A scientifically-driven approach for the sustainable development of Arctic coastal zone

Wojciech Sulisz[1], Lechosław Suszka[2], Maciej Paprota[3], Duje Veic[4], Dawid Majewski[5], Marek Szmytkiewicz[6]

[1] Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland, sulisz@ibwpan.gda.pl
[2] Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland, lechoslawsuszka@ibwpan.gda.pl
[3] Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland, mapap@ibwpan.gda.pl
[4] Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland, dujeveic@ibwpan.gda.pl
[5] Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland, d.majewski@ibwpan.gda.pl
[6] Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland, mareksz@ibwpan.gda.pl

Abstract

The Arctic coast has been strongly influenced by the effects of climate changes. Accelerating global warming and impact of storms imply a rapid permafrost degradation and drastic shoreline retreat in an Arctic coastal zone. In many regions shoreline retreat exceeds 30 meters per year. Impact of storms on permafrost coast causes much faster processes than it has been expected. These processes impose large impacts on social and economic conditions in the region including quality of life, housing, infrastructure and developments. The observed processes significantly affect activities in the Arctic area and have also drastic effects on the degradation of glaciers by accelerating breaking and melting processes and, in consequence, accelerate climate changes. More effort is necessary to reduce negative impacts of climate changes on polar areas. These require a new approach to predict and control changes in the Arctic coastal environment. It is also worthwhile to develop knowledge on increased coastal erosions through better recognition and understanding of physical processes as well as reliable modelling of permafrost thaw and shoreline shift. A novel approach to this problem has been proposed and its programme is currently under implementation. The approach is based on original experimental investigations on wave-induced erosion of permafrost, a series of field measurement campaigns, and numerical modelling of erosion processes in Arctic conditions. Extensive experimental studies have been conducted to identify physical processes responsible for increased sediment transport rates of the frozen sandy bottom. Experimental data and theoretical analysis indicate that the new approach provide novel results of significant importance for understanding of erosion processes in polar areas.

Keywords: Climate Changes, Permafrost Erosion, Sediment Transport, Arctic Coasts

1. Introduction

Arctic coastal regions experience nowadays dramatic changes resulting from global warming effects. As a result, rapid permafrost degradation and drastic shoreline retreat modify the topography and bathymetry of the Arctic coastal region. The area of the Arctic Ocean covered by ice constantly decreases and, together with extended season of open waters, results in more severe storms and higher waves approaching polar coasts (Atkinson, 2005). The reduction of shore-fast sea ice is expected to continue as the rise of mean temperature in Arctic region is predicted to reach 2.5 ºC in 50 years and even 7-9 ºC till the end of the century (Kattsov and Källén, 2007). As the presence of ice limits the effect of waves and storm surges actions on the Arctic coast, duration of the open water season (OWS) becomes one of the most important factors influencing erosion rate. Lantuit et al. (2012; 2013) claim that, in case of the Arctic coast, an average erosion rate is 0.5 m/year with regional variability. The longer open water season that expanded at a rate of 1.75 day/year over a period 1979-2009, is believed to be responsible for shoreline retreats reaching more than 17 m/year in many areas (Barnhart et al., 2014; Aguirre et al., 2008; Overeem et al., 2011). As a result, the vulnerability of Arctic coasts to geomorphic change, inundation, and damage of infrastructure increases (Barnhart et al. 2014) and the escalated erosion may occur and affect biological and human systems (Rachold et al., 2005). Despite these threats, coastal dynamics of polar areas are still not sufficiently recognised and are seldom modelled (Lantuit et al., 2012; Reda et al., 2015).

A new approach to the problem of the erosion of the Arctic coasts arising from climate changes was introduced in the frame of an ARCOASTS project (Reda et al., 2015, Sulisz et al. 2015). The primary motivation of the study was the development of appropriate tools for the Arctic coastal protection and management taking into account limited amount of data on wave climate, geomorphology, etc. The special attention was given to the effect of ocean waves and current on permafrost thaw, shoreline shift, and sediment transport (Paprota et al., 2016, Majewski et al., 2016, Sulisz and Paprota, 2016). The main objective of the project was to recognize physical processes responsible for erosion of the Arctic shore including sediment transport, permafrost vulnerability to erosion, thermodynamic processes in polar waters induced by sea waves, and the reduction of sea ice. Therefore, new methods were developed in order to achieve defined goals.

