# Rapid retreat of permafrost coastline observed with aerial drone photogrammetry - Response to Referees

**Referee #1**

General comments

The manuscript presents investigations of short-term coastal dynamics at a very rapidly retreating coastline using UAVs (drones) combined with data on long-term coastal dynamics of the same section according to satellite and aerial images. Although using multitemporal imagery analysis for coastal retreat measurements is common practice, and Herschel Island is a relatively well studied area in terms of coastal dynamics, the authors made the first attempt to provide very high temporal resolution observations of coastal erosion, including intra-seasonal dynamics presented by short-term periods (3-7 days during the summer of 2017). This is the principal novelty of the study, which gave new insights into mechanisms and rate variability of coastal erosion and proved again its episodic nature, when a coastal segments can retreat by several meters in a few days during one storm. In this way, the investigated coastal segment gave a unique opportunity for such detailed analysis, as the rates of retreat in 2017 were unprecedented. Another strong point of the manuscript is the well described methodology, giving an example of using drones for coastal dynamics monitoring, which is already popular and will surely become one of the main tools in coastal investigations in the years to come. We would advise to reduce some general comments about the evident benefits of using drones and focus on giving more technical details that can be further used for elaboration of technologic standards (flight heights, required number of ground control markers, etc. - see in Specific comments below). Overall, the manuscript is a high quality study, with valid and appropriate methods, new trustful results supporting the discussion, fluent and precise language, well-readable figures and abundant supplementary material. The discussion can be re-grouped and some sections of it shortened (see below), however, this does not hinder the general good impression of the paper. Please also note the supplement to this comment: https://www.the-cryosphere-discuss.net/tc-2018-234/tc-2018-234-RC1-supplement.pdf

**Author response: We thank Referee 1 for their very positive appraisal of our manuscript, and for their constructive suggestions. We have revised our manuscript in light of this feedback (responses to specific points of feedback provided below), and hope that the Referee will agree the manuscript is now greatly improved as a result.**

Specific comments

Abstract

The abstract might be shortened, omitting information on the Kuvluraq – Simpson Point gravel spit, which is mentioned in the text shortly. The objectives can be shortened. The phrases: Lines 28-30 ("We found drone surveys analysed with image-based modelling yield fine-grain and accurately geolocated observations that are highly suitable to observe intra-seasonal erosion dynamics") and Lines 33 Page 1 - 2 Page 2 (We conclude that the data available from drones is an effective tool to understand better the mechanistic short-term controls on coastal erosion dynamics and thus long-term coastline change, and has strong potential to support local management decisions regarding coastal settlements in rapidly changing Arctic landscapes") are somewhat repetitive, and one of them can be omitted

**Author response: Thank you for these helpful suggestions, we have revised our abstract, shortening it by ca. 25%.**

Introduction

Page 2, Line 8 - "Coastal erosion is prevalent along the Western North American Arctic coastline and Eastern Siberia" - what about significant erosion rates in Western Siberia and in Western Russia along the Pechora Sea coasts? (Vasiliev et al., 2005, Kritsuk et al., 2014, Ogorodov et al., 2016, Novikova et al., 2018). Is there direct evidence that coastal erosion prevails over accumulation in the mentioned regions? Is the sum of erosional segments overall longer than the sum of accumulative segments? If not, would be better to rephrase, e.g., "rates of coastal erosion are considerable", or "the fastest coastal erosion was documented..." or "coastal erosion has high rates"

**Author response: Thank you for highlighting this additional literature. We have refined the text here which now reads "Coastal erosion is prevalent along the Western North American Arctic coastlines, and all of Siberia, and is one of the major key processes degrading permafrost (Lantuit et al., 2012)." We have now read these papers, and where appropriate, have integrated them into our manuscript to strengthen the linkages with this body of knowledge on this topic. These papers show coastline segments characterized by erosion and accumulation with some coastlines characterized by a majority of accumulative segments (e.g. Novikova et al., 2018). Yet, the papers also showed that many of these segments have now become erosive over the past few years, reflecting a shift from accumulative to erosive coastlines also observed in the study region (Irrgang et al., 2018).**

Methods Section 3.1.

Page 4, Line 32 Artificial ground control markers were deployed along the shoreline and precisely geolocated to an absolute accuracy of centimetres using global navigation satellite system (GNSS) equipment (Leica Geosystems). If it is possible it would be interesting to mention how the used number of markers was chosen, and how many markers are sufficient, depending on the study site characteristics?

**Author response: We would recommend 13 ground control markers as the ideal number per photogrammetric reconstruction, which might cover a coastline reach of up to a few km in length. Ten markers would be used to constrain the bundle adjustment and three to evaluate the photogrammetric reconstruction (as recommended by James et al. 2017).**

Page 6, Lines 19-20: Total shoreline uncertainties were calculated as the sum of georeferencing, pixel and digitising errors (Radosavljevic et al., 2016; Río and Gracia, 2013), and survey parameters and shoreline errors are given in Table 1. Why aren't the total uncertainties calculated as the root mean square error (square root of the sum of the squares of independent errors)?

**Author response: We used additive rather than quadratic error propagation because the pixel, georegistration, and digitising errors are not independent, with high pixel error (due to coarse resolution) resulting in higher registration and digitising errors (Table 1). Consequently, it is more appropriate to use the more conservative additive approach to error propogation (as also used by Radosavljevic et a;. 2016). In any case, there is minimal difference between the total uncertainties in either shoreline position or end point rates between additive or quadratic approaches to error propagation. We have added explanation for our choice here in the methods section.**

Page 6, Lines 13-14 "Shoreline digitising errors were derived from the estimated accuracy of operator vegetation edge detection, informed by reference to finer grain aerial imagery" - not sure I understood well from this fragment how exactly the digitising errors were calculated. Was it by comparison of digitising by different operators? Why are they the same for all drone images from 2017?

**Author response: The digitising error was estimated by an experienced operator, and we believe that the estimated error terms are conservative in relation to the spatial resolution of the classified images (e.g. errors of 0.10 m when spatial grain is 0.02 m). We believe that using multi-operator comparisons to estimate digitisation error can sometimes be incomplete characterisation of error, as they do not evaluate against a true position and can fail to account for all operators making the same mistakes. We have revised the manuscript to explain this approach more clearly; it now reads "Shoreline digitising errors were estimated by the GIS operator, and ranged between 0.1 m and 4.0 m depending on image spatial resolution (Table 1)."**

Page 7, Lines 8-9 "To inform qualitative interpretation of the erosion dynamics at this location, a time-lapse camera was installed at the location indicated on Figure 1 between 2017-07-29 and 2017-08-03." - this goes to section 3.1 (it can be called "Fieldwork and UAV image acquisition") or to section 3.2. Anyway, it's neither meteorological nor oceanographic data

**Author response: We have moved this information as suggested by the reviewer (to section 2.1 in the revised manuscript).**

Results After the drone surveys, DEMs were built, from which profiles are provided in Figure 4. Why are there no calculations of volumes of the material eroded in 2016-2017? Would be good to provide pictures in 3D. The authors faced some problems with the destroyed ground control markers; however, there could be some conclusions on the volume with smaller accuracy, and/or for the periods between surveys with good quality referencing only.

**Author response: Following this constructive suggestion, we have extended our analysis of surface elevation changes to including estimates of volumes of erosion. We have updated the methods, results and discussion sections of the manuscript to reflect these changes.**

Page 7, Lines 12-15. Are you speaking about average values of retreat for the 500-m coastal segment? What was the spatial variability of coastal erosion? If 14.5 ± 3.2 m was an average distance of retreat in 2017, were there locations with greater or smaller retreat, and what were the extremes? You are showing that coastal retreat was episodic in time, and saying it was also episodic in space - could you highlight examples in the text?

**Author response: Yes, this text described average values across the 500 m segment. We have updated the text to include more description of the spatial variation in shoreline change, including the maximum (22 m) and minimum (6 m) retreat rates observed over this 40-day period.**

Page 8, Lines 23-25 "A timelapse video illustrating the erosion at this coastline over five days from the location marked in Figure 1 is presented in video S1" - could you please describe here very briefly what exactly the video shows?

**Author response: As recommended, we have expanded the text here to describe the contents of this video and added a camera symbol and viewing angle in Figure 1 (c).**

Discussion The grouping of the Discussion is not always logical and needs to be revised. One of the suggestions is to move Section 5.1 to the end of the discussion. Otherwise, the introductory paragraph (page 8, Lines 27-31, Page 9 Lines 1-2) should be put after it. According to our opinion, Section 5.1 is too long and contains much obvious information that can be omitted without harm to the general content. Part of this is somewhat repetitive to the Introduction, other information can be moved to the Introduction. Lines 10-15 belong to other sections of the Discussion, e.g., Section 5.3.

**Author response: Thank you for highlighting this area for improvement. We have extensively revised the structure and content of our discussion in line with these constructive recommendations. We now have four sections, entitled: 4.1.**

**Rapid shoreline change, 4.2. Drivers of rapid shoreline change, 4.3. Rapid coastal erosion as potential threat for the Territorial Parks infrastructure, and 4.4. Using drones to quantify fine scale coastal erosion dynamics.**

Page 10, Lines 9-10 "Fine spatial grain measurements from drone products are especially useful for isolating the drivers of coastal erosion events" - would be good to provide exact examples from the study site where you could isolate the drivers of separate coastal erosion events you are describing Section 5.2 There is no discussion on spatial variability of coastal erosion rates during short periods (e.g., 2017) and its reasons. Would be good to add it. Could you state precisely, what is the main short-term driver, according to your findings? Is it the wind speed? Might be a good idea to try to build a quantitative correlation between the wind speed and the erosion rates during the investigated period?

**Author response: Thank you for this question of attribution. In this study we unfortunately do not have sufficient continuous ancillary observations of key parameters to robustly extend this analysis further (i.e. sea level, sea surface temperature, wave direction and energy). We know that wind direction matters for erosion rates at this locale, we expect a non-linear relationship between wind speed and erosion (as found by Vasiliev et al., 2005), and we know that there are latencies between erosion (especially undercutting) and shoreline change as observed from a nadir perspective. This complexity in process interactions is confounded by there being just six short-term periods of coastline change, ranging from 3 to 17 days duration. Consequently, we feel that further attribution analysis is outside the scope of this manuscript, but we strongly agree that it would be valuable for future work in this area to use these tools we demonstrate to examine this question of attribution in greater detail. We have revised the text of our discussion for greater clarity on this point.**

Page 11,
Lines 9-10. Is there any quantitative data on sea-level fluctuations during the observations?

**Author response: Unfortunately, there are no quantitative observations of sea level fluctuations available at this location, and so consequently, we used '…appeared to be…' to indicate the qualitative nature of our observations. A tide gauge has now been installed since 2018 so we are hoping to record this parameter in the future.**

Section 5.3. Would be good to provide some brief information on hydrometeorological conditions of the past years and discuss why 2017 was characterized by such dramatic retreat rates compared with previous years. You are speaking about the ice-free period increase, temperature growth, increased wave height, war water discharge, but all of these factors were already present in 2016, 2015, etc. - what is your opinion of why coastal erosion accelerated so much namely in 2017?

**Author response: Thank you for this question. Unfortunately, while we were able to detect substantial changes over our observation period and discuss our findings in the context of broader regional hydrometeorological conditions, the limited hydrometeorological observation available at this specific location limits our ability to attribute these rapid**

**changes in 2017 to specific drivers. We have looked at the start of the open water season, inferred from MODIS observations (Nasa WorldView, https://worldview.earthdata.nasa.gov/). This suggests that the sea ice may have moved out earlier than normal in the years immediately preceding 2017 which could have helped to condition this permafrost cliff (Figure R1 below, now added to the Supplementary Information). However, this inference is highly speculative. Although it would be possible to extract data on sea ice coverage (e.g. from the National Snow and Ice Data Centre) and meteorological conditions (e.g. from the Government of Canada's observations), these records are temporally patchy and do not encompass important parameters such as sea level (the first tide gauge in the area was temporarily installed in July-August 2018) and wave regimes (the first Acoustic current doppler profiler was temporarily installed in 2018 for a period of <1 month and the closest NOAA buoy is more than 200 km away, https://www.ndbc.noaa.gov/station_page.php?station=48021). We are highly doubtful that intensive analysis of *available* hydrometeorological data would result in an explanation of the rapid change observed in 2017.**

The name of Section 5.4 does not match its content. This section describes coastal erosion at Herschel Island in the context of long-term erosion rates at different locations around the Arctic, rather than short-term coastal erosion in the context of long-term observations

**Author response: We have integrated this material into section '4.2. Drivers of rapid shoreline change', and believe that the revised text is much more coherent.**

Technical corrections
Page 1
Line 31 change to " Over a single four-day period"

**Author response: Correction implemented.**

Line 32 " exceeded 1 _ 0.1 m d -1" - Please be consistent with number formats, and the number of decimals. If you previously reported the number of "2.2 _ 0.2 m a-1", you should provide this number as "1.0 _ 0.1 m d -1"

**Author response: Correction implemented.**

Page 2
Line 11 - and affect?

**Author response: Correction implemented.**

Line 20 - "improved understanding is required"

**Author response: Correction implemented.**

Page 3
Line 6 - "repeated drone surveys"

**Author response: Correction implemented.**

Lines 5-11. I would advice to use the present tense, rather than the past tense (e.g., "In this study, we use...")

**Author response: Following scientific convention, we will continue to use past tense in this report of our results.**

Lines 10-12 "We demonstrated that lightweight drones and aerial photogrammetry can be cost effective tools to capture short-term coastal erosion dynamics and related shoreline changes along discrete sections of permafrost coasts." - This goes to the conclusions

**Author response: Correction implemented.**

Figure 1c - remove "Text" from the top right side of the map?

**Author response: Correction implemented.**

Line 17 - please add a reference for Figure 1a

**Author response: Correction implemented.**

Line 20 - "the mean annual air temperature is..."; "the mean annual precipitation is..."

**Author response: Correction implemented.**

Line 22 - "between 2000 and 2011" or "in 2000-2011"

**Author response: Correction implemented.**

Line 24 - delete "in this region"

**Author response: Correction implemented.**

Line 28 – northwesterly and easterly winds; "they exert..." "and with easterly winds facilitating the transport of warm water from the Mackenzie River to Qikiqtaruk Herschel Island" - unfinished phrase? Facilitate?

**Author response: we have rewritten this paragraph for greater clarity.**

Page 4
Line 1 - sea-level

**Author response: Correction implemented.**

Page 5
Line 14 - Processing parameters are reported...

**Author response: Correction implemented.**

Page 6
Line 20 " Río and Gracia, 2013), and survey parameters" -replace by " Río and Gracia, 2013); survey parameters" "and survey parameters and shoreline errors are given in Table 1" - this reference goes to section 3.1 (regarding the survey parameters); the reference to Table 1 in the context of shoreline position errors is repetitive with Lines 15-17.

**Author response: We have revised the manuscript to include reference to Table 1 in section 3.1, and remove unnecessary repetition.**

Line 25 - delete "calculated"

**Author response: Correction implemented.**

Page 7
Line 5 – Figure 5 should be mentioned after the reference in the text to Figures 2, 3 and 4.

**Author response: Correction implemented.**

Line 12: "by a net total of 143.7 _ 28.4 m" - is it an average value for the whole segment?

**Author response: Yes, sentence reworded for clarity.**

Line 16 "shoreline retreat was 14.5 _ 3.2 m, an average rate of 36 cm per day." - replace by "the shoreline retreated by 14.5 _ 3.2, with an average rate of"

**Author response: Correction implemented.**

Line 17 - the shoreline positionS

**Author response: Correction implemented.**

Line 18 - meant that THE shorelines

**Author response: Correction implemented.**

Lines 19-20 "Coastline retreat was highly episodic in time and space, occurring primarily over two periods" - repetitive, replace by "Coastline retreat primarily occurred over two periods"

**Author response: Correction implemented.**

Line 21: " There was minimal change in coastline position DURING SIX DAYS between August 5th and August 11th

**Author response: Correction implemented.**

Line 25: " a 13-month period"

**Author response: Omitting the conventional hyphen here was deliberate to comply with The Cryosphere's house style ("is our house standard not to hyphenate modifiers containing abbreviated units"). We will continue to follow this house style, but are happy to defer to editorial preference on this.**

Line 26: " in Figure 4, sampled across the A-B-transect indicated on Figure 3." - replace " in Figure 4; they were sampled across the A-B-transect indicated in Figure 3".

**Author response: Correction implemented.**

Page 8 Line 3 - from three to ten days

**Author response: Correction implemented.**

Line 4 -and their speed reached up to...

**Author response: Correction implemented.**

Line 5 "For zero to three days prior to the 1st 5 2017 survey (on 2017-07-06)" replace by " For zero to three days prior to the same survey"

**Author response: Correction implemented.**

Line 11 - of very strong winds

**Author response: Correction implemented.**

Line 16 - and facilitate further undercutting.

**Author response: Correction implemented.**

Line 18 – and the wind speed was low.

**Author response: Correction implemented.**

Lines 20-21 These meteorological conditions resulted in large waves and undercutting - sounds more logically.

**Author response: Correction implemented.**

Line 29 - where retreat rates typically range.

**Author response: Correction implemented.**

Line 30 - between 0 and 2 m

**Author response: Correction implemented.**

Page 9 Lines 13-14 - "In this case, however, for the total 17.4 m of shoreline retreat between 2016 and 2017 reported here to remain consistent with the long-term average of 2.2 m $a^{-1}$, no further erosion of this reach would need to occur for more than seven years" - rephrase: In this case, however, to remain consistent with the long-term average of 2.2 m $a^{-1}$, no further erosion of this reach would need to occur for more than seven years after the retreat of 17.4 m in 2016-2017.

**Author response: Correction implemented.**

Page 11
Lines 2-3 " Further factors facilitating rapid erosion at this coastal reach ARE the high ice content (ca. 40% Obu et al., 2016) and the low relief"

**Author response: Correction implemented.**

Line 10 -Although this region is microtidal - "although the studied region is microtidal"

**Author response: Correction implemented.**

Page 11,
Lines 13-14 - "Winds exert substantial control over local sea levels, with north-westerly winds driving a positive storm surge and easterly winds driving a negative storm surge (Héquette et al., 1995; Héquette and Barnes, 1990)." - repetitive; already appeared in the Introduction

**Author response: we have rewritten this paragraph to reduce repetition.**

Page 12 Line 11 - on Bykovsky Peninsula?

**Author response: Correction implemented.**

Figure 2. What is the image at the background? Figures 2, 3 and 4. Would be better readable if you used different colours for coastlines of different time periods instead of shades of grey and black

**Author response: As noted in the figure caption, the background image in Figure 2 is the 2917-07-06 image. We have experimented with a number of approaches the symbology of these shoreline positions, included various combinations of colours and patterns. Unfortunately, the proximity of the lines means that there is substantial overpotting when viewed at most scales. While we found that using colours did not materially improve the legibility of the shoreline positions, we do believe that the greyscale symbology provides sufficient information to readers in this context.**

**Referee #2**

Cunliffe et al. present a case study for an eroding permafrost coastline along the Canadian Beaufort Sea Coast using historic photos, satellite images, and airborne images acquired from a UAV. The imagery ranged in spatial resolution from 3.5 m to 0.02 m and consisted of images acquired between 1952 and 2017 and focused on a 500 m segment of coastline. It appears that the historic imagery was already published previously (could be better clarified in the paper) and the novelty of this paper was the high temporal image acquisition using UAVs in 2017. Seven UAV surveys were used to create high spatial resolution orthophotos and digital surface models to assess coastal change rates on the order of days to weeks during July and August of 2017. The paper is well written and organized. The study design and presentation of results are clear but need to be improved. In particular, the mismatch in image spatial resolution and temporal observations require further consideration in the paper. A number of suggested edits and revisions are provided below to help refine the paper to make it suitable for publication in The Cryosphere.

**Author response: We thank Referee 2 for their positive appraisal of our manuscript and for their constructive suggestions. We have revised our manuscript in light of this feedback (responses to specific points of feedback provided below), and believe that our improvements address the points raised.**

General Comments

The comparison between decadal-scale erosion rates from images with a spatial resolution that ranged from 0.5 m to 3.5 m with coastal change positions determined from images with a spatial resolution of 0.02 to 0.04 m requires further validation . This is particularly important given the assertion that erosion rates in 2017 was 14.5 m/yr compared to a long-term average rate of 2.2 m/yr, or as stated in the abstract more than six times faster. The authors need to include a suitable image from 2017 or 2018 at a resolution that is more in line with image resolutions available historically to demonstrate that the increased resolution of the UAV imagery is not responsible for the measured increase in erosion, simply due to being able to better detect the feature of interest. Doing a quick survey of images available from DigitalGlobe shows that there are some potential options available for the study site in 2017 and 2018 that could provide this necessary check.

**Author response: We agree that error estimation is an important consideration when working with different resolution data. However, we do believe that our comparison between images with different spatial resolutions is appropriate, as these differences in resolution are explicitly described by the 'pixel error' term (Table 1) and propagated through to both the uncertainty in shoreline position (Equation 1), and shoreline retreat rates (Equation 2; Table 2). This treatment of uncertainty in assimilating data sources of different quality is well established (e.g. Irrgang et al., 2018; Radosavljevic et al., 2016; Río and Gracia, 2013). We found that change in shoreline position between the coarse and fine resolution images (between 2011-08-31 – 2016-07-27) was 0.7 ± 0.3 m a-1; so our comparison between these two periods indicates a slower than average rate of change. The very rapid changes in shoreline position we found were in comparisons between fine-grain drone-derived products, and were corroborated by our own field observations. We have added a sentence to our discussion clarifying this: "Our own qualitative observations on the ground over the summer of 2017 (Video S1) confirmed the extremely rapid shoreline changes described above." We do not think that purchasing and analysing additional more coarse-resolution recent imagery would be additionally informative in this instance.**

On line 30 of the abstract the authors report that in 2017 mean coastal retreat was 14.5 m/yr. However, in table 2 it appears that there were only 40 days of erosion analyzed during this period. It appears that the 14.5 m of erosion refers to the magnitude of shoreline change and not an annual rate. This critical point needs to be better clarified and the mismatch in temporal periods among observation periods given more careful consideration . One consideration could be that the image acquired on 2016-07-27 be compared with the image acquired on 2017-08-15 to determine the most recent annual erosion rate instead of using the 2017-07-06 for this. Reporting it in this manner and then using the UAV image acquisitions within this latter annual-scale period to assess event driven erosion patterns and controls might make for a cleaner analysis and presentation of results.

**Author response: Thank you for this feedback, we have revised our manuscript to further clarify that the very rapid erosion we report was measured over a period of just 40 days. In this study, we wanted to test the capabilities of UAV-derived observations to describe intra-seasonal change in shoreline positions, and relate these observations to longer term changes. To achieve this, it is necessary to compare time periods with different lengths, and we believe that we are explicit about this comparison (especially in Table 2). We do report the recent (near) annual rate for 2016-07-27 – 2017-07-06 (21 days less than a year) in Table 2; this omits some of the open water season and is therefore conservative if considered as an annual rate. The period 2016-07-27 – 2017-08-15 would be 19 days more than year, but the additional days are biased to the open water season, thus likely overestimating an annual rate. We have expanded our discussion to state: "Over a 384-day period from 27th July 2016 to 15th August 2017, we observed a large retreat in the shoreline position, with an average of 17.4 m, although note that this period is 19 days longer than a year and includes a disproportionate number of days from the open water season." This 17.4 m value is computed from summing 2.9 m + 14.5 m (the net shoreline change between 2016-07-27 – 2017-07-06, and between 2017-07-06 – 2017-08-15).**

Considering that the historic remote sensing data was apparently previously published (is this what previously analysed refers to on line 23 page 5) the authors need to enhance their methodology and presentation of the imagery acquired with the UAV surveys. The authors should provide information on the altitude of the UAV during image acquisition, the orientation of the flight paths relative to the coastline, why they recommend using front lap and side of 10 and 20 respectively while only using 5 and 10 respectively, the number of ground control points established in the field, and why the authors did not constrain their orthophotos and digital surface models using ground check points when this method is recommended in the literature. All of this should be correctable and is not seen as a major sticking point. The authors are also encouraged to maximize the use of their UAV data by analyzing the digital surface models constructed in Agisoft. Currently this assessment consists of four sentences in the results section. The authors mention that erosion occurring after the fourth UAV survey prevented proper construction of digital surface models in the latter efforts. However, the digital surface model data acquired during the first surveys combined with the shoreline positions digitized from the latter time period orthophoto mosaics should provide sufficient information to add this element to the paper.

