Cliff retreat of permafrost coast in south-west Baydaratskaya Bay, Kara Sea, during 2005–2016

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Abstract
Recent years of increasing air temperature in the Arctic have led to a significant increase in the rate of retreat of permafrost coast, which has threatened livelihoods and infrastructure in these areas. The Kara Sea hosts more than 25% of the total Arctic coastline. However, little is known about how coastal erosion in the Kara Sea may have changed through time, and the climatic and environmental drivers remain unclear. Here we study coastal dynamics along a 4-km stretch of permafrost and sea-ice-affected coastline in south-west Baydaratskaya Bay of the Kara Sea, western Siberia, between 2005 and 2016, by using handheld differential GPS mapping and satellite imagery. We identified temporal and spatial variations in the retreat rates, ranging between 1.0 (+0.1/−0.6) and 1.9 (+0.7/−1.3) m/yr over the studied coastline during 2005–2016. We also made ground temperature measurements, subsurface resistivity measurements and estimates of wave energy flux of wind-driven ocean waves, to investigate the dominant climatic factors influencing the observed retreat rates through time. We found that wind-driven wave activity during sea-ice-free days influences the magnitude of coastal retreat in the study area, while recent temperature rise has contributed less to enhancing coastal retreat during the study period. This suggests that the amount of eroded sediment and the associated release of nutrient to the nearshore zone are controlled by the magnitude of wave activity, which may influence infrastructure along the permafrost coast and marine ecosystems in the proximal ocean.

KEYWORDS
Baydaratskaya Bay, coastal retreat, Kara Sea, permafrost coast, wind-driven ocean wave

1 INTRODUCTION

Rapid coastal retreat is occurring along many unlithified shorelines worldwide. The magnitude of this coastal retreat is variable in both time and space (e.g., 1). Because the erosion of coastal cliffs and resulting mass wasting threaten livelihoods and infrastructure, quantitative evaluations of cliff retreat are needed to assess the associated risk. Moreover, the release of eroded sediment to the nearshore zone influences the proximal marine ecosystem through increasing ocean turbidity, acidity and organic carbon supply (e.g., 2–4). In particular, recent climate change is expected to accelerate the erosion of poorly consolidated coastal cliffs, increasing both hazard risk and perturbation of the marine ecosystem. 5

More than 30% of the world’s coasts are Arctic coasts, and Arctic coastlines are known to be eroding at higher rates than temperate
coasts. However, little is known about how erosion of Arctic coasts may have changed through time, and the climatic and environmental drivers remain unclear. The rate of erosion of Arctic permafrost coasts currently averages 0.5 m/yr, although this is known to be variable over a wide periods and for different coastal geomorphologies (e.g., ice-rich permafrost bluffs or barrier islands). Along the Alaskan Beaufort Sea coast, mean annual rates of erosion range from 0.7 to 3.2 m/yr with maximum rates up to 17 m/yr. In Muosakah Island of the Laptev Sea, mean annual erosion during 1950–2014 ranged widely, between 2 and 25 m/yr. In addition, increases in coastal erosion rates in recent decades have been reported along several Arctic coasts. For example, the mean annual rates along part of the Alaskan Beaufort Sea coast doubled between 1955 and 2007. This acceleration is thought to be due to sea-ice loss that leaves the coast more exposed to wave action and storms. In contrast, coastal accretion due to sea-ice decline has also been observed in the Alaskan Chukchi Sea and Canadian Beaufort Sea coasts. Therefore, it is necessary to understand the coastal dynamics of permafrost coastal cliffs with regard to the factors (e.g., air temperature, solar radiation, ground ice content, sea-ice extent, wave action, storms, longshore sediment transport and major river discharge) that drive change in different Arctic coasts.