In the present study an original methodology is applied to assess vulnerability of the polar coastlines to erosion and to provide data for policymakers, stakeholders, and end-users involved in integrated coastal zone management of polar regions. It is a common practice in handling this kind of complex problems to introduce indexes or indicators facilitating a description of a complicated system affected by many physical processes and their interdependences in a different spatial and temporal scales. Taking into account specific nature of the polar environment, an extended Polar Coastal Risk Index (PCRI) is introduced to characterise the coastlines of the Arctic area with respect to their vulnerability to erosion. In the next section, a description of various tools used for coastal vulnerability assessment are provided and the definition of the Polar Coastal Risk Index is presented. Then, the results of the application of the PCRI approach to the arctic coastline are discussed and compared with the previous studies on PCRI calculated by applying a lower number of risk parameters. Finally, the consequences of using original and extended PCRI index are summarised and the conclusions are specified..

2. Methods

The problem of the vulnerability to erosion of coasts at different temporal and spatial scales may be addressed by applying (Ramieri et al., 2011): (a) index-based methods (Gornitz, 1990; Gornitz et al., 1991), (b) indicator-based approaches (Marchand et al., 2010), (c) GIS-based decision support techniques (Mocenni et al., 2009; Schirmer et al., 2003), and (d) methods based on dynamic computer models (Hinkel, 2005; Hinkel et al., 2010). The problem is that available approaches cannot be directly applied to the Arctic region. An apparent need to develop a new scientifically-driven approach to incorporate processes characteristic for polar regions into coastal erosion management motivated the present study.

The analyses of available data led to the conclusion that in case of polar regions it is reasonable to use an index-based method for coastal erosion risk assessment (Sulisz et al., 2017). Therefore, a concept of Polar Coastal Risk Index (PRCI) is introduced to evaluate spatial risk distribution of the whole Arctic coastline. The PCRI is calculated as a square root of a product of ranked variables (x_n) divided by the number of variables (N), namely:

$$PCRI_N = \sqrt{\prod_{n=1}^{N} x_n} \qquad (1)$$

Variables, x_n, represent geomorphology of the coast, erosion rate (m/year), coastal slope (°), wave climate defined by a representative wave height (m), surge height (m), mean tidal range (m), duration of an open water season (%), ground ice content (%). A sea level rise, which is often included in vulnerability assessment in other studies, is neglected as it is about three orders of magnitude lower than the height of waves and surges. The proposed PCRI covers two additional region-specific variables: the duration of the open water season and ground ice content which are defined as a percentage of the total time and volume, respectively. The presence of shore-fast sea ice results in weaker erosion of coasts caused by waves due to limited fetch of wind energy transfer to waves. The ground ice content is another variable, which is particularly important in ice rich permafrost bluffs (Barnhart et al., 2014). The presented Table 1 includes all considered PCRI component variables that are relevant to polar coastal erosion risk assessment.

Table 1. *Risk ranking of PCRI component variables.*

VULNERABILITY	**Very low**	**Low**	**Moderate**	**High**	**Very high**
VARIABLE	**1**	**2**	**3**	**4**	**5**
a) Geomorphology	Cliffs		Shore terraces	Flat beaches	Deltas, lagoons
b) Erosion rate (m/year)	<-0.50	-0.50- 0	0-0.5	0.5-1.5	>1.5
c) Coastal slope (º)	> 1.50	0.75-1.50	0.25-0.75	0.12-0.25	≤ 0.12
d) Wave height (m)	<2.5	2.5-3.5	3.5-5	5-6.5	>6.5
e) Surge height (m)	< 0.45	0.45-0.60	0.60-0.83	0.83-1.05	≥ 1.05
f) Mean tide range (m)	> 1.00	0.70-1.00	0.35-0.70	0.25-0.35	≤ 0.25
g) Duration of open water season (%)	< 30	30-40	40-55	55-80	> 80
h) Ground ice content (%)	≤ 10	10-20	20-30	30-50	>50

The set of available values is split into five subsets corresponding to a comparable length of a coastline. The subsets are assigned a particular risk in increasing order. A value of 1 corresponds to the lowest and 5 to the highest risk. A risk ranking is assigned to ranges of numerical variables, while the non-numerical geomorphology variable is ranked according to the relative resistance of a given landform to erosion.

3. Results and discussion

Two databases coupled together consist of 1984 segments covering the whole Arctic coastline. Unfortunately, some information is missing for a certain number of segments. A set of 369 segments lack the data on geomorphology, 589 segments on erosion rates, and 259 segments do not include data on ground ice content. Therefore, the indexes are calculated in two different ways. The first PCRI-6 corresponds to whole set of segments, but includes only six component variables - neglecting the erosion rate and the ground ice content variables. The second PCRI-8 is calculated based only on a limited number of segments having complete information.

