Estuaries and Coasts
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The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines

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Abstract Arctic permafrost coasts are sensitive to changing climate. The lengthening open water season and the increasing open water area are likely to induce greater erosion and threaten community and industry infrastructure as well as dramatically change nutrient pathways in the near-shore zone. The shallow, mediterranean Arctic Ocean is likely to be strongly affected by changes in currently poorly observed arctic coastal dynamics. We present a geomorphological classification scheme for the arctic coast, with 101,447 km of coastline in 1,315 segments. The average rate of erosion for the arctic coast is 0.5 m year^{-1} with high local and regional variability. Highest rates are observed in the Laptev, East Siberian, and Beaufort Seas. Strong spatial variability in associated database bluff height, ground carbon and ice content, and coastline movement highlights the need to estimate the relative importance of shifting coastal fluxes to the Arctic Ocean at multiple spatial scales.

Keywords Arctic · Coast · Permafrost · Erosion · Carbon cycle

Introduction

Arctic coasts are likely to become one of the most impacted environments on Earth under changing climate conditions. Under most scenarios, the Arctic is predicted to experience the strongest air and sea temperature increase at the Earth's surface (Kattsov and Källén 2005). As a result, the lengthening open water season and the increasing open water area, due to the decline of

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sea ice extent, will induce changes to the length of fetch and allow storms to affect the coasts later in the fall season (Anisimov et al. 2007; Atkinson 2005). These storms are thought to threaten community and industry infrastructure as well as to dramatically change sediment and nutrient pathways in the near-shore zone (Dunton and Cooper 2005). Unfortunately, Arctic coastal dynamics remain largely understudied and seldom modeled, which puts current adaptation and mitigation strategies in northern communities into jeopardy. A thorough systematic investigation of the coast at the circum–arctic scale is needed to better understand the processes that act upon it. Only then will it be possible to develop predictive models of coastal evolution.

Coastal erosion in the Arctic differs from its counterpart in temperate regions due to the short open-water season (3–4 months, from about June to mid-October) and the presence of ice in the marine and terrestrial environments (Fig. 1). Storms, which are often the main driver of erosion, occur throughout the year but their impact is limited due to the presence of sea ice cover during the fall, winter and spring (Atkinson 2005). Even during the summer period, chunks of sea ice in various quantities and sizes can impede the development of waves in the shore zone. Coastal retreat rates are highly variable both spatially and temporally, in relation to variations in the lithology, cryology, and geomorphology of coastal cliffs (Jones et al. 2008; Lantuit and Pollard 2008; Solomon 2005). Temporal variability is related to storminess, thermal conditions, and sea-ice conditions in the coastal zone (Solomon et al. 1994). Ice in the terrestrial part of the permafrost coastal system occurs as ground ice. It is present in the subaerial part of the shore profile, but also beneath the water column, as submarine ground ice (Mackay 1972; Rachold et al. 2007). The presence of terrestrial ground ice allows abrasion to proceed faster; a process termed "thermal abrasion" (Aré 1988) which encompasses the combined kinetic action of waves and thawing of the permafrost. Upon melting, it enhances coastal zone susceptibility to erosion, (Héquette and Barnes 1990; Kobayashi et al. 1999), especially when present as massive ice in coastal cliffs, or through the occurrence of large thermokarst features in the coastal zone (Lantuit and Pollard 2005; 2008)

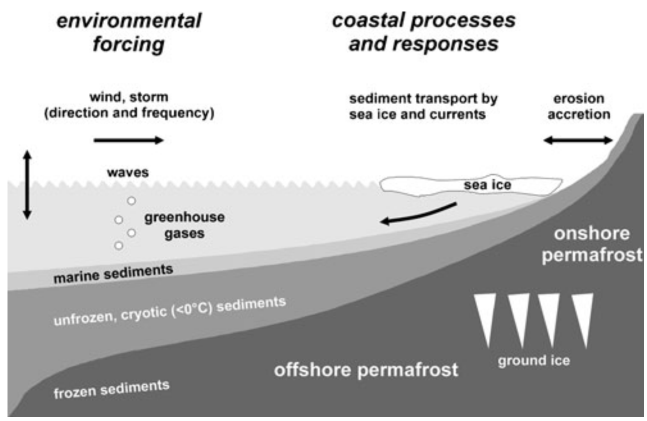

Fig. 1 Physiographic setting and processes active on Arctic permafrost coasts. Ice, in the form of sea ice or ground ice in permafrost, induces a response to environmental forcing that differs from that observed on temperate coasts

The coast, whether in temperate or polar regions, is a complex and diverse environment, at a number of spatial scales. This complexity is difficult to capture with a systematic or rigid compartmentalizing approach. Nevertheless, classifications, whether hypothesis-driven or descriptive, have been a major instrument in the pursuit of scientific knowledge, helping to delineate natural systems and achieve economy of memory (Sokal 1974). Coastal scientists have not refrained from proceeding with formal descriptions of the structure of coastal components. As early as the nineteenth century, (notwithstanding traditional descriptions of coastal processes by indigenous people), geologists attempted to describe coastal landforms and to explain their origin and development. Classification schemes were rapidly devised, mostly based on a division of the coast into areas of similar geology and environment. A review of coastal classification efforts and history is

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provided by Finkl (2004). Existing coastal classifications share a common deficiency in their description of arctic coasts, especially those affected by the presence of permafrost. Typically, they classify the arctic coastal zone as one single category. We suggest that this approach does not do justice to the wide variety of coastal landforms and processes observed at the land–sea interface in the Arctic.

Historically, the lack of a classification scheme for arctic coasts can be explained by the late exploration of polar regions, by their remoteness, and by the low population density of the arctic coastal zone, limiting the economic relevance of studies in the north. The widely used classification of the coasts by Shepard (1948) divides shorelines into two categories, primary (shaped by non-marine processes) and secondary (shaped by marine processes), but does not include sea ice in the coastal zone or the role of permafrost in thermal–mechanical erosion. Classifications based on the division between submergent and emergent coasts, such as that by Valentin (1952), also fail to mention permafrost and sea ice despite the important role of isostasy in determining geomorphology in the Arctic (Whitehouse et al. 2007). Classifications of the arctic coast exist at the national level (e.g., for Russia, Drozdov et al. 2005), but not yet at the circum-arctic scale.

Arctic permafrost coastlines represent approximately 34% of the world's coastlines and are affected by the presence of permafrost and/or seasonal sea ice cover, resulting in unique conditions, landforms, and processes. These environments are undergoing tremendous change that results in redefined societal and environmental frameworks. Traditional use of the coast by Inuit communities in Canada and Alaska is threatened by the disappearance of sea ice (Huntington and Fox 2005). The subsequent opening of the northern sea route in Russia's waters and of the Northwest Passage in the Canadian Archipelago will call upon local, regional, and international stakeholders to define new strategies for the use and protection of the coast (Matushenko 2000). The lack of a baseline dataset that accurately captures the physical state of the coast and includes the specificity of the Arctic hinders the development of such strategies. The urgency to develop such a dataset, based on a classification method specifically devised for the Arctic, is genuine and palpable.

This paper presents a classification scheme by the Arctic Coastal Dynamics (ACD) project, initiated by the International Permafrost Association in 1999 (Brown and Solomon 2000) and carried out on a cooperative basis starting in 2000 with the International Arctic Science Committee (Rachold et al. 2002, 2003, 2005; Rachold and Cherkasov 2004), with specific aims of establishing the rates and magnitudes of erosion and accumulation of arctic coasts and of creating an arctic coastal classification in digital form. ACD is also an affiliated project with the Land–Oceans Interactions in the Coastal Zone project, which in turn is part of both the International Geosphere-Biosphere Programme, and the International Human Dimension Programme.

Methods

Segmentation of the Coast

The central objective of the ACD classification is to assess the sensitivity and erosion potential of arctic coasts. The classification was therefore conceived as a framework broad enough to encompass existing classification schemes, while capturing fundamental information for the assessment of climate change impacts and coastal processes in relation to the specificity of arctic coasts.