The Kara Sea coastline is longest among the ten Arctic Ocean sectors and comprises more than 25% of the total length of Arctic coasts. Threats of coastal erosion to pipelines have encouraged an understanding of the processes of erosion in the Kara Sea. Studies have shown that mean annual rates of coastal erosion have ranged between 0.2 and 2.0 m/yr in most of the Kara Sea coasts (e.g., ). It has also been shown that thermodenudation and the action of slope processes alone can contribute up to 0.4 m/yr coastal retreat in the Kara Sea coasts. Yet, coastal dynamics along the Kara Sea coast are poorly reported despite numerous studies for more than six decades. This has hampered a better understanding of the respective influence of climate and geomorphology on erosional processes along the Kara Sea coast. Thus, studies of the Kara Sea coast hold promise for further understanding the dynamic processes at the land–ocean interface over the entire Arctic – repositioning and reshaping of the Arctic coastline. Most recently, reported on long-term coastal retreat along the Baydaratskaya Bay coast in the Kara Sea based on satellite and aerial imagery, and revealed that mean annual rates of coastal retreat had increased from the period 1964–2005 to 2005–2016 probably due to climate warming and human activity. In the present paper, we study annual retreat of coastal cliffs along the south-west Baydaratskaya Bay coast during period 2005–2016 based primarily on field measurements. This study aims to understand the driving mechanisms of coastal change along Baydaratskaya Bay, by integrating high-resolution mapping with handheld differential global positioning system (DGPS) surveys, analysis of satellite images, ground temperature measurements, subsurface resistivity measurements, and calculation of wave energy flux of wind-driven ocean waves.

2 | STUDY AREA

Baydaratskaya Bay is a shallow gulf in western Siberia along the south-west margin of the Kara Sea (Figure 1). The bay is thought to have been formed by glacial depression during the Late Pleistocene and subsequent submergence during the Holocene (e.g., ). The Baydaratskaya Bay region is located in the continuous permafrost zone. Ice starts to cover Baydaratskaya Bay between early October and early November, and becomes thickest generally by early May reaching up to 1.5 m. The bay is thus fully covered by continuous ice for around 7 months, and is ice-free for only 3–4 months. Wind distribution observed at Ust-Kara station (see Figure 1 for location) shows that the prominent sector is north-west and north in summer and south-west and south in winter. With an average wind speed of around 6 m/s during 2010–2016. Tidal range is 0.7–1.1 m although surges in autumn can reach 1.5–2.0 m. Annual average temperature and annual precipitation are around −8°C and 300–400 mm, respectively.

The study area is located 2 km south-east of the mouth of the Oyu-Yakha River running between the islands of Trasayev and Levdiev (Figure 1). The Bovanenkovo-Uhta gas pipeline crosses Baydaratskaya Bay, transporting gas from the Yamal peninsula to Europe. The study area is located 0.5–4.5 km north-west of the Bovanenkovo-Uhta pipeline Cofferdam junction (Figures 1 and 2 a,b). In the south-east part of the study area, a low marine terrace with elevations of 3–6 m above the beach is developed along the coast for more than 4 km (e.g., Figure 3), extending from the Cofferdam junction. This low marine terrace is composed of interbedded ice-rich silty clay to silty sand deposits (volumetric ice content of 50–70% in the upper 3 m) and is smoothly sloping. The low terrace decreases in height toward the north-west and then a laida (tidal flat) 1–2.5 m high is developed for 1.3 km, extending to 0.8 km south-east of the mouth of the Ngarka-Tambyakha River. The higher part of the laida surface is located above the tide level and thus is flooded only due to seawater inflow during storm surges. The laida hosts numerous depressions with thaw lakes, several of which are being drained due to coastline retreat. Lake occupancy on the high laida exceeds 50%. The laida is composed of loams overlain by sands and pebbles. A high marine terrace 10–17 m high then extends for 1 km in the north-west part of the study area. The high terrace is composed of silty sand interbedded with millimeter-thick peat layers and decimeter-thick ice layers (e.g., Figure 3). Total ice content in the cliff section is relatively high, ranging from 35% to 80%, due to massive ice inclusion and ice lenses. Slopes in the eastern part of the high terrace are generally steeper than those in the western high terrace (e.g., Figure 2 c, d). The surface of the high terrace is interrupted by deep trenches with dry thermokarst lake basins, younger thermokarst lakes, polygon-shaped frost clefts and weathering spots on the sandy soil. The thickness of the active layer varies from 0.4 and 2.0 m in the studied terraces and slopes. The thickness of the underlying permafrost along the Baydaratskaya Bay coast is thought to vary from 8 to 20 m or more. Mean annual surface temperature at 0 m altitude ranges between −8°C and −4°C.

