

Article

Downscaling Future Longshore Sediment Transport in South Eastern Australia

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Abstract: Modelling investigations into the local changes in the shoreline resulting from enhanced atmospheric greenhouse gas concentrations and global climate change are important for supporting the planning of coastal mitigation measures. Analysis of Global Climate Model (GCM) and Regional Climate Model (RCM) simulations has shown that Lakes Entrance, a township located at the northern end of Ninety Mile Beach in south-eastern Australia, is situated in a region that may experience noticeable future changes in longshore winds, waves and coastal currents, which could alter the supply of sediments to the shoreline. This paper will demonstrate a downscaling procedure for using the data from GCM and RCM simulations to force a local climate model (LCM) at the beach scale to simulate additional nearshore wind-wave, hydrodynamic and sediment transport processes to estimate future changes. Two types of sediment transport models were used in this study, the simple empirical coastline-type model (CERC equation), and a detailed numerical coastal area-type model (TELEMAC). The two models resolved transport in very different ways, but nevertheless came to similar conclusions on the annual net longshore sediment transport rate. The TELEMAC model, with the Soulsby-Van Rijn formulation, showed the importance of the contribution of storm events to transport. The CERC equation estimates more transport during the period between storms than TELEMAC. The TELEMAC modelled waves, hydrodynamics and bed-evolutions are shown to agree well with the available observations. A new method is introduced to downscale GCM longshore sediment transport projections using wave-transport-directional change parameter to modify directional wave spectra. We developed a semi-empirical equation (NMB-LM) to extrapolate the ~3.7-year TELEMAC, storm dominated transport estimates, to the longer ~30-year hindcast climate. It shows that the shorter TELEMAC modelled period had twice as large annual net longshore sediment transport of the ~30 year hindcast. The CERC equation does not pick up this difference for the two climate periods. Modelled changes to the wave transport are shown to be an order of magnitude larger than changes from storm-tide current and mean sea level changes (0.1 to 0.2 m). Discussion is provided on the limitations of the models and how the projected changes could indicate sediment transport changes in the nearshore zone, which could impact the coastline position.

Keywords: longshore transport; climate change; downscaling

1. Introduction

Investigating and predicting changes in the shoreline is important for supporting the planning of coastal mitigation measures for public and private infrastructure from severe storms—particularly under the influence of anthropogenic climate change [1].

When waves approach the coastline at an oblique angle, they dissipate in the shallowing water and create a force in the direction parallel to the shoreline, which—if strong enough—can result in

longshore sediment transport. Longshore sediment transport is a combination of; (1) longshore currents driven by these depth-induced wave forces, as well as tidal and wind driven flow and; (2) beach drift from the swash action of individual waves running up and falling down the coastline at an angle in a zig zag pattern.

Sea level rise has been considered the defining driver of coastline change with long-term climate change since the inception of the simple assumption of maintaining the cross-shore profile [2]. While important, some recent regional studies have shown longshore transport to be more important to barrier erosion than sea level rise, e.g., for the Danish North Sea coast [3], and on the Florida coast in the United States of America, where [4] found that coastlines have advanced (accreted) instead of retreated at a rate attributable to recorded sea level rise.

The study site, Ninety Mile Beach (NMB) is a 144 km long sandy barrier dune system that is located in south-eastern Australia (Figure 1). At the eastern end of the beach is a man-made ocean entrance to the Gippsland Lakes located at the township of Lakes Entrance. Previous studies have shown that Lakes Entrance is situated in a region that may experience noticeable future changes in longshore winds, waves and currents, which could alter the supply of sediments to the shoreline [5]. The study site has significant financial and environmental value [6].

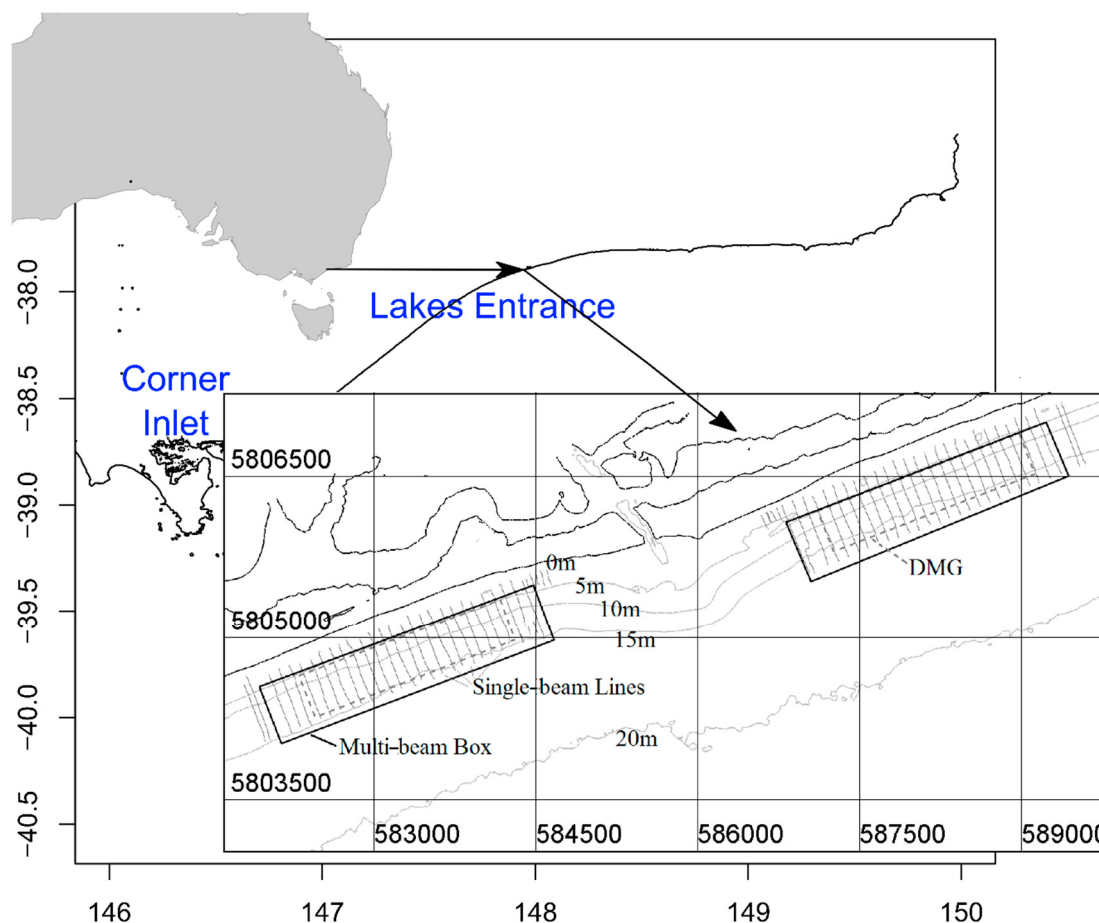


Figure 1. Map of Ninety Mile Beach in southeastern Australia (nautical coordinates) with an overlay of Australia (top right) and an insert of bathymetric surveys at Lakes Entrance (bottom right, WGS84 zone 55 coordinates). The insert of Lakes Entrance provides examples of the single-beam transects (cross-shore lines separated by 100 m) and multi-beam survey area (thick black box) at both the west and east dredge material grounds (DMG) sites (grey dashed box).

