

Full discussion: <https://egusphere.copernicus.org/preprints/2024/egusphere-2024-1656/>

Referee comments are in black

Authors responses are in blue, with proposed **new text** in bold

Author Response for Referee #1: César Deschamps-Berger

This article presents estimation of the retreat rate of an 8 km shoreline in Alaska from time series of satellite optical images (Planet) and high-resolution satellite laser altimetry (ICESat-2). The retreat is estimated for 3 years continuously along the coastline (imagery) and along three transects (altimetry). Both methods results in similar rates estimate and highlights the interannual and spatial variability of the retreat patterns. The processes potentially leading to these retreat patterns are explored. I appreciated reading this article as it is well written, presented and concise. The methods are well explained and make good use of novel datasets. I have no background on the specific topic of coastal dynamic and cannot evaluate the quality or novelty of this work to this regard. However, from the introduction, it sounds like this is the first work using ICESat-2 data at such spatial resolution to estimate coastal retreat rate. If this is the case, it should be emphasized as a novelty of this article. Furthermore, I suggest the authors to consider the following improvement before considering the article ready to be published

We thank the referee for the very thorough comments. We agree that the novelty of our application of ICESat-2 should be emphasized, and propose the following changes to achieve this:

-L3: "Here, we use **a novel combination** of shoreline boundaries from multispectral imagery from Planet and topographic profiles from ICESat-2 satellite altimetry to compare year-to-year changes in shoreline position and morphology across different shoreline types "

-L67-70: Move the last sentence of the preceding paragraph to the beginning of the next paragraph:

" Elevation measurements from airborne lidar (e.g., Jones et al., 2013) and aerial photogrammetry (e.g., Gibbs et al., 2019; Lim et al., 2020a, b) can be used to qualitatively characterize the shoreline, provide high-resolution estimates of shoreline position, capture short-term topographic change, and enable comparisons of retreat rates between different geomorphic units (e.g., Lim et al., 2020a) on seasonal (e.g., Gibbs et al., 2019; Lim et al., 2020a) to multi-year (e.g., Jones et al., 2013) timescales and over km-scale areas e.g., Lim et al. 2020a). ~~Satellite-based elevation measurements enable annual and seasonal high resolution (< 5 m) coastal elevation estimates on a pan-Arctic scale, providing the potential to expand on this work and transform our understanding of Arctic shoreline morphology and change.~~

The Ice, Cloud and land Elevation Satellite 2 (ICESat-2) laser altimeter collects repeat cross-shore elevation profiles, **providing the potential to expand on previous**

elevation-based work with satellite altimetry and transform our understanding of Arctic shoreline morphology and change..."

-L88: Add a new topic sentence to this paragraph: "**Here, we present a case study demonstrating how repeat altimetry from ICESat-2 can be used in tandem with satellite imagery to track annual shoreline change and provide insight on short-term and local shoreline processes.**"

-L445: Add a new topic sentence: "**Analyses of both the geolocated photon data and derived elevation profiles from ICESat-2 provide valuable insight on shoreline change.**"

L8 Speed formatting See the Cryosphere Author Guideline : "(e.g. 10 km h⁻¹ instead of 10 km/h)."

We thank the reviewer for bringing this to our attention and have updated the formatting for all rates mentioned in the manuscript.

L12 : "*Our topographic profiles from ICESat-2 highlight three distinct shoreline types...*"

Are the shoreline types really distinguished from the ICESat-2 data? It seems more like an optical images analysis. Maybe as well move this sentence before the previous sentence.

We realize the wording here is ambiguous, and have rephrase it as:

"Our topographic profiles from ICESat-2 **sample** three distinct shoreline types "

L15 "*can provide*" => "*provide*" (if it did, of course)

We have changed 'can provide' to 'provide'

L20 Hard to read, citations should be moved at the end of the sentence.

Although we realize this impacts readability, the citations are currently placed to make it clear which references are associated with each stated environmental process.

L29 "*During the open water season, when i.e. the coasts are not sheltered by sea ice*"

We have rephrased this sentence as: "During the open water season, **i.e.**, when the coasts are not sheltered by sea ice."

L34 "*to be highly variable on local scales (~10s of meters)*" at what temporal scale are the rate variable ? Decadal like for the regional scale rates ? Or on shorter term ? I think it is important to always specify the spatial and temporal scale of the changes considered.