3 | METHODS

3.1 | Delineation of cliff position

We studied the position of the top of the coastal cliff for around 4 km along the south-west Baydaratskaya Bay coast by DGPS surveys
The DGPS surveys were done using handheld GPS devices (Trimble R8 GPS receiver, Trimble TSC2 Controller, Trimble HPB450 radio modem) in real-time kinematic (RTK) mode in June 2013, June 2014, September 2015 and September 2016 (Figure 2, Table 1). An operator moved close to the cliff edge and placed the receiver exactly above the cliff for recording in a vertical position. The device antenna was differentially corrected to a reference station (66°53′46.502″E, 68°51′6.671″N; Figure 1). This allowed positional accuracies better than 0.2 m. Recordings were made every 0.5–1.0 m. We also used a geometrically corrected satellite image (DigitalGlobe product) taken by QuickBird-2 (QB02) spacecraft on 31 August 2005 (resolution 0.61 m). We additionally used ground control points obtained previously by DGPS surveys to improve the accuracy of the August 2005 imagery (Figure 2, Table 1). We manually chose the cliff position from the geo-corrected August 2005 satellite imagery to delineate the cliff line in August 2005. We then produced annual rates of cliff retreat for the periods August 2005 – June 2013, June 2013 – June 2014, June 2014 – September 2015, and September 2015 – September 2016. Following the assessment of uncertainty as proposed previously (e.g., 15,34,35), the cumulative uncertainty in our retreat rates was ±0.42 m/yr for the period August 2005–June 2013 and ±0.14 m/yr for the periods June 2013–June 2014, June 2014–September 2015, and September 2015–September 2016. In this paper, the observed retreat rate is expressed as $\mu_Q = Q_{3/4} - Q_{1/4}$ or $\mu(\delta_{xy})$, where $\mu$ is the mean value, $Q_{1/4}$ is the 1st quantile value, $Q_{3/4}$ is the 3rd quantile value and $\delta_{xy}$ is the error of the retreat rate.

3.2 | Ground temperature measurement

Two boreholes, MSU#4 (6 m deep) at the low terrace in the south-east study area and MSU#6 (3.5 m) at the high terrace in the north-west study area, were drilled in June 2013 and June 2014, respectively (see Figures 1 and 2 for location), using a handheld Earth auger machine. The boreholes were equipped with M-Log5W (GeoPrecision GmbH) thermistor strings to give temperature measurements of the soil during June 2013 and September 2016 (Table 1). The thermistors...
were located at intervals of 0.5–1.0 m and 0.2–0.6 m for boreholes MSU#4 and MSU#6, respectively. Temperature was measured every 6 h. Borehole MSU#4 was uninstalled in September 2015 due to unexpectedly rapid coastal retreat at this location.

3.3 | Resistivity measurement

The resistivity of frozen ice-rich material is significantly higher than unfrozen material due to the contrast in electrical properties between water and ice (e.g.,36). The transient electromagnetic method (TEM) was used at the Cofferdam site in the eastern study area (see Figure 1 for location) for imaging geocryological subsurface structure. TEM was applied along three parallel lines (50 m each) perpendicular to the coastline using “TEM-FAST 48” equipment (Applied Electromagnetic Research (AEMR)) in September 2015 and September 2016 (Table 1). The “TEM-FAST 48” has 48 geometrically spaced time gates to measure the transient within a time range of 4 μs – 15 ms. A single 50 m × 50 m loop was used for source and receiver in this study. The TEM-RES program version 8 (AEMR) was used for processing the resistivity measurements.37

3.4 | Wave energy flux of wind-driven ocean waves

We estimated the wave energy flux (power per meter of wave crest) of wind-driven ocean waves along the south-west Baydaratskaya Bay coast during 2004 and 2016 under sea-ice-free condition (open water). The wave energy flux $P$ (Jm$^{-1}$s$^{-1}$) is calculated by:

$$P = \frac{\rho g^2 H^2}{64\pi},$$

where $\rho$ is the density of water (1000 kg/m$^3$), $g$ is gravitational acceleration (9.82 m/s$^2$), $H$ (m) is the significant wave height and $T$ (s) is the peak wave period.38 Because we did not observe a significant wave height and a peak wave period, we approximated the wave energy flux based on wind shear stress on the water surface.39 The interfacial shear stress was calculated using daily
TABLE 1  Summary of the dataset used in this study

