Response to anonymous referee 2

We would like to thank the reviewer for evaluating our manuscript and for the useful comments, which helped to improve it. In the following, we provide a reply to the points discussed by the reviewer as well as changes in the manuscript.

The comments of the reviewer are written in **bold**, the extracts of the manuscript in *italics* with changes highlighted in blue and line numbers referring to the revised manuscript.

The manuscript focuses on cliff erosion along 5.5 km coastline in NW Svalbard. Four aerial surveys were used to derive decadal-scale cliff retreat rates. The study is valuable given limited research on Arctic rock coasts, in particular at the timescales exceeding a few years.

I think that the paper is well-written with very clear methods. I really appreciate error estimation. The results are concrete. The figures are of good quality. There is no redundant information.

I agree with some conserns by Referee 1 and will not re-list them here. Definitely the reference to beyond-Svalbard Acrtic cliff studies is missing, so is a more detailed study area description including cliff morphology (cliff height, typical slope of bedrock wall and overlaying soft sediment). I would expect better justification of using top of the overlaying material as the proxy for coastline, given extensive discussion on this topic in rock coast literature. In terms of limited analysis on environmental conditions influencing coastal erosion raised by Refree 1, I would say you can go either way - perform more in-depth analyses or consider it out of scope of the study (but then I would move the temperature data to appendix and take the interpretation out of conclusions). Indeed, as of now there is quite a mismatch between measuring erosion and environmental conditions.

We widened the perspective and included more references from similar studies worldwide. To do so, we added information in the introduction and placed our results in an international context in the discussion. The following changes were made in the manuscript:

Line 21: *Therefore, Arctic coasts are often eroding more rapidly than coasts in temperate regions and the average retreat rate is estimated to 0.5* $\mathrm{m\,a^{-1}}$ *(Lantuit et al., 2012). However, the variability of coastal retreat rates across the Arctic is pronounced, both on a regional and local scale. Lantuit et al. (2012) present a circum-Arctic database, where the highest rates are detected in the Laptev Sea (0.73* $\mathrm{m\,a^{-1}}$*), the East Siberian Sea (0.87* $\mathrm{m\,a^{-1}}$*), the US Beaufort Sea (1.15* $\mathrm{m\,a^{-1}}$*) and the Canadian Beaufort Sea (1.12* $\mathrm{m\,a^{-1}}$*). Numerous regional studies corroborate these numbers, for example with retreat rates along the Bykovsky peninsula (Laptev Sea) of 0.59* $\mathrm{m\,a^{-1}}$ *between 1951 and 2006 (Lantuit et al., 2011), along the US Beaufort Sea of 1.8* $\mathrm{m\,a^{-1}}$ *between 1940 and 2010 (Gibbs and Richmond, 2017) and along the Canadian Beaufort Sea with 0.7* $\mathrm{m\,a^{-1}}$

(Irrgang et al., 2018). The highest erosion rates are often found in ice-rich permafrost bluffs and barrier islands. Jones et al. (2018) present a maximum of 48.8 $\mathrm{m\,a^{-1}}$ *in such a setting along the US Beaufort Sea from 2007 to 2008.*

Line 376: *The calculated retreat rates are lower than the average change in Arctic coastlines of 0.5* $\mathrm{m\,a^{-1}}$ *(Lantuit et al., 2012). This is expected as high retreat rates are typically found along unlithified coasts, which account for 65 % of the Arctic coastline (Irrgang et al., 2022). In contrast, the coastline along Brøgger peninsula is formed by bedrock, being characterized by a higher resistance against mechanical abrasion compared to unlithified coasts, and the unconsolidated sediments on top are not exposed to wave action. However, we detected higher retreat rates compared to other lithified coasts in the Arctic, e.g. the Canadian Archipelago with 0.01* $\mathrm{m\,a^{-1}}$ *(Lantuit et al., 2012). This can be explained by the long open water season at the western coast of Svalbard (Sect. 5.2), resulting in the high importance of mechanical abrasion by wave action (Sect. 5.2). Other contributing factors might be the highly fractured bedrock, decreasing the resistance of the material towards erosion and the permafrost conditions, which show a temperature range with decreased bedrock stability (Sect. 5.2).*

We extended the description of the study site (please refer to the track-changes-document for an entire compilation of the changes), including additional information about the cliff morphology.