The goal of this study is to better resolve the present-day longshore transport climate by setting-up sediment transport models of different complexity. Nearshore wave and hydrodynamic processes are

not resolved in Global Climate Model (GCM) simulations, so downscaling methods are required to conduct climate change analysis near the shoreline (e.g., [7,8]). We first validate a detailed numerical model which we then use with empirical models to investigate the downscaled longshore transport climate of a high impact future greenhouse gas (GHG) scenario. This is done to understand the contribution of waves, currents and sea level rise to future changes to the coast. In the following section (Section 2) a review of sediment transport modelling is provided, followed by a review of downscaling methods. Sections 3 and 4 describe the data and modelling methodology applied for our study for NMB and Sections 5 and 6 provide the results, discussion and conclusions of the study.

2. Methodological Review

2.1. Longshore Sediment Transport Models

One line empirical equations—which are derived from regression analysis of measured sediment transport—have been used to find the simplest relationship (or pattern of behaviour) between sediment transport and wave and current parameters (e.g., [9–14]). The limitation for some empirical equations, for example, is that they have been calibrated to locations where transport is almost exclusively controlled by waves and therefore do not account for coastal (tide and storm) current parameters (e.g., [15]). These equations may underestimate the contribution of wind- and tide- driven currents when applied to regions of strong tide and storm surge currents [11].

Coastal numerical sediment transport models including fluid dynamic processes (e.g., Navier Stokes equations), were originally developed for river flows. Since the 1980s, these models have been applied to the coastal ocean domain with the important inclusion of surface gravity wind-wave effects [16]. These coastal sediment transport models, typically implemented in sizable software packages, employ computational fluid dynamics, through numerical computations of partial differential equations (PDEs) on a horizontal grid, to solve both the longshore and cross-shore dynamics (e.g., ADCIRC, ROMS, MIKE-21, XBEACH and TELEMAC see model comparison in [17]). The main advantages of these coastal area models are that the hydrodynamic flow and waves are more accurately resolved, and that the sediment budget can be balanced over the entire coastal area. Coupled models can take on the challenge of the most complex hydrodynamic processes in the nearshore region, in particular, the effect of depth-induced wave breaking. When ocean waves enter the nearshore region, they feel the shallowing depths and steepen as they slow down—until they eventually break. Along with generating turbulence, the effect of this breaking results in a stress applied to the water column, causing rips- and longshore-currents which scatter sediment particles [18,19]. Superimposed on the mean coastal current circulation field is the orbital motion of waves—which can mobilise sediments. Wave orbital motion occurs at the sub-grid-scale for practical model applications, and is typically formulated from linear wave theory [20]. The modelling of sediment transport is dependent on the flow or stress (quadratic flow/stress law) exceeding a critical threshold to mobilise sediments. For this reason, the coincidence of strong wave orbital flow with wind-, wave- and tide-driven currents above a critical flow threshold will result in sediment transport. For practical application of numerical models, sediment transport typically occurs at the sub-grid scale. Therefore, they require parameterisation from empirical equations, similar to all types of sediment transport models with varying complexity. Other models with reduced numerical complexity, i.e., models that do not simulate the detailed PDEs such as the Navier-Stokes equations, have shown to replicate long term shoreline change [21–23].

The choice of model complexity depends on the scale of study and what processes need to be resolved, from beach change due to individual storm event to the evolution of a coastline including climate change impacts. The choice of model also depends on the complexity of the coastline, from a simple uniform sandy beach, to a coastline with longshore hard structures (breakwaters and groins), to tidal basins, mega-renourishment and land reclamations. Careful consideration must be made regarding the type of model to use and the value of resources allocated to running the model so as to make efficient predictions or to study detailed processes.

In this study, the CERC energy flux equation is investigated as it has been widely used for this location—including the dredging program at the field site [24] and a previous study on GCM-derived transport changes [5]. The TELEMAC coastal area type model is used in this study for personal preferences, as it is open source; has unstructured grid configuration; all model packages (wave-hydrodynamic-sediment) have two-way coupling and it has high quality code formatting conventions across all files within the system and detailed model documentation with an active user community forum. The TELEMAC suite of models has been shown to provide similar results to the proprietary Mike-21 model for the Italian coast [25]. An example of TELEMAC's ability to simulate multiyear, decadal and longer timescales has been studied for the German coastline [26]. Climate change downscaling of RCMs with TELEMAC has been conducted for the English coast [27]. These regional studies demonstrate the variety of approaches, high degree of empiricism and challenges of modelling long-term sediment transport with limited computational resources.

2.2. Downscaling

Investigation of future projected GCM impacts at the local scale requires some method of modifying and refining the large-scale gridded GCM predictions down to the small-scale—a process known as downscaling [28,29]. The downscaling of wind, waves and hydrodynamics has been previously reviewed by [30]. Figure 2 provides a flow chart of different approaches to downscaling the RCP radiative forced GCM data down to the local scale, where each method (path through the flow chart) has a different level of complexity, practicality and accuracy. The methods can be categorised into three different approaches described in the next subsections.

