COASTAL EROSION AND SOIL CARBON FLUX ON BOLSHOY LYAKHOVSKY ISLAND, NE SIBERIA

EROZJA WYBRZEŻA I PRZEPŁYW WĘGLA GLEBOWEGO NA WYSPIE WIELKIEJ LACHOWSKIEJ, PÓŁNOCNO- WSCHODNIA SYBERIA

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High-resolution satellite imagery created in 1968 and 1980 is used to measure magnitude of coastal erosion of the eastern part of the Bolshoy Lyakhovsky Island, New Siberian Archipelago, NE Siberia. The two sets of images are georegistered and manual digitisation of shorelines is done. The resulting maps are used to calculate rates of coastal erosion. The information is used, together with data from the Northern Circumpolar Soil Carbon Database, to assess flux of organic carbon from the terrestrial environment of the island's coastal area to the surrounding seas. The results show high variability of local erosion rates along the coast, ranging from 7,13 m/yr, of erosion to 4,35m/year of accumulation. Different cryomorphological settings of various parts of the island and variations of wind and wave action resulting from local sea currents are pointed as possible causes of the variability. Carbon flux 45908 tonnes of carbon per year, or 251,78 tonnes per kilometre of coastline per year. The obtained results, both erosion rates and carbon flux parameters, are in good agreement with published results of similar studies in the area, despite high error margin.

Słowa kluczowe: CORONA, Wyspa Wielka Lachowska, wieloletnia zmarzlina, wybrzeże, teledetekcja, przepływ węgla.
Keywords: CORONA, Bolshoy Lyakhovsky Island, coastline, permafrost, remote sensing, carbon flux

1. INTRODUCTION

The area of the east Siberian shelf seas is an important reservoir of global carbon. Huge amount of a carbon stored in arctic permafrost soils (Soil Organic Carbon – SOC) contribute to the greenhouse gases emissions as the frozen ground thaws, or is moved to maritime environment. In warmer conditions a microbial decomposition starts and methane, as well as CO_2, are emitted (Schuur et al., 2008).

Calculations by Rachold et al. (2000) showed the great importance of coastal erosion for carbon flux in the region.

While studies of retreat of fragments of coastline of the Laptev Sea can be found (Günther et al. 2015, Lantuit et al., 2011), the island described in this work, the Bolshoy Lyakhovsky island, saw relatively little attention in the English-language literature. The sedimentological (Schirrmeister et al., 2002), paleoclimatological (Andreev et al., 2004, 2009) and geomorphological (Saijo et al., 1999) studies are present, but a detailed investigation of the coastal retreat has only been done by Russian scientists (Pižankova and Dobrynina, 2010).

High resolution satellite imagery, made during Cold War-era spy surveillance programmes, is a valuable dataset application, which has been recognised in different fields such as archaeology (Galiatsatos, 2004), environmental monitoring (Hamandawana et al., 2007) and, what is worth emphasizing, for the present work – tracking the retreat of Arctic coastlines (Lantuit et al., 2011). The study aims to discover erosion rates of the western section of the island with use of satellite images taken in 1968 and 1980 and attempts to use this knowledge to assess amount of carbon that was transferred to the sea in the process.

2. AREA OF STUDY

Bolshoy Lyakhovsky Island is the biggest of the Lyakhovsky Islands group, the southernmost part of the New Siberian Archipelago, located in the NE Siberia. The island has a regular, oval shape, without deeply incised bays. It is roughly 90 km long on the W - E axis and 70 km on the N-S. Figure 1A shows its location within the Arctic. The relief is smooth, intersected by thermo-erosional valleys (Andreev et al., 2009) with the highest peak reaching 293 m a.s.l. The southern shore consists of high cliffs, formed by thermo-abrasion of Quaternary permafrost sediments (Andreev et al., 2009). Numerous rivers flow towards the island's shores. The island vegetation is described as scarce (Isaev et al., 2010).

The Bolshoy Lyakhovsky Island lies in the Polar Tundra climate zone, according to the Koppen-Geiger classification and is a part of the continuous permafrost area (Brown et al., 2001).