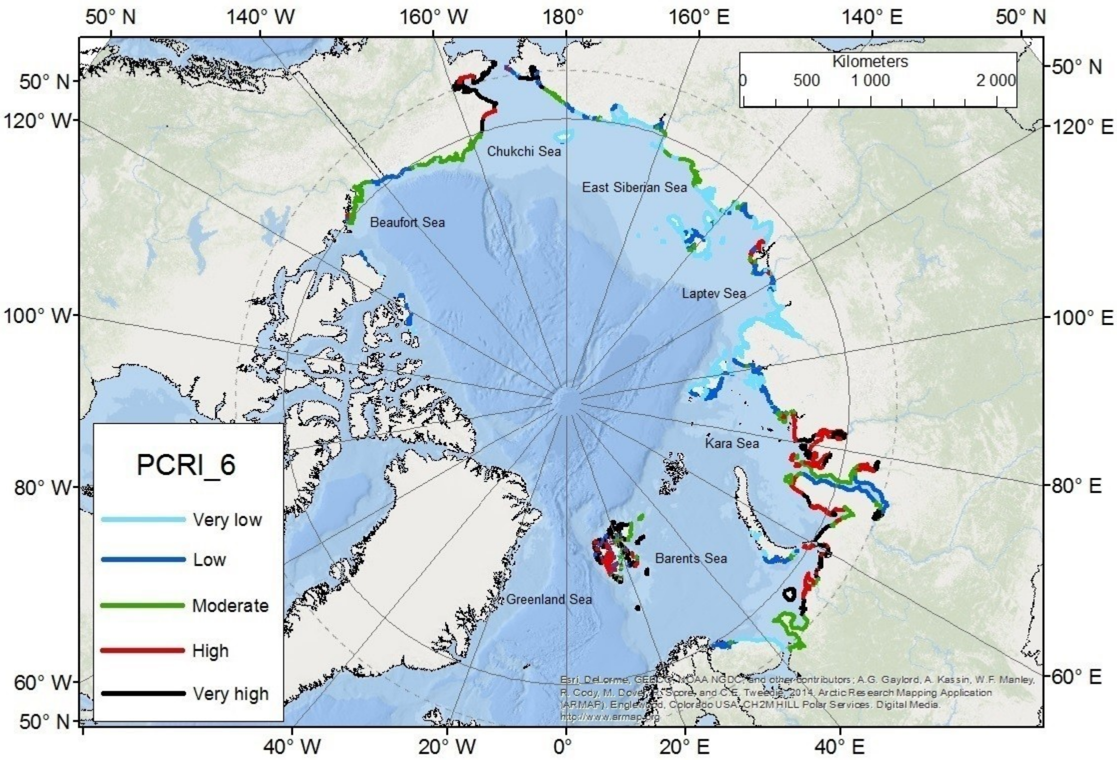

Figure 1. *Polar Coastal Risk Index PCRI-6 along the Arctic coastline.*

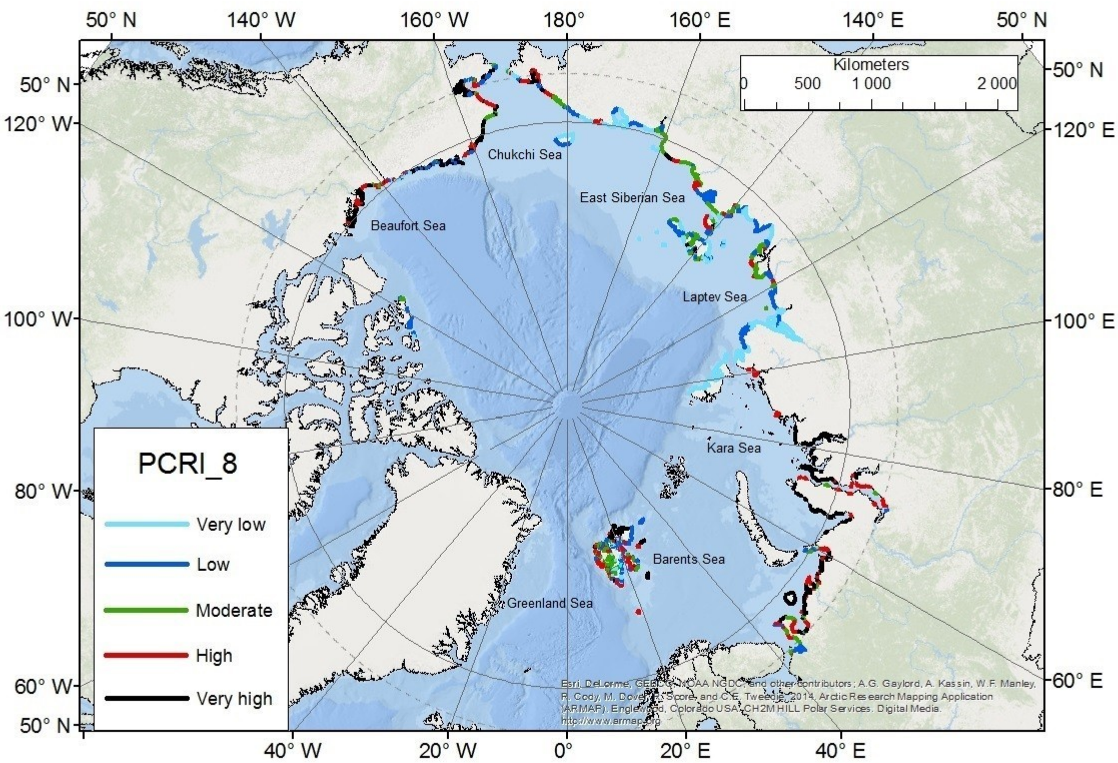

Figure 2. *Polar Coastal Risk Index PCRI-8 along the Arctic coastline.*

The vulnerability to erosion of the arctic coastline is assessed separately for PCRI-6 and PCRI-8. In Fig. 1, 1604 segments of the calculated PCRI-6 values are displayed. PCRI-6 ranges from 1.15 to 22.36 and the mean PCRI-6 value is equal to 7.46. Fig. 3 shows the variability of the calculated PCRI-6 along the coastline for 1241 segments. The PCRI-8 value ranges from 1.41 to 54.77 while the mean PCRI-8 value is 12.73. The contours of coastlines without colors represent the segments with missing information on one or more variables.