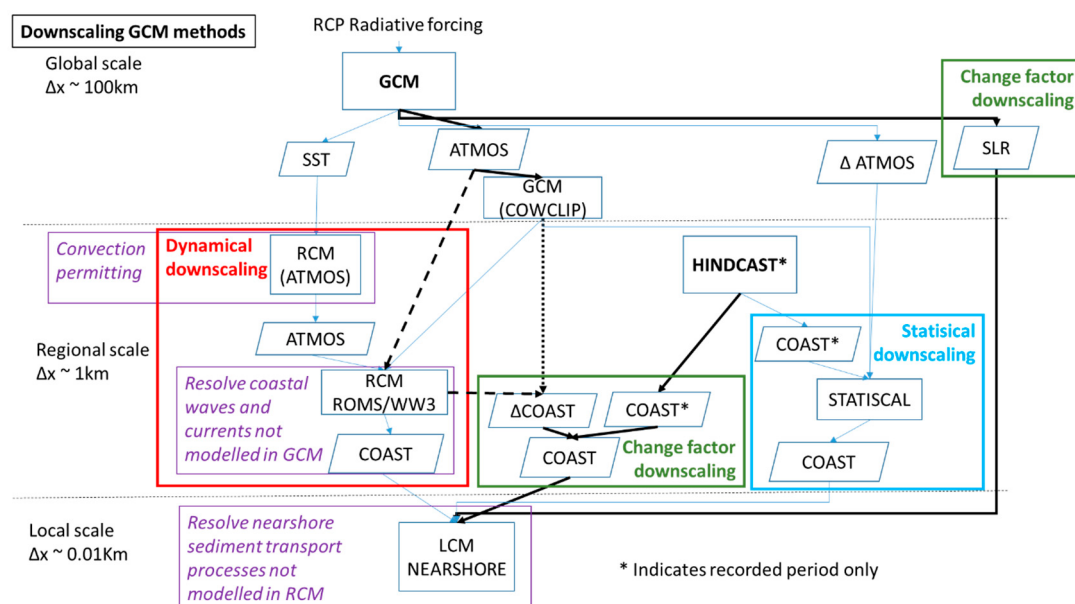


Figure 2. Flow chart of some possible methods for downscaling coastal (COAST) and nearshore (NEARSHORE) wave and current data. Boxed text indicates process (numerical or statistical models) and parallelograms indicated datasets (future and baseline periods). Black arrows indicate the method used in this study, solid for processing both wave and currents, dashed for currents only and dotted for waves only. Blue arrows indicate other possible downscaling methods not used in this study.

2.2.1. Dynamical Downscaling

Dynamical downscaling utilises a direct time series of gridded GCM output, usually bias-adjusted sea surface temperature (SST), to force a high resolution nested atmospheric circulation RCM (e.g., [31]). High resolution atmospheric RCMs can dynamically simulate internal processes such as atmospheric convection—which is otherwise parametrised in course resolution GCMs [32]. High resolution surface

winds from atmospheric RCMs have been used to force regional wave RCMs [7,33] and regional hydrodynamic RCMs [34]. Dynamic downscaling has also been used to describe the one-way-coupling of wave models run at the global scale of GCMs wind fields [35] to other wave models run at a higher resolution to resolve processes not simulated in the global model for coastal regions [36,37]. Statistically significant climate trends in the hydrodynamics have been found without the need for the atmospheric RCM dynamical downscaling step [38]. Models that run without the atmospheric downscaling step have the same limitations of the GCM, notably the inability to resolve the intensities of tightly structured storm systems such as tropical and extratropical cyclones. The dynamic downscaling of sediment transport modelling with a regional atmospheric model has been investigated for data poor and data rich locations and provides examples of where changes to wave-driven longshore transport will have a larger impact than changes to mean sea level [39,40]. Dynamical downscaling can produce an internally consistent model recreation/realisation of historic (baseline) and future climate changes at the expense of large computer resources to compute the simulations and store the datasets. While it is easy to comprehend that downscaled changes in wave height will have an impact on longshore transport, a review of the effect of wave direction changes on longshore transport projections for European coastlines highlights the relatively large impact that small projected changes in wave direction can have on longshore transport ([37] and references therein). Wave direction was identified as an important driver of erosion for a beach in south-eastern Australia [41]. A study for the coastline of France [37] used multiple GHG GCM simulations, and indicated that the inter-model variability between models with the same GHG pathway could be larger than the variability of a single model with different GHG pathway simulations. Longshore transport projections for the Spanish coastline also provided an example of how the inter-model variability of wave height and direction variables, are accentuated in terms of the single CERC transport variable [42]. Unfortunately, much of the analysis of future wave-climate change is somewhat limited to studies that focus on the parameter of significant wave height [43]. Future mean sea level projections are typically directly applied from global mean GCM output, but can be dynamically downscaled to resolve regional effects [44].

2.2.2. Statistical Downscaling

Statistical downscaling uses a simpler method by taking the observed spatial pattern of variability and then applying statistical techniques to infer local-scale changes from large-scale changes generated by GCMs. The statistical methods include regression models, weather typing and weather generators [29]. For example, waves have been statistically downscaled with a regression method for extreme value distributions [45] and hydrodynamics have been statistically downscaled with a regression model based on canonical correlation analysis [46]. The Lookup tables, clustering and hybrid methods that have been used to generate wave conditions for shoreline change can be considered to be aligned with statistical downscaling methods of weather typing and weather generators [21,47].

2.2.3. Change Factor (CF) Downscaling

The Change Factor (CF) downscaling method is the simplest method [48]. It takes a time series of the observed (measured or hindcast) climate and applies an offset based on the difference between the model's future and baseline mean periods. The CF method is usually a single value of change applied to the observed time series, but could also be applied as a seasonal or monthly mean change value.

Each of the downscaling methods has their upsides and limitations [29]. The CF method was chosen for our study of NMB because it allowed us to build on the previous analysis on the large scale changes [5] and because of the availability of regional climate and hindcast simulations. These regional hindcast simulations better capture the extreme weather forcing, where GCMs are known to do a poor job of resolving the intensities of tightly structured storm systems such as East Coast Low storm events, which can bring strong easterly winds to the region in the winter (e.g., [49,50]).

3. Datasets

All datasets and supplementary information are described in detail in the supporting dissertation paper [51]. A general overview is provided here for orientation of the analysis.

3.1. Wave and Hydrodynamic Measurements

Observations of the integrated spectral wave parameters of significant wave height (H_s), mean wave period (T_m) and mean wave direction (D_m) were measured from April 2008 to July 2012 by a directional wave buoy located 2 km off the coast at the Entrance to the Gippsland Lakes in the vicinity of the coastal current measurements in approximately 22 m of water.

