Permafrost, Phillips, Springman & Arenson (eds)
© 2003 Swets & Zeitlinger, Lisse, ISBN 90 5809 582 7

A Geo Information System (GIS) for Circum-Arctic coastal dynamics

V. Rachold & M. Lack
Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Germany

M.N. Grigoriev
Permafrost Institute, Siberian Branch of the Russian Academy of Sciences, Yakutsk, Russia

ABSTRACT: Coastal erosion forms a major source of the sediment, organic carbon and nutrient flux into the arctic basin. Recent studies indicate that sediment input resulting from the erosion of ice-rich, permafrost-dominated coasts might be equal to or greater than river input. The program Arctic Coastal Dynamics (ACD) has been developed to improve our understanding of circum-arctic coastal dynamics as a function of environmental forcing, coastal geology, geocryology and morphodynamic behavior. Under this framework a circum-arctic Geo Information System (GIS) has been developed, which is applied to display generalized information on coastal characteristics and to analyse coastal material fluxes. The coastal GIS is based on a digital elevation model, which was constructed from the International Bathymetric Chart of the Arctic Ocean, and permafrost parameters adopted from the Circumpolar Active-Layer Permafrost System. A segmentation of the Laptev Sea coastline was performed as a first step towards a GIS-based quantification of the sediment and total organic carbon (TOC) fluxes resulting from coastal erosion.

1 INTRODUCTION

The arctic coastal zone is the interface between permafrost-affected sediments and the wave and sea-ice controlled marine system. The arctic coastlines are highly variable and their dynamics are a function of environmental forcing, coastal geology, geocryology and morphodynamic behavior. Recent studies conducted in both the Beaufort and Laptev Seas indicate that considerable sections of the coasts are retreating and that coastal erosion forms an important source of arctic marine sedimentation (Reimnitz et al. 1988, Are 1999, Rachold et al. 2000). The ice-rich, permafrost-dominated coastlines of the Siberian Arctic are, in particular, rapidly eroded and it is assumed that in some regions the resulting material flux exceeds the riverine sediment and total organic carbon (TOC) input to the Arctic Ocean (Grigoriev & Rachold in press). The identification and understanding of the key processes controlling arctic coastal dynamics and the quantification of coastal change rates are therefore essential to decipher and quantitatively assess the recent role of the coasts in the arctic system. This will enable the development of scenarios of arctic coastal change and its effect on the Arctic and the global system in the future.

In order to improve our understanding of circum-arctic coastal dynamics, the multi-disciplinary, multi-national program Arctic Coastal Dynamics (ACD) has been initiated under the aegis of the International Permafrost Association (IPA), its working group on Coastal and Offshore Permafrost and its Coastal Erosion subgroup (Brown & Solomon 2000). A phased 5-year Science and Implementation Plan has been developed (IASC Arctic Coastal Dynamics 2001) and the ACD program was accepted as an official project of the International Arctic Sciences Committee (IASC). The major objectives of ACD are to:

- establish the rates and magnitudes of erosion and accumulation of arctic coasts.
- develop a network of long-term monitoring sites including local community-based observational sites.
- identify and undertake focused research on critical processes.
- estimate the amount of sediments and TOC derived from coastal erosion.
- refine and apply an arctic coastal classification (includes ground-ice, permafrost, geology etc.) in digital form (Geo Information System, GIS).
- extract and utilize existing information on relevant environmental forcing parameters (e.g. wind speed, sea level, fetch, sea ice etc.).
- produce a series of thematic and derived maps (e.g. coastal classification, ground-ice, sensitivity etc.).
- develop empirical models to assess the sensitivity of arctic coasts to environmental variability and human impacts.

In the first part of this article we present a circum-arctic GIS to display generalised information on arctic coasts, which has been developed according to the ACD Science and Implementation Plan. The second part of the paper concentrates on a GIS-based analysis, which was applied to estimate the sediment and TOC input through coastal erosion. As a first step towards a circum-arctic assessment, a segmentation and classification of the coastline of the Laptev Sea has been performed and annual sediment and TOC fluxes are reported.