The first step in establishing this classification consisted in segmenting the arctic coast in a consistent and systematic manner. Here, we apply a constrained definition of the Arctic, limiting our study area to the coasts bordering the Arctic Basin and excluding much of the Canadian Arctic Archipelago and northern Québec, southern Greenland, Iceland, the Faeroe Islands, Scandinavia, and southern Alaska (Fig. 2). Much of the Canadian Archipelago, Greenland, and the Bering Sea are excluded for three main reasons. First, the tacit objective of this classification is to focus on sediment fluxes from arctic coasts to the enclosed Arctic Ocean and not to the Pacific, which excluded the Bering Sea. Second, development of this classification relied on existing data on coastal geomorphology, which is scarce for the Canadian Archipelago and Greenland. Third, most of the coasts of the Canadian Archipelago and Greenland are consolidated and uplifting, with little to no coastal erosion, which greatly limits the impact of erosion for these coasts on the overall sediment budget.

To conform to the objective of the project, the compartmentalization of the coast was primarily geomorphological in nature, so that it emphasizes erosion and changes to the coastal tract. The basic concept underlying the segmentation, freely adapted from Howes et al. (1994), is that the shore zone can be subdivided and described in terms of a systematic collection of physical entities. In short, a coastline can be subdivided into smaller segments, and the features of each segment described and recorded. The method first segments the coastline into alongshore units that exhibit homogeneous forms and material types, then subdivides these segments into across-shore components, and describes them.

To proceed with the first step of the segmentation, the following characteristics were considered: (1) the shape or form of the terrestrial part of the coastal tract, (2) the marine processes acting upon the coast, (3) the shape or the form of

Fig. 2 The Arctic region, as defined by the Arctic Monitoring and Assessment Program (AMAP), with the extent of the classification featured in this paper and the Arctic ocean sea sectors used to divide the coastline. Average sea ice extent for September is also shown

the subaqueous part of the coastal tract, and (4) the lithofacies of the materials constituting the coastal tract. The coastal tract we use follows the definition of Cowell et al. (2003). The segmentation of the shoreline was defined by members of the ACD project and the Arctic Circumpolar Coastal Observatory Network, based on field investigations, digital and paper products, as well as on personal knowledge. Details on the segmentation procedure are given in reports of the ACD workshops in Rachold and Cherkashov (2004), Rachold et al. (2002; 2003; 2005), and Overduin and Couture (2008). The Arctic was organized into 10 sectors around the seas of the Arctic Ocean (Fig. 2, Table 1). To ensure consistency in the segmentation procedure, cross-review segmentations and independent oversight in the process were organized over the course of the ACD project (Lantuit et al. 2006; Overduin and Couture

Table 1 Divisions of the Arctic coast used in this paper based upon Arctic seas

Sea name	Length (km)	Percentage of total coastline length (%)
Russian Chuckchi Sea	2,736	2.7
American Chuckchi Sea	4,662	4.6
American Beaufort Sea	3,376	3.3
Canadian Beaufort Sea	5,672	5.6
Greenland Sea and Canadian Archipelago	4,656	4.6
Svalbard	8,782	8.7
Barents Sea	17,965	17.7
Kara Sea	25,959	25.6
Laptev Sea	16,927	16.7
East Siberian Sea	8,942	8.8
Total	101,447	100.0

Coastline lengths are based on the World Vector Shoreline (Soluri and Woodson, 1990)

2006, 2008; Overduin et al. 2007). The segments were then organized in an ISO-compliant geodatabase and individually referenced according to a predefined template. The geospatial processing and referencing process are described in detail by Lantuit et al. (2010a).

Cross-shore Characterization

The second step consisted in characterizing the cross-shore components of each segment. Each along-shore unit was divided into four cross-shore units which were described in terms of their shape (or morphology) and their material type. The cross-shore units were identified as the onshore, backshore, frontshore, and offshore (Fig. 3). These designations are defined in Appendix A and are specific to this classification, although largely inspired by existing schemes (e.g., Komar 1998; Cowell et al. 2003). The specific shape of the shoreface in arctic settings, as highlighted by Are et al. (2008) and Are and Reimnitz (2008), does not preclude the use of these generic terms in describing its morphology. The term "backshore" was defined to refer primarily to the area landward of the active beach, whereas the term "frontshore" was defined to include both the foreshore and the surf zone. The "onshore" category referred to the local and regional setting adjacent to those zones which are immediately affected by marine processes. The offshore zone was defined as the zone extending from the lower end of the frontshore zone to the 100 m isobath. The offshore zone, like the onshore zone, provided context for the classification of the coastal region, and was described in terms of its steepness and relief characteristics (i.e., slope) using resources such as topographic maps, bathymetric maps and digital terrain models. Onshore relief was expressed as distances to topographical contours. Offshore, the relief was expressed as distances to the 2, 5, 10, and 100-m isobaths. The backshore and frontshore zones were labeled using categories that described the shape of those zones in genetically neutral, geometrically defined terms. The range of morphological terms used to describe each of these zones is listed in Appendix A and included forms such as ridged or terraced frontshore deposits, beaches, or cliffs.

For all cross-shore zones, the material was specified as shown in Appendix A. Unlithified and lithified coastal segments were differentiated in the process. For unlithified coasts, a detailed account of the grain size was provided, encompassing standard grain-size categories (gravel, sand, silt, clay). Lithified coastal sections were characterized by the geological and mineralogical nature of the exposed bedrock. For the purpose of quantifying sediment and organic carbon release to the near-shore zone, erosion and redeposition in the frontshore and offshore zone were considered to be transient phenomena; and detailed characterization of soil geotechnical and geocryological properties focused only on the backshore zone (e.g., bulk density and volumetric ground ice contents).

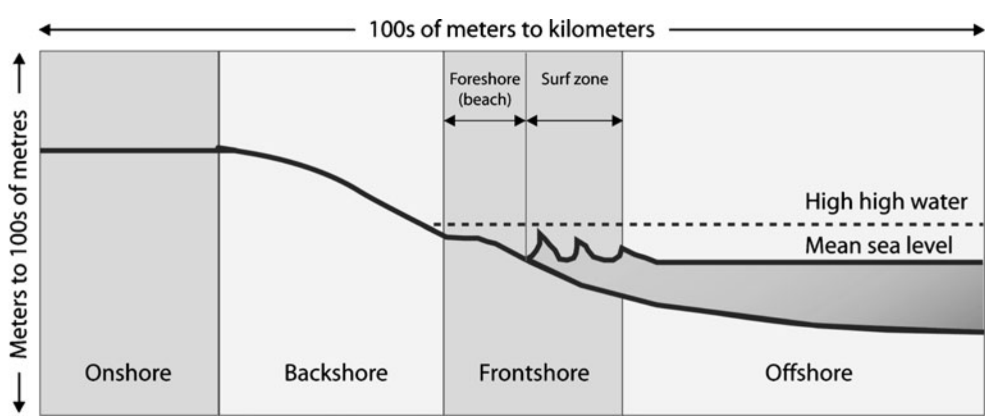

Fig. 3 The cross-shore units used to describe the coastal zone in the classification. Adapted from the coastal tract concept from Cowell et al. (2003)

Cryolithology and Geochemistry

The third step consisted in populating each segment with additional characteristics including cryolithology (i.e., permafrost characteristics), geomorphology and geochemistry. A summary of the geochemical and cryolithological parameters used to characterize each segment is provided in Appendix A.

