Marine Geology 257 (2009) 1–10

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Towards a calculation of organic carbon release from erosion of Arctic coasts using non-fractal coastline datasets

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ARTICLE INFO

Article history:
Received 11 July 2007
Received in revised form 4 October 2008
Accepted 11 October 2008

Keywords:
fractals
coastal erosion
shoreline
Arctic
carbon cycle

ABSTRACT

Changing environmental conditions in the Arctic will affect patterns of coastal erosion processes and thus modify the carbon cycle in the Arctic Ocean. To address this issue, a coastal classification of the Arctic was established to provide the first reliable estimate of organic carbon input from coastal erosion to the Arctic Ocean. The calculation relies on geomorphic parameters and the length of the coastline in the form of a line dataset used in geographical information systems (the World Vector Shoreline). The statistical self-similarity of Arctic shorelines (i.e. the fact that they exhibit similar features and hence different lengths at different scales) hampers the calculation process. Delineating the same section of shoreline at different spatial scales produces changes in the calculated length of the coastline and therefore in the volume of sediment released by up to 30% in some cases. The amount of change differs depending on the type and morphology of the coastline. The length of the World Vector Shoreline does not correlate well to any one scale and is inappropriate for use at the global level. Computations of erosion based on areas instead of lengths (i.e. buffers instead of shoreline lengths) provide a valuable yet simple substitute to the length-based method. Differences in quantities of eroded sediment are, on average, 70% less affected by scale changes when areas are used. Area-based methods are therefore recommended for circum-polar, computation-demanding, shoreline-based erosion calculations.

1. Introduction

1.1. Definition and role of arctic coastal erosion in the global system

Arctic coasts are highly sensitive to even small changes in their environment and are therefore vulnerable to the potential impacts of climate change. Thawing permafrost, sea level rise, changing sea ice conditions and increased wave activity interact synergistically and may result in accelerated rates of coastal erosion and thermokarst activity (the process by which characteristic landforms result from the thawing of ice-rich permafrost) in areas of ice-rich permafrost (Anisimov et al., 2007). In these regions, considerable quantities of nutrients are released in the nearshore zone by coastal erosion (Rachold et al., 2003a). According to Rachold et al. (2000), sediment input to the Arctic shelf resulting from erosion of ice-rich, permafrost-dominated coastlines may be equal to or greater than inputs from river discharge. Higher rates of coastal retreat will release greater quantities of organic matter contained in sediments to the nearshore zone. The fate of this organic carbon varies, for example it may enter local food webs and persist over most parts of arctic shelves (Aré, 1999; Wegner et al., 2003; Dunton et al., 2006). This could in turn result in complex and potentially dramatic changes in organic carbon pathways throughout the Arctic and organic carbon storage (Stein and Macdonald, 2003, p.21). Greater coastal erosion is also likely to lead to the release of greenhouse gases trapped in permafrost such as methane and carbon dioxide; it could also impact the entire food chain through the release of metals and/or contaminants in the nearshore zone and represent a threat to social infrastructure (Johnson et al., 2003; Rachold et al., 2003a).

Coastal erosion is the removal of land/sediment from shore–backshore area to the ocean due to wave action, sea level rise and/or anthropogenic intervention. It affects the entire shore profile, including the lower and upper shoreface and the backshore, and results from cumulative effects of several processes occurring at different spatial and temporal scales (Cowell et al., 2003). Short-term shoreline variability is associated mostly with seasonal to annual stochastic fluctuations in environmental conditions, while long-term shoreline changes are driven mostly by trends in sea level and sediment supply (Stive et al., 2002). Geomorphologically, short-term

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0025-3227/$ – see front matter
doi:10.1016/j.margeo.2008.10.004

coastal changes are generally detected in the upper shoreface and correlate with changes in shoreline position. Low-order trends in coastal change (10^2 to 10^3 yr) on the other hand are reflected in the evolution of the lower shoreface (Cowell et al., 2003). The latter is related to the findings of Bruun (1962, 1988) on the relationship between long-term (structural) coastal erosion and sea-level rise.

Yearly fluxes from coastal erosion are established using rates of erosion compiled over long (10 to 10^2 yr) time series (Lantuit and Pollard, 2008; Solomon, 2005). These time series are used to attenuate the effect of interannual and sub-decadal shore variability and to reduce uncertainties associated with space- and air-borne imagery geoprocessing on the computation of coastal erosion rates (Anders and Byrnes, 1991; Crowell et al., 1993; Thieler and Danforth, 1994; Dolan et al., 1980, 1992). We therefore consider the intercentennial scale to be the reference for the calculation of fluxes associated with coastal erosion.

The effects of coastal processes at the intercentennial scale will be visible on both the upper and lower shoreface as well as on the backshore. Sediment volume losses in the shore zone will therefore be associated with displacement in all sections of the shore profile. However, the hypothetical inclusion of the upper and lower shorefaces in flux calculations is impractical for two reasons. First, because the quality of the bathymetric data between 0 and 10 m is generally poor and not consistent throughout the Arctic and second, it would have to be coupled to numerical models incorporating both on-offshore and longshore sediment dynamics operating at the circum-Arctic scale, which is unrealistic.