Line 84: *The coastal cliffs have a mean height of 15.5* m *with a maximum of 28.0* m*, whereof the bedrock accounts for approximately 10.5* m *on average. The average slope angle of the unconsolidated sediments is approximately 35°.*

We agree with the reviewer that a better explanation was needed why we used the cliff top retreat as a proxy for coastal erosion along Brøgger peninsula. To follow the suggestion of the reviewer, we added a new analysis in the revised manuscript. It is explained in the methods (Sect. 3.3), has an own new section in the results with two new figures (Sect. 4.2) and is mentioned at the beginning of the discussion (Sect. 5.1). The changes are as following:

Explanation in the methods:

Line 178: *The coastline was digitized along the top of the cliff (Fig. 1), which is slightly retreated compared to the actual shoreline, i.e. the boundary between water and land, due to unconsolidated sediments on top of the bedrock (Sect. 2). The top of the cliff has been used as a proxy for the shoreline in previous studies (e.g. Irrgang et al., 2018). However, it is important to note that the cliff top and the cliff foot can erode at different rates, and that the presence of frontal beaches can affect the erosion processes (Swirad and Young, 2022). To address this, we conducted an analysis to confirm the suitability of the cliff top retreat as a proxy for coastal retreat at our field site. To do so, we compared the distance between the cliff top and the shoreline, as well as the width of the frontal beaches for 53 cross-sections along the coast with a proximate distance of 100* m*. Hereby, we used the orthoimages from 2010 and 2021 since the shoreline could not be reliably detected in the orthoimages* *from 1990 and 1970.*

The new section in the results:

Line 282: ***4.2 Cliff top retreat as a proxy for coastal retreat***

The analysis of 53 cross-sections along the investigated coastline of Brøgger peninsula shows that the distance between the cliff top and the shoreline changed only slightly by less than 0.10 m *between 2010 and 2021. An example of a representative cross-section is given in Fig. 4. Here, the distance from the cliff top to the shoreline was 32.35* m *in 2010 and reduced marginally to 32.19* m *in 2021. Meanwhile, the width of the beach increased slightly from 2.82* m *in 2010 to 3.05* m *in 2021. This example showcases that the cliff top retreats at similar rates as the shoreline.*

The mean distance for all cross-sections was 17.44 m *in 2010 and reduced marginally to 17.35* m *in 2021. The change in distance of 0.09* m *is considerably smaller than the uncertainty associated with the digitization of the coastline (Table 2), i.e. the position of the cliff top. Also, the distribution of the distances is comparable between those two years with clusters of cliff top-shoreline-distances around 4* m*, 12* m *and 24* m *(Fig. 5).*

In addition, we analyzed the width of the frontal beaches along the 53 cross-sections. The results show that the width was only slightly reduced from 2.23 m *in 2010 to 2.09* m *in 2021. Furthermore, the characteristics of the cliff morphology did not change significantly: Seawater reaching the cliff foot directly was detected for 40 % (2010) and 42 % (2021) of the cross-sections, while 47 % (2010) and 45 % (2021) had frontal beaches with a high potential of inundation during stormy conditions (as the example given in Fig. 4), and only 7 % (2010, 2021) had extended frontal beaches, which could limit the effect of wave activity on the cliff foot. Both the small change in beach width and cliff morphology are indicators, that the eroded material is transported away effectively from the foot of the cliff and that no significant accumulation of eroded material occurs. Furthermore, we can conclude that the potential for wave activity is not affected due to changes in the cliff morphology over the years.*

As our results suggest that the average distance between the cliff top and the shoreline or the width of the beach does not change significantly over time, we are confident that the retreat of the cliff top is an applicable proxy for the coastal retreat at our field site.