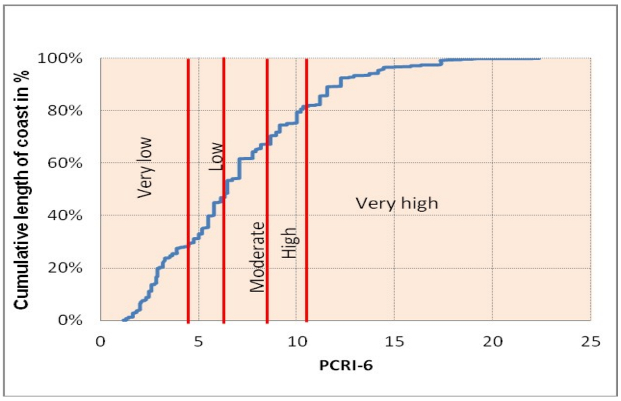

Figure 3. *Cumulative distribution of PCRI-6.*

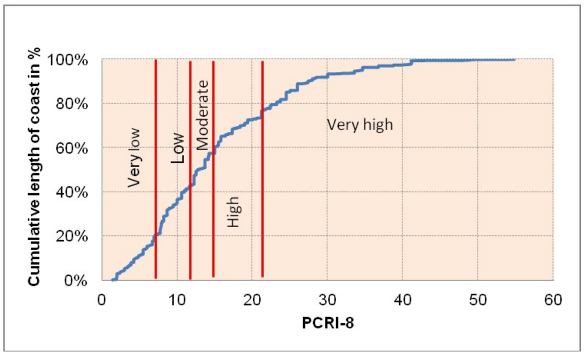

Figure 4. *Cumulative distribution of PCRI-8.*

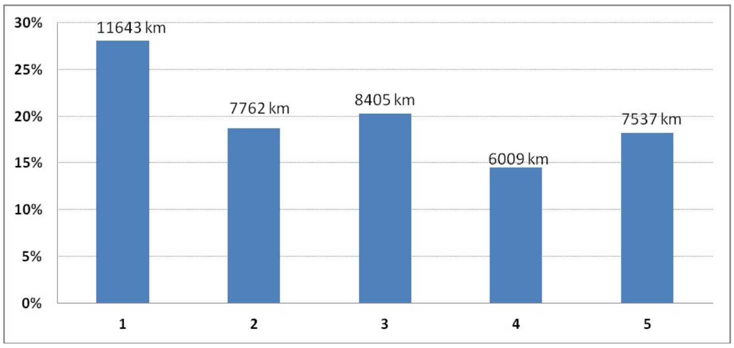

Figure 5. *Length of the shoreline in each risk category for PCRI-6.*

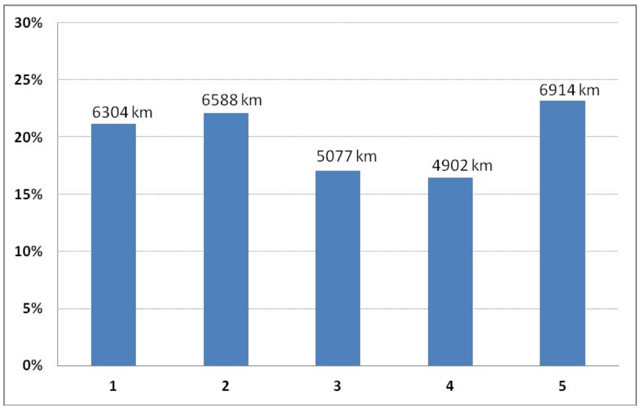

Figure 6. *Length of the shoreline in each risk category for PCRI-8.*

The cumulative distributions of PCRI-8 and PCRI-8 values are presented in Figs. 3 and 4. In Figs. 5 and 6, the bar graph indicating the length of the Arctic coastline in each risk category is plotted. The PCRI values are split into very low, low, moderate high, and very high risk categories based on approximately equal coastline length. Calculated PCRI-6 and PCRI-8 vary along the coast. The highest calculated risks for both indexes cover Russian coast of the Barents Sea, the western coast of the Yamal Peninsula, the coast of the Kara Sea, the northern coast of Alaska and some fragments of the Spitsbergen Archipelago, including the northern coast of the Nordaustlandet Island and the smaller islands of eastern Spitsbergen. Additionally, the highest value of PCRI-6 covers the western coast of Alaska and the northern coast of the Chukchi Peninsula in Russia and also the coast of the Kara Sea for which PCRI-8 is missing due to the lack of information on erosion rates. The simplified PCRI-6 index can be used to determine the most vulnerable coastlines in case of a lack of all necessary values to calculate PCRI-8. The lowest calculated values of PCRI-8 vary spatially in the similar way as the highest ones. They cover the coastlines of the East Siberian Sea, the Laptev Sea, the Greenland Sea and the Canadian Archipelago and some small fragments of Alaska coasts. Additionally, the PCRI-6 index indicates the lowest risk for some fragments of the Kara Sea which were overlooked by PCRI-8 index due to missing erosion rate data. In Table 2 the coastline length for all calculated risk categories are presented separately for each Arctic sea.

Table 2. *Length of coastline in subsequent risk categories.*

		PCRI-6					PCRI-8						
Sea	**Risk rank**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**No of all segments**	**Length of all segments [km]**
Barents Sea		6,7	7,6	12,6	7,4	9,0	0	3,3	4,6	5,6	11,5	265	11 567
Canadian Beaufort Sea		0,2	13,6	46,1	0,8	0	0	0,1	3,6	15,5	33,8	104	2 195
Chukchi Sea		21,7	26,6	24,8	3,7	36,1	13,3	18,2	20,7	29,0	19,0	44	1 381
East Siberian Sea		63,1	20,0	16,9	0	0	29,3	33,0	26,3	8,0	3,4	104	5 338
Greenland Sea and Canadian Archipelago		3,3	10,3	0	0	0	0,3	10,6	2,6	0	0	152	2 418
Kara Sea		8,8	21,6	14,6	20,3	14,3	0,1	0,1	0,4	4,0	10,6	477	14 793
Laptev Sea		76,7	12,1	6,8	4,4	0	54,6	25,4	16,0	3,6	0,4	199	7 398
Svalbard		0	0	10,4	6,3	32,8	7,8	24,7	23,3	25,1	19,1	478	5 102
US Beaufort Sea		0,7	23,7	75,6	0	0	7,0	21,0	3,2	12,0	56,8	75	1 013
US Chukchi Sea		0	0	21,0	12,7	66,4	1,6	15,1	9,7	24,2	49,4	76	2 524