| Data                                      | Time                          | Resolution/interval | Accuracy      |
|-------------------------------------------|-------------------------------|---------------------|---------------|
| Handheld GPS position                     | June 2013, June 2014, September 2015, September 2016 | 0.5–1.0 m           | < 0.2 m       |
| QB02 satellite image (geo-corrected)      | August 2005                   | 0.61 m              | 0.81 m        |
| Belowground temperature (MSU#4)           | June 2013 – September 2015    | 0.5–1.0 m 6 h       | ±0.1°C at 0°C |
| Belowground temperature (MSU#6)           | June 2014 – September 2016    | 0.2–0.6 m 6 h       | ±0.1°C at 0°C |
| Meteorological data                       | January 2004 – December 2016  | 1 day               | N/A           |
| Resistivity                               | September 2015 & September 2016 | 12.5 m (horizontal) | 1–3 m (vertical) |
averaged wind speed observed at Marresale meteorological station on the south-west coast of Yamal Peninsula (see Figure 1 for location), with a wind-speed-dependent drag coefficient (for wind speeds up to 30–35 m/s)\textsuperscript{40,41} which is valid within a range of observed wind speed (0.6–22.0 m/s). Variation in wind direction was not taken into account because this was not available at Marresale station, although the dominant wind direction is reported to be north-west and north in summer\textsuperscript{25,32} which promotes the wave activity that will erode the coast in the study area. Fetch length was assumed to be 100 km. Sea-ice-free days in Baydaratskaya Bay during 2004 and 2016 were identified with the help of MODIS Corrected Reflectance (True Color) imagery available from NASA’s Worldview application. We used only the total wave energy integrated over the identified sea-ice-free days, in order to evaluate the influence of ocean wave activity upon observed coastal retreat.

4 | RESULTS

4.1 | Rate of retreat of coastal cliffs

We mapped the temporal and spatial variations in annual retreat rates of coast cliffs along south-west Baydaratskaya Bay (Figure 4). The results revealed that retreat rates were variable between August 2005 and September 2016. The annual retreat rate was highest at $1.9^{+0.7}_{-1.3} \pm 0.4$ m/yr during the period August 2005 – June 2013, intermediate at $1.4^{+0.2}_{-1.0} \pm 0.1$ m/yr during June 2014 – September 2015,

FIGURE 4  (a) Coastal retreat rates (m/yr) in the studied area in the periods August 2005 – June 2013, (b) June 2013 – June 2014, (c) June 2014 – September 2015, and (d) September 2015 – September 2016. Gray dots indicate stable or aggrading at a given location. The satellite image is the same as in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]
but low at 1.0 ± 0.1 (±0.1) m/yr and 1.1 ± 0.2 (±0.1) m/yr during the periods June 2013 – June 2014 and September 2015 – September 2016, respectively (Table 2). The observed cliff retreat rate was also variable in the different morphological and lithological settings. Retreat rates in the laida area (66°51.2'E–66°53.2'E) were highest for the periods 2005–2013 (4.4 ± 0.4 m/yr on average) and 2013–2014 (1.1 ± 0.1 m/yr), whereas they were intermediate for the periods 2014–2015 (1.4 ± 0.1 m/yr) and 2015–2016 (1.0 ± 0.1 m/yr). Retreat rates along the high terrace in the north-west study area (66°49.5'E–66°51.2'E) were lowest for the periods 2005–2013 (1.0 ± 0.4 m/yr), 2014–2015 (1.1 ± 0.1 m/yr) and 2015–2016 (0.8 ± 0.1 m/yr). Retreat rates along the low terrace in the south-east study area (66°53.2'E–66°54.5'E) were lowest for the period 2013–2014 (0.7 ± 0.1 m/yr) in the studied coastal sections and periods, whereas they were highest for the periods 2014–2015 (1.5 ± 0.1 m/yr) and 2015–2016 (1.2 ± 0.1 m/yr). By contrast, several of the coastal sites near the mouth of the Ngarka-Tambyakha River were accumulative during June 2013 and September 2016. The north-west boundary between the laida and the high terrace and several sites near a large thermokarst in the eastern study area were also either stable or accumulative during the periods 2013–2014 and 2014–2015.