Ground ice contents were provided in terms of visible volumetric ice contents (vol%), both in a quantitative and qualitative fashion, using the classes inspired by the circum-arctic permafrost map (Brown et al. 1998). All forms of ground ice were included including massive ice bodies, wedge ice, pore ice, ice complexes (fully penetrated by large ice wedges), injection ice, buried snow bank, and buried glacier ice. For a definition of these terms, the reader is referred to Mackay (1972) and Pollard (1990). In any section, the percentage volume of ice vs. soil was determined and assigned a value of poor (0–2 vol%), low (2–20 vol%), medium (20–50 vol%), or high (>50 vol%). The estimates of ground ice content were based on a variety of sources, including field observations of large natural exposures, use of published material, boreholes and cores, geophysics (seismic, ground penetrating radar, electrical resistivity, gravity), terrain analysis from remotely sensed datasets, and to a large extent on the map of permafrost conditions for the northern hemisphere published by the International Permafrost Association (Brown et al. 1998).

The geochemical characterization of the coastal segments builds on recently developed methods to characterize coastal stretches of the Arctic in Canada and in Alaska (Couture et al. 2004; Jorgenson and Brown 2005; Ping et al. 2008). At present, it includes organic carbon content of the entire coastal exposure and soil organic carbon content, and allows for expansion to include additional geochemical characteristics. In the context of climate change, organic carbon was regarded as the most pressing quantity to be assessed along the arctic coastal rim, but ultimately, other nutrients, metals and contaminants could and should be included in the geochemical part of the classification. Organic carbon content in the entire vertical backshore section was expressed as percent carbon content based on weight relative to the sampled sediment (wt.%). Soil organic carbon (SOC) indicates the same parameter but is limited to the upper 1 m of the profile. The reason for computing organic carbon content relative to sediment weight, rather than on a bulk weight or volumetric basis (including the matrix of water, ground ice, and sediment) was primarily driven by the existing datasets and methodologies of carbon sampling. Organic carbon has traditionally been sampled as the particulate organic matter (POM) fraction of sampled sediments, since dissolved organic carbon (DOC) contents in pore water as well as in ground ice have generally been considered to be negligible. As a result, most existing organic carbon datasets are based on analysis of POM contents relative to dry sediment weight. In some cases, TOC or organic carbon estimates in POM were available only for the soil part of the coastal backshore area (SOC), that is, for the upper 1 m of the backshore area. To assess the TOC contents for the rest of the profile, an empirical formula based on existing coastal exposures from North America and Siberia was used to model the TOC contents for the lower part of the coastal exposure. Data from Jorgenson and Brown (2005), Couture et al. (2004), and Schirrmeister et al. (2002) formed the basis for the computation of Eq. 1, which extrapolates SOC values to the rest of the backshore profile:

$$C_{org} = \frac{SOC \cdot 2 + \alpha \cdot SOC \cdot (h - 2)}{h} \quad (1)$$

where C_{org} is the organic carbon content expressed in wt.%, SOC, the soil organic carbon content for the upper 2 m of the backshore cliff, α a constant (0.1) expressing the ratio used to characterize the C_{org} content for the lower part of the cliff, and h the backshore cliff elevation.

To relate carbon contents to fluxes in the coastal zone, we seek to relate concentrations on a relative weight basis to fluxes observed using length, areal, or volumetric change rates. The spatial density of the flux components (initially, water/ice, sediment, and organic carbon) can only be determined if we can relate weight to volume. The classification includes data on the bulk density of the soil, which is defined as the ratio of the mass of dry solids to the bulk volume of the soil. In most cases, bulk density values were not available throughout the backshore profile. In these cases, unadjusted bulk density from the upper part of the profile was used to characterize the rest of the profile. In addition, ground ice was omitted in the computation of bulk densities, and the values used in the classification virtually referred to the density of soil particles after thaw settlement. In cases where field investigations could not be performed, the values for bulk densities were extrapolated from the circum-arctic map on permafrost conditions (Brown et al. 1998) by using the grain size of the sediment.

Since this classification also features ground ice contents and bulk densities, it is possible to combine these parameters to obtain the total amount of carbon available in a given coastal segment. Assuming that DOC contents are negligible, that POM can be considered to provide the TOC contents and that these organic carbon measurements can be averaged in a meaningful way so that calculated values are representative for the coastal segment, this value will form a best estimate.

Coastal Erosion

Coastline erosion or aggradation is an ongoing process characterized by high interannual variability (Solomon et al.

1994). Characterizing shoreline position is therefore better done with long-term datasets that attenuate the seasonal and annual variability. These datasets typically report rates ranging from 0 to 20 m year^{-1}, although based on very different time spans. Here, we report on erosion using yearly coastal erosion (and aggradation) rates based on the best datasets available, that is, the ones covering the longest time span. The rates are expressed in meters per year, and refer to the distance between the shoreline location from one year to the next in a direction essentially perpendicular to the coast. In the best-case scenario, rates of erosion compiled at high resolution (less than every 500 m) were used to populate the classification. These rates were extracted from the most recently published datasets, including data from Jorgenson and Brown (2005), Lantuit and Pollard (2008), Solomon (2005), Jones et al. (2008, 2009a, 2009b) and Lantuit et al. (2010b). They generally use remote sensing imagery from the second half of the twentieth century and sometimes cover over 50 years of coastline evolution. These datasets are restricted spatially, however, and most of the database segments were characterized using discrete measurements of erosion along the coastline that were then extrapolated to the rest of the segment. These records are generally from local scientific investigations, industry reports, ship-based observations, or local monitoring efforts. In remote areas, north of 80°N, such records were often unavailable and the erosion data was generated from maps of sea ice cover: using the average 1970–2001 sea ice extent for late September, a rate of 0 m year^{-1} was assigned to coasts located within the extent of the sea ice cover, and no rate was assigned for the ones located outside of this area. This is consistent with observations of erosion in the Canadian High Arctic and elsewhere (Shaw et al. 1998; Zenkovich 1985; Walker 2005).

Data Quality Assessment, Spatial Accuracy, and Metadata Standards

Data quality was assessed relative to the database specifications using a template to characterize coastal segments and through the use of metadata standards. Consistency was ensured through the cross-evaluation of neighboring seas in a series of five international workshops. To assess the quality of quantitative parameters, a data quality rating was added by the regional expert to the fields related to geomorphology (backshore elevation and dry bulk density), cryolithology (ground ice content), and geochemistry (organic carbon content). The rating was coupled to a "data quality comment" field that was left to the expert for further precision on the rating. The ratings were expressed as low, medium, or high data quality. These referred mostly to the spatial accuracy and resolution of the measurements. In short, a high quality rating was assigned to a segment when the record was extracted from more than one discrete measurement in the segment. A medium rating was assigned to segments where records were extracted from a single-field measurement or interpolated from a neighboring segment. A low rating referred to data being generated using existing maps such as the circum-arctic map of permafrost and ground ice conditions (Brown et al. 1998), or the Northern Circumpolar Soils Map (Tarnocai et al. 2002), or to data interpolated from non-neighboring segments. Because of the sparse nature of the data available for the classification, a quantitative assessment of the accuracy of the data records was deemed irrelevant at this stage.

The metadata standards were developed in a two-stage process. The geospatial framework was developed to match the ISO 19115 standard (ISO 2003), while the data itself was documented in an ad hoc systematic procedure. The ad hoc protocol to implement the metadata for the database focused primarily on the identification of the sources used to populate the field of the database. It was inherently coupled to the data quality assessment process since it also reports on the nature of the source used to create the data records. Despite the wide range of sources potentially available to the authors, a special effort was made to use consistent (i.e., best available circum-arctic) sources to populate the fields, and the number of sources used to create the classification is therefore small.

Finally, to avoid miscalculations due to the misrepresentation of the coast by nonfractal datasets such as the World Vector Shoreline (Soluri and Woodson 1990), a study conducted by Lantuit et al. (2009) investigated the potential effects of the use of linear datasets to compute fluxes of sediments and nutrients. The authors concluded that using the length of the coastline to compute these fluxes was inappropriate at best, and wrong in most cases. Since the length of the coastline varies with scale, there is no "absolute" coastline length and the range of lengths can vary greatly. They emphasized the need to use planimetric rates to increase the accuracy of the predicted fluxes. This is the method advocated in the framework of the present classification. The length of the World Vector Shoreline is used in the rest of this paper to provide some baseline statistics about the arctic coastline, but not to compute volumetric sediment and geochemical fluxes.