**Author response: Thank you for this suggestion and constructive thoughts about how to approach data collection and analyses of landscape change using drones. In our other work, we are strong advocates for the inclusion of ground control markers, sufficient overlap and appropriate methods to facilitate the best-possible 3D model construction (Cunliffe et al. 2016; Cunliffe and Anderson, 2019; Assmann et al. 2018, https://arcticdrones.org/). However, this particular data collection was opportunistic and not a part of our planned data collection. Thus, we were not able to collect data using our prefered method, though we still believe our results are robust given our data collection constraints. We have added additional information describing the UAV surveys, including the range of altitudes and the number of ground control markers uses to constrain each photogrammetric build in Table 1. The orientation of the flight paths varied between surveys, often due to weather (wind) constraints, but we do not believe that flight line orientation relative to the coast make a material difference to this photogrammetric approach. We recommended higher levels of overlap than we used because we wanted to help future users of this approach avoid making the mistake of insufficient overlap, which can have negative implications of image alignment and the geometric stability of photogrammetric reconstructions. Unfortunately, we did not have sufficient ground control markers to allow independent evaluation of the photogrammetric reconstructions. Our qualitative evaluations of the orthomosaic co-registrations indicated that the RMSE errors (Table 1) appeared to be conservative assessments of the registration error. We wanted to highlight best practice in this area, so that future studies would be able to improve upon our data collection. We have also extended our analysis of surface elevation change, measuring removal rates of ca. 0.79 $m^3$ $m^2$ $d^{-1}$ of material (ca. 13,800 $m^3$ over 500 m over 35 days), and have extended the methodology, results and discussion sections of the manuscript accordingly.**

Specific Edits and Questions
- Replace the use of grain with resolution throughout the paper

**Author response: As requested, 'grain' has been replaced with 'resolution'.**

- Consider changing the use of drone to UAV throughout the paper

**Author response: Thank you for this suggestion. In line with the large and growing body of literature on drones in environmental science, we would prefer to continue using the term 'drone' in this manuscript as we feel this term is**

**becoming more dominant in the literature as other terms such as UAV, UAS, RPAS are becoming less frequently used. We believe that our meaning of this term is clear from the text on page two; however, we are happy to defer to Editorial preference regarding this nomenclature in The Cryosphere.**

- Equation 1 seems to be incomplete according to variables presented in Table 1 to determine shoreline change uncertainty. Check this.

**Author response: The input parameters for Equation 1 (now Eq. 2) are present in Table 1, and we have revised the wording to increase clarity.**

- Was the CTD data acquired in 2015 or during the study period in 2017. Check line 7 on page 7. If from 2015 how is it relevant to this study?

**Author response: The CTD data reported was collected during 2017, and this typo has been corrected in the manuscript.**

- Specify whether the time-lapse camera in operation for 4 days imaged the study coastline during the observation period.

**Author response: The time-lapse camera was observing the study coastline, and we have amended the manuscript to make this more explicit.**

- Change cm per day on line 16, page 7 to m per day

**Author response: Unit change implemented.**

- Please explain the significance of the linear regression method being more conservative than the end point method as reported on lines 23-25, page 12

**Author response: We have revised this text, which now reads: "Erosion rates from linear regression tend to underestimate rates calculated from end point rates (Dolan et al., 1991; Radosavljevic et al., 2016), which is consistent with our findings of 1.9 m a 1 versus 2.2 m a-1, but linear regression and end point rates alone do not account for uncertainty in shoreline positions (Himmelstoss et al., 2018). Changes in the rate of mean shoreline position for all time points are shown on Figure S4." Figure S4 is a new addition to the Supplementary Information, depicting the differences in average shoreline position over time and the linear regression rate.**

- Adding field photos of the study coast would add useful information to the paper and provide a context for understanding the permafrost characteristics at the site.

**Author response: We agree that photographs (and videos) can be extremely helpful in conveying useful information regarding research subjects. We included such additional information in the Supplementary Information (Figure S3 and Video S1). As these resources would be available with this manuscript, and photographs of this coastline have previously been published in Radosavljevic et al. (2016), we did not think that it would be necessary to include them in the body of the paper. Again, we are very happy to defer to editorial guidance on whether including additional photographs of this site in the manuscript itself would be helpful.**

References cited:


Assmann, J.J., Kerby, J.T., Cunliffe, A.M., Myers-Smith, I.H., 2018. Vegetation monitoring using multispectral sensors - best practices and lessons learned from high latitudes. Journal of Unmanned Vehicle Systems 334730. https://doi.org/10.1101/334730

Carrivick, J. L., Smith, M. W. and Quincey, D. J.: Structure from Motion in the Geosciences, John Wiley & Sons, Ltd, Chichester, UK., 2016.

Cunliffe, A., Anderson, K., 2019. Measuring Above-ground Biomass with Drone Photogrammetry: Data Collection Protocol. Protocol Exchange. https://doi.org/10.1038/protex.2018.134

Cunliffe, A.M., Brazier, R.E., Anderson, K., 2016. Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry. Remote Sensing of Environment 183, 129–143. https://doi.org/10.1016/j.rse.2016.05.019

Irrgang, A. M., Lantuit, H., Manson, G. K., Günther, F., Grosse, G. and Overduin, P. P.: Variability in Rates of Coastal Change Along the Yukon Coast, 1951 to 2015, Journal of Geophysical Research: Earth Surface, 123(4), 779–800, doi:10.1002/2017JF004326, 2018.

James, M.R., Robson, S., Smith, M.W., 2017. 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. Earth Surf. Process. Landforms 42, 1769–1788. https://doi.org/10.1002/esp.4125

Kritsuk, L.N.; Dubrovin, V.A.; Yastreba, N.V. Some results of integrated study of the Kara Sea coastal dynamics in the Marre-Sale meteorological station area, with the use of GIS technologies. Earth's Cryosphere, 2014, 4, 59–69. http://www.izdatgeo.ru/pdf/earth_cryo/2014-4/52_eng.pdf

Novikova A., Belova N., Baranskaya A., Aleksyutina D., Maslakov A., Zelenin E., Shabanova N., and Ogorodov S., Dynamics of permafrost coasts of Baydaratskaya bay (Kara sea) based on multi-temporal remote sensing data, Remote Sensing 10 (2018), no. 1481.

Ogorodov, S.A., Baranskaya, A., Belova, N.G., Kamalov, A.M., Kuznetsov, D.E., Overduin, P., Shabanova, N.N., Vergun, A.P., 2016. Coastal Dynamics of the Pechora and Kara Seas Under Changing Climatic Conditions and Human Disturbances. Geography, Environment, Sustainability 9, 53–73. https://doi.org/10.15356/2071-9388_03v09_2016_04

Radosavljevic, B., Lantuit, H., Pollard, W., Overduin, P., Couture, N., Sachs, T., Helm, V. and Fritz, M.: Erosion and Flooding-Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada, Estuaries Coasts, 39(4), 900–915, doi:10.1007/s12237-015-0046-0, 2016.

Río, L. D. and Gracia, F. J.: Error determination in the photogrammetric assessment of shoreline changes, Nat Hazards, 65(3), 2385–2397, doi:10.1007/s11069-012-0407-y, 2013.

Vasiliev, A.; Kanevskiy, M.; Cherkashov, G.; Vanshtein, B. Coastal dynamics at the Barents and Kara Sea key sites. Geo-Mar. Lett. 2005, 25, 110–120. https://link.springer.com/article/10.1007%2Fs00367-004-0192-z Ogorodov, S., Baranskaya,

# Rapid retreat of permafrost coastline observed with aerial drone photogrammetry

Andrew M. Cunliffe[ǂ1,2], George Tanski[ǂ3,4], Boris Radosavljevic[5], William F. Palmer[6], Torsten Sachs[5], Hugues Lantuit[4], Jeffrey T. Kerby[7], and Isla H. Myers-Smith[2]

ǂ These authors contributed equally to this work.
[1] Geography, University of Exeter, Exeter, EX4 4RJ, UK
[2] School of GeoScience, University of Edinburgh, Edinburgh, UK
[3] Faculty of Sciences, Earth and Climate, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[4] Department of Permafrost Research, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany
[5] GFZ German Research Centre for Geosciences, Helmholtz-Centre, Potsdam, Germany
[6] Landscapes, Paris, France
[7] Neukom Institute for Computational Science, Dartmouth College, NH, USA

*Correspondence to*: Andrew M. Cunliffe (a.cunliffe@exeter.ac.uk)

**Abstract.**

Permafrost landscapes are changing around the Arctic in response to climate warming, with coastal erosion being one of the most prominent and hazardous features. Using drone platforms, satellite images and historic aerial photographs~~s~~, we observed the rapid retreat of a permafrost coastline on Qikiqtaruk – Herschel Island, Yukon Territory, in the Canadian Beaufort Sea~~. Erosion of this coast increasingly threatens the settlement located on the Kuvluraq – Simpson Point gravel spit~~. This coastline is adjacent to a gravel spit accommodating~~es~~ several culturally significant sites and is the logistical base for the Qikiqtaruk – Herschel Island Territorial Park operations. ~~The~~ In this study we sought to ~~objectives of this study were to demonstrate the effective use of low-cost lightweight drones for:~~ (i) assess~~ing~~ short-term coastal erosion dynamics over fine temporal resolution, (ii) evaluate~~ing~~ short-term shoreline change ~~detection~~ in the context of long-term observations~~ of shoreline change~~, and (iii) demonstrate~~ing~~ the potential of low-cost lightweight unmanned aerial vehicles (‘drones’) to inform~~these measurement tools for~~ coastline studies and ~~park~~ management ~~and~~ decision~~ maker~~s. ~~Using drones,~~W~~ w~~e resurveyed a 500 m permafrost coastal reach at high temporal frequency (seven surveys over 40 days in 2017). ~~The observed~~I~~ i~~ntra-seasonal shoreline changes were related to meteorological and oceanographic variables to understand controls on intra-seasonal erosion patterns~~ dynamics~~. To put our short-term observations into historical context, we ~~integrated~~ combined our analysis of shoreline positions in 2016 and 2017 with historical observations from 1952, 1970, 2000, and 2011. ~~We found drone surveys analysed with image-based modelling yield fine-grain and accurately geolocated observations that are highly suitable to observe intra-seasonal erosion dynamics.~~ In just the summer of 2017, we observed coastal retreat of 14.5 m~~ $a^{-1}$~~, more than six times faster than the long-term average rate of 2.2 ± 0.1~~2~~ m $a^{-1}$ (1952–2017). Coastline retreat rates exceeded 1.0 ± 0.1 m $d^{-1}$ ~~O~~over a single four~~4-~~day period~~, coastline retreat exceeded 1 ± 0.1 m $d^{-1}$~~. Over 40 days, we estimated ~~volume~~ removal of ca. 0.96 $m^3$ $m^{-1}$ $d^{-1}$. ~~Our~~ These findings highlight the episodic nature of shoreline change and the important role of storm events, which are~~is~~ poorly

understood along permafrost coastlines. We found drone surveys combined with image-based modelling yield fine spatial resolution and accurately geolocated observations that are highly suitable to observe intra-seasonal erosion dynamics We conclude that the data available from drones is an effective tool to understand better the mechanistic short-term controls on coastal erosion dynamics and thus long-term coastline change, and has strong potential to support local management decisions regarding coastal settlements in rapidly changing Arctic landscapes.

## 1 Introduction

The Arctic is the most rapidly warming region on Earth (Richter-Menge et al., 2017; Serreze and Barry, 2011). Increasing temperatures result in fundamental changes to the physical and biological processes that shape these permafrost landscapes (IPCC, 2013). Permafrost in the Northern Hemisphere is substantially degrading in many high latitude locations, resulting in direct and indirect impacts on natural systems as well as human activities and infrastructure (Schuur et al., 2015; UNEP, 2012). Coastal erosion is prevalent along Arctic coastlines in Western North American Arctic and the Western North American Arctic coastline all of and Eastern Siberia, and is one of the major key processes degrading permafrost degradation processes (Lantuit et al., 2012). Coastal erosion mobilizes large amounts of sediment, organic matter and nutrients from permafrost (Lantuit et al., 2012; Overduin et al., 2014; Retamal et al., 2008; Wegner et al., 2015), which that are released into the nearshore waters and affecting marine ecosystems (Bell et al., 2016; Dunton et al., 2006; Fritz et al., 2017). Several studies have reported signs of accelerating coastal erosion rates at locations around the arctic At a number of locations, coastal erosion has been reported to be accelerating (Barnhart et al., 2014; Günther et al., 2013a; Jones et al., 2008, 2009b; Kritsuk et al., 2014; Mars and Houseknecht, 2007; Novikova et al., 2018; Ogorodov et al., 2016; Radosavljevic et al., 2016)(Barnhart et al., 2014; Günther et al., 2013a; Jones et al., 2008, 2009b; Mars and Houseknecht, 2007; Radosavljevic et al., 2016); however, but the current spatio-temporal resolution of circum-arctic studies limits inferences of wide-spread changes in coastal erosion rates (Fritz et al., 2017). Erosion plays a critical role in the longer-term evolution of permafrost coastlines (Barnhart et al., 2014) and biogeochemical cycling in coastal zones (Fritz et al., 2017; Semiletov et al., 2016; Vonk et al., 2012), and Tthe majority of permafrost erosion studies compare multi-annual coastline changes to infer annualised erosion rates over periods of several years (Irrgang et al., 2018; Overduin et al., 2014). However, such coarse observation frequencies neglect the intra-seasonal dynamics including episodic thaw and abrupt erosion events during the open water season, including episodic thaw and abrupt erosion events. K, knowledge of these intra-seasonal dynamics which is essential to understand the mechanistic processes and drivers leading controlling erosion patterns over time, and for better projecting future erosion rates in light of ongoing Arctic changes to rapid coastal erosion (Obu et al., 2016; Vasiliev et al., 2005)(Obu et al., 2016)..

Erosion plays a critical role in the longer-term evolution of permafrost coastlines (Barnhart et al., 2014) and biogeochemical cycling in coastal zones (Fritz et al., 2017; Semiletov et al., 2016; Vonk et al., 2012), and improved understanding of the drivers of coastal erosion is required to better project future erosion rates with Arctic change.

The use of remote sensing approaches to measure ~~C~~changes in permafrost landscapes is increasingly common (Novikova et al., 2018)~~are commonly measured using remote sensing~~. However, optical image coverage in high latitude regions has historically been widely limited to relatively coarse temporal and spatial resolutions, due to frequent cloud cover and logistical challenges that limit both satellite observations and aerial surveys (Hope et al., 2004; Stow et al., 2004). Recently there has been a widespread interest in the use of lightweight drones, also known as remotely piloted aerial systems or unmanned aerial vehicles (UAVs), to enable landscape managers and researchers to self-service their data collection needs (Klemas, 2015; Westoby et al., 2012), thus democratizing data acquisition (DeBell et al., 2015). Lightweight drones combined with image-based modelling can provide highly accurate and detailed measurements of rapidly changing features. These aerial observations can be obtained at user-determined frequencies (e.g. weekly, daily, or even hourly if weather conditions permit), using relatively inexpensive tools as suitable multirotor drones are available for less than ~~<~~$1,~~5~~000 USD. Over the last few years, drone surveys are increasingly used for monitoring coastal systems (Casella et al., 2016; Duffy et al., 2017b; Mancini et al., 2013; Turner et al., 2016). However, there have been very few examples of their application to monitor the ongoing rapid changes along permafrost coastlines (although see Whalen, 2017; Whalen et al., 2017).~~ Lightweight drones combined with image-based modelling can provide highly accurate and detailed measurements of rapidly changing permafrost coastlines. These aerial observations can be obtained at user-determined frequencies (e.g. weekly, daily, or even hourly if weather conditions permit), using relatively inexpensive tools as suitable multirotor drones are available for <$1,500 USD. Information products include geolocated orthomosaics and digital surface models at temporal resolutions not available from more traditional forms of remote sensing (Casella et al., 2016; Stow et al., 2004; Whalen et al., 2017).~~

In this study, we used repeated drone surveys to investigate short-term dynamics of an eroding permafrost coastline at Qikiqtaruk – Herschel Island (Yukon Territory) in the Canadian Beaufort Sea across a 13-month period. We investigated what additional insights are available from observing shoreline positions at fine~~r~~ spatial and temporal ~~grain~~resolution, whether fine resolution ~~-grain~~ observations of shoreline change could be related to meteorological and oceanographic variables, and compared intra-seasonal shoreline change with historical shoreline changes over the last 65 years. ~~We demonstrated that lightweight drones and aerial photogrammetry can be cost effective tools to capture short-term coastal erosion dynamics and related shoreline changes along discrete sections of permafrost coasts.~~ For our study area, we hypothesize that the erosion of the observed permafrost coastline adjacent to the settlement on Qikiqtaruk – Herschel Island varies greatly between years and continuing erosion could threaten key infrastructure to human activities on the island.

## 2 ~~Study Area~~Methods

### 2.1 Study site

Qikiqtaruk – Herschel Island is located in the western Canadian Arctic in the Beaufort Sea (69°N, 139°W, ~~see supplementary~~Figure 1a~~ figure S1~~). The island is an ice-thrust push-moraine formed during the maximal advance of the

Laurentide ice sheet (Fritz et al., 2012; Pollard, 1990), and is underlain by ice-rich continuous permafrost (Brown et al., 1997; Lantuit and Pollard, 2008; Obu et al., 2016). Low spits composed of coarse material occur on the east and west sides of the island (Couture et al., 2018). The ~~M~~mean annual air temperature is -11°C (1970-2000) and the mean annual precipitation is ca. 200 mm $a^{-1}$ (Burn, 2012). The average coastal erosion rate for the whole of Qikiqtaruk – Herschel Island was 0.45 m $a^{-1}$ between 1970 and 2000 (Lantuit and Pollard, 2005; Obu et al., 2015), and 0.68 m $a^{-1}$ between 2000 and ~~-~~2011 (Obu et al., 2016).

Ice-breakup ~~in this region~~ typically commences in late June and open water conditions persist until early October (Dunton et al., 2006; Galley et al., 2016), although ~~. F~~for Herschel Basin and Thetis Bay~~,~~ land-fast sea ice can ~~be~~ persist~~ent~~ for longer periods. The continental shelf ~~at~~ in this part of the Beaufort Sea is very narrow and intersected by a deeper sea canyon, the Mackenzie Trough located north of Qikiqtaruk – Herschel Island (Dunton et al., 2006) (Figure 1b). This area is microtidal, with a mean range of just 0.15 m for semidiurnal and monthly tides, but these are superimposed on a ca. 0.66 m annual tidal cycle which peaks in late July (Barnhart et al., 2014; Huggett et al., 1975). The interaction between meteorological factors including wind and wave action and coastal morphology exert more influence on water levels than tidal cycles ~~in this microtidal setting (ca. 0.3-0.5 m range)~~. ~~(Huggett et al., 1975)~~ ~~.~~ The study area is characterised by dominant ~~northwest~~north-westerly (NW) and prevailing easterly (E) winds. North-westerly winds drive a positive storm surge and easterly winds drive a negative surge at Qikiqtaruk – Herschel Island (Héquette et al., 1995; Héquette and Barnes, 1990),~~. Winds exert an strong influence on the wave and tide regime, and~~ with easterly winds also facilitating the transport of relatively warmer water discharged from the Mackenzie River towards ~~Qikiqtaruk~~ the ~~– Herschel I~~Island (Dunton et al., 2006). ~~The interaction between meteorological factors including wind and wave action and coastal morphology exert more influence on water levels than tidal cycles in this microtidal setting (ca. 0.3-0.5 m range) (Huggett et al., 1975). North-westerly winds drive a positive storm surge and easterly winds drive a negative surge at Qikiqtaruk – Herschel Island (Héquette et al., 1995; Héquette and Barnes, 1990).~~ The contemporary rate of relative sea~~-~~level rise along this part of the Canadian Beaufort Sea is thought to range between ca. 1.1 to 3.5 mm $a^{-1}$ (James et al., 2014; Manson et al., 2005).

This study focusses on a 500 m long coastal stretch located to the east of Kuvluraq – Simpson Point, a coarse clastic spit (Figure 1c). The study ~~stretch~~ reach is along the edge of an alluvial fan, comprised of redeposited marine and glaciogenic sediments that form Qikiqtaruk – Herschel Island (Fritz et al., 2011; Rampton, 1982). The spit is attached to the alluvial fan, and is supplied by sediment from the alluvial fan and the high bluffs to the east (Radosavljevic et al., 2016). The focal coastline is characterized by low to moderately high bluffs (ca. 1~~0.5~~ – 5 m in elevation). Ice contents in these bluffs are high, at ~~ca.~~typically ca. 40% ice by volume (Obu et al., 2016), ~~although~~ which~~this value~~ is slightly lower than the typical 50-60% ice content modelled for ice-thrust moraines along this portion of the Yukon Coast (Couture and Pollard, 2017). Permafrost temperatures are approximately -8°C (Burn and Zhang, 2009), and are known to be warming in recent decades (Burn and Zhang, 2009; Myers-Smith et al., In Press)~~(Burn and Zhang, 2009; Myers-Smith et al., Accepted)~~. This study area lies entirely within the slightly larger 'Coastal Reach 3' unit considered by Radosavljevic *et al*. (2016), who reported coastal retreat rates of 1.4 ± 0.6 m $a^{-1}$, 1.7 ± 0.7 m $a^{-1}$ and 4.0 ± 1.1 m $a^{-1}$ for the periods 1952-1970, 1970-2000 and 2000-2011, respectively. For further details on the changing ecological and erosional context of this site, see Burn (2012), Radosavljevic *et al.* (2016) and Myers-Smith *et al.* (In Press)(Accepted).

Coastal erosion at our study site threatens the human settlement and infrastructure on Qikiqtaruk – Herschel Island, located on Kuvluraq – Simpson Point (Olynyk, 2012; Radosavljevic et al., 2016). This gravel spit bounds the natural anchorage of Ilutaq – Pauline Cove, and is an important regional hub for local and indigenous travellers, park administration and rangers, tourists, and researchers in the western Canadian Arctic (e.g. Burn and Zhang, 2009; Myers-Smith et al., In Press)(e.g. Burn and Zhang, 2009; Myers-Smith et al., Accepted). The currently seasonally-inhabited settlement is part of the Qikiqtaruk – Herschel Island Territorial Park, and accommodates a number of culturally and historically significant sites resulting in its candidature for UNESCO World Heritage status (UNESCO, 2004). The proximity to the sea and low elevation of this settlement at ≤ 1.2 m above sea level leads to high risk of coastal hazards, particularly flooding (Myers-Smith and Lehtonen, 2016; Olynyk, 2012; Radosavljevic et al., 2016).