4.2 Ground temperature

Ground temperature profiles were successfully obtained from boreholes MSU#4 (6 m deep) at the low terrace in the south-east study area and MSU#6 (3.5 m) at the high terrace in the north-west study area (Figure 5). Ground temperature at a depth of 2.0 m in borehole MSU#4 ranged between −25°C (in January 2014) and +27°C (August 2015) for the period June 2013 – September 2015, while temperatures measured below 4 m depth in borehole MSU#4 were not higher than 0°C during the same period (Figure 5b). Similarly, ground temperature at a depth of 0.2 m in borehole MSU#6 ranged between −22°C (December 2014) and +35°C (July 2016) during the period June 2014 – September 2016 (Figure 5c). Together with the data from the two boreholes recorded over four summer periods, ground temperature in summer was found to have increased gradually since 2013. Ground temperatures in December 2015 – February 2016 and summer 2016 were highest among the recorded three winter and four summer seasons, respectively, matching the air temperature data at the Marresale meteorological station, which showed that winter 2015–2016 and summer 2016 were anomalously warm (Figure 5a). These results indicated that ground temperature in both summer and winter increased gradually during 2013 and 2016.

4.3 Resistivity cross-sections

At the Cofferdam site, we imaged resistivity cross-sections extending 50 m along three parallel lines perpendicular to the coastline by TEM measurements in September 2015 and September 2016 (Figure 6). Resistivity was found to decrease with depth, from 100–1000 Ωm at 0–10 m depth to 1–10 Ωm at 10–20 m depth. We interpreted high-resistivity zones as frozen layers (permafrost: 100–1000 Ωm; transitional: 10–100 Ωm) and a low-resistivity zone as a thawing soil (1–10 Ωm). In September 2015, the upper high-resistivity zone extended to depths of ~10 m (seaward) and ~20 m (landward). In September 2016, the high-resistivity zone decreased to depths of ~4–8 m (seaward) and ~8–17 m (landward) (Figure 6). This suggests that the thickness of frozen soil decreased by approximately 10 m within a year. This rate of ice-layer thinning was much higher than expected from a one-dimensional thermal model for permafrost thinning42 that the base of the ice layer could increase at tens of centimeters per year even with the thin permafrost we studied (10–20 m). Although this topic is beyond the scope of this study, we assumed that this significant decrease could be associated with relatively higher air and ground temperatures during winter 2015 and summer 2016 (see Section 4.2) and/or sufficient rates of seawater transported into the sediments, lowering the freezing point of sediment pore water.

4.4 Wave energy flux of wind-driven ocean waves

We calculated the wave energy flux (power per meter of wave crest) of wind-driven ocean waves during 2004 and 2016 for sea-ice-free conditions (Figure 7). The total wave energy integrated over the sea-ice-free period changed annually due to variations in wind speed and number of ice-free days. Total wave energies for ice-free periods in 2005 and 2015 were highest (~25×10^9 J/m), while those in 2013 and 2014 were lowest (~10×10^9 J/m) during 2005–2016, probably related to the shortest ice-free days. By contrast, the fluctuation in total wave energy was relatively small during 2006–2011, ranging from 16×10^9 to 24×10^9 J/m, as the number of ice-free days during this period did not vary considerably.

5 DISCUSSION

5.1 Coastal retreat in Baydaratskaya Bay

Numerous studies have looked at the coastal dynamics in the Kara Sea coasts since the 1960s based on field measurements and analyses of satellite and aerial images (e.g., 17–26). They revealed that mean annual rates of coastal retreat ranged between 0.2 m/yr and 2.0 m/yr for most of the Kara Sea coasts in the last 50 years while several coastal sites were stable or accreting. Although no significant relationships were found between coastal retreat rates and geomorphology or ground composition, the retreat rates probably differed between regions.21,22 Most coastal sites in the Taymyr Peninsula, located in the eastern Kara Sea region, were eroding at the lowest rates for the entire Kara Sea coast with a mean value of

