Relative sea level changes as a driver of coastal dynamics in the Russian Arctic

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ABSTRACT

Changes of the relative sea level (RSL) are among the drivers of coastal dynamics in the Arctic, along with hydrometeorological conditions, including air and water temperature, wave energy, storm frequency, ice-free period duration and other parameters, and morphological, geological and permafrost properties of the coasts. In the western Russian Arctic, patterns of modern and past RSL changes are highly variable, mainly depending on the interplay between the eustatic sea level changes and glacioisostatic adjustment (GIA). While coasts of the Kola Peninsula, Karelia and Franz-Josef Land and Novaya Zemlya archipelagoes were covered by an ice sheet during the Last Glacial Maximum (LGM), and experience post-glacial RSL fall, coasts of the Kara sea and Laptev seas were not covered by land-based ice masses and show sea level rise. Here, we analyze how the changing RSL influences coastal morphology and dynamics, based on literature data on past and present RSL changes in previously ice-covered regions and those regions which were ice-free at the LGM. We also observe results of satellite imagery processing allowing to calculate modern average coastal erosion rates in the Arctic in different conditions in terms of RSL and GIA. We show that the difference in coastal morphology and dynamics depends on the trend (RSL fall or rise). If areas with the same trend, but different rates are compared, RSL becomes a secondary driver, and the difference in erosion rates mainly depends on the interplay between the modern hydrometeorological conditions and permafrost properties of the coasts.

KEY WORDS: RSL; coastal erosion; thermal abrasion; GIA; Arctic

INTRODUCTION

The morphology and evolution of the Arctic coasts is determined by a great variety of factors (Shabanova et al., 2018), both internal (geology, geomorphology, sediment composition, presence of permafrost and its properties, ground ice, etc.) and external (changing air temperatures, sea ice conditions, mechanical erosion by waves, etc.). While the internal factors are relatively stable and create the pattern of spatial variability in coastal erosion rates (Baranskaya et al., 2021), external factors vary considerably in space and time. Most of the hydrometeorological factors, such as wave energy, ice-free period duration, length of wave fetch determined by the position of the sea ice margin, air temperature, determining the rate of permafrost thawing, all act on relatively short timescales of years or decades, changing fast and creating the temporal variability of coastal erosion rates at different sites, relatively well studied in the 20th-21st century (Ogorodov et al., 2020). However, there is one more external factor, which is important for coastal morphology and dynamics both at short timescales of decades and at geological timescales of millennia, namely changes in the relative sea level (RSL), which varies considerably in different parts of the Russian Arctic, depending on differences in glacial isostatic adjustment (GIA) and deglaciation history of the eastern Eurasian ice sheet, imposed on eustatic sea level changes, tectonics and other factors (Baranskaya et al., 2018). Although they act slower compared to climate events like increasing storm activity or fast ice-free period extension, changes in RSL set up conditions in which coasts evolve and therefore determine the appearance of the coasts and their accumulation or erosion rates.

RSL in the Russian Arctic is mainly known from geological data; recently, a database on postglacial RSL changes on the coasts of the Russian Arctic seas has been collected (Baranskaya et al., 2018). Together with modeling of GIA processes (e.g., Peltier et al., 2015), these data allow to reconstruct how RSL changed in the past on the coasts with different geomorphic and paleogeographical conditions. At the same time, little is known so far on the interaction between sea level and coastal erosion in the Arctic, especially in permafrost areas, as it is still challenging to divide the influence of different drivers on the resulting rates of shoreline change. This problem remains an important open question, as coasts in the Arctic retreat fast, with an average rate of 0.5 m/yr (Lantuit et al., 2013), reaching up to 17 m/yr in separate locations (Ogorodov et al., 2020), and understanding how the rising sea level, among all other drivers, will impact them in the future is important for planning any development and construction in the coastal areas.

Here we analyze and compare RSL histories of the western and eastern Russian Arctic (White, Barents, Kara and Laptev Seas) and the evolution of coasts situated in different conditions in terms of RSL and GIA. We further discuss how RSL patterns can influence coastal morphology and dynamics in the Arctic conditions, and how these coasts will change in the future.

