settling of sediment from suspension and river plumes to deposit in topographic lows. Energy increases again and is intermediate on the outermost shelf to upper slope due to the presence and surges of the Beaufort Shelf-break Jet (BSJ), the generation of eddies associated with the BSJ, and the generation and descending of cold dense winter water. These processes cause periodic, moderate to strong resuspension and transport of sediments on the Beaufort shelf edge and upper slope (Forest et al., 2008, 2015; O'Brien et al. 2011; Li et al., 2020).

2. Methods

This paper uses the modelling results derived from a collaborative project undertaken in 2005-2008 (National Morphodynamic Framework project of the Geoscience for Ocean Management Program of the Geological Survey of Canada). Although the results were obtained from a legacy project, the publication of the modelling results is still worthwhile because a framework of the magnitude and frequency of seabed disturbance by physical processes does not exist on the continental shelves of Canada, and because shelf-scale quantitative analyses of sediment mobilization and dominant mobilization processes on the world's continental shelves are still sparse. Considering the available grain size data and model products at the study time, and the uncertainty of funding over the project duration, we made the decision that the best tidal current and wave model products available at the study time and uniform grain size would be used to derive benchmark results in the first phase of the project. Data of other current processes, our own modelled wave data and observed grain size would be used to derive updated results in the second phase of the study. Our approach was to extract available sources of wave hindcast data and model predictions of tidal current amplitude for the period of September 2002 to August

2005 for all Canadian continental shelf regions. The wave and current data were coupled with bathymetry and seabed sediment data in a sediment transport model to predict bed shear stresses due to waves, tidal currents and the combined effects of waves and tidal currents. The computed bed shear stresses were then compared with the critical shear stress for the initiation of sediment transport to quantify the magnitude and frequency of sediment mobilization by wave and tidal processes, and to regionalise the Canadian continental shelves based on the dominant disturbance process types.

Spatial resolutions are quite different among various wave hindcast data, tidal current models, and bathymetry data. To balance the needs of spatial resolution and computation time, a Canada-wide modelling domain using structured rectangular grid was constructed. Wave, tidal current and bathymetry data were interpolated to this common grid for the shear stresses and sediment mobility calculations. This common domain was defined from 40 to 85°N and 42 to 140°W, with a spatial resolution of 0.1° (roughly 10 km). The total sea points are approximately 68,000. Figure 1 (high-resolution image given in Supplementary Fig. S1) shows the modelling domains and key geographic locations. As stated previously, the main goal of this study was to produce a national framework of seabed disturbance and sediment mobilization by various oceanographic processes for all three continental shelves of Canada. The 0.1° resolution is adequate to present shelf-scale patterns of seabed forcing and sediment mobilization and to display broad-scale changes within coastal regions as well. The resolution, however, is not suitable to show the detailed variations within individual coastal areas. High-resolution image files for selected figures are available as Supplementary Materials through the CJES link.

2.1 Wave 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 data parameters required for this study were extracted mainly from two existing sources of hindcast data. As described at the start of the Methods section, this paper uses the modelling results derived from a project undertaken in 2005-2008. Our assessments at the start of the study in 2005-06 indicated that the combined wave model products would give the best coverage and

highest resolution of wave data for the Canadian continental shelves. The first source was the Meteorological Service of Canada 50-year wave hindcast data for the Canadian Atlantic shelf, MSC50 data (Swail et al. 2006). The climatology was developed by applying the 3rd generation wave model OWI-3G to predict the wave fields in the North Atlantic over a continuous 50-year period from 1954 to 2005. The historical wind fields used to drive the wave model were derived by synthesizing data from a number of sources, including wind fields developed by the NCEP-NCAR (US National Centers for Environmental Prediction/National Center for Atmospheric Research) Wind Fields Reanalysis Project and a kinematic reanalysis of all major storms. Comparison between model predictions of wave heights and buoy data indicates very good agreement with a mean bias of 0.08 m (Swail et al. 2006). The MSC50 wave data were hourly and at 0.1° resolution over the eastern Canada coast region, and were three-hourly and at 0.5° resolution over the North Atlantic Basin.

The second wave data source was the wave hindcast data generated by the NCEP of the U.S. National Oceanic and Atmospheric Administration (NOAA). The wave predictions were performed using a sophisticated third generation spectral wind-wave model known as WAVEWATCHIII™ or WW3 (version 2.22; Tolman 2002). The wind fields used to drive the model were obtained from operational products prepared by NCEP. The NCEP/NOAA wave model has been implemented on several different regular grids, spanning various ocean basins. The Western North Atlantic (WNA) grid has a 0.25° by 0.25° resolution and contains over 54,000 nodes spanning the region between latitudes 0°N to 50°N and longitudes 98°W to 30°W . The Eastern North Pacific (ENP) grid features 0.25° by 0.25° resolution and contains over 81,000 nodes spanning the region between latitudes 5°N to 60.25°N and longitudes 170°W to 77.5°W . The wave data from both regions have a 3 hour temporal resolution. The model results are freely available via the internet (<ftp://polar.ncep.noaa.gov/pub/history/waves>). The WW3 model has been validated by comparison with data from buoys and satellites. The comparison between model-predicted significant wave height against the buoy measurements for the period 2008–2010 shows that the bias ranges from -0.33 to 0.13 m for the Western North Atlantic grid. The bias for the Eastern North Pacific is from 0.06 to 0.56 m. These biases in wave height could mean more substantial uncertainties of the modelled wave shear stresses in shallow coastal areas, which are not the focus of this study.

287

288 A comparison of operational implementations of modern wave forecast models is given by
289 Perrie et al. (2018), focusing on three rather strong nor'easters that occurred in recent years in the
290 Northwest Atlantic. The inter-comparison considers several physics parameterizations for the
291 basic wave processes. The discussed parameterizations range from those of the original third
292 generation wave model by the WAM Group (1988) to more modern state-of-the-art
293 formulations by Ardhuin et al (2010), Zieger et al. (2015) and Liu et al. (2017) . While Perrie et
294 al. (2018) show that tuning of parameters can unsurprisingly produce very good results in
295 comparisons of advances in wave physics parameterizations, improvements in simulations of
296 significant wave heights are less than 10%. Therefore, the simulations by wave models used in
297 the present study are certainly acceptable, given the variability and errors in the wind fields.

298

299 For the Atlantic shelf, the wave data are mainly from the MSC50 data. The 0.1° resolution data
300 were used for the eastern Canada coast region, and the 0.5° resolution data were used for the
301 North Atlantic Basin. Since the 0.5° resolution of the MSC50 North Atlantic Basin data is much
302 coarser than the NCEP/NOAA data, the latter were used for areas between 40°N - 50°N outside
303 the coast region covered by the 0.1° resolution MSC50 data. No hindcast wave data were
304 available for the area north of 75°N . For the Pacific shelf, the wave data were exclusively from
305 the NCEP/NOAA data. The NCEP Eastern North Pacific wave data are consistent with more
306 recent hindcast studies by Chawla et al. (2013). For the Arctic shelf, the only hindcast wave data
307 available at the time of this study were the MSC Beaufort Sea 20 year data (MSCB20, Swail et
308 al. 2007). These data are still among the best for wave climate in the Beaufort (see Wang et al. ,
309 2015). Unfortunately MSCB20 data only cover the Beaufort Sea, about 10% of the Arctic shelf
310 region (Figure 1). The same wind data and wave model as MSC50 were used in generating the
311 wave data of MSCB20, which provides hourly wind and wave data with 5 km resolution for the
312 Canadian Beaufort Sea. The wave data for the period of September 2002 to August 2005 were
313 extracted from the above-described sources with their original temporal resolution. These were
314 then interpolated to the common domain (Figure 1) of 0.1° resolution used through this study.
315 Wave data were linearly interpolated in time so that hourly estimates were available to coincide
316 in time with tidal current estimates (see below) for the eventual shear stress and sediment
317 mobilization computations.

