Answer to the interactive comment on "Contribution of Coastal Retrogressive Thaw Slumps to the Nearshore Organic Carbon budget along the Yukon Coast" ***by*** **Justine L. Ramage et al.**

We thank the two reviewers and the editor for the thorough revision of our manuscript and their constructive comments that helped to improve the paper. Our replies to the comments are written in green. Line numbers given in our replies refer to the revised version of the manuscript.

Anonymous Referee #1

This paper entitled, "Contribution of coastal retrogressive thaw slumps to the nearshore organic carbon budget along the Yukon Coast," by Ramage and others uses repeat analysis of satellite and LiDAR imagery to assess the number, area, and volume of retrogressive thaw slumps. They found that the number of slumps increased from 1952-2011, but the area affected by slumps changed little. Slumps displaced a large volume of soil and dissolved organic carbon. This study produces an data set that is very relevant to an important source of uncertainty in understanding how permafrost landscapes and the organic matter they contain are responding to climate change: thermo-erosion. This process has proven difficult to model and the geophysical and ecological consequences of thermos-erosion on landscape and regional scales remain uncertain.

I have a few questions and comments about the methodology, but my main concern is that the current paper quickly gets into the details of these sites and then remains largely descriptive and stops short of positioning these findings in a broader ecological/landscape perspective. If revised with a broader focus, I think this paper would be a valuable contribution to this journal and the larger discourse on the effects of thermo-erosion features on permafrost landscape evolution during climate change. I outline my main questions and concerns below, followed by line edits:

1. This study presents valuable data that are difficult to acquire about the extent and volume of sediment affected by thermo-erosion on decadal timescales. However, I felt it did not fully exploit these data, remaining largely observational and not providing a clear discussion of how these data relate to larger questions about ecosystem carbon balance, links between geomorphology and climate, and permafrost ecology. Given the spatial and temporal richness of this data set, in addition to describing the changes in thermo-erosion area and volume, are there underlying mechanisms the authors could explore? For example, do differences in precipitation, aspect, or other parameters affect rate of thermo-erosion? How representative is this area compared to other Arctic coasts? How different were changes in air temperature for the two periods and is this associated with changes in thermo-erosion? How much of the slowdown in feature formation is due to depletion of ground ice versus external forcing?

We agree, there is a need for a better understanding of the role of these processes on the development of retrogressive thaw slumps along the Yukon Coast (RTSs). However, this goes beyond the scope of our manuscript and requires a publication on its own.

However, we updated the manuscript to draw the attention on these issues in the section 5.1 of the revised manuscript. Based on the climate records provided by Environment Canada, we looked at the change in the mean air temperature and average precipitations for the periods 1957-1971 and 1971-2000. Based on these data we could show that:

Page 14, line 27: "*Climate data recorded at Komakuk Beach (segment 2) and Shingle Point (segment 36) show that the average summer air temperature decreased between the periods 1957-1971 (Komakuk, 7.4°C; Shingle Point, 10.8°C) and 1971-2000 (Komakuk, 4.9°C; Shingle Point, 7.4°C). However, the annual average precipitation increased at both stations by 30% and 41%, respectively during the same periods (Environment Canada, http://climate.weather.gc.ca/historical_data/search_historic_data_e.html). Similar patterns were observed for the summer months (July to September). As suggested by Kokelj et al. (2015) in other Arctic areas, higher rainfall might intensify RTS activity. However, a series of environmental factors seems to be jointly responsible for the intensification of RTS activity along the Yukon Coast (Ramage et al., 2017).*"

2. At the end of the study, I was left wondering what the conclusions were in relation to the core questions/purposes of the study (how is thermo-erosion changing through time). Clearer statement of the purpose of the study would help this, as currently the results quickly get into comparisons within the dataset (e.g. % of sediment reworked done by an individual feature), leaving me confused as to whether thermo-erosion is expanding in this area and if formation is accelerating. The issue of units (addressed below) compounded this confusion.

We modified the conclusion to remove any confusion and to make our statement clear: RTSs have a non-negligible impact on the nearshore zone.

Page 17, line 17: "*The number of RTSs along the Yukon Coast increased by 73% between 1952 and 2011 and the total areal coverage of RTSs increased by 14%. We observed disparities between geomorphic units: the largest increase was on ice-thrust moraines, where the number of RTSs increased at an annual rate of 1.2 RTSs/yr. Many RTSs are polycyclic and reactivated between 1972 and 2011. RTSs reworked at least 16.6*106 m3 of material within a 190-km portion of the coastal fringe. Majority of the material came from erosion of the headwall (53%) and 3% remained in the RTS floors. A large amount of the material from RTSs was eroded and transported alongshore due to coastal retreat (45%). The OC flux from 17% of the RTSs identified in 2011 was 1.3*103 kg/km/yr and represented 0.6% of the annual OC fluxes from coastal retreat in the study area. Not all the OC mobilized by RTSs is immediately* *transported to the nearshore zone; an important part is mobilized in the RTS floors. Therefore RTSs alter the OC budget of the nearshore zone by affecting the OC release process. Our results show that the contribution of RTSs to the nearshore OC budget is non-negligible and should be included when estimating the quantity of OC released from the Arctic coast to the ocean."*

3. I found the units of sediment and carbon counterintuitive and difficult to compare with other studies. Results are presented in absolute terms (total amount of carbon or sediment displaced from the whole study region) and it would be useful to state units normalized to area. Expressing material balance in terms of m2 would immediately let researchers unfamiliar with this area relate to the units and assess how important this process is. That would allow comparison of thermokarst mobilization of SOC and DOC to carbon release via active layer deepening. In this same vein, the number of features, which is focused on in the abstract and throughout the paper, seems immaterial com- pared to changes in area and volume. Ultimately, I had a hard time concluding at the end of the paper if thermo-erosion was increasing, decreasing, or remaining stable.

To make our statement more clear, we modified the units of material eroded and OC mobilized. For RTSs, we provide the stock estimates /per km of coast or /per RTS. For the RTSs that initiated after 1972 we provided estimates /per km of coast/yr or /per RTS/yr.

The reason why we initially showed the evolution of the number of features in Table 1 was because the increase in the number of RTSs explains the increase in coverage. RTSs increased in number but did not become larger.

However, to give a better overview to the reader and highlight our results better, we followed your advice and created a figure (Fig.3), combining the former Table 1 and 2.

4. It is unclear how/if uncertainties were propagated through this exercise. Absolute numbers are given, rather than ranges or estimates of center and standard deviation (e.g. all the tables and figures). Without measures of uncertainty, it is difficult to assess the reliability of these estimates or identify sources of that uncertainty in the analysis.

Uncertainties are indeed an important part to estimate. To improve our manuscript we added some description of the values we used from previous publications.

Page 7, line 3: "*To differentiate between the volumes of ice and sediments eroded, we used the volumetric ice content provided for each coastal segment in Couture and Pollard (2017). The model interpolates the data collected on 19 coastal segments to the whole Yukon Coast based on similarities between surficial geology and permafrost conditions. Ice contents were determined from shallow cores collected from upper soil layers and from bluff exposures."*

Page 7, line 19: "*The OC values were derived from in-situ measurements collected at 31 locations and were interpolated to each coastal segment following the same approach as for the determination of ground ice (Couture, 2010). The SOC was measured for different soil unit layers along the bluffs and averaged for the upper first meter and lower meter of the soil columns (Couture, 2010). It therefore takes into account the heterogeneity of SOC contents at depth. DOC values account for the differences in DOC concentrations between wedge ice, massive ice and non-massive ice (Tanski et al., 2016), based on the ice volumes summarized in Couture and Pollard (2017). The OC values are therefore coarse but consistent for the whole Yukon Coast. The dataset is provided in supplementary material (S1_TableS1).*"

We also provided the range or standard deviations for the mean values of our results. We also show the variation in the dataset in the Figures 6 and 7.

5. There are multiple issues with visualizations particularly the stacked bar plots using a logarithmic y-axis and the reliance on tables. Stacked bar plots on a logarithmic scale are visually misleading since the ice volume, which represents the majority of material lost, appears negligible. Additionally, could the x-axis of these plots be organized by some salient ecological parameter (e.g. precipitation, climate, surficial geology) instead of by geographic position? This would help provide insight into processes driving these patterns. The use of tables is fine in some cases, but I wanted a figure showing rate of thermo-erosion (normalized by area) for the two time periods (1952-1972, 1972-2011), which seems like one of the key punchlines of this paper. The tabular form makes it harder to rapidly compare changes and trends and ultimately is not more compact than a (non-logarithmic) stacked barplot of those time periods.

   We removed the former Tables 1 and 2 and replaced them by a Figure (Fig. 5), summarizing both tables and showing the changes in number and coverage of RTS per geologic unit and years.
   We modified the Figures 6 and 7: we removed the logarithmic scale and created boxplots to give better estimates of the volumes of material eroded per RTS for each coastal segment. We added the geologic unit that underlies each segment in the x-axis.

6. To cryosphere scientists, the subject of this paper is immediately of interest, but I fear that the abstract and introduction do not provide enough context for a non-specialist to see the need and implications of the study. Defining key terms (e.g. active layer) and providing more context for why this process is of general interest would increase the impact of this paper.

   We provide more information as well as defined terms such as active layer and retrogressive thaw slumps in the introduction.

7. The paper builds on many previous studies, but sometimes relies too heavily on explanations given in those studies. Especially on key issues like determining pre- formation ice content, DOC, and SOC, enough methodological detail should be given for the reader to assess the approach. At the bare

minimum, given that many of these estimates are highly uncertain (e.g. reconstructions of ice content), an explicit treatment of uncertainties and how uncertainties were propagated is necessary.

As mentioned above, we added these details in the Methods section:

Page 7, line 3: "*To differentiate between the volumes of ice and sediments eroded, we used the volumetric ice content provided for each coastal segment in Couture and Pollard (2017). The model interpolates the data collected on 19 coastal segments to the whole Yukon Coast based on similarities between surficial geology and permafrost conditions. Ice contents were determined from shallow cores collected from upper soil layers and from bluff exposures.*"

Page 7, line 19: "*The OC values were derived from in-situ measurements collected at 31 locations and were interpolated to each coastal segment following the same approach as for the determination of ground ice (Couture, 2010). The SOC was measured for different soil unit layers along the bluffs and averaged for the upper first meter and lower meter of the soil columns (Couture, 2010). It therefore takes into account the heterogeneity of SOC contents at depth. DOC values account for the differences in DOC concentrations between wedge ice, massive ice and non-massive ice (Tanski et al., 2016), based on the ice volumes summarized in Couture and Pollard (2017). The OC values are therefore coarse but consistent for the whole Yukon Coast. The dataset is provided in supplementary material (S1_TableS1).*"

Line edits:

Page 1

Line 10: An additional line introducing the general context would evaluable.

We added this sentence:

" Retrogressive thaw slumps (RTSs) are among the most active thermokarst landforms in the Arctic and deliver a large amount of material to the Arctic Ocean. However, their contribution to the organic carbon (OC) budget is unknown."

Line 17-18: Standard SI format for number should be used (i.e. 8.6 x 10ˆ6 not 8600x10ˆ3). There are issues with this throughout the manuscript.

Modified throughout the manuscript.

Line 18: 53% of which was ice

Modified accordingly.

Line 21: 0.3% of the total OC flux for the Arctic Ocean? Unclear why this is of interest at this point in the paper. What percentage of the SOC stocks in the affected areas of the study region was mobilized by these features?

We adjusted this number to take into account the changes that we applied to our dataset and clarify this sentence as:

*“Between 1972 and 2011, 17% of the RTSs displaced 8.6*10^3 m^3/yr of material, adding 0.6% to the OC flux released by coastal retreat along the Yukon Coast.”*

Line 25:I believe this estimate is for the entire permafrost zone, not just the Arctic

Modified accordingly:

Page 1, line 26:" *Soil organic carbon (SOC) stocks in the top three meters of soils, in deltas and the Yedoma regions across the northern circumpolar permafrost region are estimated to 1307 Pg; 76.4% (999 Pg) of them are stored in perennially frozen soils (Hugelius et al., 2014).*

Line 27:Is it meant that air temperature has increased by approximately 3-4 degrees C? Air temperature in Celsius is expressed on a relative scale and it does not make senseto say increased by a factor of 3-4 (unless referring to change relative to absolute zero)

To take into account a new publication on Arctic warming, we replaced this sentence with:

Page 1, line 29:*"Surface air temperature in the Arctic increased by 0.755°C per decade during 1998–2012 (Huang et al., 2017).”*

Line 31: Non-standard terminology for thermo-erosion features. Following Kokelj,Jorgenson, Fortier etc., thermo-erosion or thermal erosion are the blanket terms that include thermokarst (permafrost collapse) and other erosive processes associated with permafrost degradation.

We modified the sentence.

Page 2, line 10: *“Thermokarst and thermo-erosional processes occur by the thawing of ice-rich permafrost and the melting of massive ice.”*

Page 2

Line 5: Consider including more recent modeling studies such as Koven et al.2015, Kessler 2017, or Sudakov and Vakulenko

Thank you for this suggestion.

Koven et al. (2015) published estimations of permafrost thaw feedback based on the distribution of carbon in the soils. Kessler (2017) measured the economic coast of the permafrost carbon feedback. Sudakov and Vakulenko (2014), developed a mathematical model to constrain the permafrost carbon feedback using methane emission data.

In this part of the introduction we mention the impact of carbon stocks on the global greenhouse gas emission. We therefore added the references to the 2 first publications in our introduction.

Page 1, line 34: *"Permafrost carbon stocks were only recently included in calibrating global carbon models, highlighting a relevant contribution of thawing permafrost to the overall climate and economic response to human greenhouse gas emissions (Kessler, 2017; Koven et al., 2015; MacDougall et al., 2012; Burke et al., 2012; von Deimling et al., 2012)."*

Line 9: Consider citing Abbott et al. 2016 or McGuire et al. 2016, which summarize current modeling uncertainties stemming from exclusion of these parameters. Both of these studies directly support the need for the current study by emphasizing the importance of constraining thermo-erosion.

We added a sentence in the text to take into account the conclusions of both studies:

Page 2, line 7: *"Both expert assessments (Abbott et al. 2016) and model evaluations (McGuire et al., 2016) identified permafrost degradation as one of the most important sources of uncertainty in predicting the timing and magnitude of the permafrost carbon feedback."*

Line 25: Word choice (potentially control or influence rather than forcing)

Modified accordingly: "control".

Figure 1: Really nice figure. Potentially put the specific reach names in the SI (not of interest to most readers)

Modified accordingly.

Page 6

Line 9: "In order to" can always be replaced by "To"

Modified accordingly in the whole manuscript.