VARIABILITY OF RSL HISTORIES IN THE RUSSIAN ARCTIC

RSL in the Russian Arctic in the past 18-20 ka was mainly determined by the processes connected to deglaciation of the ice sheets that existed during the Last Glacial Maximum (LGM) (Lambeck et al., 2014). Because of the input of meltwater into the World Ocean, the eustatic sea level was rising since the LGM, coming to a slowdown and reaching its present position in the mid-Holocene (Peltier, 2002). At the same time, areas covered by ice sheets, experienced post-glacial isostatic rebound after unloading of the ice mass, raising the coasts and former sea bottom, while areas situated near the ice margins, forming a compensational forebulge, must have experienced subsidence. These movements of the lithosphere, leading to vertical displacements of the coasts and bottom, together with other smaller, but still significant factors like the effect of ocean syphoning and continental levering (Mitrovica and Milne, 2002), tectonics and other processes, were imposed on the eustatic sea level rise, creating the variability of RSL histories in the Russian Arctic.

Areas of prevailing RSL fall are located under the former Eurasian ice sheet (Fig. 1A). At the

LGM, the depression of land beneath them caused a migration of mantle material away from ice-load centers. This migration resulted in the formation of a forebulge in regions adjacent to ice sheets. Following the ice-sheet retreat, mantle material flowed toward the former load centers. These centers experienced postglacial rebound (Li et al., 2020). In the Russian Arctic, these are the coasts of the White and Barents sea within the Baltic shield, where the thickness of the ice sheet reached more than 2 km (Clason et al., 2014), and sea level fell by up to 80-100 m in the last 10 ka (Baranskaya et al., 2018), coasts of Franz-Josef Land archipelago, where RSL fell from about 40 m since 11 ka, and Novaya Zemlya, where the ice sheet was thinner and lasted longer than in other areas, and where RSL fell from less than 15 m in the last 8 ka (Forman et al., 2004). An example of a point within the area of postglacial RSL fall is Polyarniy at Kola Peninsula, where the GIA predicted past RSL shows a constant fall since deglaciation (Fig. 1B, Region 1).