318
319 Compared to the Australia shelves, one of the distinctive features of Canada is the perennial and
320 seasonal cover of sea ice in numerous regions on the Canadian continental shelves, which can
321 have substantial effects on waves and other oceanographic processes. The daily polar gridded sea
322 ice concentrations of National Snow and Ice Data Center with a horizontal resolution of 25 km
323 (Fetterer, et al., 2017) were used to analyze the sea ice extents in the time period of 2002-2005.
324 The maximal and minimal ice coverage for the 2002-05 period (Figure 2) demonstrate that the
325 entire Arctic shelf and an extensive portion of the Atlantic shelf (as south as NE Newfoundland
326 shelf and the Gulf of St. Lawrence) have 100% ice coverage during the maximum winter
327 conditions. Sea ice has no effect on the Pacific shelf. The minimal ice coverage during the
328 summer (Figure 2b) shows that the western Arctic shelf, southern part of the Arctic Archipelago
329 and most parts of the Atlantic shelf are essentially ice free, although the high Arctic is still
330 covered by 80% ice concentration. It is worth to note that the sea ice in the CAA has strong inter-
331 annual and spatial variations (Howell and Brady, 2019). The purpose of statistical results of the
332 minimum and maximum extents in 2002-2005 is to show the potential areas of wave impact on
333 sediments, while they may under- or over- estimate the realistic conditions. Considering the
334 effect of rapidly changing climate, the ice coverage will likely decrease in the present day
335 condition. The seasonal variations of the ice coverage of Figure 2 would suggest that wave
336 parameters (e.g. wave height and wave power) and seabed shear stress and sediment mobility
337 due to waves are near zero in the high Arctic which is covered by ice year round. These values
338 should be lower over areas which are only partly covered by ice in a year, i.e. Beaufort Sea,
339 Baffin Bay, Labrador and Northeast Newfoundland shelves, and Gulf of St. Lawrence (Figure
340 2a). As demonstrated in the next section, tidal models simulated tidal currents over all shelf
341 regions. Hence shear stress and sediment mobility by tidal currents have been modelled for all
342 regions whether covered or not covered by ice.

344 ***2.2 Tidal Current Data***

345
346 The Canadian Department of Fisheries and Oceans (DFO) Webtide models (Dupont et al. 2002)
347 and Oregon State University's TPXO6.2 global model (Egbert and Erofeeva 2002) available at
348 the study time were combined to provide complete coverage of tidal current predictions for all

the open Canadian continental shelf regions. Our basic idea is that we choose to use the best available tidal models where highest resolution could be achieved and there had been careful evaluation of the solutions and tidal currents for the region of interest on the continental shelf. Since TPXO6.2 had coarser resolution and was not carefully evaluated over the Canadian continental shelves, the use of Webtide took first precedence and TPXO6.2 was used only in areas not covered by the Webtide models. The Webtide models are further divided into several regional models. The tidal currents for the Pacific shelf came exclusively from the Northeast Pacific regional model with seven tidal constituents (Foreman et al. 2000). The tidal currents for the Arctic shelf came exclusively from the Arctic regional model with five constituents (Dunphy et al. 2005). For the Atlantic shelf, several regional models were merged to derive the best coverage of tidal current prediction. 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 with five tidal constituents. Bay of Fundy and eastern 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 where there was no Webtide model coverage. The harmonic constituents available from the various models are listed in Table 1. Although TPXO6.2 data cover all the shelf regions of Canada, Web tide models provide higher resolution and are better calibrated for Canadian waters. We therefore chose to use different regional Web tide models in order to achieve the best coverage and include the most tidal constituents.

The Webtide models provide harmonic constituents on a unstructured triangular grid which allows higher resolution in shallow waters and around coasts. The OSU global model is specified on a structured rectangular grid. The tidal constituents from various models were interpolated to the structured rectangular grid of 0.1° resolution used in the wave data compilation. Then the 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 model validation suggests that the surface elevation predictions are accurate to around 0.1 m over most regions. For the Arctic model, the root-mean-square error of the M2 tidal constituent is about 0.14 m (Dunphy et al. 2005). For tidal current predictions, Foreman et al. (2000) reports errors of less than $0.05 \text{ m}\cdot\text{s}^{-1}$ in the M2 currents at 3 stations for the NE Pacific regional model.

For the NW Atlantic regional model, Dupont et al. (2002) report M2 current errors of typically 0.05–0.1 m·s⁻¹.

There have been developments of basin or global scale circulation models such as HYCOM (Hybrid Coordinate Ocean Model, Halliwell, 2004), NEMO (Nucleus for European Modelling of the Ocean, Madec et al., 2019), and MOM (The Modular Ocean Model, Reichl and Hallberg, 2018), and modelling systems that integrate data assimilation and re-analysis e.g. GLORYS (Global Ocean Reanalysis, <https://resources.marine.copernicus.eu/>) and SODA (Simple Ocean Data Assimilation, <https://climatedataguide.ucar.edu/climate-data/soda-simple-ocean-data-assimilation>). The current data from these models can be downloaded and used for various purposes. However, most of these products are daily or coarser frequency, and the temporal scales are not suitable to quantify bed shear stress and sediment mobilization at short temporal scales. Besides the Webtide product, a number of tidal models have been developed more recently. Using the Finite Volume Community Ocean Model (FVCOM), for example, Han et al. (2011) developed a tidal model over the Grand Banks and Newfoundland Shelf. Wu et al. (2012) developed a tidal model in the BoF. Foreman et al. (2012) investigated the tidal circulation in the Discovery Island region of British Columbia. Using FVCOM, two regional tidal models were developed in the Hecate Strait (Wu et al., 2017) and the Vancouver Harbor (Wu et al., 2019), respectively. In the Canadian Arctic Archipelago (CAA) and Baffin Bay, Guo et al. (2020) reported the use of a tidal model for the summer season. Based on the results of model comparisons (Wu et al., 2012), the tidal currents from the FVCOM model were improved compared to the Webtide product in the BoF. In the inner bay, the difference of the semi-major axis of M2 between the FVCOM model and observations is 0.06 m·s⁻¹, lower than that of Webtide at 0.15 m·s⁻¹. However, the tidal currents based on FVCOM models are not available so far for all three of the Canadian shelves covered in the present study because of complicated temporal and spatial variations of tidal currents, such as tidal damping due to sea ice in the CAA.

2.3 Shear Stresses and Threshold Exceedance Computations

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 (Varma et al. 2008). The NWATL dataset was compiled from several sources, including Etopo2, single beam, multibeam, and Lidar data contributed from various Canadian and international academic and government agencies to achieve complete coverage of Canadian oceans with the then best spatial resolution. NWATL data are composed of 64 m tiles and defined by boundaries of 20°–90°N and 20°–155°W. The bathymetry data of the NWATL data set were 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 were further interpolated on to the common structured grid of 0.1° resolution as shown in Fig. 1.

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. Because observed grain size data for the entire Canadian continental shelves were not consistently available when this modelling study was undertaken, a uniform mean grain size of $D = 0.35$ mm (medium sand) was used to provide a bench-mark assessment of seabed disturbance and sediment mobility without potential complication by possible uncertainty (e.g. errors and poor data coverage) that could be introduced in interpolated grain size data. The use of this uniform grain size would mean that the results from this study should be taken as potential values, and only represent true sediment mobility in regions where medium sand is found. Observed grain size was in development for the Scotian Shelf at the time of this study (Kostylev and Hannah, 2007). We opted not to use these observed grain size data because the use of observed grain size on the Scotian Shelf and use of uniform medium sand on other shelves would lead to incompatible seabed disturbance and sediment mobility estimates. The use of the mean grain size of 0.35 mm is partially justified because this represents approximately the averaged grain sizes on the Grand Banks and Scotian Shelf (Barrie and Collins, 1989; Kostylev and Hannah, 2007), and because the value has been used in previous sediment transport modelling studies (Amos and Judge, 1991; Li et al., 2017). Sensitivity tests undertaken in this study (see below) and in Hemer (2006) also show that a doubling of grain size only moderately affects combined-flow bed shear stress under typical oceanographic conditions. Ultimately, observed grain size data based on seabed samples should be used to provide more

realistic quantification of seabed disturbance and sediment mobility on the Canadian continental shelves. The threshold for the initiation of bedload transport was based on the modified Yalin method of Miller et al (1977) as described by Li and Amos (2001). For $D = 0.35$ mm, the critical shear velocity for the onset of bedload transport u_{*cr} is $1.5 \text{ cm} \cdot \text{s}^{-1}$.

For tidal current effect, the model-predicted hourly depth-averaged mean tidal current was taken as the mean current at 1 m above bottom, U_{100} , and was used to compute the tidal current shear velocity from:

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

where f_c is the steady current friction factor and takes a value of 0.006 for unrippled sandy seabed (Soulsby 1983; Dyer 1986). The “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 , were used in 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 is calculated according to Jonsson (1966) as modified by Nielsen (1979):

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

$$f_w = 0.28 \quad k_b/A_b \leq 1.7 \quad (2b)$$

where k_b is the grain-size related bottom roughness height given by $2.5D$. Wave shear velocity u_{*ws} is then calculated from:

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

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, is calculated from:

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

where ρ is fluid density. 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 tidal current. The SEDTRANS 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. 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). This model was also used by Hemer (2006) to compute the combined-flow bed shear stress on the Australian continental shelf. For the present study, hourly wave and tidal current data together with water depth and mean grain size $D = 0.35$ mm were input into SEDTRANS to calculate u_{*cws} for each hour of the modelling period of 2002 to 2005.