2 STRUCTURE AND CONTENT OF THE CIRCUM-ARCTIC COASTAL GIS

A digital elevation model (DEM) forms the basis of the circum-arctic coastal GIS. To establish this DEM, data of the International Bathymetric Chart of the Arctic Ocean (IBCAO), which are available in ASCII format (x, y, z) on the Internet (www.ngdc.noaa/mgg/bathymetry/artic/arctic.html), were used. The data were imported into ArcView/ArcInfo and transferred to a GRID with a spatial resolution of 2.5×2.5 km. The Lambert Azimuth Equal Area Projection with the North Pole in the center (0,0) has been selected.

Permafrost parameters adopted from the CircumPolar Active-Layer Permafrost System CD-ROM were incorporated and are available in a separate layer.

In accordance with the recommendations given in the ACD Science and Implementation Plan, up to now 20 key monitoring sites have been established. For those sites detailed metadata information (site location and description, observational methods and periods, oceanographic and meteorological conditions, photographs etc.) are available. The key monitoring sites and the metadata information are available at the ACD web

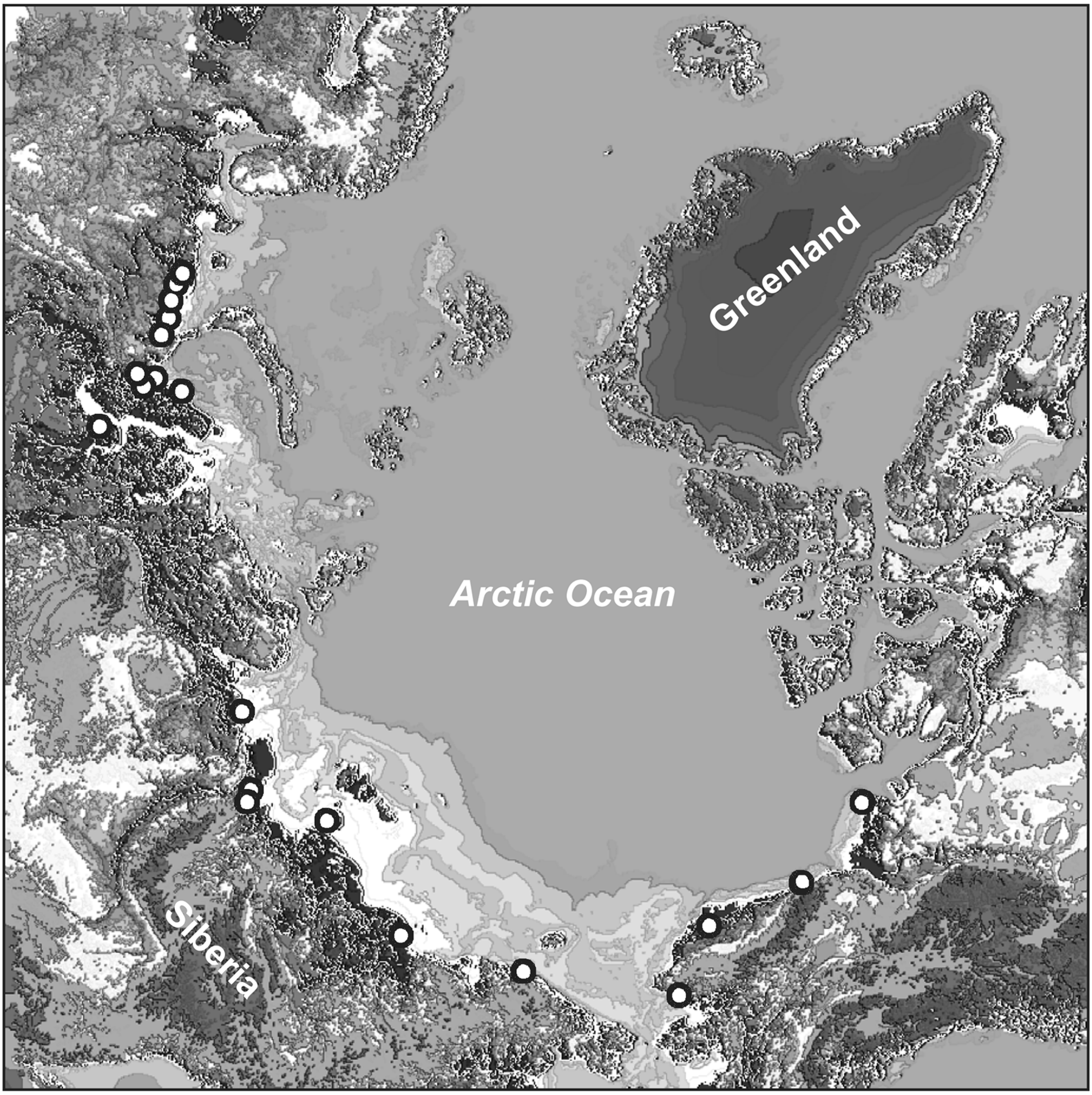

Figure 1. ACD key sites and digital elevation model.

site (www.awi-potsdam.de/www-pot/geo/acd.html) and have been added to the circum-arctic GIS.

Figure 1 shows the digital elevation model of the circum-arctic coastal GIS and the location of the current key monitoring sites. The detailed metadata information for each key site can be displayed by clicking on the point.