We thank the reviewer for pointing this out and have updated this sentence to clarify the timescales:

"studies that consider the spatial distribution of **decadal and annual** retreat rates have found them to be highly variable on local scales (~10s of meters) (Gibbs and Richmond, 2015; Farquharson et al., 2018; Irrgang et al., 2018; Jones et al., 2018)."

L67 “*Satellite-based...*” unclear if this is what will be developed in this article or pre-existing studies? In the latter case, cite studies. For instance, is there no work based on the ArcticDEM dataset?

We are not aware of any work using Arctic DEM for coastal studies. We have cited a couple of previous ICESat-2-based studies in the next paragraph (L77-78). We have also made the following change to make the transition between previous elevation-based work and our planned work more clear:

"Elevation measurements from airborne lidar (e.g., Jones et al., 2013) and aerial photogrammetry (e.g., Gibbs et al., 2019; Lim et al., 2020a, b) can be used to qualitatively characterize the shoreline, provide high-resolution estimates of shoreline position, capture short-term topographic change, and enable comparisons of retreat rates between different geomorphic units (e.g., Lim et al., 2020a) on seasonal (e.g., Gibbs et al., 2019; Lim et al., 2020a) to multi-year (e.g., Jones et al., 2013) timescales and over km-scale areas e.g., Lim et al. 2020a). ~~Satellite-based elevation measurements enable annual and seasonal high resolution (< 5 m) coastal elevation estimates on a pan-Arctic scale, providing the potential to expand on this work and transform our understanding of Arctic shoreline morphology and change.~~

The Ice, Cloud and land Elevation Satellite 2 (ICESat-2) laser altimeter collects repeat cross-shore elevation profiles, **providing the potential to expand on previous elevation-based work and transform our understanding of Arctic shoreline morphology and change...**"

L76 “*cm-to-dm*” write in full letter, dm is not so clear
We have rewritten this to "centimeter-to-decimeter"

L79 “*sub-satellite ground track*” ?
We have simplified this to "ground track"

L80 “*repeat-track mode*” what other mode is there?
We have removed the mention of "repeat-track mode" here and instead provided a brief explanation of ICESat-2 pointing modes in section 2.4:

"Outside of the poles, the majority of ICESat-2 revisits were off-pointed from their nominal ground track location to increase areal coverage, such that subsequent revisits did not cover the same ground location. However, "Target of Opportunity" requests over the North Slope of Alaska resulted in exact repeats of every fifth reference ground track starting in April 2019"

L83 “*water(Jasinski)*” missing space
We have added a space

L85 “*< 10 m*” write with words
We have rephrased this to be "sub-10 meter"

L88 “*photon data (ATL03)*”

We have added "(ATL03)"

L93 "*Jones et al. (2009)*" I would delete this to alleviate the ()
We have moved this citation to the end of the sentence for readability.

L110 "*(with negative shoreline change indicating retreat)*" to move at the first occurrence of rates description in the text
We have moved this phrase up to the second sentence of the introduction (L3), where retreat rates are first mentioned.

L112 "*storm occurrence, and storm power*" ?
We have rephrased this as "storm activity"

L117 "*by CNES Airbus*" maybe give the satellite name. From a rapid check on <https://www.intelligence-airbusds.com/en/4871-ordering>, I get the feeling that what is shown on Google Earth might be a mosaic of a Pléiades and SPOT-6-7 images possibly on 19-09-2018 https://www.intelligence-airbusds.com/satellite-image/?id=DS_PHR1A_201809192213155_FR1_PX_W154N70_0219_03392
https://www.intelligence-airbusds.com/satellite-image/?id=DS_SPOT7_201809192147155_FR1_FR1_FR1_FR1_W153N71_02602
We agree that the images listed above may be the source imagery for the Google Earth mosaic image we used. However, we have been unable to definitively confirm whether our image is derived from Pleiades, SPOT, or both, and as such feel that it is appropriate to just use the general CNES Airbus attribution provided by Google Earth.

L120 "*composition*" ? Could it be more precise? geometry ?
We have rephrased this as:

"These classifications are based on **the substrate and morphology** of the shoreline as well as dominant erosion and accretion processes thought to be present."