The hourly skin-friction shear velocity by tidal current (u_{*cs}), waves (u_{*ws}) and combined wave-current (u_{*cws}) was then compared to the critical shear velocity u_{*cr} of $1.5 \text{ cm} \cdot \text{s}^{-1}$ to determine if mobilization of sediments with $\sim$ medium sand diameter 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 threshold exceedance maps due to tidal current, waves, and combined waves and tide for the Canadian continental shelves.

2.4 Quality and sensitivity of modelled seabed shear stress and sediment mobility

Good agreements between modelled and observed tidal elevation and current and wave heights

have been presented in Sections 2.1 and 2.2 to demonstrate the adequacy of the tidal current and wave models used in this study. This study uses the sediment transport model SEDTRANS (Li and Amos 2001) and the combined wave-current bottom boundary layer theory of Grant and Madsen (1986) to compute the seabed shear velocity and the initiation of sediment transport. Numerous field studies have established that the combined-flow bottom boundary layer model of Grant and Madsen (1986) adequately estimates the enhanced bottom shear stresses and bottom roughness scales (within 90-95% confidence intervals) under the combined wave and current conditions on continental shelf environments (Grant et al., 1984; Cacchione et al., 1987; Huntley and Hazen, 1988; Drake and Cacchione, 1992). 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; Bastos et al. 2004; Hemer 2006). Comparisons of measured and modelled sediment transport rates over fine to medium sands and over muddy sediments showed that SEDTRANS accurately predicts the initiation of sediment motion and the errors of the model-predicted sediment transport rates are less than a factor of five under either steady current or complex combined wave and current conditions (e.g. Li et al. 1997; Neumeier et al. 2008).

A site on central middle Scotian Shelf, 43.84°N 60.7°W in 40 m water depth, with typical wave and current conditions, was used in various computations to demonstrate the sensitivity of the modelled shear stress and sediment mobilization frequency (SMF) to the variation of the input wave, tidal current and grain size values. The original mean wave and current parameters for this site are $H_s = 1.18$ m, $T_p = 7.76$ s, $U_{100} = 0.24$ m·s⁻¹. The modelled combined wave-current shear velocity u_{*cws} averaged over the 3-year simulation period is 1.95 cm·s⁻¹, and medium sand with D of 0.35 mm is mobilized for 61.2% of the time. The typical errors of modelled tidal current speed are 0.05–0.1 m·s⁻¹ (Foreman et al., 2000; Dupont et al., 2002; Section 2.2). The bias of model-predicted significant wave heights ranges from -0.33 to 0.13 m for the Western North Atlantic region (Section 2.1). In Case 1 of the sensitivity tests, the original wave parameters and D of 0.35 mm were kept and U_{100} values of ± 0.05 and ± 0.1 m·s⁻¹ bias were used to re-run SEDTRANS to compute u_{*cws} and SMF. In test Case 2, the original U_{100} , T_p , and D data were kept and H_s data with 0.13 m and -0.33 m bias were used to compute u_{*cws} and SMF. In the final

test Case 3, the original wave and current data were kept and a range of D for mud (0.016 mm), fine sand (0.18 mm) and coarse sand (0.7 mm) were used to compute u_{*cws} and SMF. The input variables and the computed u_{*cws} and SMF values as well as the change percentages of these computed values are listed in Table 2.

The errors of 0.1 m s^{-1} of the modelled tidal current speed would result in maximum changes of 18% and 21% of the predicted shear velocity respectively (Table 2 Case 1) and cause maximum reduction of 36% and maximum increase of 41% in SMF. In contrary to the significant changes caused by the tidal current errors, the bias in the modelled significant wave heights only lead to 2% to 5% changes in both the shear velocity and SMF (Table 2 Case 2). For the variation of input grain size ranging from fine silt to coarse sand (Table 2 Case 3), the shear velocity may decrease by 17% and increase by 7%. These are compatible to the values of 15% for similar grain size changes presented by Hemer (2006). Relative to the values of medium sand (0.35 mm), the modelled u_{*cws} for fine sand (0.18 mm) decreases to 1.85 cm s^{-1} yet SMF is increased by 24% due to the lower critical shear velocity (1.24 cm s^{-1}) for fine sand. For coarse sand (0.7 mm), the modelled u_{*cws} increases to 2.1 cm s^{-1} but SMF actually decreases by 29% due to a much higher critical shear velocity (1.91 cm s^{-1}). If the site was covered by muddy sediment (fine silt of 0.016 mm), the modelled shear velocity would further decrease to 1.62 cm s^{-1} . However, SMF only decreases slightly by 3% because of the relatively higher critical shear velocity of 1.4 cm s^{-1} for cohesive sediments. In summary, the modelled shear stress and sediment mobilization are most sensitive to the errors of modelled tidal current speeds as these errors may result in shear velocity changes up to 20% and SMF up to 40%. Variations of sediment grain size cause moderate uncertainty as maximum change of shear velocity is up to 17% and that of SMF up to 30%. The modeled outputs are the least sensitive to the bias of modelled significant wave height. The bias of modelled H_s only led to 2 – 5% changes in both shear velocity and sediment mobilization frequency.

3. Results

3.1 Waves

Mean significant wave height and spectral peak wave period averaged from September 2002 to August 2005 are shown in Figures 3 and 4 respectively. The strongest waves occur in the open ocean off the Atlantic and Pacific shelves. Mean significant wave heights reach similar values of 3 – 3.5 m in these areas (Fig. 3) while the maximum waves reach 15 m and 12 m respectively (not shown). Due to ice coverage (Fig. 2), mean wave height in the Beaufort Sea is less than 0.4 m. Wave height progressively decreases from the open ocean, through the shelf, to the coastal zone. This pattern is particularly well seen on the Atlantic Shelf. Due to the steep bathymetry gradient on the Pacific Shelf, mean wave heights of ~2.5 m occur immediately offshore of the coast line. In contrast, a zone of moderate wave heights of 1–2 m is well recognized on the shelves of the Atlantic Canada. Because of sheltering, mean wave height is significantly lower in bays and coastal basins, generally less than 1.2 m in the BoF and less than 2 m in the basins east of Vancouver Island and Haida Gwaii on the Pacific Shelf. Due mostly to ice coverage (Fig. 2) and partially to sheltering, mean wave height is also less than 1.2 m in Baffin Bay and in Gulf of St. Lawrence. Mean wave period ranges from 6.5 to 8.5 s on the Atlantic Shelf (Fig. 4); wave period is greater on the Pacific Shelf reaching 9–10 s. Due to ice coverage (Fig. 2a), mean wave period is the lowest in the Beaufort Sea at less than 1.5 seconds.

The wave energy flux (or wave power), integrating the effect of wave height and period, is presented in Fig. 5. Both mean and maximum wave power are significantly stronger on the Pacific shelf and southern Atlantic shelf than in the Beaufort Sea and northern Atlantic shelf (Baffin Bay) as the latter two regions are partially covered by ice (Fig. 2a). These patterns are well correlated with the distribution of wave height and wave period (Figs. 3 and 4). The greatest mean wave energy occurs in the deep waters off the British Columbia coast and off the Newfoundland and southern Labrador shelves where mean wave power can reach or exceed 100,000 W m⁻². The maximum wave power reaches 1.4 and 2.2 million W m⁻² respectively. Moderately high and high wave power is also predicted on the British Columbia shelf (mean wave power ~70,000 W m⁻²) and on the Scotian Shelf and Newfoundland shelf (mean wave power ~50,000 W m⁻²). The lowest wave energy is predicted on the Beaufort shelf where the mean wave power is <200 W m⁻². Wave power is zero on the high Arctic shelf as it is covered by permanent ice year-round. Due to partial ice coverage, wave energy is also low in Baffin Bay, mean wave power being less than ~1000 W m⁻². Wave energy is also low in protected coastal

embayments. Mean wave power is $<20,000 \text{ W m}^{-2}$ in Queen Charlotte Sound and $\sim 10,000 \text{ W m}^{-2}$ in the BoF and Gulf of St. Lawrence where the low wave power is also due to partial ice coverage (Fig. 2a).