Line 8: How was uncertainty for the compound assumptions in these analyses dealt with? Need more detail generally.

To clarify this point, we described the data we used from other publication with more details:

Page 7, line 3: "*To differentiate between the volumes of ice and sediments eroded, we used the volumetric ice content provided for each coastal segment in Couture and Pollard (2017). The model interpolates the data collected on 19 coastal segments to the whole Yukon Coast based on similarities between surficial geology and permafrost conditions. Ice contents were determined from shallow cores collected from upper soil layers and from bluff exposures.*"

Page 7, line 19: "*The OC values were derived from in-situ measurements collected at 31 locations and were interpolated to each coastal segment following the same approach as for the determination of ground ice (Couture, 2010). The SOC was measured for different soil unit layers along the bluffs and averaged for the upper first meter and lower meter of the soil columns (Couture, 2010). It therefore takes into account the heterogeneity of SOC contents at depth. DOC values account for the differences in DOC concentrations between wedge ice, massive ice and non-massive ice (Tanski et al., 2016), based on the ice volumes summarized in Couture and Pollard (2017). The OC values are therefore coarse but consistent for the whole Yukon Coast. The dataset is provided in supplementary material (S1_TableS1).*"

Line 12: Why were these processes not included? How does that affect the estimates?

In the first manuscript we decided to leave aside these two processes because we did not have accurate erosion rates for the area. Meanwhile, a new study from our colleagues was accepted for publication in JGR:Earth Surface (Irrgang et al., 2017, in review). We therefore modified our dataset to take into account:

1. the 5.5% of material that subside in the slump floors (Obu et al., 2016)
2. the area of the slump that is being washed away by coastal retreat yearly. For this we used coastal rates of change from the study from Irrgang et al., 2017

We added the previously Figure 6 in the method section as Figure 4 and clarified out methodology:

"3.2.3 Volume of eroded material

To calculate the volume of eroded material from the headwall of the RTS identified in 2011, we subtracted the mean surface elevation values obtained from the LiDAR dataset from the mean interpolated surface elevation values (Fig. 3). However, these volumes do not account for the material eroded from the RTS headwalls that settles within the RTS floors and for the material eroded and transported alongshore by coastal retreat (Fig. 4). Due to ground ice melting, ca. 5.5% of the reworked sediments subside and remain compacted in the RTS floor (Obu et al., 2016). We therefore adjusted the material volumes based on this value (Fig.4, c). Additionally, we measured the volumes of material eroded and transported by coastal retreat using the rate of coastal change between 1952 and 2011 from Irrgang et al. (2017). Using this rate, we calculated the volumes of eroded material between 1952 and 2011 for each RTS. For the RTSs that initiated after 1972, calculated the volumes of eroded material between 1972 and 2011 (Fig. 4, d).

To differentiate between the volumes of ice and sediments eroded, we used the volumetric ice content provided for each coastal segment in Couture and Pollard (2017). The model interpolates the data collected on 19 coastal segments to the whole Yukon Coast based on similarities between surficial geology and permafrost conditions. Ice contents were determined from shallow cores collected from upper soil layers and from bluff exposures.

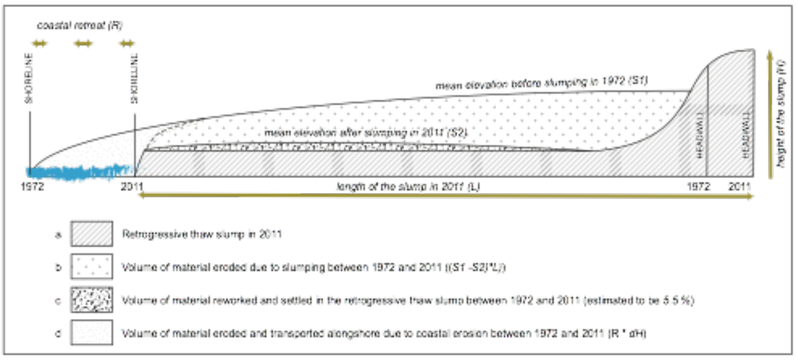


Figure 4: Cross-section of a retrogressive thaw slump (RTS) illustrating the calculated and omitted volumes of sediments eroded through slumping between 1972 and 2011. The calculation estimates the amount of material released to the nearshore zone through slumping (b) and takes into account the material eroded from the RTS headwalls that remains within the RTS floors where it settles (c), and (d) the material eroded and transported alongshore by coastal erosion. The volumes of material that remains within the RTS floors were estimated from Obu et al. (2016)."

Page 7

Line 6-26: With the presented information, it is not clear if these estimates were downscaled from measurements of fluxes at feature outlets or if they are inferred from the mass of SOC there previously multiplied by volume displaced. If the latter, how are vertical differences in SOC accounted for this this framework?

We clarified our methodology at the beginning of the section 3.3:

Page 7, line 17: "*We inferred mobilized SOC and DOC stocks and fluxes from RTSs from the mass of SOC and DOC per meter column in each coastal segment provided in Couture (2010) and Tanski et al. (2016) in relation to the estimated volume of material displaced by each RTS. The OC values were derived from in-situ measurements collected at 31 locations and were interpolated to each coastal segment following the same approach as for the determination of ground ice (Couture, 2010). The SOC was measured for different soil unit* *layers along the bluffs and averaged for the upper first meter and lower meter of the soil columns (Couture, 2010). It therefore takes into account the heterogeneity of SOC contents at depth. DOC values account for the differences in DOC concentrations between wedge ice, massive ice and non-massive ice (Tanski et al., 2016), based on the ice volumes summarized in Couture and Pollard (2017). The OC values are therefore coarse but consistent for the whole Yukon Coast. The dataset is provided in supplementary material (S1_TableS1).*

Page 8

Line 3: Focusing on the number of features doesn't seem terribly relevant to the question of the permafrost climate feedback. The area and volume results are more informative. In general, a few clear figures would more effectively communicate the observed patterns.

It is certain that the change analysis in area and volume of RTSs is more relevant to the question of the permafrost climate feedback. However, we show that the increase in RTS coverage (14%), is mostly driven by an increase in the number of RTSs more than y a growth in the size of the RTSs. This is the reason why we decided to emphasize that there is an increase in single RTS features along the coast, which causes an increase in the total coverage of RTSs.

We removed the Tables 1 and 2 and added a figure (Fig. 5) to better visualize both increases through time: in number and total coverage of RTSs.

Table 1: This would be more compelling in figure form. If table is retained, no need to use cryptic acronyms in the first column (i.e. L, Mm, Mr). There is enough room to spell out the parameters

This information is now displayed in the Figure 5.

Page 9

Table 2 would also be more effective in figure format. As currently presented, it is hard to tease apart what is changing across the time series.

This information is now displayed in the Figure 5.

Page 10

Table 3: This should be normalized to area covered by the geologic units. Are some of the units displacing more material per unit area or are the differences due to different relative coverage? No estimates of uncertainty are given.

We normalized the values according to the coastal length of the geologic units in the study area. We chose to normalize the values by the coastal length in km because we only mapped coastal RTSs. We now show volumes in m^3 / km. See Table 3 and 4.

Figures 4 and 5. Problematic to show a stacked bar plot with a logarithmic axis.

We modified the Figures 4 and 5 to take into account this comment. We removed the logarithmic axis and showed boxplots providing information on the material released for each coastal segment.

Page 14

Line 18: Good example of why estimates should be normalized by area (i.e. expressed on a kg m2 yr basis or in mm/yr for sediment)

Following this comment, we decided to present the results as m^3/yr, m^3/ RTS and m^3/km of coast in the whole manuscript. We could not calculate fluxes for the 162 RTSs as we do not know when they initiated.

Line 27: Still not clear how this affects the analysis. If the question is about total sediment and carbon balance, these processes, which are caused or at least facilitated by thermo-erosion seem pertinent

As explained above, we took into account these processes and therefore modified the section 5.2 of the manuscript.

"5.2 Eroded material from RTSs and OC fluxes

*The expansion of RTSs along the coast causes the displacement of large volumes of material from the land to the sea. We show that 56% of the RTSs identified in 2011 (162 RTSs) have reworked at least 16.6*106 m3 of material along the Yukon Coast, which is 102.5*103 m3/RTS of material eroded per RTS. Among these RTSs, 49 RTSs initiated after 1972 and reworked 27.2*103 m3/yr of material, which is 0.6*103 m3/RTS/yr . These estimates are low compared to material removal from other RTSs in the Arctic. Lantuit and Pollard (2005) calculated a sediment volume loss of 105*103 m3 between 1970 and 2004 for a single RTS located on Herschel Island; Kokelj et al. (2015) and Jensen et al. (2014) measured material displacements up to 106 m3 per RTS located in NW Canada and Alaska; the Batagay mega-slump located in Siberia eroded more than 24*106 m3 of ice rich permafrost in 2014 (Günther et al., 2015). The size of the observed RTSs is one reason behind such differences: most of the RTSs examined in the above studies are classified as mega slumps (> 0.5 ha). The RTS studied in Lantuit and Pollard (2005) was the largest RTS identified along the entire Yukon Coast in 2011, 24 ha. However most of RTSs along the Yukon coast are small, with an average size of 0.2 ha (Ramage et al., 2017). This has implication for studies that attempt to model the impact of RTSs on the eroded material budgets in the Arctic.*

*Couture (2010) estimated the annual flux of mineral sediment eroded by coastal retreat along the Yukon Coast to 7.3*106 kg/km/yr. We show that along a 190-km portion of the Yukon Coast, 17% of the RTSs identified along the coast in 2011 (49 RTSs) contributed to 1% of the annual flux of material eroded along the Yukon Coast (61*103 kg/km/yr). These RTSs initiated after 1972 incised 1% (2 km) of the coastline in 2011 and were on* *average smaller than the average RTSs. Increasing the number and areal coverage of coastal RTSs has therefore large consequences on the flux of eroded material along the Arctic coasts.*

*We estimated the annual OC fluxes (SOC and DOC) from these 49 RTSs to 1.3*103 kg/km/yr, including 0.02 kg/km/yr DOC. The average OC flux from coastal retreat along the entire Yukon Coast is 157*103 kg/km/yr (Couture, 2010) with an average DOC flux of 0.2*103 kg/km/yr (Tanski et al., 2016). We show that the annual OC flux released by the 49 RTSs initiated after 1972 was 0.6% the annual OC flux from coastal retreat. Most of these fluxes originated from ice thrust moraines, where the number of RTS initiated after 1972 was the highest. RTSs develop mainly on ice-thrust moraines because of the presence of large volumes of massive ground ice (Ramage et al., 2017). As a result, only half of the material eroding from the RTS headwall is sediment and most of the OC is released as DOC."*

Page 16

Line 20: I think the authors are referring to Abbott and Jones 2015

Modified accordingly.

Anonymous Referee #2

The submitted paper 'Contribution of Coastal Retrogressive Thaw Slumps to the Nearshore Organic Carbon Budget along the Yukon Coast' by Ramage et al. gives an indication of the specific impacts of slumps on the sediment budget and on the carbon budgets of Arctic tundra coasts in northern Canada. The focus is on three main topics as stated at the end of the introduction: 1) definition, quantification and temporal analysis of RTSs; 2) estimation of sediment/ice and OC budgets related to these slumps; and 3) measure the OC fluxes between 1972 and 2011. Looking to these aims of the study, I have some specific comments related to these different goals and will come with suggestions to restructure some parts of the paper to make it more focused on the RTSs. The data presented is very valuable and the paper will after restructuring be a valuable contribution to better understand Arctic coastal environments and its changes.

Ad 1) The coastal stretch in NW Canada is probably very representative for a large part of the Arctic coastal environments. The different geomorphological units (or geological units as stated in Figure 1) cover a wide range of environments and the coastal stretch with its units can probably be used to upscale the findings. You can state explicitly that you use the findings along this stretch to upscale in the future.
We are not sure we understand correctly this comment.
Ground ice and OC data from Couture (2010), Couture and Pollard (2017) and Tanski et al. (2016) were upscaled from single field sites to the entire coastal segments. These data were further interpolated to costal segments showing similar permafrost conditions.
We added more details in the methods sections 5.2 and 5.3.

We did not upscale our data in the future. The number of RTS and their size were mapped based on 3 type of imagery from 1952, 1972 and 2011.
Volumes of material and OC stocks were estimated for a subset of the number of RTSs identified in 2011. OC fluxes were calculated for RTSs that initiated after 1972.

Upscaling our results to the future would require a more complex approach, including changes in temperature, precipitations and sea ice properties, which are major controls for RTSs development.

Use Figures 2 and 6 to define what RTSs are.
We added a definition of RTSs in the introduction and described them further in the methods section.
Page 2, line 12: *"Retrogressive thaw slumps (RTSs), a type of slope failure caused by permafrost thaw, (...)"*

Tables 1 and 2 give an indication of the amount and sizes of RTSs for different units. It would be good to start the explanation of the spatial pattern, followed by the development in time. Now, it starts with changes in time, without having an idea how many and how large the RTSs are in the different units.

We described the current (2011) distribution of RTSs in a paper published in 2017: Ramage, J.L., Irrgang A.M, Herzschuh U., Morgenstern A., Couture N., Lantuit H.: Terrain Controls on the Occurrence of Coastal Retrogressive Thaw Slumps along the Yukon Coast, Canada. *Journal of Geophysical Research: Earth Surface,* 2017.

We replaced the tables 1 and 2 by a Figure (Fig.5), combining the information provided in both Tables.

Another thing is the use of the terms active or stable RTS. What kind of conditions do you use to call a RTS active or stable? Is it related to fresh scarps, vegetation coverage?

To clarify this information to the reader, we added this information in the section 3.1:

Page 4, line 7: *"Active RTSs are characterized by steep headwalls exposing ice-rich permafrost, slump floors with thawed sediments, and incised gullies. Stable RTSs comprise gently sloping and vegetated headwalls, vegetated slump floors, and no visible active gully systems (Ramage et al., 2017; Lantuit and Pollard, 2008; Wolfe et al., 2001)."*

Ad 2) Estimation of the sediment/ice erosion due to RTS and OC budgets is quite straightforward and the best you can do with the limited Lidar data. Figure 6 in your discussion is very nice and can be used to explain your estimation of budgets in an earlier phase.