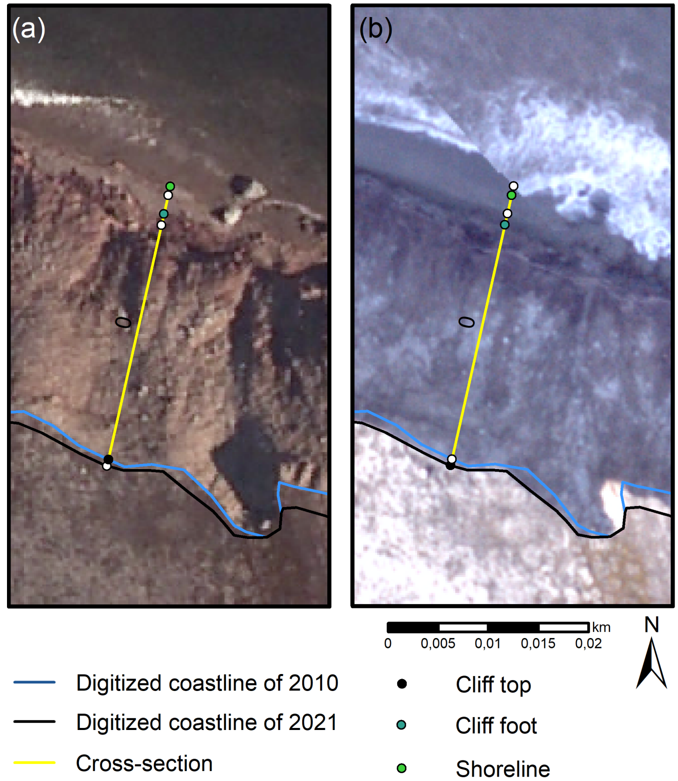

Figure 4. *Cross-section with cliff top, cliff foot and shoreline for (a) 2010 and (b) 2021. The background shows the respective orthoimages. Source of the orthoimage: (a) Norwegian Polar Institute, https://geodata.npolar.no/; (b) Svalbard Integrated Arctic Earth Observing Systems SIOS, not publicly available.*

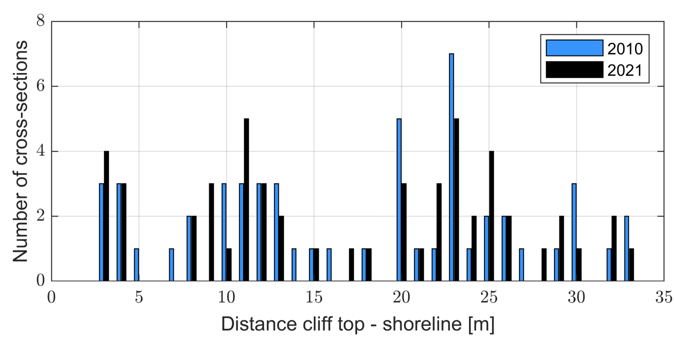

Figure 5. *Number of cross-sections that show a certain distance between cliff top and shoreline for 2010 and 2021. The distribution only changes slightly with clusters around 4* m*, 12* m *and 24* m*.*

At the beginning of the discussion, we added the following statement:

Line 370: *In this study, we analyzed the retreat of the cliff top along the lithified coast of Brøgger peninsula. We showed that this rate is representative of the coastal retreat (Sect. 4.2) so that a comparison with the erosion along other coastlines on Svalbard and in the Arctic can be drawn.*

We performed a more detailed analysis on environmental conditions influencing coastal erosion. This includes a new section in the methods (Sect. 3.5) and results (Sect. 4.4), as well as a more thoroughly discussion (Sect. 5.2). The revised version includes the following changes:

Changes in the methods:

Line 249: ***3.5 Analysis of climate conditions***

We analyzed trends in wind speed and changes in the distance to the sea ice edge (potential wave fetch), as these factors control the interaction between wind and water and therefore the wave field (Barnhart et al., 2014), playing an important role along the coastline of Brøgger peninsula due to mechanical abrasion through wave action. The wind speeds records were taken from the Ny-Ålesund climate station SN99910 (78°55'23" N, 11°55'55" E; Fig. A1), covering the time period 1975 to 2020 (Norwegian Centre for Climate Services, 2023). We extracted days during which mean hourly wind speeds of at least 10.8 $\mathrm{m\,s^{-1}}$ *(strong breeze or stronger) were recorded, corresponding to large waves of approximately 3 to 4* m *(NTNU, 2023).*

We also analyzed the distance to the sea ice edge in northwesterly direction (corresponding to the open Fram Strait), which is the potential distance over which waves can build up. The analysis of this potential fetch was based on data provided by the Norwegian Meteorological Institute (2023) for the time period 1997 to 2023. Hereby, we define the sea ice edge as the given category of 10 to 40 % sea ice concentration, following Meier and Stroeve (2008) and Overeem et al. (2011), who applied a threshold of 15 %. We determined the distance to the sea ice edge for September for which 22 ice charts per year were available on average. For trend detection, we applied a Bayesian regression analysis (Särkkä, 2013), which is explained in Appendix A. In all other cardinal directions, land is found in about 10 to 15 km *distance, so that the potential fetch is limited.*

In addition, we used hourly ERA5 reanalysis data (Hersbach et al., 2020) in conjunction with the topography-based downscaling routing TopoSCALE (Fiddes and Gruber, 2014) to analyze trends in mean annual air temperature, annual rain- and snowfall, as well as mean annual incoming longwave and shortwave radiation. The methods and detailed results for these climatic parameters are presented in Appendix A and Appendix B.

Changes in the results:

Line 349: ***4.5 Changes in climatic conditions***

Given the lithology along the coastline of Brøgger peninsula, mechanical abrasion through wave action is likely a dominant factor for erosion. Therefore, we focus in this section on the wind conditions and changes in the sea ice cover. Other factors, such as precipitation patterns, air temperature and radiation, are presented in Appendix B.

The trend analysis of wind speeds in Ny-Ålesund defined as a strong breeze or stronger (wind speeds >= 10.8 $\mathrm{m\,s^{-1}}$*, corresponding to large waves of approximately 3 to 4* m*; NTNU, 2023) shows an increase by 5.4 days per decade from approximately 65 days on average in the 1970s to 90 days in the last decade (Fig. 8a). However, due to the strong variability, the evidence in favor of a trend remains weak (Bayes factor < 0.5, Appendix A). Years with exceptionally many days of high wind speeds occurred in the early 1990s, while they decreased slightly in recent years. We emphasize that the climate station providing the data, is located approximately 8* km *away from the field area inside Kongsfjorden, where wind speeds are lower compared to the investigated field site. Wind speed measurements at the tip of Brøgger peninsula (available only since 2021) recorded 112 days with strong breezes in 2022 compared to 84 days in Ny-Ålesund (Norwegian Centre for Climate Services, 2023), thus highlighting the potential differences in wind regimes.*

In most cardinal directions, land is found in about 10 to 15 km *distance, so that the potential wave fetch over open water is limited here. However, in northwestern direction, the coastline of Brøgger peninsula is exposed to the open sea towards Fram Strait and the potential wave fetch is limited by the distance to the sea ice edge, which is displayed in Fig. 8b for the month of September. We detected an increasing trend from about 150* km *to 250* km *between 1997 and 2023, which accounts for approximately 39* km *per decade (Bayes factor 1-2, strong evidence in favor of the trend, Appendix A). The largest values with a mean distance to the sea ice edge of more than 300* km *were observed in 2020 and 2021.*