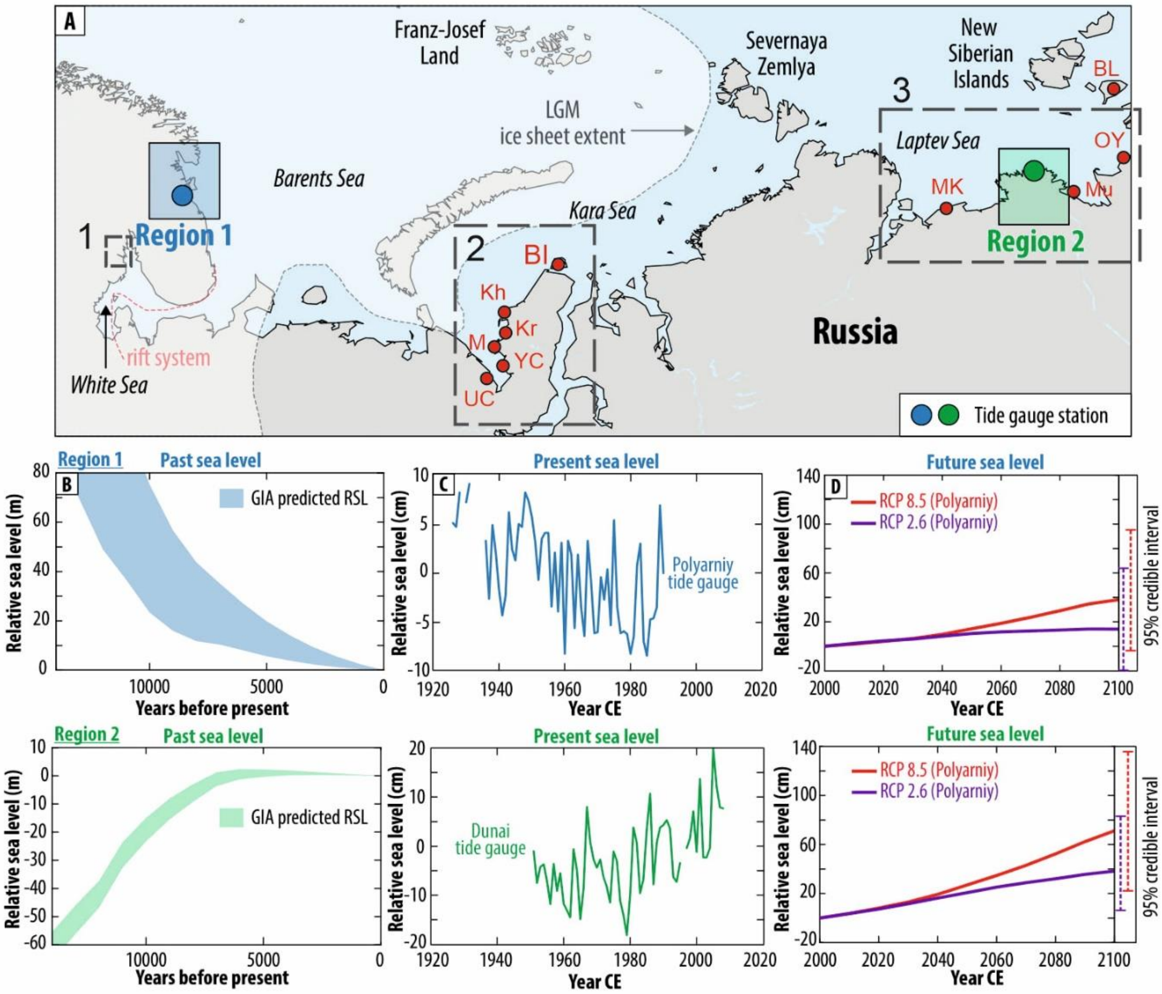

Figure 1. (A) Russian Arctic study area and the 2 selected regions illustrating spatial variability of relative sea-level (RSL) changes. Ice sheet limit at the last glacial maximum (LGM) from ICE-6G_C (VM5a) model (Peltier et al., 2015). 1 – Karelian coast of the White Sea (Fig. 2); 2 – Kara Sea coasts (Figure 3A, B); 3 – Laptev Sea coasts (Figure 3C, D). Red dots show sites of coastal erosion rates monitoring, data on which are shown in Table 1: UC – Ural Coast of the Baydaratskaya Bay, YC – Yamal Coast of the Baydaratskaya Bay, M – Marre-Sale, Kr – Gulf of Kruzenstern, Kh – Kharasavey, BI – Beliy Island, MK – Mamontov Klyk, Mu – Muostakh, OY – Oyogos Yar, BL – Bolshoy Liakhovskiy Island; (B) Glacial isostatic adjustment model predictions of past RSL change in regions 1 and 2. (C) Tide-gauge

records from Polyarniy tide gauge in region 1 and Dunai tide gauge in region 2. (D) Probabilistic future sea-level projections (Kopp et al., 2014) for Polyarniy and Dunai tide gauges showing mean and 95% credible intervals under RCP 2.6 and RCP 8.5 emissions scenarios (modified after Li et al., 2020).

Areas of prevailing RSL rise are situated along the former ice sheet margin (southeastern Barents Sea, Kara Sea), where there could be compensational lowering of the Earth's crust as a result of the proglacial forebulge collapse, and in the far-field, on the coasts of the Laptev Sea, where GIA has a smaller impact on the RSL curves, and other processes such as tectonics or isostasy become visible. In the areas uncovered by the ice sheet, the RSL curve shows a steady rise, reaching a position close to present at 6-7 ka (an example is Dunai station in the Lena Delta, Laptev Sea, Fig, 1B, Region 2).

Today, RSL is still rising in areas previously uncovered by the ice sheet, and its rates are even accelerating, which is well seen on the recent curve obtained from measurements on Dunai tide gauge (Fig. 1C). At the same time, RSL at Polyarniy, an example of a coastal area with crustal GIA uplift, is now slowing down, which means that the eustatic sea level rise is starting to be comparable with the remaining lithospheric rebound of the Baltic shield (Fig. 1C). In the future, the ongoing RSL rise will continue at Dunai station (Fig. 1D), and the trend will probably change even for Polyarniy, because of the slowing down lithospheric rebound and accelerating eustatic sea level rise.