Thank you for the suggestion. We move the Figure 6 to the method section and renamed it as Figure 4 and clarified the methodology:

"3.2.3 Volume of eroded material

To calculate the volume of eroded material from the headwall of the RTS identified in 2011, we subtracted the mean surface elevation values obtained from the LiDAR dataset from the mean interpolated surface elevation values (Fig. 3). However, these volumes do not account for the material eroded from the RTS headwalls that settles within the RTS floors and for the material eroded and transported alongshore by coastal retreat (Fig. 4). Due to ground ice melting, ca. 5.5% of the reworked sediments subside and remain compacted in the RTS floor (Obu et al., 2016). We therefore adjusted the material volumes based on this value (Fig.4, c). Additionally, we measured the volumes of material eroded and transported by coastal retreat using the rate of coastal change between 1952 and 2011 from Irrgang et al. (2017). Using this rate, we calculated the volumes of eroded material *between 1952 and 2011 for each RTS. For the RTSs that initiated after 1972, calculated the volumes of eroded material between 1972 and 2011 (Fig. 4, d).*

To differentiate between the volumes of ice and sediments eroded, we used the volumetric ice content provided for each coastal segment in Couture and Pollard (2017). The model interpolates the data collected on 19 coastal segments to the whole Yukon Coast based on similarities between surficial geology and permafrost conditions. Ice contents were determined from shallow cores collected from upper soil layers and from bluff exposures.

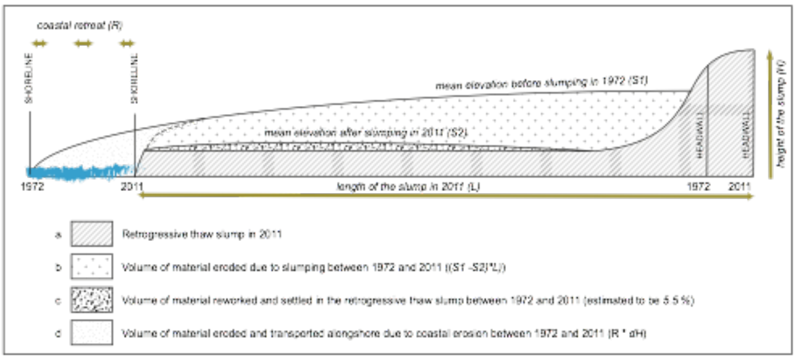


Figure 4: Cross-section of a retrogressive thaw slump (RTS) illustrating the calculated and omitted volumes of sediments eroded through slumping between 1972 and 2011. The calculation estimates the amount of material released to the nearshore zone through slumping (b) and takes into account the material eroded from the RTS headwalls that remains within the RTS floors where it settles (c), and (d) the material eroded and transported alongshore by coastal erosion. The volumes of material that remains within the RTS floors were estimated from Obu et al. (2016)."

The presentation in Figures 4 and 5 is often a bit confusing. You followed a spatial axis on the x-axis, but you don't use this in the rest of the discussion. It would probably more interesting to group it according to the geomorphologic/geologic unit and discuss this variation in time. You also gave this unit related results in tables 3,4 and 5. The volumes of eroded materials will be better visible if you don't use a cumulative sediment and ice volume on a logarithmic Yaxis, but come with values for sediment and ice (different symbols).

We modified the Figures 6 and 7. We removed the logarithmic axis and plotted the material released per RTS for each coastal segment. We did not group the values by geologic unit because we present those results in the tables 1 and 2.

Ad 3) I wonder why you made a separate aim only following OC budgets in time. I think it is more logical to describe the estimation of budget terms under 2) and thereafter discuss all terms (sediment / ice / OC) in more detail in time.

In the section 4.2, we use 2 different dataset:

1. 162 RTSs that were identified on the 2011 imagery. We don't know when those RTSs were initiated
2. 49 RTSs that were identified on the 2011 imagery but not on the 1972 imagery. We named those RTSs "RTSs initiated after 1972". For these we were able to calculate fluxes.

We initially described the volumes of eroded material for both of these dataset and then described the different parts (sediment / ice / OC), as you suggested. However, we found difficult for the reader to distinguish between the 2 datasets and decided to talk first about the volumes of material and related stocks of sediment, ice and OC and then to focus more on the fluxes using the dataset 2.

Discussion and conclusions

The discussion of the paper is now in 4 subsections (erroneous numbered 5.1, 5.2, 5.3 and 5.3). Following the three aims and the structure of the results, it is perhaps very attractive to start a discussion about the 'static' description of RTSs (sizes, amounts, coupling to geo units) and about the uncertainties in determining the RTSs using the data set. This can be followed by a second section about the changes in slump activity (your acceleration of slump activity). Then we have two sections related to the second aim: your sections about Eroded material from RTSs and Calculated OC fluxes. Finally, you can place it in a broader prespective as you tried to do in 5.4. This can also include some remarks about upscaling to Arctic shorelines.

Thank you for these suggestions. We modified the discussion following the points 2,3 and 4. The "static" description of RTSs for 2011 was already done in Ramage et al. (2017). We added a sentence at the beginning of the section 5.1 to mention the results of this previous study.

We kept the first section of the discussion 5.1 on the evolution of RTSs along the coast. We then merged the previous sections 5.2 and 5.3 into a section 5.2 on the Eroded material from RTSs and calculated OC fluxes and kept section 5.4 renamed as 5.3.

The conclusions are to the point.

Title The title is not covering the work done. You have showed many more results on the losses of ice and sediments and its changes in time as well. Impact not only OC budgets.

Following your suggestion, we modified the title of the manuscript: "Increasing coastal slump activity impacts the release of sediment and organic carbon into the Arctic Ocean"

Line edits:

Page 2

line 9: Hugelius et al., 2014 is not in the reference list.

Thank you for noticing. We added the citation in the reference list.

Page 5

line 20: n=125 refers to?

The n = 125 refers to the number of RTSs discarded. We modified the sentence to

"We discarded the 125 RTSs outside of the LiDAR scan from the volume and flux analyses."

Page 6

Figure 3: Are all splines in the RTSs giving a sloping surface from N to S?

Not all splines give a looping surface from N to S in the study area. The orientation of the splines depends on the orientation and the topography of the coast surrounding the RTSs on which RTSs occur. On the Figure 3, all RTSs are facing south because the example is taken from a south facing and sloping coastline. We decided to modify Figure 3 in order to clarify this point.

line 12: Can you estimate the coastal retreat impact (or assume ..%)?

In the first manuscript we decided to leave aside these two processes because we did not have accurate erosion rates for the area. Meanwhile, a new study from our colleagues was accepted for publication in JGR:Earth Surface (Irrgang et al., 2017, in review). We therefore modified our dataset to take into account:

1. the 5.5% of material that subside in the slump floors (Obu et al., 2016)
2. the area of the slump that is being washed away by coastal retreat yearly. For this we used coastal rates of change from the study from Irrgang et al., 2017

We added the previously Figure 6 in the method section as Figure 4 and clarified out methodology (section 5.2.2 and 5.2.3).

Page 11

Figure 4: Only Mr?

Thank you for pointing out the mistake. Following the recommendations of the other reviewer, we modified the figure.

Page 13

line 21: Wolfe and Dallimore or Wolfe et al. (see reference list)

We modified the reference as Wolfe et al., 2001.

Page 16

line 13: Should be section 5.4.

Changed accordingly.

Increasing coastal slump activity impacts the release of sediment and organic carbon into the Arctic Ocean

Justine L. Ramage[1,2], Anna M. Irrgang[1,2], Anne Morgenstern[1], Hugues Lantuit[1,2]

[1]Department of Periglacial Research, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany

[2]University of Potsdam, Institute of Earth and Environmental Science, Potsdam, Germany

Correspondence to: Justine L. Ramage (justine.ramage@awi.de)

Abstract. Retrogressive thaw slumps (RTSs) are among the most active thermokarst landforms in the Arctic and deliver large amounts of material to the Arctic Ocean. However, their contribution to the organic carbon (OC) budget is unknown. We provide the first estimate of the contribution of RTSs to the nearshore OC budget of the Yukon Coast, Canada, and describe the evolution of coastal RTSs between 1952 and 2011 in this area. We 1) describe the evolution of RTSs during 1952-1972 and 1972-2011; 2) calculate the volume of eroded material and stocks of OC mobilized through slumping, including soil organic carbon (SOC) and dissolved organic carbon (DOC); 3) estimate the OC fluxes mobilized through slumping between 1972 and 2011. We identified RTSs using high-resolution satellite imagery from 2011 and geocoded aerial photographs from 1952 and 1972. To estimate the volume of eroded material, we applied spline interpolation on an airborne LiDAR dataset acquired in July 2013. We inferred the stocks of mobilized SOC and DOC from existing related literature. Our results show a 73% increase in the number and 14% areal expansion of RTSs between 1952 and 2011. In the study area, RTSs displaced at least 16.6*10^6 m^3 of material, 53% of which was ice, and mobilized 145.9*10^6 kg of OC. Between 1972 and 2011, 49 RTSs displaced 8.6*10^3 m^3/yr of material, adding 0.6% to the OC flux released by coastal retreat along the Yukon Coast. Our results show that the contribution of RTSs to the nearshore OC budget is non-negligible and should be included when estimating the quantity of OC released from the Arctic coast to the ocean.

1 Introduction

Soil organic carbon (SOC) stocks in the top three meters of soils, in deltas and the Yedoma regions across the northern circumpolar permafrost region are estimated to 1307 Pg; 76.4% (999 Pg) of them are stored in perennially frozen soils (Hugelius et al., 2014). These stocks resulted from slow decomposition of soil organic matter in permanently frozen soils, caused by low soil temperatures and impeded drainage. Surface air temperature in the Arctic increased by 0.755°C per decade during 1998–2012 (Huang et al., 2017). As the active layer, the upper part of the permafrost that thaws during summer and refreezes in winter, thickens due to warmer air, increased microbial activity in the soil mobilizes more organic carbon (OC) that is eventually released to the atmosphere (Mackelprang et al., 2011; Schuur et al., 2008). Organic carbon and nutrients are also released to streams, rivers and to the Arctic Ocean by thermokarst and thermo-erosional processes (Schuur et al., 2015; Abbott et al., 2015; Vonk et al., 2012; Ping et al., 2011; Lamoureux and Lafrenière, 2009). Permafrost carbon stocks were only recently included in calibrating global carbon models, highlighting a relevant contribution of

Justine Ramage 22/12/2017 10:38
Deleted: Contribution of Coastal Retrogressive Thaw Slumps to the Nearshore Organic Carbon budget along the Yukon Coast

Justine Ramage 8/1/2018 11:27
Deleted: retrogressive thaw slumps (RTSs) ... [1]

Justine Ramage 1/2/2018 10:14
Deleted: Soil organic carbon (SOC) stocks in the Arctic are estimated to 1307 Pg; 76.4% (999 Pg) of them are stored in permafrost terrains (Hugelius et al., 2014). …hese stocks resulted from slow ... [2]

thawing permafrost to the overall climate and economic response to human greenhouse gas emissions (Kessler, 2017; Koven et al., 2015; MacDougall et al., 2012; Burke et al., 2012; von Deimling et al., 2012). Schaefer et al. (2014) predicted 120 ± 85 Gt carbon emissions from thawing permafrost by 2100, which represents 5.7 ± 4.0% of the total anthropogenic emissions. Nevertheless, these carbon models underestimate the potential impact of the permafrost feedback on the global climate because they do not account for the spatial heterogeneity of permafrost terrains and omit the contribution of coastal erosion and abrupt thaw processes, such as thermokarst and thermo-erosion (Hugelius et al., 2014; MacDougall et al., 2012; Vonk et al., 2012). Both expert assessments (Abbott et al. 2016) and model evaluations (McGuire et al., 2016) identified permafrost degradation as one of the most important sources of uncertainty in predicting the timing and magnitude of the permafrost carbon feedback.

Thermokarst and thermo-erosional processes occur by the thawing of ice-rich permafrost and the melting of massive ice. Thermokarst landscapes cover up to 20% of the northern circumpolar permafrost region and store half of the SOC from this region (Olefeld et al., 2016). Retrogressive thaw slumps (RTSs), a type of slope failure caused by permafrost thaw, are among the most active thermokarst landforms in the Arctic and have increased both in number and size over the past decades (Ramage et al., 2017; Segal et al., 2016; Brooker et al., 2014; Lacelle et al., 2010). RTSs rework sediments and mobilize carbon, nitrogen, and nutrients; as a result, RTSs affect terrestrial (Cassidy and Henry, 2016; Tanski et al., 2016; Cray and Pollard 2015; Cannone et al., 2010) and aquatic ecosystems (Malone et al., 2013; Kokelj et al., 2013, 2009a). Along the coast of the Arctic, RTSs directly contribute to the transport of terrestrial OC to the nearshore zone (Obu et al., 2016), which has the potential to affect the nearshore marine ecosystem (Fritz et al., 2017). However, there are currently no estimates on the volume of sediments and thus on the OC displaced by RTSs from the land to the nearshore zone in the Arctic. To provide better estimates of the contribution of abrupt thaw processes on the OC budget along the Arctic coasts, our study quantifies the impact of thermokarst disturbances on the OC budget in a coastal permafrost environments along the Yukon Coast, Canada. We 1) describe the evolution of RTSs in the area between 1952 and 2011; 2) calculate the volume of material eroded and stocks of organic carbon (OC) mobilized through slumping – including soil organic carbon (SOC) and dissolved organic carbon (DOC) – and 3) estimate the OC fluxes mobilized through slumping between 1972 and 2011.

2 Study area

The study area is located in the Canadian Arctic, along the westernmost coast of the Yukon Territory (Fig. 1). The study area comprises a 238-km portion of the Yukon Coastal Plain, including Herschel Island (Fig. 1). The area is in the continuous permafrost zone (Rampton, 1982) and tundra vegetation zone dominated by mosses, graminoids, and shrubs (CAVM Team, 2003). The area is characterized by a subarctic climate with mean summer air temperature of 6°C on the East end and 8.7°C on the West end; the mean summer precipitations (June, July and August, 1971-2000) are 79.8 mm on the East end, and 112.9 mm on the West end (Environment Canada, 2017). The Mackenzie River influences seawater temperature and sea ice

Justine Ramage 22/12/2017 10:27
Deleted: ; Koven et al., 2011; Schaefer et al., 2011

Justine Ramage 22/12/2017 10:29
Deleted: global

Justine Ramage 22/12/2017 09:22
Deleted: either

Justine Ramage 22/12/2017 09:23
Deleted: or

Justine Ramage 22/12/2017 09:23
Deleted: for

Justine Ramage 22/12/2017 10:31
Deleted: (such as thermokarst), post-fire dynamics, or coastal erosion

Justine Ramage 22/12/2017 09:24
Deleted: This gap can be addressed by quantifying the impact of the above processes on the carbon budget (Kuhry et al., 2010).

Justine Ramage 18/12/2017 15:21
Deleted: Mass wasting processes along the Arctic coast, such as coastal retrogressive thaw slumps (RTSs), contribute to the transport of terrestrial OC to the nearshore zone (Obu et al., 2016).