This first version of the circum-arctic coastal GIS presented here will be extended in the following years. A coastal classification (including ground-ice, permafrost, geology etc.), which forms the basis to produce thematic maps, will be added.

3 ANALYSIS OF THE COASTAL EROSION SEDIMENT AND TOC FLUXES TO THE LAPTEV SEA (SIBERIAN ARCTIC)

The quantification of the sediment and TOC flux through coastal erosion is based upon simple geometric considerations and requires a segmentation of the coastline and a knowledge of 6 basic parameters for each individual segment. If the coast is divided into segments and for each segment the parameters (1) shoreline length, (2) cliff height and (3) coastal retreat rate are known, then the volume of the eroded material can be easily calculated for each segment (Fig. 2). It should be noted that for accumulative coasts, i.e. river deltas, we used a negative retreat rate and negative values for the sediment and TOC flux. The obtained estimates of the coastal material flux can be transferred into the coastal sediment and TOC flux considering (4) average ice content, (5) dry bulk density and (6) TOC concentrations of the sediments. In principle, the procedure is relatively simple but requires some steps, which are discussed in more detail later.

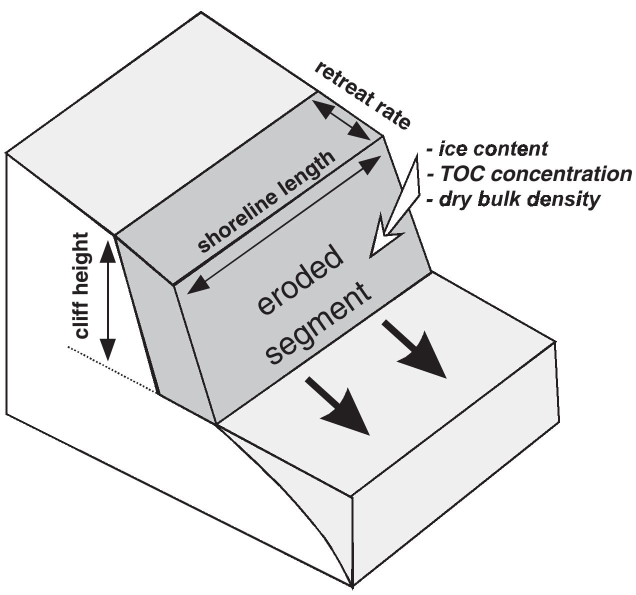

Figure 2. Schematic illustration of an eroded coastal segment and the 6 parameters considered for the quantification of the sediment and TOC flux through coastal erosion.