3.2 Wave shear velocity and threshold exceedance

The wave impact on the seafloor, however, predominantly depends on the water depths rather than the distribution of waves on the ocean surface. Mean wave shear velocity (Fig. 6; Supplementary Fig. S6) demonstrates that the strongest waves in the open ocean on the Atlantic and Pacific shelves do not translate to impact at the seabed due to the deep water in these areas. Wave impact on the seabed generally occurs in shallower waters on the inner shelf, over outer shelf banks, and in coastal embayments. The spatial distribution of the mean wave shear velocity (Fig. 6) shows that the strongest wave impact on the seabed occurs along the coasts in northern Hecate Strait and offshore at the northern tip of Vancouver Island where mean wave shear velocity reaches $\sim 4 \text{ cm} \cdot \text{s}^{-1}$. Moderate wave shear velocity up to $2 - 3 \text{ cm} \cdot \text{s}^{-1}$ is found offshore of western Vancouver Island and along the coast of Washington State. On the Atlantic Shelf, moderate wave shear velocity of $2 - 3 \text{ cm} \cdot \text{s}^{-1}$ occurs on the Grand Banks, Georges Bank, the banks on the outer Scotian Shelf, in southern Gulf of St. Lawrence, and along the coast of Labrador Shelf. Low values of wave shear velocity (approximately $0.5 - 1 \text{ cm} \cdot \text{s}^{-1}$) are found in the Strait of Juan de Fuca, upper BoF, southern Gulf of St. Lawrence, and the Beaufort Sea. Wave shear is minimal in the remaining areas of the Canadian continental shelves.

Figure 7 presents the wave threshold exceedance map for the Canadian continental shelves (Supplementary Fig. S7). Corresponding with the spatial patterns of the wave shear velocity of Fig. 6, the highest wave mobilization frequencies, which are up to 30–50%, occur in Hecate Strait, around the northern tip of Vancouver Island, offshore of western Vancouver Island and Washington State, and on the East Coast, over Sable Island Bank (SIB) on central outer Scotian Shelf. Moderate frequency of wave mobilization of 10–30% is found in the Strait of Juan de Fuca, on the Grand Banks, Georges Bank, the banks on the outer Scotian Shelf, and along the coast of Labrador Shelf. Low to moderate wave mobilization, up to 10%, occurs in the Beaufort Sea, over southern Gulf of St. Lawrence and over eastern Davis Strait. Low wave mobilization

frequency of 1–5% is predicted for the upper BoF, on the inner Scotian Shelf, and on the banks of outer Labrador Shelf. The low values of shear velocity and sediment mobilization by waves in the Beaufort Sea, in the Gulf of St. Lawrence and on the Labrador Shelf are partially attributed to the partial ice coverage in these areas as shown in Figure 2.

Given that the shelf break occurs in water depths down to 300–500 m over significant parts of the Atlantic shelf (Piper 1991), the depth range of 10 – 500 m is used to define the shelf areas around Canada, to be consistent across all three shelves. 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 3. Figure 7 and Table 3 demonstrate that waves are capable of mobilizing medium sand at least once over 59% of the Pacific shelf area, 49% of the Atlantic shelf area, and only 6% of the Arctic shelf area, due to ice coverage. Canada-wide, excluding the Arctic shelf (due to limited wave data and year round coverage of ice for significant part of the shelf, Fig. 2), waves can cause mobilization of medium sand at least once over 50% of the Canadian continental shelves. As a function of the combined effect of the maximum H_s and T_p , the maximum depth that waves are capable of mobilizing medium sand is down to ~209 m on the Atlantic shelf, whereas the maximum depth reaches ~190 m on the Pacific shelf.

3.3 Tidal currents

Mean tidal current speed in Fig. 8 (Supplementary Fig. S8) shows that tidal currents tend to be stronger on the Atlantic shelf than on the Pacific shelf. The highest tidal currents are up to 0.8–1.2 $\text{m}\cdot\text{s}^{-1}$ on the Atlantic Shelf and occur in the BoF, on Georges Bank and at the entrance to Hudson Strait on the Southeast Baffin Shelf. Only moderately strong tidal currents of 0.5–0.6 $\text{m}\cdot\text{s}^{-1}$ are found in coastal seaways (northern Hecate Strait and Strait of Juan de Fuca) on the Pacific shelf. Moderately strong tidal currents are also predicted on western Scotian Shelf and in Davis Strait on the Atlantic Shelf. Moderate tidal currents of 0.3–0.4 $\text{m}\cdot\text{s}^{-1}$ are predicted for Queen Charlotte Sound, Dixon Entrance, on the shelf off Vancouver Island, on the banks of the outer Scotian Shelf and in part of the Arctic Archipelago. Low to moderate tidal currents of 0.2–0.3 $\text{m}\cdot\text{s}^{-1}$ are found on the Grand Banks, in Gulf of St. Lawrence, and in Beaufort Sea.

The high tidal currents in the BoF and at the entrance to Hudson Strait, and the moderately high tidal current in Hecate Strait, are attributed to the higher tidal ranges, as the mean tidal ranges are 3.6 – 10 m, 2.4 – 3.6 m and 3.6 m respectively in these areas (Cornett 2006). Mean tidal range is only 1.2–1.6 m in the Arctic Archipelago and 1.6 – 2 m in the Strait of Juan de Fuca. However, acceleration by topographic constriction causes moderate ($0.3\text{--}0.4\text{ m}\cdot\text{s}^{-1}$) and moderately strong ($0.5\text{--}0.6\text{ m}\cdot\text{s}^{-1}$) tidal currents in these areas respectively. The strong tidal current on Georges Bank with its mean tidal range of 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 (Garrett, 1972) and the bank also causes topographic acceleration of the tidal flow.

3.4 Tidal current shear velocity and threshold exceedance

The pattern of the mean tidal current shear velocity in Fig. 9 (Supplementary Fig. S9) shows strong correlation with the mean tidal current speed (Fig. 8). The highest mean tidal current shear velocity, $\sim 4\text{ cm}\cdot\text{s}^{-1}$, occurs in the BoF, on Georges Bank and at the entrance to Hudson Strait. Moderately high tidal current shear velocities of $2\text{--}3\text{ cm}\cdot\text{s}^{-1}$ can be found in northern Hecate Strait, the Strait of Juan de Fuca, in central Queen Charlotte Sound, on the banks of the outer Scotian Shelf, in Davis Strait, and in southern part of the Arctic Archipelago. Moderate tidal current shear velocity of $1\text{--}2\text{ cm}\cdot\text{s}^{-1}$ is predicted for the remaining Pacific shelf coastal basins, on the inner shelf off Vancouver Island, on western and southeastern Grand Banks, in Gulf of St. Lawrence, in Nares Strait (top of Baffin Bay), and in the Beaufort Sea. Low values of mean tidal current shear velocity ($0.3\text{--}0.5\text{ cm}\cdot\text{s}^{-1}$) are found in central and western Gulf of Maine, on the inner Scotian Shelf, on central and northern Grand Banks, on the outer Northeast Newfoundland Shelf and outer Labrador Shelf, and in patches in Baffin Bay and on the Arctic Shelf.

The percentage of time that the tidal current alone causes mobilization of medium sand on the Canadian continental shelves is presented in Fig. 10 (Supplementary Fig. S10). On the west coast, tidal current causes high frequency (50–70% of the time) mobilization of medium sand in northern Hecate Strait, the Strait of Juan de Fuca and in central Queen Charlotte Sound. Moderate mobilization frequency, about 30% of the time, is predicted for the remaining areas of

the Pacific shelf coastal basins and on the inner shelf off Vancouver Island. Tidal current alone causes no or little mobilization of medium sand on the shelf off Haida Gwaii and in the southeastern Queen Charlotte Sound. On the Atlantic Shelf, maximum frequency of mobilization (close to 100% of the time) occurs in the BoF, on Georges Bank and western Scotian Shelf, and at the entrance to Hudson Strait. Moderately high mobilization frequency up to 30–50% occurs on the banks of outer Scotian Shelf, in Northumberland Strait and patches in Gulf of St. Lawrence, and in Davis Strait. Low mobilization frequency, ~10%, is predicted for patches on the southeastern Grand Banks and in Nares Strait. Tidal current alone does not cause mobilization of medium sand in central and western Gulf of Maine, on the inner Scotian Shelf, on the Labrador Shelf and Northeast Newfoundland Shelf, and over most parts of the Grand Banks. Tidal current causes moderate mobilization (up to 30% of the time) only over the southern part of the Arctic Archipelago, and is not strong enough to mobilize medium sand in Baffin Bay, on the Beaufort Sea shelf and on the open Arctic Shelf.