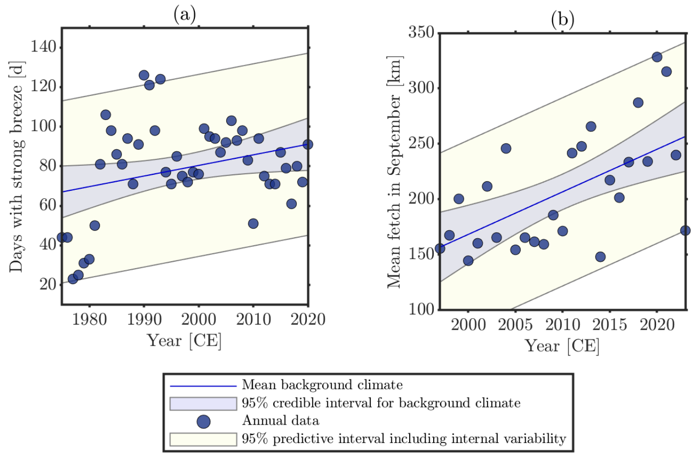

Figure 8. *(a) Days with a strong breeze (wind speeds >= 10.8* $\mathrm{m\,s^{-1}}$*) measured by the Ny-Ålesund climate station SN99910. They increased by 5.4 days per decade between 1975 and 2020. (b) Mean distance to the sea ice edge (potential wave fetch) in September in northwesterly direction. The distance to the sea ice edge increased by approximately 39* km *per decade between 1997 and 2023.*

Changes in the discussion:

Line 418: *Retreat rates of Arctic coastlines are governed by various drivers, dependent on the local coastal setting and environmental conditions (Irrgang et al., 2022). The lower part of the coastal cliffs is prone to abrasion, acting through the thermal and wave-driven mechanical energy of the sea (Are, 1988a, b) and intensive wetting-drying during open-water season (Strzelecki et al., 2017). We assume that these factors play an important role in coastal erosion along Brøgger peninsula, as overhanging rock walls with a retreated foot of the cliff can be observed (Fig. 1c). Abrasion is especially effective during stormy weather, which likely intensified in the area around Brøgger peninsula during the past decades, showing a positive trend of days with a strong breeze in the last decades (Fig. 8a). Furthermore, extreme cyclone events regularly occur in the Arctic North Atlantic, with 20 to 40 events during winter. In Ny-Ålesund, an increasing trend of six cyclones per decade was detected from 1979-2015, which can be related to a decreasing sea ice extent in the region and large-scale atmospheric circulation changes (Rinke et al., 2017). Single weather events like this can support landsliding and consequently, they can have a localized but pronounced influence on the retreat rates.*

However, the impact of windiness and wind-induced wave action is expected to vary along the coastline of Brøgger peninsula. The northeast facing coastline is characterized by a relatively sheltered position within the Kongsfjorden system, with land in most cardinal directions within a range of 10 to 15 km*. This likely restricts the fetch and consequently wave activity, which may explain the lower coastal retreat rates in this sector. In contrast, the southwest facing coastline is more exposed to* *the open sea, especially in westerly and northwesterly directions in which the potential wave fetch is controlled by the distance to the sea ice edge in Fram Strait, which has clearly increased in the last decades (Sect. 4.5). Previous studies have shown that an increasing fetch results in wave growth (Casas-Prat and Wand, 2020b), increasing the capability for wave-driven erosion (Casas-Prat and Wang, 2020a). Therefore, the increasing distance to the sea ice edge towards the open Fram Strait likely increase the wave activity and thus mechanical abrasion along southwest sector of Brøgger peninsula, likely explaining the higher erosion rates found here.*

In addition to the large-scale sea ice conditions in Fram Strait, local sea ice coverage around the Brøgger peninsula can influence the thermal regime of the rock walls (Schmidt et al., 2021) and potentially also wave action and mechanical abrasion (Barnhart et al., 2014). Dahlke et al. (2020) provides an overview of sea ice extent around Svalbard from 1980 to 2016. The results show a considerable decrease in sea ice coverage during winter and spring in Forlandsundet (where the southwest facing coastline is located), decreasing from 50-70 % until the early 2000s to below 10 % in recent years. Kongsfjorden (where the northeast facing coastline is located) experienced an increase in sea ice extent from around 40 % to 60 % in the 1990s and a subsequent decrease to around 10 %. However, as our field area is located in the outer parts of Kongsfjorden (NE sector) and near the open Arctic ocean (SW sector) where typically less sea ice develops, even lower percentages of sea ice coverage are likely, with mostly ice-free conditions in the last decade.