Justine Ramage 22/12/2017 08:55
Deleted: RTSs

Justine Ramage 22/12/2017 09:06
Deleted:

Justine Ramage 22/12/2017 09:13
Deleted: Active RTS headwalls retreat faster than the coast, displace a large volume of sediments, and considerably impact the surrounding ecosystems ().

Justine Ramage 22/12/2017 09:29
Deleted: TS

Justine Ramage 22/12/2017 09:29
Deleted: s a

Justine Ramage 2/1/2018 18:23
Deleted: analyse

Justine Ramage 1/2/2018 10:15
Deleted: measure

Justine Ramage 1/2/2018 10:15
Deleted:

extent and is the main control on the local precipitation patterns (Burn and Zhang, 2009). The western margin of the Laurentide ice sheet, which reached its maximum ice extent around Herschel Island at ca. 16 200 years BP (Fritz et al., 2012), shaped the topography of the Yukon Coastal Plain. Long and high moraine ridges characterize most of the previously glaciated area. Herschel Island is a moraine thrust at the margin of the formerly glaciated area, and is one of the largest moraine deposits in the region (Mackay, 1959). Stream valleys, fluvial deltas, alluvial fans, and thermokarst basins characterize the unglaciated area. Due to widespread moraine deposits, 35% of the Yukon Coast is composed of ice-rich cliffs (Harper, 1990). Volumetric ground ice contents (massive ice, pore ice and wedge ice) vary along the coast and range from 0% to 74% (Couture and Pollard, 2017). Previous studies divided the study area into 36 coastal segments (Fig. 1), based on ground ice contents, surficial geology and geomorphology (Lantuit et al., 2012b; Couture, 2010; Lantuit and Pollard, 2005). Most segments fall into three surficial geologic units: ice-thrust moraines (30%); lacustrine plains (23%) and rolling moraines (16%). Alluvial fans, stream terraces, floodplains, and outwash plains underlay the remaining segments (Rampton, 1982). The coast is rapidly retreating (Harper, 1990): during the period 1951-2011, the average rate of coastal change was –0.7 m/yr and was characterized by decreasing erosion rates from West to East (Irrgang et al., 2017). RTSs are common along the coast and mostly develop on segments with massive ground ice thicker than 1.5 m and coastal slope greater than 3.9° (Ramage et al., 2017).

Justine Ramage 18/12/2017 15:26
Deleted: forcing

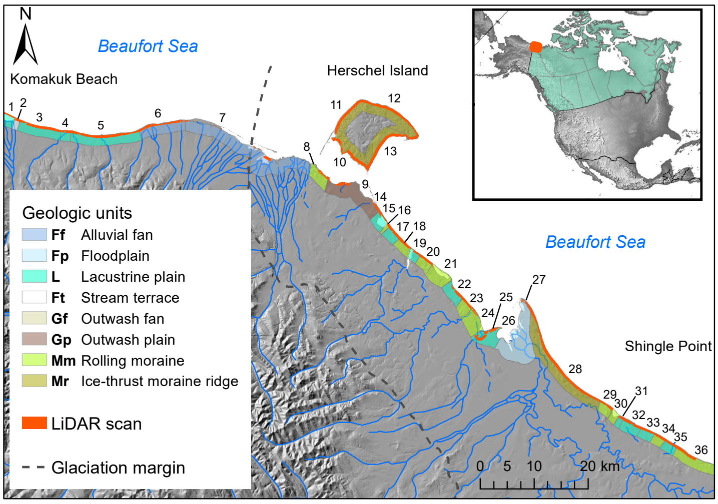


Figure 1: Study area. The coastal subset defined as the LiDAR scan is represented in red. The limit of the glaciation was reproduced after Dyke and Prest (1987) and the surficial sediments after Rampton (1982). The numbers stand for the coastal

segments stretching along the coast from west to east (the names of the coastal segments are available as Supplementary Information).

3 Methods

3.1 Evolution of RTSs

We used two data inputs to measure the evolution of RTSs between 1952 and 2011: a dataset with RTSs present in 1972 and 2011 (dataset A) and a dataset with RTSs present in 1952 (dataset B). All RTSs were mapped using ArcMap 10.3 (ESRI) on a scale of 1:2000 and classified as active or stable. Active RTSs are characterized by steep headwalls exposing ice-rich permafrost, slump floors with thawed sediments, and incised gullies. Stable RTSs comprise gently sloping and vegetated headwalls, vegetated slump floors, and no visible active gully systems (Ramage et al., 2017; Lantuit and Pollard, 2008; Wolfe et al., 2001).

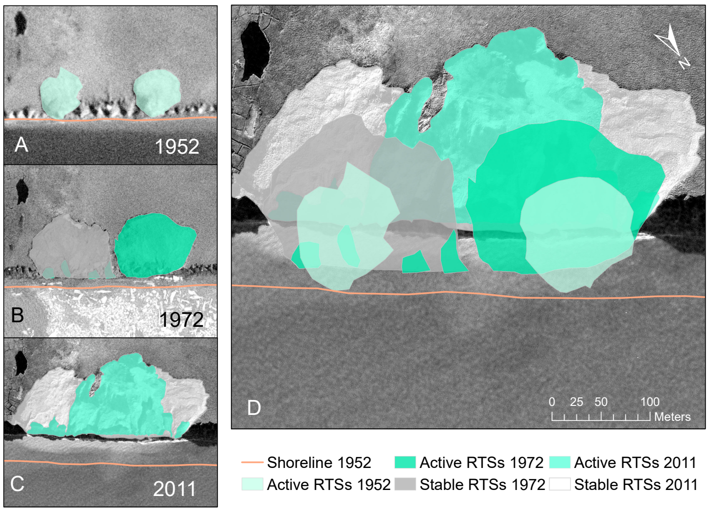


Figure 2: Geomorphological map of retrogressive thaw slumps (RTSs) illustrating the complexity of RTS evolution along the Yukon Coast. D) RTSs identified in 1952 (A) and in 1972 (B) are overlapping the 2011 RTSs (C). The underlying imagery is a GeoEye-1 satellite image from 2011 (July 18th). RTSs areas from 1952 and 1972 closer to the shore eroded due to coastal retreat. The remaining parts had either extended and merged with other RTSs or stabilized in 2011. A) Two active RTSs in 1952 (aerial photo from 1952, National Air Photo Library, Canada). B) RTSs in 1972 (aerial photo from 1972,

Justine Ramage 2/1/2018 15:24
Deleted: :

Justine Ramage 2/1/2018 15:26
Deleted: 1) Clarence Lagoon West; 2) Clarence Lagoon East; 3) Komakuk Beach West 2; 4) Komakuk Beach West 1; 5) Komakuk Beach; 6) Malcom River Fan; 7) Malcom River Fan with barrier Islands; 8) Workboat Passage West; 9) Workboat Passage East; 10) Herschel Island South; 11) Herschel Island West; 12) Herschel Island North; 13) Herschel Island East; 14) Whale Cove West; 15) Whale Cove; 16) Whale Cove East; 17) Roland Bay northwest; 18) Roland Bay West; 19) Roland Bay East; 20) Stokes Point West; 21) Stokes Point; 22) Stokes Point Southeast; 23) Phillips Bay northwest; 24) Phillips Bay West; 25) Phillips Bay; 26) Babbage River Delta; 27) Kay Point Spit; 28) Kay Point South East; 29) King Point Northwest; 30) King Point Lagoon; 31) King Point; 32) King Point Southeast; 33) Sabine Point West; 34) Sabine Point; 35) Sabine Point East; 36) Shingle Point West.

Justine Ramage 2/1/2018 15:26
Deleted: .

National Air Photo Library, Canada). RTSs expanded and one had stabilized. New active RTSs developed within the stabilized RTS. C) RTSs in 2011 (GeoEye-1, July 18th 2011). Former RTSs had partly stabilized and newer RTSs developed within the boundaries of the stabilized RTSs.

Ramage et al. (2016) provided dataset A. RTSs present in 2011 were mapped based on multispectral GeoEye-1 and WorldView-2 satellite images acquired in July, August and September 2011. RTSs present in 1972 were mapped using a series of geocoded aerial photographs from the 1970s obtained from the National Air Photo Library in Canada (Irrgang et al., 2017). The mapping methodology is explained in detail in Ramage et al. (2017).

Dataset B comprises RTSs present in 1952 that we mapped using a series of geocoded aerial photographs from 1952, obtained from the National Air Photo Library in Canada (Irrgang et al., 2017).

We compared the number and size of RTSs present in 1952, in 1972, and in 2011. RTSs are polycyclic and can occur on surfaces previously affected by RTSs. As a result, several active RTSs can be located within the boundary of a stable RTS (Fig. 2). In this case, stable polycyclic RTSs include the areal surfaces of active RTSs located within their boundaries.

3.2 Volume estimations

3.2.1 LiDAR dataset

For each RTS identified in 2011 we extracted morphological information – size and mean surface elevation – from an airborne LiDAR dataset acquired in July 2013 (Kohnert et al., 2014). The LiDAR dataset has a scan width of 500 m; the LiDAR point data was interpolated with inverse distance weighting to obtain digital elevation models with a horizontal resolution of 1 m (Obu et al., 2016). The LiDAR dataset has a final georeferenced point cloud data vertical accuracy of 0.15 ± 0.1 m and covers 80% of the coastline in our study area.

We selected a subset of the 2011 RTSs dataset comprising RTSs that occurred within the boundary of the LiDAR dataset to measure the volume of eroded material from RTSs, (Fig. 1). We discarded the 125 RTSs outside of the LiDAR scan from the volume and flux analyses.

Additional to the RTSs present in 2011 within the LiDAR area, we defined a subgroup with RTSs present in 2011 on surfaces not affected by slumping before 1972; we defined this subgroup as *RTSs initiated after 1972*.

3.2.2 Interpolation method

We applied a regularized spline interpolation technique to model pre-slump topographies used for calculating the volume of material eroded through slumping. The spline method allows to estimate elevation points outside the range of input sample points and to minimize the total curvature of the surface. We therefore selected spline among other interpolation methods.

Justine Ramage 1/2/2018 10:17

Deleted: Geomorphological map of retrogressive thaw slumps (RTSs) illustrating the complexity of RTS evolution along the Yukon Coast. The underlying imagery is a GeoEye-1 satellite image from 2011 (July 18th). RTSs areas from 1952 and 1972 closer to the shore eroded due to coastal retreat. The remaining parts had either extended and merged with other RTSs or stabilized in 2011. A) Two active RTSs in 1952 (aerial photo from 1952, National Air Photo Library, Canada). B) RTSs in 1972 (aerial photo from 1972, National Air Photo Library, Canada). RTSs expanded and one had stabilized. New active RTSs developed within the stabilized RTS. C) RTSs in 2011 (GeoEye-1, July 18th 2011). Former RTSs had partly stabilized and newer RTSs developed within the boundaries of the stabilized RTSs. D) RTSs present in 1952, in 1972 are overlapping the 2011 RTSs.

Justine Ramage 22/12/2017 10:05

Deleted: in order

Justine Ramage 18/12/2017 15:51

Deleted: all

Justine Ramage 18/12/2017 15:51

Deleted: (n = 125)

We based our interpolation on the extensive point elevation data available for the study area from the LiDAR dataset (Fig. 3).

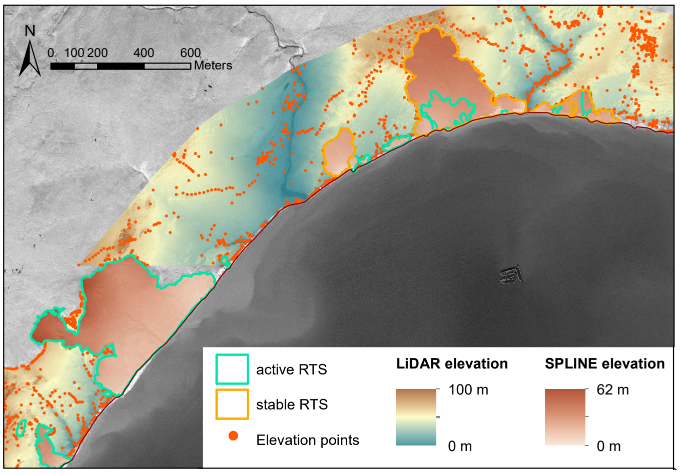


Figure 3: Map illustrating the different datasets used to model pre-slump topographies. Retrogressive thaw slumps (RTSs) are outlined in green for the active RTSs and orange for the stable RTSs. The background satellite imagery is a GeoEye-1 image taken on July 18th 2011. The background elevation and the random elevation points outside the RTS areas are derived from the LiDAR dataset. Elevation surface within the RTS borders represent the elevation before RTS occurred and is interpolated using a Spline.

3.2.3 Volume of eroded material

To calculate the volume of eroded material from the retrograding headwall of the RTS identified in 2011, we subtracted the mean surface elevation values obtained from the LiDAR dataset from the mean interpolated surface elevation values (Fig. 3). However, these volumes do not account for the material eroded from the RTS headwalls that settles within the RTS floors and for the material eroded and transported alongshore by coastal retreat (Fig. 4). Due to ground ice melting, ca. 5.5% of the reworked sediments subside and remain compacted in the RTS floor, i.e. do not get transported out of the RTS (Obu et al., 2016). We therefore adjusted the material volumes to take into account the 5.5% of the material that subside in the RTS floors (Fig.4, c). Additionally, we measured the volumes of material eroded and transported by coastal retreat using the rate of coastal change between 1952 and 2011 from Irrgang et al. (2017). Using this rate, we calculated the volumes of eroded

Justine Ramage 22/12/2017 09:36
Deleted: In order t

Justine Ramage 22/12/2017 14:57
Deleted: a

Justine Ramage 22/12/2017 14:57
Deleted: part

material between 1952 and 2011 for each RTS. For the RTSs that initiated after 1972, we calculated the volumes of eroded material between 1972 and 2011 (Fig. 4, d).

To differentiate between the volumes of ice and sediments eroded, we used the volumetric ice content provided for each coastal segment in Couture and Pollard (2017). The model interpolates the data collected on 19 coastal segments to the whole Yukon Coast based on similarities between surficial geology and permafrost conditions. Ice contents were determined from shallow cores collected from upper soil layers and from bluff exposures.