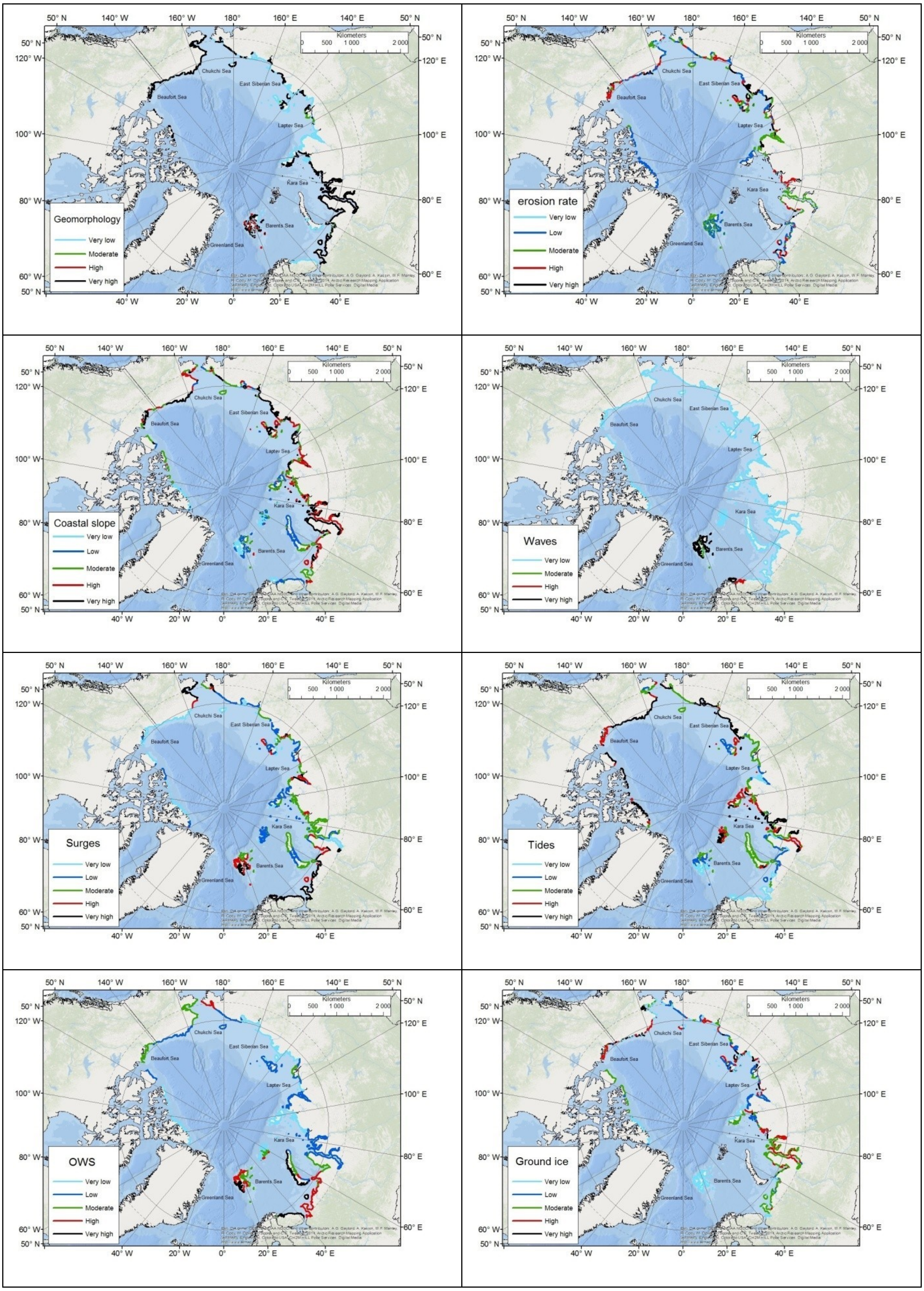

Figure 7. *PCRI component variables along the Arctic coastline.*

The values of the PCRI components along the Arctic coastline are presented in Fig. 9. The maps provide information on risk corresponding to geomorphology, erosion rate, coastal slope, wave climate, surges, tide ranges, the period of open water season, and ground ice content. With regard to geomorphology the lowest risk was assigned to 24.5% of the total length and it covers parts of the Barents Sea, the Laptev Sea, the East Siberian Sea, the Chukchi Sea and Svalbard, whereas 48.4% was assigned to the highest risk and it covers most of the Kara Sea, the Chukchi Sea, the US Chukchi Sea, the Barents Sea and most of Svalbard. The erosion rate describes accretion or erosion in meters per year. Although this variable is of significant importance, only 70% of segments include data on erosion rate. The highest erosion occurs in the Laptev Sea, the East Siberian Sea, the US Beaufort Sea, and in the northern part of Alaska. The coastal slope ranges between 0.006º and 4.77º. The highest coastal slopes occur mainly in the Yamal Peninsula, and along the coast of the East Siberian Sea and the US Beaufort Sea. In turn, the coasts of the Greenland Sea, the Barents Sea and the Severnaya Zemlya Archipelago are characterised by the lowest coastal slopes. As far as the wave climate is concerned, the highest risk corresponding to waves greater than 6.5 m occurs in Svalbard and near the coast of the Barents Sea. Other coasts are assigned lower risk. The surge height corresponding to 1 in 100-year extreme sea level implies the highest risk