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Massive ice beds in coastal dynamics of the Kara Sea

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ABSTRACT

Massive ice beds are ice layers in permafrost one to tens of meters in thickness, contributing to the development of retrogressive thaw slumps in the coastal zone. They are common for part of the Arctic coastal lowlands; in Russia, the main region of their distribution (north of Western Siberia) coincides with the region of oil and gas fields exploration and development. The data on the distribution of massive ice beds were compared with the data on the coastal retreat rates collected in the database of the Arctic Coastal Dynamics project and in the Atlas of Abrasion and Ice-Gouging Hazards of the Coastal Shelf Zone of the Seas of the Russian Arctic (Version 12.2020). On a regional scale, no direct relationship was found between the presence of massive ice beds and the mean annual rates of coastal retreat, since other factors smooth out the effect of accelerated erosion caused by massive ice degradation. However, for specific coastal segments and on a short time scale, presence of massive ice beds leads to a significant (2 times or more) increase in the rate of coastal erosion. The role of thermodenudation (permafrost melting) increases in warmer years. At the same time, in one of the considered key areas, land development had a greater impact on the retreat rate than the presence of massive ice beds or an increase in air temperatures.

KEY WORDS: Massive ice beds; Ground ice; Retrogressive thaw slumps, Coastal dynamics; Western Siberia

INTRODUCTION

It is assumed that the predicted climate warming in the Arctic will cause permafrost degradation. The greatest changes in permafrost landscapes can potentially occur in areas with high ice content in permafrost. An active restructuring of the terrain and activation of cryogenic processes occurs when large volumes of ice melt. On the other hand, the thawing of icy deposits from the surface can lead to subsidence, which is imperceptible in the relief. Also, the greater the ice content of the permafrost, the greater the heat capacity and the more energy is required for the ice-water phase transition. Therefore, warming does not always directly lead to the degradation of icy permafrost. Icy permafrost is unstable to thermal effects under conditions of disturbance of the natural cover and active exogenous processes. The importance of accounting for ground ice for studies of coastal abrasion was noted by J.R. Mackay (1963), since the destruction of frozen coasts occurs both as a result of mechanical erosion by waves and due to permafrost thawing. However, taking this factor into account requires, first of all, data on the spatial distribution of various types of ground ice.

Massive Ice Beds Distribution

Ice in permafrost can be represented either by massive ice (massive ice beds, wedge ice), or pore and segregated ice that forms cryostructure.

Massive ice beds are layers of ground ice more than 1 m thick with ice content of at least 250% on an ice-to-dry-soil weight basis (Mackay, 1971). In Russia, massive ice beds has been actively explored since the 1960s. They are widely distributed in West Siberia (Figure 2) and Chukotka and are also found in other regions, see publications database on massive ice beds (Streletskaya et al., 2001). In Western Siberia, massive ice beds distribution is explained in different ways in various paleogeographic concepts. Those who claim the existence of the Kara ice sheet on the shelf of the Kara Sea in the Pleistocene associate massive ice with the boundaries of the Pleistocene glaciation (Fig.2, State geological map, 2015, 2018, 2018) and refer them to buried glaciers. Other researchers argue that Quaternary sediments were formed exclusively under the influence of changes in sea level. Thus, massive ice was formed during the freezing of marine sediments and in Yamal is more often found within the so-called third terrace. Verification of hypotheses is hampered by the limited data on massive ice distribution; mapping of their distribution is necessary. However, a unified map of massive ice distribution in Russia (except for general schemes) has not been created yet. This is partly due to the sporadic distribution of massive ice compared to wedge ice. According to the estimations of of Yu.K. Vasil’chuk (2014), massive ice beds occupies no more than 1% of the area even in the regions of their maximum distribution. The massive ice beds are often not

Figure 1. Retrogressive thaw slump caused by massive icy sediments thawing at the eastern coast of Yugorskiy Peninsula, Kara Sea, Russia (69.749º N, 61.819º E).
2019, photo by N.Belova

expressed in modern relief which also complicates their mapping. To indicate the presence of massive ice beds, retrogressive thaw slumps (thermocirques) – identified by direct observation or from remote-sensing imagery – can be used (Couture, 2017). Mapping of the massive ice beds distribution areas using retrogressive thaw slumps is promising and becomes more accessible due to the availability of high-resolution space images online in the public domain for many areas where massive ice beds are widespread (for example, the north of Western Siberia). In this case, it is necessary to involve data on the geocryological structure, since retrogressive thaw slumps can form not only due to massive ice beds degradation, but also during the melting of the ice complex or ice-rich permafrost.