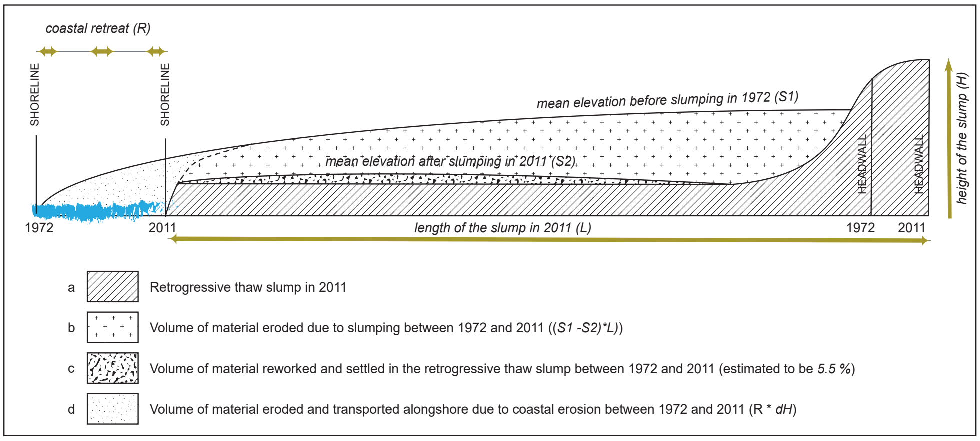


Figure 4: Cross-section of a retrogressive thaw slump (RTS) illustrating the calculated and omitted volumes of sediments eroded through slumping between 1972 and 2011. The calculation estimates the amount of material released to the nearshore zone through slumping (b) and takes into account the material eroded from the RTS headwalls that remains within the RTS floors where it settles (c), and (d) the material eroded and transported alongshore by coastal erosion. The volumes of material that remains within the RTS floors were estimated from Obu et al. (2016).

3.3 Estimates of soil and dissolved organic carbon values

We inferred mobilized SOC and DOC stocks and fluxes from RTSs from the mass of SOC and DOC per meter column in each coastal segment provided in Couture (2010) and Tanski et al. (2016) in relation to the estimated volume of material displaced by each RTS. The OC values were derived from in-situ measurements collected at 31 locations and were interpolated to each coastal segment following the same approach as for the determination of ground ice. The SOC was

Justine Ramage 4/1/2018 18:17
Deleted: Moreover, coastal retreat erodes the base of RTSs. We did not account for these processes in our analyses. our estimates do not include all of the material eroded by the RTSs; they only represent the amount of material released to the nearshore zone through slumping. We did not include the material eroded from the RTS headwalls that settles within the RTS floors and the material eroded and transported alongshore by coastal erosion (Fig. 6).

Justine Ramage 4/1/2018 13:55
Deleted: ... [3]

Justine Ramage 22/12/2017 13:37
Deleted: estimated

Justine Ramage 22/12/2017 13:38
Deleted: based on the values

Justine Ramage 1/2/2018 10:18
Deleted: in-situ measurements

Justine Ramage 22/12/2017 13:47
Deleted: (Tanski et al., 2016; Couture, 2010)

Justine Ramage 10/1/2018 14:59
Deleted: available

Justine Ramage 10/1/2018 14:59
Deleted: for

Justine Ramage 10/1/2018 15:00
Deleted: .

measured for different soil unit layers along the bluffs and averaged for the upper first meter and lower meter of the soil columns (Couture, 2010). It does not take into account the heterogeneity of SOC contents at depth. DOC values account for the differences in DOC concentrations between wedge ice, massive ice and non-massive ice (Tanski et al., 2016), based on the ice volumes summarized in Couture and Pollard (2017). The OC values are therefore coarse but consistent for the whole Yukon Coast. The dataset is provided in supplementary material (S1_TableS1).

3.3.1 SOC and DOC stocks

We used Equation (1) to calculate the stocks of SOC eroded from RTSs:

(1) $\mathrm{RTS_{SSOC}} = \sum_{i=1,\, j=1}^{n,\, m} (\mathrm{M}_{\mathrm{CT}j} * \mathrm{A}_i) + \left(\mathrm{M}_{\mathrm{CB}j} * (\mathrm{VS}_i - \mathrm{A}_i)\right),$

where $\mathrm{RTS_{SSOC}}$ is the stock of SOC eroded from RTSs (expressed in kg); $\mathrm{M}_{\mathrm{CT}j}$ is the mass of SOC in the upper 1 m (expressed in kg) per coastal segment *j* out of *m* total; A_i is the total surface area of an RTS *i* out of *n* total (expressed in m^2); $\mathrm{M}_{\mathrm{CB}j}$ is the mass of SOC in the lower soil column (expressed in kg), per coastal segment *j*; and VS_i is the volume of sediment eroded by per RTS (expressed in m^3). $\mathrm{M}_{\mathrm{CT}j}$ and $\mathrm{M}_{\mathrm{CB}j}$ take into account differences in dry bulk density per coastal segment *j* (Couture, 2010). We used Equation (2) to calculate the stocks of DOC eroded from RTSs:

(2) $\mathrm{RTS_{SDOC}} = \sum_{i=1,j=1}^{n,m} \mathrm{D}_j * \mathrm{VI}_i,$

where $\mathrm{RTS_{SDOC}}$ is the total stock of DOC eroded from RTSs (expressed in kg); D_j is the stock of DOC per coastal segment *j* (expressed in kg/m^3); and VI_i is the volume of ice eroded from a RTS (expressed in m^3). D_j is given per coastal segment *j* (Tanski et al., 2016).

3.3.2 SOC and DOC fluxes

We calculated the flux of material – including ice and sediments – as well as SOC and DOC fluxes for the RTSs initiated after 1972. To calculate the SOC flux we used Equation (3):

(3) $\mathrm{RTS_{FSOC}} = \mathrm{RTS_{SSOC}} / 39,$

where $\mathrm{RTS_{FSOC}}$ is the annual flux of SOC mobilized from RTSs (expressed in kg/yr); $\mathrm{RTS_{SSOC}}$ is the quantity of SOC eroded from an RTS (expressed in kg) (Eq. 1); 39 is the number of years during the time period 1972-2011. Similarly, we used Equation (4) to calculate the DOC flux:

(4) $\mathrm{RTS_{FDOC}} = \mathrm{RTS_{SDOC}} / 39,$

where $\mathrm{RTS_{FDOC}}$ is the annual flux of DOC eroded from RTSs (expressed in kg/yr); $\mathrm{RTS_{SDOC}}$ is the quantity of DOC eroded from an RTS (expressed in kg) (Eq. 2); 39 is the number of years during the time period 1972-2011.

Justine Ramage 22/12/2017 13:52
Deleted: estimate

Justine Ramage 22/12/2017 13:52
Deleted: estimate

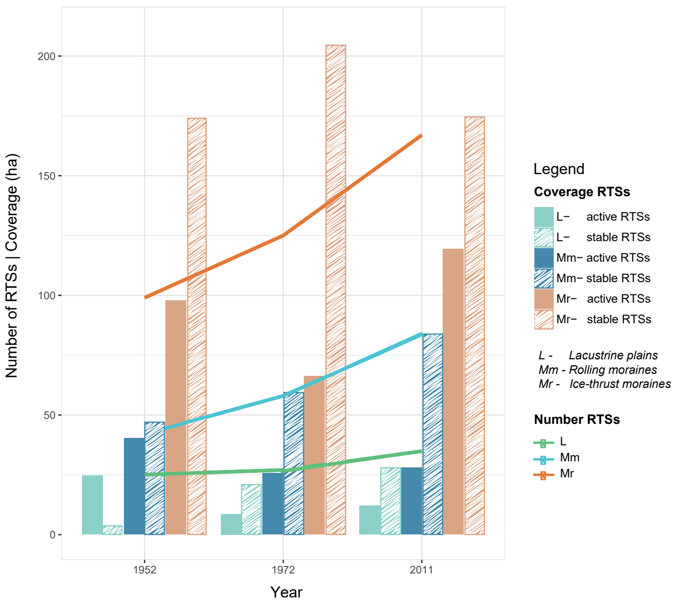
Justine Ramage 4/1/2018 23:16
Deleted: amount

4 Results

4.1 Evolution of RTSs between 1952 and 2011

4.1.1 RTS evolution along the coast

The number of RTSs increased by 73% between 1952 and 2011. The increase was more pronounced throughout the time period 1952-1972 (Fig. 5). Between 1952 and 2011, active RTSs were more abundant and their number increased faster than stable RTSs. While the number of active RTSs progressed steadily throughout the period, the number of stable RTSs decreased between 1972 and 2011; stable RTSs had either reactivated or eroded due to coastal retreat. Between 1952 and 2011, the number of RTSs increased by 40% on lacustrine plains and by 100% on rolling moraines (Fig. 5). On ice-thrust moraines, the number of RTSs increased by 69% between 1952 and 2011 (1.2 RTS/yr). On both moraine units, the rise was greater between 1952 and 1972.



Justine Ramage 11/1/2018 08:50
Deleted: Table 1

Justine Ramage 11/1/2018 12:05
Deleted: (Table 1)

Justine Ramage 11/1/2018 08:50
Deleted: Table 1

Justine Ramage 2/1/2018 06:54
Deleted:

Justine Ramage 29/12/2017 17:34
Deleted: **Table 1:** Number of RTSs in 1952, 1972 and 2011 and number of RTSs initiated after 1972, per geologic unit (lacustrine plains, L; rolling moraines, Mm; ice-thrust moraines, Mr). RTSs initiated after 1972 are a subgroup of RTSs identified in 2011.
RTSs in 1952 ... [4]

Figure 5: Graph showing the evolution in the number and areal coverage of RTSs between 1952 and 2011 for each geologic units (L, lacustrine plains; Mm, rolling moraines; Mr, ice-thrust moraines). The y-axis shows variations in the number of RTSs. The z-axis shows variations in the areal coverage of RTSs (ha), which differentiate between active and stable RTSs.

The total areal coverage (sum of the total RTSs sizes) expanded by 14% between 1952 and 2011 and was observed in all geologic units (Fig. 5). This expansion was driven by an increase in the areal coverage of stable RTSs (25%); the areal coverage of active RTSs decreased by 2% (Fig. 5). The expansion in areal coverage was caused by an increase in the number of RTSs rather than by a growth in the size of single RTSs alone: RTSs became smaller, their median size decreased by 67% throughout the period.

Among RTSs present in 2011, 119 initiated after 1972 on previously undisturbed surfaces: in 2011, 72 were still active and 47 had stabilized (S1_TableS1). RTSs initiated after 1972 were on average smaller than other RTSs and occupied 98.6 ha of the whole study area, or 22% of the total area affected by RTSs in 2011. Most of the RTSs initiated after 1972 (74%) developed on ice-thrust moraines.

4.2 Eroded material and estimated amount of mobilized SOC and DOC

In the following sections, volumes are given for the RTSs that occurred within the LiDAR area. This comprises 56% of the total number of RTSs present in the investigated coastal area (n = 162) and 41% of the number of RTSs initiated after 1972 (n = 49).

4.2.1 Eroded material and OC stocks mobilized from RTSs

The total volume of material displaced by the 162 RTSs was 16.6$*10^6$ m^3, 54% of which was ice (S1, Table S1). It corresponds to 0.1$*10^6$ m^3/km along the Yukon Coast. On average each RTS eroded 102.2$*10^3$ m^3 of material. The volume of eroded material was positively correlated to the size of the RTSs ($r^2 = 0.5$, $p < 0.05$). On average, 52% of the material was reworked by erosion of the RTS headwalls and 45% was eroded and transported alongshore due to coastal retreat. The remaining 3% of material remained in the RTS floors where it settled. Overall, 65% of the material reworked by RTSs originated from ice-thrust moraines, 19% from lacustrine plains and 16% from rolling moraines (Table 1). However, RTSs located on lacustrine plains eroded more material per single RTS (135.5$*10^3$ m^3/RTS) than RTSs located on ice-thrust moraines (103.9$*10^3$ m^3/RTS) and on rolling moraines (75.1$*10^3$ m^3/RTS).

Table 1: Volume of material, including ice and sediments, eroded by RTSs along the Yukon Coast per geologic units. The values are normalized to the coastal length of the geologic units (km).

Justine Ramage 11/1/2018 12:06
Deleted: (Table 2)

Justine Ramage 11/1/2018 08:50
Deleted: Table 2

Justine Ramage 10/1/2018 15:51
Deleted:
RTSs in 1952 ... [5]

Justine Ramage 11/1/2018 12:06
Deleted: (Table 1)

Justine Ramage 11/1/2018 12:06
Deleted: (Table 2)

Justine Ramage 3/1/2018 11:55
Deleted: 86

Justine Ramage 18/12/2017 15:08
Deleted: 00

Justine Ramage 18/12/2017 15:08
Deleted: ^{3}

Justine Ramage 5/1/2018 17:42
Deleted:

Justine Ramage 3/1/2018 11:56
Deleted: 53

Justine Ramage 3/1/2018 12:01
Deleted: 64

Justine Ramage 3/1/2018 12:00
Deleted: 19% from rolling moraines

Justine Ramage 3/1/2018 11:59
Deleted: 17% from lacustrine plains

Justine Ramage 7/1/2018 16:44
Deleted: 3

Justine Ramage 3/1/2018 12:05
Deleted: 61

Justine Ramage 3/1/2018 12:06
Deleted: 53

Justine Ramage 3/1/2018 12:07
Deleted: 48

Justine Ramage 7/1/2018 16:44
Deleted: 3

	Sediments ($10^3 m^3$ / km)	Ice ($10^3 m^3$ / km)	Total Material ($10^3 m^3$ / km)
Lacustrine Plains (L)	16.1	40.1	56.2
Rolling moraines (Mm)	46.2	44.7	90.9
Ice-thrust moraines (Mr)	75.8	76.9	152.7

The largest volumes of eroded material came from RTSs occurring at the glaciation limit (Fig. 6). The 24 RTSs located on Herschel Island East (segment 13) reworked 22% of the total volume of material displaced by the 162 RTSs. The RTSs located on Herschel Islands West (segment 11) had the highest volume of material eroded per RTS, on average 4% of the total volume of material displaced by RTSs (Fig. 6). Ice-thrust moraine deposits underlie both coastal segments 11 and 13.