| Table 2 Summary of coastal retreat rates (m/yr) observed in south-west Baydaratskaya Bay. Q1/4 and Q3/4 are the 1st and 3rd quantiles, respectively |
| --- |
| Duration | Q1/4 | Median | Mean | Q3/4 | Maximum |
| Aug 2005 – June 2013 | 0.6 | 1.3 | 1.9 | 2.6 | 10.8 |
| June 2013 – June 2014 | 0.4 | 0.7 | 1.0 | 1.1 | 19.1 |
| June 2014 – Sept 2015 | 0.4 | 0.8 | 1.4 | 1.6 | 29.1 |
| Sept 2015 – Sept 2016 | 0.4 | 0.7 | 1.1 | 1.4 | 23.2 |
The Gulf of Yenisei coast was also reported to be retreating relatively slowly, between 0.2 m/yr and 0.4 m/yr.21,22 The Gulf of Ob coast was eroding at moderate rates for the Kara Sea coasts, with mean erosion rates of 0.33–0.7 m/yr.21,22 In contrast, the Western Yamal Peninsula coast showed variable retreat rates, with mean annual rates of 0.1 m/yr and 2.5 m/yr.17-19,21-24,28,43 A coastline along the Kharasaveyskoye gas field in the western Yamal Peninsula, located ~90 km north of the Bovanenkovskoye gas field (see Figure 1 for location), retreated by 28.5–39.1 m between 1976 and 2007 (ref.23), with a maximum rate of 4.5 m/yr during 1980s. At the Marresale site (Figure 1) , the cliff retreated at mean annual rates of 0.5–2.5 m/yr between 1978 and 2010, with a maximum rate of 3.3 m/yr in 1989 and 1990.19 By contrast, the south-east coast of Baydaratskaya Bay in the south-west Yamal Peninsula was eroding at mean annual rates of 0.1–0.6 m/yr.21,22,28 which were lower than those reported in the central-west and north-west Yamal Peninsula coasts. Most coastal sites in the western Baydaratskaya Bay and the western Yugorsky Peninsula were retreating at mean annual rates of 0.4–2.0 m/yr.19,21,22,28 although several of the sites were stable during 2005 and 2012.44 Arctic climate warming and human activity have probably enhanced coastal retreat in this area from the period 1960–2005 to 2005–2016.28 For the south-west Baydaratskaya Bay coast we studied, annual retreat rates were variable even during the relatively rapid period of retreat in 2005–2016. In particular, the mean annual retreat rate during 2005–2013 (1.9±0.7 (±0.4) m/yr) was probably highest for 1991–2016 for the entire Baydaratskaya Bay coasts, and was comparable to the highest rates observed during the last 50 years along the entire Kara Sea coast.21,22,28 These changes may be related to annual variations in climatic factors. In the Baydaratskaya Bay region, summer 2015 was very stormy for example, the 26th of July 2015 was the most notable stormy day among any of the 2013–2016 summer periods, as also observed at the Marresale meteorological station. This might have influenced coastal retreat in summer 2015, perhaps
enhancing the retreat rate as observed for the period June 2014 – September 2015, although a correlation between the coastal retreat rate and number of stormy days had been reported to be weak at the Marresale site.19 We also found geomorphological variations in coastal retreat rates during the study period. For example, the low-lying laida (1–2.5 m height) retreated faster than the low (3–6 m) and high terraces (10–17 m) during the periods 2005–2013 and 2013–2014, whereas several sites near the mouth of the Ngarka-Tambyakha River within the laida area were accumulative or stable during 2013–2016. This fast retreat might be due to that the low-elevation laida was readily exposed to the activity of strong waves that enhanced erosion. We therefore discuss below some of the climatic drivers that may influence the observed cliff retreat rates.