Coastal dynamics of the seas of Russian Arctic

The coasts of the Arctic seas are retreating at an average annual rate of 0.5 m/yr (Lantuit et al, 2012). This value was calculated based on the results of the Arctic Coastal Dynamics Project (https://arcticcoast.info/), in which experts from different countries compiled a database containing information on the rate of retreat, ice content of the Arctic coasts and other parameters (see. Fig. 2). For the seas of the Russian Arctic, data on the types of coasts and rates of retreat were refined during the preparation of the Atlas of Abrasional and Ice-Gouging Hazards (Ogorodov et al., 2020). The longest coastal retreat observation series are point-based and are obtained by measuring the distance from buildings (e.g., the Marre-Sale and Kharasavey weather stations) to the coastline. In some areas (Kharasavey, Baydaratskaya Bay coasts), direct field monitoring has been carried out since the 1980s-1990s. At the present stage, high-resolution satellite imagery data is actively used. Their comparison with space and aerial photographs up to the 1960s (for example, CORONA satellite imagery) makes it possible to estimate the dynamics of the coast for more than half a century. In the coastal dynamics databases (Lantuit et al., 2012; Ogorodov et al., 2020), observations at individual sites are extrapolated to larger coastal segments, based on lithodynamic processes features and coastal structure.

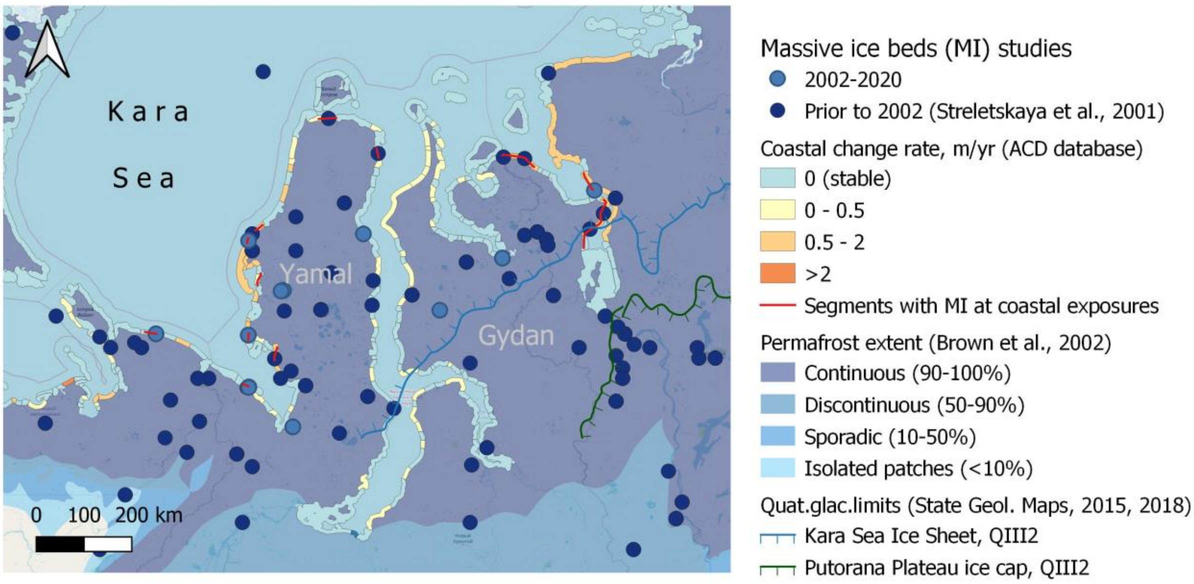

Figure 2. Massive ice beds study sites (based on published literature) and coastal retreat rates (Lantuit et al., 2012) at the north of Western Siberia

The main regions of massive ice beds distribution in Russia are the coastal lowlands of the north of Western Siberia and Eastern Chukotka. Further in the article the coast of the north of Western Siberia – the Kara Sea – will be considered since here active gas fields development is taking place.

The Kara Sea Coasts

The work used coastal segmentation used in the Atlas of Abrasional and Ice-Gouging Hazards (Ogorodov et al., 2020). Retreating thermoabrasional and thermodenudational coasts make up 11 and 20% of the Kara Sea coastline (including islands), respectively (Ogorodov et al., 2020). Thermoabrasional coasts retreat at an average rate of 0.5-2 m/yr. Most of the thermodenudational coasts retreat at the rate of less than 0.5 m/yr, a smaller part – at rates from 0.5 to 2 m/yr.