The area and percentages of shelf area over which tidal currents are capable to mobilize medium sand at least once were calculated for each shelf and for all shelves of Canada (Table 3). Tidal current impact is the strongest on the Pacific shelf, causing mobilization of medium sand over 58% of the shelf area. Tidal currents can mobilize medium sand over 35% of Atlantic shelf area. The tidal exceedance decreases substantially to 14% for the Arctic shelf. Canada-wide, excluding the Arctic shelf, tidal currents can mobilize medium sand over 37% of the shelf areas around Canada.

3.5 Combined wave-current shear velocity and threshold exceedance

The mean shear velocity due to the combined wave and tidal current, u_{*cws} , is shown in Fig. 11 (Supplementary Fig. S11). The strongest combined wave-current shear velocity $>5 \text{ cm} \cdot \text{s}^{-1}$ occurs along the coast of Haida Gwaii in northern Hecate Strait, offshore at the northern tip of Vancouver Island, in the BoF, and at the entrance to Hudson Strait. Moderately high values of 3–4 $\text{cm} \cdot \text{s}^{-1}$ are found offshore of western Vancouver Island and of Washington State, in the Strait of Juan de Fuca, on Georges Bank and western Scotian Shelf, and on SIB. Moderate values of 2–3 $\text{cm} \cdot \text{s}^{-1}$ are predicted for northern Hecate Strait, central Queen Charlotte Sound, the Grand

Banks, the banks on the outer Scotian Shelf, southern Gulf of St. Lawrence, and Davis Strait. Low values of u_{cws} of $1\text{--}2\text{ cm}\cdot\text{s}^{-1}$ are found in Dixon Entrance, in southern Hecate Strait and over patches in Queen Charlotte Sound, in Beaufort Sea, and in southern part of the Arctic Archipelago. Minimal combined shear velocity of $0.5\text{--}1\text{ cm}\cdot\text{s}^{-1}$ is predicted for southeastern Queen Charlotte Sound, the Gulf of Maine, inner and middle Scotian Shelf, Northeast Newfoundland Shelf, southern Labrador Shelf, shelves around Baffin Bay, and most of the Arctic Archipelago.

The percentage of time that the combined wave-current shear velocity exceeds the threshold shear velocity or sediment mobilization frequency (SMF) is shown in Figure 12 (Supplementary Fig. S12). This map demonstrates that the enhanced wave-current shear velocity can keep medium sand in transport for nearly 100% of the time in several areas. These include the BoF, Georges Bank/western Scotian Shelf, entrance to Hudson Strait, northern Hecate Strait, central Queen Charlotte Sound, and offshore of the northern tip of Vancouver Island. The combined wave-current shear velocity also causes high frequency of mobilization (50–70% of the time) on the banks of outer Scotian Shelf, on the inner shelf off Vancouver Island and Washington State, and in the Strait of Juan de Fuca. Moderately high frequency of mobilization (30–50% of the time) occurs on southeastern Grand Banks, in Davis Strait, in Queen Charlotte Sound, and in Dixon Entrance. Moderate mobilization (10–30% of the time) is predicted for Gulf of St. Lawrence, along the coast of Labrador Shelf, in southern part of the Arctic Archipelago, and in Beaufort Sea. The combined wave and tidal current also causes weak mobilization (1–10% of the time) on the eastern inner Scotian Shelf and on the banks of the outer Labrador Shelf. The combined wave and tide shear stress is not competent to mobilize sediment for southeastern Queen Charlotte Sound, the Gulf of Maine, inner and middle Scotian Shelf, Northeast Newfoundland Shelf, southern Labrador Shelf, the shelves around Baffin Bay, and most of the Arctic Archipelago.

The estimates of areas and percentage of shelf area over which medium sand is mobilized at least once by the combined wave-current shear velocity are also listed in Table 3. The shear stress due to the combined effect of waves and tidal current can mobilize medium sand at least once over 86%, 67%, and 20% of shelf areas for the Pacific, Atlantic and Arctic shelf

respectively. For the total shelves of Canada excluding the Arctic shelf, the combined wave-current shear stress can mobilize medium sand over 68% of the shelf area.

4. Discussion

4.1 Enhancement of Shear Stress by Wave-Current Interaction and Impact on Sediment Mobilization

As stated previously, wave processes during storms will interact non-linearly with steady currents to generate an enhanced combined wave-current shear stress (e.g. Grant and Madsen 1986). Currents produced during storm events include strong wave oscillatory flows and steady wind-driven currents. The energy expended and the amount of sediment transported during one storm event may equal many months (or years) of non-storm background processes. Even on dynamic tide-dominant shelves, the effect of storms is to initiate sediment transport in greater depths and at higher rates in shallower depths than is experienced under normal conditions. It is expected that tidal currents can constantly transport sediments of average grain size but only the high wave shear stress of major storms is capable of suspended-load transport and mobilization of coarser fractions of the sediments.

Comparison of wave shear velocity (Fig. 6) and tidal current shear velocity (Fig. 9) with the combined wave-current shear velocity (Fig. 11) clearly shows that the maximum mean shear velocity by waves and tides alone is $\sim 4 \text{ cm} \cdot \text{s}^{-1}$ while the maximum mean combined wave-current shear velocity is greater than $5 \text{ cm} \cdot \text{s}^{-1}$. On the banks of Scotian Shelf and on the Grand Banks, the mean shear velocity under wave or tidal current alone is generally $< 2 \text{ cm} \cdot \text{s}^{-1}$, but the seabed shear velocity increases to $3\text{--}4 \text{ cm} \cdot \text{s}^{-1}$ under the combined effects of waves and tidal current. As a result of the enhanced shear due to combined waves and tidal current, the combined-flow shear velocity can mobilize medium sand over 69% of the Canadian continental shelf, while tidal current or waves alone only cause sediment mobilization over 37% and 50% of the shelf respectively. Therefore the magnitude and frequency of seabed exposure and sediment mobilization on continental shelves will be severely under-estimated if the effect of wave and current interaction is not considered.

4.2 Shelf Regionalisation Based on Disturbance Types

For the entire shelves around Canada (excluding the Arctic), waves are moderately more important than tides for sediment mobilization; waves can mobilize medium sand over 50% of the shelf area while tides cause sediment mobility over 36% of the shelf area (Table 3). However, the relative importance of tides and waves varies significantly for individual shelves. Despite the limited availability of wave data, the Canadian Arctic shelf is tide dominant (except for the Beaufort Sea) as threshold exceedance by tide is 13.6% of the shelf area and that by waves only occurs over 6.5% of the Arctic shelf. The impact on sediment mobility of tides and waves is roughly equal on the Pacific shelf, as the threshold exceedance occurs on ~58% of the shelf area for both processes. In contrast, the Atlantic shelf is dominated by wave mobilization as waves can mobilize medium sand over 49% of the shelf area whereas tidal mobilization only occurs over 34% of the area of the Atlantic Shelf.

Continental shelves can be classified into disturbance types based on quantitative estimates of the spatial variation of the relative importance of wave and tidal current exceedance. Following the approach of Porter-Smith et al. (2004), supported by other publications in the literature (e.g. Grant and Madsen 1986; Lyne et al. 1990), six disturbance types are defined for the Canadian continental shelves. Shelf regions where neither the tides and waves are capable of mobilising bottom sediment are classified as “unaffected” (zero-mobility) regions. Shelf regions where mobilisation of bottom sediments is either only by waves or by tides are classified as “wave only” or “tide only”. Shelf regions where both waves and tides are capable of mobilising sediment are classified into three categories: “wave-dominant” regions where the percentage of time of wave mobilisation is $\geq$ three times the percentage of time of tide mobilisation; “tide-dominant” regions where the percentage of time of tide mobilisation is $\geq$ three times the percentage of time of wave mobilisation; and “mixed” regions where the ratio of time percentage of wave/tidal mobilization is between 1/3 and 3.

The spatial distribution of the seabed disturbance categories is presented in Figure 13 (Supplementary Fig. S13). The main features of the distribution patterns are that tidal

disturbances tend to be dominant in partially protected areas such as Queen Charlotte Sound and the BoF and within or over areas of restricted seaways (Dixon Entrance, Davis Strait to SE Baffin Shelf, and in the Arctic Archipelago), while wave disturbances are dominant on the open shelves (inner and mid-Scotian Shelf, the Grand Banks, the Beaufort Sea shelf) and on the offshore banks (banks on the outer Scotian Shelf and outer Labrador Shelf).