Summary

The resulting template provides a comprehensive, yet expandable individual geomorphological description of each of the segments, and forms the most comprehensive available dataset on coastlines at the circum-arctic scale. The database tables listed in Appendix A provide 23 characteristics which can be searched and queried to obtain statistics that relate both to traditional coastal geomorphology, geochemistry and coastal erosion as well as to arctic-specific features (geocryology). The database is published as a freely available dataset on the PANGAEA information system (Diepenbroek et al. 2002) in ISO compliant formats. In the following section, we describe selected information extracted from this dataset.

Results

General Statistics

The coastline classified in this study spans five countries located along the Arctic Ocean, namely Russia, Alaska (USA), Canada, Greenland (Denmark), and Svalbard (Norway). The total length of the coastline affected by the presence of permafrost in the northern hemisphere is 407,680 km, which represents around 34% of the world coastline, while the coastline classified in this study covers 101,447 km, which represents about 25% of these coasts. The Russian coastline represents close to three quarters of that dataset, extending over ten time zones from the meridian at 31°E–169°W. Extending the dataset to include the inner waterways of the Canadian Archipelago would make the Canadian arctic coastline much longer than the Russian one. However, the current dataset only covers a smaller portion of the Canadian coastline, including the Beaufort Sea and the outer western edge of the Canadian Archipelago. In total, 1,314 segments were created along the arctic coast. The length of these segments varies greatly, mostly as a result of the level of knowledge acquired about a specific stretch of coast. Well-known coastlines were segmented in detail, while hardly accessible ones were generally summarized broadly in long segments. A general trend is seen along a latitudinal gradient, with southern coastlines segmented in more detail than northern ones. The coast of Novaya Zemlya, for instance, is made up of only a few segments, while the Alaskan Beaufort Sea coast is made up of 71. This is reflected in the mean and median lengths of the segments at the Arctic scale: the mean length of a segment is 74 km, while the median length is 28 km. This skewed distribution is further explained by the fact that 85% of the segments are below 100 km and 42% of them below 20 km. The trend is not only latitudinal but also geomorphological, in that most very long segments correspond to low coastal erosion rates and low organic carbon values.

The arctic seas are characterized by large differences in geomorphology, geochemical properties of the sediments, and erosion rates. These are summarized in Table 2. For all criteria, the variability is large across sea sectors, but there is also considerable variability within each sector. For instance, backshore elevations range between 1 and 50 m in the Laptev Sea area, and erosion rates between 0.0 and 5.0 m year^{-1} in the same sector. The fact that variability is large at the regional scale is not new. Solomon (2005)

Table 2 Overview of parameters extracted from the classification and averaged by sea sector

Sea name	Weighted mean backshore elevation (m a.s.l.)	Weighted mean coastal erosion rate (m year^{-1})	Weighted mean organic carbon content (wt.%)	Weighted mean volumetric ground ice content (vol%)
Russian Chukchi Sea	14.54	0.27	1.09	13.90
American Chuckchi Sea	4.98	0.49	3.78	23.99
American Beaufort Sea	1.54	1.15	5.70	26.92
Canadian Beaufort Sea	6.74	1.12	2.43	29.42
Canadian Archipelago	No data	0.01	1.87	14.23
Svalbard	13.96	0.00	2.86	0.00
Barents Sea	10.52	0.42	0.92	16.22
Kara Sea	14.04	0.68	1.51	23.65
Laptev Sea	11.91	0.73	1.63	17.13
East Siberian Sea	8.79	0.87	1.64	19.62
Overall	8.38	0.57	2.05	18.44

All parameters displayed in the table exhibit large differences across sea sectors. The term "weighted" indicates that the parameters were weighted with the length of the coastline in each segment to accurately represent the input of each stretch of coast in the calculation showed that the range of geomorphological settings and erosion rates in the southern Canadian Beaufort Sea challenged the notion of homogeneous coastal types. However, the differences across sea sector are an indication that Arctic permafrost coasts are multifaceted and need to be examined at multiple spatial scales.

Geomorphology

The coastline in this study was classified as 65% unlithified and 35% lithified (66,386 and 35,051 km), a roughly 2:1 proportion which is similar to the one found using the International Permafrost Association permafrost map (66,208 and 35,238 km) on the same coastline (Brown et al. 1998). This ratio is difficult to compare with other coasts of the world, as most efforts to compile such statistics have focused on the ratio between sea cliffs and sedimentary coasts, and not between unlithified and lithified coasts. Emery and Kuhn (1982) indicate an 80–20% ratio for sea cliffs and sedimentary coasts, but include cohesive coasts (i.e., nonrocky) in the first category. Most of the unlithified coasts in the Arctic are characterized by the presence of excess ice (i.e., an ice volume that exceeds the total sediment pore volume). The effect of warming, and especially thawing, on soil volume and cohesion depends on ice content. Permafrost and ground ice therefore play an important role in maintaining coastal stability, but are uniquely susceptible to changes in land–ocean and land–atmosphere heat fluxes.

The coasts are also characterized by variable backshore elevations, ranging from submeter elevations, mostly along deltas and sedimentary coasts, to several tens of meters and up to 120 m for the coast around the Inchoun and Irgutunnen Capes on the Russian Chukchi Sea coastline. The mean backshore elevation for the Arctic coasts, weighted by segment length, is 8.4 m. There is no global data on cliff heights to the knowledge of the authors, but these backshore elevations compare to both stable or rapidly eroding coasts in more temperate latitudes. Backshore elevations at the pan-Arctic scale are higher along lithified costs (10.9 m) and lower along unlithified ones (4.4 m). The Svalbard, Kara Sea, and Russian Chukchi Sea are all characterized by weighted mean backshore elevations above 14 m (Fig. 4a). In comparison, the weighted mean backshore elevation in the US Beaufort Sea is less than 2 m.

Cryolithology and Geochemistry

Arctic coasts are characterized by an average volumetric ground ice content of 18.4%, which is larger than ground ice contents normally observed in the upper 10 m of permafrost (Zhang et al. 2000). As was the case with backshore elevations, however, the range of observed values is large, with extreme values of 0% and 70%, the latter all corresponding to stretches of coast located along the US Beaufort Sea and coincidentally showing recent signs of increasing coastal erosion (Jones et al. 2009a; 2009b). On the Kara Sea coasts, for instance, volumetric ground ice contents extend from 1% up to 55%. The frequency distribution of ground ice contents (Fig. 5a) shows that most volumetric ground ice contents range between 0% and 30%, with close to 10% of the coastline characterized by contents between 0% and 2%.

Sea sectors also differ substantially in cryolithology: Svalbard coasts contain virtually no visible ground ice with average ground ice contents of 0%. At the other end of the spectrum, the Canadian Beaufort Sea is the richest in ice, with weighted mean volumetric ground ice contents close to 30%, somewhat comparable to values (46%) along the Yukon Coastal Plain and on Richards Island, which are areas richer in ground ice. The Beaufort Sea as a whole with its Canadian and US parts is the most ice-rich, followed by the US Chukchi and the Kara Seas (Fig. 4b).