A general assumption in this paper is therefore that coastal erosion is restricted to its subaerial component (backshore and subaerial part of the upper shoreface) and a second assumption is that the detection and quantification of coastal erosion can be achieved using the position of the shoreline only. On intercentennial scales, on-offshore and longshore sediment movement can be considered to be transient phenomena, in particular in regards to the carbon cycle (Stein and Macdonald, 2003; Denman, 1993). The volume of sediment released by subaerial erosion can therefore be linked to the erosion of the shore profile when averaged over long time spans. Consequently, the assessment of volumetric erosion can be extracted from the movements of the shoreline position.

1.2. Calculation of shoreline erosion

Monitoring changes in shoreline position and computing volumes of released sediment and TOC can be obtained by several methods including; (a) the combined use of digital terrain models and sea level models to mark the intersection, (b) by digitizing the shoreline from aerial photos or (c) from measurements made using high resolution satellite imagery like IKONOS or Quickbird (Li et al., 2001). Volumetric measurements have been assessed directly using softcopy photogrammetry (Lantuit and Pollard, 2005) or indirectly using photogrammetry-derived planimetric erosion rates (Lantuit and Pollard, 2008; Solomon, 2005, etc.). Such approaches are inappropriate at the global scale because of the associated costs and limited data availability. Estimates of fluxes from coastal erosion have hence been mostly based on the extrapolation of a limited number of records to long stretches of coastline. The extent to which these estimates are performed and the uneven distribution of case studies in the Arctic greatly limits the confidence of these predictions (Rachold et al., 2003b).

One of the solutions to overcome this difficulty is to develop a consistent coastline segmentation and classification and assign a yearly rate of erosion to each segment. This has been done for the Arctic coast over the past ten years using the information provided by regional experts, resulting in an Arctic-wide dataset on the coast (Lantuit et al., in press; IASC, 2001; Brown and Solomon, 2000; Rachold et al., 2002). The classification scheme was used to create geomorphically homogeneous segments, based on a single globally-consistent shoreline dataset, the World Vector Shoreline (WVS) (Soluri and Woodson, 1990). The WVS is a digital data file extracted from each country's national map series at the 1:250,000 scale to represent shorelines globally. The lengths of these segments vary between 1 and 50 km. Each of the segments is defined by common geomorphological, sedimentological and geochemical characteristics.

The subaerial erosion and carbon flux are then calculated using the following equation:

$$C_{\mathrm{tot}} = \sum_{j=1}^{n} \left[C_j \cdot \rho_{S_j} \cdot (1-\theta_{ij}) \cdot (h_j \cdot l_j \cdot R_j) \right] \tag{1}$$

where C_{tot} is the total amount of organic carbon released to the nearshore zone, n is the total number of segments, C the total organic carbon content (by weight) of the cliff in %, ρ the dry bulk density of the enclosing sediment, θ the volumetric ice content in the cliff in %, h the height of the cliff, l the length of the segment and R the annual coastal retreat rate (Lantuit et al., in press). This equation combines inputs from the classification itself (organic carbon content, dry bulk density of the material, ground ice content, backshore elevation and coastal retreat rates), and a geospatial characteristic extracted from the WVS (coastline length). The generalization of yearly rates over entire segments makes this empirical solution usable on vast areas and only requires the one geospatial input. Its main limitation, however, is that the accuracy of the coastline length is correlated with the intrinsic quality of the shoreline dataset and the scale of analysis to which it is applied. There is no indication that the scale of the WVS (1:250,000) or one of any other globally-consistent shoreline is better than any other scale.

1.3. Fractal coastlines

Shoreline representations are *de facto* different for different scales and therefore estimates of shoreline length will vary with different scales of representation. Richardson (1961) and Mandelbrot (1967) first conceptualized the fact that shorelines are fractals, that is, that the same coastline extracted from maps at different scales will have different lengths. Mandelbrot (1967) expressed the relationship between scale and linear measure as the *fractal dimension* of the coastline, which is generally expressed through the D factor in Eq. (2),

$$L(G) = MG^{1-D} \tag{2}$$

Using the length of a shoreline dataset to compute volumetric coastal erosion as in Eq. (1) is therefore problematic since the resulting values can vary greatly depending on the scale of the shoreline used. The errors in the calculation of volumetric coastal erosion associated with shorelines created at different scales are identified in several international projects attempting to quantify nutrient release to the nearshore zone (Bartley et al., 2001; Smith, 2005), but have not been systematically assessed.

The WVS is widely recognized as the most consistent global shoreline dataset, and is therefore an ideal proxy for calculations at the global scale. However, the WVS is a digital vector shoreline and is composed of arcs independent of scale. A WVS arc length will, for that reason, be distinguished by a constant length over scale gradients. There is no indication, however, that this length will provide accurate volumetric coastal erosion estimates. The WVS, as pointed out by Bartley et al. (2001), is relevant only within a certain range of scales, which are not necessarily compatible with volume computations. The use of a single line dataset and a consistent methodology to provide estimates of volumetric erosion at the Arctic scale is necessary, but calculations based on length need to be tested to provide realistic numbers.