L124 "*by Gibbs and Richmond (2015) and Jones et al. (2009)*" a bit too much importance given to citations, makes reading complicated in this part.
We agree this is a bit confusing, and have rephrased this as:

"Region 1, the westernmost portion of the study area, primarily consists of steep, ice-rich coastal bluffs (Jones et. al, 2009, Harper and Morris, 2014, Gibbs and Richmond, 2015)."

L130 "*as an inundated*"?
We have corrected this typo

L130 "*by low elevations*" isn't this characteristic of all the area ? Maybe give the range of elevation in the area in Study Site.
We acknowledge that this is a bit vague, and have clarified this statement:

"The easternmost portion of this shoreline is classified as an inundated tundra environment, **where the nearshore elevation is below sea-level, and there has been significant thaw subsidence and flooding.**"

We will also provide the typical shoreline elevations in this region based on previous studies

L156 "*when retreat when ocean*" ?

We have removed "when retreat", which was a typo

L162 "*time interval*" ? Interval between two successive data acquisition?

We have clarified this sentence:

"We also recorded the mean air and ocean temperature **between 1 June and 31 October of each year**"

L172 "*using implemented in matplotlib contour in Python*" ?

This was a typo, and we've added in the missing text:

"We identified the sub-pixel land-water boundary from our NDWI images using a **marching squares algorithm** implemented in matplotlib contour in Python"

L197 "*(ground tracks 3r,2r, and 1r, labeled in Fig. 1 (a))*" this is, the most surprising methodological point to me. Due to the switch between forward and backward orientation, the right and left beam can be the strong or the weak beam. I understand that the time series obtained here is composed of weak and strong beam data. Although I would not expect big differences between the elevation of either beam, it should be at least commented and explained. As well, why only use the right beam? Adding the left one would increase the data sampling and if too redundant, it would provide an estimation of the uncertainty of the method.

We thank the reviewer for pointing this out, and we acknowledge that the time series is a combination of strong and weak beam data. Brunt et. al (2019) found the elevation difference between strong/weak beams in a pair to range from 0.6 cm (ground tracks 2l and 2r) to 1.3 cm (ground tracks 3l and 3r). These elevation biases, which are based on analysis of ICESat-2 release 001 data so are likely maximum estimates, are small compared to other potential sources of elevation change (such as changes in snowcover and morphologic change), and we do not anticipate that they would impact our estimates of horizontal shoreline position. We have updated Table 1 to show which acquisitions correspond with strong vs weak beams.

When inspecting the available ICESat-2 data in this region, we found that for a given acquisition date, we sometimes only have "good" data (i.e. enough signal photons to derive a reliable surface) from either the left or the right beam. For example, the photon returns from the left beam on 2021-07-02 are insufficient to characterize the shoreline. Focusing our study on the right beam allowed us to ensure that we consistently had data at the same location on each sampling date, allowing for a more straightforward

comparison of shoreline evolution between beams. Furthermore, focusing on just three beams allows for a more in-depth discussion of each individual beam. Future work will focus on bulk analysis of ICESat-2, such that all beam pairs for a given RGT are considered.

L207 *“the SlideRule Python Client”* I know that SlideRule is public but is the code of this article available somewhere?

The full code is not available publicly at this time. We have tried to be explicit in describing our methods such that it can be replicated even without the exact code.

L213 *“uncertainties propagated from ATL03”* what error field from ATL03 are used for this uncertainty calculation?

We have updated this for clarity:

"SlideRule provides the RMS error between the photons used in the final fitting and the final linear fit, as well as the photon-level elevation error that is propagated through the linear fit. **The photon elevation error is assumed to be uniform for a given segment and is estimated as the maximum of the segment RMS error and the background-corrected standard deviation.**"

L215 Why using 80 % overlap ? Sounds like a lot of repetitive data? Were other values tried (no need to reprocess anything if not)?

To address this, we have added the following explanation:

"For coastal applications, a high along-track resolution is preferable to capture abrupt elevation changes at the shoreline. However, shorter segments may not provide enough photons for a robust linear fit (particularly for low-albedo surface, such as the snow-free tundra), and may result in height estimates that are subject to along-track variations in photon density. A longer segment length results in a smoother profile, at the cost of not capturing small-scale features. In order to strike a balance between these two considerations, we implemented the SlideRule ATL06 algorithm for 10 m long segments spaced every 2 m along track"

We note that this 80% overlap does mean that consecutive along-track elevation segments are not independent of each other. The specific values were chosen due to providing a good visual fit with the underlying photon data. We acknowledge that future work would benefit from experimenting with different segment lengths and postings.