Organic carbon contents along the arctic rim are on average 2 wt.%, but are characterized by large variability, ranging from close to 0 wt.% to above 15 wt.% for some stretches of coast in the US Beaufort and Kara Seas. The Brownlow Coast, west of Kaktovik on the US Beaufort Sea coast is for instance characterized by organic contents of 15 wt.%. There exists a skew towards higher concentrations for the Beaufort Sea coast: out of the 22 segments with organic carbon contents above 10%, two only are located in the Kara Sea, four in the Canadian Beaufort Sea, and 16 on the US Beaufort Sea coast. In recent estimates of the permafrost soil organic carbon pool (Tarnocai et al. 2009) that were obtained using higher resolution data, the largest values of carbon content were retrieved from stretches of coast where high resolution sampling was performed, such as along the US Beaufort Sea (Jorgenson and Brown, 2005). The extreme values just mentioned are not representative for the arctic coast since 87% of the segments classified in this study feature organic carbon contents below 5% and 57% below 2%. Large discrepancies in organic carbon contents are not only recorded between segments, but also between sea sectors of the Arctic (Fig. 4c). Here, as mentioned above, the largest organic carbon contents are found along the US Beaufort Sea coast, with an average C_{org} value of 5.7%, followed closely by the US Chukchi Sea (3.8%). The Russian arctic seas feature consistent average organic carbon contents between 0.9% and 1.7%. Variations in carbon contents are primarily a function of geologic, cryologic, and climatic history. However, the size of the dataset

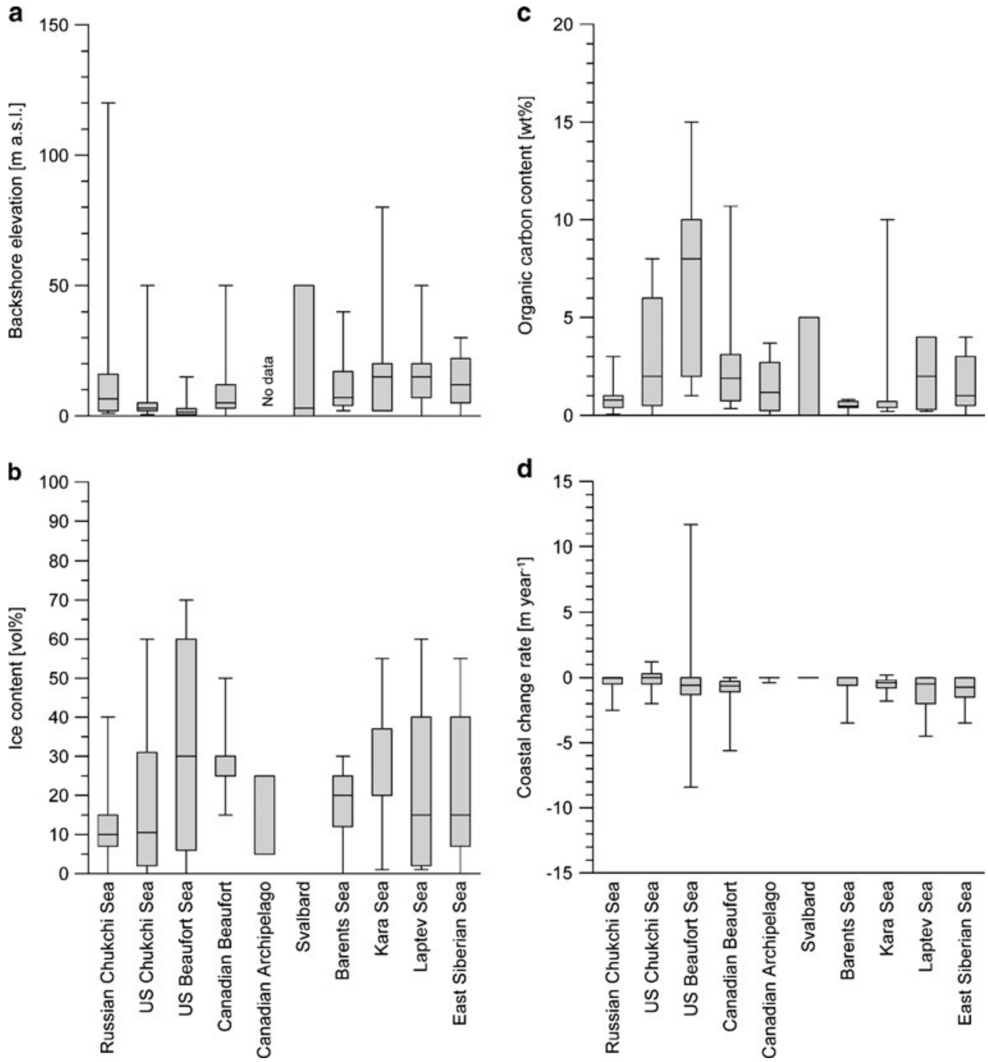

Fig. 4 Unweighted minimum, mean, maximum and quartiles of coastal parameters summarized for each sea sector: **a** backshore elevation in meters above sea level (m a.s.l.), **b** volumetric ground ice content (vol%), **c** total organic carbon content (wt.%), **d** coastal change rate (m year^{-1})

must also be considered. In certain cases, a detailed analysis can result in lower carbon values than initial estimates (e.g., Streletskaya et al. 2009), but a recent determination of the size of the overall organic carbon pool in permafrost regions shows it to be much larger than previously thought (Tarnocai et al. 2009), partly because deeper and higher resolution data was used. This may help explain part of the discrepancy between sea sectors since, as noted above, the highest carbon contents have been retrieved from stretches of coast where high resolution sampling has been performed. This implies that estimates for other sea sectors may be underestimated.

These numbers for organic carbon provide an indication of what the flux of carbon may be due to erosion of the coastal sediments, however, they do not provide information on the lability of that carbon. Terrestrially derived organic matter generally contains a significant proportion of vascular plant material composed of molecules of relatively refractory carbon (Hedges et al. 1997). However, the cold and wet environments in which Arctic soils form serve to limit oxidation so the organic matter they contain is less degraded than it would be at lower latitudes (Shaver et al. 1992; Hobbie et al. 2000). In addition, frost churning of permafrost-affected soils moves surface carbon deeper into the colder part of the soil profile where decomposition is further restricted (Bockheim 2007), while changes in the depth of the active layer over time can have the same result (Tarnocai et al. 2002; Schuur et al. 2008). Once it is eroded, organic carbon from terrestrial sources has in some cases been shown to supply a significant proportion of the energy needs of coastal food webs (Dunton et al. 2006). Nevertheless, much of this material is likely to be buried in shelf sediments or exported off-shelf, rather than being remineralized in the water column as is the case with more labile marine carbon derived from photosynthesis. So although the fate of organic carbon can vary depending on regional physical and biological dynamics, it depends to a large extent on its source and its quality (de Haas et al. 2002; O'Brien et al. 2006; Stein and Macdonald 2004 and references therein). A characterization of this latter param-

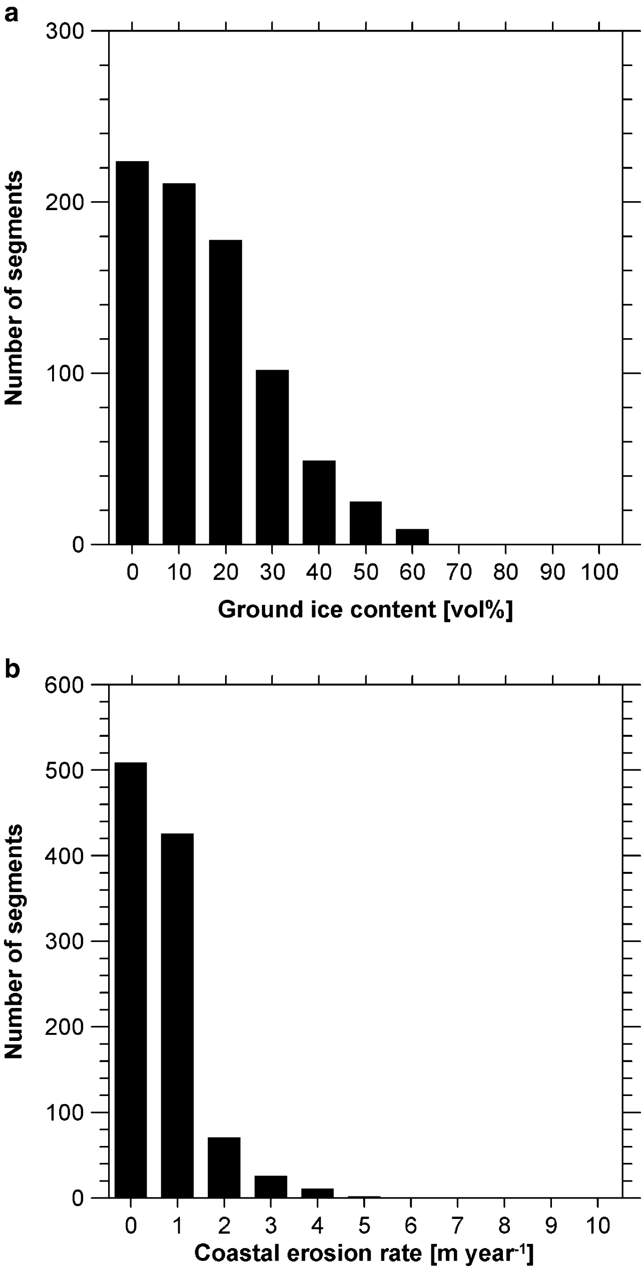

Fig. 5 Frequency distribution of **a** ground ice contents and **b** coastal erosion rates along the Arctic coastline. The *Y*-axis indicates the number of segments and does not take into account the length of each of these segments

eter will be the focus of future refinements of the ACD database.