COASTAL MORPHOLOGY AND DYNAMICS IN THE RUSSIAN ARCTIC

Areas of past and modern RSL fall

Areas of the Russian Arctic that were covered by an LGM ice sheet where RSL was falling in the last several thousand years mostly have rocky coasts with little or no permafrost. Because of long-term RSL fall, these coasts often have several levels of uplifted coastlines, which can be either marine terraces where shells of marine molluscs, driftwood and bones of marine mammals can be found, or uplifted coastal barriers of rounded boulders and pebble. In areas where uplift was especially fast, former gulfs become isolated from the sea and get transformed into lakes. An example of this is the area of Babye More on the coasts of the White Sea (box 1 on Figure 1A), which formerly was an area where local people went fishing from large boats in the 18th-19th century, and now is even hardly accessible by motor boat, as the two straits by which this gulf could be entered are becoming shallower (Repkina et al. 2017; Fig. 2A).

The coasts around this gulf, and coasts of the western White Sea and southwestern Barents Sea in general are composed by exposed Pre-Cambrian metamorphic and igneous rocks. Because these rocks are resistant to erosion by waves or sea ice, abrasional segments usually are tectonic coasts and scarps, sometimes skerries, which experience almost no retreat and are very stable (Fig. 2B). Accumulative segments are often composed by coarse-grained sediments, and sometimes even form beaches of boulders (Fig. 2C). Generally, such rocky areas with stable or prograding coastlines were characterized by fast RSL fall throughout the Holocene (Fig. 2D), which left traces of former lower coastline position on the former land, creating marine terraces, coastal bars and isolation basins. Because areas of RSL fall are situated in the western part of the Russian Arctic with a milder climate and are mostly rocky, permafrost processes such as thermal abrasion, thermal erosion or thermal denudation do not act on these coasts. Therefore, they are relatively resistant to temperature increases, sea ice loss and other global environmental processes in the Arctic.