3. DATA AND MATERIALS

The satellite images used in the study were made in the 1960s and 1980s, in the course of CORONA and successor HEXAGON satellite spy surveillance missions. With 2 to 6 metres per pixel, the ground resolution is matched only by modern, commercial satellites. Nowadays the imagery is available freely on the United States Geological Survey website - Earth Explorer (U.S. Geological Survey, 2015), delivered in packets of several files per scanned scene. The KH-9 frame came in two parts, of which only one was useful. It covers the eastern part of the Bolshoy Lyakhovsky Island (Figure 1A), which limits the scope of the study. The other images were taken by a KH-4B

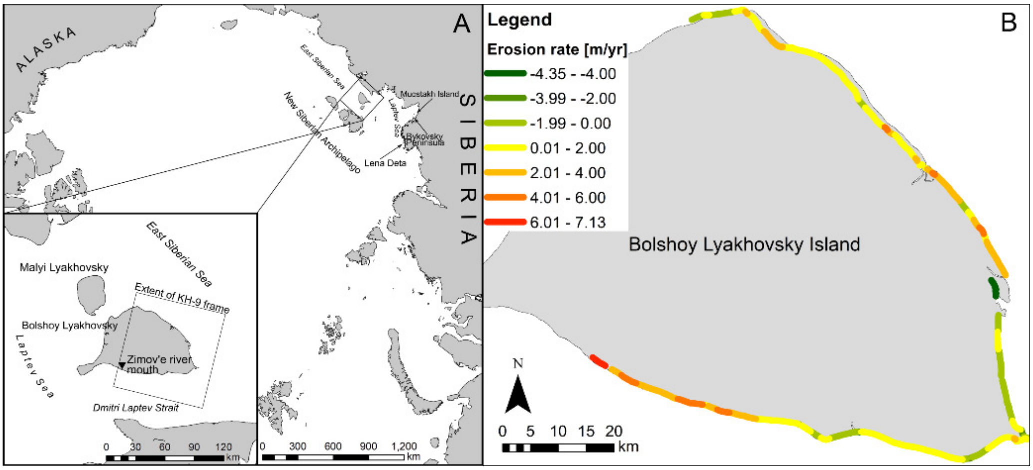

Fig. 1. A: Map of Bolshoy Lyakhovsky Island within the Arctic. B: Erosion rates in the studied part of Bolshoy Lyakhovsky Island. Source of coastline shapes is NOAA (2015).

mission. Each photograph is delivered as four overlapping sections (Figure 1B), of which 6 subsets containing the island's landmass overlapping with the extent of the KH-9 frame were chosen for further processing. The downloaded datasets comprised only of raster images, without metadata allowing for direct georegistration.

Soil Organic Carbon Content (SOCC) is a relative measure of amount of organic carbon stored in a square metre of soil (Hugelius et al. 2013). Two sources of information about soil SOCC in the soils of the island were used: the Northern Circumpolar Soil Carbon Database (Hugelius et al., 2013, 2014), hosted by Stockholm-based Bolin Centre for Climate Research (Bolin Centre for Climatic Research, 2015), and a study by Schirrmeister and colleagues (2011). Together they include information about concentration of organic carbon in kg/m^2 down to the depth of 10 metres, collected on a single site. The mouth of Zimov'e River is an area of cliffs described from sedimentary (Andreev et al, 2004, 2009) and geomorphologic (Saijo et al 1999) point of view. This allows for intermixing of the data in the informed geological context.

4. METHODS

4.1 PRE-PROCESSING OF IMAGERY

The satellite imageries had to be put in a common coordinate system to facilitate comparison. WGS1984 UTM (zone 54N) datum was chosen for this purpose. A LANDSAT 7 scene acquired on 8.10.2002 was used as a base for registration due to its easy availability as free, readily georegistered dataset and low cloud cover allowing for clear recognition of features. The KH-9 frame was first registered to the LANDSAT scene and served as a master image, to which each of the CORONA slices was registered separately. The images were resampled to uniform 6m/pixel (KH-9) and 3m/pixel (CORONA) resolutions with cubic convolution method of resampling, which produces edges easier to work with by a living interpreter (Sannel and Brown, 2010).