Line 19: what about rising SST?

We added this point in the revised manuscript. It is also mentioned by Irrgang et al. (2022) so that the reference requires no changes.

Line 19: *This is especially true for Arctic coastlines where sea level rise, sea ice retreat, increasing seawater temperatures and loss of permafrost and glaciers have pronounced effects on coastal dynamics (Irrgang et al., 2022).*

Line 21: state timespan of these observations

The average rate of 0.5 $\mathrm{m\,a^{-1}}$ given by Lantuit et al. (2012) is compiled by several studies, covering different timespans and an extrapolation between those values. Therefore, it is not possible to state an exact timespan. The authors state: "The dataset that we present is mostly a static view of the coast and functions as a baseline for future comparative investigations: erosion rates change yearly, and are undergoing trends (local, regional, or global) which are not represented here. In that sense, this database cannot be considered as a dynamic tool to look into seasonal or annual variability in coastal change.". To account for this, we changed the formulation in the revised manuscript.

Line 21: *Therefore, Arctic coasts are often eroding more rapidly than coasts in temperate regions, and the average retreat rate is estimated to 0.5* $\mathrm{m\,a^{-1}}$ *(Lantuit et al., 2012).*

Line 46: specify that it is the coastal cliff erosion (there are decadal-scale coastal erosion studies in Svalbard such as Zagorski et al., 2015)

We changed the wording in the revised manuscript.

Line 66: *Previous studies on coastal cliff erosion on Svalbard cover only a few years...*

Line 65: Are there any estimates (in days) of the snow cover season shortening?

We only found information about the onset of snow melt. We added this in the revised manuscript.

Line 113: *Both snowfall and rainfall can occur at any time during the year, but the snow season typically lasts from October to June (Hop and Wiencke, 2019). Following the trend of warming air temperatures, a shifting of the onset of snow melt to earlier dates is observed with -5.8±8.3 days per decade (Maturilli et al., 2015).*

Line 69: do they provide values for the increase?

We added some information about how much the precipitation increased since the 1980s.

Line 112: *The mean annual precipitation between 2010 and 2021 in Ny-Ålesund was 526* mm*, showing an increasing trend in the last decades since the 1980s with 384* mm *(Norwegian Meteorological Institute, 2022a).*

Line 26: replace 'comparatively' with 'relatively'

We changed the wording in the revised manuscript.

Line 35: *In contrast, lithified coastlines in the Arctic are assumed to be relatively stable...*

Line 264: replace '1970-2021' with '51 years'

We changed the manuscript according to the suggestion of the reviewer.

Line 398: *In contrast to that, we only consider the retreat rate at the top of the cliff, but extent the analysis over a much longer segment of the coastline (5.5* km*) and a longer time period (51 years).*

Line 293: perhaps replace 'release of large blocks' with 'landsliding' because the former term means something different in rock coast literature

We changed the manuscript accordingly.

Line 427: *Single weather events like this can support landsliding and consequently, they can have a localized but pronounced influence on the retreat rates.*

Fig. 1. Add an arrow pointing to the study area on the map of Svalbard.

We added an arrow to Fig. 1.

Fig. 1. Perhaps add names of water bodies on panel a (and inset?).

We added the name "Kongsfjorden" in Fig. 1.

Fig. 1. Something is wrong with the scale bar given your study area is 5.5 km

We thank the reviewer for pointing out this issue. The scale bar is now corrected.