As a first step, the coastline had to be divided into homogeneous segments depending on where there are substantial changes in morphology, coastal change rates (i.e. coastal retreat rates), sediment texture, ice content or TOC concentration. This means that all parameters, which have an influence on the sediment or TOC flux, must be constant within each individual segment. For the Laptev Sea this segmentation was performed based on a combination of field studies conducted over the last few years (Grigoriev et al. in prep., Pfeiffer & Grigoriev 2002, Rachold 2000, Rachold & Grigoriev 2001) and the analyses of topographic and geological maps of different scales. A total number of 75 coastal segments were identified (Fig. 3), each of which was defined by its start and end coordinates.

The second step involved the classification of each segment in respect of the parameters, upon which the calculation is based. Thanks to the extensive field work, which had been performed in the Laptev Sea coastal region during the last few years, we were able to classify many segments regarding the cliff height, coastal change rate, average ice content, dry bulk density and TOC concentration based on data already compiled. Additional information on cliff height was obtained from topographic maps. It must be noted however that for several segments no field data were available. Those segments were preliminarily classified on the basis of topographic and geological maps. The parameters of similar coastal types, for which field data were available, could then be assigned to the unknown segments.

After all segments had been satisfactorily classified, the final step was to import the information on the segments into the coastal GIS to determine the shoreline lengths of the segments. The start and end coordinates were imported into the GIS and their positions were manually corrected to exactly match the digital coastline. The ArcView extension "network analyst" was applied to quantify the shoreline length of each segment. Offshore islands attributed to the segments were treated separately and their shoreline lengths were added to that of the mainland for each segment.

Finally, the sediment and TOC input was quantified for each segment and the sum for all 75 segments represents our current estimate of the fluxes to the Laptev Sea: 71.9×10^6 t/y of sediment and 2.3×10^6 t/y of TOC are imported through coastal erosion. Our previous estimates, which were based on a combination of available key sites information and the analyses of topographic maps, had been 58.4×10^6 t/y of sediments and 1.9×10^6 t/y of TOC (Grigoriev & Rachold this volume) and are in general agreement.

Figure 3. Segmentation of the Laptev Sea coastline, which was performed based on a combination of own field studies and the analyses of topographic and geological maps (see text).

We are aware however that our new estimates still contain a considerable error due to several uncertainties:

1. The data base for the classification is incomplete and for several segments empirical values had to be applied.
2. The calculation does not take into account the erosion of the shoreface but only deals with subaerial erosion. In the Laptev Sea however the shallow coastal regions with water depths of <10 m are undergoing erosion as well (Are et al. 2002).
3. The shoreline length of the coastal segments was determined on the basis of the World Vector Shoreline, which had been generated from maps with a scale of 1:250,000. It is well known that as a result of the so-called fractal error the actual length of the shoreline can be considerably larger.
4. It should be noted that our estimates correspond to the gross coastal erosion fluxes, presently we have no information about the fate of the sediments and organic matter derived from coastal erosion once they enter the shelf.

Due to the multitude of possible errors we are not in the position to provide an accurate error analysis. The agreement between our GIS-based values and the conservative estimate indicates however that at least the order of magnitude is correct.

The results confirm that in the Laptev Sea the coastal erosion sediment input exceeds the river input (28.6×10^6 t/y, Holmes et al. in press). The TOC flux through coastal erosion cannot be neglected although the riverine TOC flux is considerably larger (6.8×10^6 t/y, Gordeev & Rachold in press).

4 OUTLOOK

In the near future the coastal segmentation as presented here for the Laptev Sea will be performed for the entire circum-arctic coastline. Following the recommendations given in the report of the 2nd ACD workshop (Rachold et al. 2002), regional experts will apply a coastal mapping template to their coastal sector and the web-deliverable data system PANGAEA (www.pangaea.de) will be used to make the complete data set available. For further GIS based analyses the coastal data can be exported from the PANGAEA system.

To check the accuracy of the GIS determination of the length of the coastline (fractal error), GIS-experts will compare the values obtained on the basis of the World Vector Shoreline with that obtained from high-resolution digital coastlines, which are available for test areas.