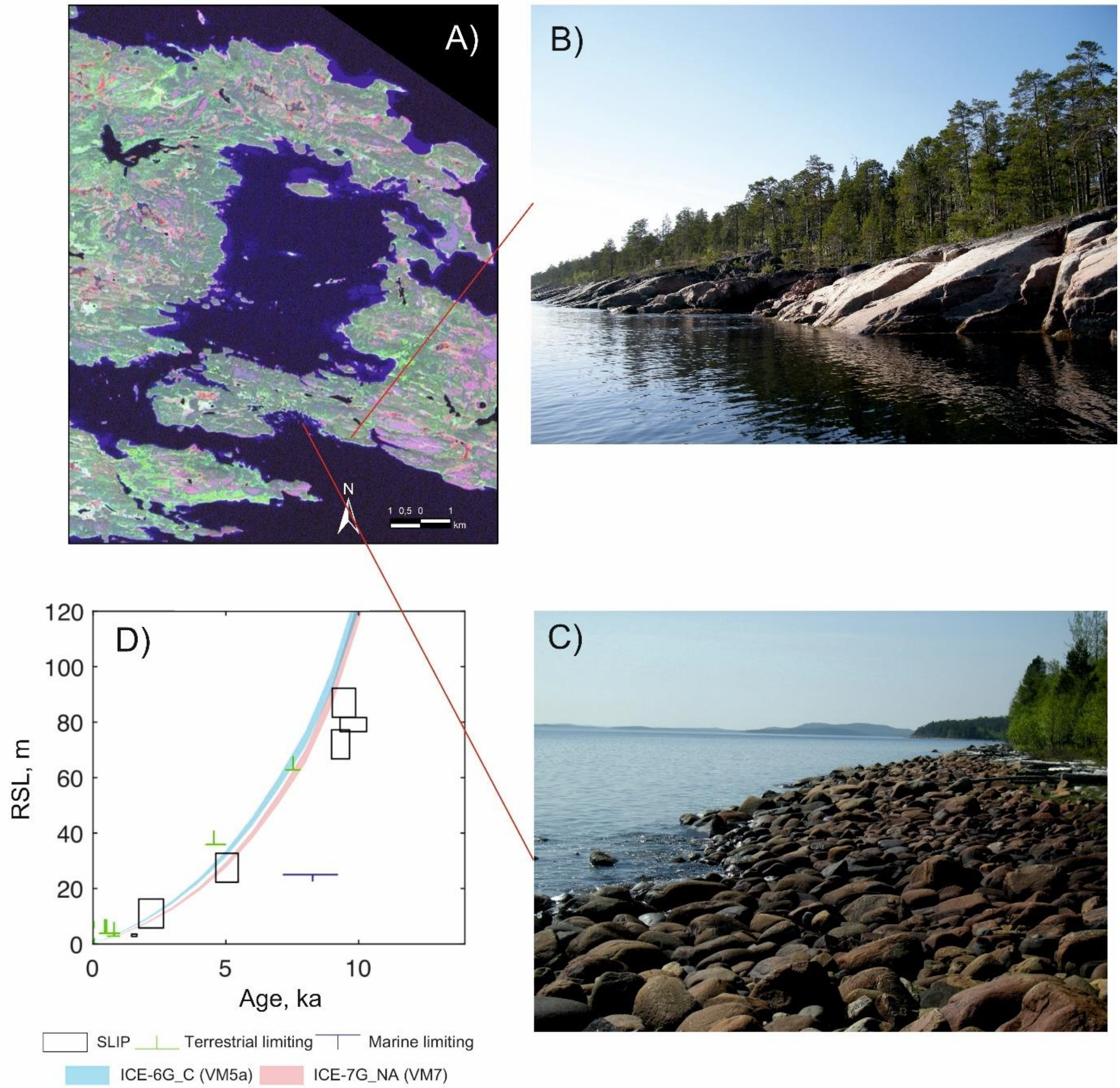

Figure 2. Karelian coast of the White Sea (area 1 in Fig.1A): A) Satellite view of the uplifting Babye More Gulf and its shallowing straits; B) Rocky abrasional coast; C) Accumulative coast; D) Example of post-glacial RSL change history (model data provided according to Peltier et al., 2015)

Areas of RSL rise

The coasts of the Kara and Laptev seas, where RSL showed a predominant post-glacial rise (Fig. 3 A, C), differ significantly from the western part of the Russian Arctic in terms of their morphology. They are composed by perennially frozen grounds, sometimes with abundant ground ice, and form frozen bluffs of up to 50 m in height (Fig. 3 B, D), which retreat fast because of thermal abrasion. Thermal abrasion is the combined action of the mechanical energy of waves and the thermal energy of the sea water and air with positive temperatures (Are, 1988).

With the ongoing climate change, both of the factors contribute to faster erosion of the coastal bluffs.
One of the most important features is the presence of ground ice: it has been proved that areas where there is much ice in the coastal bluffs experience faster erosion compared to segments with smaller ice content in the sediments. On the coasts of the Kara Sea, the largest ground ice bodies are massive ice beds – long flat layers of ice, sometimes interbedded with ground, of up to tens of meters thick. On the coasts of the Laptev Sea, sediments of the Ice Complex. or Edoma prevail, which have even higher ice content of up to 80%: most of their volume is ice of old Pleistocene ice wedges which have been growing for thousands of years, merging together and forming a dense net of polygons with sediment inclusions at the centre (Fig. 3D). As a result, the coastal bluff looks like a steep icy wall which thaws very fast with the growing air temperatures, and even small waves can erode the insignificant volume of sediments left after thawing.