L231 *“We identified the intersection between each ICESat-2 track and the corresponding imagery- derived shoreline and compared the shoreline positions and north-south retreat estimates derived from Planet and the two ICESat-2 boundaries”* I have one doubt: were the retreat from Planet and ICESat-2 calculated along the same direction (the only one possible being the ICESat-2 track) for the comparison?

Rather than report the along-track retreat from ICESat-2, we calculated only the change in the north-south component of the ICESat-2-derived shoreline position. We will revise this to instead project our profiles in the direction perpendicular to the local shoreline,

based on the assumption that the observed change is predominantly due to cross-shore movement. We have added L231-233 accordingly:

“We identified the intersection between each ICESat-2 track and the corresponding imagery- derived shoreline and compared the shoreline positions and ~~north-south~~ **cross-shore** retreat estimates derived from Planet and the two ICESat-2 boundaries. **We projected our profiles in the direction perpendicular to the local planet-derived shoreline, based on the assumption that any observed change is predominantly due to cross-shore movement.**”

L241 “*find that they range*”?

We have added the word "that"

L245 “2019” This is just style and nothing mandatory but I would avoid starting a sentence with a year. For instance, a few sentence further: “*in late October. 2021 saw*” is not easy to read. The “.” seems an error.

We have rephrased this section as:

"We observed the most extreme environmental conditions by all measured metrics in 2019 (Table 2). **The 2019 erosion year** had the longest open water season, with sea ice breaking up sooner (late June) and re-forming later (mid-November) than in the other 2 years"

The '.' was a typo and has been removed.

L251 “*Imagery-derived shorelines **position and retreat rates***” alternative title to avoid shoreline repetition

We agree that this is a clearer title and have updated it.

L258 “*corresponding to a **position** change estimate uncertainty of 3.1 m*”

We have updated add the word "position"

L258 : “*2.2 m, corresponding to a change estimate uncertainty of 3.1 m*” this assumes uncorrelated error of both shoreline, maybe worth mentioning

We agree that this is worth mentioning and have revised this section to:

"Based on the uncertainty estimation described in Section 2.3, we estimated the precision of our shoreline positions estimates to be 2.2 m. **Assuming that the error in each shoreline is independent of the others**, this corresponds to a change estimate uncertainty of 3.1 m."

L260 “*Only 6 segments across the 3-year*” maybe give somewhere the total number of segments

We will update section 2.3 paragraph 2 to include the total number of shoreline segments.

L264 “*Region 1 showed moderately high retreat*” Moderate or high? Sounds opposite. We've removed the word 'moderately'

L267 “*with 15% of valid shoreline segments*” maybe provide this metric for other years. It is hard to evaluate its meaning otherwise. We have updated the text to clarify:

"While every shoreline segment in region 1 underwent retreat in 2019 and 2020, 15% of valid shoreline segments (all in the western half of Region 1) did not exhibit substantial (> 3.1 m) shoreline change in 2021."

L275 “*(-70.1 m of shoreline change)*” this made me think: could tides and waves have an impact on the shore detection (depending on the tide, wave amplitude and the bathymetry)?

We thank the reviewer for bringing this to our attention. We have added following passage to Section 2.3:

"The tides in this region tend to be less than 0.2 m, but storm surges can result in temporary relative sea level increases of 1.4 m (Jones et al, 2018). However, given that much of this region consists of steep bluffs with narrow, or no beaches (Gibbs and Richmond, 2015), changes in the local relative sea level are not expected to have a large impact on the observed land-water boundary."

We expect that variations in the shoreline due to changes in the instantaneous water level are captured in our uncertainty analysis (L179-L187).

L288 “*we note that it consistently falls between the upper and lower*” is this result consistent with the errors estimated for both estimates (ICESat-2 and Planet). Do the error bars overlap?