Finally, the circum-arctic coastal segmentation and classification, which forms the basis for the production of thematic and derived maps, will be accompanied by focused research on critical processes (e.g. shoreface erosion, fate of eroded material) and the extraction of relevant environmental forcing parameters in the framework of the ACD program.

ACKNOWLEDGEMENTS

This study was supported by the International Arctic Sciences Committee (IASC project "Arctic Coastal Dynamics"), by the International Permafrost Association (IPA), by the German Ministry of Education and Research (BMBF) and the Russian Ministry of Research and Technology within the project "Laptev Sea 2000". Constructive comments of the reviewers Stephan Gruber and Viktor Kaufmann and the review editor Andy Kaeaeb are greatly appreciated.

REFERENCES

Are, F.E. 1999. The role of coastal retreat for sedimentation in the Laptev Sea. In H. Kassens., H. Bauch, I. Dmitrenko, H. Eicken, H.-W. Hubberten, M. Melles, J. Thiede & L. Timokhov (eds), *Land-Ocean systems in the Siberian Arctic: dynamics and history*: 287–299. Berlin: Springer.

Are, F.E., Grigoriev, M.N., Hubberten, H.-W., Rachold, V., Rasumov, S. & Schneider, W. 2002. Comparative shoreface evolution along the Laptev Sea coast. *Polarforschung 70*: 135–150.

Brown, J. & Solomon, S. (eds.) 2000. Arctic Coastal Dynamics – Report of an International Workshop, Woods Hole, MA, November 2–4, 1999. *Geological Survey of Canada Open File* 3929.

Gordeev, V.V. & Rachold, V. in press. Modern terrigenous organic carbon input to the Arctic Ocean – river input. In R. Stein & R.W. Macdonald (eds), *Organic Carbon Cycle in the Arctic Ocean: Present and Past.* Berlin: Springer.

Grigoriev, M.N. & Rachold, V. in press. The degradation of coastal permafrost and the organic carbon balance of the Laptev and East Siberian Seas. *This volume.*

Grigoriev, M.N., Rachold, V., Bolshianov, D. Yu., Schirrmeister, L., Pfeiffer, E.-M. & Hubberten, H.-W. in prep. Russian-German Cooperation System Laptev Sea 2000: The Expedition LENA 2002. *Reports on Polar Research.*

Holmes, M.R., McClelland, J.W., Peterson, B.J., Shiklomanov, I.A., Shiklomanov, A.I., Zhulidov, A.V., Gordeev, V.V., Bobrovitskaya, N.N. in press. A circumpolar perspective on fluvial sediment flux to the Arctic Ocean. *Global Biogeochemical Cycles.*

IASC 2001. *Arctic Coastal Dynamics (ACD) – Science and Implementation Plan.* Oslo: International Arctic Sciences Committee.

Pfeiffer, E.-M. & Grigoriev, M.N. 2002. Russian-German Cooperation System Laptev Sea 2000: The Expedition LENA 2001. *Reports on Polar Research* 426.

Rachold, V. (ed) 2000. Expeditions in Siberia in 1999. *Reports on Polar Research* 354.

Rachold, V., Grigoriev, M.N., Are, F.E., Solomon, S., Reimnitz, E., Kassens, H. & Antonow, M. 2000. Coastal erosion vs. riverine sediment discharge in the Arctic shelf seas. *Intern. J. of Earth Sciences* 89: 450–460.

Rachold, V. & Grigoriev, M.N. 2001. Russian-German Cooperation System Laptev Sea 2000: The Expedition LENA 2000. *Reports on Polar Research* 388.

Rachold, V., Brown, J. & Solomon, S. 2002. Arctic Coastal Dynamics – Report of an International Workshop, Potsdam (Germany) 26–30 November 2001. *Reports on Polar Research* 413.

Reimnitz E, Graves S.M. & Barnes, P.W. 1988. Beaufort Sea coastal erosion, sediment flux, shoreline evolution and the erosional shelf profile. *U.S. Geological Survey*: Map I-1182-G and text.