Most of the Kara Sea coasts (64% length) is stable or aggrading (Fig. 3). At 36% of the length, the coasts retreat, mainly at rates <0.5 m/yr (23%). 12% and 1% of the coasts retreat at rates of 0.5-2 m/yr and >2 m/yr, respectively.

For this work, the mainland coast of the Kara Sea and adjacent islands in the north of Western Siberia were considered. Here, the eroding coasts make up about a half, of which 20% retreat at rates of more than 0.5 m/yr (Fig. 3b). When considering morpholithodynamic coastal types, less than 40% of the coasts (thermodenudational and thermoabrasional) can actively retreat under natural conditions (Fig.4). Only within their limits, massive ice can affect the rate of coastal destruction.

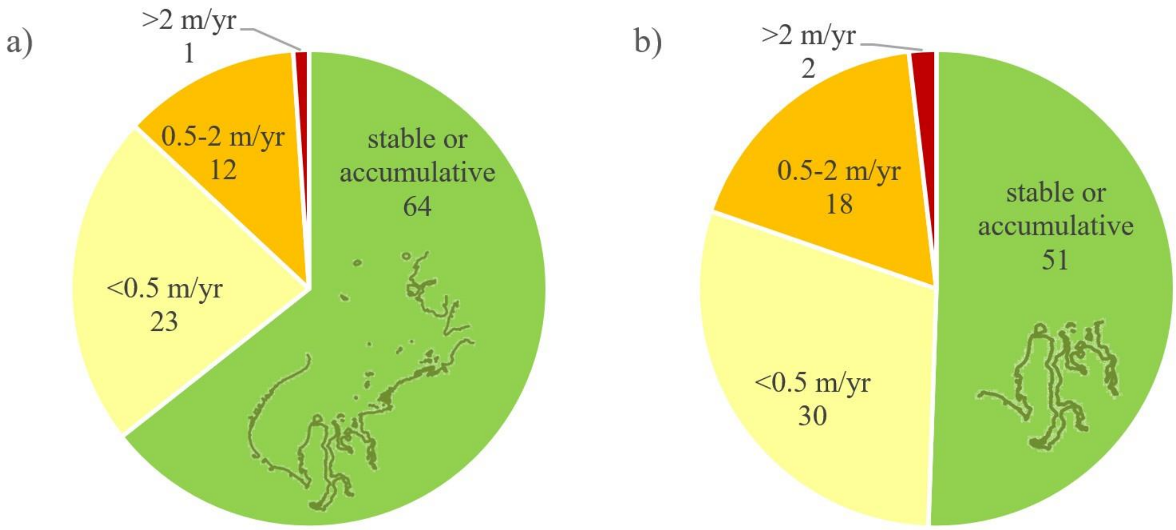

Figure 3. Distribution of the coasts of the Kara Sea by the rate of retreat, % of the length: a) for the Kara Sea as a whole; b) for the north of Western Siberia from the Yugorskiy Shar Strait to Cape Severo-Vostochny on Taymyr. Based on (Ogorodov et al., 2020)

Regional assessments of the dynamics of the Arctic coasts are based on studies at key sites, where the rate of retreat is determined by direct long-term field observations and using multitemporal remotely sensed data. Such works make it possible to single out the role of the main factors of coastal dynamics (coastal structure, permafrost conditions, hydrometeorological factors, technogenic factor) at the local level. The thermoabrasional and thermodenudational coasts of the southwestern sector of the Kara Sea are characterized by mean annual retreat rates of about 1 m/yr at open-sea coasts (Novikova et al., 2018; Belova et al., 2020), slightly lower – 0.5 m/yr – for the coasts of the bays (Baranskaya et al., 2021).