The georeferencing was executed by means of rubber sheeting. An image was stretched or shrunk, so that coordinates of pixels of rubber sheeted image are adjusted to the coordinates of the master. River confluences were used as Ground Control Points (GCPs) to tie the imageries together. They are stable places with low discharge, where no significant sediment bars are accumulated (Best and Rhoads, 2008) and thus assumed unchanging over the course of 12 years. Additionally, a number of GCPs were located at the edges of oxbow lakes, found in the lower course of the rivers.

On the CORONA images significant distortions are present, gradually increasing from the image's centre towards its edges. The data obtained for this study are of high quality and depict flat area, thus the only necessary corrections of the images were related to geometrical distortions. Rubber sheeting does not discriminate between geometrical distortion and wrong placement within coordinate system, fixing the optical distortion in the course of registration.

4.2 EROSION RATE CALCULATION

Two separate vector layers were created for each CORONA image – one for the older and one for the newer coastline position. Polylines along the sea/land border were manually traced on the raster images. Their location was subsequently corrected, to account for an imperfect overlay of CORONA images over the KH-9 master. Control points were identified on both datasets and distances measured between them served to move CORONA-derived coastlines relative to KH-9-related ones, as the latter, based on a single picture, were assumed more stable.

To calculate the change of coastline position a set of points was placed along the KH-9 polylines in equal spacing of 30 metres. The distance to the nearest CORONA line was assigned to points, with erosion values listed as positive, and accumulation as negative. Similar convention was used in the Arctic Coastal Database (ACD) (Lantuit et al., 2011). The points were aggregated basing on visual identification of geomorphic features such as bays, peninsulas or, straight stretches of coastline. Within them the distances were averaged and divided by 12, the number of years elapsed between the images, to produce final values presented on the Figure 1B.

The uncertainty of digitisation is in this study is related to the precision of location of a digitised coastline relative to the actual sea/water divide position and was assessed to be 2,5 pixels, basing on Sannel and Brown (2010) analysis of manual delineation of thermokarst lakes on high-resolution imagery. This corresponds to maximum total error of distance between the two coastline polylines of 22,5 metres. It is important to notice, that the value is, more often than not, greater, than the measured value. The error is random – each vertex of each polyline is misplaced to a different degree. The aggregation such measurements over long stretches allowed to filter out the “noise” of uncertainty – as points misplaced landward compensated for points misplaced seaward.

4.3 CARBON FLUX CALCULATION

The erosion rates served as a basis for assessment of the magnitude of organic carbon transfer from the terrestrial environment to the surrounding seas. A method used by Are (1999) to calculate mass of sediment displaced in the course of erosion was adopted. The heights of the cliffs were taken from a set of 1:200000 scale topographical maps issued in the Soviet Union in 1989. The cliffs were divided into 1-metre-thick layers, each of which had a SOCC in kg/m^2 assigned, basing on the NCSCD (up to 5 metres of depth) and Schirrmeister et al. (2011) (below 5 metres). The threshold was set at 5 metres because of change in sedimentary profile of cliffs at this depth (Saijo et al., 1999). The equation used to calculate the mass of SOC transferred by means of coastal erosion on a single, uniform stretch of coastline was following:

$$m_{SOC} = [E \cdot (n \cdot 30)] * \left(h * SOCC_{L6} + \sum_{i=1}^{b} SOCC_{Li} \right)$$

Where m_{SOC} is the mass of displaced SOC, E is eroded distance [m] , n*30 represents length of the stretch (number of points time 30 m), h is depth of sediment below 500 cm [m], b is number

Table 1: Comparison of calculated values to the data from published sources.

Value	Calculated	Published	Source	Type of carbon
SOC displaced total/yr	0,046 Tg	1,32 Tg	Sanchez-Garcia et al. 2011	Only particulate carbon
		12 +/- 8 Tg/yr	Vonk 2012	C as a whole, not only coastal erosion
Yearly carbon flux	251,78 tC/yr/km	471+/- 32,9 tC/km/yr (88 to 800 tC/km/yr)	Gunther et al. 2013	Only carbon from Yedoma and Alas coasts

of layers and $SOCC_{Ln}$ is the SOCC at the n-th layer of soil [kg/m^2].The overall method is similar to the methodology of Grigoriev and Rachold (2004).

Any negative retreat distance was always counted as "0" movement, not negative, when calculating the displaced organic carbon. Influx of carbon from the sea to the land was assumed impossible and calculation of carbon displacement by means of riverine sediment transport was not within the scope of the study.