**3 Methods**

**32.12 UAV Drone and time-lapse image acquisition**

In 2016, one drone survey was conducted in late July, followed by seven additional drone surveys over a 40-day period between July 6th and August 15th 2017. Drone surveys were conducted using two platforms: (i) a lightweight flying-wing Zeta Phantom FX-61 with a PixHawk flight controller equipped with a Sony RX-100ii camera (1" CMOS sensor with 20.2 Megapixels), and (ii) a multi-rotor DJI Phantom 4 Pro (1" CMOS sensor with 20 Megapixels). Drone operations were conducted in accordance with an SFOC issued by Transport Canada (to assist others seeking such permission, our full application is available at https://arcticdrones.org/regulations/). Artificial Black and white ground control markers were deployed along the shoreline and precisely geolocated to an absolute accuracy of approximately 0.02 m centimetres using a -real time kinematic global navigation satellite system (GNSS) equipment (Leica Geosystems). We used between 3 to 132 markers in the surveys, depending on survey extents and destruction of markers by natural processes; and ideally, we recommend using n=13 ground control markers, distributed evenly across the area of interest (Carrivick et al., 2016; Cunliffe and Anderson, 2019). Image overlap, a function of front-lap and side-lap, captured each part of the study area in at least five and usually >10 photographs; this . Image overlap of five and 10 photos equates to fore-/side-lap values of 56% and 69%, respectively. FFor 2D orthomosaics and 3D elevation models, we ideally we would recommend higher levels of overlap, aiming for ca. 8-10 and ca. 12-20 overlapping images respectively. Drone surveys over this study area had flight times of ca. 15-25 minutes, at altitudes ranging from 30 m to 120 m (Table 1). The geotagged RGB photographs from each aerial survey had ground-sampling distances ranging from 10 mm to 40 mm. Although this study presents drone surveys for a limited (500 m) extent of shoreline, drone surveys could be optimised to observe larger reaches of up to ca. 1.5 to 2 km, particularly in jurisdictions such as Canada where current regulations permit UAV operations up to 0.5 nautical miles (926 m) from the remote pilot(s). For example, using two drones we found it possible to survey over eight km$^2$ in a single day with two drones operated by two remote pilots. Survey parameters including date and time of day, aircraft, altitude and number of ground control markers are given in Table 1.- For further discussion of recommended drone survey parameters for different applications, see Carrivick *et al*. (2016) and Duffy *et al.* (2017a). Drone images were processed with structure-from-motion photogrammetry using Agisoft PhotoScan (version 1.3.3) (Agisoft, 2018; Sona et al., 2014), and processing parameters are reported in Table S1. GNSS-derived geolocations for each individual image and the precisely geolocated ground control markers provided additional spatial constraint of the photogrammetric processing (Carrivick et al., 2016; Cunliffe et al., 2016; Westoby et al., 2012). The photogrammetric processing yielded georegistered orthomosaic composite images and digital surface models. Note that the heightfield approaches to surface modelling used in this analysis are not capable of capturing topographic change related to the undercutting of bluffs. Capturing such overhanging features with photogrammetric methods can be possible, but requires optimising image acquisition and more computationally intensive post-processing. To inform qualitative interpretation of the erosion dynamics at this location, a time-lapse camera was installed at the location indicated on Figure 1, imaging the study coastline at hourly intervals for four days between 2017-07-29 and 2017-08-03.

### 32.23 Image alignment and , shoreline mapping and shoreline analysis

Drone images were processed with structure-from-motion photogrammetry techniques, using Agisoft PhotoScan (version 1.3.3) (Agisoft, 2018; Sona et al., 2014), and processing parameters reported in Table S1. GNSS-derived geolocations for each individual image and precisely geolocated ground control markers provided additional spatial constraint of the photogrammetric processing (Carrivick et al., 2016; Cunliffe et al., 2016; Westoby et al., 2012). This processing yielded georegistered orthomosaic composite images and digital surface models. Note that the heightfield approaches to surface modelling used in this analysis are not capable of capturing topographic change related to undercutting of bluffs. Capturing such overhanging features with photogrammetric methods can be possible, but requires optimising image acquisition and more computationally intensive post-processing.

In addition to the drone surveys, we also used four ‘historic’ panchromatic aerial photographs from 1952 and 1970, and satellite images from 2000 and 2011 (previously analysed by Radosavljevic et al., 2016). These four images had already been orthorectified in PCI Orthoengine to minimise image distortion. We co-registered these four ‘historic’ orthorectified images to the 2017-07-06 orthomosaic image in a geographic information system (ArcGIS, version 10.5, ESRI), as we considered this orthomosaic to have the best spatial constraint and coverage of the all of the seveavailable datasetsn drone datasets.. The (composite) images fromA all twelve images surveys were aligned to a common spatial framework,: NAD83 UTM 7N (EPSG: 26907). Further details of all images and composite orthomosaics are summarised in Table 1. Alignment errors estimated as the root mean square error (RMSE) of the control points. ~~Further details of all images and composite orthomosaics are summarised in Table 1.~~ While this approach to quantifying alignment error is standard practice in shoreline change analysis (Irrgang et al., 2018; Novikova et al., 2018; Río and Gracia, 2013)~~(Irrgang et al., 2018; Río and Gracia, 2013)~~, we note that the RMSE of control points is not a strong metric of this uncertainty, as ~~both~~ transformation parameters (georeferencing) and the intrinsic and extrinsic camera parameters (structure-from-motion photogrammetry) are adjusted to ~~optimise~~ minimise the RMSE~~this metric~~~~e RMSE of control points~~. Consequently, for an independent assessment of image registration error, in future work it would be preferable to use the RMSE of *independent* check points, which were not used to constrain transformation or bundle adjustment parameters (James et al., 2017). Visual comparison of each dataset indicated excellent spatial agreement and suitability for further analysis~~, in spite of different image acquisitions~~ (Jones et al., 2018). Pixel error refers to the spatial resolution ~~grain~~ of the digital satellite and orthomosaic composite images, and for aerial photographs is a metric of image quality calculated ~~for aerial photographs~~ based on the scale factor of each image multiplied by the typical resolution of a 9 x 9-in aerial photogrammetric camera (after Radosavljevic et al., 2016).

~~The~~ ~~S~~Sshorelines were digitised manually ~~of all twelve images were digitised manually~~ in ArcGIS for all twelve images, at a scale of 1:600 for the four, older, coarser spatial resolution ~~-grained~~ panchromatic images~~,~~ and a scale of 1:80 for the eight, finer spatial resolution~~-grained~~ red-green-blue (RGB) orthomosaics. The shoreline was defined as the vegetation edge~~, which is generally the preferred shoreline proxy,~~ rather than the wet-dry line previously used in this region (Radosavljevic et al., 2016), because the vegetation edge was both more visually distinct and temporally consistent than the wet-dry line (Boak and Turner, 2005). ~~T~~Temporal consistency was essential to ensure meaningful assessment of ~~rapid~~ coastal retreat over short time intervals (Río and Gracia, 2013). Mapping shoreline edges was possible with much greater fidelity on the fine spatial resolution RGB orthomosaic images compared to the coarser spatial resolution panchromatic images where low contrast was sometimes an issue (Boak and Turner, 2005; Río and Gracia, 2013). Shoreline digitising errors were estimated by the GIS operator~~derived from the estimated accuracy of operator vegetation edge detection, informed by reference to finer grain aerial imagery~~, and ~~.~~ranged between 0.1 m and 4.0 m depending on image spatial resolution (Table 1). ~~Mapping shoreline edges was possible with much greater fidelity using the fine spatial grain RGB orthomosaic images compared to the coarser-grained panchromatic images, where low contrast was sometimes an issue (Boak and Turner, 2005; Río and Gracia, 2013). These differences contributed to the estimated digitising errors, which contribute towards the overall uncertainty estimates (Table 1).~~

## 2.4. Shoreline and elevation analysis

Total shoreline uncertainties were calculated as: ~~the sum of georeferencing, pixel and digitising errors (Radosavljevic et al., 2016; Río and Gracia, 2013), and survey parameters and shoreline errors are given in Table 1~~

$$U = E_G + E_P + E_D \qquad \text{(Equation. 1)}$$

Where U is total shoreline uncertainty, $E_G$ is georeferencing error, $E_P$ is pixel error, and $E_D$ is digitising error (Table 1) (Irrgang et al., 2018; Radosavljevic et al., 2016; Río and Gracia, 2013). Additive error propagation is appropriate because these error terms are not independent.

Shoreline position statistics were calculated with the USGS Digital Shoreline Analysis System (DSAS version 4) extension for ArcGIS (Thieler et al., 2009), using ~~the same baseline and~~ shore normal transects at 5 m intervals ~~as used by Radosavljevic *et al.* (2016)~~. Shoreline retreat rates in this study are given in end point rates for comparison between surveys, and both end point rate and linear regression rate for the entire time period of the study. The linear regression rate uncertainty is the standard error of the slope parameter ~~of~~ at the 95% confidence interval. For further discussion on erosion rate calculation, see Thieler *et al*. (2009). The accuracy of ~~calculated~~ shoreline change rates was calculated as ~~the dilution of accuracy (DOA) (Dolan et al., 1991; Irrgang et al., 2018), as shown in Equation 1~~:

$$DOA = \frac{\sqrt{U_i^2 + U_{ii}^2}}{\Delta t} \qquad \text{(Equation. 2~~1~~)}$$

Where DOA is the dilution of accuracy (Dolan et al., 1991; Himmelstoss et al., 2018; Irrgang et al., 2018), $U_i$ is the total shoreline uncertainty of the first point in time (from Table 1), $U_{ii}$ is the total shoreline uncertainty of the shoreline position from the second point in time, and $\Delta t$ is the duration of the time period in years or days, as appropriate. Erosion rate errors refer to DOA values, unless otherwise stated, and ~~.~~Table 2 displays the DOAs for all ~~analysed time~~ periods. ~~Erosion rate errors refer to DOA values, unless otherwise stated.~~

We compared differences in modelled surface elevations between all periods across a cross-sectional transect, and across the whole study area ~~across~~for a 35-day period from 2017-07-06 to 2017-08-11 (dates constrained by DSM quality as discussed below). During the survey 2017-07-06, sea level was generally at -2.5 m relative to the EPSG: 26907 datum. To exclude erroneous elevation observations from the sea, we digitised the water's edge at a scale of 1:80 and assigned a constant elevation of -2.5 m to this seaward area. This approach excludes potential submarine elevation change from the subsequent volume calculations. The volume of material eroded ~~from this difference in~~ was~~surface volume~~ ~~as~~ calculated with the surface volume tool in ArcMap.

### ~~3~~2.4~~3~~. Meteorological and oceanographic observations

Meteorological observations were obtained from an Environment Canada weather station located on Kuvluraq – Simpson Point (station ID: 'Herschel Island - Yukon Territory', World Meteorological Organisation ID: 71501; downloaded from http://climate.weather.gc.ca/climate_data on 2018-01-03), and processed to extract ~~. M~~mean six~~6~~-hour air temperature, wind speed, and wind direction throughout the 2017 observation period~~. are displayed in Figure 5, and general wind conditions are summarised in Figure S1 and Radosavljevic *et al.* (2016).~~ Conductivity-temperature-depth (CTD) profiles (see supporting figure S2) were collected in July and August 201~~5~~7 with a CastAway CTD (SonTek, USA) from a small research vessel ca. 1

km from the study area (near to 69.552°N, 138.923°W).~~ To inform qualitative interpretation of the erosion dynamics at this location, a time-lapse camera was installed at the location indicated on Figure 1 between 2017-07-29 and 2017-08-03.~~

## ~~4~~3 Results

### 3~~4~~.1. Shoreline position analysis

Over our observational ~~record~~ period ~~from~~ of 1952 to 2017, the coastline along the study reach retreated by an average of ~~a net total of~~ 143.7 ± 28.4 m (where ± is the standard deviation of observations from each transect). The overall retreat rate was 2.2 ± 0.1~~2~~ m a$^{-1}$ as calculated by end-point rate, and 1.9 ± 0.5 m a$^{-1}$ as calculated by the linear regression rate. Average retreat rates over decadal periods ranged between 0.7 ± 0.3~~5~~ m a$^{-1}$ to 3.0 ± 0.5~~8~~ m a$^{-1}$. The net shoreline change and end-point rates for all periods are presented in Table 2~~ presents the net shoreline change and end-point rates for all periods~~.

Over a 40-day period in the summer of 2017, shoreline retreat was 14.5 ± 3.2 m, ranging between 21.8 m to 6.1 m, at an ~~an~~ average rate of 0.36 ~~c~~m per day~~.~~. The observed shoreline positions ~~during different drone surveys~~ are ~~illustrated~~ depicted in Figures 2 and 3, although ~~. T~~the high temporal frequency of observations throughout the summer of 2017 and ~~the highly~~ episodic ~~nature~~ pattern of ~~coastal~~ retreat meant that the shorelines were sometimes very close in space~~, as illustrated in Figure 2a and 2b, Figure 3~~. Most of the ~~C~~coastline retreat ~~was highly episodic in time and space,~~ occurred~~ing~~ ~~primarily~~ over two periods: (i) 27 days between July 13th to July 30th and (ii) four days between August 11th to August 15th (Figures 2, 3, and 5, Table 2). There was minimal change in coastline position during the six days between August 5th and August 11th, the seven days between July 6th to July 13th, and the six days between July 30th and August 5th (Figure 2, Table 2). The erosion at this coastline over four days is illustrated in a time-lapse video (Video S1). Thise camera was ~~looking~~orientated facing west by southwest (Figure 1) with the alluvial fan and the eroding cliff in the foreground and the structures of the settlement in the background. This video illustrates the fluctuations in sea level and wave conditions and shows the undercutting, block failure and denudation of detached blocks between 2017-07-29 and 2017-08-03.

### 3~~4~~.2. Surface elevation change~~Digital elevation profiles~~

We generated ~~D~~digital surface models (DSM) of the coastal topography ~~were generated~~ from all eight ~~the~~ photogrammetric surveys undertaken in 2016 and 2017, spanning a ~~13 month~~13-month period~~.~~ (Figure 4). However, in several cases, the DSMs did not yield reliable data across the entire coastal reach, due to insufficient spatial constraint of the photogrammetric reconstructions. This issue was due in part to the destruction of ground control markers by faster than anticipated ~~erosion~~coastal retreat, as well as sub-optimal distribution of GCPs and insufficient image overlap from some surveys due to weather constraints. Over the 35 days between two, well-constrained DSMs from 2017-07-06 and 2017-08-11, ca. 28 m$^3$ m$^2$ of material was removed (totalling ca. 13 800 m$^3$ across the 500 m coastline), at an ~~and~~ average rate of ca. 0.79 m$^3$ m d$^{-1}$ ~~(ca. 395 m$^3$ d$^{-1}$ across the 500 m coastline)~~ (Figure 4a). The~~he~~se ~~volume~~ estimates do not include the 4.1 ± 1.1 retreat ~~which occurred~~ observed between the 11th and 15th of August. During this ~~four day~~four-day period, a further ca. 5 300 m$^3$ of material ~~may~~was probably

~~have been~~ removed (ca. ~~-~~2.7 $m^3$ $m^2$ $d^{-1}$), assuming ~~that~~an ~~the~~ average cliff height ~~remained~~of ~~at~~ 2.65 m as measured across the preceding 35 days. Combined, this resulted in an estimated 19,100 $m^3$ of material removed over the 40 days, The elevation change map (Figure 4a) ~~reflects~~illustrates the increase in bluff elevation from ca 1 m in the west to ca. 5 m east across the ~~shoreline~~coastal reach. Inland of the shoreline, there were scattered small increases in surface elevation, typically on the order of 0.1-0.2 m, these ~~likely~~might relate to the development (esp. leafing out) of tundra vegetation during the short summer growing season (Myers-Smith et al., In Press)~~(Myers-Smith et al., Accepted)~~. In the centre of the study reach, the DSMs were of sufficient quality to allow cross-sectional comparisons across a ca. 3 m high bluff shown in Figure 4b; these cross sections were sampled across the A-B transect indicated on Figure 3 and Figure 4a. ~~Cross-sectional profiles through these digital surface models across a ca. 3 m high bluff are shown in Figure 4, sampled across the A-B transect indicated on Figure 3.~~ The depression in the 2017-08-15 elevation profile corresponds with the ca. 1 m gap behind a detached block, depicted in Figure 3c, illustrating the sensitivity of the surface models.

### 3~~4~~.3. Meteorological, oceanographic and time-lapse video observations

Erosion rates for each observation period through the summer of 2017 were compared to meteorological and oceanographic conditions, in order to better describe the controls on episodic and rapid erosion of this coastline (Figure 5). From three to ten~~10~~ days prior to the first 2017 survey (on 2017-07-06), winds were consistently strong from the east and their six-hour average speed reached up to 40 km $h^{-1}$ (Figure 5). For zero to three days prior to the ~~1st 2017 survey (on 2017-07-06)~~same survey the dominant wind direction shifted to the northwest with strong winds up to 40 km $h^{-1}$ (Figure 5), which raised the water level and refracted waves around the bluffs at Collinson Head to the northeast of the study reach. Over the seven days between the 6th and 13th of July 2017, winds were predominantly from the southeast, with brief periods of ~~high strength~~strong winds (ca. 30 km $h^{-1}$ over six hours) from the northwest (Figure 5). These meteorological conditions generally promoted waves from the southeast, which ~~attacked~~ eroded the exposed cliff base (Figures 4 and 5). Over the 17 days between the 13th and 30th of July, winds were variable, but predominantly from the southeast, with two notable periods of very high strength winds (ca. 40 km $h^{-1}$ for 24 and 12 hours, respectively) (Figure 5), and surface water temperatures reached nearly 10°C (see Fig. S3, CTD profile d). These conditions combined to drive rapid erosion resulting in 7.4 ± 5.6 m (SD) of shoreline retreat in just 17 days (Figures 3 and 4).

Over the six days between the 30th of July to the 5th of August, winds were variable in direction and typically weaker (Figure 5). This resulted in minimal shoreline retreat (Table 2), but did remove cliff debris from the beach facilitating further undercutting (V~~v~~ideo S1, Figure 4) ~~and facilitating further undercutting~~. Over the six days between the 5th to the 11th of August, the wind direction was variable and wind speed was low (6-hour averages mostly below 20 km $h^{-1}$), with relatively slow coastline retreat of ca. 0.17 m $d^{-1}$. Over the four days between the 11th and 15th of August, a larger storm event developed, with wind shifting from east through north to west and wind speeds increasing to excess of 45 km $h^{-1}$ for more than six ~~>6~~ hours (Figure 5). These meteorological conditions ~~resulted~~ generated~~in~~ large waves and causing undercutting ~~and large waves~~ that caused drove 4.1 ± 1.1 m (SD) of shoreline retreat in just four days, largely through block failure (Figures 3, 4 and S4, Table 2). Sea surface temperatures were relatively warm at 6-10°C when measured between the 21st of July and the 2nd of August (Figure 5, Figure S2). Figure S1 summarises wind vectors and velocities observed during the summer of 2017. A time-lapse video

**54. Discussion**

Over the 65-year record, we consistently observe substantial erosion along the focal coastline on Qikiqtaruk – Herschel Island. This part of the coast retreated on average by 2.2 m $a^{-1}$, which is fast relative to the spatially weighted means of 1.1 m $a^{-1}$ for the Canadian Beaufort Sea and 0.57 m $a^{-1}$ for the circum-Arctic (Lantuit et al., 2012) where retreat rates typically ranges between 0-2 m $a^{-1}$ (Overduin et al., 2014). Shoreline retreat varied substantially throughout the 65-year period (Radosavljevic et al., 2016). In 2017, we observed 14.5 m of coastline retreat within a single year, which exceeds the long-term average retreat of 2.2 m $a^{-1}$ by more than a factor of six. The potential factors driving this rapid retreat are discussed below, and include both long-term pre-conditioning factors over timescales of years to decades and short-term factors over timescales of days to weeks.

**4.1. Rapid shoreline change**

Over the 65-year record from 1952 to 2017, we found substantial erosion along the 500 m study coastline of Qikiqtaruk – Herschel Island. The average rate of retreat was 2.2 m $a^{-1}$, ranging over decadal periods from 0.7 to 3.0 m $a^{-1}$ (Table 2). This long-term retreat rate is fast compared with 0.7 m $a^{-1}$ for the Yukon coast (Irrgang et al., 2018), 1.1 m $a^{-1}$ for the Canadian Beaufort Sea (Lantuit et al., 2012), and circum-arctic observations where rates are typically between 0-2 m $a^{-1}$ (Overduin et al., 2014) with a weighted mean of 0.57 m $a^{-1}$ (Lantuit et al., 2012). Our study reach lies within the slightly larger 'coastal reach 3' unit considered by Radosavljevic *et al.* (2016); consequently, differences in reach length and historic image co-registration result in some slight differences between the erosion rates reported herein and those previously reported for the historic imagery. Coastal retreat rates in the neighbouring Alaskan Beaufort Sea were typically 0.7 to 2.4 m $a^{-1}$ depending on coast type (Jorgenson and Brown, 2005), with extremes of up to 25 m $a^{-1}$ (Jones et al., 2009b). Yet, the Alaskan Beaufort Sea coastline is more similar to the western formerly non-glaciated part of the Yukon Coast, with low cliffs, overall strong erosion rates and longer sea ice cover (Irrgang et al., 2018; Jorgenson and Brown, 2005; Ping et al., 2011). This is quite different from our study coastline in the formerly glaciated part of the Yukon Coast (Rampton, 1982), which is characterised by high cliffs and high ground ice contents due to former movement and burial of glacier ice (Couture and Pollard, 2017; Fritz et al., 2011). Furthermore, the sea-ice free season in our study area is longer than further west along the Alaska Coast due to the warming influence of the Mackenzie River, but in turn is modulated by the breakup of land-fast ice, which can be persistent in Herschel Basin and Thetis Bay (Dunton et al., 2006). Erosion rates from linear regression tend to underestimate rates calculated from end point reports (Dolan et al., 1991; Radosavljevic et al., 2016), which is consistent with our findings of 1.9 m a$^{-1}$ versus 2.2 m a$^{-1}$, but both linear regression and end point rates alone do not account for uncertainty in shoreline positions (Himmelstoss et al., 2018). Changes in the rate of mean shoreline position for all time points are shown on Figure S4.

Over a 384-day period from 27$^{th}$ July 2016 to 15$^{th}$ August 2017, we observed a large retreat in the shoreline position, with an average of 17.4 m, although note that this period is 19 days longer than a year and includes a disproportionate number of days from the open water season. Most of this rapid retreat occurred in the summer of 2017, when we measured 14.5 m of coastline retreat over just 40 days. Our own qualitative observations on the ground over the summer of 2017 (Video S1) confirmed the extremely rapid shoreline changes ~~described~~reported above. In this time, we estimate approximately 19,000 m$^3$ of material was eroded at a rate of ca. 0.96 m$^3$ m d$^{-1}$. The coastal erosion processes we observed during 40 days of 2017 correspond with the conceptual model described by Barnhart *et al.* (2014) (Video S1 and Figure S3). The bluffs along the alluvial fan were affected by both thermo-denudation but particularly thermo-abrasion due to the combined mechanical and thermal action of sea water causing undercutting and subsequent block failure (Barnhart et al., 2014; Günther et al., 2012; Vasiliev et al., 2005). These thermal processes are likely influenced by warm surface waters delivered from the Mackenzie River Delta during easterly wind conditions (Dunton et al., 2006). Additional factors facilitating rapid erosion at this site are the high ice content (ca. 40% Obu et al., 2016) and the low relief, as less material is deposited at the base of the bluff following cliff failure, thus reducing protection of the bluff base from further wave action (Héquette and Barnes, 1990). Given the episodic nature of coastal retreat, it can be difficult to compare short-term rate changes with long-term observation periods (<2 vs. >10 years, respectively) (Dolan et al., 1991). However, to remain consistent with the long-term average rate of 2.2 m a$^{-1}$, no further erosion of this coastline would need to occur for more than seven years after the retreat observed in 2016 and 2017.

The rapid coastline retreat observed in this study reach is consistent with, but greater than, earlier analysis of neighbouring coastal reaches on Qikiqtaruk – Herschel Island between 1952 and 2011 (Radosavljevic et al., 2016) and also coastal retreat observed in other Arctic permafrost coastlines (Günther et al., 2013b; Irrgang et al., 2018; Jones et al., 2009a; Whalen et al., 2017). Coastline retreat rates almost doubled from 7.6 m a$^{-1}$ (1955-2009) to 13.8 m a$^{-1}$ (2007-2009) at Cape Halkett on the Alaskan Beaufort Sea (Jones et al., 2009a), and more than doubled from 2.2 m a$^{-1}$ (1952-2010) to 5.3 m a$^{-1}$ (2010-2012) on Bykovsky Peninsula, Siberia (Günther et al., 2013b). Increases in erosion rates greater than two-fold are more commonl~~;~~y observed on low elevation coasts, such as the one examined herein and in Jones *et al.* (2009a). On the Yukon Coast, average coastal retreat rates were 0.5 m a$^{-1}$ between 1950-1970 (Harper et al., 1985) and 0.7 m a$^{-1}$ between 1950-2011 (Irrgang et al., 2018), with maximum reported rates of 22 m a$^{-1}$ on Pelly Island (NWT) 130 km to the east along the Yukon-NWT Coast (Whalen et al., 2017). Robustly detecting changes in the trends of permafrost coastline erosion in this region and more widely requires further analyses of shoreline position changes at (near-)annual temporal resolution, considering a larger range of representative coastal reaches and study sites.