Coastal Erosion

Coastal erosion rates actually refer in our dataset to erosion or aggradation, being marked negative when the coast is aggradational, but the overwhelming part of the coasts referenced in our ca. 100,000 km classification is erosional. The average rate of erosion for the 61,919 km of coast for which data is available is 0.5 m year^{-1}. As for other parameters though, the variability between segments and notably between neighboring segments is large. Solomon (2005), Lantuit and Pollard (2008), and Lantuit et al. (2009) depicted similar situations along Canadian coasts in even greater detail at the local scale. This variability is therefore not new, but it is striking in that it applies to all sea sectors referenced here (Fig. 4d). With the exception of Svalbard and the Canadian archipelago, the range of erosion rates observed in all sea sectors is large. At Drew Point, on the Alaskan coast, the rate of erosion is 8.4 m year^{-1} (this rate was later revised by Jones et al. (2008; 2009a; 2009b) but is used here as entered in the database) and the largest in the Arctic, but on the nearby Pogik Bay coast, the rate of erosion is only 0.3 m year^{-1}.

Strong rates of erosion are not unique to the US Beaufort Sea: out of the ten segments with the strongest erosion rates, four are located in the Laptev Sea sector, three in the US Beaufort Sea, two in the East Siberian Sea and one in the Canadian Beaufort Sea. In total, 25 segments are characterized by rates greater than 3 m year^{-1} and are located mostly in the Laptev Sea (11) and in the East Siberian, US Beaufort and Canadian Beaufort seas (5, 4, and 3, respectively). The significance of the extreme rates is however limited. These 25 segments represent around 3% of the length of the coastline studied in this paper. Generally, most of the erosion rates lie between 0 and 2 m year^{-1}: 89.2% of the segments fall in this category and 48.6% have erosion rates below 1 m year^{-1} (Fig. 5b).

The map featured in Fig. 6 provides a good idea of the differences in coastal erosion across sea sectors. Mean coastal erosion rates vary from one sector to another between 0.00 m year^{-1} (Svalbard) to 1.15 m year^{-1} (US Beaufort Sea; Fig. 4d). The Beaufort Sea coastline as a whole is characterized by the strongest retreat, with coastal erosion rates exceeding 1.1 m year^{-1}. In comparison, the rates of erosion observed on Russia's coastlines are much lower, ranging from 0.27 m year^{-1} (Chukchi Sea) to 0.87 m year^{-1} (East Siberian Sea). Svalbard and the Canadian Archipelago exhibit rates close to 0 m year^{-1}, which is largely explained by the overwhelmingly rocky nature of the coastline, the persistence of sea ice throughout the summer season for the Canadian Archipelago, and the strong vertical isostatic component associated with both these regions. Not surprisingly, rates of erosion are larger on unlithified coastlines, with a rate of 0.57 m year^{-1} for the unlithified stretches of coast and of 0.27 m year^{-1} for the rest. The latter value demonstrates the impact of the necessary generalization implicit in the segmentation process. The rate is probably larger than for lithified coasts due to erosional stretches in these lithified segments.

Erosion is positively yet poorly correlated with ground ice content, with 23% of the variance in erosion rates being

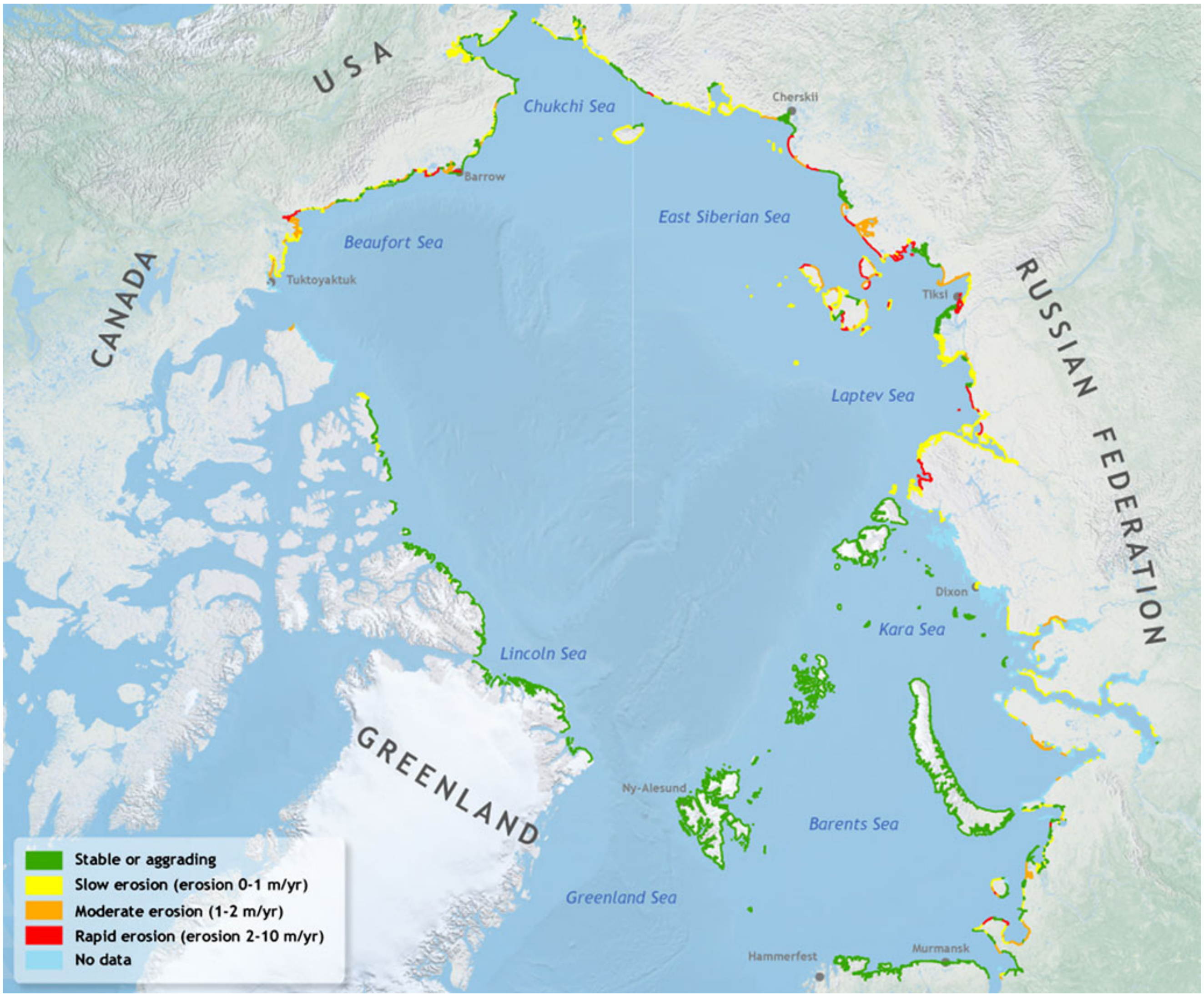

Fig. 6 Circum-Arctic map of coastal erosion rates. The spatial variability in erosion rates generally observed at local scales is also a prominent regional feature

explained by volumetric ground ice contents (Fig. 7a). This relatively low coefficient of determination is slightly lower than the one presented by Héquette and Barnes (1990) in the Canadian Beaufort Sea for the same statistical relationship, but close enough to provide a backdrop to the present study. In our dataset, a significant number of ice-rich segments, mostly in the Canadian Archipelago, are not affected by erosion because of sea ice presence, and alter the statistical relation. Even during the dramatic September 2007 sea ice low, sea ice was fronting the shoreline on these coasts.