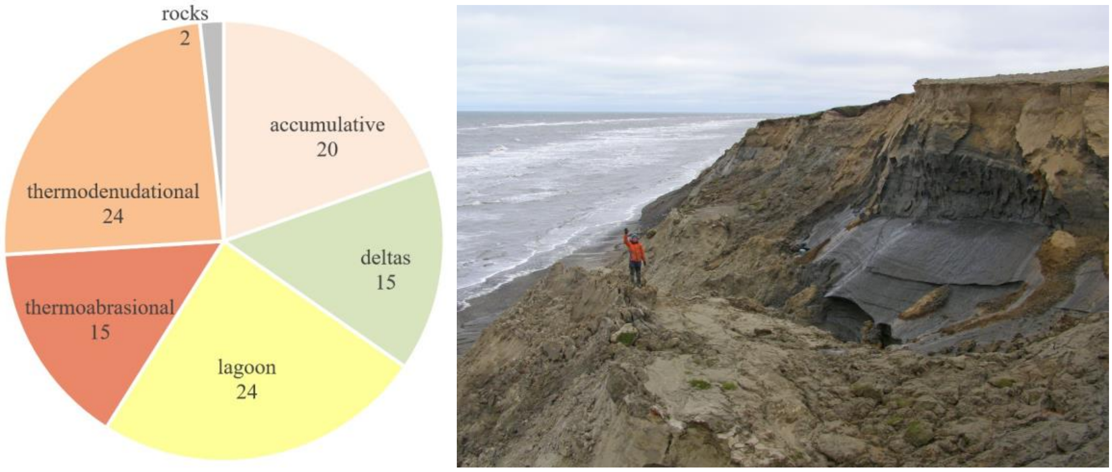

Figure 4. Morpholitodynamic types of the coasts in the southwestern sector of the Kara Sea,% of the length. Calculated for the north of Western Siberia from the Yugorskiy Shar Straight to Cape Severo-Vostochny on Taymyr. Based on (Ogorodov et al., 2020). Photo: massive ice 3.5 m thick at western thermodenudational coast of Baydaratskaya Bay (69.004º N, 67.444º E), 2007, photo by N. Belova

Coastal retreat and ground-ice content

A number of studies have investigated the relationship between the erosion rates of the Arctic coasts and ground ice parameters. Sensitivity of coastal erosion to ground ice contents has been estimated (Lantuit et al., 2008) based on ACD database. Ground ice content and retreat rates only weakly correlated statistically ($r = 0.48$, relationship statistically significant at $\alpha = 0.01$). This result does not contradict the significant role of ice content of the sediments in coastal dynamics. However, a significant correlation is only possible for coasts that are eroding relatively intensively. At rates of retreat of <0.5 m/year, it is difficult to distinguish the contribution of a separate natural factor; for such coasts usually there is one leading limiting factor smoothing out the influence of others (for example, the position of the coast in the bay when it is closed from direct wave action from the open sea).

For the coast of the north of Western Siberia (from the Yugorskiy Shar Strait to Cape Severo-Vostochny in Taymyr), we compared the segmentation performed for the Atlas of Abrasion and Ice-Gouginh Hazards (Ogorodov et al., 2020) with data on the key sites where massive ice beds studies were carried out. Data on massive ice beds studies was taken from the database of publications on massive ice beds (Streletskaya et al., 2001), expanded by modern publications (http://mice.nextgis.com/resource/1/display?panel=layers). Among 288 segments identified by the coastal dynamics characteristics only within 12 (4.6% of the total length) there are massive ice beds discovered by research (see Fig. 2). There are more than 12 segments within the coasts where massive ice beds have been found, but often they are exposed in the lower reaches of river valleys or found during drilling and are not exposed in the sea coastal bluffs. All segments of the sea coast with massive ice beds belong to the thermoabrasional or thermodenudational types of the coast. On 2% of the coast, massive ice beds occur at coasts retreating at rates <0.5 m/yr, and by another 3% at rates of 0.5-2 m/yr. Thermoabrasional and thermodenudational coasts occupy 39.2% of the length, but only at 1/10 of the segments massive ice beds are exposed. At the local level, massive ice beds become a significant factor of coastal dynamics not only for open sea coastal segments with more or less intensive retreat (>1 m/yr). Even in bays with insignificant rates of coastal destruction (0.5 m/yr), segments with massive ice beds can retreat much more intensively, e.g., up to 1.7 m/yr in Kruzenshtern Bay (Baranskaya et al., 2021) within the not yet developed Kruzenshternskoye gas condensate field.

CONCLUSIONS

On the example of the Kara Sea region, it is shown that, on a regional scale, the presence of massive ice beds does not affect the rate of coastal retreat. Massive ice beds are characterized by sporadic distribution, therefore, their contribution to the resulting value of coastal retreat can be significant only at the local level. In the north of Western Siberia, massive ice beds can be found in coastal bluffs at less than 5% of the coastline, and in these areas, they should be considered as one of the leading factors of coastal dynamics.

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