## 4.2. Drivers of rapid shoreline change

The rapid retreat observed in 2016 and especially 2017 was likely driven by a range of factors, including longer term conditioning factors acting over timescales of decades to years and also shorter-term factors acting over timescales of weeks to days and hours. Over the longer term, this region experiences a relative sea level rise of ca. ~~A range of drivers potentially contribute to the rapid retreat observed in 2016 and 2016, including longer-term conditioning factors acting over timescales of decades to years and shorter-term factors acting over timescales of weeks to days and hours.~~ 1.1 to 3.5 mm $a^{-1}$ (James et al., 2014; Manson et al., 2005), progressively subjecting more permafrost to thermos-abrasional processes. Seasonal sea ice break up has advanced earlier by 46 days per decade between 2002-2016 (Assmann, 2019), with ice-free seasons lengthening by nine days per decade between 1979-2013 (Stroeve et al., 2014) and summer minimum sea ice concentrations decreasing over the last 39 years in this area (Myers-Smith et al., In Press). This region generally is experiencing longer open water seasons and increasing wave heights (Barnhart et al., 2014; Farquharson et al., 2018; Stroeve et al., 2014), and there is increased heat influx to the ocean during the open water season, due to increasing discharge from the Mackenzie River and atmospheric warming. Atmospheric warming has increased permafrost temperatures and deepened the active layer at sites just 1 km from the study reach (Burn and Zhang, 2009; Myers-Smith et al., In Press), lowering the energy required to thaw the permafrost, although lengthening open water seasons is likely to most significant factor (Farquharson et al., 2018).

Attribution of the rapid change in shoreline position in 2017 to a single main driver is not possible with the available datasets. Examination of MODIS observations indicates sea ice break up was ca. 15 days earlier in 2015 and 2016, but in 2017 it was in line with the 10-year average (Figure S5). The direction and frequency of wind patterns observed in 2017 (Figure 5, Figure S1) are similar to those reported in June-Sept from 2009 to 2012 (Radosavljevic et al., 2016, figure 4 therein). However, overall wind speeds were higher in 2017, with a greater proportion of periods with mean speeds in excess of >30 km $h^{-1}$ (Figure S1). The role of wind is discussed further below. A large portion of beach and cliff debris appeared to have been removed between our survey in 2016 (2016-07-26) and our first survey in 2017 (2017-07-06) (Figure 4b, and corroborated by our ~~and our~~ field observations). ~~suggests that a large portion of beach and cliff debris appeared to have been removed between our survey in 2016 (2016-07-26) and our first survey in 2017 (2017-07-06),~~ potentially either during storm events in the autumn of 2016 and/or ice bulldozing during ice-breakup in spring 2017. We hypothesise that ~~. R~~removal of this protective material may have increased the susceptibility of these cliffs to rapid erosion in the summer of 2017. Field observations from 2018 suggest that the shoreline retreat has stabilised at rates closer to the long term average.~~The direction and frequency of wind patterns observed in 2017 (Figure 5, Figure S1) are similar to those reported in June-Sept from 2009 to 2012 (Radosavljevic et al., 2016 figure 4 therein). However, overall wind speeds were higher in 2017, with a greater proportion of periods with mean speeds in excess of >30 km h-1 (Figure S1).~~

Through the summer of 2017, coastal retreat was highly episodic. Figure 4b and our field observations suggests that a large portion of beach and cliff debris appeared to have been removed between our survey in 2016 (2016-07-26) and our first survey in 2017 (2017-07-06), potentially either during storm events in the autumn of 2016 and/or ice bulldozing during ice-breakup in spring 2017. Removal of this protective material may have increased the susceptibility of these cliffs to rapid erosion in the summer of 2017. The main mode of erosion was block failure drivenfollowing  by thermo-abrasional undercutting. This , whundercutting ich aappeared to be largely influenced by fluctuations in water level combined with wave action. Water level fluctuations appeared to be mainly determined by wind generated surges and waves, superimposed on tidal patterns (Héquette et al., 1995; Héquette and Barnes, 1990). Although this region is microtidal, with a mean range of just 0.15 m for semidiurnal and monthly tides, these are superimposed on a ca. 0.66 m annual tidal cycle which peaks in late July (Barnhart et al., 2014), corresponding with our intensive observation period. Annual tides therefore likely influence the timing of coastal retreat within the ice-free season in this area.

The two periods with the most rapid erosion in 2017 (the 27 days between July 13$^{th}$ to July 30$^{th}$, and the four days between August 11$^{th}$ to August 15$^{th}$) were both associated with strong winds (six-hour moving averages exceeding >40 km $h^{-1}$), both easterly and north-westerly and preceded by relatively high air and water temperatures (Figure 5). Together, these conditions likely enhanced the thermo-abrasional processes undercutting the ice-rich bluff, creating the conditions for abrupt erosion. The direction and frequency of wind patterns observed in 2017 (Figure 5, Figure S1) are similar to those reported in June-Sept from 2009 to 2012 (Radosavljevic et al., 2016 figure 4 therein). However, overall wind speeds were higher in 2017, with a greater proportion of periods with mean speeds in excess of >30 km $h^{-1}$ (Figure S1). The high temporal frequency of shoreline position observations is essential to studying highly episodic erosion processes. For example, ca. 30% (4.2 m) of the 14.5 m of shoreline retreat in the summer of 2017 happened in just four days (August 11$^{th}$ to August 15$^{th}$), indicating discrete storm events can play a major role in the geomorphic development of permafrost shorelines  evolution (Farquharson et al., 2018; Solomon et al., 1993)(Solomon et al., 1993). Future work relating coastline change to meteorological and oceanographic factors over short timescales will –need to consider the latencies involved between meteorological and oceanographic conditions, undercutting of permafrost cliffs, and planform change as observed from an aerial perspective.

Our observations suggest that the rapid coastal retreat in 2017 may have resulted from multiple factors interacting over several years. On Qikiqtaruk – Herschel Island, atmospheric warming (Burn and Zhang, 2009; Myers-Smith et al., Accepted) has increased the temperature of permafrost (Burn and Zhang, 2009; Myers-Smith et al., Accepted) and deepened the active layer (Myers-Smith et al., Accepted) at locations just ca. 1 km from the study reach. Permafrost temperatures along the study reach may also be influenced by discharge from a creek across part of the alluvial fan (Figure 1); however, long-term discharge records do not exist for this stream. In this area, the onset of seasonal sea-ice melt has moved earlier over the last 18 years, with ice-free seasons lengthening by nine days per decade between 1979-2013 (Stroeve et al., 2014), and summer minimum sea ice concentrations decreasing over the last 39 years (Myers-Smith et al., Accepted). Long term, the thermo-abrasion of

**Field Code Changed**

permafrost bluffs at this site is likely enhanced by (i) relative sea level rise of 1.1 to 3.5 mm $a^{-1}$ (James et al., 2014; Manson et al., 2005), (ii) earlier ice-break up (Mahoney et al., 2014), (iii) longer open water seasons (Barnhart et al., 2014; Stroeve et al., 2014), (iv) increased wave heights (Barnhart et al., 2014), and (v) increased discharge of warm water from the nearby Mackenzie River . XXXXX

### 5.1. The advantages and disadvantages of using drones to quantify short-term coastal erosion dynamics

The use of drone surveys in this study proved to be an effective tool to measure the dynamics of short-term erosion along this permafrost coastline. Photogrammetric analysis of drone-acquired image data yielded orthomosaics, inferred shoreline positions (Figures 3 and 4), and elevation models (Figure 4) that provide quantitative information on coastal structure. Drone surveys can provide fine spatial grain and accurate measurements of the coastline position at high temporal frequencies, allowing coastline change to be quantified and related to meteorological observations on a supra-annual timescale (Figure 5). Over a 384-day period from July 2016 to August 2017, we were able to observe a very rapid and substantial change in the shoreline position using drone surveys, on average 17.4 m of retreat across the 500 m study reach. Given the episodic nature of coastal retreat, it is difficult to compare short-term rate changes with long-term observation periods (<2 vs. >10 years, respectively) (Dolan et al., 1991). In this case, however, for the total 17.4 m of shoreline retreat between 2016 and 2017 reported here to remain consistent with the long-term average of 2.2 m $a^{-1}$, no further erosion of this reach would need to occur for more than seven years.

Lightweight drones can be deployed at relatively low cost when suitably trained and equipped personnel are on-site. However, the costs of accessing high latitude sites can be substantial, potentially contributing to uneven distributions of monitoring sites (Metcalfe et al., 2018). The temporal resolution of drone surveys can greatly exceed those available by more traditional forms of remote sensing, for example satellite observations or surveys from manned aircraft (Casella et al., 2016; Stow et al., 2004; Whalen et al., 2017). High temporal frequency surveys can provide quantitative insights into erosion processes that vary greatly in time and space, and these quantitative measurements may have stronger physical meaning that previously available proxies, such as the apparent cross sectional area of detached blocks extracted from time-lapse photography (e.g. Barnhart et al., 2014). Surveyable spatial extents are also limited by safety and regulatory restrictions, and depend on the size and the range of the remotely piloted drone. When supplemented by other monitoring of environmental variables (such as wave field and sea surface temperature), such spatial observations could be used to robustly evaluate and subsequently refine process-based numerical models of coastal erosion over multiple temporal scales (Barnhart et al., 2014; Casella et al., 2014; Wobus et al., 2011).

By allowing measurement of the volume and consequently mass of eroded material, digital elevation models can be more informative than simple 2D representations of shoreline position. Digital elevation models were generated following the eight drone surveys (Figure 4). However, faster than anticipated coastal retreat destroyed some ground control markers, resulting in insufficient spatial constraint of the photogrammetric reconstructions of two of the latter surveys (2017-08-05 and 2017-08-15). This weaker constraint contributed to larger elevation errors in these two reconstructions, resulting in the apparent datum shift in Figure 4. If 3D elevation observations are required, care should be taken when deploying ground control markers and conducting drone surveys to ensure that there will be sufficient spatial constraint of the photogrammetric modelling process, even if coastal retreat is faster than expected. For further recommendations on optimising ground control placement, see Carrivick *et al.* (2016) and James *et al.* (2017).

In summary, drone surveys are highly suitable when there is a need to accurately measure small changes (e.g. ≤ 0.3 m) in shoreline positions over limited extents (e.g. ≤ 5-10 km in length). Fine spatial grain measurements from drone products are especially useful for isolating the drivers of coastal erosion events, and continued miniaturization of thermal and multispectral cameras for drone platforms will create opportunities to better understand these mechanisms of change. While drone surveys can also be used when shoreline position changes are much greater, traditional data sources such as optical satellite observations can be better suited for observing change across larger sections of coastline. High levels of cloud cover in Arctic regions limits the frequency of successful observations (Hope et al., 2004; Stow et al., 2004), but continuing advances in satellite sensors have increased the spatial resolution and revisit frequency of observations. Despite this, freely available products are currently only available for spatial grains of ca. ≥ 10 m (e.g. Sentinel 2), and finer-grain (< 4 m) products have non-trivial costs for each scene.

**5.2. Short-term coastal erosion dynamics**

Between the survey in 2016 (2016-07-26) and the first survey in 2017 (2017-07-06), a large portion of beach and cliff debris appeared to have been removed (Figure 4), potentially during storm events in the autumn of 2016 or ice bulldozing during ice-breakup in spring 2017. Removal of this protective material may have increased the susceptibility of these cliffs to rapid erosion in the summer of 2017. The two periods with the most rapid erosion in 2017 (the 27 days between July 13th to July 30th, and the four days between August 11th to August 15th) were both associated with strong wind events (six-hour moving averages exceeding >40 km $h^{-1}$) preceded by relatively high air and water temperatures. Together, these conditions likely enhanced the thermo-abrasional processes undercutting the ice-rich bluff prior to the first survey, creating the conditions for abrupt erosion. Further work relating coastline change to meteorological and oceanographic factors over short timescales would need to further consider the latencies involved between meteorological and oceanographic conditions, undercutting of permafrost cliffs, and planform change as observed from an aerial perspective.

The coastal erosion processes we observed during 40 days of 2017 correspond with the conceptual model described by Barnhart *et al.* (2014) (Video S1 and Figure S3). The bluffs along the alluvial fan were affected by both thermo-denudation but particularly thermo-abrasion due to the combined mechanical and thermal action of sea water causing undercutting and subsequent block failure (Barnhart et al., 2014; Günther et al., 2012). These thermal processes are likely influenced by warm surface waters delivered from the Mackenzie River Delta during easterly wind conditions (Dunton et al., 2006). Further factors facilitating rapid erosion at this coastal reach is the high ice content (ca. 40% Obu et al., 2016) and the low relief, as less material is deposited at the base of the bluff following cliff failure, thus reducing protection of the bluff base from further wave action (Héquette and Barnes, 1990).

Over shorter timescales through the summer of 2017, coastal retreat was highly episodic. The main mode of erosion was block failure driven by thermo-abrasional undercutting, which appeared to be largely influenced by fluctuations in water level combined with wave action. Water level fluctuations appeared to be mainly determined by wind generated surges and waves, superimposed on tidal patterns. Although this region is microtidal, with a mean range of just 0.15 m for semidiurnal and monthly tides, these are superimposed on a ca. 0.66 m annual tidal cycle which peaks in late July (Barnhart et al., 2014), corresponding with our intensive short-term observation period. Annual tides may influence the timing of coastal retreat within the ice-free season in this area. Winds exert substantial control over local sea levels, with north-westerly winds driving a positive storm surge and easterly winds driving a negative storm surge (Héquette et al., 1995; Héquette and Barnes, 1990). The direction and frequency of wind patterns observed in 2017 (Figure 5, Figure S1) are similar to those reported in June-Sept from 2009 to 2012 (Radosavljevic et al., 2016 figure 4 therein). However, overall wind speeds were higher in 2017, with a greater proportion of periods with mean speeds in excess of >30 km $h^{-1}$. During the two periods with highest erosion rates, there were multiple strong storm events with both easterly and north-westerly winds with 6-hour average speeds in excess of 30 km $h^{-1}$ and 40 km $h^{-1}$, respectively (Figure 5). We were able to provide quantitative insights into these highly episodic erosion processes, because of the high temporal frequency of shoreline position observations. For example, ca. 30% (4.2 m) of the 14.5 m of shoreline retreat occurring in the summer of 2017 happened in just four days (August 11th to August 15th), suggesting that discrete storm events can play a major role in permafrost shoreline evolution (Solomon et al., 1993).

### 5.3 Long-term pre-conditioning of coastal erosion

Our observations suggest that the rapid coastal retreat in 2017 may have resulted from multiple factors interacting over several years. On Qikiqtaruk – Herschel Island, atmospheric warming (Burn and Zhang, 2009; Myers-Smith et al., Accepted) has increased the temperature of permafrost (Burn and Zhang, 2009; Myers-Smith et al., Accepted) and deepened the active layer (Myers-Smith et al., Accepted) at locations ca. 1 km from the study reach. Permafrost temperatures along the study reach are likely also be influenced by a creek, which discharges across parts of the alluvial fan (Figure 1); however, long-term discharge records do not exist for this stream. In this area, the onset of seasonal sea-ice melt has moved earlier over the last 18 years, with ice-free seasons lengthening by 9 days per decade between 1979-2013 (Stroeve et al., 2014), and decreasing summer minimum sea ice concentrations over the last 39 years (Myers-Smith et al., Accepted). The combination of relative sea level rise of 1.1 to 3.5 mm a$^{-1}$ (James et al., 2014; Manson et al., 2005), earlier ice-break up (Mahoney et al., 2014) and longer open water seasons (Barnhart et al., 2014; Stroeve et al., 2014), increased wave heights (Barnhart et al., 2014), and increased transport of warm water discharged from the nearby Mackenzie River (Carmack and Macdonald, 2002; Dunton et al., 2006; van Vliet et al., 2013) are long-term factors which likely enhance the thermo-abrasion of permafrost bluffs at this site.

**5.4. Short-term coastal erosion in the context of long-term observations**

The overall rapid coastline retreat observed in this study reach is consistent with, but greater than, earlier analysis of neighbouring coastal reaches on Qikiqtaruk – Herschel Island between 1952 and 2011 (Radosavljevic et al., 2016) and also coastal retreat observed in other Arctic permafrost coastlines (Günther et al., 2013b; Irrgang et al., 2018; Jones et al., 2009a; Whalen et al., 2017). Coastline retreat rates almost doubled from 7.6 m a$^{-1}$ (1955-2009) to 13.8 m a$^{-1}$ (2007-2009) at Cape Halkett on the Alaskan Beaufort Sea (Jones et al., 2009a), and more than doubled from 2.2 m a$^{-1}$ (1952-2010) to 5.3 m a$^{-1}$ (2010-2012) on Bykovsky Island, Siberia (Günther et al., 2013b). Increases in erosion rates greater than two-fold are generally reported for low elevation coasts, such as the one shown in this paper and in (Jones et al., 2009a). On the Yukon Coast, average coastal retreat rates were 0.5 m a$^{-1}$ between 1950-1970 (Harper et al., 1985) and 0.7 m a$^{-1}$ between 1950-2011 (Irrgang et al., 2018), with maximum reported rates of 22 m a$^{-1}$ on Pelly Island (NWT) 130 km to the east along the Yukon-NWT Coast (Whalen et al., 2017). Robustly testing whether erosion of permafrost coastlines may be accelerating in this region and more widely will require further analysis of shoreline position change at (near-)annual temporal resolution, considering a larger range of representative coastal reaches and study sites.

Over the 65 years from 1952 to 2017, the coastline in this study reach retreated at a rate of 2.2 m a$^{-1}$, with average rates over decadal periods ranging between 0.7 to 3.0 m a$^{-1}$ (Table 2). This study reach lies within the slightly larger 'coastal reach 3' unit considered by Radosavljevic *et al.* (2016); consequently, differences in reach length and historic image co-registration result in some slight differences between the erosion rates reported herein and those previously reported. Our finding that the overall retreat rate calculated from the linear regression method (1.9 m a$^{-1}$) is more conservative than the rate calculated by the end-point method (2.2 m a$^{-1}$) is consistent with earlier reports (Radosavljevic et al., 2016). In either case, this long-term rate is fast relative to circum-arctic observations, where retreat rates are typically between 0-2 m a$^{-1}$ (Overduin et al., 2014), with a weighted mean of 0.57 m a$^{-1}$ for the entire Arctic, 1.1 m a$^{-1}$ for the Canadian Beaufort Sea (Lantuit et al., 2012), and 0.7 m a$^{-1}$ for the Yukon coast (Irrgang et al., 2018). Coastal retreat rates in the neighbouring Alaskan Beaufort Sea were typically 0.7 to 2.4 m a$^{-1}$ depending on coast type (Jorgenson and Brown, 2005), with extremes of up to 25 m a$^{-1}$ (Jones et al., 2009b). Yet, the Alaskan Beaufort Sea coastline is more similar to the western formerly non-glaciated part of the Yukon Coast, with low cliffs, overall strong erosion rates and longer sea ice cover (Irrgang et al., 2018; Jorgenson and Brown, 2005; Ping et al., 2011). This

~~is quite different from our study coastline in the formerly glaciated part of the Yukon Coast (Rampton, 1982), which is characterised by high cliffs and high ground ice contents due to former movement and burial of glacier ice (Couture and Pollard, 2017; Fritz et al., 2011). Furthermore, the sea-ice free season in our study area is longer than further west along the Alaska Coast due to the warming influence of the Mackenzie River, but in turn is modulated by the breakup of land-fast ice, which can be persistent in Herschel Basin and Thetis Bay (Dunton et al., 2006).~~

### ~~5~~4.~~5~~3. Rapid coastal erosion as potential threat for the Territorial Parks infrastructure

Coastal change ~~in~~ near the Ilutaq – Pauline Cove ~~is~~ area influences the stability and evolution of the adjacent gravel spit, which accommodates culturally and historically significant sites, as well as infrastructure essential to the operation of the Qikiqtaruk – Herschel Island Territorial Park. Shoreline change and flooding in recent history has already necessitated the relocation and raising of several historic buildings at the Ilutaq – Pauline Cove settlement, as well as the relocation of the gravel airstrip essential to the operation of the Park (Olynyk, 2012). However relocation efforts are hindered by the fragility of several buildings, particularly the 'Community House', the oldest building in the Yukon, and it is increasingly difficult to find safer locations for these buildings on the spit (Olynyk, 2012). These historic buildings underpin the site's candidature for UNESCO status (UNESCO, 2004). Erosion of the observed coastal reach ~~adjacent to the settlement~~ exposes the base of the spit to coastal processes, ~~and~~ increas~~es~~ing the risk of changes to the position of the spit itself. Flooding during storm events can isolate ~~has already been observed to cut off~~ the spit from the island (Myers-Smith and Lehtonen, 2016), and ~~these~~ such events are projected to become more common in the future (Radosavljevic et al., 2016). Knowledge of coastal processes, particularly patterns of contemporary coastal retreat as a proxy for future patterns, is therefore ~~critical~~ valuable for informing ~~the~~local ~~the~~ management decisions ~~of Qikiqtaruk – Herschel Island Park~~.

### 4.4. Using drones to quantify fine scale coastal erosion dynamics

Drone surveys and photogrammetric analysis are effective tools for measure fine scale erosion dynamics along permafrost coastlines, yielding orthomosaics, inferred shoreline positions (Figures 2 and 3), and surface elevation models (Figure 4). When supplemented by other monitoring of environmental variables (such as wave fields, sea surface temperature, wind strength and direction), drone-acquired observations at fine spatiotemporal resolutions can be related to meteorological and oceanographic observations on supra-annual timescales, providing quantitative insights into erosion processes that vary greatly in time and space. The temporal resolution of drone surveys can greatly exceed those available by more traditional forms of remote sensing, for example satellite observations or surveys from manned aircraft (Casella et al., 2016; Stow et al., 2004; Whalen et al., 2017), and such observations can be more informative than previously available proxies (such as the apparent cross sectional area of detached blocks, Barnhart et al., 2014). Such spatial observations could be used to robustly evaluate and refine process-based numerical models of coastal erosion over multiple temporal scales (Barnhart et al., 2014; Casella et al., 2014; Wobus et al., 2011).

Lightweight drones can be deployed at relatively low cost when suitably trained and equipped personnel are on-site. However, the costs of accessing high latitude sites can be substantial, potentially contributing to uneven distributions of monitoring sites (Metcalfe et al., 2018). Surveyable spatial extents depend on the size and the range of the remotely piloted drone, and are also limited by safety and regulatory restrictions. Observations from optical satellites may be better suited for observing change across larger sections of coastline; however, high levels of cloud cover in Arctic regions limits the frequency of successful optical satellite observations (Hope et al., 2004; Stow et al., 2004). Continuing advances in satellite sensors have increased the spatial resolution and revisit frequency of observations, yet freely available products are currently only available for spatial resolutions of ca. ≥ 10 m (e.g. Sentinel 2), and finer spatial resolution (< 4 m) products have non-trivial costs for each scene.

In summary, lightweight drone surveys can be suitable when there is a need to accurately measure small changes (e.g. ≤ 0.3 m) in shoreline positions or elevations over limited extents (e.g. ≤ 5-10 km in length). Fine resolution measurements from drone products will be especially useful for isolating the drivers of coastal erosion events, and continued miniaturization of thermal and multispectral cameras for drone platforms will create opportunities to better understand these mechanisms of change. Measurements of surface elevation and consequently volume change can be more informative than simple 2D representations of shoreline position. We generated digital surface models following our drive surveys; however, issues with insufficient spatial constraint meant that full area coverage was only possible from some of the surveys. If elevation observations are required, care should be taken when ~~deploying ground control markers and~~ conducting drone surveys to ensure that there will be sufficient spatial constraint of the photogrammetric modelling process, even if coastal retreat is faster than expected. For further recommendations on optimising placement of ground control, see Carrivick *et al.* (2016) and James *et al.* (2017).

~~Information products include geolocated orthomosaics and digital surface models at temporal resolutions not available from more traditional forms of remote sensing (Casella et al., 2016; Stow et al., 2004; Whalen et al., 2017).~~

## ~~6~~5. Conclusion

We used drones as a highly effective instrument to observe the dynamics of permafrost coastline changes associated with supra-seasonal erosion on Qikiqtaruk – Herschel Island. In 2017, average shoreline retreat was extremely rapid at 14.5 m over 40 days, well in excess of the long-term average of 2.2 m $a^{-1}$ from 1952 to 2017. The volume of material removed was ca. 0.96 $m^3$ m $d^{-1}$ in 2017. Thirty percent of the rapid 2017 shoreline change in ~~shoreline position~~ (4.1 m retreat) occurred in just four~~4~~ days during one storm event. Block failure was the prevailing mode of erosion, seemingly driven by multiple factors that increase the susceptibility of the permafrost coastline to thermo-abrasional processes. These rapid erosion events observed on Qikiqtaruk – Herschel Island appear to have been driven by short-term fluctuations in water levels due to meteorological conditions, possibly superimposed on annual tidal cycles~~,~~ on a longer-term background of relative sea level rise and increasing heat flux from the Mackenzie River discharge and the atmosphere.