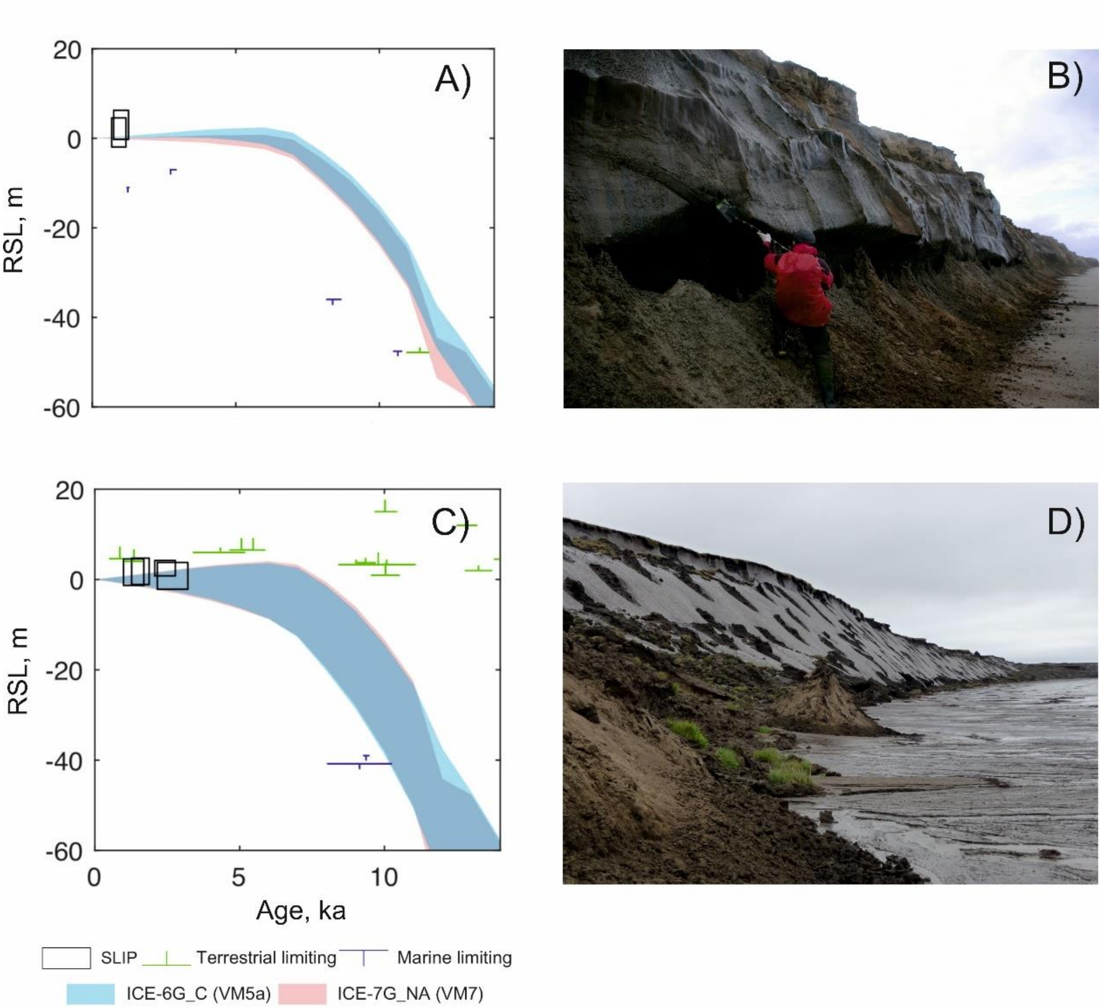

Figure 3. A) Post-glacial RSL changes of the Kara Sea according to geological and modeling data; B) Typical view of a thermoabrasional coast of the Kara Sea (Beliy Island); C) Post-glacial RSL changes of the Laptev Sea according to geological and modeling data; D) Typical view of a thermoabrasional coast of the Laptev Sea (Mamontov Klyk, photo by F. Günther)

Comparison of coastal erosion rates at different sites in the areas of prevailing RSL rise on the coasts of the Kara and Laptev seas (Table 1) shows considerable spatial variability in erosion rates despite similar patterns of RSL change in these regions. For example, the greatest retreat rates at separate segments can differ by several times at different locations. Generally, the coasts of the Laptev Sea retreat faster than the coasts of the Kara Sea. Taking into consideration the longer ice-free period in the Kara Sea and comparable wave energy potential in the two seas (Ogorodov et al., 2020), it can be concluded that the main reason for this difference in erosion rates lies in the ground ice content. In fact, sites where deposits of the Ice Complex, or Edoma, outcrop (Günther et al., 2013, 2015), retreat very fast compared to sites with massive ice beds, and sites with large massive ice beds such as Marre-Sale (Kritsuk et al., 2014) or the Ural coast of the Baydaratskaya Bay (Novikova et al., 2018). Sites with massive ice beds, in their turn, are eroded faster than sites with no ground ice, an example being the Yamal coast of the Baydaratskaya Bay (Novikova et al., 2018).

Table 1. Comparison of coastal erosion rates in the western Russian Arctic (Kara Sea) and eastern Russian Arctic (Laptev Sea). Ground ice type: MB – massive ice beds; IW – separate ice wedges; IC – Ice Complex. or Edoma.