Depth-averaged 3D coastal current and water level observations are available from 18 two-month deployments between April 2008 and September 2010. The measurements were from a bottom mounted Teledyne RDI Workhorse Sentinel Acoustic Doppler Current Profiler (ADCP) located at a depth of 21 m, 2 km off the coast at Lakes Entrance. The current meter was located in the vicinity of the wave buoy.

3.2. Regional Wave and Hydrodynamic Model Forcing Data

2D frequency and directional spectral wave data was sourced from the Centre for Australian Weather and Climate Research (CAWCR) WaveWatchIII (WW3) wave hindcast [52]. This dataset was simulated with the WW3 model, v4.08 at 4 arc-minute resolution around the Australian coast.

The hydrodynamic model (ROMS) simulated the depth-averaged tide and atmospheric forced currents and water levels around Australia at a 5 km resolution [53]. Change factor values for both the longshore wave and current transport projections for the HadGEM2-ES, ACCESS1.0, INMCM4 and CNRM-CM5 GCM projections were sourced from the analysis in [5].

3.3. Morphologic Measurements

Three types of bathymetric surveys were used in this study. An airborne LiDAR survey of the entire NMB seaboard was conducted from November 2008 to April 2009 and provided a 2.5 m resolution gridded elevation dataset over land to a depth of approximately 20 m [54]. As part of the ongoing dredging operations at Lakes Entrance, ten bathymetric depth single beam sonar surveys of two large rectangular Dredge Material disposal Grounds (DMGs) and bordering regions of the open coast were undertaken from June 2009 to March 2012 [24]. These 1 m surveys span ~2 km along the coast and extend from ~100 to ~800 m off the coast, framing the design DMG with a 100 m ribbon of extra survey area (Figure 1). One metre Multi-beam soundings superseded the single-beam surveys after 2011. They are available for both sites for five surveys, each between 2012 and 2013, and cover the domains shown in Figure 1.

Field work by [55] sampled marine sediments at Eastern Beach to show constant medium mean grain sizes of around 0.3–0.4 mm from the coastline to 10 m depth. From 10 to 20 m depth the grain size increases somewhat linearly to coarse mean grain sizes of around 0.8 mm at 20 m depth.

4. Methodology

As a general overview, the model simulations were run between the 15 surveys (10 single beam surveys and 5 multibeam). Each of the 14 simulations were initiated with updated survey bathymetry and forced at the ocean boundary by the hindcast datasets to create a ~3.7 years model dataset of the survey period. The simulations were then repeated with a change factor applied to ocean boundary conditions to simulate the future sediment transport climate. In the next three subsections the nearshore model setup is described, followed by the novel method for downscaling GCM derived longshore transport changes to directional wave spectrum and then a new semi-empirical equation to extrapolate the nearshore model to the ~30 year hindcast is presented.

4.1. Nearshore Numerical Local Climate Model

OpenTELEMAC, TELEMAC-MASCARET or just TELEMAC is a suite of finite element numerical programs to solve geophysical fluid dynamics [56]. Since January 2010, the software suite became open source and now has a strong community supporting it. A summary of TELEMAC's ability to model sediment transport is given in [57]. A detailed summary of the model setup used is described in [51]. Three programs from the TELEMAC (version 7.1r1) suite are required to model sediment transport in the nearshore region. The first is TELEMAC2D, used to model the flow hydrodynamics, the second is TOMAWAC, used to model the sea-swell waves and the third is SISYPHE, used to model sediment transport and seabed evolution. Figure 3 shows the design of the model coupling, boundary forcing and downscaling setup.

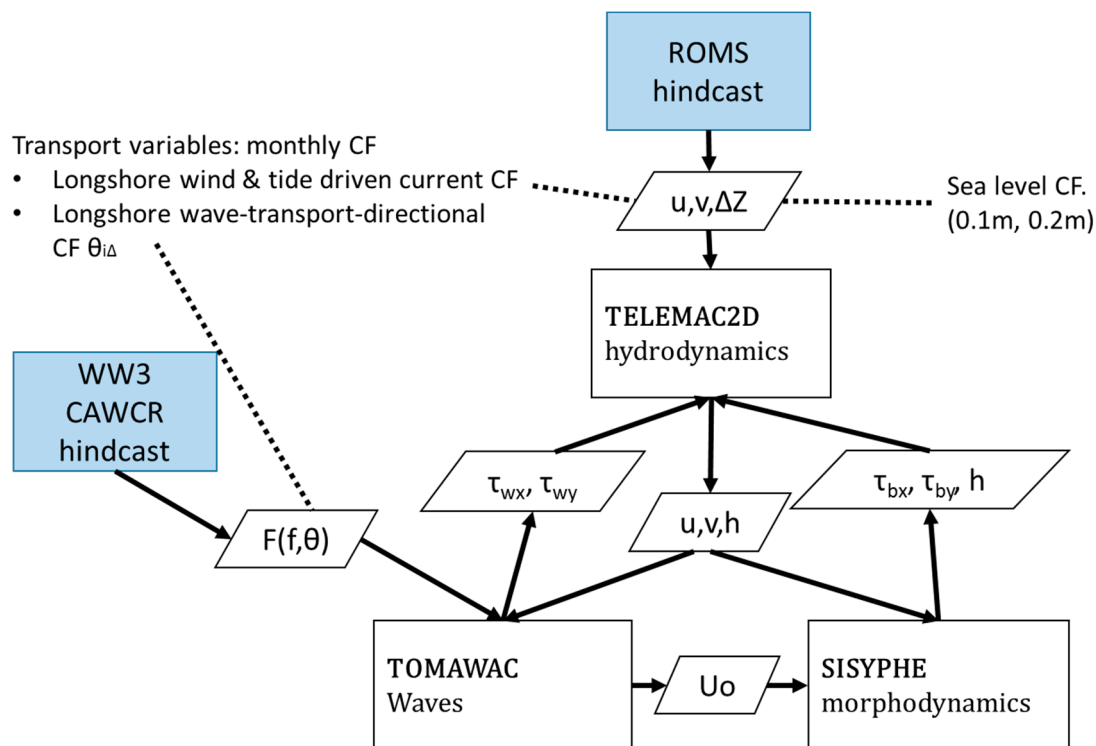


Figure 3. LCM Nearshore model configuration. The flow chart corresponds to the “LCM NEARSHORE” process at the bottom of Figure 2. Equation (1) was used to apply the CF downscaling method to both the ROMS hindcast longshore wind and tide driven currents and to rotate the WW3 2D spectrum by the wave-transport-directional CF. The addition of 0.1 or 0.2 m to the hindcast sea level simulated the effect of sea level rise.