We ~~demonstrated~~found that lightweight drones and aerial photogrammetry can be cost effective tools to capture short-term coastal erosion dynamics and related shoreline changes along discrete sections of permafrost coasts. At our study site on Qikiqtaruk – Herschel Island further erosion and removal of this coastal reach could threaten the infrastructure of the settlement over the long-term. With the rapid maturation of drone platforms and image-based modelling technologies, these approaches can now be easily deployed at both supra and sub-annual timescales to obtain new insights into coastal erosion and inform management decisions. These approaches are particularly relevant in permafrost coastlines, where erosion ~~is~~ can be highly episodic, with long-term rates dominated by short-term events. By combining new methods of observation with long-term records, we can improve predictions of coastal erosion dynamics and subsequent consequences for the management of fragile Arctic coastal ecosystems and cultural sites.

**Video Supplement**

A supplementary time-lapse video of the coastal erosion reported here is available at https://doi.org/10.5446/40250.

**Acknowledgements**

This work was made possible by support from NERC (ShrubTundra - NE/M016323/1), the loan of GNSS equipment from NERC Geophysical Equipment Facility (GEF:1063 and 1069), the National Geographic Society (Grant CP-061R-17), and the Helmholtz Young Investigators Group 'COPER' (grant #VH-NG-801). This study was supported by funding from the European Union's Horizon 2020 research and innovation programme (Nunataryuk - grant #773421). Drone flight operations were authorised by a Special Flight Operations Certificate granted by Transport Canada. We wish to thank the Qikiqtaruk Territorial Park staff including Richard Gordon, Edward McLeod, Samuel McLeod, Ricky Joe, Paden Lennie, and Shane Goesen, as well as the Yukon Government and Yukon Parks for their permission and support of this research (Permit number Inu-02-16). We also thank the Inuvialuit people for their permission to work on their traditional lands. We thank James Duffy, and anonymous reviewers for insightful feedback that helped us to refine earlier versions of this manuscript.

**Statement of Contribution**

Conceptualization, AC, GT, JK and IM-S; Data curation, AC; Formal analysis, AC and GT; Funding acquisition, IM-S, TS, and HL; Investigation, AC, GT, BR, WP and JK; Methodology, AC; Project administration, AC; Supervision, TS, HL and IM-

S; Visualization, AC, GT and WP; Writing – original draft, AC; Writing – review & editing, AC, GT, BR, WP, TS, HL, JK and IM-S.

**Conflicts of Interest**

The authors declare that they have no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

**References**

Agisoft: Agisoft PhotoScan User Manual: Professional Edition, V 1.4, Agisoft., 2018.

Assmann, J. J.: Arctic tundra plant phenology and greenness across space and time, PhD, University of Edinburgh., 2019.

Barnhart, K. R., Anderson, R. S., Overeem, I., Wobus, C., Clow, G. D., Gary D. Clow, and Urban, F. E.: Modeling erosion of ice-rich permafrost bluffs along the Alaskan Beaufort Sea coast, Journal of Geophysical Research: Earth Surface, doi:10.1002/2013JF002845, 2014.

Bell, L. E., Bluhm, B. A. and Iken, K.: Influence of terrestrial organic matter in marine food webs of the Beaufort Sea shelf and slope, Marine Ecology Progress Series, 550, 1–24, doi:10.3354/meps11725, 2016.

Boak, E. H. and Turner, I. L.: Shoreline definition and detection: a review, Journal of Coastal Research, 688–703, doi:10.2112/03-0071.1, 2005.

Brown, J., Ferrians Jr., O. J., Heginbottom, J. A. and Melnikov, E. S.: Circum-Arctic map of permafrost and ground-ice conditions, USGS Numbered Series. [online] Available from: http://pubs.er.usgs.gov/publication/cp45 (Accessed 9 April 2018), 1997.

Burn, C. R.: Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, 1st ed., Calgary University Press., 2012.

Burn, C. R. and Zhang, Y.: Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada, J. Geophys. Res., 114(F2), F02001, doi:10.1029/2008JF001087, 2009.

Carrivick, J. L., Smith, M. W. and Quincey, D. J.: Structure from Motion in the Geosciences, John Wiley & Sons, Ltd, Chichester, UK., 2016.

Casella, E., Rovere, A., Pedroncini, A., Mucerino, L., Casella, M., Cusati, L. A., Vacchi, M., Ferrari, M. and Firpo, M.: Study of wave runup using numerical models and low-altitude aerial photogrammetry: A tool for coastal management, Estuarine, Coastal and Shelf Science, 149, 160–167, doi:10.1016/j.ecss.2014.08.012, 2014.

Casella, E., Rovere, A., Pedroncini, A., Stark, C. P., Casella, M., Ferrari, M. and Firpo, M.: Drones as tools for monitoring beach topography changes in the Ligurian Sea (NW Mediterranean), Geo-Mar Lett, 36(2), 151–163, doi:10.1007/s00367-016-0435-9, 2016.

Couture, N. J. and Pollard, W. H.: A Model for Quantifying Ground-Ice Volume, Yukon Coast, Western Arctic Canada, Permafrost and Periglac. Process., 28(3), 534–542, doi:10.1002/ppp.1952, 2017.

Couture, N. J., Irrgang, A., Pollard, W., Lantuit, H. and Fritz, M.: Coastal Erosion of Permafrost Soils Along the Yukon Coastal Plain and Fluxes of Organic Carbon to the Canadian Beaufort Sea, J. Geophys. Res. Biogeosci., 2017JG004166, doi:10.1002/2017JG004166, 2018.

Cunliffe, A. and Anderson, K.: Measuring Above-ground Biomass with Drone Photogrammetry: Data Collection Protocol, Protocol Exchange, doi:10.1038/protex.2018.134, 2019.

Cunliffe, A. M., Brazier, R. E. and Anderson, K.: Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry, Remote Sensing of Environment, 183, 129–143, doi:10.1016/j.rse.2016.05.019, 2016.

DeBell, L., Anderson, K., Brazier, R. E., King, N. and Jones, L.: Water resource management at catchment scales using lightweight UAVs: current capabilities and future perspectives, J. Unmanned Veh. Sys., doi:10.1139/juvs-2015-0026, 2015.

Dolan, R., Fenster, M. S. and Holme, S. J.: Temporal analysis of shoreline recession and accretion, Journal of Coastal Research, 7(3), 723–744, 1991.

Duffy, J. P., Cunliffe, A. M., DeBell, L., Sandbrook, C., Wich, S. A., Shutler, J. D., Myers-Smith, I. H., Varela, M. R. and Anderson, K.: Location, location, location: considerations when using lightweight drones in challenging environments, Remote Sens Ecol Conserv, doi:10.1002/rse2.58, 2017a.

Duffy, J. P., Pratt, L., Anderson, K., Land, P. E. and Shutler, J. D.: Spatial assessment of intertidal seagrass meadows using optical imaging systems and a lightweight drone, Estuarine, Coastal and Shelf Science, doi:10.1016/j.ecss.2017.11.001, 2017b.

Dunton, K. H., Weingartner, T. and Carmack, E. C.: The nearshore western Beaufort Sea ecosystem: Circulation and importance of terrestrial carbon in arctic coastal food webs, Progress in Oceanography, 71(2), 362–378, doi:10.1016/j.pocean.2006.09.011, 2006.

Environment Canada: [online] Available from: http://climate.weather.gc.ca/climate_data (Accessed 3 January 2018), 2017.

ESRI, TerraColor and Earthstar Geographics: Basemap, [online] Available from: http://goto.arcgisonline.com/maps/Arctic_Imagery, 2018.

Farquharson, L. M., Mann, D. H., Swanson, D. K., Jones, B. M., Buzard, R. M. and Jordan, J. W.: Temporal and spatial variability in coastline response to declining sea-ice in northwest Alaska, Marine Geology, 404, 71–83, doi:10.1016/j.margeo.2018.07.007, 2018.

Fritz, M., Wetterich, S., Meyer, H., Schirrmeister, L., Lantuit, H. and Pollard, W. H.: Origin and characteristics of massive ground ice on Herschel Island (western Canadian Arctic) as revealed by stable water isotope and Hydrochemical signatures, Permafrost Periglac. Process., 22(1), 26–38, doi:10.1002/ppp.714, 2011.

Fritz, M., Wetterich, S., Schirrmeister, L., Meyer, H., Lantuit, H., Preusser, F. and Pollard, W. H.: Eastern Beringia and beyond: Late Wisconsinan and Holocene landscape dynamics along the Yukon Coastal Plain, Canada, Palaeogeography, Palaeoclimatology, Palaeoecology, 319–320, 28–45, doi:10.1016/j.palaeo.2011.12.015, 2012.

Fritz, M., Vonk, J. E. and Lantuit, H.: Collapsing Arctic coastlines, Nature Clim. Change, 7(1), 6–7, doi:10.1038/nclimate3188, 2017.

Galley, R. J., Babb, D., Ogi, M., Else, B. G. T., Geilfus, N.-X., Crabeck, O., Barber, D. G. and Rysgaard, S.: Replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea since 2004, J. Geophys. Res. Oceans, 121(3), 1806–1823, doi:10.1002/2015JC011583, 2016.

Günther, F., Overduin, P. P., Sandakov, A., Grosse, G. and Grigoriev, M. N.: Thermo-erosion along the Yedoma coast of the Buor Khaya peninsula, Laptev Sea, East Siberia, in Proceedings of the Tenth International Conference on Permafrost, Volume 1: International Contributions, edited by K. Hinkel, pp. 137–142., 2012.

Günther, F., Overduin, P. P., Baranskaya, A., Opel, T. and Grigoriev, M. N.: Observing Muostakh Island disappear: erosion of a ground-ice-rich coast in response to summer warming and sea ice reduction on the East Siberian shelf, Cryosphere Discussions, 7(4), 4101–4176, doi:10.5194/tcd-7-4101-2013, 2013a.

Günther, F., Overduin, P. P., Sandakov, A. V., Grosse, G. and Grigoriev, M. N.: Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region, Biogeosciences, 10(6), 4297–4318, doi:10.5194/bg-10-4297-2013, 2013b.

Harper, J. R., Reimer, P. D. and Collins, A. D.: Canadian Beaufort Sea physical shore-zone analysis, Report for Northern Oil and Gas Action Plan, Indian and Northern Affairs Canada Ottawa, Canada. [online] Available from: http://engineerradcc.library.link/portal/Canadian-Beaufort-Sea-physical-shore-zone/Gu3YaBSD3Pk/, 1985.

Héquette, A. and Barnes, P. W.: Coastal retreat and shoreface profile variations in the Canadian Beaufort Sea, Marine Geology, 91(1), 113–132, doi:10.1016/0025-3227(90)90136-8, 1990.

Héquette, A., Desrosiers, M. and Barnes, P. W.: Sea ice scouring on the inner shelf of the southeastern Canadian Beaufort Sea, Marine Geology, 128(3), 201–219, doi:10.1016/0025-3227(95)00095-G, 1995.

Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G. and Farris, A. S.: Digital Shoreline Analysis System (DSAS) version 5.0 user guide, Report, Reston, VA., 2018.

Hope, A. S., Pence, K. R. and Stow, D. A.: NDVI from low altitude aircraft and composited NOAA AVHRR data for scaling Arctic ecosystem fluxes, International Journal of Remote Sensing, 25(20), 4237–4250, doi:10.1080/01431160310001632710, 2004.

Huggett, W. S., Woodward, M. J., Stephenson, F., Hermiston, F. V. and Douglas, A.: Near and Bottom Currents and Offshore Tides, Ocean and Aquatic Sciences, Depatment of Envrionment., 1975.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, p. 996, Cambridge University Press, Cambridge, United Kingdom., 2013.

Irrgang, A. M., Lantuit, H., Manson, G. K., Günther, F., Grosse, G. and Overduin, P. P.: Variability in Rates of Coastal Change Along the Yukon Coast, 1951 to 2015, Journal of Geophysical Research: Earth Surface, 123(4), 779–800, doi:10.1002/2017JF004326, 2018.

James, M. R., Robson, S., d'Oleire-Oltmanns, S. and Niethammer, U.: Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment, Geomorphology, 280, 51–66, doi:10.1016/j.geomorph.2016.11.021, 2017.

James, T. S., Henton, J. A., Leonard, L. J., Darlington, A., Forbes, D. L. and Craymer, M.: Relative sea-level projections in Canada and the adjacent mainland United States, Geological Survey of Canada, Ottawa, Ontario. [online] Available from: Retrieved from http://ftp2.cits.rncan.gc.ca/pub/geott/ess_pubs/295/295574/of_7737.pdf, 2014.

Jones, B. M., Hinkel, K. M., Arp, C. D. and Eisner, W. R.: Modern erosion rates and loss of coastal features and sites, Beaufort Sea coastline, Alaska, Arctic, 61(4), 12, 2008.

Jones, B. M., Arp, C. D., Beck, R. A., Grosse, G., Webster, J. M. and Urban, F. E.: Erosional history of Cape Halkett and contemporary monitoring of bluff retreat, Beaufort Sea coast, Alaska, Polar Geography, 32(3–4), 129–142, doi:10.1080/10889370903486449, 2009a.

Jones, B. M., Arp, C. D., Jorgenson, M. T., Hinkel, K. M., Schmutz, J. A. and Flint, P. L.: Increase in the rate and uniformity of coastline erosion in Arctic Alaska, Geophys. Res. Lett., 36(3), L03503, doi:10.1029/2008GL036205, 2009b.

Jones, B. M., Farquharson, L. M., Baughman, C. A., Buzard, R. M., Arp, C. D., Grosse, G., Bull, D. L., Günther, F., Nitze, I., Urban, F., Kasper, J. L., Frederick, J. M., Thomas, M., Jones, C., Mota, A., Dallimore, S., Tweedie, C., Maio, C., Mann, D. H., Richmond, B., Gibbs, A., Xiao, M., Sachs, T., Iwahana, G., Kanevskiy, M. and Romanovsky, V. E.: A decade of remotely sensed observations highlight complex processes linked to coastal permafrost bluff erosion in the Arctic, Environmental Research Letters, 13(11), 115001, doi:10.1088/1748-9326/aae471, 2018.

Jorgenson, M. T. and Brown, J.: Classification of the Alaskan Beaufort Sea Coast and estimation of carbon and sediment inputs from coastal erosion, Geo-Mar Lett, 25(2–3), 69–80, doi:10.1007/s00367-004-0188-8, 2005.

Klemas, V. V.: Coastal and environmental remote sensing from unmanned aerial vehicles: an overview, Journal of Coastal Research, 1260–1267, doi:10.2112/JCOASTRES-D-15-00005.1, 2015.

Kritsuk, L. N., Dubrovin, V. A. and Yastreba, N. V.: Some results of integrated study of the Kara Sea coastal dynamics in the Marre-Sale meteorological station area, with the use of GIS technologies. Earth's Cryosphere, Earth's Cryosphere, 4, 59–69, 2014.

Lantuit, H. and Pollard, W. H.: Temporal stereophotogrammetric analysis of retrogressive thaw slumps on Herschel Island, Yukon Territory, Natural Hazards and Earth System Science, 5(3), 413–423, 2005.

Lantuit, H. and Pollard, W. H.: Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada, Geomorphology, 95(1–2), 84–102, doi:10.1016/j.geomorph.2006.07.040, 2008.

Lantuit, H., Overduin, P. P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D. L., Graves-Gaylord, A., Grigoriev, M., Hubberten, H.-W., Jordan, J., Jorgenson, T., Ødegård, R. S., Ogorodov, S., Pollard, W. H., Rachold, V., Sedenko, S., Solomon, S., Steenhuisen, F., Streletskaya, I. and Vasiliev, A.: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines, Estuaries and Coasts, 35(2), 383–400, doi:10.1007/s12237-010-9362-6, 2012.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S. and Gabbianelli, G.: Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments, Remote Sensing, 5(12), 6880–6898, doi:10.3390/rs5126880, 2013.

Manson, G. K., Solomon, S. M., Forbes, D. L., Atkinson, D. E. and Craymer, M.: Spatial variability of factors influencing coastal change in the Western Canadian Arctic, Geo-Mar Lett, 25(2–3), 138–145, doi:10.1007/s00367-004-0195-9, 2005.

Mars, J. C. and Houseknecht, D. W.: Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska, Geology, 35(7), 583–586, doi:10.1130/G23672A.1, 2007.

Metcalfe, D. B., Hermans, T. D. G., Ahlstrand, J., Becker, M., Berggren, M., Björk, R. G., Björkman, M. P., Blok, D., Chaudhary, N., Chisholm, C., Classen, A. T., Hasselquist, N. J., Jonsson, M., Kristensen, J. A., Kumordzi, B. B., Lee, H., Mayor, J. R., Prevéy, J., Pantazatou, K., Rousk, J., Sponseller, R. A., Sundqvist, M. K., Tang, J., Uddling, J., Wallin, G., Zhang, W., Ahlström, A., Tenenbaum, D. E. and Abdi, A. M.: Patchy field sampling biases understanding of climate change impacts across the Arctic, Nature Ecology & Evolution, 2(9), 1443, doi:10.1038/s41559-018-0612-5, 2018.

Myers-Smith, I. H. and Lehtonen, S.: NOAA's Arkctic: The Great Flood of July 2016, Team Shrub: Tundra Ecology Lab [online] Available from: https://teamshrub.com/2016/07/22/noaas-arkctic-the-great-flood-of-july-2016/ (Accessed 11 February 2018), 2016.

Myers-Smith, I. H., Grabowski, M., Thomas, H. J. D., Angers-Blondin, S., Daskalova, G., Bjorkman, A. D., Cunliffe, A. M., Assmann, J., Boyle, J., McLeod, E., McLeod, S., Joe, R., Lennie, P., Arey, D., Gordon, R. and Eckert, C.: Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change, Ecology Monographs, In Press.

Novikova, A., Belova, N., Baranskaya, A., Aleksyutina, D., Maslakov, A., Zelenin, E., Shabanova, N. and Ogorodov, S.: Dynamics of permafrost coasts of Baydaratskaya Bay (Kara Sea) based on multi-temporal remote sensing data, Remote Sensing, 10(9), 1481, doi:10.3390/rs10091481, 2018.

Obu, J., Lantuit, H., Myers-Smith, I., Heim, B., Wolter, J. and Fritz, M.: Effect of terrain characteristics on soil organic carbon and total nitrogen stocks in soils of Herschel Island, Western Canadian Arctic, Permafrost and Periglac. Process., n/a-n/a, doi:10.1002/ppp.1881, 2015.

Obu, J., Lantuit, H., Fritz, M., Pollard, W. H., Sachs, T. and Guenther, F.: Relation between planimetric and volumetric measurements of permafrost coast erosion: a case study from Herschel Island, western Canadian Arctic, Polar Res., 35, 30313, doi:10.3402/polar.v35.30313, 2016.

Ogorodov, S. A., Baranskaya, A., Belova, N. G., Kamalov, A. M., Kuznetsov, D. E., Overduin, P., Shabanova, N. N. and Vergun, A. P.: Coastal Dynamics of the Pechora and Kara Seas Under Changing Climatic Conditions and Human Disturbances, Geography, Environment, Sustainability, 9, 53–73, doi:10.15356/2071-9388_03v09_2016_04, 2016.

Olynyk, D.: Buildings, in Herschel Island - Qikiqtaryuk: A natural and cultural history of Yukon's Arctic island, edited by C. R. Burn, pp. 202–209, University of Calgary Press, Calgary, Canada., 2012.

Overduin, P. P., Strzelecki, M. C., Grigoriev, M. N., Couture, N., Lantuit, H., St-Hilaire-Gravel, D., Günther, F. and Wetterich, S.: Coastal changes in the Arctic, in Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences, vol. 388, pp. 103–129, Geological Society, London, UK.

[online] Available from: http://sp.lyellcollection.org/content/388/1/103 (Accessed 8 February 2018), 2014.

Ping, C.-L., Michaelson, G. J., Guo, L., Jorgenson, M. T., Kanevskiy, Shur, Y., Dou, F. and Liang, J.: Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline, Journal of Geophysical Research: Biogeosciences, 116(G2), doi:10.1029/2010JG001588, 2011.

Pollard, W.: The Nature and Origin of Ground Ice in the Herschel Island Area, Yukon Territory., 1990.

Radosavljevic, B., Lantuit, H., Pollard, W., Overduin, P., Couture, N., Sachs, T., Helm, V. and Fritz, M.: Erosion and Flooding-Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada, Estuaries Coasts, 39(4), 900–915, doi:10.1007/s12237-015-0046-0, 2016.

Rampton, V. N.: Quaternary geology of the Yukon Coastal Plain, Bulletin, Geological Survey of Canada. [online] Available from: https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=111347, 1982.

Retamal, L., Bonilla, S. and Vincent, W. F.: Optical gradients and phytoplankton production in the Mackenzie River and the coastal Beaufort Sea, Polar Biol, 31(3), 363–379, doi:10.1007/s00300-007-0365-0, 2008.

Richter-Menge, J., Overland, J. E., Mathis, J. T. and Osborne, E.: Arctic Report Card 2017. [online] Available from: http://www.arctic.noaa.gov/Report-Card, 2017.

Río, L. D. and Gracia, F. J.: Error determination in the photogrammetric assessment of shoreline changes, Nat Hazards, 65(3), 2385–2397, doi:10.1007/s11069-012-0407-y, 2013.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520(7546), 171–179, doi:10.1038/nature14338, 2015.

Semiletov, I., Pipko, I., Gustafsson, Ö., Anderson, L. G., Sergienko, V., Pugach, S., Dudarev, O., Charkin, A., Gukov, A., Bröder, L., Andersson, A., Spivak, E. and Shakhova, N.: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon, Nature Geoscience, 9(5), 361–365, doi:10.1038/ngeo2695, 2016.

Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis, Global and Planetary Change, 77(1), 85–96, doi:10.1016/j.gloplacha.2011.03.004, 2011.

Solomon, S. M., Forbes, D. L. and Kierstead, B.: Coastal impacts of climate change : Beaufort Sea erosion study / S.M. Solomon, D.L. Forbes, and Brian Kierstead.: M183-2/2890E-PDF - Government of Canada

Publications - Canada.ca, Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario. [online] Available from: http://publications.gc.ca/site/eng/9.820125/publication.html (Accessed 5 December 2018), 1993.

Sona, G., Pinto, L., Pagliari, D., Passoni, D. and Gini, R.: Experimental analysis of different software packages for orientation and digital surface modelling from UAV images, Earth Sci Inform, 7(2), 97–107, doi:10.1007/s12145-013-0142-2, 2014.

Stow, D. A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrich, F., Houston, S., Racine, C., Sturm, M., Tape, K., Hinzman, L., Yoshikawa, K., Tweedie, C., Noyle, B., Silapaswan, C., Douglas, D., Griffith, B., Jia, G., Epstein, H., Walker, D., Daeschner, S., Petersen, A., Zhou, L. and Myneni, R.: Remote sensing of vegetation and land-cover change in Arctic Tundra Ecosystems, Remote Sensing of Environment, 89(3), 281–308, doi:10.1016/j.rse.2003.10.018, 2004.

Stroeve, J. C., Markus, T., Miller, J. and Barrett, A.: Changes in Arctic melt season and implications for sea ice loss, Geophysical Research Letters, 41, 1216–1225, doi:https://doi.org/10.1002/2013GL058951, 2014.

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L. and Ergul, A.: The Digital Shoreline Analysis System (DSAS) Version 4.0 - An ArcGIS extension for calculating shoreline change (Ver.4.4, July 2017), USGS Numbered Series, U.S. Geological Survey, Reston. [online] Available from: http://pubs.er.usgs.gov/publication/ofr20081278 (Accessed 23 January 2018), 2009.

Turner, I. L., Harley, M. D. and Drummond, C. D.: UAVs for coastal surveying, Coastal Engineering, 114, 19–24, doi:10.1016/j.coastaleng.2016.03.011, 2016.