in the Barents Sea, the western coast of Svalbard and in the US Chukchi Sea. Next variable taken into considerations is the mean tidal range. As it was indicated by Thieler et al. (1999), the macrotides have less influence on inundation than microtides. This concept was used herein. The highest risk has been determined for the coastline of the East Siberian Sea, the US Chukchi Sea, and the Greenland Sea. The lowest risk has been assigned to the Barents Sea, Svalbard, and the Laptev Sea. Based on everyday satellite images of the ice edge in the Arctic available from OSISAF application of EUMETSAT, the percentage of OWS was calculated. For OWS lower than 10% of the total time, the risk value is assumed as equal to 1 and for OWS greater than 50% the risk is equal 5, which means that the ice cover for half of the total time does not sufficiently protect the coastline against wave action. The intermediate OWS values are given in Table 1. Taking into account data from the period 2012-2016, the maximum risk was assigned to the Kola Peninsula, the Novaya Zemlya, and the western coast of Svalbard covering 35% of total Svalbard coastline. The minimum was assigned to the East Siberian Sea where the ice cover was detected for the whole considered period. The maximum risk related to ground ice content may be observed in the coast of Alaska and in several places of Russian coast mainly in the Taymyr Peninsula, the Bykovsky Peninsula, and in the Eastern Oyagoss Cape of the East Siberian Sea. The lowest ground ice content risk is assigned to the coasts of Svalbard, the coasts of the Greenland Sea, the Laptev Sea, and the Chukchi Sea.