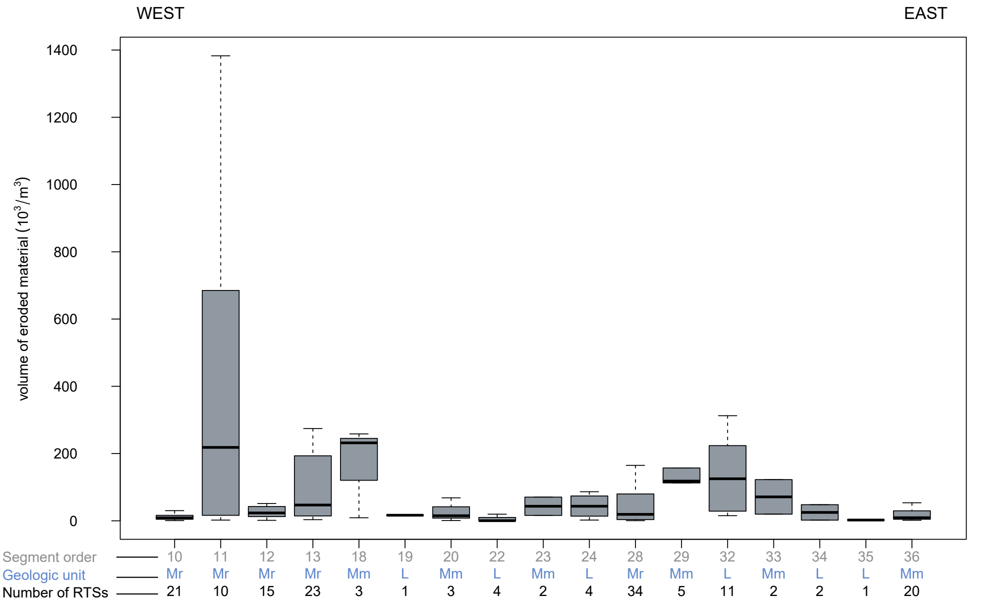


Figure 6: Boxplot of volumes of eroded material (sediments and ice) per RTS for the coastal segments where RTSs occurred in 2011. Each bar corresponds to a coastal segment, following a geographic order from West on the left to East on the right. The number of the respective coastal segment is indicated in the first line on the x-axis. The geologic units are indicated

Justine Ramage 2/1/2018 14:58
Deleted: 6

Justine Ramage 2/1/2018 14:58
Deleted: 6

Justine Ramage 2/1/2018 14:58
Deleted: 6

Justine Ramage 2/1/2018 14:45
Deleted: 0.4

Justine Ramage 2/1/2018 14:45
Deleted: 1.0

Justine Ramage 2/1/2018 14:45
Deleted: 1.4

Justine Ramage 2/1/2018 14:45
Deleted: 0.9

Justine Ramage 2/1/2018 14:45
Deleted: 0.8

Justine Ramage 2/1/2018 14:45
Deleted: 1.7

Justine Ramage 2/1/2018 14:45
Deleted: 2.7

Justine Ramage 2/1/2018 14:45
Deleted: 2.8

Justine Ramage 2/1/2018 14:45
Deleted: 5.5

Justine Ramage 7/1/2018 16:44
Deleted: 4

Justine Ramage 3/1/2018 12:29
Deleted: 5

Justine Ramage 3/1/2018 12:32
Deleted: 2

Justine Ramage 7/1/2018 16:44
Deleted: 4

Justine Ramage 1/2/2018 10:23
Deleted:

Justine Ramage 22/12/2017 14:52
Deleted: 4

below the bars and referred as L (lacustrine plains); Mm (rolling moraines); and Mr (ice-thrust moraines). The values on the lowest line of the x-axis indicate the total number of RTSs per coastal segment.

Between 1952 and 2011, the 162 RTSs reworked 7.6*10^6 m^3 of sediments (S1, Table S1), eroding a mass of mineral sediment of 6.8*10^9 kg. RTSs on ice thrust-moraines eroded 72% of the mass of mineral sediments, on rolling moraines 19%. During this period, RTSs mobilized a total SOC stock of 145.7*10^6 kg, with the upper 1 m of soil contributing 49%. RTSs on ice-thrust moraines contributed to 72% of the total SOC stock. Out of this, RTSs on Herschel Island West and East (segments 11 and 13) mobilized 47% of the total SOC stock. The total stock of DOC mobilized by RTSs was 164.5*10^3 kg. RTSs on ice-thrust moraines mobilized 63% of the total DOC stock mobilized by the 162 RTSs (103.8*10^3 kg) (S1, Table S1).

4.2.2 Eroded material and OC fluxes from RTSs initiated after 1972

The 49 RTSs initiated after 1972 eroded a volume of material of 1.1*10^6 m^3, 50% of which was ice (S1, Table S1). It corresponds to 27.2*10^3 m^3/yr (0.6*10^3 m^3/RTS/yr) between 1972 and 2011. This represents 6% of the total volume of material eroded by the 162 RTSs. Most of the material was eroded and transported alongshore due to coastal retreat (67%). Erosion of the RTS headwalls contributed to 31% of the reworked material from RTSs and 2% of material remained in the RTS floors where it settled.

Table 2: Volume of material, including ice and sediments, eroded by RTSs initiated after 1972 along the Yukon Coast per geologic unit. The values are normalized to the coastal length of the geologic units (km).

	Sediments (10^3 m^3 / km)	Ice (10^3 m^3 / km)	Total Material (10^3 m^3 / km)
Lacustrine Plains (L)	0,24	0.52	0.75
Rolling moraines (Mm)	0.46	0.46	0.92
Ice-thrust moraines (Mr)	6.84	7.18	14.02

In total, 94% of the reworked material from RTSs initiated after 1972 came from those located on ice-thrust moraines (Table 2), where the largest volumes of material per RTS initiated after 1972 was (23.6*10^3 m^3/RTS). The RTSs initiated after 1972 on Herschel Island North (segment 12) reworked the largest volume of material: 42.4*10^3 m^3/RTS (Fig. 7).

Justine Ramage 1/2/2018 11:19
Deleted: Boxplots of volumes of eroded material (sediments and ice) for the coastal segments where RTSs occurred in 2011 (logarithmic scale). Each bar corresponds to a coastal segment, following a geographic order from west on the left to east on the right. The geologic units are indicated below the bars and referred as L (lacustrine plains); Mm (rolling moraines); and Mr (ice-thrust morain ... [6]

Justine Ramage 6/1/2018 11:41
Deleted:

Justine Ramage 3/1/2018 14:35
Deleted: 81

Justine Ramage 18/12/2017 15:10
Deleted: 46.6

Justine Ramage 18/12/2017 15:10
Deleted: ^{3}

Justine Ramage 3/1/2018 14:35
Deleted: kg

Justine Ramage 6/1/2018 11:42
Deleted: mobilizing

Justine Ramage 3/1/2018 11:39
Deleted: 819

Justine Ramage 18/12/2017 15:09
Deleted: 00

Justine Ramage 18/12/2017 15:09
Deleted: ^{3}

Justine Ramage 3/1/2018 11:50
Deleted: 56

Justine Ramage 3/1/2018 12:39
Deleted: 69

Justine Ramage 3/1/2018 12:41
Deleted: 47

Justine Ramage 3/1/2018 12:43
Deleted: 65

Justine Ramage 3/1/2018 12:43
Deleted: 156

Justine Ramage 3/1/2018 14:39
Deleted: 8.6*10^3 m^3/yr between 1972 and 2011,

Justine Ramage 3/1/2018 14:40
Deleted: 4

Justine Ramage 5/1/2018 13:35
Deleted: 17

Justine Ramage 7/1/2018 16:43
Deleted: 5

Justine Ramage 5/1/2018 13:28
Deleted: In total, 95% of the reworked mat ... [7]

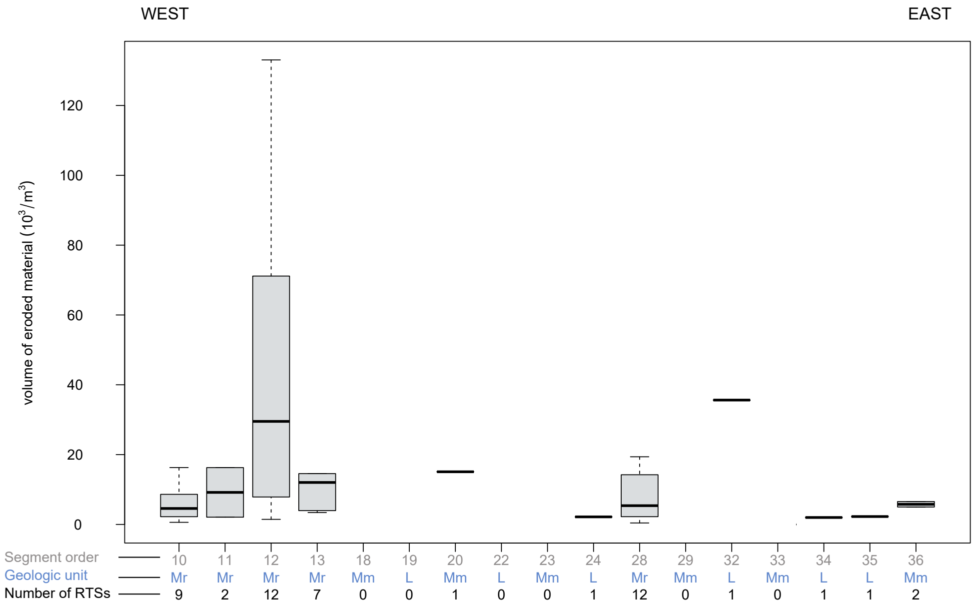


Figure 7: Boxplot of volumes of eroded material (sediments and ice) per RTS for the coastal segments where RTSs initiated after 1972 occurred in 2011. Each bar corresponds to a coastal segment, following a geographic order from West on the left to East on the right. The number of the respective coastal segment is indicated in the first line on the x-axis. The geologic units are indicated below the bars and referred as L (lacustrine plains); Mm (rolling moraines); and Mr (ice-thrust moraines). The values on the lowest line of the x-axis indicate the number of RTSs on the coastal segments.

The 49 RTSs initiated after 1972 eroded a mass of mineral sediments of 454.1*10^6 kg, which represent a flux of 11.6*10^6 kg/yr. Since 1972, these RTSs mobilized an SOC flux of 250.1*10^3 kg/yr (Table 3), representing an average of 0.5 kg/m^3/yr. Most of the SOC fluxes originated from the RTSs initiated after 1972 on Herschel Island North (segment 12, 123.4*10^3 kg/yr) and on Kay Point South East (segment 28, 36.8*10^3 kg/yr) (S1, Table S1). On ice-thrust moraines, RTSs initiated after 1972 mobilized 94% of the total SOC flux (Table 3). The total DOC flux from RTSs initiated after 1972 was 5.1 kg/yr, with high variability between the geologic units: 0.1 kg/yr from rolling moraines and from lacustrine plains and 4.9 kg/yr on

Justine Ramage 22/12/2017 14:52
Deleted: 5

Justine Ramage 1/2/2018 11:20
Deleted: Boxplots of vVolumes of eroded material (sediments and ice) from for the coastal segments where RTSs initiated after 1972 occurred in 2011 (logarithmic scale). Each bar corresponds to a coastal segment, following a geographic order from West on the left to East on the rightlowest. The values on the x-axis indicate the number of RTSs on the coastal segments. The geologic units are indicated below the bars and referred as L (la ... [8]

Justine Ramage 7/1/2018 16:42
Deleted: **Table 4:** Volume of material, incl ... [9]

Justine Ramage 4/1/2018 23:30
Deleted: reworked 341.2*10^3 kg/yr of ma ... [10]

Justine Ramage 3/1/2018 14:57
Deleted: 82.3

Justine Ramage 3/1/2018 14:57
Deleted: ^{3}

Justine Ramage 7/1/2018 16:45
Deleted: 5

Justine Ramage 3/1/2018 14:58
Deleted: 10

Justine Ramage 5/1/2018 14:38
Deleted: 4

Justine Ramage 3/1/2018 15:44
Deleted: 43.2

Justine Ramage 3/1/2018 15:44
Deleted: ^{3}

Justine Ramage 3/1/2018 15:45
Deleted: 18.9

Justine Ramage 3/1/2018 15:45
Deleted: ^{3}

Justine Ramage 3/1/2018 15:00
Deleted: 92

Justine Ramage 7/1/2018 16:45
Deleted: 5

Justine Ramage 3/1/2018 15:01
Deleted: 182.6

Justine Ramage 3/1/2018 15:03
Deleted: coastal segments

Justine Ramage 3/1/2018 15:04
Deleted: from 0.6

Justine Ramage 3/1/2018 15:05
Deleted: to

Justine Ramage 3/1/2018 15:03
Deleted: 122.7

ice-thrust moraines (S1, Table S1). The highest DOC fluxes came from ice-thrust moraines from Herschel Island North (segment 12) where 12 RTSs initiated after 1972 mobilized a total flux of 3.1 kg/yr of DOC (Table 3).

Table 3: Total SOC and DOC flux mobilized between 1972 and 2011 by RTSs initiated after 1972, per year and km for each geologic unit.

	SOC flux (kg / km / yr)	DOC flux (g / km / yr)
Lacustrine plains (L)	115.5	4.3
Rolling moraines (Mm)	308.5	4.6
Ice-thrust moraines (Mr)	3316.6	68.6

5 Discussion

5.1 Acceleration of slump activity

With a total of 287 RTSs in 2011, the Yukon Coast is one of the Arctic areas most affected by retrogressive thaw slumping (Ramage et al., 2017). The number of RTSs along the Yukon Coast increased by 73% between 1952 and 2011, when on average 2 RTSs initiated per year (Fig. 5). The rise was more pronounced between 1952 and 1972 and the number of RTSs continued to increase steadily between 1972 and 2011. The evolution of RTSs along the Yukon Coast is consistent with the observations made in other parts of the Canadian Arctic, where RTS activity is accelerating since the 1950s (Segal et al., 2016; Lacelle et al., 2010; Lantz and Kokelj, 2008; Lantuit and Pollard, 2008). Lantuit and Pollard (2008) showed that the number of RTSs on Herschel Island increased by 61% between 1952 and 2000. RTSs develop following changes that affect geomorphic settings (Ramage et al., 2017; Kokelj et al., 2017) and are induced by climatic conditions – such as increased air temperature (Lacelle et al., 2010), precipitation events (Kokelj et al., 2015; Lacelle et al., 2010) and storm events (Lantuit et al., 2012a; Lantuit and Pollard, 2008; Dallimore et al., 1996). Many RTSs that were stable or stabilized between 1952 and 1972 re-activated between 1972 and 2011. Our results confirm the pattern of RTS reactivation previously observed on Herschel Island (Lantuit and Pollard, 2008) and between Kay Point and Shingle Point (Wolfe et al., 2001) and referred to as polycyclicity. Reactivation of RTSs is associated with incomplete melting of massive ice during the first period of RTS development (Burn, 2000) and depends on the capacity of the slump headwall to remain exposed until ice is exhausted. In coastal settings, storm events can re-activate RTSs (Lantuit et al., 2012a). The period of RTS activity partly depends on the equilibrium between thermodenudation and coastal erosion rates: the RTS remains active if the RTS headwall erodes at a rate exceeding coastal retreat (Lantuit et al., 2012a; Are, 1999). This equilibrium is strongly linked to the changing climatic

Justine Ramage 3/1/2018 15:06
Deleted: 122.7

Justine Ramage 7/1/2018 16:46
Deleted: 5

Justine Ramage 7/1/2018 16:45
Deleted: 5

Justine Ramage 2/1/2018 15:09
Deleted: (lacustrine plains, L; rolling moraines, Mm; ice-thrust moraines, Mr)

Justine Ramage 2/1/2018 15:04
Deleted: 10^3

Justine Ramage 5/1/2018 15:13
Deleted: k

Justine Ramage 2/1/2018 15:04
Deleted: 3.6

Justine Ramage 2/1/2018 15:06
Deleted: 4.3

Justine Ramage 2/1/2018 15:08
Deleted: Mm

Justine Ramage 2/1/2018 15:04
Deleted: 3.4

Justine Ramage 2/1/2018 15:06
Deleted: 3.1

Justine Ramage 2/1/2018 15:08
Deleted: Mr

Justine Ramage 2/1/2018 15:05
Deleted: 75.3

Justine Ramage 2/1/2018 15:06
Deleted: 175.2

Justine Ramage 2/1/2018 09:06
Deleted: and Dallimore

and sea conditions that act on coastal retreat, such as storm events and sea ice duration. Climate data recorded at Komakuk Beach (segment 2) and Shingle Point (segment 36) show that the annual average air temperature remained stable between the periods 1957-1971 and 1971-2000 However, the annual average precipitations increased at both stations by 30% and 41%, respectively during the same periods (Environment Canada, *http://climate.weather.gc.ca/historical_data/search_historic_data_e.html*). Similar patterns were observed for the summer months (July to September). As suggested by Kokelj et al. (2015), higher rainfall might intensify RTS activity and seems to be the main climatic factor behind the development of RTSs along the Yukon Coast.