5. RESULTS AND DISCUSSION

Most of the area exhibits erosion rates within -1,5 to 1,5 m/yr. The highest erosional coast value is 7,13 m/yr, while highest aggradation is -4,35m/yr. The lowest erosion rates are found in the areas of intensive accumulation related to river outlets, confirmed by Pižankova and Dobrynina (2010). A mixture of positive and negative erosion values was found in the protruded peninsula in the south-east, a surprising result in an exposed area, prone to erosion. The highest erosion rates on the island (over 3 m/yr) are seen in the western section of the southern coast, a result in agreement with other studies (Are 2000, Pižankova and Dobrynina, 2010). Similar variability of erosion rates occurred in other studies of coastal erosion rate in the Arctic (Lantuit et al., 2011; Günther et al., 2013).

The cliffs of Bolshoy Lyakhovsky seem susceptible to erosion, compared to the surrounding areas. Mean coastline retreat rates of Muostakh Island and Bykovsky Peninsula, south-west to the Bolshoy Lyakhovsky Island, respectively are 0,95 m/yr (Günther et al. 2015) and 0,59 m/yr (Lantuit et al, 2011). The mean coastal erosion rate, weighted by lengths of the coasts undergoing erosion at different rates, was estimated by Lantuit et al. (2012) to be 0,73m/yr for the Laptev Sea and 0,87 for the East Siberian Sea (ESS). The respective value for the studied section of Bolshoy Lyakhovsky is higher, at 1,21 m/yr.

The result of carbon flux calculation was 45908 tonnes of carbon per year (equivalent to 0,046 Tg/yr) displaced from the area and time in question. This value should be treated as approximation due to uncertainty. All assessments of carbon content along the geomorphically diverse coastline are based on information derived from a single site, which leads to obvious inaccuracy. Additionally, the sources did not state any uncertainty assessment of the data.

It is hard to compare the figure to other estimates of carbon mobilisation, as such estimates usually cover different subsets of permafrost carbon, than the one analysed in the present study. Table 1 presents comparison of the obtained result with various other studies. Its final comment contains details on kinds of carbon covered in referenced papers.

Geometry of the shoreline and cryolithology of the ground at the coastline can explain the variability of erosion rates. A bimodal process of thermal erosion of Arctic coasts consists of thermo-abrasion, the action of warmer sea water on the bottom part of the cliff, and thermo-denudation - thawing of ice-rich sedimentary complexes on its top (Günther et al., 2013). The two processes work in concert to collapse cliffs onto underlying beaches. Lantuit et al. (2011) showed, that alas and thaw slump coasts were eroded faster, with sand bars being most resistant. The diversity of values along the coasts of the studied area can be thus attributed to varied cryomorphology of the cliffs.

The most eroded areas are straight stretches of coast. Sea current patterns can be blamed for the concentration of erosion in the island's southern and north-eastern parts. In the shallow shelf of Laptev and East Siberian seas, flow of water is aligned to dominant directions of the winds (Dmitrenko et al., 2005) driven by Arctic Oscillation – a bimodal scheme of variations of sea level pressure in high northern and temperate latitudes first described by Lorenz (1951). Of 12 investigated years only 5 (1968-1972 and 1980) belonged to the cyclonic phase, which favours westward flow of water, while the rest belong to the anticyclonic phase favouring eastward flow (Proshutinsky and Johnson, 1997). Therefore, the erosional pressure on the western seaboards was stronger, than on the east-exposed ones.

6. CONCLUSIONS

The results presented here show that CORONA and KH-9 imagery can be successfully used for detection of shoreline changes. Simple GIS-based techniques are enough to produce plausible values and distributions of coastline erosion. The values obtained are relevant for the Bolshoy Lyakhovsky Island and other sites of the region. The erosion rates are highly variable along the coastline, possibly because of wind patterns resulting from large-scale climatic oscillations and geomorphological differences between various types of soils. The information about carbon export was obtained with use of highly simplified methodology and its uncertainty is high. Use of more and more modern datasets, such as commercial, high-resolution satellite imagery, detailed meteorological data, or fieldwork in the northern and eastern parts of the island could form a sounder foundation for explanation of physical processes behind the erosion of coastlines of Bolshoy Lyakhovsky.

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