The TELEMAC2D code solves depth-averaged free surface flow Navier-Stokes equations first solved by Saint-Venant [58]. Boundary conditions of water levels and currents were sourced from the 5-km-resolution, regional hindcast of storm tides around Australia using the ROMS hindcast [53]. Longshore coastal currents were generated within the grid by applying a longshore gradient in the water levels from two neighbouring ROMS grid points. Additionally, the flow was modified by prescribing flow velocities in and out of the boundary. In preliminary model setups, the coastal-current velocities and water levels were prescribed at all the boundary points, but yielded poor advection into the domain because the boundary was too constrained. In order to free up the flow constraint, the model source code was modified, to prescribed free flow boundaries depending on the down flow direction of the ROMS flow velocities.

Wave are resolved with TOMAWAC, a third generation spectral wave model [59]. The 2D spectral wave model TOMAWAC was forced at the open sea boundary by 2D (direction and frequency) spectral

output from WW3 hourly $\frac{1}{2}$ -degree gridded global wave hindcast. TOMAWAC provides four methods for parametrising depth-induced wave breaking. Sensitivity tests in [51] led to the selection of the frequently used equations in [60] model using the Miche criterion with a breaking parameter of 0.8 [61].

SISYPHE is used to parametrise transport estimates from input from the hydrodynamic and wave models and to then balance the transport and bed evolution with the Exner equation. For simplicity and efficiency, the Soulsby Van Rijn [62] formulations were chosen for this study because, among other things, they can be used to simply estimate the suspended-load contribution to the bed-load components of the total sand transport. To replicate the cross-shore varying sediment grain size described in [55], three sediment classes are defined. The populations of the three sediment classes were divided into two zones at the 12 m-depth contour. In waters shallower than 12 m, there were 50% fine sediment diameters ($d_{50,1} = 0.3$ mm) and 50% medium ($d_{50,2} = 0.4$ mm) sand grain sizes. In waters deeper than 12 m, there were 50% medium ($d_{50,2} = 0.4$ mm) and 50% coarse ($d_{50,3} = 0.8$ mm) sand grain sizes. Summing the sediment populations resulted in an initial D_{50} of 0.035 mm in waters less than 12 m and 0.6 mm in waters deeper than 12 m. A second combination of sediment classes was tested, but showed small internal model sensitivity compared to the different wave breaking parameterisation [51].

In the calibration process, the model was found to underestimate the surveyed seabed evolution. This difference could be explained by the use of constant horizontal viscosity $\epsilon_t = 10^{-6}$ across the model domain, where field studies have measured a value in the vertical direction ~ 100 times greater within the surf zone [63]. Kinematic viscosity ν has also been noted to be 100 times larger when there is sediment in the water column during large wave events [16]. With this underestimation of ν , the dimensionless grain size (D_*) in the Soulsby Van Rijn [62] formulae would be overestimated, leading to an underestimation of the suspended transport by a multiple of ~ 30 during large wave events. The increased eddy viscosity at the bed level would also impact bed load transport, which cannot be accounted for in the Soulsby Van Rijn transport equations. Hence, total sediment transport is scaled up to improve the model's ability to replicate the bed evolution surveys and represent an increased viscosity/diffusivity in the sediment transport model.

4.2. Change Factor Downscaling

GCM derived monthly change values were identified in [5]. Normalised climate monthly mean (accented with a bar over the variable) model anomalies ($\bar{A}$) were calculated as the difference between the monthly mean future ($\bar{F}_G$) 2081–2100 and baseline ($\bar{B}_G$) 1981–2000 GCM model output relative to the standard deviation of the baseline ($sd(\bar{B}_G)$) output, where

$$\bar{A} = (\bar{F}_G - \bar{B}_G) / sd(\bar{B}_G). \quad (1)$$

The downscale CF for the future longshore current forcing was found by rearranging Equation (1) and replacing the monthly climate model baseline mean ($\bar{B}_G$) with the hourly hindcast longshore current data (B_{HU}) and calculating the hindcast monthly mean standard deviation ($sd(\bar{B}_{HU})$). The boundary conditions for future longshore currents (Figure 3) are therefore defined by the following equation;

$$F_U = \bar{A} \cdot sd(\bar{B}_{HU}) + B_{HU}, \quad (2)$$

where F_U is the hourly time series of the imposed future longshore current speed and $\bar{A}$ is the GCM derived mean normalised anomaly for a given month [5]. The future current speeds were scaled to the hindcast longshore current vector on the prescribed flow boundary.

For waves, the CERC longshore wave transport equation was used for the CF downscaling (Equation (1)) and was sourced again from [5]. The CERC equation is a function of both the breaking wave height (H_b) and breaking incident wave direction (θ_{ib}) [15]. The CERC equation is written as;

$$Q_w(H_b, \theta_{ib}) = K_s H_b^{5/2} \sin(2\theta_{ib}) / 2, \quad (3)$$

$$K_s = \frac{0.023g^{1/2}}{(s-1)},$$

where $g = 9.8 \text{ m/s}^2$ is acceleration due to gravity and $s = 2.6$ is the ratio of sediment and water densities. Wave breaking parameters were not available, so H_b was assumed to have the value of the nearshore H_s . θ_{ib} was calculated from the nearshore mean wave direction (θ) clockwise from true north so that θ_i equals $\theta - \theta_N$, where θ_N is the angle of the shore normal.