4. Conclusions

Climate changes significantly affects the coastlines in Arctic regions. Global warming and an increased impact of storms imply a rapid permafrost degradation and, in consequence, a drastic shoreline retreat in an Arctic coastal zone. A novel approach to assess the vulnerability to erosion for Arctic coastline is proposed. An original concept of a Polar Coastal Risk Index is introduced to facilitate description of wave-induced erosion of polar coastal regions. The PCRI is calculated by applying data from the DIVA and ACD databases. Due to a lack of available data, two PCRI indexes including a different number of component variables are defined. The calculated indexes are applied to the whole Arctic coastline and their ability to reflect a distribution of risk is discussed. The derived concept seems to be better method of determining the vulnerability to erosion for polar coastal regions than previous approaches. The proposed PCRI provides a simple numerical tool for ranking sections of Arctic coastline in terms of their potential for erosion that can be used by managers and policymakers to identify regions where risks may be relatively high.

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References

Aguirre, A., Tweedie, C.E., Brown, J., Gaylord, A., 2008. Erosion of the Barrow Environmental Observatory coastline 2003-2007, Northern Alaska, in: Proceedings of the Ninth International Conference on Permafrost, University of Alaska, Fairbanks, Vol. 1, pp. 7-12.

Atkinson, D.E., 2005. Observed storminess patterns and trends in the circum-Arctic coastal regime. Geo-Marine Letters, 25, 98-109.

Barnhart, K.R., Overeem, I., Anderson, R.S., 2014. The effect of changing sea ice on the physical vulnerability of Arctic coasts. The Cryosphere, 8, 1777-1799.

Gornitz, V.M., 1990. Vulnerability of the East Coast, U.S.A. to future sea level rise. Journal of Coastal Research, Special Issue, 9, 201-237.

Gornitz, V.M., White, T.W., Cushman, R.M., 1991. Vulnerability of the U.S. to future sea-level rise, in: Proceedings of the Seventh Symposium on Coastal and Ocean Management, Long Beach, CA, pp. 2354-2368.

Hinkel, J. 2005. DIVA: an iterative method for building modular integrated models. Advances in Geosciences, 4, 45-50.

Hinkel, J., Nicholls, R., Vafeidis, A., Tol, R., Avagianou, T., 2010. Assessing risk of and adaptation to sea level rise in the European Union: an application of DIVA. Mitigation and Adaptation Strategies for Global Change, 15, 703-719.

Kattsov, V.M., Källén, E., 2005. Future climate change: modelling and scenarios for the Arctic, in: Symon, C., Arris, L., Heal, B. (Eds.), Arctic climate impact assessment, Cambridge University Press, pp. 99-150.

Lantuit, H., Overduin, P.P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D.L., Graves-Gaylord, A., Grigoriev, M., Hubberten, H.W., Jordan, J., Jorgenson, T., Ødegård, R.S., Ogorodov, S., Pollard, W.H., Rachold, V., Sedenko, S., Solomon, S., Steenhuisen, F., Streletskaya, I., Vasiliev, A., 2012. The Arctic Coastal Dynamics Database: A new classification scheme and statistics on Arctic permafrost coastlines. Estuaries and Coasts, 35, 383-400.

Lantuit, H., Overduin, P.P., Wetterich, S., 2013. Recent progress regarding permafrost coasts. Permafrost and Periglacial Processes, 24, 120-130.

Majewski, D., Sulisz, W., Paprota, M., Szmytkiewicz, M., 2016. Water wave measurements at Bellsund in the western Spitsbergen, in: Proceedings of the Sixth International Junior Researcher and Engineer Workshop on Hydraulic Structures, Utah State University, 79-85.