UNEP: Policy Implications of Warming Permafrost, UNEP. [online] Available from: https://epic.awi.de/33086/1/permafrost.pdf, 2012.

UNESCO: Ivvavik / Vuntut / Herschel Island (Qikiqtaruk), UNESCO World Heritage Centre. [online] Available from: http://whc.unesco.org/en/tentativelists/1939/ (Accessed 7 February 2018), 2004.

Vasiliev, A., Kanevskiy, M., Cherkashov, G. and Vanshtein, B.: Coastal dynamics at the Barents and Kara Sea key sites, Geo-Mar Lett, 25(2), 110–120, doi:10.1007/s00367-004-0192-z, 2005.

Vonk, J. E., Sánchez-García, L., Dongen, B. E. van, Alling, V., Kosmach, D., Charkin, A., Semiletov, I. P., Dudarev, O. V., Shakhova, N., Roos, P., Eglinton, T. I., Andersson, A. and Gustafsson, Ö.: Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia, Nature, 489(7414), 137–140, doi:10.1038/nature11392, 2012.

Wegner, C., Bennett, K. E., Vernal, A. de, Forwick, M., Fritz, M., Heikkilä, M., Łącka, M., Lantuit, H., Laska, M., Moskalik, M., O'Regan, M., Pawłowska, J., Promińska, A., Rachold, V., Vonk, J. E. and

Werner, K.: Variability in transport of terrigenous material on the shelves and the deep Arctic Ocean during the Holocene, Polar Research, 34(1), 24964, doi:10.3402/polar.v34.24964, 2015.

Wessel, P. and Smith, W. H. F.: Shorelines: Wessel, Pål, and Walter H. F. Smith. "A Global, Self-Consistent, Hierarchical, High-Resolution Shoreline Database." Journal of Geophysical Research: Solid Earth 101, no. B4 (1996): 8741–8743. https://doi.org/10.1029/96JB00104., Journal of Geophysical Research: Solid Earth, 101(B4), 8741–8743, doi:https://doi.org/10.1029/96JB00104, 1996.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. and Reynolds, J. M.: 'structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology, 179, 300–314, doi:10.1016/j.geomorph.2012.08.021, 2012.

Whalen, D.: Monitoring, understanding and predicting costal change in the Mackenzie-Beaufort Region, NT, Quebec City, Quebec, Canada., 2017.

Whalen, D., Fraser, R. and MacLeod, R.: The acceleration of change – how UAV technology is being used to better understand coastal permafrost landscapes in the Mackenzie-Beaufort Region, NT, ArcticNet. [online] Available from: http://www.arcticnet.ulaval.ca/pdf/media/IRIS-1-newsletter-Dec-2017.pdf, 2017.

Wobus, C., Anderson, R., Overeem, I., Matell, N., Clow, G. and Urban, F.: Thermal erosion of a permafrost coastline: improving process-based models using time-lapse photography, Arctic, Antarctic, and Alpine Research, 43(3), 474–484, doi:10.1657/1938-4246-43.3.474, 2011.

Agisoft: Agisoft PhotoScan User Manual: Professional Edition, V 1.4, Agisoft., 2018.

Barnhart, K. R., Anderson, R. S., Overeem, I., Wobus, C., Clow, G. D., Gary D. Clow, and Urban, F. E.: Modeling erosion of ice-rich permafrost bluffs along the Alaskan Beaufort Sea coast, Journal of Geophysical Research: Earth Surface, doi:10.1002/2013JF002845, 2014.

Bell, L. E., Bluhm, B. A. and Iken, K.: Influence of terrestrial organic matter in marine food webs of the Beaufort Sea shelf and slope, Marine Ecology Progress Series, 550, 1–24, doi:10.3354/meps11725, 2016.

Boak, E. H. and Turner, I. L.: Shoreline definition and detection: a review, Journal of Coastal Research, 688–703, doi:10.2112/03-0071.1, 2005.

Brown, J., Ferrians Jr., O. J., Heginbottom, J. A. and Melnikov, E. S.: Circum-Arctic map of permafrost and ground-ice conditions, USGS Numbered Series. [online] Available from: http://pubs.er.usgs.gov/publication/cp45 (Accessed 9 April 2018), 1997.

Burn, C. R.: Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, 1st ed., Calgary University Press., 2012.

Burn, C. R. and Zhang, Y.: Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada, J. Geophys. Res., 114(F2), F02001, doi:10.1029/2008JF001087, 2009.

Carmack, E. C. and Macdonald, R. W.: Oceanography of the Canadian Shelf of the Beaufort Sea: A Setting for Marine Life, ARCTIC, 55(5), 29–45, doi:10.14430/arctic733, 2002.

Carrivick, J. L., Smith, M. W. and Quincey, D. J.: Structure from Motion in the Geosciences, John Wiley & Sons, Ltd, Chichester, UK., 2016.

Casella, E., Rovere, A., Pedroncini, A., Mucerino, L., Casella, M., Cusati, L. A., Vacchi, M., Ferrari, M. and Firpo, M.: Study of wave runup using numerical models and low-altitude aerial photogrammetry: A tool for coastal management, Estuarine, Coastal and Shelf Science, 149, 160–167, doi:10.1016/j.ecss.2014.08.012, 2014.

Casella, E., Rovere, A., Pedroncini, A., Stark, C. P., Casella, M., Ferrari, M. and Firpo, M.: Drones as tools for monitoring beach topography changes in the Ligurian Sea (NW Mediterranean), Geo-Mar Lett, 36(2), 151–163, doi:10.1007/s00367-016-0435-9, 2016.

Couture, N. J. and Pollard, W. H.: A Model for Quantifying Ground-Ice Volume, Yukon Coast, Western Arctic Canada, Permafrost and Periglac. Process., 28(3), 534–542, doi:10.1002/ppp.1952, 2017.

Couture, N. J., Irrgang, A., Pollard, W., Lantuit, H. and Fritz, M.: Coastal Erosion of Permafrost Soils Along the Yukon Coastal Plain and Fluxes of Organic Carbon to the Canadian Beaufort Sea, J. Geophys. Res. Biogeosci., 2017JG004166, doi:10.1002/2017JG004166, 2018.

Cunliffe, A. and Anderson, K.: Measuring Above-ground Biomass with Drone Photogrammetry: Data Collection Protocol, Protocol Exchange, doi:10.1038/protex.2018.134, 2019.

Cunliffe, A. M., Brazier, R. E. and Anderson, K.: Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry, Remote Sensing of Environment, 183, 129–143, doi:10.1016/j.rse.2016.05.019, 2016.

DeBell, L., Anderson, K., Brazier, R. E., King, N. and Jones, L.: Water resource management at catchment scales using lightweight UAVs: current capabilities and future perspectives, J. Unmanned Veh. Sys., doi:10.1139/juvs-2015-0026, 2015.

Dolan, R., Fenster, M. S. and Holme, S. J.: Temporal analysis of shoreline recession and accretion, Journal of Coastal Research, 7(3), 723–744, 1991.

Duffy, J. P., Cunliffe, A. M., DeBell, L., Sandbrook, C., Wich, S. A., Shutler, J. D., Myers-Smith, I. H., Varela, M. R. and Anderson, K.: Location, location, location: considerations when using lightweight drones in challenging environments, Remote Sens Ecol Conserv, doi:10.1002/rse2.58, 2017a.

Duffy, J. P., Pratt, L., Anderson, K., Land, P. E. and Shutler, J. D.: Spatial assessment of intertidal seagrass meadows using optical imaging systems and a lightweight drone, Estuarine, Coastal and Shelf Science, doi:10.1016/j.ecss.2017.11.001, 2017b.

Dunton, K. H., Weingartner, T. and Carmack, E. C.: The nearshore western Beaufort Sea ecosystem: Circulation and importance of terrestrial carbon in arctic coastal food webs, Progress in Oceanography, 71(2), 362–378, doi:10.1016/j.pocean.2006.09.011, 2006.

Environment Canada: [online] Available from: http://climate.weather.gc.ca/climate_data (Accessed 3 January 2018), 2017.

ESRI, TerraColor and Earthstar Geographics: Basemap, [online] Available from: http://goto.arcgisonline.com/maps/Arctic_Imagery, 2018.

Fritz, M., Wetterich, S., Meyer, H., Schirrmeister, L., Lantuit, H. and Pollard, W. H.: Origin and characteristics of massive ground ice on Herschel Island (western Canadian Arctic) as revealed by stable water isotope and Hydrochemical signatures, Permafrost Periglac. Process., 22(1), 26–38, doi:10.1002/ppp.714, 2011.

Fritz, M., Wetterich, S., Schirrmeister, L., Meyer, H., Lantuit, H., Preusser, F. and Pollard, W. H.: Eastern Beringia and beyond: Late Wisconsinan and Holocene landscape dynamics along the Yukon Coastal Plain, Canada, Palaeogeography, Palaeoclimatology, Palaeoecology, 319–320, 28–45, doi:10.1016/j.palaeo.2011.12.015, 2012.

Fritz, M., Vonk, J. E. and Lantuit, H.: Collapsing Arctic coastlines, Nature Clim. Change, 7(1), 6–7, doi:10.1038/nclimate3188, 2017.

Galley, R. J., Babb, D., Ogi, M., Else, B. G. T., Geilfus, N.-X., Crabeck, O., Barber, D. G. and Rysgaard, S.: Replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea since 2004, J. Geophys. Res. Oceans, 121(3), 1806–1823, doi:10.1002/2015JC011583, 2016.

Günther, F., Overduin, P. P., Sandakov, A., Grosse, G. and Grigoriev, M. N.: Thermo-erosion along the Yedoma coast of the Buor Khaya peninsula, Laptev Sea, East Siberia, in Proceedings of the Tenth International Conference on Permafrost, Volume 1: International Contributions, edited by K. Hinkel, pp. 137–142., 2012.

Günther, F., Overduin, P. P., Baranskaya, A., Opel, T. and Grigoriev, M. N.: Observing Muostakh Island disappear: erosion of a ground-ice-rich coast in response to summer warming and sea ice reduction on the East Siberian shelf, Cryosphere Discussions, 7(4), 4101–4176, doi:10.5194/tcd-7-4101-2013, 2013a.

Günther, F., Overduin, P. P., Sandakov, A. V., Grosse, G. and Grigoriev, M. N.: Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region, Biogeosciences, 10(6), 4297–4318, doi:10.5194/bg-10-4297-2013, 2013b.

Harper, J. R., Reimer, P. D. and Collins, A. D.: Canadian Beaufort Sea physical shore-zone analysis, Report for Northern Oil and Gas Action Plan, Indian and Northern Affairs Canada Ottawa, Canada. [online] Available from: http://engineerradcc.library.link/portal/Canadian-Beaufort-Sea-physical-shore-zone/Gu3YaBSD3Pk/, 1985.

Héquette, A. and Barnes, P. W.: Coastal retreat and shoreface profile variations in the Canadian Beaufort Sea, Marine Geology, 91(1), 113–132, doi:10.1016/0025-3227(90)90136-8, 1990.

Héquette, A., Desrosiers, M. and Barnes, P. W.: Sea ice scouring on the inner shelf of the southeastern Canadian Beaufort Sea, Marine Geology, 128(3), 201–219, doi:10.1016/0025-3227(95)00095-G, 1995.

Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G. and Farris, A. S.: Digital Shoreline Analysis System (DSAS) version 5.0 user guide, Report, Reston, VA., 2018.

Hope, A. S., Pence, K. R. and Stow, D. A.: NDVI from low altitude aircraft and composited NOAA AVHRR data for scaling Arctic ecosystem fluxes, International Journal of Remote Sensing, 25(20), 4237–4250, doi:10.1080/01431160310001632710, 2004.

Huggett, W. S., Woodward, M. J., Stephenson, F., Hermiston, F. V. and Douglas, A.: Near and Bottom Currents and Offshore Tides, Ocean and Aquatic Sciences, Depatment of Envrionment., 1975.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, p. 996, Cambridge University Press, Cambridge, United Kingdom., 2013.

Irrgang, A. M., Lantuit, H., Manson, G. K., Günther, F., Grosse, G. and Overduin, P. P.: Variability in Rates of Coastal Change Along the Yukon Coast, 1951 to 2015, Journal of Geophysical Research: Earth Surface, 123(4), 779–800, doi:10.1002/2017JF004326, 2018.

James, M. R., Robson, S., d'Oleire-Oltmanns, S. and Niethammer, U.: Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment, Geomorphology, 280, 51–66, doi:10.1016/j.geomorph.2016.11.021, 2017.

James, T. S., Henton, J. A., Leonard, L. J., Darlington, A., Forbes, D. L. and Craymer, M.: Relative sea-level projections in Canada and the adjacent mainland United States, Geological Survey of Canada, Ottawa, Ontario. [online] Available from: Retrieved from http://ftp2.cits. rncan.gc.ca/pub/geott/ess_pubs/295/295574/of_7737.pdf, 2014.

Jones, B. M., Hinkel, K. M., Arp, C. D. and Eisner, W. R.: Modern erosion rates and loss of coastal features and sites, Beaufort Sea coastline, Alaska, Arctic, 61(4), 12, 2008.

Jones, B. M., Arp, C. D., Beck, R. A., Grosse, G., Webster, J. M. and Urban, F. E.: Erosional history of Cape Halkett and contemporary monitoring of bluff retreat, Beaufort Sea coast, Alaska, Polar Geography, 32(3–4), 129–142, doi:10.1080/10889370903486449, 2009a.

Jones, B. M., Arp, C. D., Jorgenson, M. T., Hinkel, K. M., Schmutz, J. A. and Flint, P. L.: Increase in the rate and uniformity of coastline erosion in Arctic Alaska, Geophys. Res. Lett., 36(3), L03503, doi:10.1029/2008GL036205, 2009b.

Jones, B. M., Farquharson, L. M., Baughman, C. A., Buzard, R. M., Arp, C. D., Grosse, G., Bull, D. L., Günther, F., Nitze, I., Urban, F., Kasper, J. L., Frederick, J. M., Thomas, M., Jones, C., Mota, A., Dallimore, S., Tweedie, C., Maio, C., Mann, D. H., Richmond, B., Gibbs, A., Xiao, M., Sachs, T., Iwahana, G., Kanevskiy, M. and Romanovsky, V. E.: A decade of remotely sensed observations highlight complex processes linked to coastal permafrost bluff erosion in the Arctic, Environmental Research Letters, 13(11), 115001, doi:10.1088/1748-9326/aae471, 2018.

Jorgenson, M. T. and Brown, J.: Classification of the Alaskan Beaufort Sea Coast and estimation of carbon and sediment inputs from coastal erosion, Geo-Mar Lett, 25(2–3), 69–80, doi:10.1007/s00367-004-0188-8, 2005.

Klemas, V. V.: Coastal and environmental remote sensing from unmanned aerial vehicles: an overview, Journal of Coastal Research, 1260–1267, doi:10.2112/JCOASTRES-D-15-00005.1, 2015.

Kritsuk, L. N., Dubrovin, V. A. and Yastreba, N. V.: Some results of integrated study of the Kara Sea coastal dynamics in the Marre-Sale meteorological station area, with the use of GIS technologies. Earth's Cryosphere, Earth's Cryosphere, 4, 59–69, 2014.

Lantuit, H. and Pollard, W. H.: Temporal stereophotogrammetric analysis of retrogressive thaw slumps on Herschel Island, Yukon Territory, Natural Hazards and Earth System Science, 5(3), 413–423, 2005.

Lantuit, H. and Pollard, W. H.: Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada, Geomorphology, 95(1–2), 84–102, doi:10.1016/j.geomorph.2006.07.040, 2008.

Lantuit, H., Overduin, P. P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D. L., Graves-Gaylord, A., Grigoriev, M., Hubberten, H.-W., Jordan, J., Jorgenson, T., Ødegård, R. S., Ogorodov, S., Pollard, W. H., Rachold, V., Sedenko, S., Solomon, S., Steenhuisen, F., Streletskaya, I. and Vasiliev, A.: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines, Estuaries and Coasts, 35(2), 383–400, doi:10.1007/s12237-010-9362-6, 2012.

Mahoney, A. R., Eicken, H., Gaylord, A. G. and Gens, R.: Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability, Cold Regions Science and Technology, 103, 41–56, doi:10.1016/j.coldregions.2014.03.003, 2014.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S. and Gabbianelli, G.: Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments, Remote Sensing, 5(12), 6880–6898, doi:10.3390/rs5126880, 2013.

Manson, G. K., Solomon, S. M., Forbes, D. L., Atkinson, D. E. and Craymer, M.: Spatial variability of factors influencing coastal change in the Western Canadian Arctic, Geo-Mar Lett, 25(2–3), 138–145, doi:10.1007/s00367-004-0195-9, 2005.

Mars, J. C. and Houseknecht, D. W.: Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska, Geology, 35(7), 583–586, doi:10.1130/G23672A.1, 2007.

Metcalfe, D. B., Hermans, T. D. G., Ahlstrand, J., Becker, M., Berggren, M., Björk, R. G., Björkman, M. P., Blok, D., Chaudhary, N., Chisholm, C., Classen, A. T., Hasselquist, N. J., Jonsson, M., Kristensen, J. A., Kumordzi, B. B., Lee, H., Mayor, J. R., Prevéy, J., Pantazatou, K., Rousk, J., Sponseller, R. A., Sundqvist, M. K., Tang, J., Uddling, J., Wallin, G., Zhang, W., Ahlström, A., Tenenbaum, D. E. and Abdi, A. M.: Patchy field sampling biases understanding of climate change impacts across the Arctic, Nature Ecology & Evolution, 2(9), 1443, doi:10.1038/s41559-018-0612-5, 2018.

Myers-Smith, I. H. and Lehtonen, S.: NOAA's Arketic: The Great Flood of July 2016, Team Shrub: Tundra Ecology Lab [online] Available from: https://teamshrub.com/2016/07/22/noaas-arkctic-the-great-flood-of-july-2016/ (Accessed 11 February 2018), 2016.

Myers-Smith, I. H., Grabowski, M., Thomas, H. J. D., Angers-Blondin, S., Daskalova, G., Bjorkman, A. D., Cunliffe, A. M., Assmann, J., Boyle, J., McLeod, E., McLeod, S., Joe, R., Lennie, P., Arey, D., Gordon, R. and Eckert, C.: Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change, Ecology Monographs, Accepted.

Novikova, A., Belova, N., Baranskaya, A., Aleksyutina, D., Maslakov, A., Zelenin, E., Shabanova, N. and Ogorodov, S.: Dynamics of permafrost coasts of Baydaratskaya Bay (Kara Sea) based on multi-temporal remote sensing data, Remote Sensing, 10(9), 1481, doi:10.3390/rs10091481, 2018.

Obu, J., Lantuit, H., Myers-Smith, I., Heim, B., Wolter, J. and Fritz, M.: Effect of terrain characteristics on soil organic carbon and total nitrogen stocks in soils of Herschel Island, Western Canadian Arctic, Permafrost and Periglac. Process., n/a-n/a, doi:10.1002/ppp.1881, 2015.

Obu, J., Lantuit, H., Fritz, M., Pollard, W. H., Sachs, T. and Guenther, F.: Relation between planimetric and volumetric measurements of permafrost coast erosion: a case study from Herschel Island, western Canadian Arctic, Polar Res., 35, 30313, doi:10.3402/polar.v35.30313, 2016.

Ogorodov, S. A., Baranskaya, A., Belova, N. G., Kamalov, A. M., Kuznetsov, D. E., Overduin, P., Shabanova, N. N. and Vergun, A. P.: Coastal Dynamics of the Pechora and Kara Seas Under Changing Climatic Conditions and Human Disturbances, Geography, Environment, Sustainability, 9, 53–73, doi:Ogorodov, S. A. , Baranskaya, A. , Belova, N. G. , Kamalov, A. M. , Kuznetsov, D. E. , Overduin, P. , Shabanova, N. N. and Vergun, A. P. (2016) Coastal Dynamics of the Pechora and Kara Seas Under Changing Climatic Conditions and Human Disturbances , Geography, Environment, Sustainability, 9 (3), pp. 53-73 . doi:https://doi.org/10.15356/2071-9388_03v09_2016_04 <https://doi.org/10.15356/2071-9388_03v09_2016_04> , hdl:10013/epic.49211, 2016.

Olynyk, D.: Buildings, in Herschel Island – Qikiqtaryuk: A natural and cultural history of Yukon's Arctic island, edited by C. R. Burn, pp. 202–209, University of Calgary Press, Calgary, Canada., 2012.

Overduin, P. P., Strzelecki, M. C., Grigoriev, M. N., Couture, N., Lantuit, H., St-Hilaire-Gravel, D., Günther, F. and Wetterich, S.: Coastal changes in the Arctic, in Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences, vol. 388, pp. 103–129, Geological Society, London, UK. [online] Available from: http://sp.lyellcollection.org/content/388/1/103 (Accessed 8 February 2018), 2014.

Ping, C.-L., Michaelson, G. J., Guo, L., Jorgenson, M. T., Kanevskiy, Shur, Y., Dou, F. and Liang, J.: Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline, Journal of Geophysical Research: Biogeosciences, 116(G2), doi:10.1029/2010JG001588, 2011.

Pollard, W.: The Nature and Origin of Ground Ice in the Herschel Island Area, Yukon Territory., 1990.

Radosavljevic, B., Lantuit, H., Pollard, W., Overduin, P., Couture, N., Sachs, T., Helm, V. and Fritz, M.: Erosion and Flooding-Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada, Estuaries Coasts, 39(4), 900–915, doi:10.1007/s12237-015-0046-0, 2016.

Rampton, V. N.: Quaternary geology of the Yukon Coastal Plain, Bulletin, Geological Survey of Canada. [online] Available from: https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=111347, 1982.

Retamal, L., Bonilla, S. and Vincent, W. F.: Optical gradients and phytoplankton production in the Mackenzie River and the coastal Beaufort Sea, Polar Biol, 31(3), 363–379, doi:10.1007/s00300-007-0365-0, 2008.

Richter-Menge, J., Overland, J. E., Mathis, J. T. and Osborne, E.: Arctic Report Card 2017. [online] Available from: http://www.arctic.noaa.gov/Report-Card, 2017.

Río, L. D. and Gracia, F. J.: Error determination in the photogrammetric assessment of shoreline changes, Nat Hazards, 65(3), 2385–2397, doi:10.1007/s11069-012-0407-y, 2013.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520(7546), 171–179, doi:10.1038/nature14338, 2015.

Semiletov, I., Pipko, I., Gustafsson, Ö., Anderson, L. G., Sergienko, V., Pugach, S., Dudarev, O., Charkin, A., Gukov, A., Bröder, L., Andersson, A., Spivak, E. and Shakhova, N.: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon, Nature Geoscience, 9(5), 361–365, doi:10.1038/ngeo2695, 2016.

Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis, Global and Planetary Change, 77(1), 85–96, doi:10.1016/j.gloplacha.2011.03.004, 2011.

Solomon, S. M., Forbes, D. L. and Kierstead, B.: Coastal impacts of climate change : Beaufort Sea erosion study / S.M. Solomon, D.L. Forbes, and Brian Kierstead.: M183-2/2890E-PDF - Government of Canada Publications - Canada.ca, Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario. [online] Available from: http://publications.gc.ca/site/eng/9.820125/publication.html (Accessed 5 December 2018), 1993.

Sona, G., Pinto, L., Pagliari, D., Passoni, D. and Gini, R.: Experimental analysis of different software packages for orientation and digital surface modelling from UAV images, Earth Sci Inform, 7(2), 97–107, doi:10.1007/s12145-013-0142-2, 2014.

Stow, D. A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrich, F., Houston, S., Racine, C., Sturm, M., Tape, K., Hinzman, L., Yoshikawa, K., Tweedie, C., Noyle, B., Silapaswan, C., Douglas, D., Griffith, B., Jia, G., Epstein, H., Walker, D., Daeschner, S., Petersen, A., Zhou, L. and Myneni, R.: Remote sensing of vegetation and land-cover change in Arctic Tundra Ecosystems, Remote Sensing of Environment, 89(3), 281–308, doi:10.1016/j.rse.2003.10.018, 2004.

Stroeve, J. C., Markus, T., Miller, J. and Barrett, A.: Changes in Arctic melt season and implications for sea ice loss, Geophysical Research Letters, 41, 1216–1225, doi:https://doi.org/10.1002/2013GL058951, 2014.