2D wave spectra changes (with frequency and direction dimensions) were not available for GCM derived TELEMAC simulations. The GCM normalised wave change analysis was summarised by the single bulk CERC parameter of Q_w , which is a function of two parameters, H_s and θ_i [5]. For simplicity in the TOMAWAC model setup it is assumed that the change in the GCM derived CERC Q_w can be entirely defined by an offset in wave climate direction alone. We define the wave-transport-directional CF (θ_Δ) term to describe more than the simple change in the mean wave direction, as it takes into account changes in wave height to modify the longshore transport. For the future longshore wave transport, Equation (3) is written as the following;

$$F_Q = Q_w(H_{sH}, \theta_{iH} + \overline{\theta_\Delta}), \quad (4)$$

where F_Q is the hourly time series of future mean longshore wave transport resulting from the hourly input from the wave hindcast (H_{sH}, θ_{iH}) and the monthly mean offset in wave-transport-directional CF ($\overline{\theta_\Delta}$). Future longshore wave transport can be solved a second way. By using Equation (1) again, we can solve for the CF change applied to the hindcast;

$$F_Q = \overline{A} \cdot \text{sd}(Q_w(H_{sH}, \theta_{iH})) + Q_w(H_{sH}, \theta_{iH}) \quad (5)$$

where A is the GCM-derived mean normalised anomaly for a given month from Equation (1), $\text{sd}(Q_w(H_{sH}, \theta_{iH}))$ is the standard deviation of the monthly-mean longshore transport across each of the ~30 years. The monthly values of θ_Δ (Equation (4) substituted into Equation (3)) were found numerically by minimising (optimising) the absolute error between Equations (4) and (5). The optimisation method was implemented using the statistical software package R [64].

To generate the future rotated 2D wave spectrum boundary condition (Figure 3), the monthly mean $\overline{\theta_\Delta}$ was subtracted from the direction coordinate of the hindcast 2D wave spectrum. This spectrum (with the shifted direction coordinates) was then interpolated back onto the original direction coordinates.

Future climate simulations forced with sea level rise were achieved by simply adding the value of sea level increase to the boundary free surface water level data (Figure 3). Estimates of global mean sea level rise for the period 2081–2100—compared to 1986–2005—is likely (medium confidence) to be in the 5% to 95% range of projections from process-based models, which give 0.26 to 0.55 m for RCP2.6 and 0.45 to 0.82 m for RCP8.5 [65]. For RCP8.5, the rise by 2100 is 0.52 to 0.98 m with a rate during 2081–2100 of 8 to 16 mm year⁻¹. Increasing the water level by an additional one metre would result in a separation of the bottom sediment transport from the water surface waves within the 3.7 year climate simulation, whereas the natural climate sea level rise would gradually change over decades. Instead, future simulations included an instantaneous increase in sea level rise, which is less than the tidal amplitude.

4.3. Semi-Empirical NMB-LM Equation

The empirical CERC formulation (Equation (3)) was reformulated to include the effect of longshore wind- and tide-driven currents to better represent the transport modelled by TELEMAC. Once calibrated, the updated CERC equation (NMB-LM) was used to extrapolate the ~3.7 year TELEMAC hindcast simulation to the full ~30 year WW3 and ROMS hindcast datasets, to get a larger picture of the transport climate estimated by TELEMAC. It was then used with CF input wave and flow parameters to estimate the effect of climate change on the longer ~30 year hindcast. The reformulated empirical flow equation was composed of the following;

$$Q_{wu} = D_1 K_s H_s^{D_2} \frac{\sin(2\theta_i D_3)}{2} + D_4 U_l |U_l| \left| D_1 K_s H_s^{D_2} \frac{\sin(2\theta_i D_3)}{2} \right|, \quad (6)$$

where D_1 , D_2 , D_3 and D_4 are the calibrated values and U_l is the longshore current velocity, positive (negative) eastward (westward). The parameters of D were found by minimising (optimising) the absolute error between the simulated longshore transport of TELEMAC (with 2D spectral input) and Equation (6) (with the bulk WW3 parameters). The optimisation method of [64] implemented in the statistical software package R, was used.

The first term on the right of Equation (6) is the CERC equation scaled by D_1 and has H_s changed from the power of 5/2 to D_2 . Different expressions of the power of H_s have been explained by [13,66]. The power of H_s was increased because the CERC equation predicted more transport than TELEMAC during low wave conditions compared to large wave conditions. The incident angle (θ_i) is also scaled down by D_3 because the offshore waves input in ~20 m of water has a greater incident angle to the coast than the required CERC wave breaking angle. The second term on the right of Equation (6) is the product of the longshore current U_l , a scale parameter D_3 , the absolute value (magnitude) of U_l and the absolute value of the first term on the right (scaled CERC wave term). This formulation replicated the TELEMAC-derived transport, where the longshore flow (U_l) only had a significant effect when the wave transport is large.

5. Results

In the following three subsections, validation is provided for the TELEMAC sediment transport model, followed by comparison of the transport estimates from the TELEMAC model and the CERC and novel NMB-LM empirical equations and then the results from the novel downscaled method for climate change projections are presented respectively. Supplementary information is described in detail in the supporting dissertation paper [51].

5.1. TELEMAC Sediment Transport Model Validation

Morphodynamic model validation was undertaken by comparing the measured elevation change to the modelled bathymetric evolution between single-beam surveys for the first nine simulations (10 surveys over 33 months). The bathymetric change was compared between the model and the surveys in the vicinity of the storm trough (100–200 m from the coast) and storm bar (200–300 m from the coast) at both the west and east DMGs (Figure 1). The storm bar and trough are the most active features in the bathymetry. The calibrated model does a reasonable job of capturing the magnitude and direction (down/erosion or up/accretion) of bed evolution of the storm bar and trough in all but a few surveys (Figure 4). Any differences between model and observations could be a result of dredge disposal between surveys, the effect of the channel, or from under resolving the sediment transport forcing (e.g., 3D effects). The validation statistics on all data points results in a Pearson's R-value of 0.9, a P-value 6.2×10^{-14} and a standard error of 0.068 m.