Erosion rates are even less satisfactorily explained by backshore elevations (Fig. 7b). The height of the backshore shows a statistically insignificant correlation with low R^2 (0.006). The highest backshore elevations (>40 m) nevertheless, as expected, are retreating a little more slowly than cliffs with elevations of less than 10 m, probably because a larger quantity of debris must be removed before additional retreat can occur, but as a whole, and consistent with the findings of Héquette and Barnes (1990), erosion is poorly linked to backshore elevations.

Discussion

The ACD classification of arctic coasts provides a comprehensive, yet intricate view of arctic coastal erosion, where no one factor compiled here emerges as the single explanatory variable for coastal erosion at the circum-arctic scale. In fact, the spatial variability of erosion emphasized in this paper is itself a product of the spatial variability of other parameters such as ground ice content or backshore elevation. In addition, it should be noted that waves and storm surges are a large, if not the largest, explanatory factor for coastal erosion along the arctic coastal rim and

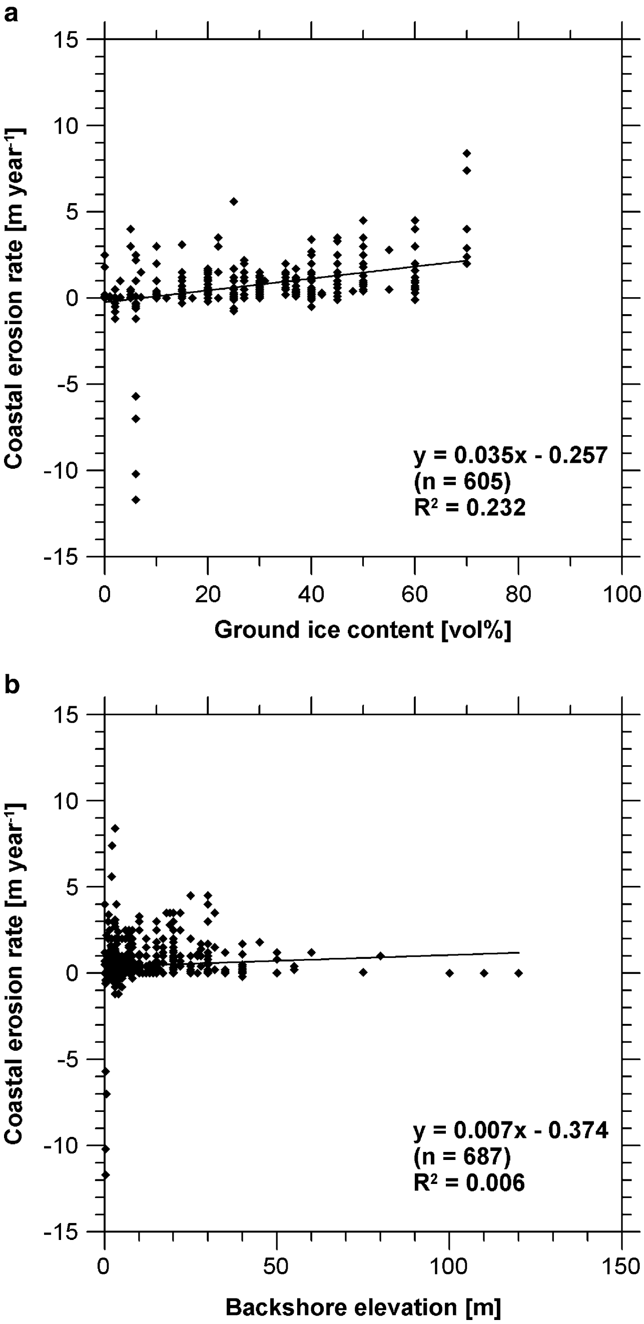

Fig. 7 Regression **a** between erosion rates and volumetric ground ice contents and **b** between erosion rates and backshore elevations

that storms are not considered in our classification scheme. Despite these limitations and the multiple factors influencing the pace of erosion, it is possible to extract some general regional traits related to the evolution of the coast. The recent dramatic increase of erosion reported on the US Beaufort Sea coasts (Jones et al. 2008; 2009a; 2009b; Mars and Houseknecht 2007), for instance, can be linked to the high ground ice contents and very low backshore elevations of these coasts. Both these variables limit the quantity of eroded material generated by a storm, so erosion products are quickly removed from the beach and shoreface by waves, leaving the coast vulnerable to the next storm. On other coasts around the Arctic, a lengthening open water season and the increase in storm frequency would probably not lead to increases in erosion rates as large as the ones observed in Alaska, because of the greater quantities of eroded material that must be removed from the beach and the shoreface. In turn, these coasts, while not eroding as quickly, can nevertheless deliver much more material to the near-shore zone, which, if carbon-rich can lead to the alteration of the near-shore carbon budget.

The dataset that we present is mostly a static view of the coast and functions as a baseline for future comparative investigations: erosion rates change yearly, and are undergoing trends (local, regional, or global) which are not represented here. In that sense, this database cannot be considered as a dynamic tool to look into seasonal or annual variability in coastal change. Yet, it provides a basis for such studies, including modeling studies, to constrain boundary parameters in erosion prognoses in the context of shifting climatic and environmental forcing. At the global level and in the Arctic, an acceleration or simply an increase in sea level rise (Proshutinsky et al. 2001; Church and White 2006) will alter the dynamics of erosion through higher storm surges. Relative sea level rise in the Arctic is also predicted to be approximately 0.2 m higher than the global average for the twenty first century (Meehl et al. 2007, p.813). Readjustments of the wave climate following synoptic changes in the Arctic and enhanced long-shore transport may lower that trend locally, but overall, sea level rise will lead to greater wave impact on arctic shorelines. Relative sea level rise will not be equally distributed in the Arctic. The North American arctic offshore and the shores of the Canadian Archipelago will see the strongest increase. The regional impact of this process is difficult to measure, but it could lead to greater storm surges in these sea sectors, thereby exposing ice-rich layers that were previously too high above water level to direct wave contact. Such deposits exist along coastline stretches of the Yukon Coastal Plain, in the southern Canadian Archipelago, and for long stretches of coast along the Kara and Laptev Seas.

One of the driving forces behind a potential increase in erosion is the lengthening of the open-water season, which is thought to have a much greater impact on the coasts than the increased fetch associated with disappearing sea ice, at least in the Canadian Beaufort Sea (Manson and Solomon 2007). In that sense, it is legitimate to think that erosion can and will increase where rates of erosion are already substantial, but in light of this study, one can equally assume that some dramatic changes can be expected regionally on coasts where the open water season was virtually nonexistent until now. Such is the case for the southern part of the Canadian Archipelago for instance, where a substantial portion of the coast is unconsolidated and could prove susceptible to erosion.

Permafrost and sea surface temperatures and their evolution over the next century will influence rates of erosion, though probably to a lesser extent globally than other forcing parameters mentioned above. The amount of heat required to bring permafrost temperatures to just below the melting point is often substantially less than the amount of heat required to melt interstitial or massive ground ice, and sea surface temperatures, when in contact with the shore, are likely to have a greater impact on the rate of erosion than air temperatures in providing the heat necessary to thaw ice-bonded or ice-rich sediments. However, both these driving forces are generally secondary to wave energy as shown by Aré (1988) and thought to impact mostly ice-rich coasts of the Arctic, that is, mostly those located at lower latitudes (although, as seen in the results section, the distribution of ground ice is spatially variable and it can also occur in quantity at high latitudes as well). Our results suggest that the regions most sensitive to a potential increase in permafrost and sea surface temperatures are the US Beaufort Sea, the US Chukchi Sea, the Canadian Beaufort Sea, and the Kara Sea. In most cases, this effect will be less important than the impact from coastal storms, but it could become prominent in isolated local situations such as low-lying ice-rich coasts from Alaska (Jones et al. 2009a; 2009b).