More specifically for the Pacific Shelf, wave-dominant disturbance types mainly occur on the inner shelf off Vancouver Island, along the coast off central British Columbia, and offshore of the US Washington State and Alaska State. Tide-only and tide-dominant types occur in partially protected basins such as Queen Charlotte Sound and Dixon Entrance. Exceptions are northern Hecate Strait where wave-dominant and mixed disturbance types are important, and the offshore of the northern tip of Vancouver Island where the mixed disturbance type dominates. Sediment mobilization in the Strait of Juan de Fuca mostly falls into the tide-dominant category. An unique pattern can be recognized in the Queen Charlotte Sound and Dixon Entrance where tide-only disturbance type occurs in the centre and the disturbance types change to tide-dominant or mixed types and eventually to wave-only and wave-dominant towards the shallower coastal areas.

On the Atlantic Shelf, sediment mobilization by tide-only occurs in most parts of the BoF, at the entrance to Hudson Strait, on Southeast Baffin Shelf, in Davis Strait and in the restricted seaways of the western Gulf of St. Lawrence. The tide-dominant category occurs on Georges Bank, western Scotian Shelf, in Northumberland Strait, and over eastern Davis Strait. The wave-only category is predicted for the Grand Banks, inner and mid-Scotian Shelf, on the inner shelf and outer shelf banks on Labrador Shelf, and over southern Gulf of St. Lawrence. Wave-dominant disturbance is less significant and occurs as perimeters around the mixed disturbance patches on the outer Scotian Shelf and on the southeastern Grand Banks. Mixed disturbance primarily occurs on the banks of outer Scotian Shelf. A clear transition from tide-only to tide-dominant then to mixed or wave-dominant and eventually to wave-only disturbance is seen from BoF, through western Scotian Shelf, to central and eastern Scotian Shelf and then to the Grand Banks. On the Arctic Shelf, wave only disturbance occurs in Beaufort Sea while tide only disturbance is predicted for the southern Arctic Archipelago. However, wave data were only

available for the Beaufort Shelf.

The statistics of the areas and percentages of shelf areas for each of the six disturbance types have been calculated and are given in Table 4 which shows that with the Arctic shelf excluded, tide-only disturbance occurs on 18% of the shelf and the tide-dominant type occurs on 8% of the shelf. Areas dominated by wave disturbances are larger, as wave-only disturbance occurs on 28% of the shelf and wave-dominant disturbance occupies 3% of the shelf (mostly on the southeastern Grand Banks). Mixed disturbance is relatively insignificant and only accounts for 3.5% of the shelf area. There are, however, significant differences among each individual shelves. Wave disturbance is relatively more important on the Atlantic shelf as wave-dominated disturbances account for 31% of the shelf area and tide-dominated disturbance types occur on 24% of the shelf. Tidal effects are more important on both the Pacific and the Arctic shelves. Tide-only and tide-dominant disturbance types occur on nearly 40% of the Pacific shelf, while wave-only and wave-dominant disturbance only accounts for 28% of the shelf. Because of the much smaller area in predominantly shallow waters, the unaffected area is the lowest and at 24% for the Pacific shelf. The unaffected area increases significantly to 41% for the Atlantic shelf, while most of the Arctic shelf (83%) is unaffected due to the year-round ice cover on most part of the Arctic shelf. However, this may not always be the case, for example in ice-minimum years like 2007, or with expected climate warming when the Arctic may have largely ice-free summers by 2060 (IPCC 2013; Melia et al. 2016).

Porter-Smith et al. (2004) also estimated the spatial distribution of the six disturbance types for the Australia shelves. They similarly found that wave disturbances account for ~30% of the Australia shelf area and that the mixed disturbance was insignificant. There are, however, several major differences between the Canadian and Australian shelves. The Australian shelf is largely tide-dominant as the tide-only and tide-dominant disturbance types combine to account for ~40% of the shelf area and wave disturbance accounts for only 30% on the Australian shelf. The Canadian continental shelf is largely wave-dominant as wave-only and wave-dominant disturbance accounts for 31% of the shelf area and the combined tide-only and tide-dominant disturbance types occur on only 25% of the shelf. The disturbance by waves occurs nearly completely as wave-only type and the spatial extent of the wave-only and the tide-only

disturbance regions are mutually exclusive on the Australian shelf. In contrast, disturbance by waves on the Canadian shelf occurs in both wave-only and wave-dominant disturbance types. The changes from tide-only and tide-dominant disturbance types to wave-dominant disturbance are also more transitional on the Canadian continental shelves as demonstrated in Queen Charlotte Sound on the Pacific shelf and on the southern Atlantic shelf.

4.3 Universal Indices of Seabed Disturbance and Sediment Mobility

The effectiveness of oceanographic processes in impacting the seabed and shaping 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. 11 quantifies only the magnitude of the mean combined-flow bed shear stress and does not reflect the effect of how often shear stresses with various magnitudes occur. For instance, the influence of extreme storm events, which produce maximum shear stresses and hence, the greatest impact on the benthic community, but occur rarely, is limited when the mean combined-flow bed shear stress is averaged over one or several years. In contrast, the threshold exceedance map of Figure 12 demonstrates how often the combined wave-current shear stress causes mobilization of sediment on the Canadian continental shelves, but reveals no information about how strong the mobilization is. Consequently, indices that incorporate the effect of both magnitude and frequency of these processes are needed to better quantify the exposure of the seabed to oceanographic processes and sediment mobility 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. Also the parameters have been arbitrarily categorized based on the range of parameter values only from the Australian shelf. Therefore they cannot be readily used to quantify seabed disturbance and sediment mobility levels on other shelf regions of the world.

Two ‘universal indices’ are suggested here that can be used to quantify the level of seabed exposure to oceanographic processes and the levels of sediment mobilization on any continental

shelf of the world. The first one is termed Seabed Disturbance Index (SDI) and is adopted from Hemer (2006): SDI is defined as the maximum value of $\tau_{cws}^{1.5} P$. Here τ_{cws} is the skin-friction combined wave-current shear stress ($= \rho u_{cws}^2$) 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 of whether 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 percentage of threshold exceedance (i.e. SMF of Fig. 12). The time percentage of threshold exceedance is the time percent that the combined-flow shear stress τ_{cws} exceeds the critical shear stress for sediment transport initiation τ_{cr} . 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 SDI map of Fig. 14 (Supplementary Fig. S14) shows that high seabed disturbance (or exposure), showing values up to 1.2 – 1.4, occurs in the tide-dominated BoF, on Georges Bank, and on the shelf off Hudson Strait. Moderately high seabed disturbance with values of 0.6–0.8 is found on western Scotian Shelf, over small patches on SIB on central Scotian Shelf, over the northwest corner of Grand Banks, over patches of eastern Davis Strait, over the narrow and along the coast off northeastern Haida Gwaii in northern Hecate Strait, offshore at the northern tip of Vancouver Island, and in the Strait of Juan de Fuca. Moderate seabed disturbance with values of 0.3–0.5 is predicted for central Queen Charlotte Sound, over a patch on the inner shelf off central Vancouver Island, on the banks of outer Scotian Shelf, and on southeastern Grand Banks. Low seabed disturbance of 0.1 – 0.3 is found for Dixon Entrance, the remaining areas of Queen Charlotte Sound, the remaining areas of the inner shelf off Vancouver Island, in western Gulf of Maine, on inner and middle Scotian Shelf, in Gulf of St. Lawrence and over banks on the outer Northeast Newfoundland Shelf and Labrador Shelf, over patches in Baffin Bay, on the Beaufort shelf, and over the southern part of the Arctic Archipelago.

Significant changes can be recognized when the SDI map in Fig. 14 is compared with Fig. 11,

where only the magnitude of combined wave-current shear velocity is used to quantify seabed disturbance. According to Fig. 11, the strongest seabed disturbance will be assigned to the areas along the coast of Haida Gwaii in northern Hecate Strait and offshore at the northern tip of Vancouver Island as the values of combined wave-current shear velocity reach $5 \text{ cm} \cdot \text{s}^{-1}$ in these areas. When both magnitude and frequency of combined wave-current shear velocity is considered (Fig. 14), because of the effect of low frequency storms, only moderately high seabed disturbance (SDI values of 0.6–0.8) is predicted for these areas. Another difference is observed for the Grand Banks and eastern Davis Strait. With only the value of the combined wave-current shear velocity being considered (Fig. 11), seabed disturbance is defined as moderate for both of these areas as mean combined-flow shear velocity reaches $2\text{--}3 \text{ cm} \cdot \text{s}^{-1}$. Since Davis Strait is dominated by high-frequency tidal energy while the Grand Banks is dominated by low-frequency storms, the values of SDI categorize eastern Davis Strait as moderately high but the disturbance on the Grand Banks is characterized as only moderate .