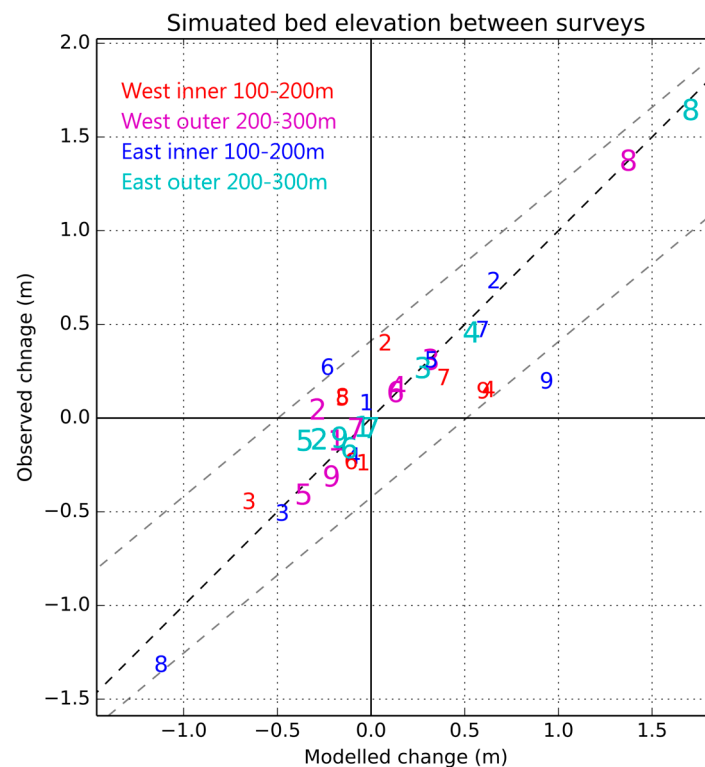


Figure 4. Model bed evolution validation in the location of the storm-bar and trough at both single-beam survey sites. Plotted are the model bed elevation median changes over the first nine simulations (10 surveys over 33 months). The dashed grey line is plus or minus one standard deviation of a linear fit to all data. The dashed black line is the one-to-one line.

5.2. Model Comparison

The time series plot of modelled longshore transport (Figure 5) shows that in the periods between storms, the CERC equation predicts more gross transport than the TELEMAC model. The same plot shows that during storms, the CERC equation predicts less transport than TELEMAC. Over the ~3.7 year period the cumulative/net effect of larger prediction by the CERC equation between storms and lower prediction during storms, balances out to match the TELEMAC storm-driven transport (Table 1). The reason for the difference between CERC and TELEMAC is the modelling regime, i.e., TELEMAC limits transport to occur only when the non-linear combination of coastal flow and orbital wave velocity is above a critical mobility velocity in the Soulsby Van Rijn equations. On the other hand, the CERC equation will predict transport for all wave heights and non-zero incident wave directions. The CERC equation is based on the work of [12] and was designed for a wave-dominated coast. The newly developed semi-empirical equation (NMB-LM) used to include the effect of currents modelled by TELEMAC is detailed in Section 4.3. The calibrated values of the NMB-LM model (Equation (6)) to the TELEMAC simulations are $D_{i=1:4} = \{0.30625, 5.65716, 0.07662, 2.77079\}$. NMB-LM matches the pattern of net longshore transport modelled by TELEMAC, differing in magnitude for only a few storm events (Figure 5).

The ~30 year hindcast forcing was applied to the NMB-LM and CERC models to predict the long-term annual transport rate (Table 1). The CERC equation predicts a similar annual transport modelled to the ~3.7 year bathymetric survey period, however the NMB-LM equation estimates only 50% of the transport in the shorter period because of the storm-driven transport modelling regime.

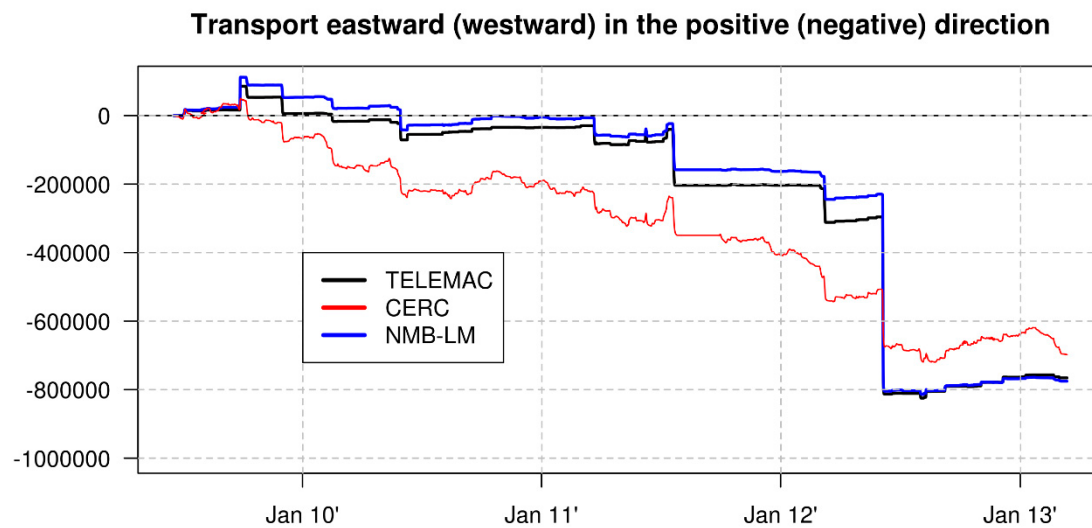


Figure 5. Time series of net longshore transport (m^3) from TELEMAC and empirical equations. On the vertical axis, positive (negative) values represent transport in the eastward (westward) direction.

Table 1. Net modelled longshore sediment transport rate Q estimates averaged per year.

Transport Per Year ($\text{m}^3 \text{m}^{-1} \text{year}^{-1}$)	TELEMAC	CERC	NMB-LM
~3.7 year TELEMAC survey simulation period	−211,598	−193,379	−214,308
~30 year hindcast ROMs period	Not resolved.	−206,494	−100,741

5.3. Downscaled Climate Change Analysis

Prior to analysing the wave transport change, the wave-transport-directional CF was first checked for correctness. The CERC-derived wave transport climate modelled with the wave-transport-directional CF in Equation (4), resulted in the same wave transport climate as that modelled with the normalised GCM wave transport anomaly and Equation (5). This confirms that the wave-transport-directional CF can account for the GCM-derived changes in wave transport. In other words, the wave-transport-directional CF can account for the added dependence in the changes in wave height. Also, the wave CF factor applied to the NMB-LM equation (Equation (6)) and then used to rotate the TELEMAC directional spectrum resulted in similar wave change climates.

The time series of baseline, net longshore sediment transport (m^3) climate (Figure 5), is replotted with the five CF climate sensitivity runs in Figure 6. It is difficult to numerically model a steady sediment transport (and bed evolution) simulation over long time scales, because of cumulative errors. Therefore, it is difficult to simulate the period of predicted gradual increased sea level rise by the end of the century (i.e., a 100 year simulation) to around 0.8–1.0 m predicted by high GHG future simulations. To stabilise the TELEMAC climate sensitivity simulations, the bathymetry was reset to the measured profiles to be consistent with the baseline simulations. The modelling here showed little impact (1.3%–2.1% change) on the longshore transport, for relatively large changes in sea level (0.1–0.2 m over ~3.7 years). The nonlinear influence of the increase in sea level means it difficult to extrapolate these changes out to the end of the 21st century (0.8–1.0 m) levels.