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L. and Ergul, A.: The Digital Shoreline Analysis System (DSAS) Version 4.0 - An ArcGIS extension for calculating shoreline change (Ver.4.4, July 2017), USGS Numbered Series, U.S. Geological Survey, Reston. [online] Available from: http://pubs.er.usgs.gov/publication/ofr20081278 (Accessed 23 January 2018), 2009.

Turner, I. L., Harley, M. D. and Drummond, C. D.: UAVs for coastal surveying, Coastal Engineering, 114, 19–24, doi:10.1016/j.coastaleng.2016.03.011, 2016.

UNEP: Policy Implications of Warming Permafrost, UNEP. [online] Available from: https://epic.awi.de/33086/1/permafrost.pdf, 2012.

UNESCO: Ivvavik / Vuntut / Herschel Island (Qikiqtaruk), UNESCO World Heritage Centre. [online] Available from: http://whc.unesco.org/en/tentativelists/1939/ (Accessed 7 February 2018), 2004.

Vasiliev, A., Kanevskiy, M., Cherkashov, G. and Vanshtein, B.: Coastal dynamics at the Barents and Kara Sea key sites, Geo-Mar Lett, 25(2), 110–120, doi:10.1007/s00367-004-0192-z, 2005.

van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P. and Kabat, P.: Global river discharge and water temperature under climate change, Global Environmental Change, 23(2), 450–464, doi:10.1016/j.gloenvcha.2012.11.002, 2013.

Vonk, J. E., Sánchez-García, L., Dongen, B. E. van, Alling, V., Kosmach, D., Charkin, A., Semiletov, I. P., Dudarev, O. V., Shakhova, N., Roos, P., Eglinton, T. I., Andersson, A. and Gustafsson, Ö.: Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia, Nature, 489(7414), 137–140, doi:10.1038/nature11392, 2012.

Wegner, C., Bennett, K. E., Vernal, A. de, Forwick, M., Fritz, M., Heikkilä, M., Łącka, M., Lantuit, H., Laska, M., Moskalik, M., O'Regan, M., Pawłowska, J., Promińska, A., Rachold, V., Vonk, J. E. and Werner, K.: Variability in transport of terrigenous material on the shelves and the deep Arctic Ocean during the Holocene, Polar Research, 34(1), 24964, doi:10.3402/polar.v34.24964, 2015.

Wessel, P. and Smith, W. H. F.: Shorelines: Wessel, Pål, and Walter H. F. Smith. "A Global, Self-Consistent, Hierarchical, High-Resolution Shoreline Database." Journal of Geophysical Research: Solid Earth 101, no. B4 (1996): 8741–8743. https://doi.org/10.1029/96JB00104., Journal of Geophysical Research: Solid Earth, 101(B4), 8741–8743, doi:https://doi.org/10.1029/96JB00104, 1996.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. and Reynolds, J. M.: 'structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology, 179, 300–314, doi:10.1016/j.geomorph.2012.08.021, 2012.

Whalen, D.: Monitoring, understanding and predicting costal change in the Mackenzie-Beaufort Region, NT, Quebec City, Quebec, Canada., 2017.

Whalen, D., Fraser, R. and MacLeod, R.: The acceleration of change – how UAV technology is being used to better understand coastal permafrost landscapes in the Mackenzie-Beaufort Region, NT, ArcticNet. [online] Available from: http://www.arcticnet.ulaval.ca/pdf/media/IRIS-1-newsletter-Dec-2017.pdf, 2017.

Wobus, C., Anderson, R., Overeem, I., Matell, N., Clow, G. and Urban, F.: Thermal erosion of a permafrost coastline: improving process-based models using time-lapse photography, Arctic, Antarctic, and Alpine Research, 43(3), 474–484, doi:10.1657/1938-4246-43.3.474, 2011.

Agisoft: Agisoft PhotoScan User Manual: Professional Edition, V 1.4, Agisoft., 2018.

Barnhart, K. R., Anderson, R. S., Overeem, I., Wobus, C., Clow, G. D., Gary D. Clow, and Urban, F. E.: Modeling erosion of ice-rich permafrost bluffs along the Alaskan Beaufort Sea coast, Journal of Geophysical Research: Earth Surface, doi:10.1002/2013JF002845, 2014.

Bell, L. E., Bluhm, B. A. and Iken, K.: Influence of terrestrial organic matter in marine food webs of the Beaufort Sea shelf and slope, Marine Ecology Progress Series, 550, 1–24, doi:10.3354/meps11725, 2016.

Boak, E. H. and Turner, I. L.: Shoreline Definition and Detection: A Review, Journal of Coastal Research, 688–703, doi:10.2112/03-0071.1, 2005.

Brown, J., Ferrians Jr., O. J., Heginbottom, J. A. and Melnikov, E. S.: Circum-Arctic map of permafrost and ground-ice conditions, USGS Numbered Series. [online] Available from: http://pubs.er.usgs.gov/publication/cp45 (Accessed 9 April 2018), 1997.

Burn, C. R.: Herschel Island Qikiqtaryuk: A Natural and Cultural History of Yukon's Arctic Island, 1st ed., Calgary University Press., 2012.

Burn, C. R. and Zhang, Y.: Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada, J. Geophys. Res., 114(F2), F02001, doi:10.1029/2008JF001087, 2009.

Carmack, E. C. and Macdonald, R. W.: Oceanography of the Canadian Shelf of the Beaufort Sea: A Setting for Marine Life, ARCTIC, 55(5), 29–45, doi:10.14430/arctic733, 2002.

Carrivick, J. L., Smith, M. W. and Quincey, D. J.: Structure from Motion in the Geosciences, John Wiley & Sons, Ltd, Chichester, UK., 2016.

Casella, E., Rovere, A., Pedroncini, A., Mucerino, L., Casella, M., Cusati, L. A., Vacchi, M., Ferrari, M. and Firpo, M.: Study of wave runup using numerical models and low-altitude aerial photogrammetry: A tool for coastal management, Estuarine, Coastal and Shelf Science, 149, 160–167, doi:10.1016/j.ecss.2014.08.012, 2014.

Casella, E., Rovere, A., Pedroncini, A., Stark, C. P., Casella, M., Ferrari, M. and Firpo, M.: Drones as tools for monitoring beach topography changes in the Ligurian Sea (NW Mediterranean), Geo-Mar Lett, 36(2), 151–163, doi:10.1007/s00367-016-0435-9, 2016.

Couture, N. J. and Pollard, W. H.: A Model for Quantifying Ground-Ice Volume, Yukon Coast, Western Arctic Canada, Permafrost and Periglac. Process., 28(3), 534–542, doi:10.1002/ppp.1952, 2017.

Couture, N. J., Irrgang, A., Pollard, W., Lantuit, H. and Fritz, M.: Coastal Erosion of Permafrost Soils Along the Yukon Coastal Plain and Fluxes of Organic Carbon to the Canadian Beaufort Sea, J. Geophys. Res. Biogeosci., 2017JG004166, doi:10.1002/2017JG004166, 2018.

Cunliffe, A. M., Brazier, R. E. and Anderson, K.: Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry, Remote Sensing of Environment, 183, 129–143, doi:10.1016/j.rse.2016.05.019, 2016.

DeBell, L., Anderson, K., Brazier, R. E., King, N. and Jones, L.: Water resource management at catchment scales using lightweight UAVs: current capabilities and future perspectives, J. Unmanned Veh. Sys., doi:10.1139/juvs-2015-0026, 2015.

Dolan, R., Fenster, M. S. and Holme, S. J.: Temporal analysis of shoreline recession and accretion, Journal of Coastal Research, 7(3), 723–744, 1991.

Duffy, J. P., Cunliffe, A. M., DeBell, L., Sandbrook, C., Wich, S. A., Shutler, J. D., Myers-Smith, I. H., Varela, M. R. and Anderson, K.: Location, location, location: considerations when using lightweight drones in challenging environments, Remote Sens Ecol Conserv, doi:10.1002/rse2.58, 2017a.

Duffy, J. P., Pratt, L., Anderson, K., Land, P. E. and Shutler, J. D.: Spatial assessment of intertidal seagrass meadows using optical imaging systems and a lightweight drone, Estuarine, Coastal and Shelf Science, doi:10.1016/j.ecss.2017.11.001, 2017b.

Dunton, K. H., Weingartner, T. and Carmack, E. C.: The nearshore western Beaufort Sea ecosystem: Circulation and importance of terrestrial carbon in arctic coastal food webs, Progress in Oceanography, 71(2), 362–378, doi:10.1016/j.pocean.2006.09.011, 2006.

Environment Canada: [online] Available from: http://climate.weather.gc.ca/climate_data (Accessed 3 January 2018), 2017.

ESRI, TerraColor and Earthstar Geographics: Basemap, [online] Available from: http://goto.arcgisonline.com/maps/Arctic_Imagery, 2018.

Fritz, M., Wetterich, S., Meyer, H., Schirrmeister, L., Lantuit, H. and Pollard, W. H.: Origin and characteristics of massive ground ice on Herschel Island (western Canadian Arctic) as revealed by stable water isotope and Hydrochemical signatures, Permafrost Periglac. Process., 22(1), 26–38, doi:10.1002/ppp.714, 2011.

Fritz, M., Wetterich, S., Schirrmeister, L., Meyer, H., Lantuit, H., Preusser, F. and Pollard, W. H.: Eastern Beringia and beyond: Late Wisconsinan and Holocene landscape dynamics along the Yukon Coastal Plain, Canada, Palaeogeography, Palaeoclimatology, Palaeoecology, 319–320, 28–45, doi:10.1016/j.palaeo.2011.12.015, 2012.

Fritz, M., Vonk, J. E. and Lantuit, H.: Collapsing Arctic coastlines, Nature Clim. Change, 7(1), 6–7, doi:10.1038/nclimate3188, 2017.

Galley, R. J., Babb, D., Ogi, M., Else, B. G. T., Geilfus, N.-X., Crabeck, O., Barber, D. G. and Rysgaard, S.: Replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea since 2004, J. Geophys. Res. Oceans, 121(3), 1806–1823, doi:10.1002/2015JC011583, 2016.

Günther, F., Overduin, P. P., Sandakov, A., Grosse, G. and Grigoriev, M. N.: Thermo-erosion along the Yedoma coast of the Buor Khaya peninsula, Laptev Sea, East Siberia, in Proceedings of the Tenth International Conference on Permafrost, Volume 1: International Contributions, edited by K. Hinkel, pp. 137–142., 2012.

Günther, F., Overduin, P. P., Baranskaya, A., Opel, T. and Grigoriev, M. N.: Observing Muostakh Island disappear: erosion of a ground-ice-rich coast in response to summer warming and sea ice reduction on the East Siberian shelf, Cryosphere Discussions, 7(4), 4101–4176, doi:10.5194/tcd-7-4101-2013, 2013a.

Günther, F., Overduin, P. P., Sandakov, A. V., Grosse, G. and Grigoriev, M. N.: Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region, Biogeosciences, 10(6), 4297–4318, doi:10.5194/bg-10-4297-2013, 2013b.

Harper, J. R., Reimer, P. D. and Collins, A. D.: Canadian Beaufort Sea physical shore-zone analysis, Report for Northern Oil and Gas Action Plan, Indian and Northern Affairs Canada Ottawa, Canada. [online] Available from: http://engineerradcc.library.link/portal/Canadian-Beaufort-Sea-physical-shore-zone/Gu3YaBSD3Pk/, 1985.

Héquette, A. and Barnes, P. W.: Coastal retreat and shoreface profile variations in the Canadian Beaufort Sea, Marine Geology, 91(1), 113–132, doi:10.1016/0025-3227(90)90136-8, 1990.

Héquette, A., Desrosiers, M. and Barnes, P. W.: Sea ice scouring on the inner shelf of the southeastern Canadian Beaufort Sea, Marine Geology, 128(3), 201–219, doi:10.1016/0025-3227(95)00095-G, 1995.

Hope, A. S., Pence, K. R. and Stow, D. A.: NDVI from low altitude aircraft and composited NOAA AVHRR data for scaling Arctic ecosystem fluxes, International Journal of Remote Sensing, 25(20), 4237–4250, doi:10.1080/01431160310001632710, 2004.

Huggett, W. S., Woodward, M. J., Stephenson, F., Hermiston, F. V. and Douglas, A.: Near and Bottom Currents and Offshore Tides, Ocean and Aquatic Sciences, Depatment of Envrionment., 1975.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, p. 996, Cambridge University Press, Cambridge, United Kingdom., 2013.

Irrgang, A. M., Lantuit, H., Manson, G. K., Günther, F., Grosse, G. and Overduin, P. P.: Variability in Rates of Coastal Change Along the Yukon Coast, 1951 to 2015, Journal of Geophysical Research: Earth Surface, 123(4), 779–800, doi:10.1002/2017JF004326, 2018.

James, M. R., Robson, S., d'Oleire-Oltmanns, S. and Niethammer, U.: Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment, Geomorphology, 280, 51–66, doi:10.1016/j.geomorph.2016.11.021, 2017.

James, T. S., Henton, J. A., Leonard, L. J., Darlington, A., Forbes, D. L. and Craymer, M.: Relative sea-level projections in Canada and the adjacent mainland United States, Geological Survey of Canada, Ottawa, Ontario. [online] Available from: Retrieved from http://ftp2.cits. rncan.gc.ca/pub/geott/ess_pubs/295/295574/of_7737.pdf, 2014.

Jones, B. M., Hinkel, K. M., Arp, C. D. and Eisner, W. R.: Modern erosion rates and loss of coastal features and sites, Beaufort Sea coastline, Alaska, Arctic, 61(4), 12, 2008.

Jones, B. M., Arp, C. D., Beck, R. A., Grosse, G., Webster, J. M. and Urban, F. E.: Erosional history of Cape Halkett and contemporary monitoring of bluff retreat, Beaufort Sea coast, Alaska, Polar Geography, 32(3–4), 129–142, doi:10.1080/10889370903486449, 2009a.

Jones, B. M., Arp, C. D., Jorgenson, M. T., Hinkel, K. M., Schmutz, J. A. and Flint, P. L.: Increase in the rate and uniformity of coastline erosion in Arctic Alaska, Geophys. Res. Lett., 36(3), L03503, doi:10.1029/2008GL036205, 2009b.

Jones, B. M., Farquharson, L. M., Baughman, C. A., Buzard, R. M., Arp, C. D., Grosse, G., Bull, D. L., Günther, F., Nitze, I., Urban, F., Kasper, J. L., Frederick, J. M., Thomas, M., Jones, C., Mota, A., Dallimore, S., Tweedie, C., Maio, C., Mann, D. H., Richmond, B., Gibbs, A., Xiao, M., Sachs, T., Iwahana, G., Kanevskiy, M. and Romanovsky, V. E.: A decade of remotely sensed observations highlight complex processes linked to coastal permafrost bluff erosion in the Arctic, Environmental Research Letters, 13(11), 115001, doi:10.1088/1748-9326/aae471, 2018.

Jorgenson, M. T. and Brown, J.: Classification of the Alaskan Beaufort Sea Coast and estimation of carbon and sediment inputs from coastal erosion, Geo-Mar Lett, 25(2–3), 69–80, doi:10.1007/s00367-004-0188-8, 2005.

Klemas, V. V.: Coastal and environmental remote sensing from unmanned aerial vehicles: an overview, Journal of Coastal Research, 1260–1267, doi:10.2112/JCOASTRES-D-15-00005.1, 2015.

Lantuit, H. and Pollard, W. H.: Temporal stereophotogrammetric analysis of retrogressive thaw slumps on Herschel Island, Yukon Territory, Natural Hazards and Earth System Science, 5(3), 413–423, 2005.

Lantuit, H. and Pollard, W. H.: Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada, Geomorphology, 95(1–2), 84–102, doi:10.1016/j.geomorph.2006.07.040, 2008.

Lantuit, H., Overduin, P. P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D. L., Graves-Gaylord, A., Grigoriev, M., Hubberten, H.-W., Jordan, J., Jorgenson, T., Ødegård, R. S., Ogorodov, S., Pollard, W. H., Rachold, V., Sedenko, S., Solomon, S., Steenhuisen, F., Streletskaya, I. and Vasiliev, A.: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines, Estuaries and Coasts, 35(2), 383–400, doi:10.1007/s12237-010-9362-6, 2012.

Mahoney, A. R., Eicken, H., Gaylord, A. G. and Gens, R.: Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability, Cold Regions Science and Technology, 103, 41–56, doi:10.1016/j.coldregions.2014.03.003, 2014.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S. and Gabbianelli, G.: Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments, Remote Sensing, 5(12), 6880–6898, doi:10.3390/rs5126880, 2013.

Manson, G. K., Solomon, S. M., Forbes, D. L., Atkinson, D. E. and Craymer, M.: Spatial variability of factors influencing coastal change in the Western Canadian Arctic, Geo-Mar Lett, 25(2–3), 138–145, doi:10.1007/s00367-004-0195-9, 2005.

Mars, J. C. and Houseknecht, D. W.: Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska, Geology, 35(7), 583–586, doi:10.1130/G23672A.1, 2007.

Metcalfe, D. B., Hermans, T. D. G., Ahlstrand, J., Becker, M., Berggren, M., Björk, R. G., Björkman, M. P., Blok, D., Chaudhary, N., Chisholm, C., Classen, A. T., Hasselquist, N. J., Jonsson, M., Kristensen, J. A., Kumordzi, B. B., Lee, H., Mayor, J. R., Prevéy, J., Pantazatou, K., Rousk, J., Sponseller, R. A., Sundqvist, M. K., Tang, J., Uddling, J., Wallin, G., Zhang, W., Ahlström, A., Tenenbaum, D. E. and Abdi, A. M.: Patchy field sampling biases understanding of climate change impacts across the Arctic, Nature Ecology & Evolution, 2(9), 1443, doi:10.1038/s41559-018-0612-5, 2018.

Myers-Smith, I. H. and Lehtonen, S.: NOAA's Arktic: The Great Flood of July 2016, Team Shrub: Tundra Ecology Lab [online] Available from: https://teamshrub.com/2016/07/22/noaas-arktic-the-great-flood-of-july-2016/ (Accessed 11 February 2018), 2016.

Myers-Smith, I. H., Grabowski, M., Thomas, H. J. D., Angers-Blondin, S., Daskalova, G., Bjorkman, A. D., Cunliffe, A. M., Assmann, J., Boyle, J., McLeod, E., McLeod, S., Joe, R., Lennie, P., Arey, D., Gordon, R. and Eckert, C.: Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change, Ecology Monographs, Accepted.

Obu, J., Lantuit, H., Myers-Smith, I., Heim, B., Wolter, J. and Fritz, M.: Effect of terrain characteristics on soil organic carbon and total nitrogen stocks in soils of Herschel Island, Western Canadian Arctic, Permafrost and Periglac. Process., n/a-n/a, doi:10.1002/ppp.1881, 2015.

Obu, J., Lantuit, H., Fritz, M., Pollard, W. H., Sachs, T. and Guenther, F.: Relation between planimetric and volumetric measurements of permafrost coast erosion: a case study from Herschel Island, western Canadian Arctic, Polar Res., 35, 30313, doi:10.3402/polar.v35.30313, 2016.

Olynyk, D.: Buildings, in Herschel Island - Qikiqtaryuk: A natural and cultural history of Yukon's Arctic island, edited by C. R. Burn, pp. 202–209, University of Calgary Press, Calgary, Canada., 2012.

Overduin, P. P., Strzelecki, M. C., Grigoriev, M. N., Couture, N., Lantuit, H., St-Hilaire-Gravel, D., Günther, F. and Wetterich, S.: Coastal changes in the Arctic, in Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences, vol. 388, pp. 103–129, Geological Society, London, UK. [online] Available from: http://sp.lyellcollection.org/content/388/1/103 (Accessed 8 February 2018), 2014.

Ping, C.-L., Michaelson, G. J., Guo, L., Jorgenson, M. T., Kanevskiy, Shur, Y., Dou, F. and Liang, J.: Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline, Journal of Geophysical Research: Biogeosciences, 116(G2), doi:10.1029/2010JG001588, 2011.

Pollard, W.: The Nature and Origin of Ground Ice in the Herschel Island Area, Yukon Territory., 1990.

Radosavljevic, B., Lantuit, H., Pollard, W., Overduin, P., Couture, N., Sachs, T., Helm, V. and Fritz, M.: Erosion and Flooding-Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada, Estuaries Coasts, 39(4), 900–915, doi:10.1007/s12237-015-0046-0, 2016.

Rampton, V. N.: Quaternary geology of the Yukon Coastal Plain, Bulletin, Geological Survey of Canada. [online] Available from: https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=111347, 1982.

Retamal, L., Bonilla, S. and Vincent, W. F.: Optical gradients and phytoplankton production in the Mackenzie River and the coastal Beaufort Sea, Polar Biol, 31(3), 363–379, doi:10.1007/s00300-007-0365-0, 2008.

Richter-Menge, J., Overland, J. E., Mathis, J. T. and Osborne, E.: Arctic Report Card 2017. [online] Available from: http://www.arctic.noaa.gov/Report-Card, 2017.

Río, L. D. and Gracia, F. J.: Error determination in the photogrammetric assessment of shoreline changes, Nat Hazards, 65(3), 2385–2397, doi:10.1007/s11069-012-0407-y, 2013.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520(7546), 171–179, doi:10.1038/nature14338, 2015.

Semiletov, I., Pipko, I., Gustafsson, Ö., Anderson, L. G., Sergienko, V., Pugach, S., Dudarev, O., Charkin, A., Gukov, A., Bröder, L., Andersson, A., Spivak, E. and Shakhova, N.: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon, Nature Geoscience, 9(5), 361–365, doi:10.1038/ngeo2695, 2016.

Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis, Global and Planetary Change, 77(1), 85–96, doi:10.1016/j.gloplacha.2011.03.004, 2011.

Solomon, S. M., Forbes, D. L. and Kierstead, B.: Coastal impacts of climate change : Beaufort Sea erosion study / S.M. Solomon, D.L. Forbes, and Brian Kierstead.: M183-2/2890E-PDF - Government of Canada Publications - Canada.ca, Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario. [online] Available from: http://publications.gc.ca/site/eng/9.820125/publication.html (Accessed 5 December 2018), 1993.

Sona, G., Pinto, L., Pagliari, D., Passoni, D. and Gini, R.: Experimental analysis of different software packages for orientation and digital surface modelling from UAV images, Earth Sci Inform, 7(2), 97–107, doi:10.1007/s12145-013-0142-2, 2014.

Stow, D. A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrich, F., Houston, S., Racine, C., Sturm, M., Tape, K., Hinzman, L., Yoshikawa, K., Tweedie, C., Noyle, B., Silapaswan, C., Douglas, D., Griffith, B., Jia, G., Epstein, H., Walker, D., Daeschner, S., Petersen, A., Zhou, L. and Myneni, R.: Remote sensing of vegetation and land-cover change in Arctic Tundra Ecosystems, Remote Sensing of Environment, 89(3), 281–308, doi:10.1016/j.rse.2003.10.018, 2004.

Stroeve, J. C., Markus, T., Miller, J. and Barrett, A.: Changes in Arctic melt season and implications for sea ice loss, Geophysical Research Letters, 41, 1216–1225, doi:https://doi.org/10.1002/2013GL058951, 2014.

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L. and Ergul, A.: The Digital Shoreline Analysis System (DSAS) Version 4.0 - An ArcGIS extension for calculating shoreline change (Ver.4.4, July 2017), USGS Numbered Series, U.S. Geological Survey, Reston. [online] Available from: http://pubs.er.usgs.gov/publication/ofr20081278 (Accessed 23 January 2018), 2009.

Turner, I. L., Harley, M. D. and Drummond, C. D.: UAVs for coastal surveying, Coastal Engineering, 114, 19–24, doi:10.1016/j.coastaleng.2016.03.011, 2016.

UNEP: Policy Implications of Warming Permafrost, UNEP. [online] Available from: https://epic.awi.de/33086/1/permafrost.pdf, 2012.

UNESCO: Ivvavik / Vuntut / Herschel Island (Qikiqtaruk), UNESCO World Heritage Centre. [online] Available from: http://whc.unesco.org/en/tentativelists/1939/ (Accessed 7 February 2018), 2004.

van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P. and Kabat, P.: Global river discharge and water temperature under climate change, Global Environmental Change, 23(2), 450–464, doi:10.1016/j.gloenvcha.2012.11.002, 2013.