Marchand, M., Sanchez-Arcilla, A., Ferreira, M., Gault, J., Jiménez, J. A., Markovic, M., Mulder, J., Van Rijn, L., Stanica, A., Sulisz, W., Sutherland, J., 2011. Concepts and science for coastal erosion management - an introduction to the Conscience framework. Ocean & Coastal Management, 54, 859-866.

Mocenni, C., Casini, M., Paoletti, S., Giordani, G., Viaroli, P., Zaldivar Comenges, J. 2009. A Decision Support System for the management of the Sacca di Goro (Italy), in: Marcomini A., Suter II G. W., Critto, A. (Eds), Decision Support Systems for Risk-Based Management of Contaminated Sites, Springer, pp. 399-422.

Muis, S., Verlaan, M., Winsemius, H.C., Aerts, J.C.J.H., Ward, P.J., 2016. A global reanalysis of storm surges and extreme sea levels, Nature Communications, 7, 11969.

Overeem, I., Anderson, R.S., Wobus, C.W., Clow, G.D., Urban, F.E., Matell,N., 2011. Sea ice loss enhances wave action at the Arctic coast. Geophysical Research Letters, 38, L17503.

Özyurt, G., Ergin, A., 2009. Application of Sea Level Rise Vulnerability Assessment Model to Selected Coastal Areas of Turkey. Journal of Coastal Research, 2009, 248–251.

Paprota, M., Majewski, D., Sulisz, W., Szmytkiewicz, M., Reda, A., 2015. Effects of climate changes on coastal erosion in Svalbard, in: Proceedings of the Seventh Short Course and Conference on Applied Coastal Research, Florence, 499-508.

Paprota, M., Sulisz, W., Majewski, D., 2016. Wave-induced temperature profile evolution of a frozen sand bottom and its effect on erosion, in: Proceedings of the Twelfth International Conference on Hydrodynamics (ICHD), Egmond aan Zee.

Pickering, M., 2014. The impact of future sea-level rise on the tides. University of Southampton, Ocean and Earth Science, Doctoral Thesis.

Rachold, V., Aré, F.E., Atkinson, D.E., Cherkashov, G., and Solomon, S.M., 2005. Arctic Coastal Dynamics - An Introduction. Geo-Marine Letters, 25, 63-68.

Ramieri, E., Hartley, A., Barbanti, A., Duarte Santos, F., Gomes, A., Hilden, M., Laihonen, P., Marinova, N., Santini, M., 2011. Methods for assessing coastal vulnerability to climate change, European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC CCA) Technical Paper, Bologna (IT) 93.

Reda, A., Sulisz, W., Majewski, D., Paprota, M., Szmytkiewicz, M. 2015. Application of a new approach for modeling coastal erosion in Arctic areas, in: Proceedings of the Second International Workshop on Hydraulic Structures: Data Validation, Carvalho, R.F., Pagliara, S. (Eds.), Coimbra, 217-221.

Schirmer, M., Schuchardt, B., Hahn, B., Bakkenist, S., and Kraft, D., 2003. KRIM: Climate change risk construct and coastal defence, in: DEKLM German climate research programme - proceedings, pp. 269–273.

Sulisz, W., Paprota, M. 2016. An efficient approach for optimization of physical modeling of wave-induced phenomena, in: Proceedings of the Fifth International Conference on Engineering Optimization. Rio de Janeiro: Federal University of Rio de Janeiro.

Sulisz, W., Szmytkiewicz, M., Majewski, D., Paprota, M., Reda, A. 2016. A new approach for the prediction of coastal erosion in Arctic areas, in: Proceedings of the Ninth Symposium on River, Coastal and Estuarine Morphodynamics. Center for Research and Education of the Amazonian Rainforest CREAR.

Thieler, E.R, Hammar-Klose, E., 1999. National assessment of coastal vulnerability to sea-level rise. Preliminary results for U.S. Atlantic Coast, Open-file report 99-593, U.S. Geological Survey, Reston, VA.

Vafeidis, A.T., Nicholls, R.J., McFadden, L., Tol, R.S.J., Hinkel, J., Spencer, T., Grashoff, P.S., Boot, G., Klein, R.J.T., 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise, Journal of Coastal Research, 24, 917-924.

Vasiliev, A., Kanevskiy, M., Cherkashov, G., Vanshtein, B., 2005. Coastal dynamics at the Barents and Kara Sea key sites, 25, 110-120.

Yin, J., Yin, Z., Wang, J., Xu, S., 2012. National assessment of coastal vulnerability to sea-level rise for the Chinese coast. Journal of Coastal Conservation, 16, 123-133.