Along the Yukon Coast, RTSs developed mainly on ice-thrust moraines, where their number increased by 1.1 RTS/yr throughout the whole period. Differences in ice content and coastal geomorphology explain the disparities in the evolution of RTSs observed among geologic units (Ramage et al., 2017; Lewkowicz, 1987). Our results confirm the results of Kokelj et al. (2017), who showed evidence of a spatial link between RTS occurrence in North America and the maximum extent of the Laurentide Ice Sheet. Similar to our observations along the Yukon Coast, most of the RTSs in North America are found along the marginal moraines of the Laurentide Ice Sheet.

Along with the increase in number of RTSs along the Yukon Coast, the total areal coverage of RTSs increased by 14% between 1952 and 2011 (Fig. 5). However, RTSs along the Yukon Coast were on average smaller in 2011 compared to 1952 and 1972. This differs from RTSs observed in other parts of the Canadian Arctic (Segal et al., 2016; Kokelj et al., 2017). Our results support those reported by Ramage et al. (2017); coastal RTSs are on average smaller compared to inland RTSs, and coastal RTSs along the Yukon Coast are smaller than the ones found in other coastal areas of the Arctic. The large number of RTSs initiated after 1972 along the Yukon Coast partly explains this: RTSs initiated after 1972 represented 17% of the total number of RTSs in 2011; these RTSs were still developing in 2011 and thus did not reach their maximal expansion size.

5.2 Eroded material from RTSs and OC fluxes

The expansion of RTSs along the coast causes the displacement of large volumes of material from the land to the sea. We show that the 56% of the RTSs identified in 2011 for which we could calculate volumes (162 RTSs out of ??? that occur in the coastal area investigated) have reworked at least 16.6*10^6 m^3 of material along the Yukon Coast, which is 102.5*10^3 m^3/RTS of material eroded per RTS (Fig. 6). Among these RTSs, 49 RTSs initiated after 1972 and reworked 27.2*10^3 m^3/yr of material, which is 0.6*10^3 m^3/RTS/yr (Fig. 7). These estimates are low compared to material removal from other RTSs in the Arctic. Lantuit and Pollard (2005) calculated a sediment volume loss of 105*10^3 m^3 between 1970 and 2004 for a single RTS located on Herschel Island; Kokelj et al. (2015) and Jensen et al. (2014) measured material displacements up to 10^6 m^3 per RTS located in NW Canada and Alaska; the Batagay mega-slump located in Siberia eroded more than 24*10^6 m^3 of ice rich permafrost in 2014 (Günther et al., 2015). The size of the observed RTSs is one reason behind such differences: most of the RTSs examined in the abovementioned studies are classified as mega slumps (> 0.5 ha). The RTS studied in Lantuit and

Justine Ramage 3/1/2018 11:11
Deleted: .

Justine Ramage 7/1/2018 10:20
Deleted: 41

Justine Ramage 7/1/2018 10:18
Deleted: amount

Justine Ramage 5/1/2018 18:03
Deleted: According to our estimates

Justine Ramage 5/1/2018 18:03
Deleted: ,

Justine Ramage 3/1/2018 16:34
Deleted: 86

Justine Ramage 18/12/2017 15:12
Deleted: 00

Justine Ramage 18/12/2017 15:12
Deleted: ^{3}

Justine Ramage 3/1/2018 11:27
Deleted: among which 335*10^3 m^3 of material was reworked by 49 RTSs initiated after 1972

Pollard (2005) was the largest RTS identified along the entire Yukon Coast in 2011, 24 ha. However, most of the RTSs along the Yukon coast are small, with an average size of 0.2 ha (Ramage et al., 2017). This has implications for studies that attempt to model the impact of RTSs on the eroded material budgets in the Arctic.

Couture (2010) estimated the annual flux of mineral sediment eroded by coastal retreat along the Yukon Coast to $7.3*10^{6}$ kg/km/yr. We show that along a 190-km portion of the Yukon Coast, 17% of the RTSs identified along the coast in 2011 (49 RTSs) contributed to 1% of the annual flux of material eroded along the Yukon Coast ($61*10^{3}$ kg/km/yr). These RTSs initiated after 1972 incised 1% (2 km) of the coastline in 2011 and were on average smaller than the average RTSs. Increasing the number and areal coverage of coastal RTSs has therefore large consequences on the flux of eroded material along the Arctic coasts.

We estimated the annual OC fluxes (SOC and DOC) from these 49 RTSs to $1.3*10^{3}$ kg/km/yr, including 0.02 kg/km/yr DOC. The average OC flux from coastal retreat along the entire Yukon Coast is $157*10^{3}$ kg/km/yr (Couture, 2010) with an average DOC flux of $0.2*10^{3}$ kg/km/yr (Tanski et al., 2016). We show that the annual OC flux released by the 49 RTSs initiated after 1972 was 0.6% the annual OC flux from coastal retreat. Most of these fluxes originated from ice thrust moraines, where the number of RTS initiated after 1972 was the highest. RTSs develop mainly on ice-thrust moraines because of the presence of large volumes of massive ground ice (Ramage et al., 2017). As a result, only half of the material eroding from the RTS headwall is sediment and most of the OC is released as DOC.

The volumes and stocks of material and OC mobilized by RTSs along the Yukon Coast account for 56% of the RTSs identified on the 2011 imagery. We did not calculate the volumes for all RTSs present along the Yukon Coast due to the restricted area covered by the LiDAR dataset. Therefore, the fluxes of sediment and OC mobilized by 49 RTSs initiated after 1972 underestimate the annual contribution from RTSs to the nearshore sediment and OC budgets along the Yukon Coast. These fluxes account for 41% of the flux from RTSs initiated after 1972 and 17% of the total number of RTSs identified in 2011 along the Yukon Coast.

5.3 Impact of RTSs on the coastal ecosystem

RTSs erode surfaces and scar the landscape, impacting the coastal fringe ecosystems. RTSs alter the vegetation composition: after they stabilize, their effects on the vegetation persist over centuries (Cray and Pollard, 2015; Lantz et al., 2009). Inland, RTSs modify stream sediment transport by raising the stream turbidity and the concentration of total suspended sediments (Kokelj et al., 2013). Moreover, RTSs alter coastal retreat (Obu et al., 2016; Lantuit and Pollard, 2008; Leibman et al., 2008). The spatial variability of coastal erosion along the Yukon Coast relates to RTS activity: segments with intense slumping show the highest volume of eroded and accumulated material (Obu et al., 2016).

Justine Ramage 4/1/2018 23:34
Deleted: Furthermore,

Justine Ramage 5/1/2018 17:50
Deleted: Another part of the material mobilized through slumping is transported alongshore by coastal erosion (Fig. 6). In our study area, RTSs incised 8.3% (15.8 km) of the coastline in 2011 and the average rate of coastal change is -0.7 m/yr (Irrgang et al., 2017).

Justine Ramage 6/1/2018 11:55
Deleted: the annual flux of material eroded by coastal retreat along the Yukon Coast

Justine Ramage 6/1/2018 10:45
Deleted: Scaled to the 190-km LiDAR scan in this study, the annual flux of eroded material is $1387*10^{6}$ kg/yr. We estimate that RTSs contribute to 8.3% ($111*10^{6}$ kg) of the annual material budget eroded from coastal erosion along the Yuko ... [11]

Justine Ramage 6/1/2018 12:00
Deleted: initiated after 1972

Justine Ramage 3/1/2018 16:44
Deleted: 82.5

Justine Ramage 3/1/2018 16:44
Deleted: ^{3}

Justine Ramage 5/1/2018 17:54
Deleted: annual

Justine Ramage 5/1/2018 17:54
Deleted: In the 190-km coastline of the LiDAR scan, the OC flux from coastal retreat is therefore $29830*10^{3}$ kg/yr (including $38*10^{3}$ kg/yr of DOC).

Justine Ramage 6/1/2018 12:18
Deleted: T

Justine Ramage 3/1/2018 16:47
Deleted: 0.3

Justine Ramage 6/1/2018 12:22
Deleted: (0.5% of the DOC flux)

Justine Ramage 6/1/2018 12:25
Deleted: OC

Justine Ramage 6/1/2018 12:25
Deleted: from RTSs

Justine Ramage 5/1/2018 17:57
Deleted:

Justine Ramage 1/2/2018 11:22
Deleted: calculate the volumes for allpresent along the Yukon Coast

Most of the material eroded through slumping and mobilized OC is transported to the nearshore zone (Vonk et al., 2012). However, a fraction of this material and OC remains in the slump floor for several years (Tanski et al., 2017; Obu et al., 2016) where it degrades and is mineralized by microorganisms. Hence, RTSs mobilize OC prior to its release to the ocean and modify the amount of OC available to the coastal ecosystem (Tanski et al., 2017; Cassidy and Henry, 2016; Pizano et al., 2014). Tanski et al. (2017) show that SOC and DOC decrease by 77% and 55%, respectively before reaching the nearshore zone. Abbott and Jones (2015) describe similar processes for RTSs in upland areas: after RTSs develop, 51% of organic-layer SOC and 21 kg/m^2 of mineral-layer SOC is removed. Following headwall erosion, water transports melted ground ice and most sediments to the nearshore zone. Without enough viscous flow, the remaining part of the sediments accumulates and settles on the RTS floor, as indicated by higher bulk densities in samples from RTS floors (Tanski et al., 2017; Lantuit et al., 2012a). The OC in the sediments is released to the atmosphere as CO_2 (Cassidy and Henry, 2016), buried in the RTS floor or transported to the nearshore zone (Tanski et al., 2017).

RTSs are transient phenomena in coastal settings; coastal retreat eventually erodes and transports alongshore 45% of the material reworked by RTSs. However, as explained above, RTSs affect the OC release process and alter the OC budget of the nearshore zone.

Conclusions

The number of RTSs along the Yukon Coast increased by 73% between 1952 and 2011 and the total areal coverage of RTSs increased by 14%. We observed disparities between geomorphic units: the largest increase was on ice-thrust moraines, where the number of RTSs increased at an annual rate of 1.2 RTSs/yr. Many RTSs are polycyclic and reactivated between 1972 and 2011. RTSs reworked at least 16.6*10^6 m^3 of material within a 190-km portion of the coastal fringe. Majority of the material came from erosion of the headwall (53%) and 3% remained in the RTS floors. A large amount of the material from RTSs was eroded and transported alongshore due to coastal retreat (45%). The OC flux from 17% of the RTSs identified in 2011 was 1.3*10^3 kg/km/yr and represented 0.6% of the annual OC fluxes from coastal retreat in the study area. Not all the OC mobilized by RTSs is immediately transported to the nearshore zone; an important part is mobilized in the RTS floors. Therefore, RTSs alter the OC budget of the nearshore zone by affecting the OC release process. Our results show that the contribution of RTSs to the nearshore OC budget is non-negligible and should be included when estimating the quantity of OC released from the Arctic coast to the ocean.

Justine Ramage 5/1/2018 17:56

Deleted: Our fluxes of sediment and OC mobilized by 49 RTSs initiated after 1972 underestimate the annual contribution from slumping processes to the nearshore sediment and OC budgets along the Yukon Coast. These fluxes account for 41% of the flux from RTSs initiated after 1972 and 17% of the total number of RTSs present in 2011 along the Yukon Coast (Ramage et al., 2017).

... [12]

Justine Ramage 5/1/2018 18:28

Deleted: 8

Justine Ramage 18/12/2017 15:13

Deleted: 00

Justine Ramage 18/12/2017 15:13

Deleted: ^{3}

Justine Ramage 7/1/2018 13:44

Deleted: 49

Justine Ramage 7/1/2018 13:44

Deleted: initiated after 1972 and present

Justine Ramage 5/1/2018 18:31

Deleted: 82.5*10^3 kg/yr

Justine Ramage 5/1/2018 18:31

Deleted: 0.3

Justine Ramage 7/1/2018 13:43

Deleted: erosion

Author contribution: JLR and HL designed the study. AMI geocoded the historical photographs used for mapping. JLR created the spline interpolation and calculated the eroded volumes of material from retrogressive thaw slumps. JLR prepared the manuscript with contributions from all co-authors.

Aknowledgments: This study was supported by the Helmholtz Association through the COPER Young Investigators Group (VH-NG-801) and by the Alfred Wegener Institute in Potsdam. J. L. Ramage was financially supported by a PhD stipend by the University of Potsdam. A.M. Irrgang was financially supported by a PhD stipend from the German Federal Environmental Foundation. We thank J. Obu and G. Hugelius who provided insight and expertise at the early stage of the study.

Competing interests: The authors declare that they have no conflict of interest.

Justine Ramage 7/1/2018 13:44

Deleted: This number accounts for 17% of the RTSs present along the Yukon Coast in 2011. Our results do not include the volume of material eroded from the RTS headwalls (that remained within the RTS floors where it subsided) and material eroded from the RTS bluff by coastal retreat and transported alongshore. However, we provide a first estimate on the contribution of RTSs to the nearshore carbon budget along the Yukon Coast.