Vonk, J. E., Sánchez-García, L., Dongen, B. E. van, Alling, V., Kosmach, D., Charkin, A., Semiletov, I. P., Dudarev, O. V., Shakhova, N., Roos, P., Eglinton, T. I., Andersson, A. and Gustafsson, Ö.: Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia, Nature, 489(7414), 137–140, doi:10.1038/nature11392, 2012.

Wegner, C., Bennett, K. E., Vernal, A. de, Forwick, M., Fritz, M., Heikkilä, M., Łącka, M., Lantuit, H., Laska, M., Moskalik, M., O'Regan, M., Pawłowska, J., Promińska, A., Rachold, V., Vonk, J. E. and Werner, K.: Variability in transport of terrigenous material on the shelves and the deep Arctic Ocean during the Holocene, Polar Research, 34(1), 24964, doi:10.3402/polar.v34.24964, 2015.

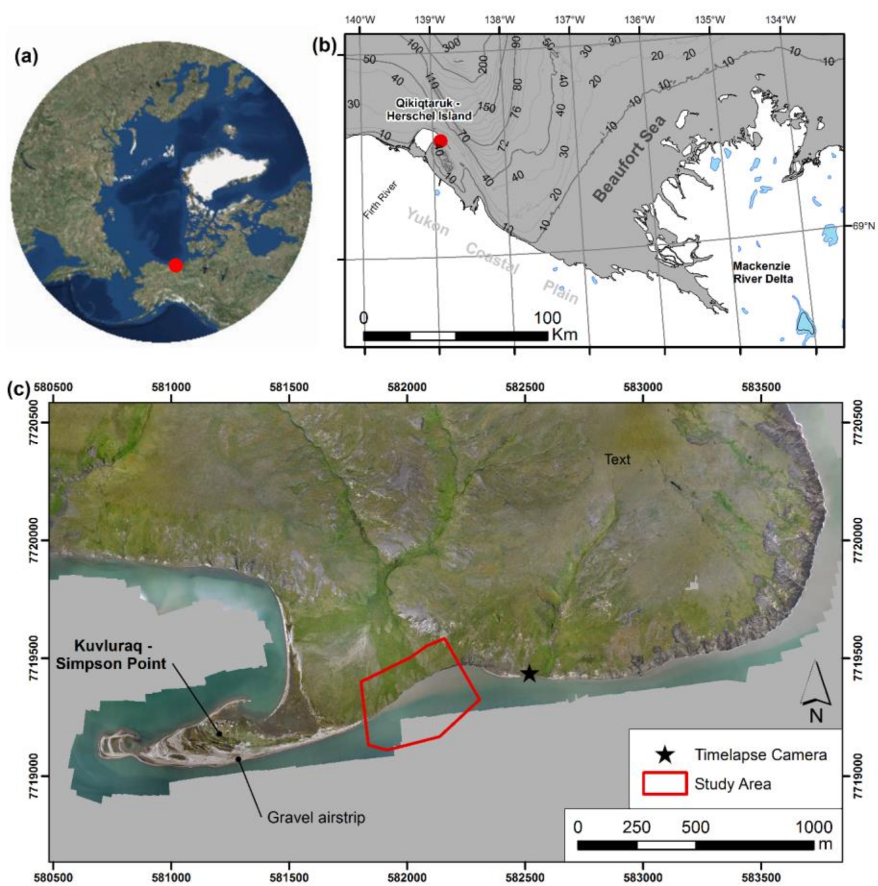
Wessel, P. and Smith, W. H. F.: Shorelines: Wessel, Pål, and Walter H. F. Smith. "A Global, Self-Consistent, Hierarchical, High-Resolution Shoreline Database." Journal of Geophysical Research: Solid Earth 101, no. B4 (1996): 8741–8743. https://doi.org/10.1029/96JB00104., Journal of Geophysical Research: Solid Earth, 101(B4), 8741–8743, doi:https://doi.org/10.1029/96JB00104, 1996.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. and Reynolds, J. M.: 'structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology, 179, 300–314, doi:10.1016/j.geomorph.2012.08.021, 2012.

Whalen, D.: Monitoring, understanding and predicting costal change in the Mackenzie-Beaufort Region, NT, Quebec City, Quebec, Canada., 2017.

~~Whalen, D., Fraser, R. and MacLeod, R.: The acceleration of change – how UAV technology is being used to better understand coastal permafrost landscapes in the Mackenzie-Beaufort Region, NT, ArcticNet. [online] Available from: http://www.arcticnet.ulaval.ca/pdf/media/IRIS-1-newsletter-Dec-2017.pdf, 2017.~~

~~Wobus, C., Anderson, R., Overeem, I., Matell, N., Clow, G. and Urban, F.: Thermal erosion of a permafrost coastline: improving process-based models using time-lapse photography, Arctic, Antarctic, and Alpine Research, 43(3), 474–484, doi:10.1657/1938-4246-43.3.474, 2011.~~



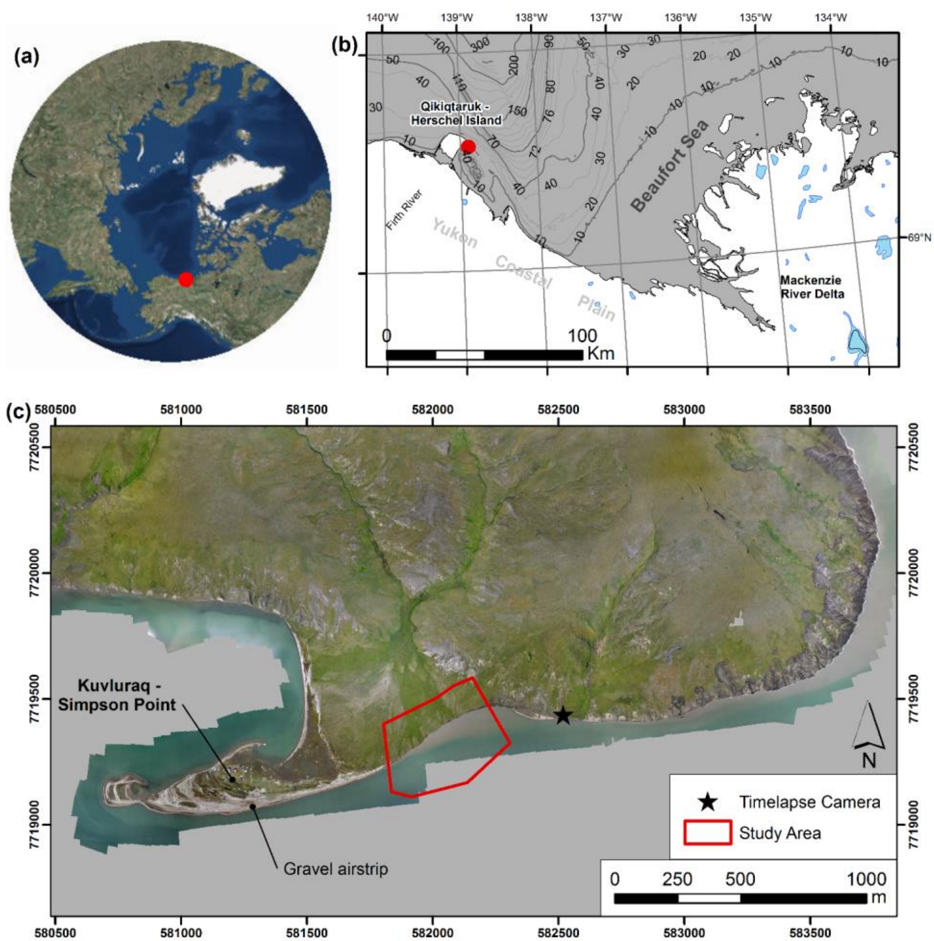



**Figure 1: (a) The location of the study region in the western Canadian Arctic (Basemap from (ESRI et al., 2018), polar stereographic projection), (b) Qikiqtaruk – Herschel Island in the Beaufort Sea (shorelines from (Wessel and Smith, 1996)), and (c) true-colour orthomosaic compiled from ca. 9000 individual images collected by drone survey in August 2017 indicating the location of the 500 m study stretch and the time-lapse camera including viewing direction indicated by the camera symbol used to make the supplementary video (S1) relative to Kuvluraq – Simpson Point.**

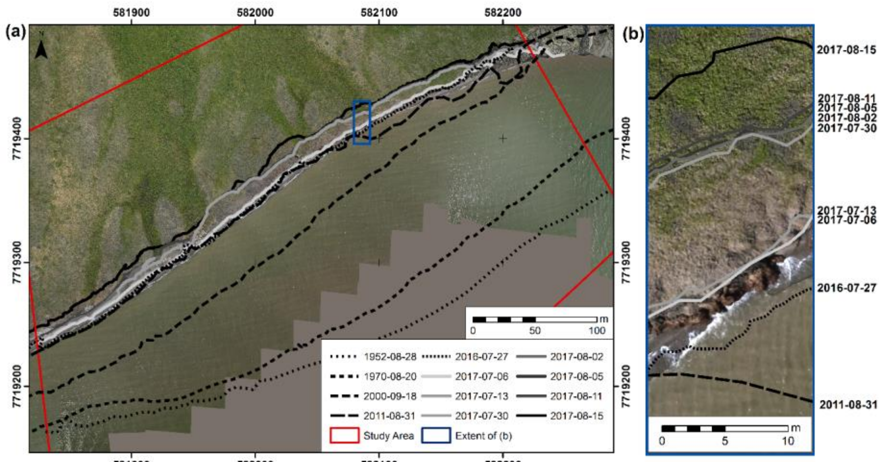



**Figure 2. (a) Overview of the 500 m study area, illustrating all twelve shoreline positions since 1952 overlaid on the 2017-07-06 orthomosaic. (b) Ten-fold magnification in scale, illustrating the episodic nature of the shoreline changes at this location.**

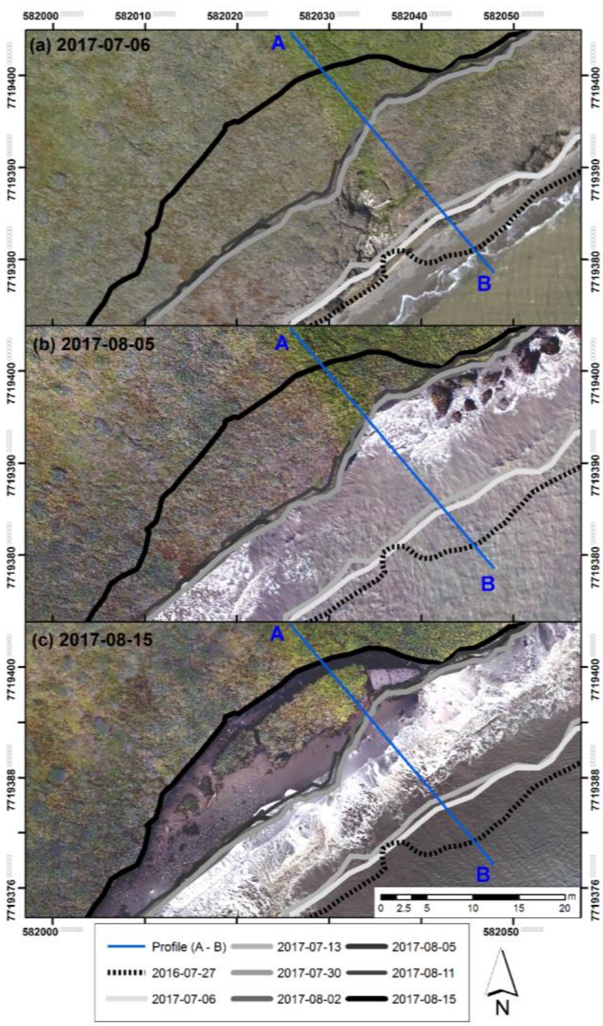
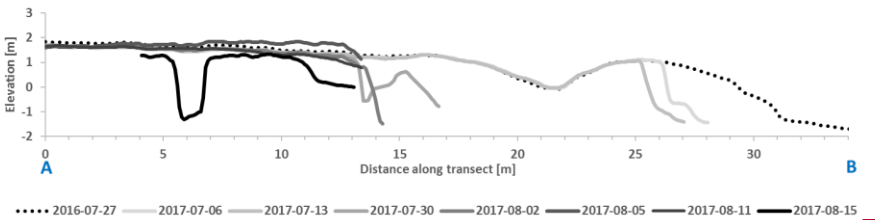



**Figure 3. Shoreline positions between 2016 and 2017 overlaid on three orthomosaics for part of the study reach. The blocks shown in (c) were detached from the bluff, with water moving freely behind during periods of higher water level (see figure S3). Profile A-B indicates the horizontal position of the cross-sectional profiles discussed in section 4.2 and depicted in Figure 4.**


Elevation [m]
Distance along transect [m]
A
B
2016-07-27
2017-07-06
2017-07-13
2017-07-30
2017-08-02
2017-08-05
2017-08-11
2017-08-15

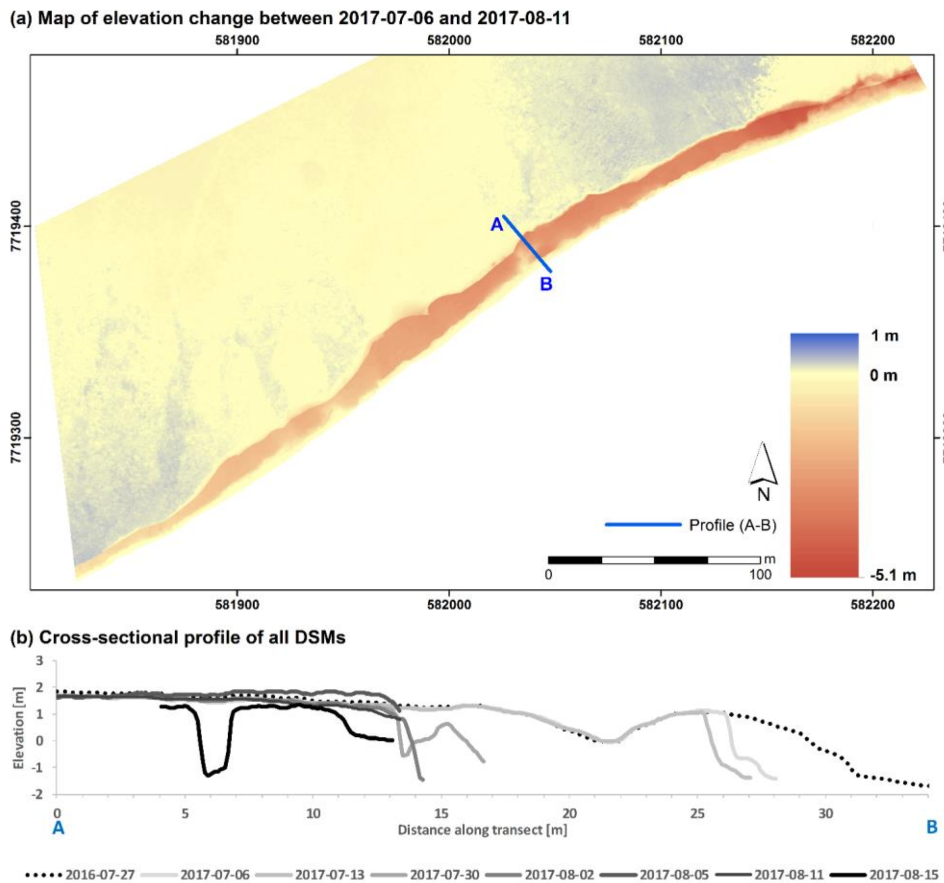



**Figure 4. (a) Map of elevation change in digital surface models between 2017-07-06 and 2017-08-11, illustrating areas of erosion along the coastline with up to -5.1 m change and also some minor (ca. 0.1 m) increases inland that we attribute to vegetation development. (b) Elevation profiles along the A-B transect shown in a and Figure 3, extracted from digital surface models ~~obtained by the structure-from-motion modelling of the drone-acquired images~~ (no vertical exaggeration). Note that two of the latter elevation models (from 2017-08-05 and 2017-08-15) both suffered from datum problems due to insufficient spatial constraint; see discussion for details.**

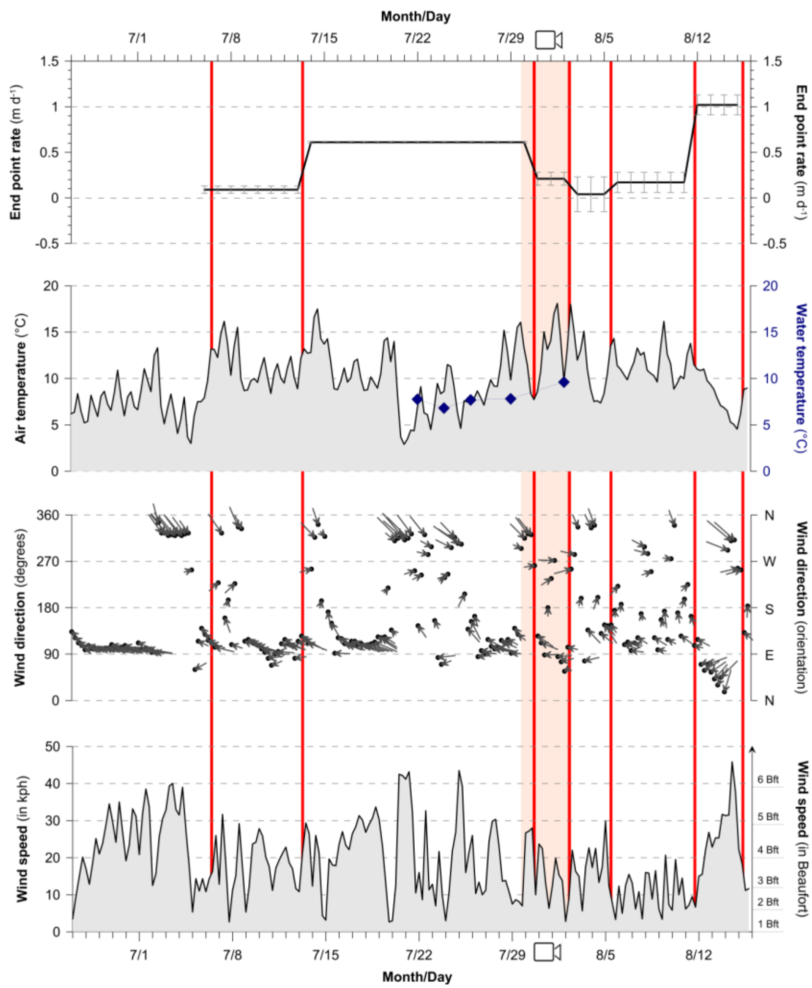



**Figure 5. Shoreline retreat (end point) rates normalised by day for each observation period in 2017, six-hour moving averages of air temperature, wind direction, and wind velocity in July-August 2017 (data from Environment Canada, 2017). Dates and times of aerial surveys are indicated by the red bars, point measurements of sea surface temperature from CTD casts are indicated by blue diamonds (see Figure S3 for full CTD profiles), and the duration of time-lapse survey shown in video S1 is indicated by the red shading.**

**Table 1. Dataset and shoreline position parameters. The approximate times of drone surveys are in local time (UTC -08:00). Total ~~S~~shoreline uncertainty~~ies~~ is ~~are~~ the root mean square error~~a combination~~ of (i) image co-registration (root mean square (RMS) error of ground control points (GCP~~s~~)), (ii) image quality (pixel error), and (ii) shoreline mapping (digitizing) error (from Equation 1).**

| Observation date | Image Type | Altitude [m] | Images [n] | Scale | GCP~~s~~ [n] | Georeferencing RMS Error [m] | | Pixel Error [m] | Digitising Error [m] | Total Shoreline Uncertainty [m] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Absolute (NAD83) | Relative | | | |
| 1952-08-28 | Panchromatic aerial photograph | | 1 | 1:70000 | 11 | - | 2.475 | 3.50 | 4.00 | 9.975 |
| 1970-08-20 | Panchromatic aerial photograph | | 1 | 1:12000 | 19 | - | 1.117 | 0.60 | 2.00 | 3.717 |
| 2000-09-18 | Panchromatic Ikonos photograph | | 1 | - | 19 | - | 5.087 | 1.00 | 2.00 | 8.137 |
| 2011-08-31 | Panchromatic GeoEye photograph | | 1 | - | 17 | - | 0.330 | 0.50 | 1.50 | 2.330 |
| 2016-07-27 | RGB orthomosaic (Drone – FX-61) | 120 | 317 | - | 26 | 0.015 | - | 0.03 | 0.15 | 0.195 |
| 2017-07-06 @ 12:20 | RGB orthomosaic (Drone – FX-61) | 120 | 1325 | - | 98 | 0.063 | Base Image | 0.02 | 0.10 | 0.183 |
| 2017-07-13 @ 08:30 | RGB orthomosaic (Drone – FX-61) | 120 | 194 | - | 13 | 0.043 | - | 0.02 | 0.10 | 0.163 |
| 2017-07-30 @ 18:00 | RGB orthomosaic (Drone – Phantom) | 31 | 383 | - | 5 | 0.037 | - | 0.02 | 0.10 | 0.157 |
| 2017-08-02 @ 08:00 | RGB orthomosaic (Drone – Phantom) | 100 | 2040 | - | 22 | 0.021 | - | 0.02 | 0.10 | 0.141 |
| 2017-08-05 @ 11:40 | RGB orthomosaic (Drone – Phantom) | 37 | 336 | - | 6 | 0.443 | - | 0.02 | 0.10 | 0.563 |
| 2017-08-11 @ 17:00 | RGB orthomosaic (Drone – FX-61) | 120 | 8994 | - | 132 | 0.167 | - | 0.04 | 0.15 | 0.307 |
| 2017-08-15 @ 10:20 | RGB orthomosaic (Drone – Phantom) | 42 | 402 | - | 3 | 0.178 | - | 0.02 | 0.10 | 0.298 |

Table 2. Summary of shoreline change for all periods, in terms of net shoreline change and end-point rates. Net shoreline change mean is the distance between the oldest and youngest shorelines, where SD is standard deviation. End-point rate is the net shoreline change normalised by time (years or days, for supra- or sub-annual periods, respectively), ~~where SD is standard deviation and~~ where DOA is Dilution of Accuracy (~~from~~ after Equation 2~~1~~).

| **Period** | **Days** | **Mean Net Shoreline Change ± SD (m)** | **Mean End Point Rate ± DOA ($m \cdot a^{-1}$)** | **($m \cdot d^{-1}$)** |
|---|---|---|---|---|
| Supra-annual periods | | | | |
| 1952-08-28 – 1970-08-20 | 6 567 | 20.7 ± 10.6 | 1.2 ± 0.6 | |
| 1970-08-20 – 2000-09-18 | 10 986 | 69.2 ± 21.9 | 2.3 ± 0.3 | |
| 2000-09-18 – 2011-08-31 | 3 986 | 33.0 ± 11.1 | 3.0 ± 0.8 | |
| 2011-08-31 – 2016-07-27 | 1 791 | 3.5 ± 4.6 | 0.7 ± 0.5 | |
| 2016-07-27 – 2017-07-06 | 344 | 2.9 ± 2.2 | 3.1 ± 0.3 | |
| 1952-08-28 – 2017-08-15 | 23 735 | 143.7 ± 28.4 | 2.2 ± 0.2 | <0.01 ± 0.00 |
| Sub-annual periods | | | | |
| 2017-07-06 – 2017-07-13 | 7 | 0.5 ± 0.5 | | 0.09 ± 0.04 |
| 2017-07-13 – 2017-07-30 | 17 | 7.4 ± 5.6 | | 0.61 ± 0.01 |
| 2017-07-30 – 2017-08-02 | 3 | 0.6 ± 1.1 | | 0.21 ± 0.07 |
| 2017-08-02 – 2017-08-05 | 3 | 0.1 ± 0.4 | | 0.04 ± 0.19 |
| 2017-08-05 – 2017-08-11 | 6 | 1.0 ± 0.4 | | 0.17 ± 0.11 |
| 2017-08-11 – 2017-08-15 | 4 | 4.1 ± 1.1 | | 1.02 ± 0.11 |
| 2017-07-06 – 2017-08-15 | 40 | 14.5 ± 3.2 | | 0.36 ± 0.01 |