We agree that this is important to clarify. We have updated the text to give the upper and lower bounds of the difference between the Planet and ICESat-2 derived boundaries as well as their associated uncertainties:

"We would expect the land-water boundary from Planet to be located seaward (north) of the lower backshore boundaries identified by ICESat-2. However, we found that the Planet-derived land-water boundary consistently falls landward of the ICESat-2-derived lower boundary (by 8.6 ± 4.2 m to 40.9 ± 4.5 m), and either seaward (by up to 36.0 ± 4.5 m) or slightly landward of the ICESat-2 derived upper boundary (by up to 3.2 ± 4.0 m) (Fig. 4)."

L306 “*that may correspond to toppled bluff material*” anything visible on the Planet imagery to back this hypothesis?

Planet imagery shows little retreat at the site of the ICESat-2 location (-3.7 m) as well as across the surrounding region (-7 m (± 3.1 m) across region 1), which would be consistent with the presence of collapsed bluff material. However, due to the resolution and image quality of the Planet imagery, we are unable to identify small features such

as toppled blocks, such that we can't directly confirm this hypothesis with Planet imagery.

L313 "(Fig. A7(b))" => "(Fig. A7.b)" I would avoid nested brackets.

We have updated our in-text figure citations to avoid nested brackets

L314 "in Airbus imagery from Google Earth (Fig. 6(c))" for another study: could Landsat images be useful?

Landsat images could be useful at looking at long-term retreat in this region, but the lower resolution would limit its use for short-term change and the more detailed shoreline analysis done here.

L319 "a slight lowering (by 0.23 m)" I would avoid brackets as much as possible to ease the reading.

We have made the following changes to try to avoid over-using using parentheses in this section:

-**L310**: "The backshore elevation remains stable, (ranging from 4.89 m to 5.02 m)"

-**L311**: "...the remnant basin of a ~~small~~(~ 150 m in diameter) lake that was breached"

-**L316**: " This resulted in a 0.40 m drop in the backshore height (from 1.33 m to 0.93 m)"

-**L319**: " We also observe a slight lowering (~~by of~~ 0.23 m)of the backshore height"

-**L335**: "...passes over a 1.71 m high dune in front of a ~~large~~(~ 2.6 km ~~across~~)**km-wide** breached thermokarst lake"

-**L328**: "We note a 0.22 m drop in the backshore elevation (from 1.89 m to 1.67 m) between 2019 and 2020, after which the elevation remains stable from 2020 to late 2021 (**ranging from** 1.64 m to 1.67 m)"

L334 "*are higher than long-term historical estimates and similar to recent observations*"

a visual way to represent that (for future work or here it seems relevant) could be to represent with lines or rectangles previous results and results of this article on the same timeline (x axis being time, y the position change). As is done for glacier mass balance. For instance, see Fig. 8 in Falashi et al. 2023

(<https://tc.copernicus.org/articles/17/5435/2023/>). Rectangles instead of lines allow to show range or uncertainty.

We agree that a figure would help illustrate our rates compared to historical rates and will add this figure to the supplement: (**Figure A7** in the updated manuscript).