The TELEMAC and NMB-LM modelled transport rates are dependent on wind-tide-driven currents. The CF climate analysis in Figure 6 showed small sensitivity (1–2%) from the impact of changes from the wind-driven current forcing.

The TELEMAC derived wave CF simulation are shown to be the primary driver of change to future longshore transport (Figure 6). The wave CF projects a 51.1% decrease in net westward longshore transport. Over the same period the CERC and NMB-LM predicted a similar 49% and 46.6% decrease, respectively.

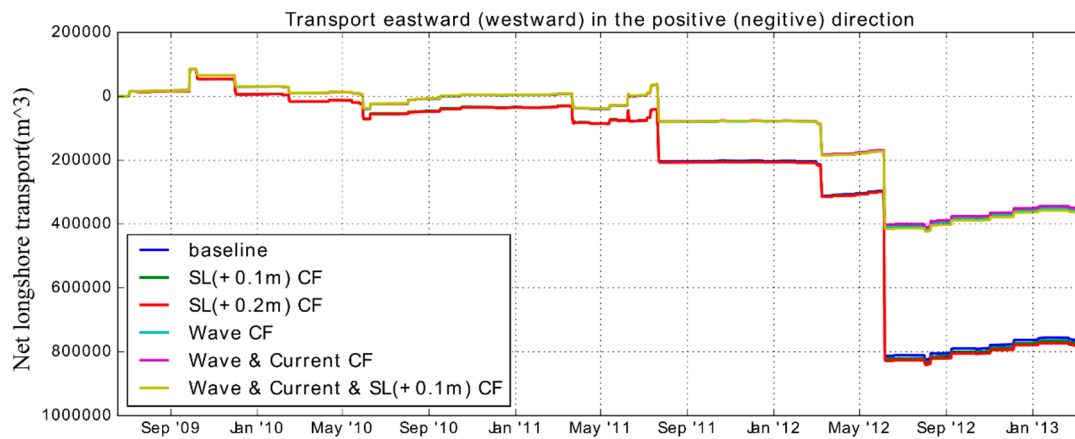


Figure 6. Time series of net longshore transport $Q_T\delta$ (m^3) from different TELEMAC downscaled climate change factor (CF) forcing. This plot has the same format as Figure 5. The legend indicates which change factor (CF) sensitivity forcing has been applied, along with the baseline transport. SL is the sea level increase (0.1 or 0.2 m).

The CERC and NMB-LM equations were used to estimate the four member ensemble model spread from the different GCM-derived wave transport changes [5]. The HadGEM2-ES predicts the largest change (95.7%), and the INMCM4 (−14.5%) the smallest change, but all projections suggest a decrease in the baseline westward transport by around 50% ($\pm 40\%$) [51].

Further investigation into the monthly contribution to the annual change value indicates June is the dominant contributor to the annual change [51]. Changes over the shorter modelled TELEMAC simulation period are similar to the CERC and NMB-LM climates for the same period and the longer hindcast period. However, analysis of the monthly contribution to the change suggests that shorter sediment transport simulations (3–5 years) are unable to accurately represent the longer climate (20 years) monthly change signal.

6. Conclusions and Future Work

This study presents a method for downscaling the GCM derived drivers of transport changes to investigate the sediment transport at a location that may be influenced by projected global circulation changes. Much of the analysis of future wave-climate change is somewhat limited to studies focusing on the parameter of significant wave height [43]. A new method is introduced to downscale GCM longshore sediment transport projections using the wave-transport-directional change parameter to modify directional wave spectra. The directional wave CF method was applied to the CAWCR hindcast in the TELEMAC simulations, checked against the empirically downscaled climate, and provided the same projected monthly transport climate results. The advantage the CF method has over the dynamically downscaled method is that the baseline variability and representation of extremes are better represented in the hindcast CF dataset than in the coarse resolution GCM datasets.

The TELEMAC coastal area-type model, CERC and new NMB-LM coastline-type models, predict a similar annual net longshore sediment transport of $\sim 200,000 m^3 year^{-1}$ westward over the bathymetric ~ 3.7 year survey period. Over the longer ~ 30 year wave and hydrodynamic hindcast period CERC predicts similar annual transport to the ~ 3.7 yr period, however, the NMB-LM predicts around half of the transport, $\sim 100,000 m^3 year^{-1}$. This is a similar value to the one used in the dredging program for the local port authority [24].

The CF downscaled sediment transport modelling predicts around a 50% ($\pm 40\%$) decrease in the westward net longshore sediment transport. The TELEMAC sediment transport climate simulations, predict a non-linear effect to increases in water levels (0.1 and 0.2 m). The sensitivity of the climate projections from the influence of increased sea level, results in only a 1% to 2% change in the transport.

Projected changes to wind-driven currents also resulted in a 1% to 2% change in the future projection of transport.

The main driver of the identified change is from the influence of wave-driven transport changes. The contribution from changes in individual months was also shown to be important [51]. While large normalised current change was captured in [5]—particularly in summer months when the subtropical ridge location (STR-L) is over NMB—the change associated with waves during the largest winter storms drive the overall transport climate. It is therefore difficult to directly associate the remote winter time STR-L position located to the north of NMB, with the overall identified transport change.

The TELEMAC modelled transport rates presented are dependent on wind-tide-driven currents. However the climate analysis showed small sensitivity (1% to 2%) from the timing, or normalised change, from the wind-driven currents. This study provides evidence of the weak secondary importance of changes to wind-driven currents compared to the dominant wave-driven transport in analysing the average change in sediment transport climate at NMB.

Sediment transport models have been applied to the nearshore coastal region since the 1980s. Today, there are several advanced numerical-based coastal area-type models, which are available to model sediment transport. Possible future additions to these models, are Lagrangian flow coordinates or adaptive grid-mesh. Arguably, more development is required on sub-grid scale parametrisations of processes such as wave asymmetry/skewness [67,68], bottom roughness [69–72]) and viscosity and diffusivity in the surf zone [16,63]. This requires more empirical measurements, which further highlights the need for continued measurements for the dredging program at Lakes Entrance.

Bringing together the modelling improvements, the ultimate aim is to be able to model complex, long-term, decadal sediment transport simulations and to run models that are able to resolve the variability and change, in the advance or retreat of the coastline position.

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