The spatial distribution of SMI on the Canadian continental shelves is shown in Figure 15 (Supplementary Fig. S15). High mobility indices of 1.6–2 occur in the BoF, on Georges Bank and western Scotian Shelf, at entrance to Hudson Strait, along the coast off northeastern Haida Gwaii Islands, and offshore at the northern tip of Vancouver Island. Moderately high sediment mobility indices of 1–1.4 are found on SIB and in the Strait of Juan de Fuca. Moderate mobility, with values of 0.5–0.8, is predicted for southeastern Grand Banks, the banks of the outer Scotian Shelf, eastern Davis Strait, central Queen Charlotte Sound, and along the coasts off western Vancouver Island and Washington States. Low SMI values of 0.1 – 0.5 occur on the remaining areas of the Grand Banks, in Gulf of St. Lawrence, along the coast of Labrador Shelf, in the remaining areas of Davis Strait, in Dixon Entrance, in southern Hecate Strait and northern Queen Charlotte Sound, in patches on the shelf off Vancouver Island, in Beaufort Sea, and over southern part of the Arctic Archipelago. Notably, zero to minimal sediment mobility is predicted for southeastern Queen Charlotte Sound, the Gulf of Maine, inner and middle Scotian Shelf, Northeast Newfoundland Shelf, southern Labrador Shelf, shelves around Baffin Bay, and most of the Arctic Archipelago.

The SMI map of Fig. 15 demonstrates significant differences from the threshold exceedance map

shown in Fig. 12 which only considers the mobilization frequency, not the magnitude. The topographic high of central Queen Charlotte Sound and the offshore area at the northern tip of Vancouver Island are both classified to have high sediment mobility, as medium sand can be mobilized nearly 100% of the time in these areas (Fig. 12). However, mean shear velocity reaches $5 \text{ cm} \cdot \text{s}^{-1}$ offshore at the northern tip of Vancouver Island (Fig. 11) but only reaches 2–3 $\text{cm} \cdot \text{s}^{-1}$ over central Queen Charlotte Sound. Thus the SMI map (Fig. 15), incorporating both the magnitude and frequency of sediment mobilization, categorizes the former as having moderately high mobility but the latter as having moderate sediment mobility. On the Atlantic shelf, western Scotian Shelf and the shelf area south of Hudson Strait entrance are both classified as having high mobility if only mobilization frequency is considered (Fig. 12). The map of mean shear velocity (Fig. 11) shows moderately high values of 3–4 $\text{cm} \cdot \text{s}^{-1}$ on western Scotian Shelf and only moderate value of 2.5 $\text{cm} \cdot \text{s}^{-1}$ for the shelf area south of Hudson Strait entrance. Therefore the SMI values calculated using both the magnitude and frequency of sediment mobilization would classify that potential sediment mobility is high on western Scotian Shelf but only moderate for the shelf area south of Hudson Strait entrance (Fig. 15).

The values of SDI range from 0 – 1.4 (Fig. 14) and that of SMI is from 0 – 2 (Fig. 15) on the Canadian continental shelves. 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. The mean grain sizes on the Australian shelf range from 0.02 – 5 mm with an overall mean of 0.9 mm, which is much coarser than the mean of 0.35 mm here used for the Canadian shelf. The mean combined-flow shear velocity on the Australian shelf ranges from 0.9 – 10 $\text{cm} \cdot \text{s}^{-1}$ which is comparable with the range on the Canadian shelves, although the maximum values are much higher (5–6 $\text{cm} \cdot \text{s}^{-1}$) on the Canadian shelves. Given these differences in the ranges of grain size and shear velocity values on the two continental shelves, the comparability of the ranges of SDI and SMI parameters attests to the robustness and universal applicability 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 respectively quantify the seabed exposure and sediment mobilization, incorporating both the frequency and magnitude of the processes. These indices, together with the seabed disturbance

type regionalisation scheme (shown in Fig. 13), potentially can be used as standard parameters to best quantify seabed disturbance and sediment mobility on other shelves of the world.

4.4 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 Scotian Shelf to gain insight on how seabed disturbance from this study correlates with sediments and grain size distribution on a continental shelf scale. The combined wave-current shear velocity (Fig. 11) and sediment mobilization frequency (Fig. 12) both indicate that seabed shear and sediment mobility are very high in the BoF and on Georges Bank and western Scotian Shelf. These energetic regimes would imply that fine sediments would be winnowed away leaving coarse-grained lags in these areas. These are corroborated by the distribution of glacial till that has been winnowed to form a sandy gravel lag in the BoF and of the gravelly sand and sandy gravel (the Sable Island Sand and Gravel and the Sambro Sand) on Georges Bank and western Scotian Shelf (Fader et al. 1991; Shaw et al. 2012 and 2014; also Fig. 4H of Kostylev and Hannah 2007). On the contrary, quiescent conditions of low shear stress and threshold exceedance are predicted for the Gulf of Maine, inner and middle central and eastern Scotian Shelf, and the Laurentian Channel. Indeed these areas are dominated by the distribution of fine-grained Lahave Clay and Emerald Silt materials; the latter locally may contain minor components of sand or gravel due to winnowing and erosion.

Kostylev and Hannah (2007) produced a 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. The seabed disturbance and sediment mobility results from our study are evaluated against the results of Kostylev and Hannah (2007) to illustrate the similarity and differences between these studies and what improvements have been made. The seabed shear stress and scope-for-growth maps for the Scotian Shelf and the eastern

Gulf of Maine (Figs. 4 and 5 of Kostylev and Hannah 2007) show a broad-scale, east-west gradient of increasing scope for growth while the disturbance produces a complex spatial pattern which generally shows stronger total shear stress on the outer-shelf banks on eastern Scotian Shelf and relatively lower stress in the BoF and on parts of Georges Bank and western Scotian Shelf. The present study has produced considerably different patterns of seabed disturbance. The maps of combined wave-current shear stress (Fig. 11) and SDI (Fig. 14) show that while moderately high shear stress and SDI are predicted on the outer shelf banks on eastern Scotian Shelf, the highest shear stress and seabed disturbance occur in the BoF 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 a skewed effect of waves and hence highest shear stress on the outer shelf banks where waves are significantly stronger (Fig. 3). Our study used time-series data of both tidal current and waves and thus weighted effects for waves and tidal currents equally. Due to the same reasons of skewed emphasis on extreme waves and discounted weighting of high-frequency tidal currents applied in Kostylev and Hannah (2007), their modelling results show different correlation between bed shear stress and grain size distribution on the Scotian Shelf. Relatively low values of total shear velocity are estimated for middle and lower BoF, on Georges Bank and Western Scotian Shelf. Yet surficial substrates of these areas are coarse grained gravelly sand and sandy gravels (Fader et al. 1991; also Fig. 4H of Kostylev and Hannah 2007). Highest values of total shear velocity are predicted for the outer shelf banks on eastern Scotian Shelf. However, these Banks are actually dominated by relatively finer sediments (fine to medium sand) compared to Georges Bank and western Scotian Shelf. Despite these differences, the quantification of seabed disturbance on the continental shelves of Canada presented here, combined with the Canada-wide scope-for-growth estimates in Kostylev et al. (2015), may provide a basis for creating a benthic habitat map for the entire Canadian continental shelf following the approach of Kostylev and Hannah (2007).

4.5 Other processes and future improvements

The approach of this study, using model predictions of seabed disturbance and sediment mobilization, only considered wave and tidal current processes. Effects of strong wind-driven

currents of storms and persistent ocean circulation currents are not included. Depth-averaged tidal currents were taken as near-bed tidal currents and this may over-estimate the effects of tides. In addition, stratification 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) and in canyons and on the shelf break on Scotian Shelf (Li et al. 2019). Due to poor coverage of observed grain size data, a uniform mean grain size of 0.35 mm was used in this study. In future efforts, high-frequency storm-induced currents and background circulation currents should be added. Near-bottom currents from 3-D current models should be used to more adequately predict the effect of currents, and observed grain size data should be used to more truthfully model the sediment mobilization intensity. Sea-ice coverage is changing rapidly in response to climate change. Therefore, our results probably underestimate wave influences in the Arctic and along the Atlantic coast (e.g. Wang et al. 2018). Our estimates are based on ice conditions for the period 2002 to 2005 and likely do not represent current conditions.