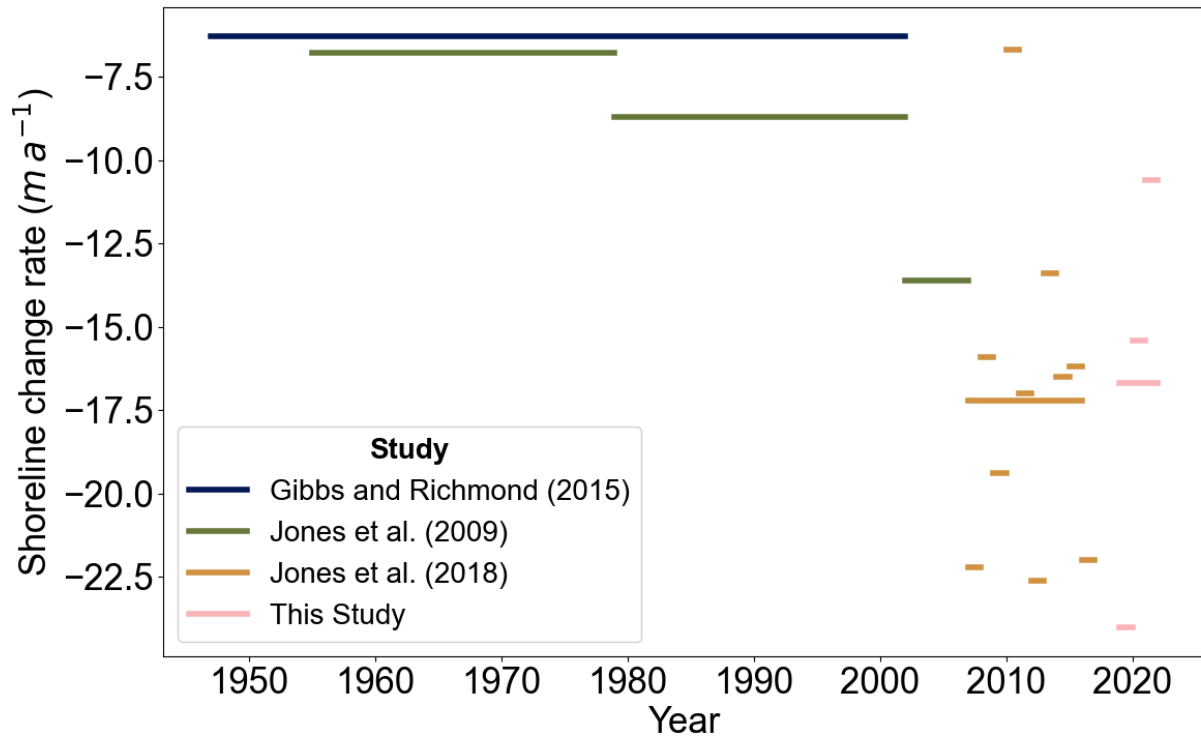


Figure A7: Long and short-term regional shoreline change rates along the Alaskan Beaufort Sea Coast near Drew point from previous work, along with the 3-year and year-to-year regional rates derived in this work.

We note that this figure appears to show increases in retreat rates over time, but that more recent studies (including ours) cover shorter time intervals than older studies. Since retreat is highly episodic, retreat rates estimated over long periods may be averaging periods of high and low retreat, leading to a lower overall rate compared to short-term estimates. While this figure provides a useful visual to put our results into the context of previous work, it also may lead readers to draw conclusions about trends in retreat rates over time that we are not trying to address in this work. Therefore, we will include this figure in the supplement, and have updated the main text (L339-342) to acknowledge the apparent trend while also acknowledging there are multiple potential explanations for it:

~~“Taken together, these studies suggest a sustained acceleration in retreat rates over the past few decades. Our observed retreat rates are consistent with this increasing trend. Our 3-year mean of observed retreat rates (-16.7 m) is higher than the long-term estimates of Gibbs and Richmond (2015) and Jones et al. (2009) and similar to the decadal-scale estimate from Jones et al. (2018). However, we note that While our elevated estimates of erosion compared to historical rates could be reflective of an increase in retreat rates over time, they may also be due to the short time period of our observations, as short-term estimates of shoreline change tend to be more variable higher in magnitude than long-term estimates (Sadler and Jerolmack, 2015).”~~

L416 “*in the 90th*”?

We have added the word "the"

L473 “AK” => “Alaska”

We have changed "AK" to "Alaska"

L474 “We found annual km-scale variability in shoreline **annual change**”?

We have changed this to "We found km-scale variability in **annual shoreline change**"

Figure 4 If I guess correctly: add in the caption that the dashed lined are drawn assuming stable shore position during ice-on periods and evolving linearly during ice-free period?

This is correct, and we have added the following to our figure caption:

"Dashed lines indicate the trajectory of the shoreline based on a linear rate of change during the open water season and no change during ice-on periods"

Figure 5 Add the 1:1 line.

We will add a 1:1 line

Figure 6 It could be useful to show a Planet image as background on the left panel. It is a bit confusing to see the shoreline more advanced into the sea, even more with the 2024 copyright date. Maybe as well zooming in a bit more? It is hard to get information from the background image at this resolution.

We note that at the current spatial scale in the left hand side of Figure 6, Planet appears over-zoomed, making it hard to distinguish small-scale shoreline features. Imagery from Google Earth was used as a higher-resolution alternative. The zoom level was set to be consistent across all 3 plots, and needed to be wide enough to include the entire drained lake basin in Figure. The 2024 copyright date is listed to comply with Google Earth's attribution guidelines, but we will add an additional annotation to each subfigure to make it clearer that the source imagery was taken in 2018.