Conclusion

The ACD classification of Arctic coasts is a first attempt to adopt a common framework to characterize the coasts of the Arctic at high resolution and to extract statistics relevant to other branches of climate science. As part of this study, over 1,000 segments were created, described and assembled in a spatial geodatabase from which the following set of findings can be extracted:

- 34% of the world's coasts are affected by permafrost and therefore subject to a completely different set of processes that interact with climate drivers, as compared with temperate seas.
- Arctic coasts are on average 8.4 m high, but a comparison between the different arctic seas shows that backshore elevations vary regionally between 1.5 and 14.5 m.
- Ground ice contents range between 0% and 70 vol% along the Arctic coast, averaging 19 vol% with a strong regional positive bias towards the Canadian Beaufort, the US Beaufort, and the US Chukchi Seas.
- Organic carbon contents in coastal exposures are on average ca. 2.0 wt.%, but vary regionally, and reach up to 5.7 wt.% on the US Beaufort Sea coast, where the most detailed data are available.
- The average rate of erosion for the arctic coast is 0.5 m $year^{-1}$, but erosion also varies dramatically locally and regionally with peaks above 3 m $year^{-1}$ in the Laptev, East Siberian, US Beaufort, and Canadian Beaufort Seas.
- Erosion appears to be driven by a multiplicity of factors that interact locally to widely varying extents.

Arctic coastlines are likely to undergo dramatic changes in a warming climate, affecting both biophysical and human systems, with countless impacts ranging from threats to infrastructure to changing biological environments affecting wildlife. Erosion is responsible for substantial fluxes of carbon and probably contaminants to the marine environment, which in turn can potentially alter the near-shore carbon cycle and affect several trophic levels. The dynamic nature of coastal erosion and its coupling with climate variables could thereby result in increasing fluxes of sediment from the coast. This dataset could help to quantify sediment, nutrient and contaminant fluxes in the future. In addition, it could include historical information on coastal erosion, based on physical data or traditional knowledge to provide it with a time dimension. In short, it opens the path for the integration over the years to come of a wider set of parameters and outputs than those presented in this paper.

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Appendix A

Classification nomenclature. Each segment of the classification was assigned a set of characteristics based on this table.

Table 3 Classification nomenclature. Each segment of the classification was assigned a set of characteristics based on this table

Field name	Field database name	Field type	Entry options
Identifiers			
Segment code	seg_code	Number	Sea code followed by Segment number
Segment	seg_name	Text	Local place names

Table 3 (continued)

Field name	Field database name	Field type	Entry options
name			
Segment number	seg_number	Number	
Regional sea code	sea_code	Number	10: Russian Chuckchi Sea west of the antemeridian
			11: Russian Chuckchi Sea east of the antemeridian
			12: American Chuckchi Sea
			20: American Beaufort Sea
			30: Canadian Beaufort Sea
			40: Greenland
			41: Canadian Archipelago
			50: Russian Barents Sea
			51: Svalbard
			52: Norwegian Barents Sea
			60: Kara Sea
			70: Laptev Sea
			80: East Siberian Sea
Sea name	sea_name	Text	See Regional sea code
Primary contact person	contact	Text	Name of primary contact person
Mappers	mappers	Text	Names of individuals involved in segmenting the shoreline and populating the fields
Sources	sources	Text	References used to populate the fields
Comments	comments	Text	General comments on the segment
Data quality (DQ) comments	com_dq	Text	General comments on data quality
Segment comment	seg_com	Text	Comments referring to the segmentation process
Geomorphology			
Onshore form	ons_form	Text	Delta: d
			Lowland (<10m): l
			Upland (10-500 m): u
			Highland (>500 m): h
			Wetland: w
Onshore comment	ons_com	Text	Comments referring to the onshore form
Backshore form	bak_form	Text	Cliff: c
			Slope: s
			Flat: f
			Ridged/terraced: r
			Anthropogenic: a
			Complicated: x
Backshore elevation	bak_elev	Number	Elevation of the backshore in meters
DQ	bak_el_dq	Text	Data quality of backshore

Table 3 (continued)

Field name	Field database name	Field type	Entry options
Backshore elevation			elevation
			Low: l
			Medium: m
			High: h
Backshore material 1	bak_mat1	Text	Lithification stage
			Lithified: l
			Unlithified: u
Backshore material 2	bak_mat2	Text	Material type
			Mud-dominated: m
			Sand-dominated: s
			Gravel-dominated: g
			Diamict: d
			Organic: o
Backshore comment	back_com	Text	Comments referring to the backshore form
Shore form	sho_form	Text	Beach: b
			Shore terrace: t
			Cliff: c
			Complicated: x
Beach form	bea_form	Text	Field to be filled if shore form is a beach
			Fringing: f
			Barrier: b
			Spit: s
Shore material 1	sho_mat1	Text	Lithification stage
			Lithified: l
			Unlithified: u
Shore material 2	sho_mat2	Text	Material type
			Mud-dominated: m
			Sand-dominated: s
			Gravel-dominated: g
			Diamict: d
			Organic: o
Shore comment	sho_com	Text	Comments referring to the shore form
Depth closure	dep_clos	Number	Depth closure in meters
Distance to 2-m isobath	iso_2m	Number	Distance to 2 m isobath orthogonal to the shoreline
Distance to 5-m isobath	iso_5m	Number	Distance to 5 m isobath orthogonal to the shoreline
Distance to 10-m isobath	iso_10m	Number	Distance to 10 m isobath orthogonal to the shoreline
Distance to 100-m isobath	iso_100m	Number	Distance to 100 m isobath orthogonal to the shoreline
Offshore material	off_mat	Text	Material type
			Mud-dominated: m

Table 3 (continued)

Field name	Field database name	Field type	Entry options
			Sand-dominated: s
			Gravel-dominated: g
			Diamict: d
			Organic: o
Cryolithology			
Ground ice 1	ice1	Text	Volumetric ground ice content in categories
			Poor (0-2 %): p
			Low (2-20%): l
			Medium (20-50%): m
			High (>50%): h
Ground ice 2	ice2	Number	Volumetric ground ice content in %
DQ ground ice 2	ice2_dq	Number	Data quality of Ground ice 2
			Low: l
			Medium: m
			High: h
Ground ice comment	ice_com	Text	Comments referring to ground ice contents
Dry bulk density	bulk_den	Number	Dry bulk density of enclosing sediments in t/m³
DQ dry bulk density	bulkd_dq	Text	Data quality of dry bulk density
			Low: l
			Medium: m
			High: h
Geochemistry			
Organic carbon	oc	Number	Organic carbon content in weight %
DQ organic carbon	oc_dq	Text	Data quality of organic carbon content
			Low: l
			Medium: m
			High: h
Soil organic carbon	soc	Number	Soil organic carbon content in kg/m²
DQ soil organic carbon	soc_dq	Text	Data quality of soil organic carbon content
			Low: l
			Medium: m
			High: h
Coastal erosion			
Coastal change rate	rate	Number	Coastal change rate in m/yr.
			Erosion: positive values
			Accumulation: negative values
Interval of observation	rate_int	Text	Interval of observation used to compute coastal change rate in years
DQ coastal change	rate_dq	Text	Data quality of coastal change rate
			Low: l
			Medium: m
			High: h
Dynamic process	dyn_proc	Text	Dynamic process at the land-sea interface Field to be filled if coastal erosion rate is unavailable
			Erosive: e
			Stable: s
			Accumulative: a

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