5. Conclusion and summary

Wave hindcast data and model-predicted tidal current data for a 3-year period were used in a combined-flow sediment transport model to estimate the seabed shear stresses from various oceanographic processes and the mobilization of uniform medium sand on the Canadian continental shelves. Although the study was done in 2005-2008, the results are valid and of significance as we have established the first national framework for the magnitude and frequency of seabed forcing and sediment mobilization by waves, tidal currents, and combined waves and tidal current on the continental shelves of Canada. These modelling results will also improve the available shelf-scale quantitative analyses of sediment mobilization and dominant mobilization processes of the world's continental shelves.

The Canadian continental shelves are affected by strong waves and tidal currents. Maximum significant wave heights are respectively 15 m and 12 m over the open ocean of the Atlantic and Pacific shelves. Mean tidal current speed often is $>1 \text{ m}\cdot\text{s}^{-1}$ in coastal bays and on outer shelf banks. The strong waves and tidal currents produce mean bed shear velocity $> 5 \text{ cm}\cdot\text{s}^{-1}$ and

bottom sediments can be mobilized >50% of the time over many areas and nearly 100% of the time for some areas on the Canadian continental shelves. When processes are considered independently, our models predict that waves are capable of mobilizing medium sand at least once during the modelled 3 year period over 50% of the shelf area while tides cause sediment mobility over 36% of the shelf area. Therefore mobilization of sediments is dominantly by waves on the Canadian continental shelves. Our modelling results also demonstrate that waves and tidal currents interact non-linearly to result in enhanced combined wave-current shear velocity that can be two times greater than either the wave or current shear velocity and further increase bottom sediment mobilization to over 68% of the shelf area. Assessments of seabed disturbance and sediment mobilization on continental shelves therefore must account for the effect of this enhanced combined-flow shear stress.

Quantitative estimates of the spatial relative importance of wave and tidal current disturbances were used to classify the continental shelves of Canada into six disturbance types which demonstrate complex distribution patterns. Two universal indices, Seabed Disturbance Index (SDI) and Sediment Mobility Index (SMI), have been proposed to quantify the exposure of the seabed to oceanographic processes and the mobilization of sediment incorporating the effect of both the magnitude and frequency of these processes. This advantage and the conformity of the values of these indices on the Australia and Canadian continental shelves suggest that the proposed SDI and SMI, 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.

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Table 1. List of tidal constituents for various tidal models used in this study. Except the OSU global model, all the regional models are from the Webtide models.

Model	Tidal constituents
Northeast Pacific	M2, N2, S2, K1, O1, K2, Q1
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

Table 2. Variation of input values of current speed U_{100} (cm s^{-1}), significant wave height H_s (m), grain size D (mm), and modelled combined shear velocity u_{*cws} (cm s^{-1}) and sediment mobilization frequency SMF (% of time), and change percentages of u_{*cws} and SMF for sensitivity test cases described in text.

Case 1

U_{100} bias	u_{*cws}	SMF	u_{*cws} change (%)	SMF change (%)
-10	1.6	39.5	-18.0	-35.8
-5	1.77	48.4	-9.2	-21.3
0	1.95	61.5	-	-
5	2.15	76.2	10.3	23.9
10	2.37	86.6	21.5	40.8

Case 2

H_s bias	u_{*cws}	SMF	u_{*cws} change (%)	SMF change (%)
0.13	1.99	62.7	2.1	2.0
0	1.95	61.5	-	-
-0.33	1.86	58.3	-4.6	-5.2

Case 3

D	u_{*cws}	SMF	u_{*cws} change (%)	SMF change (%)
0.016	1.62	59.4	-16.9	-3.4
0.18	1.85	76.6	-5.1	24.5
0.35	1.95	61.5	-	-
0.7	2.09	43.8	7.2	28.8

Table 3. Threshold exceedance of medium sand by tides, waves, and combined wave-tide on the continental shelves of Canada.

Process	Atlantic Shelf		Pacific Shelf		Arctic Shelf		All Shelves		All Shelves excl. Arctic	
	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf
Shelf area	1,342,000		129,930		809,480		2,281,410		1,471,930	
Tide	463,630	34.6	74,928	57.7	110,220	13.6	648,780	28.4	538,558	36.6
Wave	660,150	49.2	76,115	58.6	52,535	6.5	788,800	34.6	736,265	50.0
Combined	896,050	66.8	112,050	86.2	161,480	20.0	1,169,580	51.3	1,008,100	68.5

Table 4. Area and percent of total shelf area for various disturbance categories on the continental shelves of Canada.

Disturbance Type	Atlantic Shelf		Pacific Shelf		Arctic Shelf		All Shelves		All Shelves excl. Arctic	
	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf	Area (km ²)	% of Shelf
Shelf area	1,342,000		129,903		809,480		2,281,410		1,471,930	
Tide-only	226,690	16.9	37,132	28.6	93,103	11.5	356,925	15.6	263,822	17.9
Tide-dominant	98,059	7.3	14,152	10.9	171	0.02	112,382	4.9	112,211	7.6
Wave-only	376,390	28.1	31,619	24.3	45,901	5.7	453,910	19.9	408,009	27.7
Wave-dominant	42,636	3.2	5,167	4.0	502	0.06	48,305	2.1	47,803	3.3
Mixed	42,155	3.1	8,874	6.8	447	0.06	51,475	2.3	51,029	3.5
Unaffected	549,960	41.0	31,160	24.0	669,150	82.7	1,250,270	54.8	581,120	39.5

List of Figure Captions

Figure 1. Map of Canadian continental shelves showing colored bathymetry of the modelling domains and geographic locations cited in the text. Grey lines represent depth contours of 500, 1000, 2000 and 3000 m respectively. Large topographic regions have been labeled. Numbered geographic locations are 1 Georges Bank, 2 Sable Island Bank (SIB), 3 Northumberland Strait, 4 Flemish Cap, and 5 Hudson Strait. The bathymetry data are originally from Etopo2 (<https://www.ngdc.noaa.gov/mgg/global/etopo2.html>). Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S1.

Figure 2. Maps of sea ice concentration on Canadian continental shelves showing (a) maximal coverage for winter conditions and (b) minimal coverage for summer conditions over the modelled period of 2002-2005. Matlab program was used to create the map.

Figure 3. Spatial distribution of mean significant wave height (H_s , m) on the Canadian continental shelves. Matlab program was used to create the map.

Figure 4. Spatial distribution of mean spectral peak wave period (T_p , s) on the Canadian continental shelves. Matlab program was used to create the map.

Figure 5. Spatial distribution of (a) mean and (b) maximum wave power (P_w , $W\ m^{-2}$) on the Canadian continental shelves. Matlab program was used to create the map.

Figure 6. Spatial distribution of mean wave shear velocity on the Canadian continental shelves. Grey lines represent depth contours of 500, 1000, 2000 and 3000 m respectively. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S6.

Figure 7. Spatial distribution of wave threshold exceedance of medium sand (time%) for the Canadian continental shelves. Grey lines are as defined in Figure 6. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S7.

Figure 8. Spatial distribution of mean depth-averaged tidal current speed on the Canadian continental shelves. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S8.

Figure 9. Spatial distribution of mean tidal current shear velocity on the Canadian continental shelves. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S9.

Figure 10. Spatial distribution of tidal threshold exceedance of medium sand (time%) on the Canadian continental shelves. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S10.

Figure 11. Spatial distribution of mean combined wave-current shear velocity on the Canadian continental shelves. Matlab program was used to create the map. A high-resolution image of this

figure is given in Supplementary Fig. S11.

Figure 12. Spatial distribution of threshold exceedance of medium sand (time%) by combined wave and tidal current on the Canadian continental shelves. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S12.

Figure 13. Spatial distribution of the seabed disturbance types on Canadian continental shelves. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S13.

Figure 14. Spatial distribution of Seabed Disturbance Index (SDI) on Canadian continental shelves. See text for definition of SDI. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S14.

Figure 15. Spatial distribution of Sediment Mobility Index (SMI) on Canadian continental shelves. See text for definition of SMI. Matlab program was used to create the map. A high-resolution image of this figure is given in Supplementary Fig. S15.

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200x131mm (300 x 300 DPI)

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163x216mm (300 x 300 DPI)

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