5.2 | Influence of temperature rise and snowfall days

Thermal insulation with snow accumulation and temperature rise has been reported to result in the retreat of permafrost coasts. In the Mackenzie Delta area of north-west Canada, multiple retrogressive thaw slumping is enhanced once landslides occur, because less vegetation leads to higher temperatures and thermal insulation associated with snow accumulation in winter.45 In Muostakh Island of the central Laptev Sea, the mean annual rate of coastal thermo-erosion correlates strongly with mean air temperature in summer.46 At the Marresale site in the western Yamal Peninsula of the Kara Sea, the maximum retreat rate was observed in summer 1989 and 1990 when mean summer air temperature was highest (for the period 1978 and 2003).19 Based on meteorological data at Marresale station, however, close direct relationships are not found between coastal retreat and snowfall days or air temperature in the studied Baydaratskaya Bay coast (e.g., Pearson correlation coefficients between mean annual retreat rates and snowfall days or mean summer air temperature are $r = -0.39$ and $-0.41$, respectively). For example, snowfall in 2014 ended latest (16th July) and started earliest (21st August) for the period 2005–2016; this could influence erosional processes resulting from snow cover either through delaying thermodegradation or leading to nivation (e.g., 47).
but resulted in an intermediate retreat rate for the period June 2014 – September 2015 (1.4 ± 0.2 (±0.1) m/yr). On the other hand, resistivity imaging revealed that the thickness of the high-resistivity zone decreased during 2015 and 2016, suggesting degradation of the underlying ice layer (Figure 6). Ground temperature was relatively high between winter 2015 and summer 2016 in the studied period 2013–2016 (Figure 5). The decrease in ice layer thickness observed by resistivity measurement is thus partly due to an abnormally warm geothermal regime during winter 2015 and summer 2016. However, the rate of cliff retreat during the period September 2015 – September 2016 was relatively low (1.1 ± 0.3 (±0.1) m/yr), although thermal abrasion activity associated with this temperature rise might slightly increase coastal retreat during the period. These findings therefore suggest that temperature is not a primary driver that enhances yearly coastal retreat in the south-west Baydaratskaya Bay coast, although a more definitive correlation cannot be studied without further ground temperature monitoring.

5.3 Influence of wind-driven ocean wave activity

Having ruled out that the observed cliff retreat has changed primarily based on temperature variations during the study period, we evaluated the relationship between cliff retreat rates and total wind-driven ocean wave energy. The role of wind activity on erosional processes along the permafrost coast has not been clear. Leon’t’yev48 was the first to ascribe that wind-driven wave could be the primary driver determining coastline retreat in the Kara Sea coast. Vasiliev et al.19 inferred a correlation between cliff retreat rate and total wave energy at the Marresale site in the western Yamal Peninsula. It is also thought that thermodenudation and the action of slope processes can lead to annual retreat rates of up to 0.4 m/yr in the Kara Sea coasts if the wave influence is eliminated.19,22 This implies that cliff retreat in the Baydaratskaya Bay coast may be strongly influenced by the action of ocean waves, because the retreat rates observed in this study are higher than 0.4 m/yr. Here, we compare the annual retreat rates in August 2005 – June 2013, June 2013 – June 2014, June 2014 – September 2015, and September 2015 – September 2016 (Table 1), to the mean monthly wind-wave energies of wind-driven ocean waves received during the corresponding sea-ice-free days in 2005 (August–October) and 2006–2012 (all ice-free days), 2013 (all ice-free days), 2014 (all ice-free days) and 2015 (June–September), and 2015 (September–October) and 2016 (July–September), respectively (Figure 8). The comparisons show that the coastal retreat rate observed during a given period is higher when the mean monthly wind-wave energy received during the ice-free periods of interest is higher (e.g., Pearson correlation coefficient between mean annual retreat rate and mean monthly wind-wave energy is r = 0.99). This suggests that northerly wind-driven wave activity during ice-free days is important in determining the magnitude of yearly coastal retreat. Wave activity may therefore lead to higher coastal retreat rates along the south-west coast than the south-east coast of Baydaratskaya Bay. Moreover, the difference between Q2/4 and Q1/4 of the observed cliff retreat rate over the entire studied coast in a given period is larger (i.e., the retreat rate over the entire studied coast is more variable) when the received monthly wind-wave energy during ice-free days is higher (Figure 8), suggesting that stronger wave activity makes the magnitude of coastal retreat within the studied coast spatially more variable. This is probably due to different morphology and lithology among the studied coastal sections that differ in their resistance to wave activity. Further continuous monitoring and observations are necessary to verify this hypothesis, as the larger variation may also result from differences in the wind-wave energy for the study periods.