References

Abbott, B.W. & Jones, J.B.: Permafrost collapse alters soil carbon stocks, respiration, CH4, and N2O in upland tundra. Glob. Change Biol., 21, 4570– 4587, 2015.

Abbott, B.W., Jones, J.B., Schuur, E.A.G., III, F.S.C., Bowden, W.B., Bret-Harte, M.S., et al.: Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment. Environ. Res. Lett., 11, 034014, 2016.

Are, F.E.: The role of coastal retreat for sedimentation in the Laptev Sea. In *Land-Ocean Systems in the Siberian Arctic* (pp. 288-295). Springer Berlin Heidelberg, 1999.

Brooker, A., Fraser, R.H., Olthof, I., Kokelj, S.V. and Lacelle, D.: Mapping the activity and evolution of retrogressive thaw slumps by tasselled cap trend analysis of a Landsat satellite image stack. *Permafrost and Periglacial Processes*, *25*(4), pp.243-256, 2014.

Burke, E.J., Hartley, I.P. and Jones, C.D.: Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *The Cryosphere*, *6*(5), pp.1063-1076, 2012.

Burn, C.R.: The thermal regime of a retrogressive thaw slump near Mayo, Yukon Territory. *Canadian Journal of Earth Sciences 37:* 967–981, 2000.

Burn, C.R. and Zhang, Y.: Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada. *Journal of Geophysical Research: Earth Surface*, *114*(F2), 2009.

Cannone, N., Lewkowicz, A.G. and Guglielmin, M.: Vegetation colonization of permafrost-related landslides, Ellesmere Island, Canadian High Arctic. *Journal of Geophysical Research: Biogeosciences*, *115*(G4), 2010.

Cassidy, A.E. and Henry, G.H.: The effect of a permafrost disturbance on growing-season carbon-dioxide fluxes in a high Arctic tundra ecosystem. *Biogeosciences*, *13*(8), p.2291, 2016.

CAVM Team: Circumpolar Arctic Vegetation Map. (1:7,500,000 scale), *Conservation of Arctic Flora and Fauna (CAFF)* Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska. ISBN: 0-9767525-0-6, ISBN-13: 978-0-9767525-0-9, 2003.

Couture, N.: Fluxes of Soil Organic Carbon from Eroding Permafrost Coasts, Canadian Beaufort Sea, 155 pp, McGill University, Montreal, Canada, 2010.

Couture, N.J. and Pollard, W.H.: A Model for Quantifying Ground-Ice Volume, Yukon Coast, Western Arctic Canada. *Permafrost and Periglacial Processes,* 2017.

Couture, N., Irrgang, A.M., Pollard, W., Lantuit H., Fritz, M.: Coastal Erosion of Permafrost Soils along the Yukon Coastal Plain and Fluxes of Organic Carbon to the Canadian Beaufort Sea. Submitted to *Biogeosciences, 2017.*

Cray, H.A. and Pollard, W.H.: Vegetation recovery patterns following permafrost disturbance in a Low Arctic setting: case study of Herschel Island, Yukon, Canada. *Arctic, Antarctic, and Alpine Research*, *47*(1), pp.99-113, 2015.

Dallimore, S. R., Wolfe, S. A., and Solomon, S. M.: Influence of ground ice and permafrost on coastal evolution, Richards Island, Beaufort Sea coast, NWT. *Canadian Journal of Earth Sciences*, *33*(5), 664-675, 1996.

Justine Ramage 18/12/2017 13:09

Deleted: Abbott, B.W., Jones, J.B., Godsey, S.E., Larouche, J.R. and Bowden, W.B.: Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. *Biogeosciences*, *12*(12), pp.3725-3740, 2015.

Justine Ramage 7/1/2018 14:00

Deleted:

Justine Ramage 7/1/2018 14:01

Deleted: &

von Deimling, T.S., Meinshausen, M., Levermann, A., Huber, V., Frieler, K., Lawrence, D.M. and Brovkin, V.: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, *9*(2), p.649, 2012.

Dyke, A. and V. Prest (1987). Late Wisconsinan and Holocene history of the Laurentide ice sheet. *Géographie physique et Quaternaire*, *41*(2), pp.237-263.

Environment Canada: Canadian Climate Normals 1971-2000 Station Data, Available from: http://climate.weather.gc.ca/climate_normals, 2017.

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*, pp.28-45, 2012.

Fritz, M., Vonk, J.E., and Lantuit, H.: Collapsing Arctic coastlines. *Nature Climate Change*, 7, 6-7. doi:10.1038/nclimate3188, 2017.

Günther, F., Grosse, G., Wetterich, S., Jones, B. M., Kunitsky, V. V., Kienast, F., & Schirrmeister, L.: The Batagay mega thaw slump, Yana Uplands, Yakutia, Russia: permafrost thaw dynamics on decadal time scale. TERRA NOSTRA-Schriften der GeoUnion Alfred-Wegener-Stiftung, 2015.

Hansen, J., Ruedy, R., Sato, M. and Lo, K.: Global surface temperature change. *Reviews of Geophysics*, *48*(4), 2010.

Harper, J.R.: Morphology of the Canadian Beaufort Sea coast. *Marine Geology*, *91*(1-2), pp.75-91, 1990.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E., Ping, C. L., ... & O'Donnell, J. A.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, *11*(23), 6573-6593, 2014.

Irrgang, A.M., Lantuit, H., Manson, G.K., Günther, F., Grosse, G., Overduin, P.P.: Variability in rates of coastal change along the Yukon coast, 1951-2015. *Journal of Geophysical Research: Earth Surface, under review,* 2017.

Jensen, A. E., Lohse, K. A., Crosby, B. T., and Mora, C. I.: Variations in soil carbon dioxide efflux across a thaw slump chronosequence in northwestern Alaska. *Environmental Research Letters*, *9*(2), 025001, 2014.

Kessler, L.: Estimating the economic impact of the permafrost carbon feedback. Clim. Change Econ., 08, 1750008, 2017.

Kohnert, K., Serafimovich A., Hartmann J., and Sachs T.: Airborne measurements of methane fluxes in Alaskan and Canadian tundra with the research aircraft Polar 5, *Berichte zur Polar-und Meeresforschung= Reports on polar and marine research*, *673,* 2014.

Kokelj, S.V., Zajdlik, B. and Thompson, M.S.:The impacts of thawing permafrost on the chemistry of lakes across the subarctic boreal-tundra transition, Mackenzie Delta region, Canada. *Permafrost and Periglacial Processes*, *20*(2), pp.185-199, 2009a.

Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L. and Coutts, R.: Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada. *Permafrost and Periglacial Processes*, *20*(2), pp.173-184, 2009b.

Justine Ramage 22/12/2017 10:55
Deleted:

Justine Ramage 3/1/2018 11:10
Deleted: Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E., Ping, C.L., Schirrmeister, L., Grosse, G., Michaelson, G.J.,

Justine Ramage 18/12/2017 13:10
Deleted:

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D. and Chin, K.S.: Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. *Journal of Geophysical Research: Earth Surface*, *118*(2), pp.681-692, 2013.

Kokelj, S. V., Tunnicliffe, J., Lacelle, D., Lantz, T. C., Chin, K. S., & Fraser, R.: Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. *Global and Planetary Change*, *129*, 56-68, 2015.

Kokelj, S. V., Lantz, T. C., Tunnicliffe, J., Segal, R., & Lacelle, D.: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. *Geology*, *45*(4), 371-374, 2017.

Koven, C.D., Schuur, E. a. G., Schädel, C., Bohn, T.J., Burke, E.J., Chen, G., et al.: A simplified, data-constrained approach to estimate the permafrost carbon– climate feedback. Phil Trans R Soc A, 373, 20140423, 2015.

Kuhry, P., Dorrepaal, E., Hugelius, G., Schuur, E. A. G. and Tarnocai, C.: Potential remobilization of belowground permafrost carbon under future global warming. Permafrost Periglac. Process., 21: 208–214. doi:10.1002/ppp.684, 2010.

Lacelle, D., Bjornson, J. and Lauriol, B.: Climatic and geomorphic factors affecting contemporary (1950–2004) activity of retrogressive thaw slumps on the Aklavik Plateau, Richardson Mountains, NWT, Canada. *Permafrost and Periglacial Processes*, *21*(1), pp.1-15, 2010.

Lantz, T.C. and Kokelj, S.V.: Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, NWT, Canada. *Geophysical Research Letters*, *35*(6), 2008.

Lantz, T.C., Kokelj, S.V., Gergel, S.E. and Henry, G.H.: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology*, *15*(7), pp.1664-1675, 2009.

Lamoureux, S.F. and Lafrenière, M.J.: Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. Arctic, Antarctic, and Alpine Research, 41(1), pp.59-68, 2009.

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), pp.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), pp.84-102, 2008.

Lantuit, H., Pollard, W.H., Couture, N., Fritz, M., Schirrmeister, L., Meyer, H. and Hubberten, H.W.: Modern and late Holocene retrogressive thaw slump activity on the Yukon coastal plain and Herschel Island, Yukon Territory, Canada. *Permafrost and Periglacial Processes*, *23*(1), pp.39-51, 2012a.

Lantuit, H., Overduin, P.P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D.L. and Graves-Gaylord, A.: The Arctic coastal dynamics database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts*, *35*(2), pp.383-400, 2012b.

Leibman, M., Gubarkov, A., Khomutov, A., Kizyaakov, A., Vanshtein, B.: Coastal Processes at the Tabular-Ground-Ice-Bearing Area, Yugorsky Peninsula, Russia. *Proceedings of the 9th International Conference on Permafrost*, Fairbanks, Alaska, pp. 1037–1042, 2008.

Justine Ramage 22/12/2017 10:11

Deleted: Koven, C.D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G. and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming. *Proceedings of the National Academy of Sciences*, *108*(36), pp.14769-14774, 2011.

Justine Ramage 18/12/2017 13:13

Deleted:

Lewkowicz, A. G.: Headwall retreat of ground-ice slumps, Banks Island, Northwest Territories, *Canadian Journal of Earth Sciences*, *24*(6), 1077-1085, 1987.

MacDougall, A.H., Avis, C.A. and Weaver, A.J.: Significant contribution to climate warming from the permafrost carbon feedback. *Nature Geoscience*, *5*(10), pp.719-721, 2012.

Mackay, J. R.: Glacier ice thrust features of the Yukon coast. *Geographical Bulletin, 13* 5-21, 1959.

Mackelprang, R., Waldrop, M. P., DeAngelis, K. M., David, M. M., Chavarria, K. L., Blazewicz, S. J., ... & Jansson, J. K.: Metagenomic analysis of a permafrost microbial community reveals a rapid response to thaw. *Nature*, *480*(7377), 368, 2011.

Malone, L., Lacelle, D., Kokelj, S. and Clark, I.D.: Impacts of hillslope thaw slumps on the geochemistry of permafrost catchments (Stony Creek watershed, NWT, Canada). *Chemical Geology*, *356*, pp.38-49, 2013.

McGuire, A.D., Koven, C., Lawrence, D.M., Clein, J.S., Xia, J., Beer, C., et al.: Variability in the sensitivity among model simulations of permafrost and carbon dynam- ics in the permafrost region between 1960 and 2009. Glob. Biogeochem. Cycles, 30, 2016GB005405, 2016.

Obu, J., Lantuit, H., Grosse, G., Günther, F., Sachs, T., Helm, V. and Fritz, M.: Coastal erosion and mass wasting along the Canadian Beaufort Sea based on annual airborne LiDAR elevation data. *Geomorphology,* 2016.

Ping, C.-L., Michaelson G. J., Guo L., Jorgenson M. T.,Kanevskiy M.,Shur Y.,Dou F., and Liang J.: Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline, J. Geophys. Res., 116, G02004, doi:10.1029/2010JG001588, 2011.

Pizano, C., Barón, A. F., Schuur, E. A., Crummer, K. G., & Mack, M. C.: Effects of thermo-erosional disturbance on surface soil carbon and nitrogen dynamics in upland arctic tundra. *Environmental Research Letters*, *9*(7), 075006, 2014.

Ramage, J. L., Konopczak A. M.; Herzschuh U.; Morgenstern A.; Couture, N.; Lantuit, H.: Coastal retrogressive thaw slumps along the Yukon Coast (Canada), link to shapefile. PANGAEA, doi:10.1594/PANGAEA.869573, 2016.

Ramage, J.L., Irrgang A.M, Herzschuh U., Morgenstern A., Couture N., Lantuit H.: Terrain Controls on the Occurrence of Coastal Retrogressive Thaw Slumps along the Yukon Coast, Canada. *Journal of Geophysical Research: Earth Surface,* 2017.

Rampton, V. N.: *Quaternary Geology of the Yukon Coastal Plain*, Geological Survey of Canada, Canada, 1982.

Schaefer, K., Lantuit, H., Romanovsky, V.E., Schuur, E.A. and Witt, R.: The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters*, *9*(8), p.085003, 2014.

Schuur, E.A., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H. and Mazhitova, G.: Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *AIBS Bulletin*, *58*(8), pp.701-714, 2008.

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. and Natali, S.M.: Climate change and the permafrost carbon feedback. *Nature*, *520*(7546), pp.171-179, 2015.

Segal, R.A., Lantz, T.C. and Kokelj, S.V.: Acceleration of thaw slump activity in glaciated landscapes of the Western Canadian Arctic. *Environmental Research Letters*, *11*(3), p.034025, 2016.

Justine Ramage 18/12/2017 13:14
Deleted:

Justine Ramage 22/12/2017 10:25
Deleted: Schaefer, K., Zhang, T., Bruhwiler, L. and Barrett, A.P.: Amount and timing of permafrost carbon release in response to climate warming. *Tellus B*, *63*(2), pp.165-180, 2011.

Tanski, G., Couture, N., Lantuit, H., Eulenburg, A. and Fritz, M.: Eroding permafrost coasts release low amounts of dissolved organic carbon (DOC) from ground ice into the nearshore zone of the Arctic Ocean. *Global Biogeochemical Cycles*, *30*(7), pp.1054-1068, 2016.

Tanski, G., Lantuit, H., Ruttor, S., Knoblauch, C., Radosavljevic, B., Strauss, J., Wolter, J., Irrgang, A.M., Ramage, J. and Fritz, M.: Transformation of terrestrial organic matter along thermokarst-affected permafrost coasts in the Arctic. *Science of The Total Environment*, *581*, pp.434-447, 2017.

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

Wolfe, S., E. Kotler, and S. Dallimore: Surficial characteristics and the distribution of thaw landforms (1970-1999), Shingle Point to Kay Point, Yukon Territory, *Rep.*, Geological Survey of Canada, 2011.

Justine Ramage 18/12/2017 13:14
Deleted:

Justine Ramage 22/12/2017 09:34
Deleted: (2001),