Site name	Period of observations	Mean planimetric retreat rates, m/yr	Maximum planimetric retreat rates, m/yr	Ground ice type	Reference
Kara Sea					
Ural coast of the Baydaratskaya Bay	1964-2016	1.2	2.5	MB	Novikova et al., 2018
Yamal coast of the Baydaratskaya Bay	1968-2016	0.3	1.0	-	Novikova et al., 2018
Marre-Sale	1969-2009	2.0	3.0	MB	Kritsuk et al., 2014
Gulf of Kruzenstern	1964-2019	0.5	1.6	MB	Baranskaya et al., 2021
Kharasavey	1977-2016	1.1	3.2	MB	Belova et al., 2017
Beliy Island	1969-2016	1.6	4.3	IW	Baranskaya et al., 2020
Laptev Sea					
Mamontov Klyk	1965-2011	0.9-3.3	5.0	IC	Günther et al. 2013; Gavrilov, Pizhankova, 2018
Muostakh Island	1951-2013	0.5-3.1	9.6	IC	Günther et al. 2015
Bolshoy Liakhovskiy Island	1951-2000	1.9 -5.1	8.6	IC	Pizhankova, 2016
Bolshoy Liakhovskiy Island	2001-2013	3.2 - 9.4	12.0	IC	Pizhankova, 2016
Oyogos Yar	1951-2000	1.5-2.6	2.6	IC	Pizhankova, 2016; Günther et al 2013
Oyogos Yar	2007-2011	4.3-11.1	11.1	IC	Pizhankova, 2016; Günther et al 2013

Another interesting phenomenon is the acceleration of coastal erosion in the recent years, since the 2000s, coinciding with the warming and sea ice decline in the Arctic. Areas with abundant Ice Complex such as Bolshoy Liakhovsky Island or Oyogos Yar (Pizhankova, 2016; Günther et al 2013), have increased their erosion rates by 1.3-8.5 m/yr in the recent years. At the same time, on the coasts of the Kara Sea with no Ice Complex, the increase in erosion rates was smaller: by 0.3-1 m for Baydaratskaya Bay, Gulf of Kruzenstern and Kharasavey (Belova et al., 2017; Novikova et al., 2018; Baranskaya et al., 2021). Assuming that RSL rise accelerates with approximatively the same rate on the coasts of the Kara and Laptev seas, we can conclude that the dramatic growth of shoreline retreat rates on the Laptev sea coasts is rather caused by melting of the ice of the coastal bluffs rather that by sea level rise.

For temperate and tropical coasts, the relation between sea level and coastal dynamics is determined by the "Zenkovich-Bruun Rule" (Bruun, 1962; Zenkovich, 1962), when the dynamic equilibrium profile of the coast is displaced along with sea level rise or fall, preserving the sediment balance in the coastal zone. For coasts composed by permafrost, this rule does not apply (Are, 1988), as typical thermoabrasional coasts eroding at high rates have no equilibrium profile, and the underwater slope is subject to thawing as well as the coastal bluffs. Therefore, the impact of relative sea level rise or fall on erosion rates is indirect. Comparison of the coastal morphology of the western and eastern Russian Arctic shows that the difference in RSL patterns created totally different coastal morphology and settings in which the coasts evolve: the rocky uplifting coasts of the western White and Barents sea are stable or even prograde, while coasts of the Kara and Laptev Sea retreat fast at erosional segments. At the same time, short-term dramatic recent changes in erosion rates are driven by climate mechanisms enhanced by the presence of ground ice inside frozen sediments of the coastal bluffs.

CONCLUSIONS

Comparison of the morphology and erosion rates of coasts with different RSL histories in the western and eastern Russian Arctic has shown that coasts covered by the Eurasian ice sheet during the LGM have experienced a predominant RSL fall since deglaciation, and are mostly stable even at erosional segments. Coasts of the Kara and Laptev Seas, uncovered by the former ice sheets, have seen a post-glacial RSL which became slower in the mid-Holocene and is accelerating again now. These coasts are composed by permafrost with abundant ground ice and retreat at high rates of up to several meters per year. However, the connection between RSL rise and coastal erosion in these regions is indirect. Although patterns of RSL change create long-term settings in which the coasts evolve, recent dramatic acceleration of shoreline retreat on the coasts of the Kara and Laptev seas was mostly caused by air temperature rise and sea ice decline, enhanced because of thawing of the massive ice beds and Ice Complex outcropping in their coastal bluffs.

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