5.4 Release of sediment and organic carbon into the ocean

Erosional processes in the permafrost coast result in release of large amounts of sediment and organic matter to the nearshore zone.3,49

![Figure 8](wileyonlinelibrary.com)
For example, the mean annual rates of sediment release due to coastal erosion are estimated to range between 800 and 5400 m$^3$/km/yr (m$^3$ per km coastline per year) in the Barents, Kara, Laptev, East Siberian and Russian Chukchi Seas (e.g., 50,51). Lantuit et al.\textsuperscript{6} reported that 6–47 Tg/yr of organic carbon is released to the entire Arctic from coastal erosion. Because wind-driven ocean wave activity is an important factor influencing coastal retreat in the Baydaratskaya Bay, as discussed above, the amounts of sediment and organic carbon released are expected to vary with the magnitude of wave activity. We first quantify the sediment volume released to the nearshore zone associated with coastal erosion during 2005–2016 using the profile of cliff height\textsuperscript{33} and retreat rates observed in this study, based on a simple estimation and assuming taper-shaped removal from cliffs. The eroded sediment volumes from the study coast are calculated to be 5600, 2500, 3500 and 2700 m$^3$/km/yr during the periods August 2005 - June 2013, June 2013 - June 2014, June 2014 – September 2015, and September 2015 – September 2016, respectively. Thus, the mean annual eroded volume during the period of strong wave activity (i.e., 2005–2013) could be larger than the reported highest mean rate for the Russian Arctic coasts. Second, we estimate annual rates of total organic carbon released to the nearshore zone by coastal erosion, by using the calculated sediment volume fluxes and assuming an averaged bulk density of 1700 kg/m$^3$ and typical organic carbon content of 0.7–1.0% from previous studies in similar lithological settings along the Baydaratskaya Bay coast.\textsuperscript{19,22} Total organic carbon fluxes are thus $66\times 10^3$–$95\times 10^3$, $24\times 10^3$–$34\times 10^3$, $34\times 10^3$–$49\times 10^3$ and $27\times 10^3$–$39\times 10^3$ kg/km/yr (kg per km coastline per year) for the periods 2005–2013, 2013–2014, 2014–2015 and 2015–2016, respectively. These fluxes are probably significant for the entire Kara Sea coast because they are larger than the averaged fluxes of organic carbon for the entire Kara Sea coast resulting from coastal erosion ($15\times 10^3$ kg/km/yr).\textsuperscript{22} Therefore, the release of eroded sediment to the nearshore zone may influence the marine ecosystem of Baydaratskaya Bay through increasing ocean turbidity, acidity and organic carbon supply (e.g., \textsuperscript{4}), and is particularly important in summer when river discharge is low (e.g., \textsuperscript{52}). Although it is difficult to quantify its impact on the marine ecosystem, the quantities of sediment and nutrient supplied to the ocean are considered to have changed with the magnitude of wind-driven ocean wave activity during sea-ice-free days. The quantification of sediment volume together with further continuous monitoring may help to assess the long-term risk to livelihoods and infrastructure along the Kara Sea coast.

\section{Conclusion}

We have investigated coastal retreat of cliffs extending for approximately 4 km along the south-west Baydaratskaya Bay coast in the Kara Sea during 2005 to 2016, through handheld DGPS mapping, analysis of satellite imagery, ground temperature monitoring, subsurface resistivity measurements, and estimation of wave energy flux of wind-driven ocean waves. We found that the annual retreat rate changed with not only geomorphological and lithological settings of the coast but also year, ranging between 1.0$^{+0.1}_{-0.1}$ (±0.1) m/yr and 1.9$^{+0.7}_{-1.5}$ (±0.4) m/yr during 2005–2016. We conclude that wind-driven ocean wave activity during the sea-ice-free period influenced the magnitude of retreat, whereas recent temperature increases contributed less to enhancing coastal retreat during the period. This suggests that wave activity has controlled the amount of eroded sediment and organic matter released from the permafrost coast to the nearshore zone, perhaps influencing infrastructure along the coast and the marine ecosystem in Baydaratskaya Bay. We also hypothesize that the stronger wave activity has increased variability in the magnitude of coastal retreat within the same coastal section, and this needs to be examined through further continuous monitoring.

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